

# ***Triassic Evolution of the Yangtze Platform in Guizhou Province, People's Republic of China***

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## **ABSTRACT**

Deposition of shallow-water carbonates on the vast Yangtze Platform of south China spanned the late Proterozoic through Middle Triassic, accumulating as much as 4000 m during the Early and Middle Triassic. Deeper-water carbonates and siliciclastics accumulated to comparable thickness in the Nanpanjiang Basin southeast of the platform. After the demise of the platform, an additional 2500 m of mostly siliciclastics spread across the platform in Late Triassic. Deposition of platform carbonates was also widespread in the Permian of south China, but a transgression in perhaps the last 2 m.y. of the Permian combined with differential subsidence to reconfigure the Yangtze Platform in the Triassic. The margin retreated ~100 km northward in the Guiyang (eastern) sector, and a low-relief ramp developed over the flat top of the

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Permian platform, whereas the Early Triassic margin mimicked the Permian location in the Zhenfeng sector to the southwest. Nevertheless, deposition was essentially continuous from the Permian into the Triassic in most localities in Guizhou. Triassic deposition began with widespread terrigenous mud bearing thin-shelled bivalves or ammonoids. Renewed carbonate deposition within the Induan produced thin-bedded, laminated, dark-gray lime mudstone with planktonic biota in the basin interspersed with carbonate breccias. Thin-bedded lime mudstones with prominent burrows formed farther updip to the north and west. Thick intervals of oolite and of shallow-water lime mudstone interbedded with terrigenous clastic wedges that thicken and merge to the west mark the updip limit of deposition on a carbonate ramp. Platform-interior carbonates are more than three times as thick as their basinal equivalents.

The ramp configuration evolved into a flat-topped platform with a slight rim in the Olenekian, recorded by peritidal carbonate cycles at the platform margin and subtidal lagoonal muds and ultimately evaporites in the interior. Carbonate deposition spread farther westward to cover the terrigenous siliciclastics of the Induan. A major deepening event within the Olenekian is marked by black, ammonoid-bearing, nodular limestone and fissile shale. The patchy distribution of this facies indicates differential warping of the platform rather than purely eustatic causes. The basin received a starvation diet of siliciclastic and carbonate mud with minor silty turbidites and carbonate debris flows. At the end of Early Triassic, platform-interior deposits averaged 1175 m thick and basinal equivalents only 250 m.

Acidic volcanic ash spread across the Yangtze Platform at the Olenekian-Anisian transition. Anisian deposits in the Nanpanjiang Basin are dominantly siliciclastics that thicken dramatically in southwestern Guizhou and adjacent Guangxi. Biogenic framestones constructed by organisms of questionable origins, *Tubiphytes* and *Plexoramea*, assisted by sponges, arborescent corals, skeletal stromatolites, and copious encrusters, rimmed the Anisian platform. This rim collapsed along most of the Guiyang sector to form a basin-margin wedge 175 km long deposited by turbidity currents, debris flows, and rock fall. Collapse led to retreat of the margin by ~2.7 km; exceptionally by 10 km. In contrast the reef margin advanced slightly in parts of the Zhenfeng sector. Mud-dominated peritidal cycles formed in the lee of the reefs. Deposition in the platform interior was entirely subtidal with alternating episodes of normal marine water, hypersalinity, and siliciclastic influx. An increase in siliciclastic content eastward throughout the Middle Triassic signals the emergence of the Jiangnan Massif, which had been covered throughout the Permian and at least the Induan.

Platform sedimentation in the Ladinian features peritidal cycles that extended far into the interior to define a flat-topped platform. High depositional energy is reflected in grainstones and packstones composed of grapestone, bioclasts, and ooids. Barriers other than sand shoals appear to have been absent. Biogenic facies are confined to small outcrops of *Tubiphytes* and coral boundstone, interpreted as patch reefs. Tepee structures cap many cycles or disrupt successive cycles, indicating extended subaerial exposure. At the beginning of the Ladinian, the platform margin of the Guiyang sector prograded at least 0.6 km. In the Zhenfeng sector the margin retreated slightly, further indication of more rapid subsidence of the western part of the platform. The Nanpanjiang Basin apparently starved early in the Ladinian, but filled to overflowing with siliciclastic turbidites and mud in the later Ladinian or the early Carnian. Transport direction of the very fine sand of the turbidites was from the east, pointing to the Jiangnan Massif as a continued source of sediment, both by land onto the platform and by sea into the basin.

East and west sectors of the Yangtze Platform in Guizhou present stark contrasts during the Carnian and Norian. Shallow-water carbonate deposition continued into the Carnian in the Guiyang sector, but tongues of terrigenous mud and sand from the northeast reached to the platform margin and damped out carbonate deposition by the end of the Carnian. Erosion prevailed in the Norian, truncating formations

toward the north down to the level of the Anisian. Shallow-water carbonate deposition ended dramatically with the beginning of the Carnian in the Zhenfeng sector. Nodular-bedded, dark-gray lime mudstone with ammonoids overlies peritidal deposits, documenting the drowning of the Yangtze Platform. A very condensed sequence of black shale with concentrations of manganese, reduced iron, and organic carbon followed. Siliciclastic flysch and shallow-water sandstone totaling 1265 m thick filled the accommodation space resulting from the drowning by the end of the Carnian.

Norian deposits are cross-bedded sandstones and conglomerates that form thinning- and fining-upward cycles attributed to braided streams that encroached on coastal swamps represented by commercial coal and by mudrocks containing fresh-water, brackish, or marine fossils. The braided streams were rejuvenated and apparently reversed in the Rhaetian to form a coarse-grained clastic wedge that thins and fines toward the north and east across an erosion surface that cuts as deep as Anisian rocks in northern Guizhou. Jurassic and Lower Cretaceous rocks overlie the Rhaetian rocks concordantly, contradicting prevalent interpretations of a major orogeny (Indosinian) in the Late Triassic in Guizhou. The angular unconformity underlying Upper Cretaceous conglomerates dates major deformation in Guizhou as mid-Cretaceous.

**Keywords:** Yangtze Platform, Nanpanjiang Basin, carbonate platform, carbonate ramp, platform drowning, South China, Guizhou Province

## INTRODUCTION

The Yangtze Platform of south China was one of Earth's very large and very persistent regions of shallow-water deposition. Some superlatives, e.g., most persistent, thickest, and shallowest, pertain especially to the upper Yangtze region, including most of Guizhou Province and parts of neighboring Sichuan, Yunnan, Guangxi, Hunan, and points east (Fig. 1). Lower and Middle Triassic platform carbonates in Guizhou are 3100 m thick in a well-studied section at Longchang, Zhenfeng, and composite thickness exceeds 4000 m. Varied post-platform rocks of the Upper Triassic, mostly siliciclastic, add another 2500 m of strata.

There is quality as well as quantity. Sun Shu et al. (1989, p. 1250) represent the Triassic of the Yangtze block not only as the thickest sedimentary system, but also as the only one containing either potential source rock (Lower and Middle Triassic shales, cf. Zeng Hui, 1984) or "associated potential reservoir." Natural gas has been produced from the Sichuan basin for centuries; important new discoveries from Upper Triassic siliciclastic rocks are now coming online (Tom Wilker, Society of Exploration Geophysicists lecture, 2006). The global stratotype section and point (GSSP) for the base of the Triassic, i.e., the Permian-Triassic boundary, is a deep-water section within the Yangtze Platform at Meishan, Zhejiang (Yang Zunyi et al., 1995; Yin Hongfu, 1996; Jin Yugan et al., 1997). The GSSP for the Late Cambrian Furongian Series and its basal Paibian Stage is at Paibi in northwestern Hunan (Peng Shanchi et al., 2004). Stratotypes proposed from the Yangtze Platform, but not adopted, include the base of the Cambrian near Kunming, Yunnan, the base of the Carboniferous at Guilin, Guangxi (Yu Changmin, 1988), and at Dapoushang, Guizhou (Ji Qiang et al., 1989), and the base of the Olenekian at Chaohu, Anhui, (Tong Jinnan et al., 2004). One of

the most complete, best documented, and most precisely dated Scythian sections in the world, thus a potential GSSP, lies at the margin of the isolated Great Bank of Guizhou, within the Nanpanjiang Basin on the Yangtze Craton (Montgomery et al., 2000; Martin et al., 2001; Lehrmann et al., 2002, 2005, 2006b). Ongoing research in the area includes evaluating controls on the birth, development, and death of carbonate platforms through comparative analysis of the Yangtze Platform and isolated platforms within the Nanpanjiang Basin (Enos et al., 1997, 1998, 2003; Lehrmann et al., 1998, 2004a, 2006b; Druke et al., 2001; Koenig et al., 2001; Montgomery et al., 2002, 2003; Kessel et al., 2002; Minzoni, 2003a, 2003b; Minzoni et al., 2003; Gross et al., 2003; Steffen et al., 2002), recovery from the end-Permian extinction (Lehrmann, 1999; Lehrmann et al., 2003a, 2003b, 2006a; Payne et al., 2003, 2004; 2006), biota (Stiller, 2001; Bucur and Enos, 2001; Bucur et al., 2003; Lehrmann et al., 2003b, 2004b; Stiller and Chen Jinhua, 2004; Christensen and Lehrmann, 2004; Payne, 2005; G.D. Stanley, Jr., unpublished), stratigraphy (Tong Jinnan, 1998; Tong Jinnan et al., 2000; Wang Hongmei et al., 2003), magnetostratigraphy and magnetic susceptibility (Montgomery et al., 2000, 2002), cyclostratigraphy (Lehrmann et al., 2001; Yang Wan et al., 2002; Yang Wan and Lehrmann, 2003), geochronology (Martin et al., 2001; Lehrmann et al., 2002, 2006b), and geochemistry (NewKirk et al., 2002; Krull et al., 2004; Payne et al., 2004).

The Yangtze Platform covered most of the Yangtze Craton, a former tectonic plate that now extends west from beneath the South China Sea to the Longmenshan, a forerange of the Himalayas, and north from the Red River (Songma) transform in Vietnam, beyond the Yangtze River to sutured margins in the Qinlingshan and Dabieshan (Fig. 1; Wang Hongzhen, 1985; Yang Zunyi et al., 1986; Liu Baojun and Xu Xiaosong, 1994; Enos,

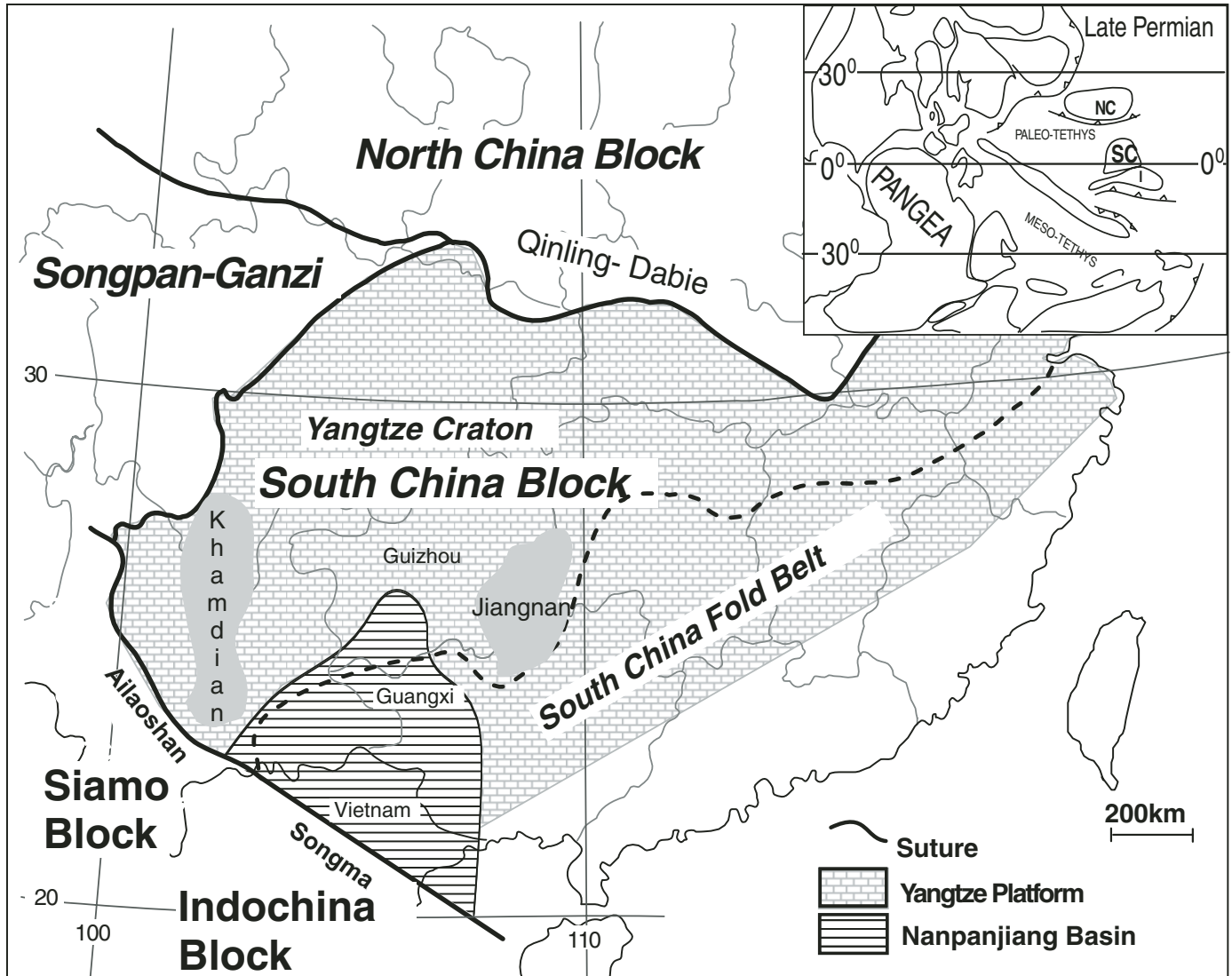


Figure 1. Location and regional setting of the Yangtze Platform. Compiled from numerous sources. Khamdian and Jiangnan Massifs (shaded) after Wang Hongzhen (1985). Paleogeographic inset is from Metcalfe (1996). Abbreviations: NC—North China Block; SC—South China Block; I—Indochina.

1995; Xu Xiaosong et al., 1996; Xu Qiang et al., 1996). Deposition near sea level of quite mature facies, predominately carbonates with intermittent shale and sandstone, extended from the late Proterozoic (late Sinian) through the Middle Triassic, from 850 to 230 Ma, punctuated by some intervals of erosion and reconfiguration. During this time the Yangtze Plate migrated from the northern margin of Gondwanaland, possibly adjacent to Australia or to the eventual Himalaya-Iran region (Metcalfe, 1996), to a suture with the Sino-Korean Craton and, ultimately, with Eurasia, beginning by at least the Late Triassic (Enos, 1995, and references therein). The Yangtze Plate was near the equator in the Permian and had reached 10°N (Enkin et al., 1992) to 30°N (Metcalfe, 1996; Zhao Xixi et al., 1996) by the Late Triassic. The Yangtze Platform formed passive margins of the Yangtze Plate until the

closing stages of this odyssey; it contains the most voluminous and longest record of marine deposition in all of China (Enos, 1995; Xu Xiaosong et al., 1996; Koenig et al., 2001). The southwestern part of the Yangtze Plate, in northern Vietnam, Guangxi, eastern Yunnan, and southern Guizhou, was markedly less stable and less positive. This region, characterized by deeper-water facies, is the Nanpanjiang Basin, also variously called the Youjiang, Dian-Qian-Gui, or Yunnan-Guizhou-Guangxi Basin. Within the basin several large, isolated carbonate platforms developed at various times. The basin was well defined in the Permian and Triassic. Probable precursor basins and platforms extend back to Early Devonian.

Guizhou Province lies entirely within the Yangtze Plate and straddles the margin of the Yangtze Platform with the Nan-

panjiang Basin. Guizhou has been called a “‘treasure-house of stratigraphy and paleontology’ ... characterized by its complete sequences through time,” beginning with the middle and late Proterozoic (Guizhou Bureau, 1987, p. 665). In detail, the sedimentary record is far from complete in many areas within Guizhou. A major unconformity between the Silurian and Devonian is recognized platform wide, and Upper Ordovician through Silurian strata are absent in south and southwest Guizhou (Xu Xiaosong et al., 1996). In southwestern Guizhou, the stratigraphic record from the Devonian through Triassic, capped by continental Jurassic rocks, is essentially complete (Guizhou Bureau, 1987; Koenig et al., 2001). Older rocks are not exposed. In contrast, most of Guizhou north of the latitude of Guiyang was exposed throughout the Devonian and Carboniferous. A major transgression beginning in the Early Permian covered virtually the entire Yangtze Plate. As a consequence, Permian strata rest on older rocks in many areas toward the north and west of Guizhou; for example, on Silurian over much of northeastern Guizhou; locally on Cambrian northeast of Guiyang; and directly on Proterozoic within the Jiangnan Massif in eastern Guizhou (Guizhou Bureau, 1987, map). Similarly, although less dramatically, the Carboniferous overlies strata of various ages, including Proterozoic in the southern Jiangnan Massif, but wedges out beneath the Permian in northern Guizhou. The Triassic continued uninterrupted deposition from the Permian, with local exceptions, but a widespread unconformity underlies latest Triassic (Rhaetian?) rocks over northern Guizhou. Paleogeologic maps of Guizhou would reveal many broad structures that have received little notice.

Triassic sedimentary rocks of varied lithologies and facies crop out over more than half of the area of central and western Guizhou. Similar rocks crop out or underlie vast areas in the adjacent provinces, Sichuan, Yunnan, Guangxi, and Hunan. The Triassic facies in Guizhou include the transition from the platform carbonates of the Yangtze Platform into the south-adjacent Nanpanjiang Basin. Such transitional zones are critical for reconstructing sequence stratigraphy and for interregional correlations. The need for a summary of the stratigraphy and sedimentology of the Triassic strata of Guizhou in a western language and an accessible source is therefore paramount. Fan Jiansong (1980) gave a relevant summary in a short paper covering the entire Yangtze Platform and the west-adjacent mobile belt. Fan's focus was on Sichuan and Hubei, and only secondarily on Guizhou. Yang Zunyi et al. (1986) include a short sketch of the Triassic of the Yangtze Platform and the Nanpanjiang (Youjiang) Basin with emphasis on Guangxi and Guangdong in their stratigraphic *Geology of China*. Wang Hongzhen (1985), Wang Liting et al. (1992), Liu Baojun and Xu Xiaosong (1994), Xu Qiang et al. (1996), and particularly Xu Xiaosong et al. (1996) placed the Yangtze Platform in the broader context of the paleogeography of China. Tong Jinnan (1998) and Tong Jinnan et al. (2000) provided detailed analyses of selected Middle Triassic sections in southern Guizhou and stressed tectonic control of facies development. Although the senior authors cannot read the Chinese literature, we have searched extensively for relevant summaries of Triassic

stratigraphy in China and failed to find any of sufficient scope to warrant translation. Many items located in the searches included useful illustrations or English summaries. These are cited in the text where relevant. Fan's coverage and the subsequent summary papers are necessarily very generalized. Moreover, important new regional and local studies have been conducted in the interim (Guizhou Bureau, 1987; Wei Jiayong and Enos, 1991; Lehrmann, 1993; Yang Shouren et al., 1995; Wei Jiayong et al., 1996; Wang Liting, 1996; Xu Xiaosong et al., 1996, Enos et al., 1997, 1998; Lehrmann et al., 1998; Tong Jinnan, 1998; Tong Jinnan et al., 2000). The goal of this paper is to provide a more detailed, up-to-date summary that incorporates past studies, presents new data from our fieldwork, introduces observations from polished slabs and thin sections, updates interpretations, and provides the stratigraphic and sedimentologic background for the numerous ongoing studies in the region.

This survey focuses on the region of Guizhou west of the Jiangnan Massif in eastern Guizhou and adjacent provinces (Wang Hongzhen, 1985; Sheng Jinzhang et al., 1985; Xuefeng massif of Fan Jiansong, 1980) and south of 27°N latitude, some 50 km north of Guiyang (Fig. 1). Most information, from both personal observations and the accessible literature, are from the general area of the Yangtze Platform margin extending from Guiyang to the vicinity of Zhenfeng. An isolated carbonate platform persisted in the Nanpanjiang Basin in southern Guizhou, between Bianyang and Luodian, throughout the Early and Middle Triassic. The evolution of this platform, the Great Bank of Guizhou, was documented by D.J. Lehrmann (1993; Lehrmann et al., 1998) and will not be included in this report. Many generalizations about the depositional history of the Yangtze Platform are valid throughout southwestern Guizhou. However, some striking differences exist within the platform, particularly in the Late Triassic, but also in the Late Permian, at the Permian-Triassic transition, and in the Anisian. For this reason it is convenient to distinguish the western part of the platform, west of the north-south trending sector of the platform margin, from the northeastern part where the platform margin trends east-northeast (Fig. 2). These will be referred to as the Zhenfeng sector to the west and the Guiyang sector to the northeast. At the very least, subsidence rates differed significantly during several episodes of deposition and entirely different Upper Triassic formations are mapped in the two sectors.

The most important single source of published information by far is the *Regional Geology of Guizhou Province*, by the Guizhou Bureau of Geology and Mineral Resources (Guizhou Bureau, 1987), part of the Geological Memoirs series of provincial geologic maps by the Ministry of Geology and Mineral Resources of the People's Republic of China. The series is in Chinese, with rather sketchy English summaries. A somewhat updated summary is provided by Liu Yuzhou (1996). The Guizhou geologic map (Guizhou Bureau, 1987) scale is 1:500,000; the structural map, 1: 1 million. The mapping practice is closer to the European biostratigraphic definition of formations than to the strictly lithologic definition that has prevailed in North America for decades.

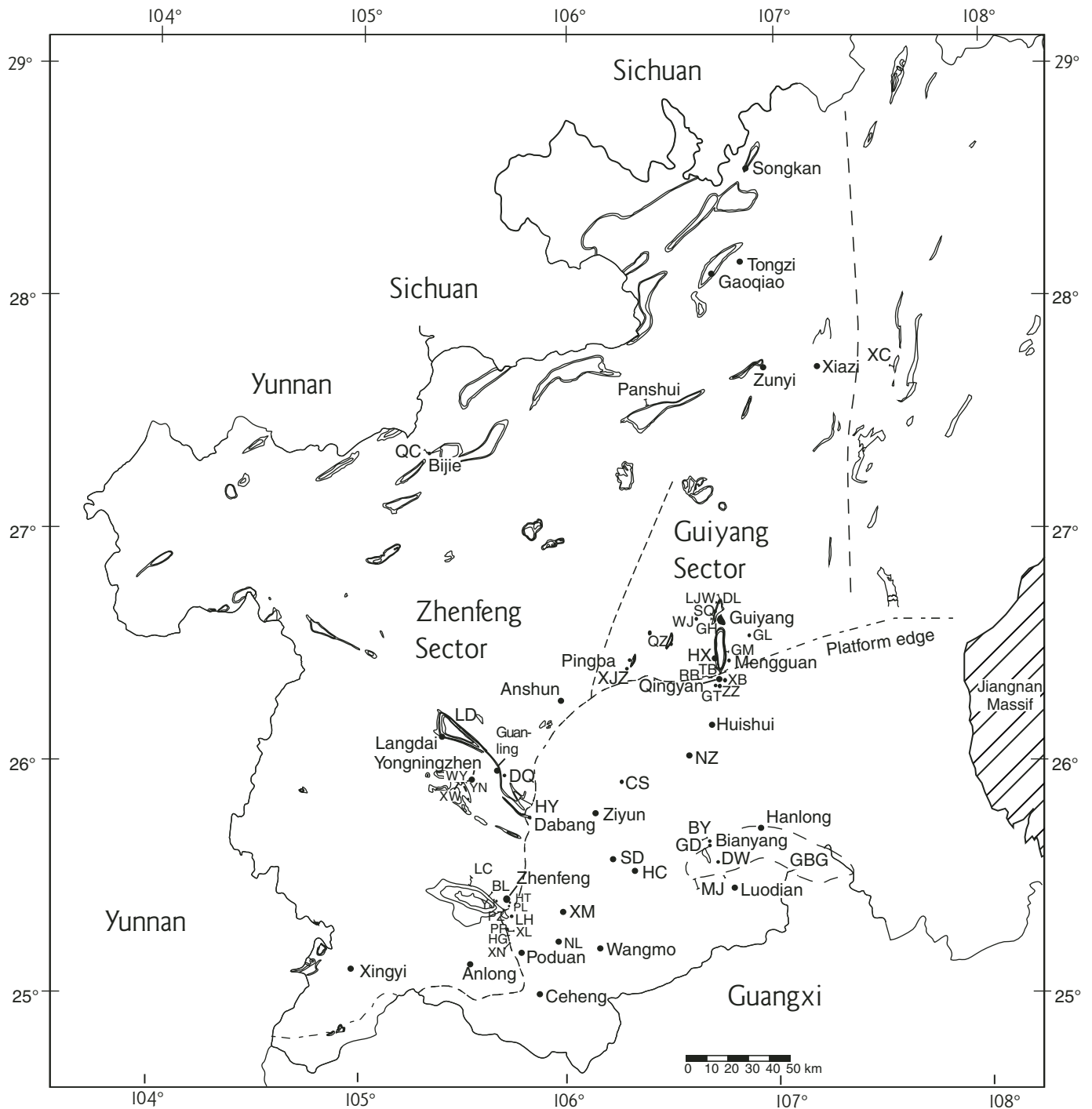


Figure 2. Guizhou locations mentioned in text. Sections measured or studied in detail for this project are in bold type. Upper Triassic outcrop patterns are shown for reference. Abbreviations: **BL**—Beila; **BY**—Bianyang; CS—Chayeshao, Bandang; **DL**—Dulaying; **DQ**—Duanqiao; **DW**—Dawen; GBG—Great Bank of Guizhou; **GD**—Guandao; GH—Gui-Huang Highway; GL—Gouli; **GM**—Gaimao; **GT**—Gutong; **HC**—Houchang; HG—Huagaoling; **HT**—Hetaoshu; **HX**—Huaxi; **HY**—Hongyan; **LC**—Longchang; **LD**—Langdai; **LH**—Lianhe; **LJW**—Lingjiawan; **MJ**—Mengjiang; NL—Niluo; NZ—Nulizhai; PL—Panlong; PP—Popin; **PZ**—Huangpingzhai; **QC**—Qingchang, Bijié; **QZ**—Houwu-Moshichong, Qingzhen; **RR**—Renrenshan; SD—Sidazhai; **SQ**—Sanqiao; **TB**—Tongmuling and **Bojishan**; **WJ**—Wenjing; **WY**—Wayao; **XB**—Xiaobaituo; **XC**—Xiazichang; **XJZ**—Xiaojianzhuang; **XL**—Xialadi; **XM**—Xuman; **XN**—Xinchin; **XW**—Xiaowa; **YJ**—Yaojiawan; **YN**—Yongningzhen; **ZZ**—Zhulinzhai.

In China most formations are initially defined to coincide with stage boundaries, although they are necessarily recognizable in the field by lithologic criteria. In Guizhou, three or more roughly time-equivalent lithofacies are distinguished as formations within most stages. In general these formations represent basin, platform-margin, and platform-interior lithofacies; finer lithofacies subdivisions are mapped within some stages. This practice has the advantages of providing a neatly compartmentalized stratigraphic overview (Table 1) and facilitating paleogeographic mapping, but it carries the liability of obscuring diachronous formation boundaries and perhaps leads to overly facile correlations with stage stratotypes, mostly located in Europe and deposited on plates with very different histories. With these caveats, the quality of the mapping is excellent.

Triassic measured sections from Guizhou, some unpublished, and several formation summaries were translated into English by Wei Jiayong and by Yu Liansheng, Nanjing. Sections, originally measured at scales of 1:2,000 or greater, were generally published without a graphic log. Descriptive units are a few meters to over 100 m thick. Descriptions include general lithology (e.g., limestone, dolostone, claystone), color, relative bed thickness (e.g., thin, medium), grain size and sorting of coarser siliciclastics, and thorough lists of megafossils. Bivalves and ammonoids are typically listed by genus for each unit. Where such sections are cited in this paper, beyond simply formation thickness, the senior author and Wei Jiayong, in some cases with accomplices, reviewed the section in the field, took additional notes, and, in some instances, sampled lithologies. Our own fieldwork included 20 measured sections, spanning slightly more than 10,000 m of strata. We studied more than 700 thin sections and 1700 polished slabs. Field time, in months, on this and related projects totaled: PE 13, DJL 15, DC 2, MM 5, AB 1 1/2, PM 1. Wei, Yu, and Xiao have spent their professional lives studying Guizhou stratigraphy.

## DALONG FORMATION (UPPER PERMIAN, TATARIAN)

The major sedimentary-tectonic sequence that extends through most of the Triassic began in the Late Permian, rather than at the Permo-Triassic boundary as in most areas of the world. A wide area of the Yangtze Platform in south-central Guizhou drowned early in the transition from Permian to Triassic, as the Nanpanjiang Basin encroached northward ~100 km in the Guiyang sector (Figs. 3, 4; Guizhou Bureau, 1987; Lehrmann, 1993; Enos, 1995; Lehrmann et al., 1998, p. 313). This drowning episode is represented by the Upper Permian Dalong Formation.

The Dalong Formation blanketed the Yangtze Platform in the Guiyang sector and extends well into the middle of the Zhenfeng sector and into provinces farther east. The Permian-Triassic boundary in most parts of Guizhou appears conformable and without a significant time gap, so this formation is of inherent interest as it represents some of the youngest Permian deposits on Earth, as well as recording this critical transition in southern Guizhou and over much of the eastern part of the Yangtze Platform to the East China Sea (Liu Baojun and Xu Xiaosong, 1994, p. 129; Enos, 1995, p. 250). This unit was not studied in any detail, but was observed in reconnaissance at Guandao and Hanlong (north margin of the Great Bank of Guizhou), Dulaying, Xiaobaituo (east of Qingyan), Gaimao, Ziyun, and Nulizhai (Fig. 2). Complete sections were described by the Guizhou Bureau (1987, p. 261, 265) and Lehrmann (1993, p. 327).

The Dalong Formation is quite thin (10 to 20 m; Guizhou Bureau, 1987, p. 265, 268; Lehrmann, 1993, p. 31, 327) over large areas where it overlies Upper Permian (upper Tatarian) platform carbonates of the Changxing Formation, but is locally as thick as 72 m in southern Guizhou (Guizhou Bureau, 1987, p. 261). The thicker Dalong in southern Guizhou overlies older carbonates of the Wujiaping Formation and may represent the entire

TABLE 1. STRATIGRAPHIC NOMENCLATURE OF THE TRIASSIC SYSTEM SOUTHWESTERN GUIZHOU PROVINCE

Stage	Platform interior	Platform margin	Basin	Guiyang sector
Rhaetian?	Erqiao Formation	Erqiao Formation	No strata preserved	Erqiao Formation
Norian	Huobachong Formation	Huobachong Formation	No strata preserved	Hiatus
Carnian	Banan Formation	Banan Formation	No strata preserved	Sanqiao Formation
	Laishike Formation	Laishike Formation	Laishike Formation (local)	Sanqiao Formation
	Wayao Formation	Wayao Formation	Bianyang Formation?	Gaicha Formation
	Zhuganpo Formation	Zhuganpo Formation	Bianyang Formation	Gaicha Formation
Ladinian	Yangliujing Formation*	Longtou Formation	Bianyang Formation	Longtou Formation
Anisian	Guanling Formation*	Poduan Formation	Xinyuan Formation Xuman Formation	Poduan Formation Qingyan Formation†
Olenekian	Yongningzhen Formation	Anshun Formation	Ziyun Formation	Anshun Formation
Induan	Yelang Formation	Daye Formation	Luolou Formation	Daye Formation
	Feixianguan Formation			

Note: Adapted from Guizhou Bureau (1987) and Yang Shouren et al. (1995).

\*Badong Formation spans Middle Triassic and perhaps part of Late Triassic in northeastern Guizhou (see Figs. 12 and 55).

†Qingyan Formation is basin margin.

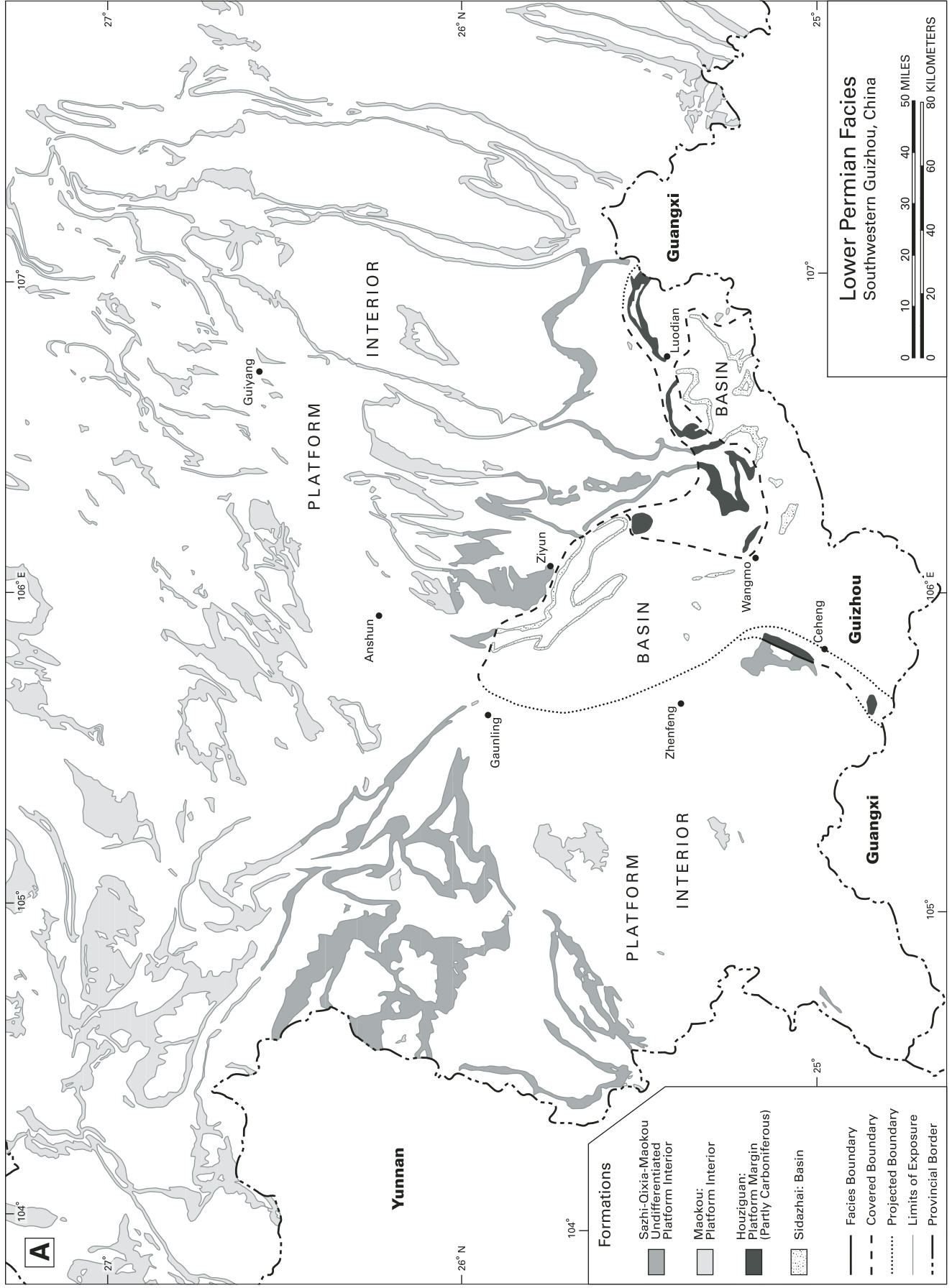


Figure 3 (on this and following page). Permian facies distribution in southwestern Guizhou Province. Compiled from the Geologic Map of Guizhou (1:500,000; Guizhou Bureau, 1987). "BASIN" corresponds to the northern end of the Nanpanjiang Basin in Figure 1. "PLATFORM" is the southern part of the Yangtze Platform. Formations, represented by patterns on the map, are essentially time-equivalent facies. (A) Lower Permian. (B) Upper Permian. Modified significantly from Enos et al. (1998, p. 58).

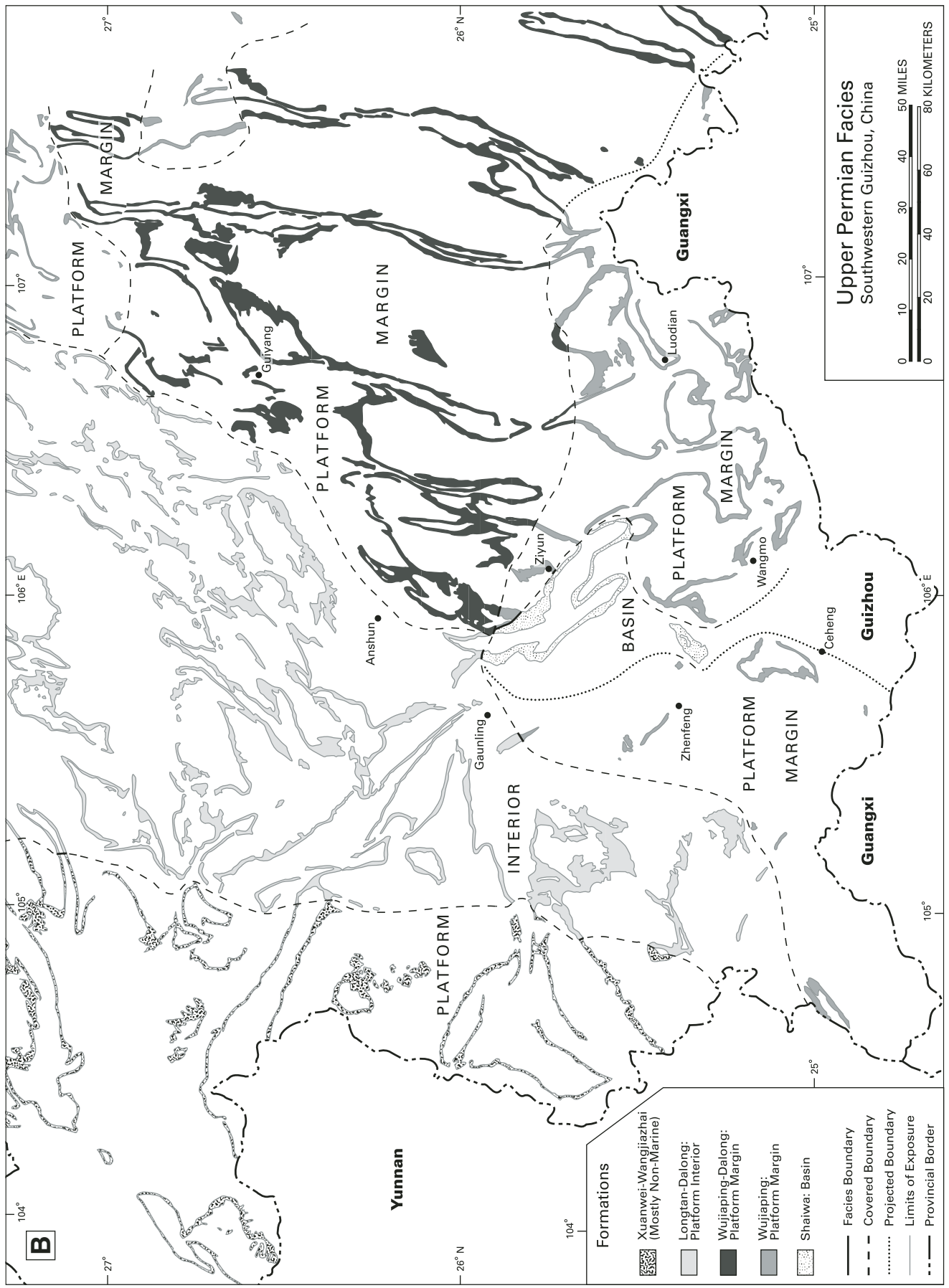


Figure 3 (continued).

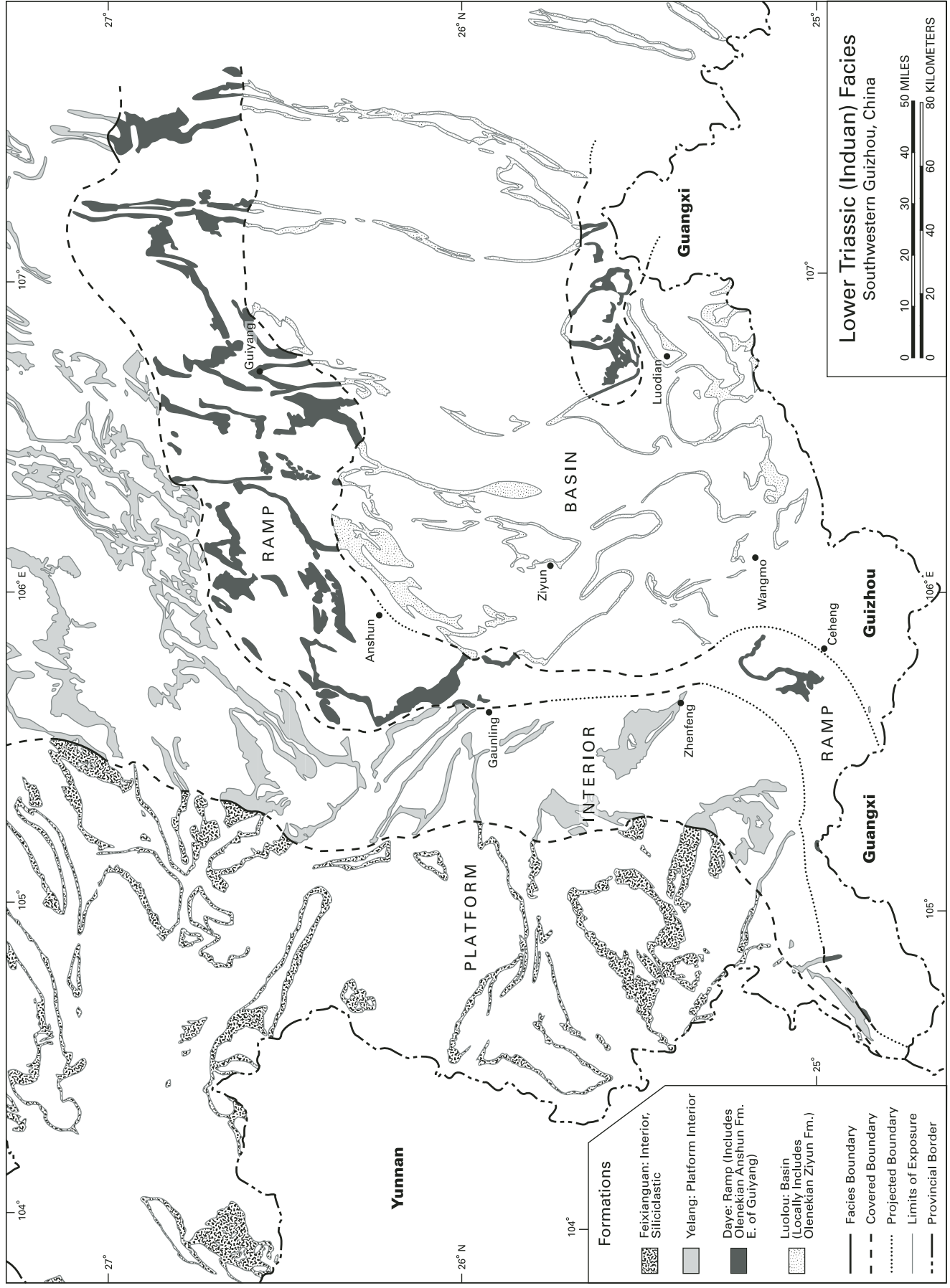


Figure 4. Induan (lower Lower Triassic) facies distribution in southwestern Guizhou. Compiled from the Geologic Map of Guizhou (1:500,000; Guizhou Bureau, 1987). "BASIN" corresponds to the northern end of the Nanpanjiang Basin in Figure 1. "PLATFORM" is the southern part of the Yangtze Platform. Formations, represented by patterns on the map, are essentially time-equivalent facies.

late Tatarian (Changxingian; Guizhou Bureau, 1987, p. 271). The lower part of the thick Dalong is thus time equivalent to the Changxing Formation and probably the upper part of the Wujiaping Formation, platform and reef limestones, elsewhere in Guizhou (cf. Guizhou Bureau, 1987, p. 259, 271; Enos, 1995, p. 231). In most areas both the lower and upper contacts of the Dalong are considered conformable (cf. Guizhou Bureau, 1987, p. 261, 265). The regional relationships with the underlying carbonates indicate, however, that the lower contact is either diachronous or disconformable. An example of disconformity occurs at Ziyun where the top of the famous Wujiaping reef section is truncated by a paleokarst surface with at least 10 m of relief (Wei Jiayong and Enos, 1991). Some of the karst depressions are filled with terrigenous mudrock that probably represents the Dalong Formation. At Houchang, 65 km southeast of Ziyun along depositional strike of the Permian platform margin, the Lower Triassic Luolou Formation rests on a very thin Upper Permian section consisting mostly of conglomerate. This indicates an appreciable hiatus with perhaps 450 m of erosional truncation between Ziyun and Houchang (Fig. 5).

Thin-bedded siliceous mudstone and chert interlayered with dark shale characterize the Dalong. Typical mudstone beds are 5 to 10 cm thick, break with straight to subconchoidal fracture, and occur in bundles several decimeters thick. Vague to well-developed millimeter lamination is interrupted by narrow, meniscate burrows. Rare, fossil-rich lenses are calcareous despite extensive silicification. Along the north margin of the Great Bank of Guizhou, the calcareous intervals are cherty lime mudstone and wackestone (Lehrmann, 1993, p. 31). Dark-gray shale or blocky claystone makes up about half of the unit. Adjacent to the Great Bank of Guizhou, shale is confined to partings in the base of the unit, but becomes progressively more abundant toward the top (Lehrmann, 1993, p. 31). The dark shades of the unit result from shreds of organic matter concentrated in burrows and along wispy stylolites and from disseminated pyrite. Flakes of biotite

are rare. Brown, translucent, nearly isotropic material filling some fossils is probably phosphate (collophane).

Fossils seen in outcrop include ammonoids, small brachiopods, and pectinid, possibly nektonic, bivalves. In thin section, numerous siliceous spheres, ~150  $\mu\text{m}$  in diameter, are probably filled and recrystallized radiolarians. Other fossils—bivalve fragments, gastropods, ostracodes, globular foraminifers, and echinoid spines—are small (less than 1 mm) and generally silicified. Larger bivalves are packed in small lenses. Biota reported from the literature elsewhere in south China includes ammonoids, radiolarians, sponge spicules, bivalves, brachiopods, including *Lingula*, and the trace fossils *Chondrites* and *Planolites* (Enos, 1995, p. 250, and references therein).

Fossils from the Dalong Formation (Guizhou Bureau, 1987, p. 261, 265; Enos, 1995, p. 250):

Plants: *Ullmannia* sp., *U. cf. bronniei*, *U. cf. frumentaria*, *Bergenia* sp.

Brachiopods: *Cathaysia sulcatifera*; *Choneinella substrophomenoides*, *Fusichonetes pigmaea*, *Keyserlingina guizhouensis*, *Waagenites barusiensis*, *Lingula* sp.

Bivalves: *Paradoxipecten latisinus*, *Pseudomonotis* sp.

Cephalopods: *Huananoceras cf. qianjiangense*, *H. cf. perornatum*, *Pachydiscoceras* sp., *Pentagonoceras? guangyuanense*, *Permiodoceras* sp., *Pleuronodoceras* sp., *P. anshunensis*, *P. cf. densiplicatum*, *Pseudogastrioceras* sp., *Pseudotirolites* sp., *P. anshunensis*, *P. asiaticus*, *P. disconnectus*, *P. laibinensis*, *P. uniformis*, *Qinglongites costatus*; *Rotodiscoceras* sp., *Sinoceltites curvatus*, *Tapashanites* sp., *Xenodiscoceras* sp.

Approximation of Dalong accumulation rates is feasible in southern Guizhou, where it appears to span the entire late Tatarian, an interval perhaps as long as 7.5 m.y. (Menning, 1989) or as short as 3 m.y. (Haq et al., 1988). The disparity in these age estimates illustrates the imprecision, or perhaps the futility, of such calculations of accumulation rates. Preserved thickness

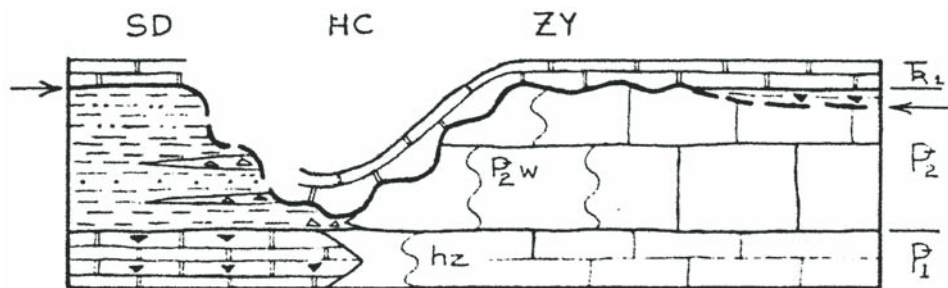


Figure 5. Permian-Triassic transitions in a schematic cross section from Ziyun (ZY) on the Permian Yangtze Platform southeast toward Houchang (HC) at the platform margin and west to Sidazhai (SD) in the Nanpanjiang Basin (Fig. 2 for locations). Arrows point to a sequence boundary overlain by the Upper Permian Dalong Formation (thin wedge of chert and mudrock at right) on the platform and directly by the Lower Triassic Luolou Formation ( $\text{Tr}_1$ ) in the basin (left). The surface generally appears conformable, but is karstic at ZY and truncates nearly the entire Upper Permian section at HC. No truncation is recognized at SD. Other Upper Permian units are the Wujiaping limestone ( $\text{P}_{2w}$ ) and Sidazhai Formation in the basin (cf. Table 1). Lower Permian units are the Houziguan Limestone (hz) at the platform margin and the Shaiwa Formation in the basin. Not to scale.

of 72 m indicates rates of 10 to 24 m/m.y. Rates for the thinner Dalong overlying late Tatarian platform carbonates can be calculated on the hefty assumption that platform drowning corresponds to the basinward shift in coastal onlap recognized at 2 m. y. before the end of the Permian (Haq et al., 1988). For an 11.6-m section (Lehrmann, 1993, p. 327) the rate would be a miniscule 5.8 m/m.y. Warping of lamination around some fossils, tigmatic folding of fracture fills, and small swarms of wispy stylolites all indicate appreciable compaction; thus original accumulation rates were greater, perhaps severalfold.

The dominance of pelagic and siliceous fossils, the fine grain sizes, uniform bedding, and slow rates of accumulation indicate deep and distal environments of deposition. Fine lamination, sparse burrows, and depauperate benthic fauna suggest low oxygen levels. Good preservation of originally aragonitic fossils, ammonoids and some bivalves, shows that the bottom lay above the aragonite compensation depth, but widespread and apparently early (pre-compaction) silicification may reflect deposition within the aragonite lysocline, a depth that is variable and difficult to quantify even in the present oceans. The change from platform limestones to deep-water deposits, which began in the mid Tatarian locally along the rim of the Nanpanjiang Basin and spread over much of the Yangtze Platform in the latest Permian, reflects a regional transgression near the end of the Permian (cf. Lehrmann, 1993, p. 189; Yang Zunyi et al., 1993; Enos, 1995, p. 251). The end of Permian has long been considered a time of maximum emergence of the continents, but Haq et al. (1988) show a transgressive cycle beginning in the mid Tatarian, which is more consistent with the stratigraphy of the Yangtze Craton.

### INDUAN (LOWER LOWER TRIASSIC) FORMATIONS

Drowning of the Yangtze Platform in south-central Guizhou in latest Permian is expressed paleogeographically by northward encroachment of the Nanpanjiang Basin margin by ~100 km in central Guizhou (Figs. 3, 4; Guizhou Bureau, 1987; Lehrmann, 1993; Enos, 1995). A new platform margin with a sigmoidal trace was established that persisted with minor changes throughout the Early and Middle Triassic (Fig. 4). In southwestern Guizhou, the Triassic platform margin apparently perpetuated the position of the Permian platform margin (Figs. 3, 4), although the Permian margin is here poorly constrained. Deposition on the Yangtze Platform continued to be dominated by shallow-water carbonates with intermittent terrigenous influx from the Khamdian massif to the west (Wu Yinglin and Yan Yangji, 1987; Wang Hongzhen, 1985; Liu Baojun and Xu Xiaosong, 1994, p. 146).

The early part of the Early Triassic, approximately the Induan Stage, is represented within the study area by four time-equivalent lithofacies: the Luolou, Daye, Yelang, and Feixianguan Formations (Fig. 4). Transitions between these formations are much broader and more gradual than in younger Triassic formations. The Luolou, Daye, and Yelang overlie the Dalong Formation, except in the northeast where shallow-water limestone of the Wujiaping Formation is the youngest Permian (Figs.

3, 4; Guizhou Bureau, 1987). Farther west, the siliciclastic Feixianguan Formation overlies mainly Upper Permian nonmarine siliciclastics, but encroaches eastward onto marginal marine deposits and the Dalong Formation. Permian-Triassic transitions are invariably reported as conformable, which, with the local exceptions mentioned above, agrees with our reconnaissance observations. The top of Permian is variously defined by last occurrences of index conodonts, fusulinids, or ammonoids or by the first occurrence of Triassic forms. Not surprisingly, the last occurrence of the respective index forms is generally not at the same level within a given section, whether because of facies control, vagaries of preservation, reworking, or real differences in time of extinction. Similar problems arise with defining the base of the Triassic, variously recognized as the first occurrence of index ammonoids, conodonts, or, most commonly in China, bivalves. The situation has improved with the widespread acceptance of the first occurrence of the conodont *Hindeodus parvus* to define the base of the Lower Triassic (Paull and Paull, 1994; Yin Hongfu et al., 1996; Lehrmann et al., 2003a). Conodonts are rare in most platform carbonates, however. More troublesome is the common occurrence at the Permo-Triassic transition of an argillaceous interval a few decimeters or meters thick that contains typical Permian brachiopods and ammonoids together with distinctive Triassic elements (cf. Sheng Jinzhang et al., 1985; Yang Zunyi et al., 1993; Lehrmann et al., 2003a). This so-called boundary clay is often not conspicuous in outcrop, because the lowermost Triassic deposits are generally argillaceous in southern Guizhou. As a field definition, the last occurrence of lithologies typical of the uppermost Permian formations, siliceous mudstone or shallow-water limestone, and the first occurrence of the bivalve *Claraia*, common in the lowermost Triassic mudrocks, is sufficiently precise for mapping. Where the uppermost Permian is carbonate, diagnostic fossils such as fusulinids, rugose corals, or productid brachiopods are generally present.

### Luolou Formation

The Luolou Formation is typically thin-bedded, dark-gray lime mudstone (Fig. 6) with local limestone breccias and varying proportions of terrigenous mudrock<sup>1</sup> concentrated toward the base. The formation is confined to the Nanpanjiang Basin; the type locality is at Lingyun, Guangxi (Yang Zunyi et al., 1993, p. 2), where it spans the entire Scythian. In Guizhou, Luolou has long been used for a couplet of terrigenous rocks grading up into lime mudstone and breccia that appear confined to the Induan Stage (Guizhou Bureau, 1987), although in some recent mapping it has been expanded to include all of the Lower Triassic. The Luolou was measured in detail at Hongyan. Locations studied in reconnaissance were Xiaobaituo (3.5 km east of Qingyan), Zhulinzhai (southeast of Qingyan) Ziyun, Bianyang, Gouli, and Nulizhai. The thickness of the Luolou Formation

<sup>1</sup>Mudrock is an inclusive term for fine-grained siliciclastic rocks: Shale, siltstone, mudstone, and claystone (Blatt et al., 1980, p. 381).



Figure 6. Typical lime mudstone from Luolou Formation (upper part). East of Qingyan 3.5 km.

was measured as 191 m at Nulizhai (Guizhou Team, unpublished section) and 85 m at Chayeshao, Bandang (19 km north-east of Ziyun; Guizhou Bureau, 1987, p. 303). Estimated thickness at Xiaobaituo is only ~18 m. The Luolou is 270 m thick at Hongyan, but cannot be considered complete because it is overstepped by the Daye Formation. Guizhou Bureau (1987, p. 302) cites a range of thickness in Guizhou of 30 to 392 m. Farther south in the Nanpanjiang Basin, including the type locality in Guangxi, the Luolou encompasses a more diverse suite of rocks, including considerable mudrock and sandstone (Zhang Jiyan, 1999, personal commun.), that represent the entire Scythian (Lower Triassic). Consequently, the unit is considerably thicker, reportedly up to 2042 m (Guangxi Zhuang Autonomous Region Bureau, 1985, p. 788), although a later report cites 40 to 538 m (Guangxi Bureau, 2000, p. 34).

The base of the Luolou is mudrock at most localities. For example, the basal 65 m at Hongyan are gray calcareous mudstone that weathers brown. Bedding is centimeter scale and generally planar, but more calcareous intervals up to several decimeters thick weather spheroidally. It is possible that in very fresh outcrops the entire interval would be logged as argillaceous lime mudstone. Tuff beds 5 to 10 cm thick occur at the Permo-Triassic contact and 13 m higher at Hongyan. Tuff or bentonitic clay is reportedly common at other localities in south China (Yang Zunyi et al., 1993). Thin-bedded lime mudstone 40 m thick overlies the basal mudrock at Hongyan. The overlying 60 m are poorly exposed but appear to be calcareous mudrock. The top 105 m is thin-bedded lime mudstone with interbedded lime breccia up to 7.5 m thick. Thin beds of gray, peloid-skeletal grainstone and packstone are sparsely distributed within the mudstones.

Shale or mudstone forms the basal meter of the Luolou at Ziyun; the overlying two meters are thinly interbedded shale and lime mudstone; lime mudstone predominates above, with several breccias, in the limited exposure. At Nulizhai, the basal 77 m are predominately light-gray, non-calcareous claystone that weathers yellow-brown with blocky or spheroidal surfaces. The overlying 63 m are mostly lime mudstone, followed by 35 m of claystone, 10.5 m of lime mudstone, and 6 m of claystone at the top of the formation (Guizhou Team, unpublished section, 1990). This section, distant from the shallow ramp at the platform margin, is more argillaceous than other sections examined, but is also relatively thick at 190 m.

The signature gray lime mudstones of the Luolou form planar to slightly nodular beds up to 30 cm thick; modal bedding thickness is ~5 cm. The medium dark-gray shades of the mudstone (N4 of Munsell color chart) result from disseminated pyrite and, in the lower part, from flakes of organic carbon. Some beds are finely laminated, others have distinct burrows, and many appear structureless, perhaps because of bioturbation. Within most intervals of lime mudstone, argillaceous partings are common; locally claystone forms beds up to 10 cm thick.

Lime breccias up to several meters thick are interbedded within the lime mudstones in the upper part of the Luolou, for example above 185 m at Hongyan where 19 breccias up to 7.5 m thick are exposed. Typical breccias are clast supported (rudstone), with a marked bedding-parallel elongation of the clasts. Clasts are overwhelmingly dark lime mudstones like the enclosing beds, but oolite and crinoidal packstone are also present. Most clasts are centimeters to decimeters in size, but a few are more than a meter long. A few breccias grade upward into grainstone or packstone.

Thin-shelled bivalves of the genus *Claraia* are common in the mudrocks and locally on partings within the lime mudstones. Ammonoids, notably *Ophiceras*, are widely dispersed in the mudrocks and concentrated in a few shelly layers in the lime mudstones. Sparse brachiopods include both articulates (*Crurithyris*, *Araxathyris*) and inarticulates (*Lingula*, *Orbiculoidea*; Guizhou Team, unpublished section; Guizhou Bureau, 1987, p. 303).

Fossils from the Luolou Formation (Guizhou Team, unpublished section at Nulizhai; Guizhou Bureau, 1987, p. 303. Conodonts were identified by Yang Shouren from Sanchahe, Luodian; reported by Wei Jiayong et al., 1996.):

Brachiopods: *Araxathyris araxaensis*, *Crurithyris habitiformis*, *Lingula* sp., *Orbiculoidea* sp.

Bivalves: *Claraia griesbachi*, *C.* cf. *claraia*, *C. aurita*, *C. wangi*, *C. concentrica*, *C. hubeiensis*, *Entolium* sp., *Eumorphotis* cf. *multiformis*, *Leptochondria* sp., *Promyalina* sp.

Gastropods: *Naticopsis*? sp.

Ammonoids: *Danubites* sp., *Koninckites* cf. *ellipticus*, *Meekoceras* sp., *Ophiceras sinensis*, *Paranorites linguisellatus*, *Prionolobus* sp., Gyronitidae

Conodonts: *Anchignathus* cf. *minutus* (now called *Hindeodus typicallus*), *Neospathodus* cf. *denggaolinensis*, *Prioniodella* sp. Samples from very proximal Luolou facies at the north margin of the Great Bank of Guizhou yielded the biostratigraphically important conodonts *Hindeodus parvus* and *Neospathodus dieneri* as well as *Ns. peculiaris*, *Ns. cristagalli*, and *H. typicallis* (Lehrmann et al., 2003a and unpublished data)

Accumulation rates for the Luolou Formation in Guizhou vary from 3 to 355 m/m.y., depending on the assumptions and locally preserved thickness. In all calculations, Luolou deposition is assumed to have occupied the entire Induan, a span of 1.3 m.y. according to Ogg (2004, p. 283) or 5.3 m.y. (interpolated from Haq et al., 1988, p. 100). The mean thickness of all values from Guizhou cited above gives mean accumulation rates of 27 and 110 m/m.y. using the age estimates of Haq and of Ogg, respectively. New data from the Nanpanjiang Basin indicate that the duration of the entire Early Triassic was only 5.0 m.y. (Martin et al., 2001; Lehrmann et al., 2006b). The Induan may have lasted ~1.1 Ma, following the interpolation of Ogg (2004). This would give a mean accumulation rate of 130 m/m.y.

Accumulation rates of the dominantly siliciclastic lower Luolou and the dominantly carbonate upper part are unlikely to have been the same. If the ascendancy of carbonate deposition reflects a gradual recovery of carbonate-producing biota after the end-Permian extinctions to mask background siliciclastic deposition, then carbonate depositional rates should have been appreciably higher. An opposing scenario would have pelagic carbonate deposition as nearer constant and siliciclastic input declining in later Induan, perhaps because of gradual reduction of relief, decrease in runoff, or trapping of sediment in estuaries during rising sea level. The climate in south China appears to have shifted dramatically from a humid Permian, with extensive coal deposi-

tion extending into the late Tatarian (Enos, 1995), to an arid Triassic, with evaporites appearing by the Olenekian (Wu Yinglin and Yan Yangji, 1987; Xu Xiaosong et al., 1996). This would be consistent with reduced runoff and chemical weathering in the later Induan. A eustatic rise in sea level during the Induan is indicated by Haq et al. (1988, p. 100), although the degree of flooding of the Yangtze Craton was remarkably similar and extensive during the Late Permian and the Induan (Xu Xiaosong et al., 1996).

As to carbonate productivity, diversity of the shallow-benthic community remained quite low throughout the Early Triassic (Payne et al., 2004, 2006). Low diversity does not necessarily mean low productivity, which depends on population size rather than diversity. However, thin-section counts indicate that the total skeletal content was reduced by an order of magnitude from Permian to Lower Triassic rocks and remained low until the Anisian (Payne et al., 2006; Lehrmann et al., 2005). Ooids and calcimicrobialites also contributed significantly to the volume of platform carbonates in the Early Triassic (Lehrmann et al., 1998). Moreover, on isolated carbonate platforms within the Nanpanjiang Basin, free from siliciclastic influx, carbonate sedimentation was continuous from the Permian into the Triassic (Lehrmann, 1993, 1999; Lehrmann et al., 1998, 2000, 2003a), although the relative accumulation rates have not been determined. For whatever reason, rates of platform-carbonate accumulation in the Early Triassic may have been essentially the same as those of Middle Triassic (Table 2) or, if we accept 5.0 m.y. as the duration of the Early Triassic, substantially higher. Thus it appears that periplatform carbonate should have been at least as abundant as in the later Triassic. We have no basis for assumptions about relative pelagic productivity in the Early Triassic, but it is well known that abundant calcified plankton did not debut until the Late Jurassic. All in all, evidence seems to favor a decline in siliciclastic delivery to the basin as the cause for the shift to carbonates in the latter part of the Induan. In any case, major parts of the basin were starved during the Early Triassic, with accumulation rates as low as 3 m/m.y., so the shift need not have been dramatic in volumetric terms. More certain is that the increase in rate resulting from corrections for compaction would be higher for the mudrocks, where fossils are completely flattened, than for the carbonates, which show little evidence of compaction.

### Daye Formation

The characteristic lithology of the Daye Formation in southern Guizhou is thin-bedded, medium-gray lime mudstone with distinct bedding-plane burrows that give a crenulated appearance in cross section (Fig. 7). The formation is recognized over most of the central part of the Yangtze block; the type locality is south of the Yangtze River in eastern Hubei Province, over 900 km east of Guiyang. It extends southeastward at least as far as Jiangxi Province (Yang Zunyi et al., 1993). A complete Daye section 276 m thick was studied at Gaimao, 20 km south of Guiyang. A complete section 295 m thick was seen in reconnaissance at Dulaying,

TABLE 2. SEDIMENT ACCUMULATION RATES BY FORMATION

Formation	Age	Section*	Thickness (m)	Duration		Rate		Remarks		
				m.y. <sup>†</sup>	(m.y. <sup>‡</sup> )	m/m.y. <sup>†</sup>	m/m.y. <sup>‡</sup>			
ERQIAO	RHAETIAN?	LONGCHANG	446	5.0	4.0	6.0	112	Incomplete		
		QINGZHEN	67	5.0	4.0	6.0	17	Complete		
		PANSHUI	175	5.0	4.0	6.0	44	Complete		
		GAOQIAO	124	5.0	4.0	6.0	31	Complete		
		<b>MEAN</b>	<b>203</b>	<b>5.0</b>	<b>4.0</b>	<b>6.0</b>	<b>51</b>	<b>34</b>	See text	
	Decompacted	914	5.0	4.0	6.0	229	152			
HUOBACHONG	NORIAN	LANGDAI	300	8.0	12.9	10.0	23	30		
		LONGCHANG	687	8.0	12.9	10.0	53	69	Maximum	
		Minimum	216	8.0	12.9	10.0	17	22		
		<b>MEAN</b>	<b>401</b>	<b>8.0</b>	<b>12.9</b>	<b>10.0</b>	<b>31</b>	<b>40</b>		
		Decompacted	1750	8.0	12.9	10.0	136	175	See text	
BANAN LAISHIKE Combined BANAN & LAISHIKE	CARNIAN CARNIAN	LONGCHANG	465						See text	
		LONGCHANG	810						See text	
			1275	4.0	6.2	6.0	206	213	Tuvallian	
			1275	2.0	3.1	3.0	638	425	1/2 Tuvallian	
			22.3-138	4.0	5.3	8.5	10	6	Indeterminate	
WAYAO ZHUGANPO	CARNIAN CARNIAN	HUANGPINGZHAI	55	4.0	5.3	8.5	14	10	Minimum	
		YONGNINGZHEN	155	4.0	5.3	8.5	39	29	Maximum	
		<b>MEAN</b>	<b>98</b>	<b>4.0</b>	<b>5.3</b>	<b>8.5</b>	<b>25</b>	<b>19</b>	<b>12</b>	7 sections
				4.0	6.2	7?	15	13		See text
				4.0	5.3	8.0	18	12		Minimum
SANQIAO GAICHA	CARNIAN CARNIAN	SANQIAO	94	4.0	5.3	8.0	22	16		
		SANQIAO	95	4.0	5.3	8.0	22	20		
		HUAXI	87	4.0	5.3	8.0	27	14		
		GUI-HUANG	108	4.0	5.3	8.0	30	22		
		LINGJIAWAN	119	4.0	5.3	8.0	26	15		
	<b>MEAN</b>	<b>102</b>	<b>4.0</b>	<b>5.3</b>	<b>8.0</b>	<b>19</b>	<b>13</b>			
YANGLIUJING	LADINIAN	GAOQIAO, ZUNYI	250	5.0	9.0		28		Truncated? Min.	
		SANQIAO	318	5.0	9.0		64	35		
		LONGCHANG	1000	5.0	9.0		200	111	Incl. Longtou	
		BEILA	1315	5.0	9.0		263	146	Incl. Longtou	
		Maximum	1200	5.0	9.0		240	133		
	<b>MEAN</b>	<b>817</b>	<b>5.0</b>	<b>9.0</b>		<b>163</b>	<b>91</b>			
LONGTOU	LADINIAN	HONGYAN	931	5.0	9.0		103			
		BOJISHAN	840	5.0	9.0		168	93		
		HUAXI	526	5.0	9.0		105	58	Minimum	
		BEILA	1315	5.0	9.0		263	146	Incl. Yangliujing	
		Maximum	1254	5.0	9.0		251	139		
	<b>MEAN</b>	<b>973</b>	<b>5.0</b>	<b>9.0</b>		<b>195</b>	<b>108</b>			

(continued)

TABLE 2. SEDIMENT ACCUMULATION RATES BY FORMATION (continued)

Formation	Age	Section*	Thickness (m)	Duration (Ma <sup>†</sup> )		Rate m/m.y. <sup>‡</sup>		Remarks
				Ma <sup>†</sup>	(Ma <sup>†</sup> )	m/m.y. <sup>‡</sup>	(m/m.y.#)	
BIANYANG	LADINIAN	BIANYANG	1976	5.0	9.0	395	220	Minimum
		LIANHE	2120	5.0	9.0	424	236	
		Maximum	2764	5.0	9.0	553	307	
		<b>MEAN</b>	<b>2287</b>	<b>5.0</b>	<b>9.0</b>	<b>457</b>	<b>254</b>	
GUANLING	ANISIAN	BOJISHAN	656	4.0	8.0	164	82	
		YONGNINGZHEN	617	4.0	8.0	154	77	
		LONGCHANG	814	4.0	8.0	204	102	
		SANQIAO	535	4.0	8.0	134	67	
		GAOQIAO	505	4.0	8.0	126	63	
		Maximum	912	4.0	8.0	228	114	
		Minimum	500	4.0	8.0	125	63	
		<b>MEAN</b>	<b>648</b>	<b>4.0</b>	<b>8.0</b>	<b>162</b>	<b>81</b>	
PODUAN	ANISIAN	HONGYAN	917	4.0	8.0	229	115	Entire Anisian >"Maximum"
		HETAOSHU	822	4.0	8.0	206	103	
		PODUAN	627	4.0	8.0	157	78	
		Maximum	813	4.0	8.0	203	102	
		Minimum	530	4.0	8.0	133	66	
		<b>MEAN</b>	<b>742</b>	<b>4.0</b>	<b>8.0</b>	<b>185</b>	<b>93</b>	
		QINGYAN	831	4.0	8.0	208	104	
		Maximum	1048	4.0	8.0	262	131	
Minimum	397	4.0	8.0	99	50			
<b>MEAN</b>	<b>759</b>	<b>4.0</b>	<b>8.0</b>	<b>190</b>	<b>95</b>			
XINYUAN	ANISIAN	NILUO	340	4.0	8.0	85	43	"Maximum"
		NULIZHAI	233	4.0	8.0	58	29	
		QINGYAN	900	4.0	8.0	225	113	
		Minimum	146	4.0	8.0	37	18	
		<b>MEAN</b>	<b>405</b>	<b>4.0</b>	<b>8.0</b>	<b>101</b>	<b>51</b>	
XUMAN	ANISIAN	WANGMO	1557	4.0	8.0	389	195	
		Maximum	1600	4.0	8.0	400	200	
		Minimum	800	4.0	8.0	200	100	
		<b>MEAN</b>	<b>1319</b>	<b>4.0</b>	<b>8.0</b>	<b>330</b>	<b>165</b>	
YONGNINGZHEN	OLENEKIAN	YONGNINGZHEN	647	4.7	4.7	138	138	165
		LONGCHANG	552	4.7	4.7	117	117	
		Maximum	875	4.7	4.7	186	186	
		Minimum	300	4.7	4.7	64	64	
		<b>MEAN</b>	<b>594</b>	<b>4.7</b>	<b>4.7</b>	<b>126</b>	<b>126</b>	
						<b>3.9</b>	<b>3.9</b>	

(continued)

TABLE 2. SEDIMENT ACCUMULATION RATES BY FORMATION (continued)

Formation	Age	Section*	Thickness (m)		Duration (m.y.)		Rate (m/m.y.)		Remarks
			m.y. <sup>†</sup>	(m.y.) <sup>‡</sup>	(m.y.) <sup>§</sup>	(m.y.) <sup>¶</sup>	m/m.y. <sup>†</sup>	(m/m.y.) <sup>‡</sup>	
ANSHUN	OLENEKIAN	WENGJING	495	4.7	3.9	105	105	126	
		RENRENSHAN	691	4.7	3.9	147	147	176	
		GAIMAO	293	4.7	3.9	62	62	75	
		HONGYAN	167	4.7	3.9	36	36	43	
		Maximum	712	4.7	3.9	151	151	182	<"Minimum"
		Minimum	280	4.7	3.9	60	60	72	
<b>MEAN</b>	<b>440</b>	<b>4.7</b>	<b>3.9</b>	<b>94</b>	<b>94</b>	<b>112</b>			
ZIYUN	OLENEKIAN	CHAYESHAO?	68	4.7	3.9	14	14	17	GB p. 302
		Maximum	210	4.7	3.9	45	45	54	
		Minimum	20	4.7	3.9	4	4	5	
		<b>MEAN</b>	<b>99</b>	<b>4.7</b>	<b>3.9</b>	<b>21</b>	<b>21</b>	<b>25</b>	
YELANG	INDUAN	LONGCHANG	773	5.3	1.1	146	146	716	
		ZUNYI	458	5.3	1.1	86	86	424	
		Maximum	905	5.3	1.1	171	171	838	
		Minimum	184	5.3	1.1	35	35	170	
		<b>MEAN</b>	<b>580</b>	<b>5.3</b>	<b>1.1</b>	<b>109</b>	<b>109</b>	<b>537</b>	
		GAIMAO	276	5.3	1.1	52	52	251	
DAYE	INDUAN	DULAYING	295	5.3	1.1	56	56	268	
		WENJING	226	5.3	1.1	43	43	205	
		HONGYAN	333	5.3	1.1	63	63	303	
		Maximum	582	5.3	1.1	110	110	448	Incl. Luolou
		Minimum	111	5.3	1.1	21	21	85	
		<b>MEAN</b>	<b>304</b>	<b>5.3</b>	<b>1.1</b>	<b>57</b>	<b>57</b>	<b>234</b>	
LUOLOU	INDUAN	NILUO	191	5.3	1.1	36	36	174	
		CHAYESHAO?	85	5.3	1.1	16	16	77	GB p. 303
		XIAOBAITO	18	5.3	1.1	3	3	14	<"Minimum"
		Maximum	392	5.3	1.1	74	74	302	
		Minimum	30	5.3	1.1	6	6	27	
		<b>MEAN</b>	<b>143</b>	<b>5.3</b>	<b>1.1</b>	<b>27</b>	<b>27</b>	<b>110</b>	
DALONG	L. TATARIAN		72	3.0	7.5	24	24	10	GB p. 261
			15	2.0		8			GB p. 265
		<b>GUANDAO/GBG</b>	<b>11.6</b>	<b>2.0</b>		<b>6</b>			<b>DJL p. 327</b>

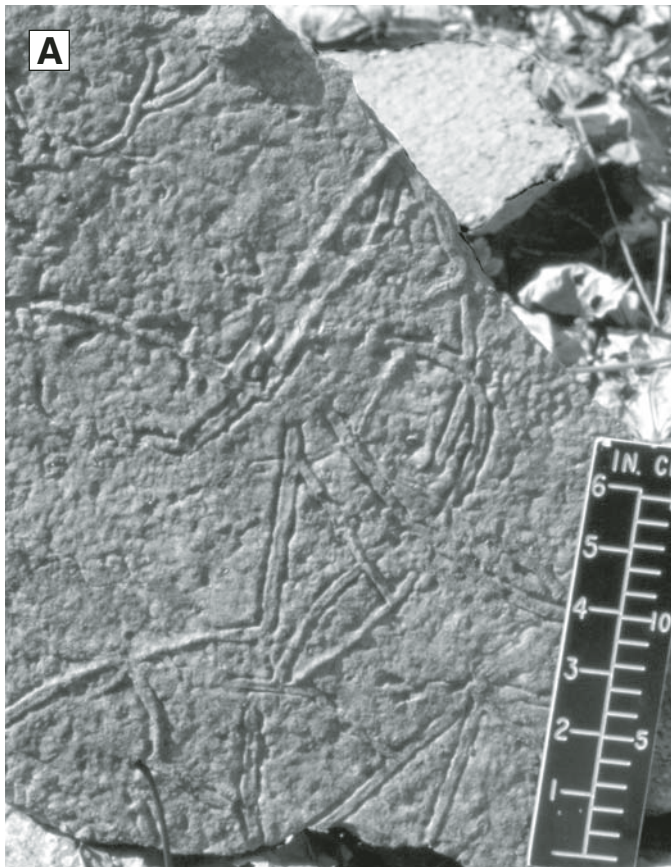
Note: Tatarian duration interpolated from Menning (1989) and from coastal onlap curve of Haq et al. (1988).

\*Maximum and minimum thickness values from Guizhou Bureau (1987, map legend), unless coincident with a measured section. Some of these ranges are discrepant with later measurements.

<sup>†</sup>From Haq et al. (1988, p. 100). Induan and Olenekian interpolated.

<sup>‡</sup>From Ogg (2004, p. 281–283).

<sup>§</sup>Early Triassic: interpolated from Bowring et al. (1998); Martin et al. (2001); Lehmann et al. (2006b); following Ogg (2004). Late Triassic: Kent and Olsen (2000).



10 km north wof Guiyang (Guizhou Team, unpublished section). The Guizhou Bureau (1987, p. 293–295) described a section 226 m thick from Wenjing, 15 km west of Guiyang, that is now entirely overgrown and cultivated. The thickness is quite consistent in these sections (226 to 295 m), but a range of 111 to 582 m is reported by the Guizhou Bureau (1987, p. 293). In a section measured by Minzoni at Hongyan, the Daye oversteps the Luolou Formation, so it is not complete, but it nevertheless reaches 333 m.

The base of the Daye Formation is generally mudrock, typical for the lowermost Triassic in the region. The interval dominated by mudrock is 34 m thick at Gaimao and 50 m at Dulaying. The lithology is gray, splintery, calcareous mudstone at Gaimao but fissile, black shale at Dulaying that grades up into soft, slightly fissile, gray mudstone, which weathers yellow-brown. Volcanic ash layers have been recognized in several sections, at or near the Permo-Triassic boundary. The mudrocks contain subordinate beds of argillaceous, muddy limestone that cluster in intervals up to 3 m thick with poorly defined, gradational contacts. These lime mudstones and a few wackestones are gray and weather to yellow-gray or reddish spheroids. Most are structureless, but shale partings define beds 3 to 15 cm thick in some intervals. Discrete burrows are lacking or vague, but the indistinct lithologic contacts may reflect mixing by infauna. Both the mudrock and limestone contain many ammonoids of the genera *Ophiceras* and *Lytrophiceras* and six species of the thin-shelled bivalve *Claraia* (Guizhou Bureau, 1987, p. 293–295). Additional ammonoids, *Meekoceras* and *Paranites*, and bivalves, *Eumorphotis* spp., are reported from mudrocks higher in the formation.

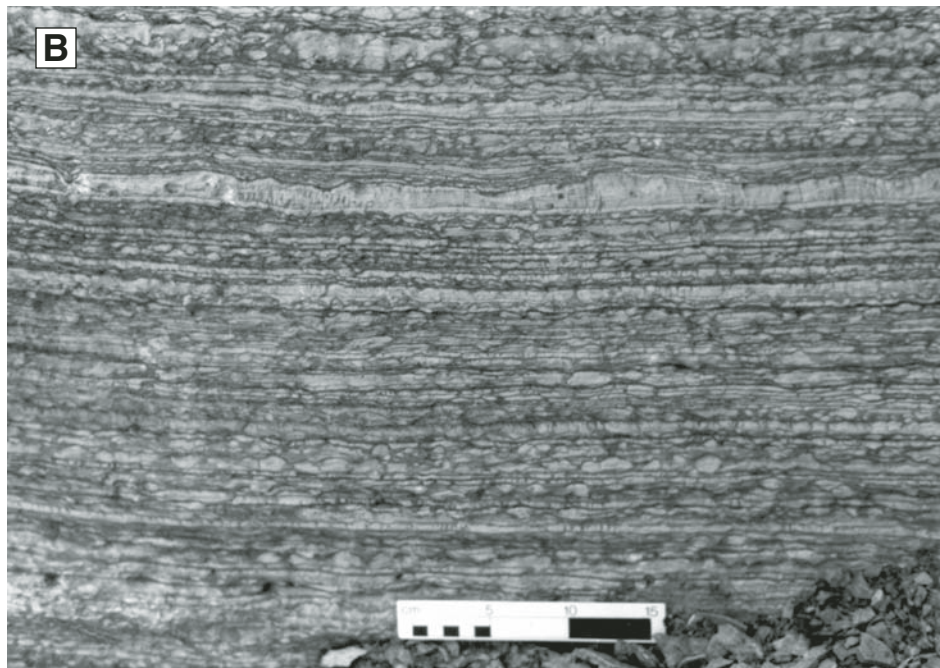


Figure 7. Burrows and traces in Daye Formation. (A) Trace fossils on upper surface of lime mudstone bed in the Gaimao section. (B) Burrowed intervals in the Daye Formation as seen in vertical profile. Gaimao section.

The flaggy limestones that characterize the Daye Formation appear above the mudrock-dominated intervals. These gray, muddy limestones are packaged into intervals of varying bedding thickness that ranges from 8 mm to several decimeters. The thinner-bedded intervals are delineated by shale partings; distinct argillaceous intervals up to a few centimeters thick punctuate the thicker-bedded intervals; otherwise no precise relationship is discernible between bed thickness and mudrock thickness. Some of the limestone beds are internally structureless or microlaminated, but most have distinct horizontal burrows and feeding traces that are best developed on the bedding surfaces, especially where a finite mudrock interval is present (Fig. 7A). Wang Shangyan (1997a) identified 15 ichnogenera (listed below) from the Daye at Gaimao and Huaxi that he ascribed to the *Nereites* (abyssal) ichnofacies. This limestone is widely quarried for flagstone, so many local villages are virtual ichnofossil museums with walkways and roofs adorned by traces (Fig. 8). The view is less striking in vertical outcrop, where the traces appear as dark circles or ovoids concentrated in argillaceous zones (Fig. 7B). The microlaminated intervals clearly had a lower incidence of burrowing, but structureless beds may have been completely bioturbated. Many of the bedding surfaces are overprinted and emphasized by stylolites. The horizontal burrows show nearly circular cross sections, however, indicating minimal mechanical compaction.

Petrographically, 43% of the muddy limestones are mudstones and 33% are wackestones. The remainder are technically packstones formed by packed micropeloids, 25 to 75  $\mu\text{m}$  in diameter. The peloids have vague margins suggesting that they were deposited as firm, but unlithified, fecal pellets. Larger pellets,

100 to 750  $\mu\text{m}$  in length, have sharp margins and, in some cases, are cylinders. These are probably fecal pellets as well, but were hardened on the seafloor prior to final deposition. Fine shards of organic carbon and pyrite are conspicuous in nearly all samples; they constitute as much as 2% of the volume. The most abundant body fossils are thin-shelled bivalves, observed in about half of the thin sections. Ostracodes, calcispheres, ammonoids, gastropods, and mollusk fragments are widespread; foraminifers and radiolarians are rare. Very rare and only tentatively identified are brachiopods, bryozoans, and echinoderms.

Although the presence of breccias is sometimes used as a mapping criterion for the Luolou, breccias interbedded within horizontally burrowed limestones are best referred to the Daye. For example, six or seven carbonate breccias up to 5.5 m thick are clustered near the top of the Gaimao section, interlayered with burrowed, flaggy, lime mudstones. These breccias are lenticular; they cannot be precisely correlated across a 3-km offset in the Gaimao section. At Hongyan, where the Daye oversteps the Luolou, the base of the Daye was placed at an abrupt onset of abundant horizontal burrow traces, which coincides with the appearance of numerous small slump structures. Thus defined, the Daye includes seven breccias up to 6.5 m thick. Breccia clasts are overwhelmingly of dark-gray lime mudstone, similar to the lime mudstone of the Daye Formation, but clasts of grainy limestone, including oolite, and dolostone, are present in a few breccias. Elongate mudstone clasts, up to 30 cm long, are locally imbricated. A range of structures from incipient slump deformation to well-developed slump folds are prominent in some Daye exposures, notably at Hongyan and Gaimao.



Figure 8. Village roofed with thin flagstones of Daye limestone, replete with trace fossils. Xiaojian-zhuang, south of Pingba.

A thick interval of predominantly oolitic grainstone occurs near the middle of the Daye, from 160 to 215 m, in the Dulaying section. Interbedded light-gray, locally stromatolitic, lime mudstone beds are up to 8 m thick. The oolite beds are several meters thick with vague cross-bedding and ripple lamination. Micritized skeletal fragments, peloids, and lime-mudstone intraclasts are minor components within the oolite. The oolite is overlain by thin-bedded, burrowed, laminated, or structureless lime mudstone. The oolite interval is probably a tongue of the Yelang Formation that is distributed to the north and west of the Daye Formation. A single bed of oolitic packstone with skeletal fragments and lime mudstone clasts is interbedded with breccia and lime mudstone near the top of the Hongyan section.

Fossils from the Daye Formation (Guizhou Bureau, 1987, p. 293, 295; Guizhou Team, unpublished section. Conodonts were identified by Yang Shouren from Xiaojiazhuang, Pingba; reported by Wei Jiayong et al., 1996. Ichnofossils are from Wang Shangyan, 1997a, and Wei Jiayong et al., 1996.):

Foraminifers: *Eoophthalmidium* sp., *Pilaminella* sp.

Bivalves: *Claraia wangi*, *C.* cf. *griesbachi*, *C. concentrica*, *C. hubeiensis*, *C. orbicularis*, *C. aurita*, *Eumorphotis* cf. *multiformis*, *E.* cf. *hinnitidea*, *Leptochondria* cf. *minimus*, *L.* cf. *bittneri*, *Posidonia* sp.

Ammonoids: *Lytospheras* sp., *L.* cf. *chamunda*, *Meekoceras* sp., *Ophiceras* sp., *O.* cf. *sinensis*, *Paranorites* sp.

Conodonts: *Cypridodella conflexa*, *C.* cf. *venusta*, *Hibbardella lantissima*, *Hindeodella* sp., *H. suevica*, *Neohindeodella* sp., *Neospathodus cristagalli*, *N. dieneri*, *N.* cf. *raridenticulata*, *Ozarkodina* cf. *tortilis*, *O. tortilis equidentata*, *Parachiognathus* sp.

Ichnofossils: *Cochlichnus anguinus*, *Cosmorhaphé* sp., *Chondrites* sp., *Gordia* sp., *Glockeria glockeri*, *Huaxichnus* sp., *Oldhamia* sp., *Paleodictyon majus*, *P. incompositum*,

*Phycosiphon inceria*, *Protopaleodictyon* sp., *Pinnatpedus huaxiensis*, *Mammilichnus* sp., *Neonereites* sp., *Mega-grapton* sp., *Thalassinoides* sp.

Accumulation rates for the Daye Formation range from 21 to 530 m/m.y., using the full range in thickness reported from Guiyang (111 to 582 m) and durations for the Induan Stage of 5.3, 1.3, or 1.1 m.y. (from, respectively, Haq et al., 1988; Ogg, 2004; and Martin et al., 2001; see Table 2). The small variation in thickness of the sections studied suggests that values of 55 to 270 m/m.y., resulting from a mean thickness of 298 m, are representative. Decompacted rates would be somewhat higher, as indicated by numerous stylolites, although slight flattening of burrows suggests that mechanical compaction was minor.

### Yelang Formation

The Yelang Formation includes red-weathering mudrock and several prominent intervals of oolite and lime mudstone. The unit is widely distributed in the Zhenfeng sector as well as farther to the northeast (Fig. 4). It was studied in the extensive section at Longchang and seen in reconnaissance at Yongningzhen and near Zhenfeng. Thus the following is essentially a description of the Longchang section, where the unit is 773 m thick and comprises ~58% terrigenous mudstone, 26% muddy limestone, 14% oolite, and 2% siltstone (Guizhou Team, 1980, p. 118). The Guizhou Bureau (1987, p. 281–283; 1997, p. 223) reported 458 m of Yelang in a section where the top is covered at Gaoqiao, Zunyi, 125 km north of Guiyang; more than half is limestone, but much of it is argillaceous. At Yongningzhen the Yelang is ~600 m thick (Wei Jiayong et al., 1996). Mudrock predominates but siltstone and oolite intervals tens of meters thick form three prominent ridges (Fig. 9). The overall range in thickness is 184 to 905 m according to the Guizhou Bureau (1987, p. 280).



Figure 9. Resistant limestones, predominantly oolite, of the Yelang Formation form ridges in the landscape at Yongningzhen. A third ridge is visible on the skyline at the right.

The Yelang conformably overlies Upper Permian cherty, shallow-water limestone of the Changxing Formation at both the Longchang and Zunyi; the Dalong is absent or represented by a few meters of mudrock. The Permian at Yongningzhen contains commercial coal seams interbedded with claystone, sandstone, and cross-laminated siltstone of the Longtan Formation. An overlying unit, tens of meters thick, of mudrock with intervals of argillaceous lime mudstone and sandy packstone with fusulinids probably represents the Changxing Formation.

The lower 270 m of the Yelang at Longchang is non-calcareous mudrock (mostly claystone) with a few limestone intervals. It bears the Early Triassic marker *Claraia griesbachi* and other species of *Claraia*. The claystone is light gray with angular fracture, but weathers light brown to red with spheroidal surfaces. Millimeter lamination is prominent in several intervals, produced in some cases by intercalations of lime mudstone. An interval of predominantly limestone extends from 127 to 141 m above the base of the Yelang. Medium-gray lime mudstone forms beds 10 to 20 cm thick with internal lamination. Toward the top of the interval, the texture is packstone with abundant *Crurithyrus* brachiopods, bivalves, and fecal pellets. The lowest oolite interval, at 270 m, is 44 m thick with beds 50 to 200 cm thick. Modal ooid size is ~0.5 mm. Cortices range from single, thin, micritized layers to thick and multilayered. Most ooid nuclei are molds filled with equant spar; these and other filled molds may have been rounded aragonitic bioclasts. Peloids and filled molds are

more abundant than ooids in some beds but rare in others. No sedimentary structures were observed in this or overlying oolite intervals. Four additional oolite units, 2 to 31 m thick, and several isolated beds are distributed through the upper part of the Yelang. They are interbedded with gray, muddy limestones and red-weathering mudrocks, in roughly equal proportions, with a few beds of wavy-laminated siltstone. Thick oolite intervals were observed within several Yelang exposures along present structural strike, approximately perpendicular to depositional strike, up to 20 km to the southeast. This indicates appreciable lateral extent of the oolite bodies. Oolite at Yongningzhen is concentrated in three ridge-forming units (Fig. 9), each many tens of meters thick. Intervening intervals, more than 100 m thick, are red-weathering, blocky mudstone with minor intercalations of thin-bedded siltstone, and a few lime packstones. All lithologies contain sparse bivalves, notably *Claraia* spp. (Fig. 10). The ridge-forming intervals start with thin beds of hard, laminated siltstone, grade up into ripple-bedded, silty peloidal packstone, followed by oolite (Fig. 11). Ooids are up to 1 mm mean diameter and occur with bioclasts, mostly thinly coated. Some beds of skeletal limestone, lime mudstone, and siltstone are interspersed.



Figure 10. Molds of *Claraia*, a useful index to the Lower Triassic in Guizhou, on mudrock bed surfaces near the base of the Triassic at Yongningzhen.



Figure 11. Lithologies from the lowest oolite ridge at Yongningzhen (Fig. 9). Thin beds at lower left, under scrutiny of Marcello Minzoni, are siltstone. They pass up into silty lime packstone, bioclastic limestone, and oolite grainstone in the cliffs at top.

Fossils in the Yelang Formation are mainly from the mudrocks (Guizhou Team, 1980, p. 118; Guizhou Bureau, 1987, p. 282–283; Yang Shouren and Chu Qingchun, 1992; Wei Jiayong et al., 1996). They include at least 11 species of the thin-shelled bivalve *Claraia* from mudrock in the lower 425 m and eight species of *Eumorphotis* from throughout the formation.

Brachiopods: *Crurithyris* sp., *Lingula* spp., *L. tenuiseima*, *L. panxianensis*, *Pugnax* sp.

Bivalves: *Bakevellia* sp., *B. costata*, *Chlamys* sp., *Claraia* sp., *C. aurita*, *C. cf. bijieensis*, *C. clarai desquamata*, *C. concentrica*, *C. griesbachi*, *C. griesbachi concentrica*, *C. guizhouensis*, *C. orbicularis*, *C. radialis*, *C. stachei*, *C. cf. tridentina*, *C. wangi*, *Curionia* sp., *Entolium discites*, *Eumorphotis cf. auri*, *E. cf. himmitidea*, *E. inaequicostata*, *E. cf. multiformis*, *E. multiformis dissimilicostata*, *E. multiformis regularaecosta*, *E. cf. teilhardi*, *E. telleri*, *E. telleri tuberculata*, *E. cf. venetiana*, *E. cf. waageni*, *Myophoria (Leviconcha) ovata*, *M. (Neoschizodus) laevigata*, *Pleuromya* sp., *Pleuromyces* sp., *Promyalina putiatinensis*, *P. intermedia*, *Pteria ussurica variabilis*, *Trigonodus* sp., *Towapteria scythicum*, *Unionites fassaensi*.

Ammonoids: *Lytosphericeras* sp., *Ophiceras* sp.

The wide range of thickness reported for the Yelang Formation in Guizhou (184 to 905 m) and the varied values for duration of the Induan result in a range of calculated accumulation rates from 35 to 840 m/m.y. (Table 2). Rates for the much-studied section at Longchang are 145 to 715 m/m.y. Grain-supported units show little evidence of compaction, but the much thicker mudrocks and argillaceous limestones must have compacted considerably, suppressing the apparent accumulation rates. Even so, the calculated rates are double those of the time-equivalent Daye Formation and four times those of the Luolou Formation.

### Depositional Environments

Mapping and biostratigraphy indicate that the Luolou, Daye, and Yelang Formations are essentially time-equivalent lithofacies (Guizhou Bureau, 1987), although the upper boundaries, defined largely by lithologic changes, seem unlikely to be precisely synchronous. The lithologic character of each formation is distinctive, but the lateral boundaries are quite gradational. The gray lime mudstones of the Luolou are distinguishable from those of the Daye through interlayering of the distinctive burrow-crenulated fabric in the Daye. The lime mudstones of the Yelang are similar in color and composition, but are generally thicker and structureless. Reddish weathering of the Yelang lime mudstones and terrigenous mudrocks provides a useful distinction. Carbonate breccias are used locally as a mapping criterion for the Luolou, but comparable breccias occur in the Daye, particularly in the upper part. Thick beds of oolite characterize the Yelang, although tongues extend into the Daye. The faunal assemblages are remarkably similar, given the lithofacies differences.

The formations have in common that they are predominantly siliciclastic mudrock at the base and more calcareous toward the

top. The mudrock intervals are quite similar in lithologic details, including altered tuff layers at the base, and in fossil assemblages, dominated by ammonoids and thin-shelled, probably quasi-planktonic, bivalves. The uniformly fine grain sizes and lack of hydrodynamic sedimentary structures indicate deposition in low-energy settings. The plankton-dominated marine fauna suggests deep water as the reason for low energy. A few intervals are laminated and a very few are dark gray, but otherwise the bottom waters seem to have been generally dysaerobic, oxygenated enough to support an infauna, but excluding a shelly benthic fauna. Episodes of marginal oxygenation are indicated by settlement of specialized brachiopods, *Crurithyris*, *Lingula*, and *Orbiculoidea*. Thickness variations of the basal mudrock intervals hint at a western source: 272 m in the Yelang at Longchang, 65 m in the Luolou at Hongyan, and 50 m and 34 m within the Daye at Dulaying and Gaimao, respectively. Mudrock of the Luolou is 77 m thick in the easternmost section at Nulizhai, however, so if the apparent trend is related to distance from source, other factors or other sources also play a role. The obvious candidate for a western source is the Khamdian massif, a persistently positive feature stretching north-south through west-adjacent Yunnan Province (Sheng Jinzhang et al., 1985; Wang Hongzhen, 1985). In western Guizhou and adjacent Yunnan and Sichuan, the Induan is represented by the sandstone and mudrock of the Feixianguan Formation (Fig. 4; Liu Baojun and Xu Xiaosong, 1994; Wei Jiayong et al., 1996). These rocks are interpreted as fluvial and littoral deposits, clearly signaling that the Khamdian massif was emergent in the Early Triassic, as it had been throughout the Late Permian (Liu Baojun and Xu Xiaosong, 1994; Enos, 1995, p. 247).

With the increased proportion of carbonate deposition higher in the formations, lateral variations become more apparent. Limestones of the Luolou Formation have the thinnest beds, best lamination, darkest shades, least variability, and lowest sedimentation rates. This indicates deeper, quieter, and less oxygenated waters than prevailed elsewhere. The distribution of the Luolou to the south and east of the Yangtze Platform (Fig. 4) clearly shows an expansion of the Nanpanjiang Basin from its Permian position (Fig. 3) that was to persist, with minor shifts, throughout the Early and Middle Triassic. A particularly significant area of outcrop of the Luolou Formation are two small outliers within the Jiangnan (Xuefeng) massif of southeastern Guizhou (at 25°58.6'N, 109°6'E and 26°25.7'N, 109°13.8'E). These locations were not visited, but the extension of the Luolou facies into this area strongly suggests that this massif ("oldland" in the Chinese literature) was deeply submerged in the lowermost Triassic, rather than emergent as it appears in most paleogeographic maps (cf. Fan Jiansong, 1980, p. 1127; Wang Hongzhen, 1985, p. 86; Sheng Jinzhang et al., 1985; Wu Yinglin et al., 1989; but shown as submerged by Liu Baojun and Xu Xiaosong, 1994, and Xu Xiaosong et al., 1996, p. 146). The limestones of the Yelang, in contrast to those of the Luolou, are consistently thicker bedded and somewhat lighter in color, lack millimeter lamination, contain some benthic megafossils, and include thick intervals of oolitic grain-

stone. This indicates episodes of carbonate formation in shallow, agitated waters, interspersed with incursions of terrigenous clay that formed the mudrocks and of deeper, less-oxygenated waters during deposition of the bioturbated lime mudstones. The Daye Formation forms a belt between the Yelang Formation on the northwest and the Luolou on the southeast. The hallmark of the formation is burrowed lime mudstones, which indicate a lively infauna, but one that was not populous enough to completely bioturbate the substrate, an intermediate condition between the dark laminites of the Luolou and the aerated oolite shoals represented in the Yelang. Wang Shangyan (1997a, p. 62) ascribed the varied trace-fossil assemblage of the Daye at Gaimao to the *Nereites* ichnofacies, considered indicative of abyssal depths, or at least the deepest water, in the ichnofacies scheme of Seilacher (1967). However, the vast majority of the traces are simple dwelling or feeding structures, not the elaborate grazing traces that characterize the *Nereites* ichnofacies (Seilacher, 1967). The Luolou was probably deposited in significantly deeper water, but trace fossils are absent because of the lack of oxygen in the deeper part of the basin. The thick, cross-bedded oolite interval in the Daye at Dulaying is a transition to Yelang environments, if not actually an extension of a Yelang oolite body.

Carbonate breccias are used locally as a criterion for the Luolou Formation in mapping, but breccias are widespread in the Daye as well. Large, spectacular slump structures are associated with breccias within the Daye at Gaimao and numerous small slumps are evident at Hongyan. The considerable thickness, appreciable matrix content, general lack of bedding or grading, and the preponderance of initially soft lime-mudstone clasts in the breccias are consistent with deposition by debris flows. The mudstone clasts were detached from the local background carbonate mud by slumping. Oolite and skeletal-limestone clasts are widespread, although sparse, reflecting contribution from oolite shoals of the Yelang area, necessarily up a depositional slope. The slope need not have been steep to generate debris flows. The uniformity of the initial terrigenous-mud deposits, the width of the intermediate Daye facies belt, and the lack of sharp boundaries between the formations all point to a very gentle slope.

The picture that emerges of the southern margin of the Yangtze Platform in the earliest Triassic is of a nearly featureless, deep sea floor over the drowned Permian carbonate platform, receiving hemipelagic mud deposition from a western source and initially some falls of volcanic ash. The eventual onset of carbonate deposition may reflect the revival of shallow-water carbonate production following platform drowning and extinctions in the Late Permian, but concomitant decrease in siliciclastic mud production, probably in response to drier climates and rising sea level in the Early Triassic, appears to have been more important. Periplatform carbonate was likely the only source for basinal carbonate mud in the Early Triassic, as highly productive planktonic communities first developed much later in the Mesozoic.

The gradual development of some facies differentiation in the carbonates from deeper, quieter, and oxygen-depleted water in the south and east (Luolou) to shallow, agitated, episodically

oxygenated conditions to the west and north (Yelang) probably reflects differential subsidence into the Nanpanjiang Basin. A eustatic drop in sea level across a gently sloping depositional surface might also emphasize depth differences that were negligible in generally deeper water during deposition of the Dalong and earliest Triassic mudrocks. The fourfold increase in accumulation rates from southeast to northwest presumably resulted in shoaling in the northwest, the Yelang area; this feedback then contributed to depth-dependent facies differentiation. The result was a ramp morphology, with reestablished shallow-water environments to the northwest, the interior of the Yangtze Platform, and encroachment of basinal deposition across the Permian margin of the platform in the Guiyang sector. Ramp morphology is most clearly expressed in the wide expanse of the burrowed grounds of the Daye Formation, the transition from shallow water to basin. The shallow end of the spectrum, represented by the Yelang Formation, was not able to keep pace continuously with relative sea level; at times deeper-water carbonate deposition was reestablished or terrigenous mud flooded the shelf. Fluctuations in relative sea level, whether tectonic or eustatic in origin, revived shallow-water deposition at three or more intervals, long enough to allow deposition of up to 45 m of oolite. Modern accumulation rates (see Enos, 1991) indicate shoaling periods of at least 45,000 yr. This would lie within the Milankovitch bandwagon, but should not be interpreted as the 40,000 yr obliquity period, as it represents only the shallow-water hemisphere. The deeper part, represented by hundreds of meters of terrigenous mudrock, undoubtedly endured much longer. Moreover, modern, short-term depositional rates are invariably too high to apply directly to longer periods of deposition (cf. Schindel, 1980; Enos, 1991).

#### **OLENEKIAN (UPPER LOWER TRIASSIC) FORMATIONS**

The later part of the Early Triassic, corresponding approximately to the Olenekian Stage, is represented by three laterally equivalent formations in southwestern Guizhou: the Ziyun, Anshun, and Yongningzhen Formations (Table 1, Fig. 12). Each formation conformably overlies its approximate environmental equivalent of the Induan (Guizhou Bureau, 1987). Contacts with the overlying Middle Triassic (Anisian) formations are also considered conformable (Guizhou Bureau, 1987).

The upper contacts are defined and correlated, where possible, by a regionally extensive, altered acidic tuff layer, the "green-bean rock" of local usage. This tuff has been considered a synchronous formational contact, although several closely spaced tuff layers are present in some exposures (Guizhou Bureau, 1987; Payne et al., 2004; Lehrmann et al., 2006b). The tuff is recognized as far north as eastern Sichuan (Wu Yinglin et al., 1989; Wang Liting, 1996), as far south as southwestern Guangxi (Wei Jiayong et al., 1996; Wang Liting, 1996), and west into Yunnan (Wang Liting, 1996, p. 32). The tuff (or tuffs) thickens southward, gradually in measured sections across Guizhou (Guizhou Bureau, 1987) and dramatically in southern Guangxi (Druke et al., 2001). It probably derives from

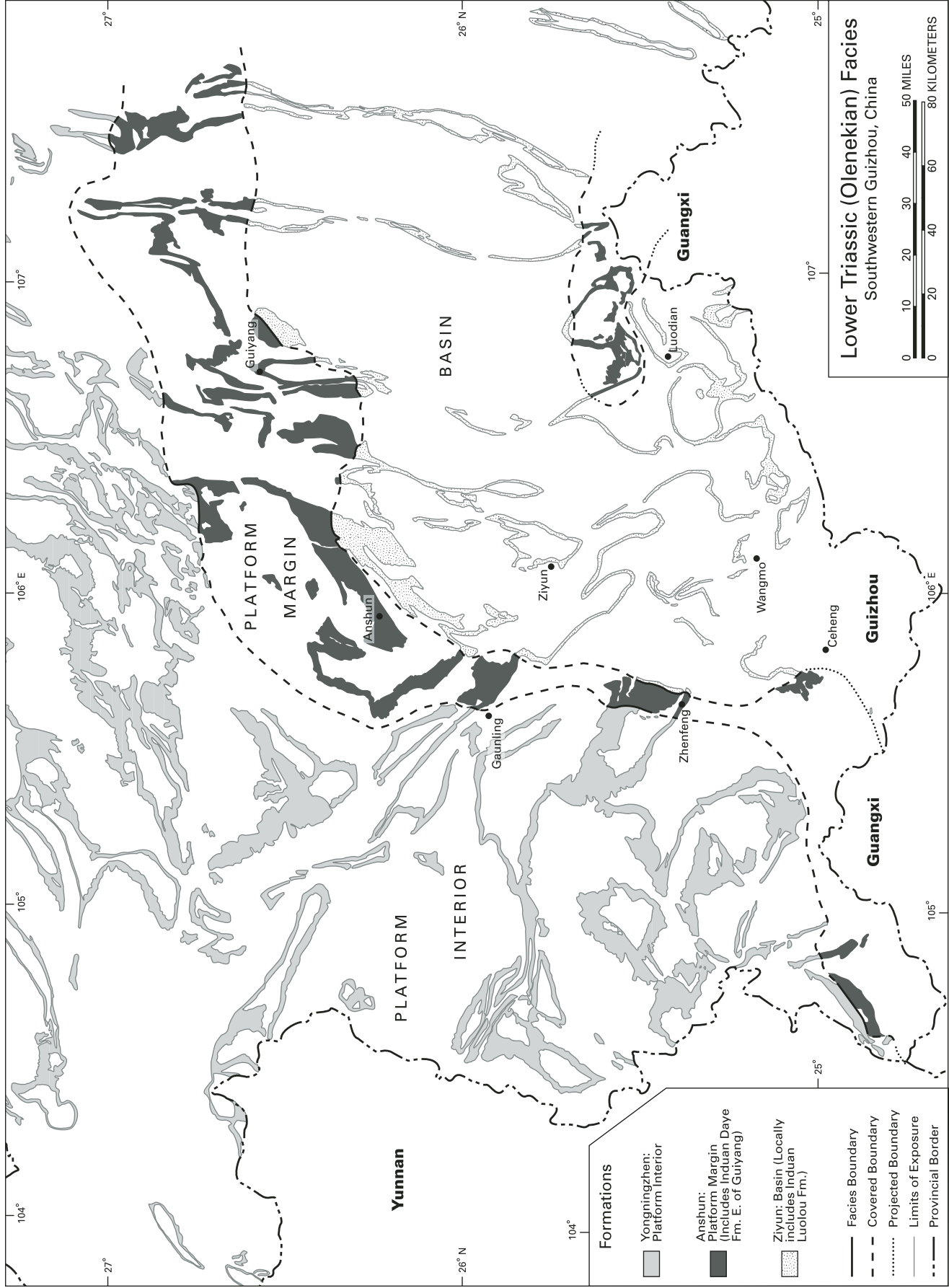


Figure 12. Olenekian (upper Lower Triassic) facies distribution in southwestern Guizhou. Compiled from the Geologic Map of Guizhou (1:500,000; Guizhou Bureau, 1987). Formations, represented by patterns on the map, are essentially time-equivalent facies.

voluminous eruptions of felsic pyroclastics, rhyolite, and “quartz-feldspar porphyrite” (Guangxi Bureau, 1985) that overwhelmed the Chongzuo carbonate platform in southern Guangxi (NewKirk et al., 2002; Lehrmann et al., 2006a). Conodont biostratigraphy from Guandao on the north slope of the Great Bank of Guizhou and a consistent magnetostratigraphy and chemostratigraphy (Lehrmann et al., 1998; Montgomery et al., 2000; Lehrmann et al., 2005, 2006b; Payne et al., 2004) show that the Olenekian-Anisian boundary at this locality is bracketed by four tuff layers. The middle pair are 6.3 m below and 2.3 m above the boundary. Concordant zircon dates from the tuffs give a boundary age of  $247.21 \pm 0.1$  by linear interpolation (Martin et al., 2001; Lehrmann et al., 2005, in 2006b). This estimate is considerably older than previous estimates for the Olenekian-Anisian boundary, e.g., 240 Ma by Haq et al. (1988) or  $241.7 \pm 4.7$  Ma by Gradstein et al. (1995), revised to  $245 \pm 1.5$  by Ogg (2004). Less precise dates from apparently correlative tuffs at Yongningzhen and at Taiping on the Chongzuo Platform in Guangxi are also in the range of 246 to 247 Ma (Montgomery et al., 2000; Martin et al., 2001).

### Ziyun Formation

The Ziyun Formation represents the Olenekian Stage in the Guizhou portion of the Nanpanjiang Basin. It is described as carbonate breccia, lime mudstone, and calcareous claystone, 20 to 210 m thick (Guizhou Bureau, 1987). Recent maps by the Guizhou Regional Geological Mapping Team have placed this interval within an expanded Luolou Formation to be consistent with usage in neighboring Guangxi Province, where the Luolou was defined. Observations were made of extensive, but intermittent, Ziyun exposures at Zhulinzhai, 3.6 km southeast of Qingyan; along route 210, 4 km north of Luodian; at Gouli; and at Xiaobaituo, 4 km east of Qingyan (Fig. 2). The type locality is the county administrative center of Ziyun, 110 km southwest of Guiyang (Fig. 2), better known for exposures of Late Permian reef limestone (Enos, 1995).

A complete section 68 m thick, measured at Chayeshao, Bandang, 19 km north of Ziyun (Guizhou Bureau, 1987, p. 302–303), may be considered the reference section. It is ~40 km seaward of the approximate shelf edge, which is not sharply defined in the Olenekian. Dark-gray, thin-bedded, ammonoid-bearing lime mudstones with a few thin shale interbeds make up most of the unit; two intervals of lime breccia are interbedded in the lower half. The breccia beds are meter scale and massive; limestone clasts are rounded to angular, up to 5 cm in diameter. The lower breccia interval, 18 m thick, conformably overlies argillaceous lime mudstone of the Luolou Formation. A second interval of four breccias lies 26 to 36 m above the formation contact. Altered tuff and siliceous shale of the “green-bean rock” mark the contact with the overlying Xinyuan Formation of the Middle Triassic. A nearby section at Xinmin, southeast of Ziyun (Fig. 13; Wei Jiayong et al., 1996) is ~130 m thick and includes three intervals dominated by carbonate breccias—two thin ones at the base and 55-m interval in the middle.

In a more proximal position at Zhulinzhai, 3.6 km south-east of Qingyan in the Guiyang sector, an unmeasured section is appreciably thicker and more terrigenous. Breccias are minor and confined to the top of the formation, rather than the base as around Ziyun. The basal 80 m of the Ziyun Formation, overlying limestones of Luolou Formation, is interbedded claystone and more resistant terrigenous mudstone in couplets 1 to 4 cm thick. The mudstone contains sparse quartz silt and white mica. The lithologic proportions vary; claystone dominates near the base, and mudstone makes up about two-thirds of the upper part of the interval. There is an abrupt, but poorly exposed, transition to fine-grained carbonates that constitute most of the upper part of the formation. Silty lime mudstone beds 0.5 to 6 cm thick (modal thickness is 1 to 2 cm) are separated by millimeter laminae of shale. Burrows are prominent on many bedding surfaces as horizontal, clay-filled, irregular and branching tubes ~3 mm in diameter. Lumps of carbonate mud ~1 cm in diameter within the shale partings may also result from burrowing. Despite the manifestations of burrowing, some lime mudstone beds are millimeter laminated. Higher in the formation dolomitization is extensive, resulting in interbedded dolostone and lime mudstone on centimeter to meter scale overlain by a completely dolomitized interval with beds 3 to 40 cm thick. Current ripples and ripple cross-lamination in the dolostone indicate that some of the original lithologies were grainy rather than lime mud. Fine lamination is also common; horizontal burrows are rare. Two beds of carbonate breccia occur in the partially dolomitized interval. The clasts are lime mudstone up to 35 mm in diameter; most are structureless or bioturbated, but a few are millimeter-laminated. The lower breccia, 1.2 m thick, is graded and clast supported with an argillaceous matrix. The upper breccia is floatstone, 0.7 m thick, with a dolomitic matrix. Near the top of the formation dolostone and shale form couplets up to 5 cm thick, a dolomitized version of the lime mudstone-shale couplets at the base of the carbonate section. The top of the formation is placed beneath a claystone, probably an altered volcanic ash, thought to represent the regional tuff layer that marks the base of the Anisian formations.

The most proximal locality studied was at Xiaobaituo (4 km east of Qingyan; Fig. 2) a few kilometers southeast of the poorly defined shelf margin. The Ziyun interval is ~100 m thick and consists mainly of centimeter-scale beds of medium-gray lime mudstone with thin shale interbeds. A lime-breccia bed ~2 m thick marks the base of the formation; six other breccias, 1 to 6 m thick, are exposed at roughly equal intervals throughout the formation. A comparably proximal section at Niluo (Fig. 13) is only ~30 m thick and consists of lime mudstone with calcarenite interbeds, but no breccia.

A Ziyun section at Nulizhai (Fig. 13), ~40 km from the margin, roughly the same distance as the type section, looks strikingly similar to the proximal Xiaobaituo section. The thickness is comparable at 117 m. The major difference is a slightly higher content of terrigenous mud, mainly in the basal 15 m and the top 5 m, and concentration of all the breccias in the basal 29 m. A breccia 3.1 m thick defines a mappable base of the unit.

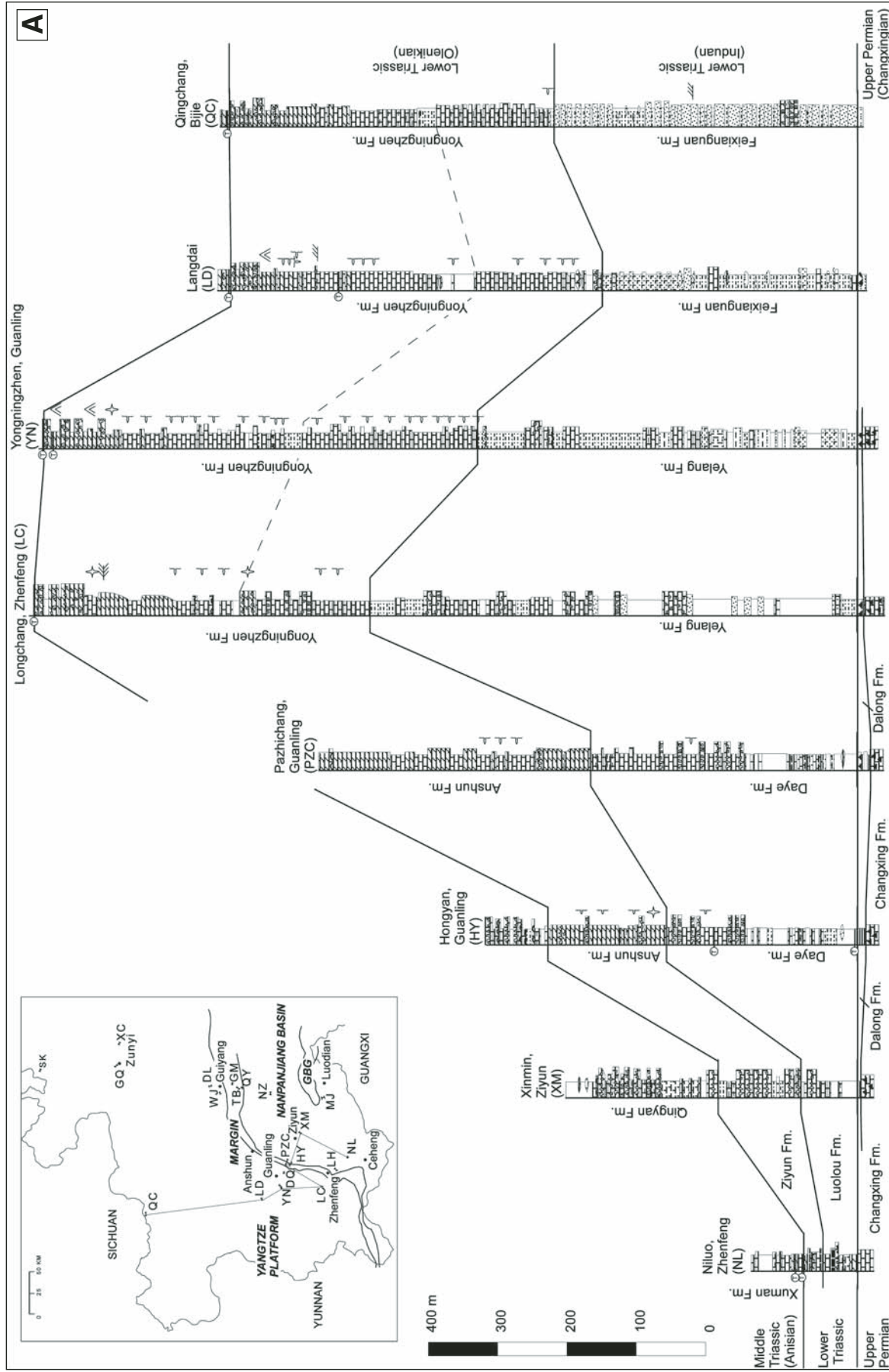


Figure 13 (on this and following 5 pages). Regional cross sections from Lower, Middle, and Upper Triassic of the Zhenfeng sector (A, C, and E, respectively) and Lower and Middle Triassic of the Guiyang sector (B and D). Legend is Figure 13F. Section locations are shown on inset maps. Middle Triassic facies boundaries are shown for reference. Modified after Wei Jiayong et al. (1996).



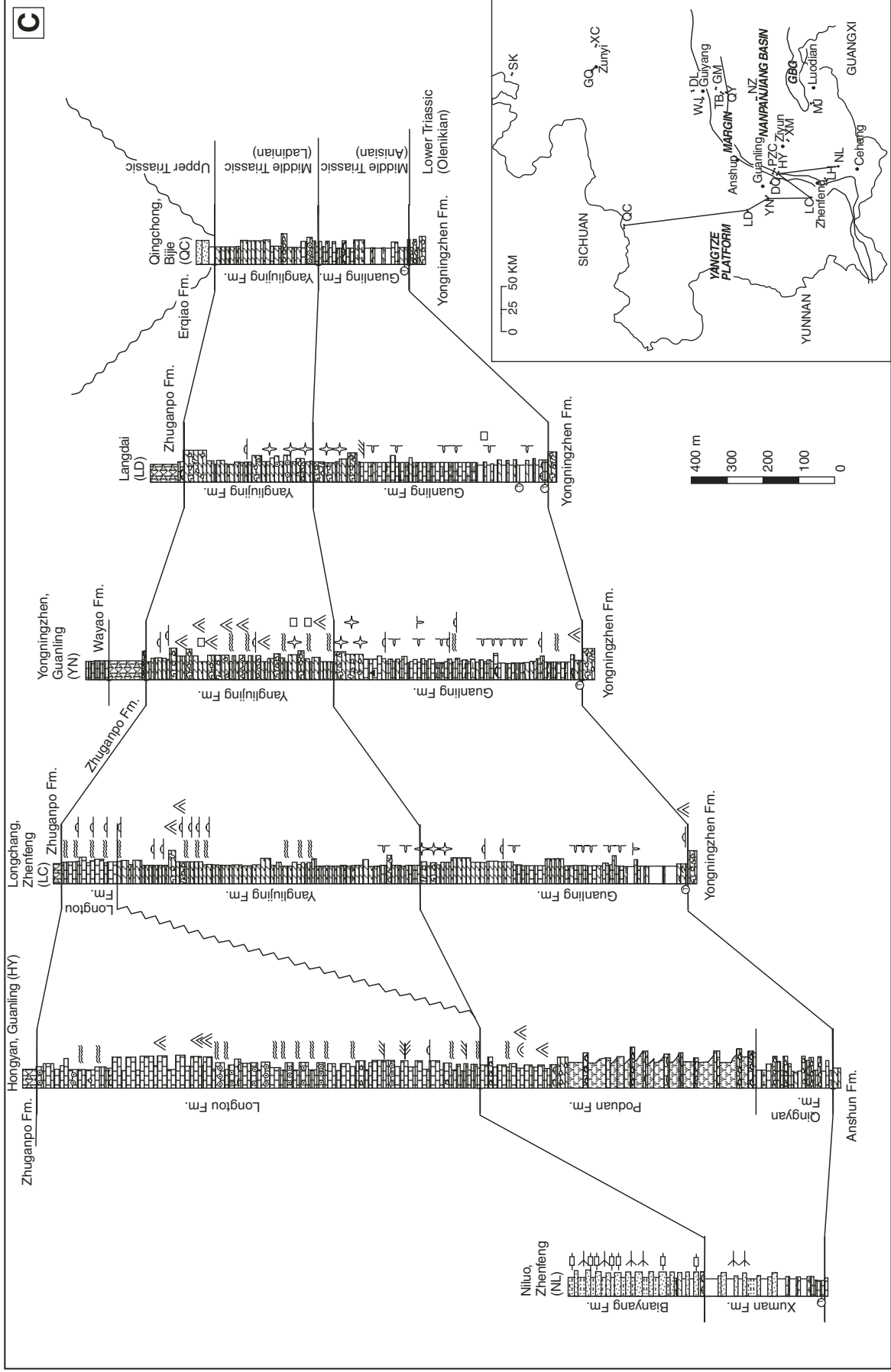


Figure 13 (continued).



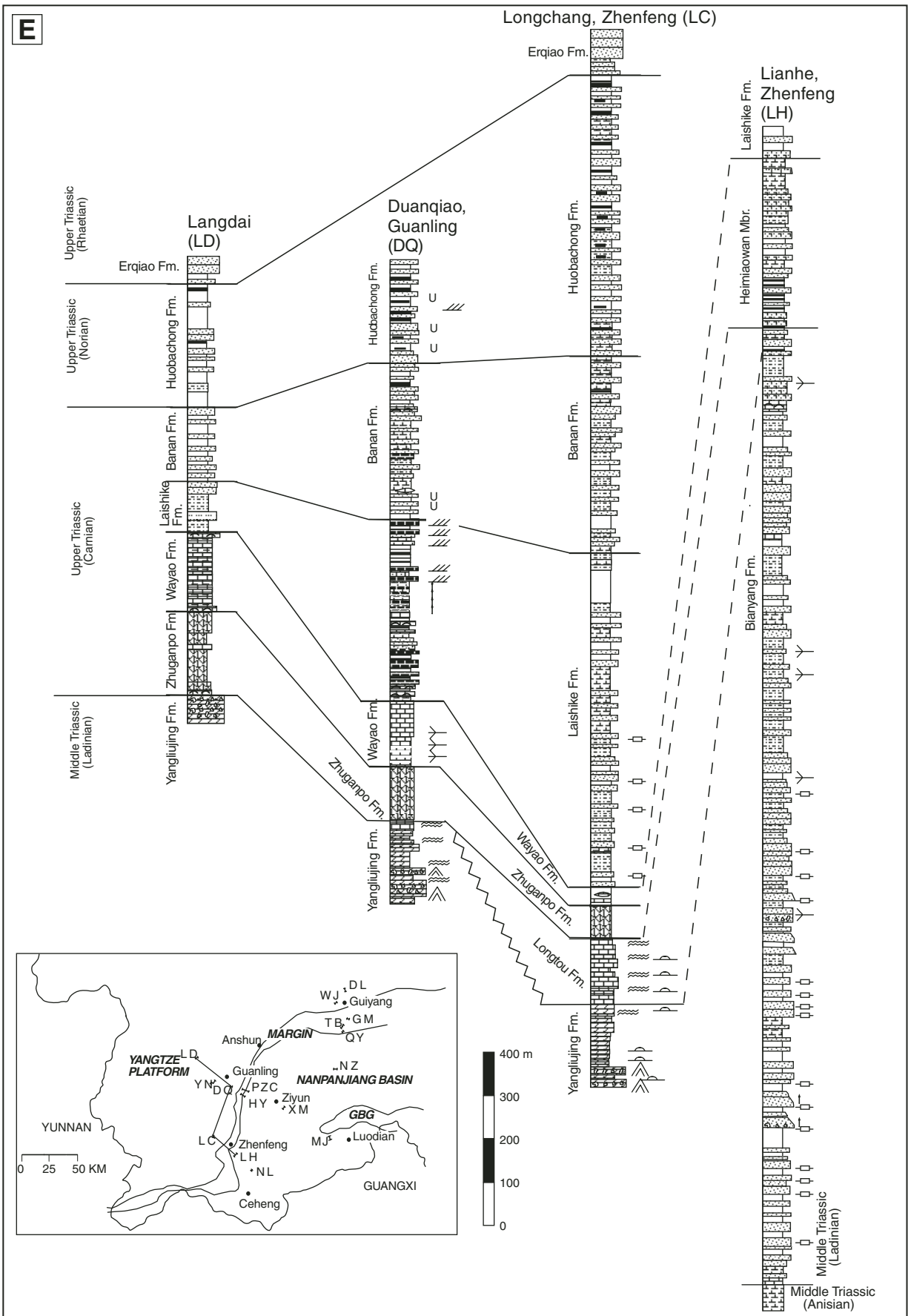


Figure 13 (continued).

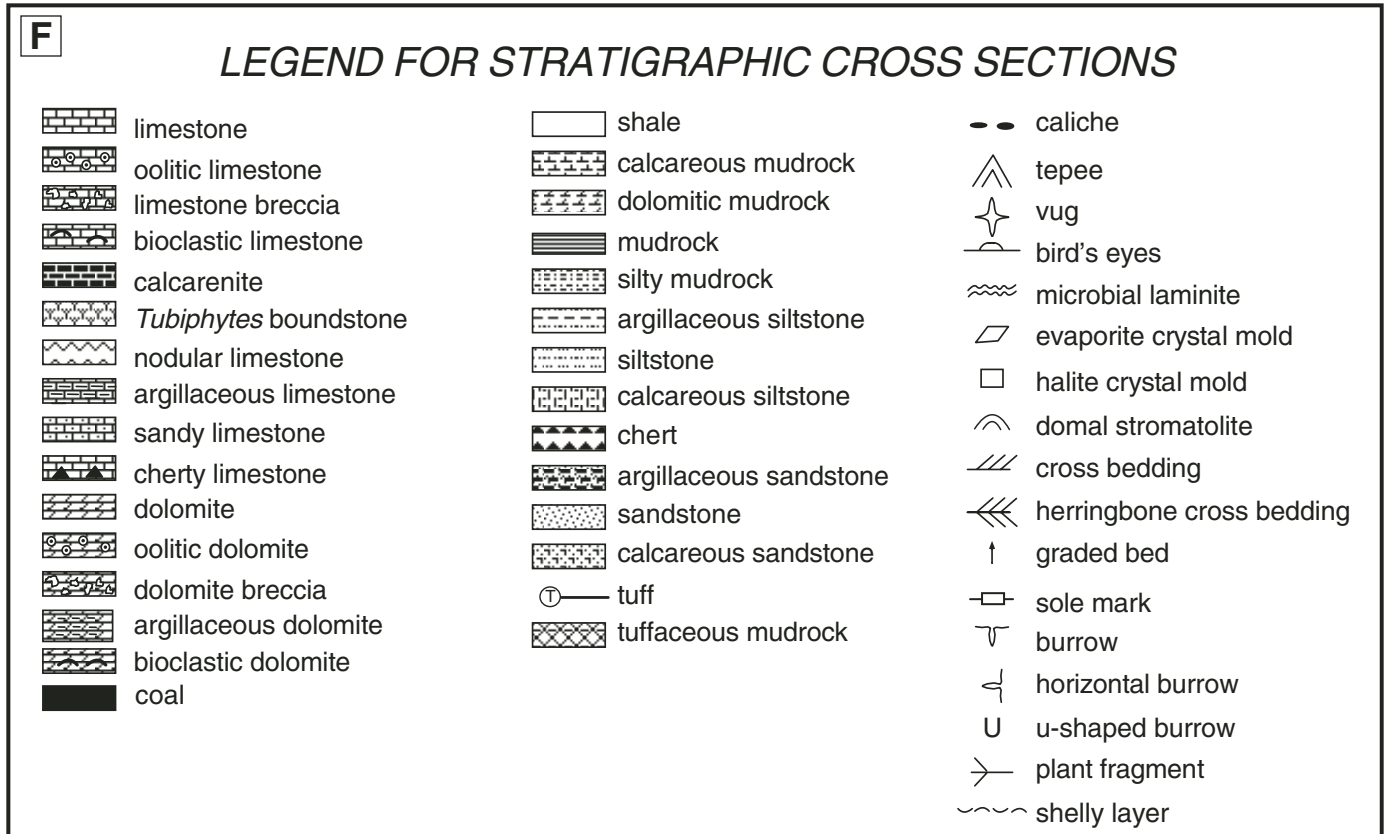


Figure 13 (continued).

Four overlying breccias range from 2.1 to 3.9 m thick; most are polymict rudstones (i.e., clast supported) and massive or graded. Clast size is generally centimeters to decimeters, but a few mudstone intraclasts are over 2 m long. Most clasts are gray, laminated lime mudstone with sparse thin-shelled bivalves, ostracodes, and calcispheres, but lithologies from argillaceous lime mudstone through skeletal and peloidal packstone to ooid grainstone are represented. The matrix is argillaceous lime mudstone with thin-shelled bivalves, ostracodes, possible radiolarians, and a few ooid fragments. Intense folding within the thin-bedded lime mudstones that make up most of the unit may be syndepositional and suggests submarine slumping as a trigger mechanism for the breccias, although the observed folds are higher in the section.

Ziyun exposures 4 km north of Luodian are the most distant from the Yangtze Platform, ~100 km, but are only 4 km south of an isolated Triassic platform, the Great Bank of Guizhou (Fig. 12; Lehrmann et al., 1998). The Ziyun here consists entirely of slightly calcareous shale with sporadic interbeds of terrigenous mudstone and siltstone, 4 to 10 cm thick, with some ripple-drift cross-lamination. Breccia is lacking. At Mengjiang, near the southwest corner of the Great Bank of Guizhou (Fig. 2), the Ziyun Formation measures 161 m thick and also devoid of breccia, although the upper half includes a few beds of sandstone (Fig. 13B). At Sanchahe, also close to the

south margin of the Great Bank of Guizhou, the Ziyun is only 92 m thick, but includes three intervals of breccia, at the base, middle, and top of the formation.

The Ziyun section at Gouli, Guiyang sector (Fig. 2), slightly more proximal than the type section, differs mainly in the considerable degree of dolomitization. The basal part, ~50 m, is massive dolostone grading up to laminated dolostone in beds 2 to 10 cm thick. The top 20 to 30 m of the Ziyun is also dolostone. The intervening exposures are predominately thin-bedded lime mudstone with the characteristic breccias, but also include some decimeter interbeds of peloidal lime packstone with sparse fossil fragments and low-angle cross-beds. Breccia beds range from less than a meter to ~10 m thick. The most spectacular is a 5-m bed near the base of the upper dolostone interval with dolograins clasts up to 2 m long and cherty, laminated dolomudstone clasts to 4 m long. Any breccias at the base of the Ziyun are obscured by dolomitization and subsequent intense fracturing.

In summary, the Ziyun Formation is predominately thin-bedded, dark lime mudstone with thin shale interbeds and thick carbonate breccias. The breccias tend to be concentrated near the base of the formation, but can occur at any level, especially in more proximal locations. Formation thickness is typically ~100 m, but reportedly ranges from 20 to 210 m. Fossils identified from the mudstones and shales are all ammonoids or conodonts except,

rarely, thin-shelled bivalves, gastropods, lingulid brachiopods, and ostracodes (Guizhou Bureau, 1987). More varied fossil fragments occur in the breccia clasts.

Although the Ziyun is appreciably more terrigenous than the upper part of the underlying Luolou Formation and has been mapped throughout the Nanpanjiang Basin in Guizhou (Guizhou Bureau, 1987), the name has largely lapsed into disuse in local mapping since the 1990s. The strata in question are referred to the upper part of the Luolou Formation. The range of lithologies in the two formations is quite similar, so the contact may be difficult to choose. The Luolou, as originally defined and currently used in Guangxi, spans the entire Scythian (Early Triassic), but only where the rocks are predominately calcareous (Guangxi Bureau, 1985, 2000). Siliciclastic rocks more distant from the carbonate platforms are designated the Nanhong Formation.

Fossils from the Ziyun Formation (Guizhou Bureau, 1987, p. 302–303; unpublished Nulizhai section by Liu Aimin in 1992; Wei Jiayong et al., 1996):

Brachiopods: *Lingula* sp.

Bivalves: *Claraia aurita*, *Entolium* sp., *Leptochondria* sp., *Posidonia* sp.

Ammonoids: *Anasibirites* sp., *Clyptopliceras* sp., *Columbites* sp., *Gyrophiceras* sp., *Lyttopliceras* sp., *Meekoceras* sp., *Owenites* sp., *Paranannites* sp. P. cf. *subglobosis*, *Pleuranectites* sp., *Pseudospidites* sp., *Pseudowenites oxynostus*?, *Subcolumbites* sp., *Tirolites* cf. *spinosis*

Conodonts: *Neospathodus triangularis*, *Parachirognathus delicatulus*

Published values for the duration of the Olenekian stage agree on 4.7 m.y. (Ogg, 2004, p. 283; Haq et al., 1988, p. 100 by interpolation), whereas our recent radiometric dates suggest 3.9 Ma, using the interpolation of Ogg (Martin et al., 2001; Lehrmann et al., 2003, 2006b). Applying these values to the reported maximum and minimum thicknesses of the Ziyun Formation without decompaction yields a range of accumulation rates from 4 to 54 m/m.y. (Table 2). Using the mean of all thickness values available, including those from Figure 13, gives rates from 22 to 26 m/m.y., among the lowest for the entire Triassic.

### Anshun Formation

The Anshun Formation forms a broad outcrop belt, which encompasses the type locality in central Guizhou, between the Ziyun Formation to the southeast and the Yongningzhen Formation to the northwest (Fig. 12). The Anshun is typically highly dolomitized, but some details of cyclicity, lithology, and sedimentary structures can generally be discerned. Reported thickness ranges from 280 to 712 m (Guizhou Bureau, 1987, p. 294). The Anshun is a prominent ridge former in western Guizhou, second only to the Longtou-Yangliujing ridge (Ladinian). It forms the threshold for Huangguoshu Falls 46 km southwest of Anshun, the largest in Asia at 84 m wide and ~70 m high (Corrigan, 1995). The most detailed observations were made at Renrenshan, 6 km west of Qingyan, a 691-m section previously measured in

considerable detail by the Guizhou Team (unpublished). Other measured sections were at Gaimao (unpublished), 12 km south-southeast of Guiyang, where the Anshun is 293 m thick, at Wenjing, Guiyang (495 m thick; Guizhou Bureau, 1987, p. 294), at Hongyan (167 m; Minzoni, unpublished), and the top 55 m at Zhenfeng (Enos, unpublished). Observations were also made at Dulaying (Fig. 2). Twenty-eight thin sections (50 × 75 mm) were studied, 23 from the Renrenshan section.

The meter-scale cycles common in the Anshun Formation are familiar from carbonates of many ages, particularly from the Tethyan Triassic (cf. Bosellini, 1967; Bosellini and Hardie, 1985; Goldhammer et al., 1990; Satterley, 1996; Enos and Samankassou, 1998). The base of a typical cycle is sharp, locally erosive. The basal unit is a thick bed of peloidal, intraclastic, skeletal, or oolitic dolostone, with depositional textures ranging from wackestone to grainstone or rudstone. Bioturbation is the norm, but a few of the grainstones are cross-bedded. Fenestral pores commonly appear at the top of the basal unit and increase in size and abundance into the overlying unit of millimeter-laminated dolomudstone or wackestone. Other structures within the capping unit include desiccation cracks, sheet cracks, and, locally, domal stromatolites (Fig. 14). Some cycle caps are overprinted by extreme diagenetic disruption into tepee structures (cf. Assereto and Kendall, 1971; Dunham, 1972). The basal unit is typically two or three times as thick as the cap, but the proportions are reversed in a few cycles. In the Renrenshan section 107 cycles were recorded with an average thickness of 4.1 m (Guizhou Team, unpublished). Of 24 cycles where individual thickness was recorded, generally the thicker cycles, thickness was  $4.61 \pm 2.38$  m. The thickest cycle was 13.9 m, including a 2-m cap; the thinnest was 1.6 m. Thinner cycles are evident in the field within some units recorded only as interbedded dolomite and laminated dolomudstone, so the total number of cycles could be appreciably greater and the average thickness concomitantly less. No persistent trends in cycle thickness or abundance are evident within the formation; they occur from base to top, except where obscured by dolomitization or disruption.

Fully 56% of the Anshun Formation in the Renrenshan section is described simply as “finely crystalline dolostone” (Guizhou Team, unpublished); but if the basal 186 m is ignored, where dolomitization was particularly brutal and exposure is poor, this figure is reduced to 40%. From the measured section, the upper 505 m of the Anshun consists of 40.3% crystalline dolostone; 24.7% dolomudstone (virtually all millimeter-laminated), 6.2% dolowackestone, 10.7% dolopackstone, and 18.0% dolograins. As seen in thin section, much of the “crystalline dolostone” is in fact peloid-intraclast dolopackstone, and many of the laminated “dolomudstone” caps are interlaminated couplets of microlaminated mudstone and peloid-intraclast packstone. This suggests that packstone may be volumetrically the most common recognizable depositional texture.

Ripple-drift cross-lamination, locally bidirectional, is reported from the upper portions of the basal cyclic units at 320 to 350 m and 460 to 485 m above the base of the Renrenshan section. Fenestral pores or “bird’s-eyes” occur throughout in the



Figure 14. Cycle cap with laminites and desiccation-related disruption in dolostone of the Anshun Formation, Renrenshan section. Disruption at center qualifies as an incipient tepee structure. Field of view is ~25 cm high.

upper parts of cycles, particularly in the laminated caps. Desiccation cracks are visible in some laminated caps. Domal stromatolites, wavy laminites, and disrupted laminites occur within the caps sporadically throughout the formation. Graded and inversely graded laminae of peloid-intraclast packstone are interlaminated with mudstone in some caps. Cut-and-fill structures occur on outcrop scale at the base of cycles, locally forming small channels, and on microscopic scale within the laminated caps. Imbricated intraclasts are associated in a few examples. Distinct burrows are uncommon, but structureless intervals in the base of cycles are likely completely bioturbated. Thin intervals of breccia within some cycles are attributed to dissolution of evaporites (Fig. 15).

As suggested by the abundance of peloid-intraclast packstone, peloids are by far the most common particle. Some peloids are identifiable as fecal pellets by their uniform shape and size, typically ovoids ~60  $\mu\text{m}$  long; by concentration in burrows, shelter, and fenestral pores; and by margins slightly deformed by compaction indicating that they were firm, but not lithified, at the time of deposition. Many other rounded or irregular, dark peloids with sharp edges are probably altered bioclasts and intraclasts. Among obvious intraclasts, structureless or laminated lime mudstone are by far the most common. Grapestone aggregates occur in a few layers. Oncoids are common particles in packstones and grainstones in the top 45 m of the Renrenshan section; they also occur at 355 and 465 m above the base. Ooids are sparsely distributed in beds 20 to 460 cm thick. The thickest ooid-bearing interval is 12 m, at 445 m above the base of the section. Other oolites are at 310, 550, 585, and 620 m above the base. Most ooids are represented only by spherical molds, 0.5 to 1 mm in diameter.

Bioclasts are sparsely distributed throughout the formation, but are the dominant particles in only a few beds. Gastropods are the most commonly identified fossil in both outcrop and thin section, followed by bivalves, foraminifers, ostracodes, calcispheres, echinoderms, and inarticulate brachiopods.

Diagenetic disruption of beds to form tepee structures is evident in many cycles in the upper part of the Renrenshan section, between 465 and 645 m. Disruption is most intense within a 12-m interval at 510 m above the base where very large and intensely deformed structures are amalgamated across several depositional cycles. This interval can be traced for several kilometers and very likely is regional in extent. Dolomitization is the most pervasive diagenetic overprint. In general the replacive dolomite is planar and unimodal crystals with modal size ~100  $\mu\text{m}$ , but ranging from 20 to 150  $\mu\text{m}$ . Preservation of particles is fair, except in coarser crystalline intervals. Dolomite cement is widespread as equant crystals in primary interparticle and fenestral pores as well as secondary molds, vugs, and fractures. As much as 20% moldic porosity remains locally in the Anshun, but total unfilled porosity is generally less than 5%.

The Anshun sections at Wenjing (495 m) and Gaimao (293 m) were measured in considerably less detail and cyclicity is much less striking on the outcrop. The basal 104 m at Wenjing is thick-bedded arenaceous limestone with thin interbeds of lime mudstone and argillaceous lime mudstone containing bivalves and lingulid brachiopods (Guizhou Bureau, 1987, p. 294–295). The overlying 196 m are similar arenitic dolostone with ooid dolostone interbeds passing up into arenitic dolo-oolite with bioclastic dolostone interbeds. Bivalves are the only fauna identi-



Figure 15. Brecciated interval at the top of a cycle, probably reflecting dissolved evaporites. Anshun Formation, Renrenshan section. Width of field is ~60 cm.

fied. The uppermost 196 m are dolomudstone containing glomospirellid foraminifers with arenitic dolostone interbeds. The many brecciated intervals are interpreted as solution-collapse breccias (Guizhou Bureau, 1987, p. 294). A few pseudomorphs of gypsum crystals strengthen this interpretation.

The Gaimao section is crystalline dolostone bedded on a scale of 5 to 30 cm with laminated dolomudstone intervals suggesting cycle caps. A lenticular conglomerate and two breccias, 1.2 and 0.4 m thick, are reported in the lower third of the formation. An offset of 3 km southward toward the basin in the Gaimao section reveals a dramatic southward gradation within the Anshun from dolostone into dominantly limestone without a hint of shoaling cycles. The medium-gray lime mudstones form centimeter to decimeter beds separated by argillaceous partings. Laminated beds are interspersed among vaguely mottled beds that are probably bioturbated beyond all recognition. Several very argillaceous beds preserve discrete horizontal burrows. A graded bed of lime-mudstone conglomerate, 50 cm thick, is in the lower third of the unit. This lithology is comparable to the underlying Daye Formation, although burrowed intervals and breccia are much less prominent. A narrow band of such limestone, thinner bedded and darker than typical Anshun dolostone, is mapped as the Gujiao facies at scales of 1:200,000 or larger in many areas along the platform margin. It forms a transition, probably just seaward of the slope break, to the predominately siliciclastic mudrock of the Ziyun Formation within the Nanpanjiang Basin.

On the Anlong Road southeast of Zhenfeng, 40 cm of tuffaceous shale may represent the “green-bean” rock and thus the top of Anshun. The basal 20 m of a 58-m measured section of Anshun includes two laminated intervals capping meter-scale cycles. The top 38 m are ooid dolograinstone (Fig. 16) incorpo-

rating five intervals of domal stromatolites with up to 70 cm of relief (Fig. 17). Although oolite is minor in the Anshun sections studied in more detail, dolo-oolite is common in the Zhenfeng area near the platform margin. Most ooids are 1 to 2 mm in diameter with thick, finely laminated cortices. Several beds include pisoids up to 12 mm in diameter.

The Anshun section at Hongyan, nearer to the type locality at Anshun, but also nearer the platform edge (Fig. 2), differs lithologically from the more typical sections. It is predominately crystalline dolomite, only ~167 m thick, that locally preserves some millimeter lamination and possible peloids or ooids. A 19-m interval of thin-bedded lime mudstone with shale partings and abundant bedding-plane trace fossils is lithologically identical to the underlying Daye Formation. This could represent the platform-margin Gujiao facies of the Anshun Formation, described above from Gaimao. However, mapping by Minzoni of the platform margin at Dabang, ~3 km distant, shows a tongue of the Daye Formation interbedded with the Anshun. This indicates time equivalence between the upper part of the Daye Formation and the Anshun, within the lower 60 m at Hongyan. Care is necessary in mapping the Gujiao facies to determine whether there is a lateral facies change at the margin of the Anshun or intertonguing with the Daye Formation, which would indicate a diachronous boundary between the Anshun and Daye.

Fossils from Anshun Formation (Guizhou Bureau, 1987, p. 294; Wei Jiayong et al., 1996; Conodonts were identified by Yang Shouren from Xiaojiazhuang, Pingba; reported by Wei Jiayong et al., 1996):

Foraminifers: *Glomospirella* sp., *G. shengi*, *G. sinensis*, *G. sygmoidalis*

Brachiopods: *Lingula* sp., *Mentzelia* sp.

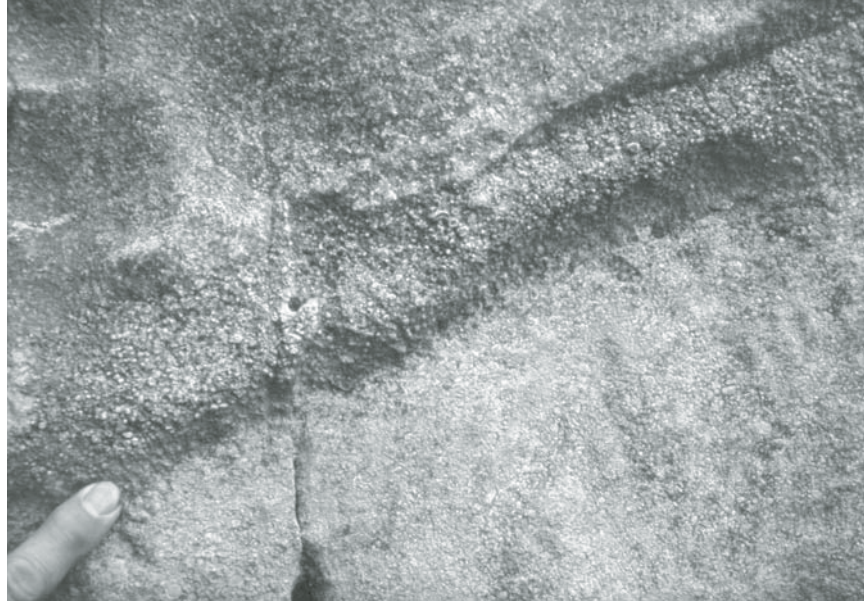


Figure 16. Ooid dolograins in the Anshun Formation. Anlong Road section, 4.7 km south of Zhenfeng.

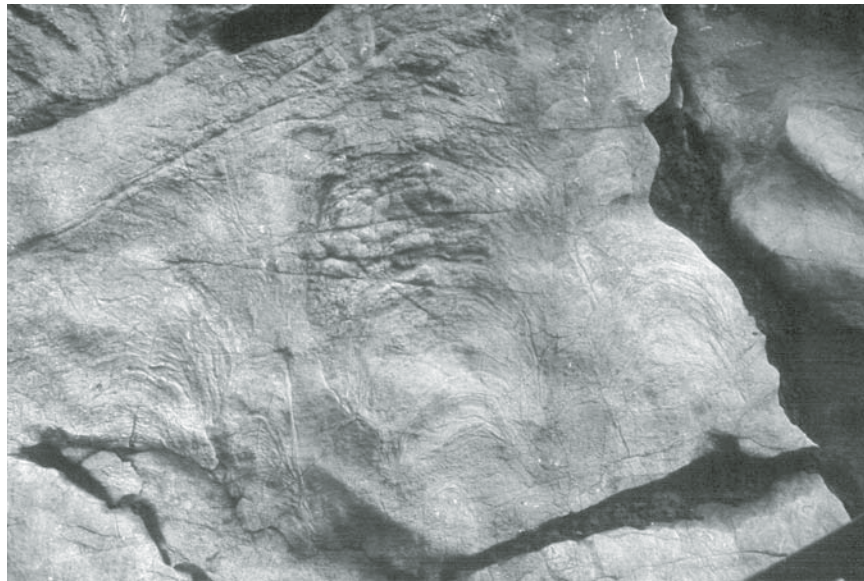


Figure 17. Domal stromatolites within oolitic dolograins; Anshun Formation, Anlong Road section, 4.7 km south of Zhenfeng. Bed is 80 cm thick.

Bivalves: *Bakevella* sp., *Claraia* sp., *Entolium discites*, *Eumorphotis* cf. *telleri*, *E.* cf. *hinmitidea*, *E.* cf. *inaequicostata*, *E. telleri*, *Leptochondria* cf. *betneri*, *Myalina* sp., *Myophoria* (*Neoschizodus*) sp., *Mytilus* sp., *Promyalina* cf. *putiatiensis*, *P.* cf. *intermedia*, *Unionites* sp., *U. fassaensis*  
 Ammonoids: *Anasibirites* sp., *Dinarites* sp., *Hellenites* sp., *Japonites* sp., *Kashmirites* sp., *Owenites* sp.

Conodonts: *Lonchodina* sp., *Neohindeodella* sp., *Neospathodus* cf. *pakistanensis*, *N.* cf. *waageni*, *Ozarkodina tortilis*, *Parachirognathus* sp.

The thickness range of 167 to 712 m reported for the Anshun corresponds to accumulation rates of 36 to 180 m/m.y. (Table 2). The mean thickness of all sections, 440 m, gives rates of 95 to 110 m/m.y. Anshun lithologies evince few signs of compaction.

### Yongningzhen Formation

The Yongningzhen Formation crops out north and west of the other Olenekian formations, farther into the interior of the Yangtze Platform. It was measured in detail at the type section west of Guanling (YN section; Fig. 2) and reconnoitered in the Longchang section (LC). Formation thickness is 647 m at Yongningzhen (594 m according to Guizhou Bureau, 1987, p. 284) and 552 m at Longchang (Guizhou Team, 1980, p. 118); the Guizhou Bureau (1987, p. 283) reports a range of 300 to 875 m.

The formation is predominately limestone, in contrast to the dolomitic Anshun Formation, although the uppermost 100 to 250 m is dolostone. The basal 125 m at Yongningzhen is uniform medium-gray lime mudstone with medium bedding, mostly in the range of 15 to 60 cm. The only exceptions are a few beds of wackestone and a very few thin beds of packstone and grainstone with peloids, skeletal fragments, and, rarely, intraclasts or coated grains. Burrowing is sparse to moderate throughout; a few intervals near the base are laminated. Sparse fossils include bivalves, gastropods, ostracodes, and lingulid brachiopods. The thin-shelled bivalves, such as *Eumorphotis*, are reported along with thicker-shelled *Myophoria* (Guizhou Bureau, 1987, p. 284). After 125 m the monotony is broken by a massive bed with 6 m of lime mudstone capped by 2 m of ooid grainstone. Burrowed lime mudstone dominates again for 70 m, broken only by ooid grainstone beds 0.2 and 2 m thick. Eleven covered intervals 0.1 to 3 m thick may conceal shale interbeds. An interval of massive beds dominated by oolite extends from 200 to 270 m at Yongningzhen. Peloids, intraclasts, and shell fragments are minor components. Muddier lithologies, ranging

from packstone to argillaceous lime mudstone constitute portions of the massive beds and some medium interbeds, totaling about half of the interval. Structures are confined to a few horizontal burrows, centimeter-scale interbeds of oolite, and some fenestrae (Fig. 18).

This massive interval is followed abruptly by 10 m of thin-bedded, dark-gray lime mudstone with thin-shelled bivalves that grades up into 15 m of black shale with variable fissility. Nodular-bedded, dark-gray lime mudstone, 40 m thick, with horizontal burrows, thin-shelled bivalves, and locally common ammonoids (*Tyrolites spinosis*) follows (Fig. 19). Variants of this lithologically distinctive, ammonoid-bearing sequence are widespread in western Guizhou, e.g., at 215 to 241 m above the base of the Yongningzhen at Longchang (Fig. 13), in southern Sichuan, and in northeastern Yunnan. Comparable intervals are not recognized in the Guiyang sector to the east nor farther south in the Zhenfeng sector.

Shale and mudstone 6 m thick separates this nodular-bedded limestone from flaggy-bedded, medium-gray lime mudstone with bedding-plane burrows, ammonoids, and thin-shelled bivalves. This interval, ~35 m thick, contains a few meter-scale shale breaks and thin shelly layers. Deposition of medium-bedded, gray lime mudstone with thicker-shelled bivalves, gastropods, ostracodes, sparse echinoderm fragments, and horizontal burrows (Fig. 20) resumed to form an interval ~180 m thick. Centimeter-bedded crystalline dolostone with brecciated intervals makes up the upper 100 m of the Yongningzhen Formation at Yongningzhen and 250 m at Longchang. Brecciation, most intense toward the top, produced dolostone clasts in an earthy matrix, recognized throughout western Guizhou (Fig. 21). A tuffaceous layer about

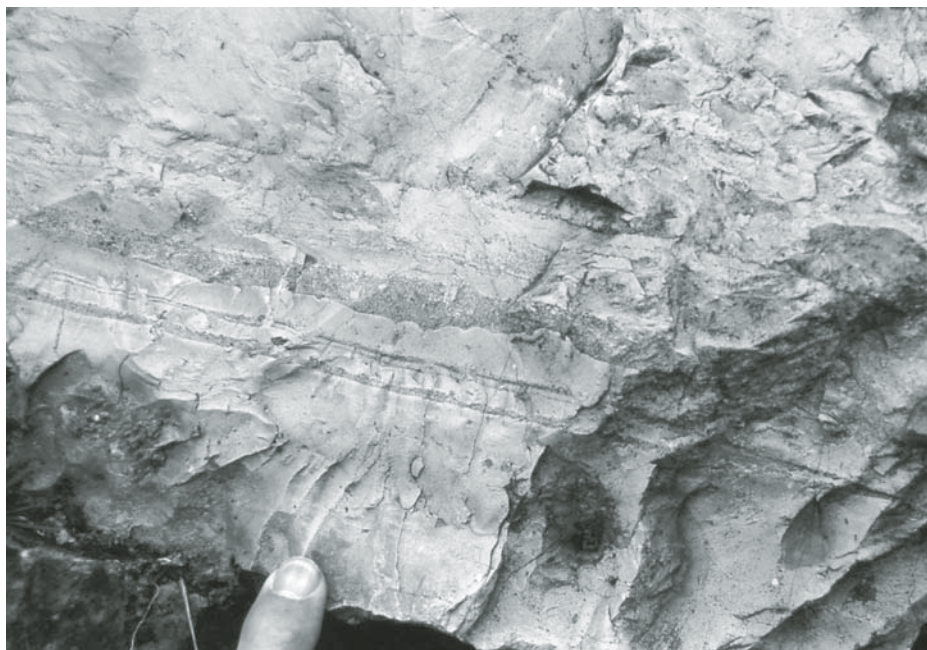


Figure 18. Pelleted lime wackestone of Yongningzhen Formation with thin interbeds of ooid-intraclast grainstone. Note the many fenestrae in the wackestone. Yongningzhen section, 215.8 m.

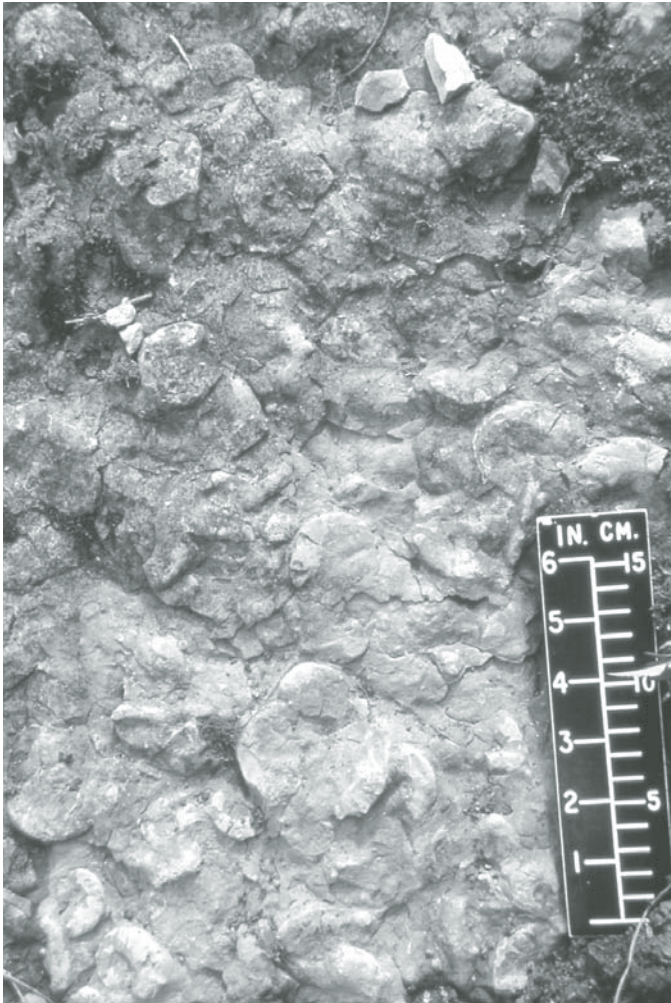


Figure 19. Approximate bedding surface in nodular lime mudstone of Yongningzhen Formation showing many ammonoids (*Tyrolites*) and some horizontal burrows. Yongningzhen section, 308 m.

a meter thick probably represents the “green-bean rock” and thus the top of the Yongningzhen. A 10-cm tuff layer ~8.3 m lower in the YN section could not be traced to adjacent outcrops.

Time-equivalent, platform-interior strata farther north and east in Guizhou are the Maocaopo Formation. A section at Gaoqiao, Zunyi, 125 km north of Guiyang, is 369 m thick. Here, too, lime mudstone, locally burrowed, predominates in the basal 164 m. Interbedded are dolostone, argillaceous limestone, and sporadic oolite. The biota includes bivalves, gastropods, and brachiopods. The overlying 36 m of dolostone, dolomitic limestone, and lime mudstone contain brecciated intervals associated with some chert, suggestive of solution-collapse breccia. This interval also contains bivalves, gastropods, and, at the top, *Tyrolites*. The upper half of the formation appears to be a replay, with 136 m of bioclastic limestone and dolomitic limestone grading up into dolostone and overlain by 33 m of dolostone with a sparse, monospecific bivalve fauna and intervals of solution-collapse

breccia. This interval of brecciated dolostone can be correlated to the northern border of Guizhou (Fig. 13; Wei Jiayong et al., 1996) and with the dolobreccia at the top of the Yongningzhen farther west.

Fossils from the Yongningzhen Formation (Guizhou Bureau, 1987, p. 283–284; Guizhou Team, 1980, p. 118; conodonts from Yang Shouren and Chu Qingchun, 1992; Wei Jiayong et al., 1996)

Brachiopods: *Lingula* sp., *L. tenuiseima*, *Lingula tenuiseima* var. *sinensis*

Bivalves: *Bakevella* sp., *B. cf. costata*, *B. leshanensis*, *Chlamys* sp., *Claraia* sp., *Entolium* sp., *E. discites microtis*, *Eumorphotis* sp., *E. telleri tuberculata*, *E. teilhardi*, *E. hinntidea*, *Gervillia mytiloides*, *G. sp.*, *Heminajas* sp., *Leptochondria* sp., *Myalina gigantus*, *Myophoria (Elegantina)* sp., *Myophoria (Leviconcha)* sp., *Myophoria (Neoschizodus) laevigata*, *Mytilus* sp., *Pleuromectites* sp., *Promyalina cf. putiatimensis*, *Promytilus* sp., *Pteria cf. purchisoni*, *Unionites* sp., *U. cf. fassaensis*

Ammonoids: *Dinarites* sp., *Meekoceras* sp., *Tirolites* sp., *T. spinosus*

Conodonts: *Chiosella timorensis*, *Cypridodella* sp., *C. dinodoides*, *Enantiognathus* sp., *E. delicatulus*, *E. zieglerei*, *Furnishius wangcangensis*, *Hadrodontina* sp., *H. cf. adunca*, *H. anceps*, *Hibbardella* sp., *H. meissneri*, *H. triassica*, *Hindeodella nevadensis*, *H. cf. raridenticulata*, *H. suevica*, *H. triassica*, *H. torta*, *H. tumida*, *Latignathus* sp., *L. magnus*, *L. multidentatus*, *Ligonodina* sp., *L. triassica*, *Lonchodina aequiarcata*, *L. disdentata*, *L. muelleri*, *L. nevadensis*, *Neogondolella* sp., *N. constricta*, *N. cf. jubata*, *N. navicula navicula*, *Neohindeodella* sp., *N. kobayashii*, *N. muelleri*, *N. nevadensis*, *N. raridenticulata*, *N. suevica*, *N. triassica*, *Neospathodus* sp., *N. conservativus*, *N. homeri*, *N. timorensis*, *N. triangularis*, *N. cf. waageni*, *Ozarkodina* sp., *O. elegans*, *Pachycladina* sp., *P. inclinata*, *P. longispinosa casta*, *P. longispinosa longispinosa*, *P. longispinosa simplex*, *P. obliqua*, *P. postdentata*, *P. trigona*, *Parachirognathus* sp., *P. delicatulus*, *P. ethingtoni*, *P. geiseri*, *P. magnus*, *P. minutus*, *P. orientalis*, *P. semicirnelus*, *P. symmetricus symmetricus*, *P. tricuspidatus tricuspidatus*, *P. tricuspidatus simplex*. *Prioniodella* sp., *P. decrescens*, *Xaniognathus* sp.

Fossils from the Maocaopo Formation (Guizhou Bureau, 1987, p. 282; Wei Jiayong et al., 1996):

Bivalves: *Bakevella* sp., *Entolium* sp., *E. discites microtis*, *Eumorphotis* sp., *E. cf. multiformis*, *Gervillia* sp., *Leptochondria* sp., *Myophoria* sp., *Myophoria (Neoschizodus) laevigata*, *Pleuromectites* sp., *Pteria* sp., *Unionites* sp.

Ammonoids: *Tirolites* sp.

Gastropods: *Loxonema* sp.

The Yongningzhen Formation varies in thickness from 300 to 875 m, indicating accumulation rates of 64 to 225 m/m.y. The mean thickness 594 m corresponds to accumulation rates of 125 to 150 m/m.y. Compaction is not evident in the Yongningzhen carbonates.

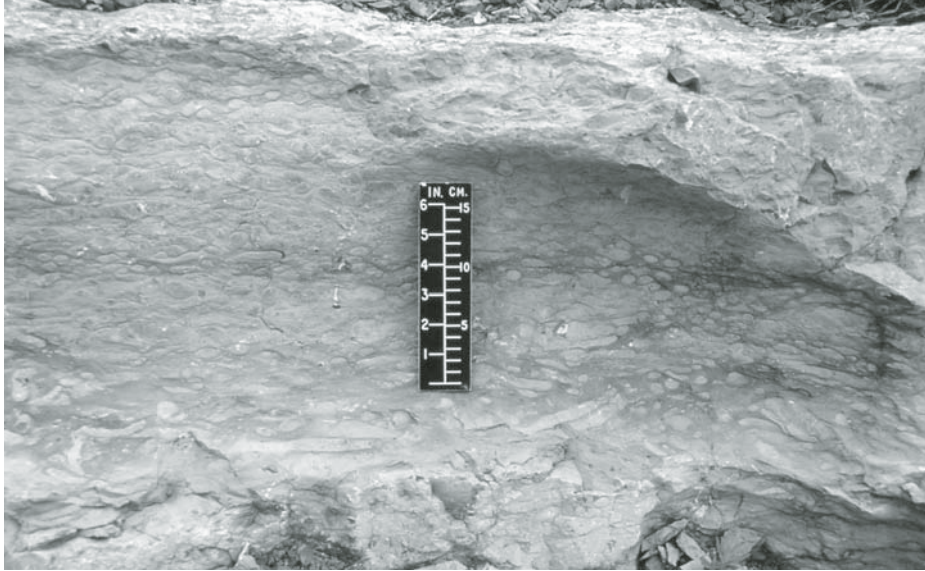


Figure 20. Extensively burrowed, slightly argillaceous, lime mudstone from Yongningzhen Formation. Yongningzhen section, 373 m.

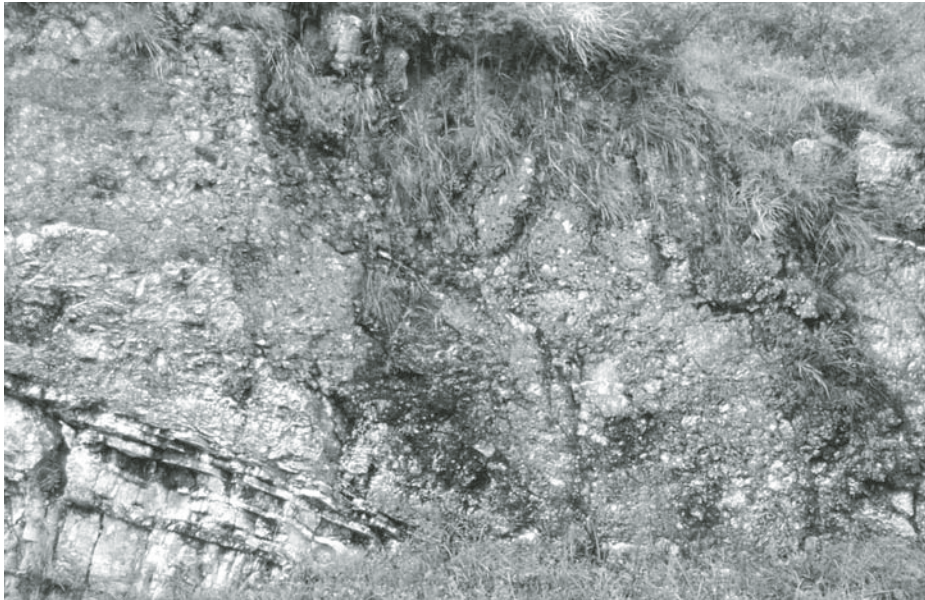


Figure 21. Breccia of dolostone clasts in earthy matrix, attributed to dissolution of evaporites. Near top of Yongningzhen Formation, Yongningzhen section.

### Depositional Environments

The general facies distribution in the Olenekian parallels that in the underlying Induan formations, with gradational lateral contacts between formations that occur in roughly the same locations (cf. Figs. 4 and 9). The Olenekian formations are lithologically more distinct from one another and the contacts are correspondingly somewhat sharper. To the southeast lay a basin that was

receiving a mixture of carbonate and terrigenous mud to form the Ziyun Formation, whose distribution approximates that of the more calcareous Luolou Formation. The character and distribution of the nearly pure carbonate formations, the Yongningzhen and the Anshun, which overlie the Yelang and the Daye, respectively, define a carbonate platform. This is in contrast to the ramp configuration of the Induan Stage. The Olenekian platform margin was less well defined than that of the Middle Triassic,

however, and probably had appreciably less relief. Variations in formation thickness in the Lower Triassic may provide a reasonable estimate of synoptic relief as all sections were measured over the drowned Permian carbonate platform, which probably had very little intraplatform topography. Formation thickness (Table 3) indicates that relief on the Induan ramp may have been ~450 m between the most distal and most proximal. Differential thickness between the Daye (mid-ramp) and Luolou (basin) is only ~150 m. The thickness contrasts between the Olenekian carbonate formations and the basinal Ziyun, 350 to 500 m, reflects the development of a carbonate platform. Combining all of the Lower Triassic thickness values indicates final differential relief of 500 to 900 m between platform and basin, post-compaction and without isostatic compensation.

The thin (~100 m) Ziyun Formation has uniformly fine-grained lithologies—carbonate mudstone, calcareous shale, mudstone, and claystone—and predominately nektonic or planktonic biota. It was deposited in a basin isolated from most terrigenous detritus, probably by the carbonate platform, which lay to the west and north. Laminated intervals could reflect rapid deposition from suspension or an oxygen-deficient bottom. The general thinness of the formation favors lack of oxygen rather than rapid deposition. The alternation of laminated and burrowed intervals and the absence of benthic biota further indicates dysaerobic bottom conditions, although there is little accumulation of organic matter. Lime breccias, interspersed mainly near the base and in more proximal sections, are deposits of debris flows generated on the platform slopes and margins. Clasts are predominately basinal lime mudstone, but platform-derived oolite and skeletal or peloidal packstones are widely distributed. The matrix was basinal lime mud with a planktonic biota mixed with a few platform-derived bioclasts and ooids. Interbeds of peloidal packstone, observed only in the Gouli section, are probably turbidity-current deposits. Thin beds of siltstone and silty mudstone with lamination and ripple-drift cross-lamination are likely distal turbidites.

The Anshun Formation occupied the outer margin of the carbonate platform. The characteristic meter-scale cycles are typical shoaling-upward cycles. The thicker cycle bases of peloidal, intraclastic, skeletal, or oolitic wackestone to rudstone represent moderate-energy, shallow-water deposits. The cyclic upward appearance of fenestral fabric followed by millimeter lamination, desiccation cracks, and domal stromatolites in the cycle caps records repeated accretion into tidal environments. More extensive periods of subaerial exposure are recorded by diagenetic disruption into tepee structures evident at several levels and especially prominent at one level where disruption has amalgamated several depositional cycles. Cyclic deposits apparently extended to the platform edge or nearly so; no distinctive marginal shoal deposits are recognized in the Guiyang sector. Judging from modern and ancient examples of tidal-flat accumulations at platform margins, some barrier must have existed to provide a sheltered environment for the accumulation of fine-grained tidal deposits; common examples are reefs, sand shoals, or antecedent islands. The higher-energy intraclastic, skeletal, and oolitic sand in the

cycle bases suggest the presence of narrow sand-shoal barriers at the platform edge. Paradoxically, oolite is common near the platform margin at Zhenfeng, but cyclicity is less prominent. Platform deposits more distant from the margin within the Anshun and in the Yongningzhen Formation appear to be entirely subtidal without the marked small-scale cyclicity. The platform margin was apparently elevated somewhat relative to an interior lagoon.

The less cyclic Anshun deposits at Wenjing are muddier, indicating somewhat lower energy, but have a slightly more diverse biota preserved, perhaps because of less pervasive dolomitization. Restriction evidently increased toward the top as indicated by monospecific bivalve faunas, increased dolomitization, gypsum molds, and breccias interpreted as the result of dissolution of evaporites. Platform-interior rocks show similar evidence of more restriction during later stages of deposition.

The marked thickness reduction in the Anshun section at Gaimao (293 m) and Hongyan (167 m) probably reflects basinward facies changes at the base of the formation into a Daye-type lithology of dark-gray, thin-bedded, laminated or burrowed, lime mudstones. Such lateral transitions are evident on small scale in the outcrop at Hongyan and in a 3-km offset of the section at Gaimao, as described above. In addition, Daye facies intertongue with Anshun lithologies in the Hongyan area, showing that the contact is diachronous. The distinction between Daye and Anshun is further complicated by the mapping criterion that the Anshun is generally dolostone and the underlying Daye is limestone. The local appearance of darker, thin-bedded limestone, the Gujiao, as a slope-break facies of the Anshun dolostones obscures placement of Daye-Anshun contact. Conversely, where dolomitization has destroyed depositional textures, as locally appears to be the case at Hongyan (M. Minzoni, 2002, personal commun.), lithologies that would ordinarily be considered Daye might be mapped as Anshun. In this case, of course, the apparent thickness of Anshun would be increased rather than reduced.

The Yongningzhen Formation and the approximately equivalent Maocaopo Formation at Zunyi are predominately muddy limestones or dolostones with claystone partings or interbeds. Brecciated dolostone is prominent in the upper part of the formations. The fauna is mostly shallow-water mollusks. The depositional setting was probably a platform-interior lagoon, persistently subtidal, with influxes of terrigenous mud from at least the Khamdian massif to the west. Terrigenous influxes episodically extended to the outer platform, where winnowing produced the arenaceous limestones and dolostones noted in the Wenjing section of the Anshun. Widespread dark, laminated or nodular limestone and dark mudrock with thin-shelled bivalves and ammonoids punctuated this lagoonal depositional mode. A regional deepening episode is indicated. The juxtaposition of this deeper-water facies over a thick oolite points to a high-energy shoaling phase just prior to the deepening. The absence of evidence for deepening in the Guiyang sector suggests that this area was tectonically more positive than the Zhenfeng sector, a relationship seen repeatedly during the Early and Middle Triassic and more dramatically in the Carnian. The absence of a deepening episode



toward the south of the Zhenfeng sector may mean that sedimentation nearer the platform margin kept pace with sea level, as suggested by the persistent peritidal cycles in the Anshun. On the other hand, this area may also have been more positive and the deepening event the reflection of intraplatform basin development (“Becken and Schwellen” in German usage), rather than eustasy. The generally higher accumulation rates in the lagoonal Yongningzhen Formation than in the Anshun Formation (Table 2), with its abundant shoal-water facies, is consistent with differential subsidence of the platform interior.

Toward the close of the Early Triassic the Yangtze Platform became more restricted and produced evaporites recorded by widespread dolomitic collapse breccias. This trend is recorded in both the Yongningzhen and Anshun Formations. Two such cycles from lagoonal mudstones to evaporites are evident within the time-equivalent Maocao Formation. The wide extent of the breccia and the lack of distinctive exposure features in the laminated dolostone suggest lagoonal rather than sabkha precipitation of the evaporites.

#### **ANISIAN (LOWER MIDDLE TRIASSIC) FORMATIONS**

The Anisian is unique among the Triassic stages of southwestern Guizhou in that it encompasses five distinct, laterally equivalent facies, the Xinyuan, Xuman, Qingyan, Poduan, and Guanling Formations (Table 1, Fig. 22). The basinal area, defined during the Lower Triassic and expanded very slightly within the Anisian (Enos et al., 1997), is subdivided into three formations. The relatively thick Xuman Formation is distributed in the area southwest of Ziyun, the Xinyuan occupies most of the basin to the east and north, but the Qingyan is mapped in a narrow belt ~175 km long at the basin margin of the Guiyang sector of the platform (Fig. 22). The Poduan Formation forms a narrow and laterally discontinuous outcrop belt that marks the margin of a carbonate platform. The areally extensive Guanling Formation represents deposits of the platform interior. Some authors recognize a sixth formation in the Guiyang sector, between the Poduan or the platform edge and the Guanling, the dolomitic Huaxi Formation (e.g., Wang Liting, 1996, p. 34). It is perhaps best regarded as a dolomitized facies of the Guanling. Still another formation, the Badong, is apparently Anisian in age in the lower part. The Badong is predominately siliciclastic and broadly borders the Jiangnan Massif in eastern Guizhou (Fig. 22).

Basal contacts with Lower Triassic (Olenekian) formations are conformable (Guizhou Bureau, 1987) and are defined where possible by the “green-bean rock,” a widespread layer of altered tuff. In the absence of this marker bed, the contacts are defined by lithologic changes. These are quite distinct at the platform margin, are generally distinct but gradational within the basin, and can be somewhat arbitrary in the platform interior. The Anisian-Ladinian contacts are likewise conformable and defined by lithologic changes with varying degrees of contrast and sharpness.

#### **Xinyuan Formation**

The Xinyuan Formation is summarized simply as “sandstone, shale and thin-bedded limestone, 146-340 m thick” by the Guizhou Bureau (1987, description of map units). Outcrops were observed at Zhulinzhai, 3.6 km southeast of Qingyan; north of Luodian; at Nulizhai; and at Mengjiang, 18 km west of Luodian (Fig. 2). A measured section at Niluo, Zhenfeng, 340 m thick, was published by the Guizhou Bureau (1987, p. 306; Fig. 2), and the Nulizhai section, 234 m thick with no upper contact, was measured by Liu Aimin of the Guizhou Regional Geologic Mapping Team (unpublished, 1992). Thickness of the Xinyuan is reported as 900 m in the area northeast of Qingyan (Qin Shourong et al., 1989). It is clear from field relations that the Xinyuan filled the basin margin in that area and provided the substrate for extensive local progradation of the Yangtze Platform margin during the Ladinian (Fig. 23; Wei Jiayong and Enos, 1991).

The base of the Xinyuan Formation is marked by a change from predominately lime mudstone at the upper part of the underlying Ziyun Formation to terrigenous mudstone or claystone of the lower Xinyuan. An altered tuff interval, the “green-bean rock,” reported in all sections except Luodian, provides a punctuation mark that is presumably synchronous. The upper contact beneath the terrigenous Bianyang Formation is less readily defined. For mapping purposes it is placed at the lowest occurrence of thick sandstone beds or at the lowest lime-breccia bed in some near-platform locations (Yu Youyi, 1995, personal commun.). The distinction between thin-bedded siltstone, common within the Xinyuan, and somewhat thicker-bedded, fine-grained sandstone of the Bianyang is not dramatic and the transition is gradational. Lime-breccia beds, which generally appear lower in the section, are sporadic and localized; they become less abundant with distance from the carbonate platforms, i.e., the Yangtze Platform (Enos et al., 1997) or the Great Bank of Guizhou (Lehrmann, 1993; Lehrmann et al., 1998). Consequently, they are unlikely to mark a synchronous boundary. Moreover, the Xinyuan at the northern basin margin grades laterally into the Qingyan Formation, which is characterized by lime breccias.

Gray claystone and silty claystone (mudrock) with a greenish or yellowish cast are the dominant lithologies in the measured sections. Fresh mudrock surfaces are dark gray near the base of the formation. The distinction of claystone from shale depends in part on the extent to which weathering accentuates the fissility that defines shale. In weathered exposures, e.g., at Zhulinzhai, southeast of Qingyan, “shale” is interspersed with indistinct, centimeter-scale intervals of structureless mudrock with sub-conchoidal fracture. This contrast may reflect incipient silicification and bioturbation in the mudrock. Locally bedding surfaces within the mudrock have myriad feeding traces of various scales and affinities. Minute bedding-plane structures are most common, but some are delicate, three-dimensional grazing structures referable to *Zoophycos* and *Chondrites*

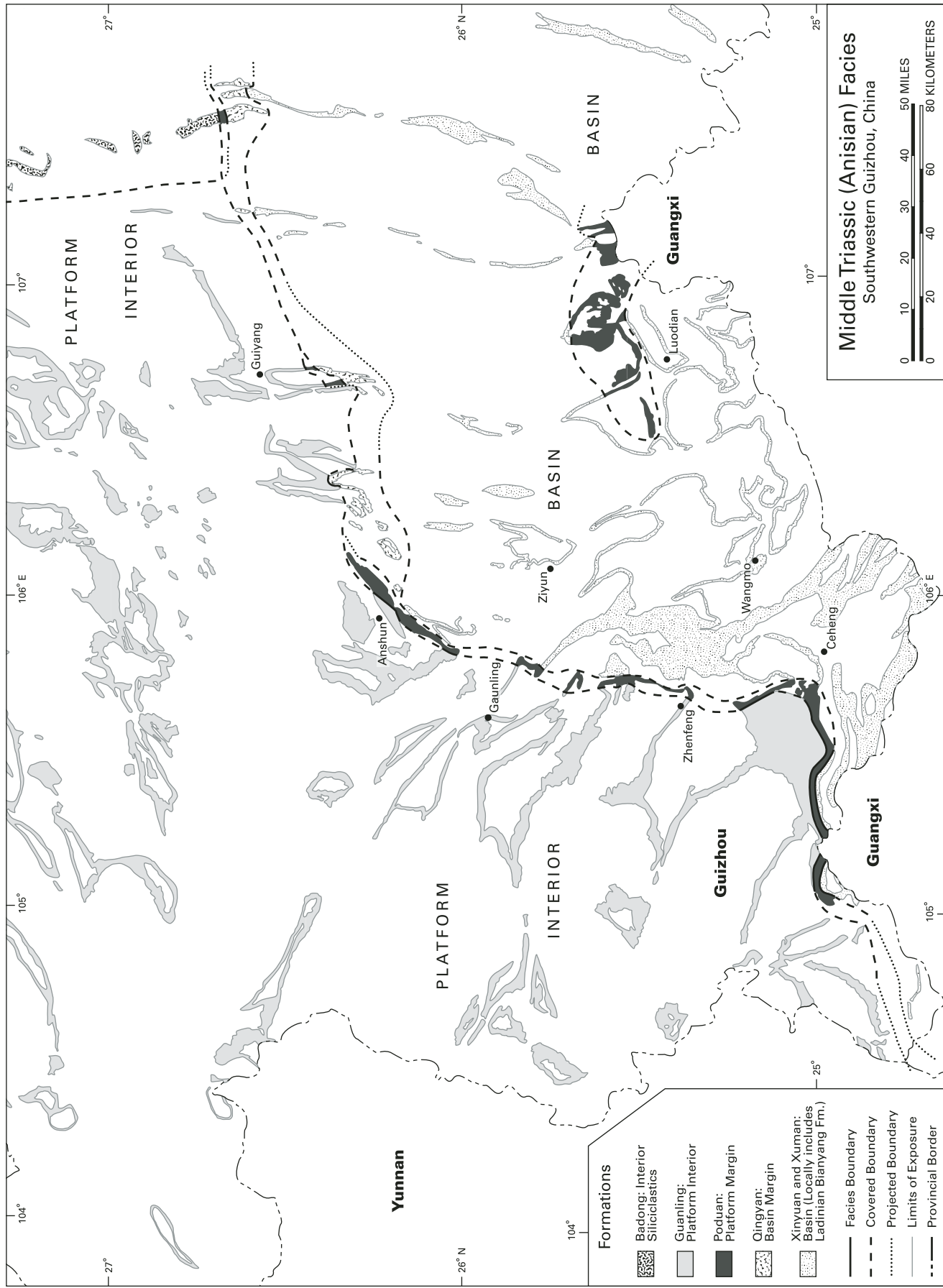


Figure 22. Anisian (lower Middle Triassic) facies distribution in southwestern Guizhou. Compiled from the Geologic Map of Guizhou (1:500,000; Guizhou Bureau, 1987). Formations, represented by patterns on the map, are essentially time-equivalent facies. The Poduan facies is shown in the syncline south of Guiyang, following the Guizhou Bureau (1987), although the rocks are clearly a dolomitized facies of the platform-interior Guanling Formation (Qin Shourong et al., 1989, 1:50,000 map; personal observations). Expanded and modified significantly from Enos et al. (1997, p. 565).

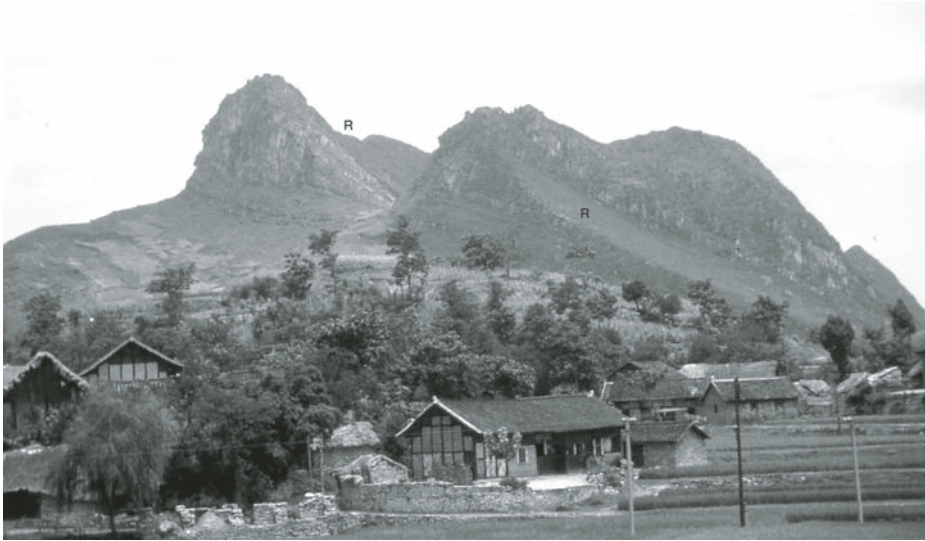


Figure 23. Field relations south of Bojishan (TB in Fig. 2). Beds dip 60° east into the syncline extending south from Guiyang. The two prominent peaks in the center are formed by a wedge of the Qingyan Formation, dominated by carbonate breccia. The recessive slope (R) is developed on mudrock of the Xinyuan Formation that onlaps the breccia wedge. The peak at the right, actually considerably higher, is formed by the Longtou Formation (Ladinian). The Longtou here oversteps the Xinyuan, and thus the Anisian basin, by at least 600 m. Unfortunately, the Ladinian platform edge was removed by modern erosion at the nose of the syncline. No compactional effects are evident where substrate of the Ladinian platform changes from carbonate to basinal mudrock of the Anisian; the outcrop trace is perfectly straight. This is best seen on the east limb of the syncline (Fig. 40; Qin Shourong et al., 1989)

(Fig. 24). Small (less than 1 cm), unbroken and locally articulated, thin-shelled, fine-ribbed bivalves are common on many bedding surfaces in the shale and mudrock. Thin-bedded or lenticular, dark-gray lime mudstone is intercalated sporadically throughout the Xinyuan, but is more common in the lower part where it is the dominant lithology in some intervals 3 to 20 m thick. The lime mudstone is typically structureless; bed thickness is a few millimeters to 20 cm. The carbonate content of the mudrock increases upward, and in the middle part of the Xinyuan between Luodian and the Great Bank of Guizhou, lime mud was the background sedimentation rather than clay.

Thin beds and lenses of silt punctuated the sedimentation of mud, generally with sharp contacts. Siltstone layers are dispersed throughout the Xinyuan at Luodian, Mengjiang, and Zhulinzhai; they are first recorded at 110 m above the base in the Niluo section and 200 m above the base at Nulizhai. Current ripples and ripple-drift cross-lamination are common; many siltstone lenses are isolated ripples (Fig. 25). Other structures include climbing ripple-drift cross-lamination, millimeter-scale planar lamination, convoluted lamination, load casts, and sole marks such as flute casts. Contorted siltstone near the top of the Xinyuan interval at Luodian probably reflects incipient slumping. Beds of fine-grained sandstone appear at the top of the incomplete Nulizhai section and in the upper 200 m at Niluo. In the other sections studied, sandstones are interspersed toward the top of the Xinyuan; they are thinner and more isolated beds than in the overlying Bianyang Formation. Typical lithology is slightly calcareous, high-matrix, very fine grained sandstone in beds 20 to 70 cm thick with sharp bases and gradational tops. Exposed soles have flute casts and other current marks. Paleocurrent directions from 74 sole marks from siltstones and sandstones at Mengjiang are toward the west-southwest,  $235^\circ \pm 23^\circ$  (Chaikin, 2004, p. 100). Isolated beds of monomictic lime breccia, 1 to 10 m thick, occur near the top of the Xinyuan (or at the

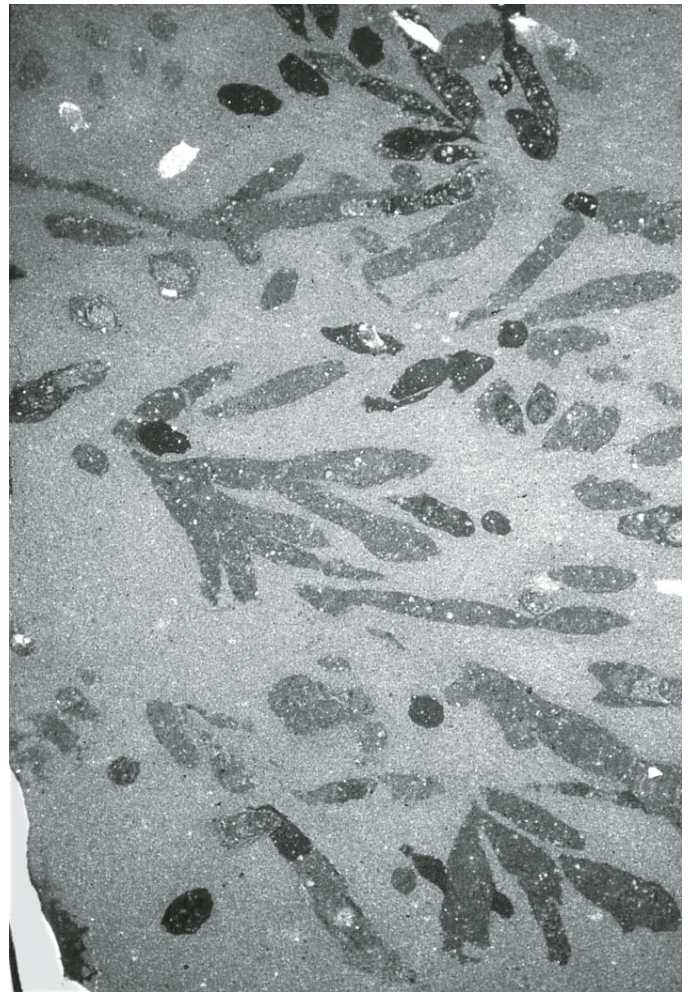


Figure 24. Burrow network, probably *Chondrites*, in siltstone of the Xinyuan Formation southwest of Qinyuan. Typical diameter of burrows is 1 mm. Thin-section photomicrograph.

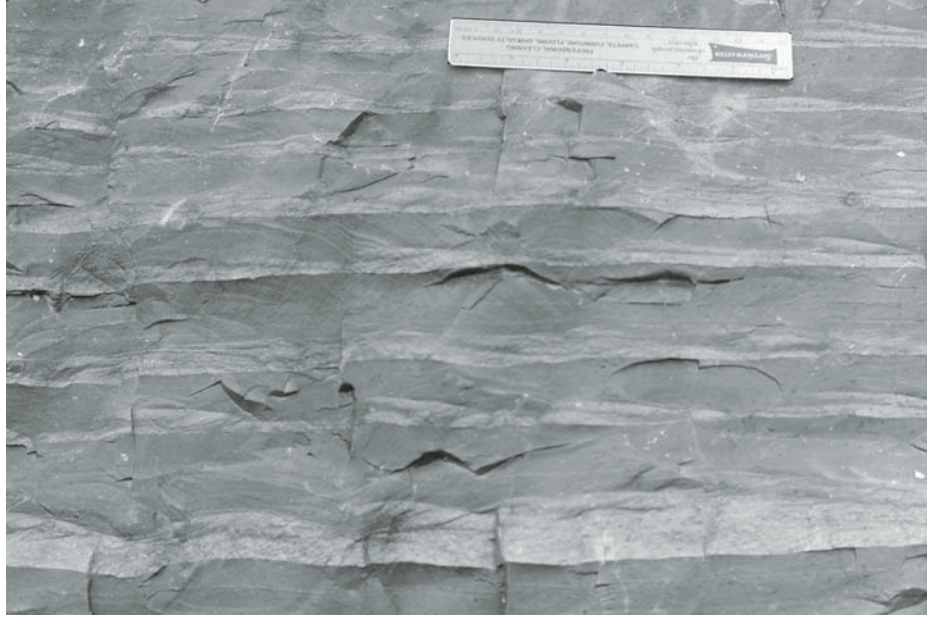


Figure 25. Xinyuan Formation 4 km north of Luodian. Mudrock (dark) and siltstone with ripple-drift cross-lamination and ripple bedforms.

base of the Bianyang, depending on mapping criteria, as noted above) at Luodian and Mengjiang. The clasts, generally less than a centimeter in diameter, are dark-gray lime mudstone in a matrix of dark lime mudstone with disseminated pyrite.

Fossils include a suite of thin-shelled bivalves, dominated by 12 species of the genus *Daonella*, and a variety of ammonoids, as well as plant fragments and various trace fossils. Bivalves are more common toward the top and ammonoids toward the base in the Niluo section, but both taxa are distributed throughout the Nulizhai section.

Fossils from the Xinyuan Formation (Guizhou Bureau, 1987, p. 305–306; Guizhou Team, unpublished section, 1992):

Bivalves: *Chlamys* sp., *Daonella* sp., *D. americana*, *D. boeckhi*, *D. candata*, *D. guizhouensis*, *D. ignobilis*, *D. cf. luganensis*, *D. moussoni*, *D. producta*, *D. pseudomoussoni*, *D. serpiensis*, *D. tacinensis*, *D. vaceki*, *Entolium* sp., *Posidonia* sp., *P. pannonica*

Ammonoids: *Acrochordiceras* sp., *Balatonites* sp., *B. multisulcatus*, *Bulogites*, sp., *Danubites* sp., *Hollandites* sp., *Huishuites* cf. *bifidus*, *Judicrites* sp., *Paraceratites* cf. *binodosus*, *Paracrochordiceras* sp.

Unidentified plant fragments.

The thickness of the Xinyuan Formation reportedly ranges from 146 to 340 m (Guizhou Bureau, 1987), although Qin Shourong et al. (1989) reported 900 m near Qingyan. The length of the Anisian is evaluated as 4 m.y. (Haq et al., 1988) to 8.0 m.y. (Ogg, 2004). These ranges give estimated accumulation rates of 18 to 225 m/m.y. (Table 2). Corrections for compaction in these predominately muddy terrigenous rocks would increase the rates as much as fourfold.

### Xuman Formation

The Xuman Formation is mapped only in southwestern Guizhou, west of a line from Ziyun to Wangmo and farther south (Fig. 22). It is much thicker than is typical for the Xinyuan at 800 to 1600 m (Guizhou Bureau, 1987, p. 306 and description of map units), and the equivalent rocks in adjacent western Guangxi are reportedly 2400 to 3600 m thick (Wei Jiayong et al., 1996). The Xuman is described as “sandstone, shale, rhythmically interbedded with limestone. . .” (Guizhou Bureau, 1987, description of map units). The only published section, from the type locality, Xuman, west of Wangmo (Fig. 2; Guizhou Bureau, 1987, p. 307), is 1557 m thick, but is devoid of sandstone. The overlying Bianyang Formation is differentiated primarily by its component of massive, fine-grained sandstone. The base of the Xuman is delineated from the lime mudstones of the Ziyun Formation by two meters of cherty mudrock that may proxy for the altered “green-bean” tuff, commonly found at the base of Middle Triassic formations. The Xuman Formation consists mainly of calcareous mudrock that is silty toward the top, interbedded with variable amounts of calcareous and argillaceous siltstone, lime mudstone, and argillaceous lime mudstone. Minor intervals of sandy and bioclastic limestone are interbedded in the upper half. Many of the siltstone and limestone beds exhibit combinations of sedimentary structures that include ripple-drift cross-lamination, convoluted lamination, graded bedding, load casts, and sole marks (flute casts, groove casts, scour marks). They also contain fragmented plant fossils and bivalves. Similar structures and fragments are reported from some of the lime mudstones, including argillaceous ones,

indicating that they were deposited from currents as discrete particles. Fossils include a nearly monogeneric suite of the thin-shelled bivalve *Daonella* and a variety of ammonoids, as well as plant fragments. The biota is, not surprisingly, quite similar to that of the Xinyuan Formation. In general bivalves are more common toward the top of the Xuman section and ammonoids toward the base, as in the Xinyuan Formation at Niluo.

Fossils from the Xuman Formation (Guizhou Bureau, 1987, p. 306–308):

Bivalves: *Daonella* sp., *D. americana*, *D. boeckhi*, *D. dubia*, *D. cf. golana*, *D. ignobilis*, *D. cf. moussoni*, *D. obtusa*, *D. producta*, *D. pseudomoussoni*, *D. serpiantensis*, *D. shitunensis*, *Posidonia* sp.

Ammonoids: *Balatonites* sp., *Danubites* sp., *Hollandites* sp., *Huishuites ellipticus*, *H. sp.*, *Japonites* sp., *Judicrites* sp., *Protrachyceras* sp.

Unidentified plant fragments.

Given a thickness range of 800 to 1600 m for the Xuman Formation and time-span estimates for the Anisian of 4 to 8 Ma, estimates of accumulation rates, uncorrected for compaction, range from 100 to 400 m/m.y. (Table 2).

### Qingyan Formation

The Qingyan Formation is described as “limestone, mudstone, and shale, 397 to 1048 m thick, confined to Qingyan reef-facies belt. ...” (Guizhou Bureau, 1987, description of map units) and as “barrier reefs ... constructed mainly by red algae ... sponges, bryozoans, and brachiopods.” (Fan Jiansong, 1980, p. 1134). In fact it essentially consists of wedges of carbonate breccia that accumulated along the slope at the northern margin of the Nanpanjiang Basin (Fig. 23; Enos et al., 1997). The formation is mapped as a belt ~175 km long parallel to the platform edge in the Guiyang sector and extending up to 20 km into the basin (Fig. 22; Guizhou Bureau, 1987). Smaller areas of basin-margin breccia in the Zhenfeng sector are interpreted as Qingyan Formation on larger-scale quadrangle maps. The Qingyan should be considered a series of tongues or wedges rather than a formation, as is evident in cross sections perpendicular to the platform edge (Qin Shourong et al., 1989; Enos et al., 1997, fig. 3). It also varies rapidly in thickness parallel to the platform edge (Qin Shourong, 1988, personal commun.) and is likely discontinuous in that dimension as well. The only published measured section is at the type locality 25 km south of Guiyang (Guizhou Bureau, 1987, p. 304–305); this area was also mapped at 1:50,000 (Qin Shourong and Jiao Huiliang, 1986; Qin Shourong et al., 1989). Comparable basin-margin breccia wedges adjacent to the Great Bank of Guizhou (Lehrmann, 1993; Lehrmann et al., 1998) and farther west near Zhenfeng and Dabang, 20 km southeast of Guanling (Fig. 2; Minzoni et al., 2003), do not extend as far into the basin and have been mapped only at 1:200,000 or larger scales.

The characteristic lithofacies of the Qingyan in the type area are lime breccia with thin-bedded lime mudstone, lime mudstone with breccia, and thin-bedded dolostone and limestone (Qin

Shourong and Jiao Huiliang, 1986; Enos et al., 1997). The predominate lithofacies higher in this section and more distant from the platform margin are mudrock and lime mudstone that would be more appropriately referred to the Xinyuan Formation. The thin-bedded dolostone-and-limestone lithofacies is a minor component, occurring adjacent to the platform margin, that appears to preserve the transition from platform deposits, predominantly dolostone, to lime mudstone of the basin. Dolostone and limestone are typically interbedded on a centimeter scale (Fig. 26). Internal structures are lacking in the lime mudstone, but the dolostones preserve millimeter-scale lamination and some cross-lamination that reflect current deposition of a silt-sized traction carpet. The

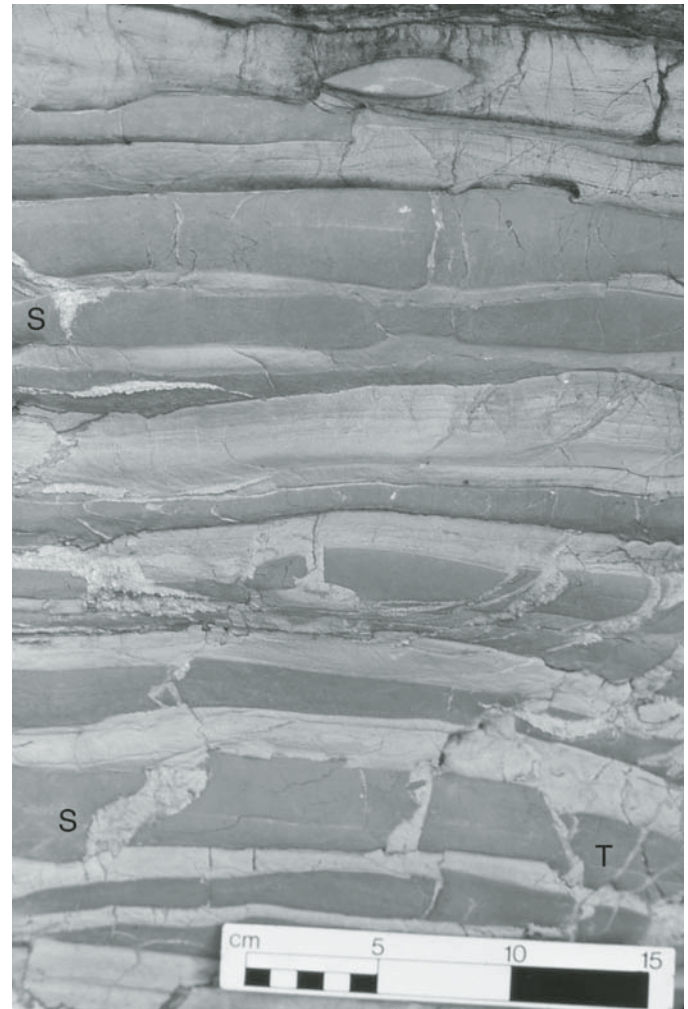


Figure 26. Interbedded lime mudstone (darker gray) and dolostone near the platform-to-basin transition; the contact between Guanling and Qingyan Formations (Fig. 22). The lime mudstone appears structureless, whereas the dolostone is laminated and locally cross-laminated, indicating deposition as silt from traction currents. Dolostone with a few limestone intraclasts fills early fractures confined to single beds of limestone (s). This indicates brittle behavior of the original lime mud whereas the dolostone, which apparently originated as non-cohesive lime silt, remained unconsolidated. Later tectonic fractures, filled with white calcite, cut all beds (T). From Enos et al. (1997, p. 569).

limestone is more highly fractured than the dolostone, reversing the norm for interbedded dolostone and limestone, and the dolostone fills early fractures in the limestone (Fig. 26). This differential in brittleness evidently reflects cohesion or early lithification, probably submarine, of the limestone before dolomitization of intervening calci-clastic layers.

The lime-mudstone-with-breccia lithofacies consists predominantly of thin-bedded (1 to 10 cm), locally cherty, lime mudstones with very thin shale partings. Some mudstone beds are laminated or convoluted and slightly nodular. Interbedded with the lime mudstone are numerous breccias and graded beds of packstone, from a few millimeters to 25 cm thick (Fig. 27). The packstone grains are peloids, skeletal fragments of diverse shallow-water biota, and muddy intraclasts comparable to the enclosing lime mudstone. Unusual fossils include large, club-shaped echinoid spines and the well-preserved rib cage of a

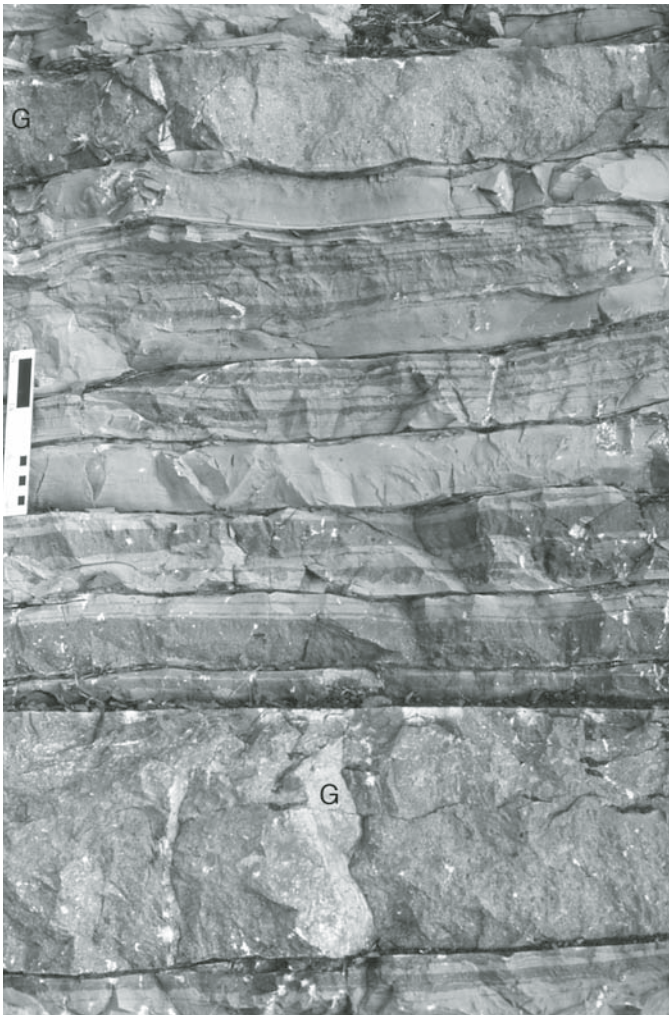


Figure 27. Grain-supported skeletal limestone, mostly packstone, and interbedded lime mudstone within the lime-mudstone-with-breccia lithofacies. Thicker beds at base and top are grain supported (G), as are the thin, dark layers within light-gray mudstone beds. Scale bar (left) is 15 cm. From Enos et al. (1997, p. 571).

vertebrate. Basal contacts are sharp but commonly deformed by load casts and flame structures. The geometry of individual grainy beds is well exposed in an isolated outcrop several tens of meters long at the north edge of Qingyan. Several thin, graded, packstone beds with ripple-drift cross-laminated caps taper and pinch out within the outcrop (Fig. 28). Shallow, localized scours are common. Coarser-grained packstones with more abundant intraclasts of muddy and bioclastic limestone suggest a gradation between the grainy interbeds and the breccias. The breccia beds, up to several meters thick, are polymictic with many platy clasts of basinal lime mudstone, derived from the enclosing thin-bedded mudstone, and more equidimensional fragments of bioclastic limestone and boundstone that contain exclusively shallow-water biota, representative of the adjacent platform (Fig. 29). Breccia contacts are sharp and generally conformable with adjacent lime mudstones, but locally incise the mudstones.

The signature Qingyan lithofacies, lime breccia with thin-bedded lime mudstone, is distributed closest to the platform margin and nearest the base of the Qingyan Formation, according to detailed mapping near Qingyan (Qin Shourong and Jiao Huiliang, 1986; Enos et al., 1997); multiple wedges occur at different levels within the formation in other areas (Guizhou Bureau, 1987, p. 304–305; Qin Shourong et al., 1989). The lime mudstones are bedded on a centimeter scale with some internal, millimeter-scale lamination (Fig. 29). Some detrital limestone is interbedded. Intercalations of fine-grained siliciclastic rocks are poorly exposed, but probably represent fingers of the more distal shale-and-lime-mudstone lithofacies. The breccias are identical to those in the lime-mudstone-with-breccia lithofacies, except that some breccias near the platform margin are completely dolomitized. Maximum observed thickness of a breccia is ~50 m. Breccias generally appear tabular in outcrop, but they must be wedges as this facies extends only a few kilometers from the platform margin. A few breccia beds vary twofold in thickness within a few tens of meters, apparently through channelization of mudrock, commonly poorly exposed, or of lime mudstones (Fig. 30). Mudstone beds are locally truncated beneath the breccias or deformed extensively as soft sediments. The breccia with thin-bedded mudstone facies contains isolated blocks of limestone, as much as 30 m thick and 100 m long (Fig. 31). The largest blocks are encased in thin-bedded lime mudstone and terrigenous mudrock (Fig. 32). Smaller blocks, up to 10 m thick, occur within bedded breccias but protrude so far above the bed surface as to resemble isolated blocks, a distinctive feature of carbonate debris flows (Cook et al., 1972; Cook and Mullins, 1983, p. 541). Isolated limestone blocks also occur in other lithofacies, primarily in portions dominated by terrigenous mudrock.

Limestone blocks are completely undolomitized and preserve fossils in exquisite detail. These fossils apparently represent the biota of the platform-margin Poduan Formation where it was subsequently destroyed by dolomitization or was entirely removed by slumping. Most of the blocks are boundstones with some framework elements (framestones of Embry and Klovan, 1971). The most common framework components are millimeter-

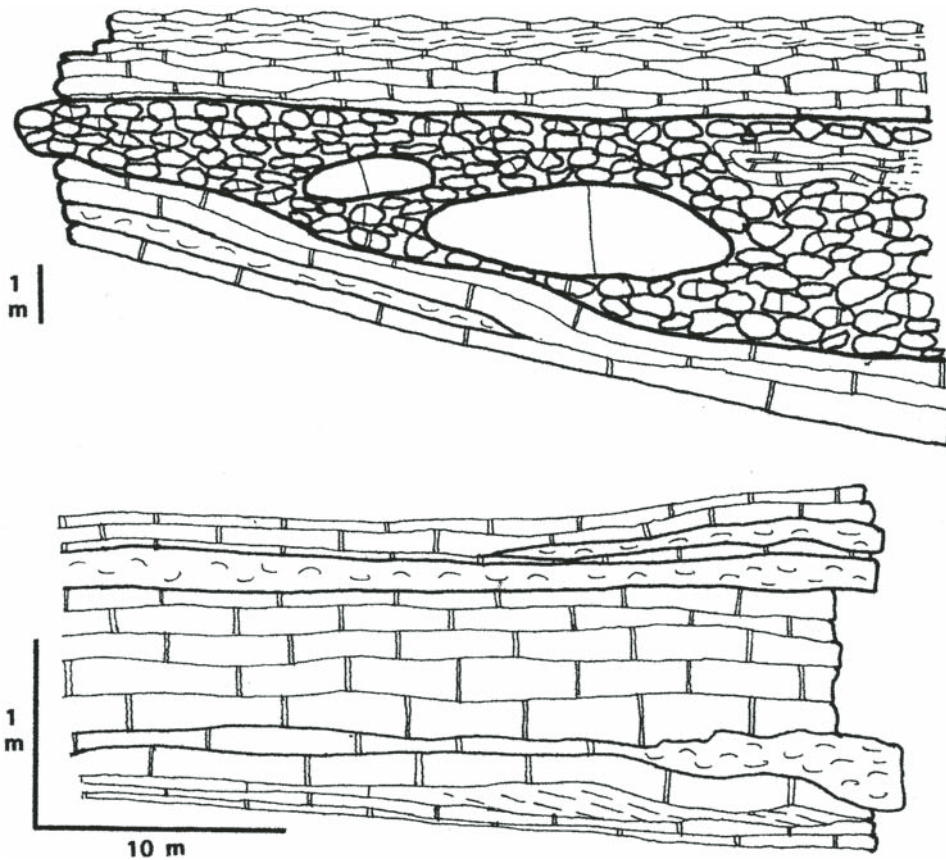


Figure 28. Bed geometry from outcrops at the north edge of Qingyan village. The lime breccia in the upper sketch is 4 m thick at the right margin, and 1 m at the left margin, and pinches out within 50 m to the left. The lower sketch, from ~3 m lower in the section, shows the pinchout of one grainy limestone (top) and the lateral transition to lime mudstone of another (near bottom), as well as a ripple-laminated calcisiltite (at base). Redrawn from field sketches. From Enos et al. (1997, p. 574).



Figure 29. Base of breccia bed, 3 m thick, and thin-bedded lime mudstone from lithofacies of that name. Breccia clasts include many platy fragments of lime mudstone and more equant clasts of grain-supported skeletal limestone. Large clast at center of photo is a grainstone of coated skeletal grains. From Enos et al. (1997, p. 572).

Figure 30. Breccia bed ~3 m thick crosscuts underlying lime mudstone (at X). Tilted slabs of bedded mudstone at lower left (B) are blocks within the breccia, probably displaced only a short distance from the site of erosion. Near top of Qingyan Formation at Gutong, Qingyan.



Figure 31. Breccia and isolated blocks of platform limestone in Qingyan Formation. View is northward toward the platform margin (vegetated hills in background at left) southwest of Qingyan. The foreground is a breccia bed ~50 m thick. Massive blocks of platform limestone dot the ridge in the background. At the right (A) is a block of framestone, 10 × 20 m, with geopetals indicating top to the east (right). A poorly exposed block, 30 × 30 m, with geopetals perpendicular to bedding protrudes from a breccia bed 4 m thick on the slope just below (A). The middle pinnacle at B is formed by a block 9 m thick, one of numerous large blocks of boundstone, each with geopetals in a different orientation. The pinnacle at the west (left) end of the ridge (C) is also formed by a single block within a breccia bed 15 to 20 m thick. The dots (between B and C) outline a platform block 30 m thick and 100 m long, elongated approximately parallel to bedding, which dips ~20° east (right). From Enos et al. (1997, p. 575).

scale, digitate, micritic skeletons with irregularly dispersed internal tubes that permeate the rock (Fig. 33). These are referable to the problematic taxon *Tubiphytes* Maslov (Senowbari-Daryan and Flügel, 1993) or its Triassic surrogate, which may be a different taxon (E. Flügel and B. Senowbari-Daryan, 1996, personal commun.). Less abundant, but also widely distributed, is a glo-

bose, cellular, branching form, *Plexoramea cerebriformis* Mello (Fig. 33), a possible alga or fungus (Flügel et al., 1988). “*Tubiphytes*” and *Plexoramea* commonly occur together, typically intertwined. Shelter and framework porosity filled by internal sediment and cement (Fig. 33) attest to the framework-building capacity of these diminutive organisms. Another common frame



Figure 32. Isolated limestone block interrupts bedding of lime mudstone and terrigenous interbeds (foreground). Blocks in background, a boundstone 9 m thick, and at right margin are other isolated blocks, each with a different orientation of geopetals. Hammer at left margin and one-liter bottle provide scale. Near middle pinnacle (B) in Figure 31. From Enos et al. (1997, p. 575).

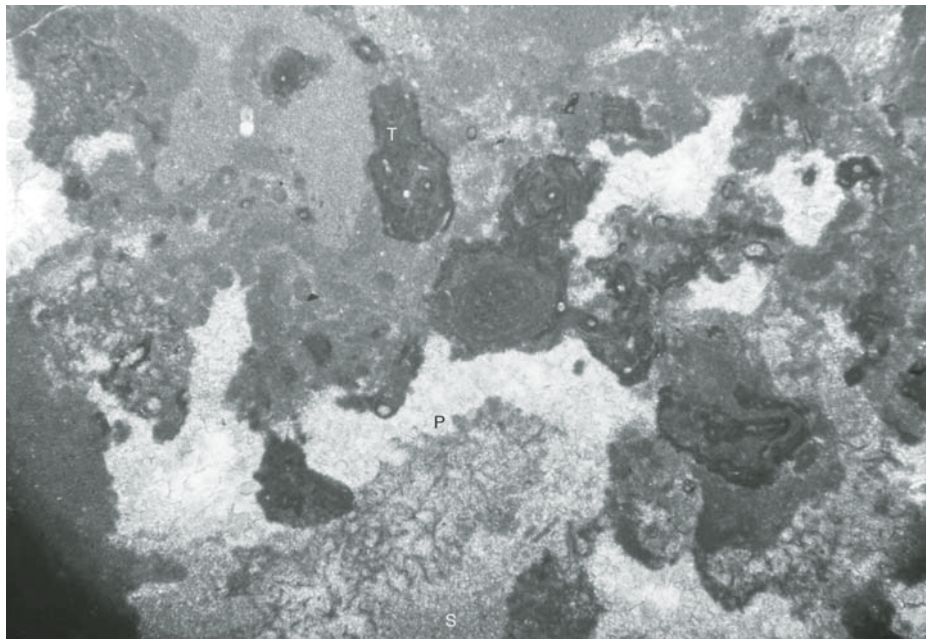


Figure 33. Biota of Qingyan block. Digitate, micritic, vaguely laminated skeletons distributed throughout the photomicrograph are "*Tubiphytes*" (T). The globose, cellular forms are *Plexoramea cerebriformis* (P; identified by Baba Senowbari-Daryan). Two generations of cement (cloudy crusts and clear spar at centers of pores) and pelleted sediment (s) fill voids generated by growth of these minute organisms, i.e., growth-framework porosity. Field of view is ~5 mm high.

builder is small stromatolites consisting of a calcareous skeleton of possible algal origin (Enos et al., 1997, figs. 23, 24). Other encrusters include bryozoans, foraminifers, bivalves, spirorbid worms, algae, and the problematic forms *Ladinella porata* and *Radiomura* (Baba Senowbari-Daryan, 1996, personal commun.). Additional framework or accessory biota are sponges and intertwining micritic tubes of various sizes. Vagile benthic fauna, gastropods and foraminifers, are also incorporated in the blocks.

In the type locality, the measured section (Guizhou Bureau, 1987, p. 304–305) and map (Qin Shourong and Jiao Huiliang, 1986) indicate two breccia wedges at the platform margin. The lower, at the base of the formation, is up to 300 m thick and extends less than 2 km into the basin (Qin Shourong and Jiao Huiliang, 1986); it contains six couplets of breccia interbedded with calcareous shale and thin-bedded lime mudstone (Guizhou Bureau, 1987, p. 305). The upper wedge (Fig. 23) is separated from the lower by 130 m of shale and lime mudstone; it is up to 175 m thick, includes five breccia layers, and extends 4 km into the basin. The Qingyan wedge 10 km farther northeast, between Gaimao and Qingyan, is up to 200 m thick. Geometry at the platform margin here suggests that the wedge may truncate, and therefore postdate, the entire Guanling Formation, generally considered the platform equivalent (Qin Shourong et al., 1989; Wei Jiayong and Enos, 1991). The Qingyan is mapped for 175 km along the platform margin; the eastern extent cannot be determined because outcrops are lacking (Fig. 22). The maximum outcrop width of 20 km approximates the maximum extent of breccias within the basin.

The fauna reported from the Qingyan is the most diverse from the Triassic of Guizhou, in part, perhaps, because it is the most extensively studied (Guizhou Bureau, 1987, p. 303–305; Qi Wentong, 1984, Yin Hongfu and Yochelson, 1983a, 1983b, 1983c; Stiller, 2001 and references therein). More significantly, the formation spans a variety of paleoenvironments and the incorporated slump deposits sampled a spectrum of platform and slope environments. Unfortunately, it is not possible from many of the published reports to distinguish fossils transported within the breccias, such as all of those mentioned above, from those that lived at the site of deposition. The bivalves, for example, clearly represent a mixture of thin-shelled, quasi-planktonic forms and benthic infauna. Ongoing studies by Frank Stiller (cf. Stiller, 2001) present a detailed analysis of in situ macrofauna from shallower-water calcareous mudstones of the upper half of the Qingyan in a transect very close to the platform edge at Bangtoupou, within the type locality. The focus is on a particularly fossiliferous interval at the Pelsonian-Illyrian (late Anisian) boundary. He records the following: Porifera, 2 genera; Anthozoa, 6 genera, 7 species; Gastropoda, 46 genera, 94 species, including 10 undescribed new genera and 43 new species; Cephalopoda, 10 genera, 10 species, 3 unnamed; Scaphopoda, 3 genera; Bivalvia, 48 genera, 77 species, of which 4 and 23, respectively, are undescribed; Annelida, 3 genera; Brachiopoda, 20 genera, 23 species; two indeterminate Bryozoans; Crinoidea, 7 genera; and Echinoidea, 4 genera, 15 species. E. Kristan-Tollmann (1983) described 83 species of Foraminifera from the Bangtoupou locality.

Fossils from the Qingyan Formation. [Guizhou Bureau (1987, p. 303–305); corals from Qi Wentong (1984). Baba Senowbari-Daryan and Ioan I. Bucur identified problematic taxa (1996, personal commun.). Foraminifer and dasyclad alga identifications are by Ioan I. Bucur (1996 and 2002, personal commun.). Conodonts were identified by Yang Shouren from Xinmin, Ziyun, and updated from Wei Jiayong et al. (1996). The extensive faunal lists published by Stiller (2001) and Kristan-Tollman (1983) are not duplicated here.]

Algae: Rivulariacean-like cyanobacteria, Solenoporaceae, Dasyclads: *Aciculella* sp., *Diplopora* sp., *D. cf. annulata* Schaffhäutl, *D. cf. sinica* Bucur and Enos, *Holosporella?*, *Julpiaella subtilis* (Pia), *Macroporella cf. dinarica* (Pia), *Oligoporella pilosa* (Pia), *Physoporella?* sp., *Pseudodiplopora proba* (Pia)

Foraminifers: *Aulotortus* sp. (or *Involutina* sp.), *A. eotriassicus* Zaninetti, Rettori and Martini, *Endoteba* sp., *Endotebanella* sp., *Endotriada* sp., *Endotriadella* sp., *E. wirzi* (Koehn-Zaninetti), *Glomospira* sp., *Glomospirella* sp., *Meandrosira dinarica* Kochanski-Devide and Pantic, *M. cf. pusilla*, *Pilamina densa* Pantic, *Pilaminella gemerica* (Salaj), *P. grandis* Salaj, *P. kuthani*, *Reophax* sp., *?Tetrataxis* sp., *Trochammina* sp., “*Trocholina*” sp., Duostominidae, Involutinidae, Nodosariaceae, unidentified encrusters

Corals: *Cyathocoenia* spp., *Montlivaltia* sp., cf. *Stylophylloporis* sp., *Thamnastraea silesiaca*, *T. spp.*, *Thecosmia* spp.

Brachiopods: *Aequispiriferina* sp., *Athyris* sp., *Aulacothyris angustaeformis*, *A. sp.*, *Crurirhynchia subfissicostata*, *Diholkorhynchia sinensis*, *Leiolepismatina*, *Lepismatina hsui*, *Lissorhynchia* sp., *Mentzelia* sp., *Neoretzia subcircularis*, *Nudirostralina subtrinodosi*, *Paralepismatina* sp., *Pseudospirifer* sp., *Rhaetina angustaeformis*, *Septaliphorioidea paucicostata*, *Spiriferina* sp.

Bivalves: *Bakevelloides cf. subelegans*, *Cassianella gryphaeatooides*, *C. qingyanensis*, *C. subcislonensis*, *C. sp.*, *Chlamys* sp., *Costatoria* sp., *Daonella cf. boeckhi*, *D. guizhouensis*, *Entolium* sp., *Leptochondria gratiosus*, *Myophoria (Elegantinia) elegans*, *Ornithopecten subarcoidea*, *Palaeolima* sp., *Palaeoneilo cf. subexcentrica*, *P. cf. distincta*, *Pinna cf. becki*, *Pleuronectites cf. difformis*, *Posidonia ussurica simplex*, *P. pannonica*, *P. sp.*, *Protostrea sinensis*, *Pteria japonica rugosa*

Ammonoids: *Acrochordiceras* sp., *Balatonites* sp., *Bulogites* sp., *Cuccoceras* sp., *Danubites* sp., *Discoptychites* sp., *Gymnotoceras* sp., *Japonites* sp., *Judicaries* sp., *Leiophyllites cf. pitamaha*, *Paraceratites binodosus*, *P. trinodosus*, *Paracrochordiceras* sp., *Ptychites cf. everesti*, *P. sp.*, *Ussurites cf. kingi*

Conodonts: *Neogondolella constricta*, *N. germanica*, *N. jubata*, *N. kockli*

Problematic taxa: *Tubiphytes* Maslov, *Plexoramia cerebriformis* Mello, *Ladinella porata* Ott, *Radiomura cautica*

Miscellaneous: Sponges, bryozoans, spirorbid worms, gastropods, crinoids, echinoid spines, vertebrate.

The wedge shape of the Qingyan and its interfingering relationship with the Xinyuan Formation pose questions about how to estimate realistic accumulation rates for this lithofacies. Moreover, it is clear that the breccias and clastic limestones must have accumulated much more rapidly than the “background sediments,” calcareous and terrigenous mud. Conversely, grain-supported breccias and limestones probably compacted very little, in contrast to the muddy sediments. With these caveats, we simply report calculations based on published thickness values: 50 to 262 m/m.y. (Table 2).

### Poduan Formation

The Poduan Formation forms a discontinuous, narrow band 3 to 7 km wide (Fig. 22) of “algal ... and rudaceous limestone,” 500 to 1100 m thick, along the Yangtze Platform margin (Guizhou Bureau, 1987, p. 297). In general it is absent where the Qingyan is developed and vice versa. A Poduan section at Hongyan, Guanling, was measured by Xiao Jiafei, Huang Xunhua, and Kuang Shunda, ca. 1992; reconnoitered in 1993 by Lehrmann, who recognized *Tubiphytes* and scleractinian boundstones; studied by Enos and Wei in 1995, including petrology of 19 large thin sections (up to 100 × 150 cm); and measured in detail by Minzoni in 2001. At this location, Poduan facies is 395 m thick, but overlies Qingyan facies 260 m thick and is overlain by 290 m of Anisian bioclastic rocks referable to the Guanling Formation. The Poduan was measured at Hetaoshu, Zhenfeng, and 12 large thin sections (mostly 75 × 100 mm) were examined. The 822-m section probably includes the entire formation, although the base is poorly exposed and therefore problematic. At the type locality, Poduan, Ceheng (Fig. 2), the formation was measured at 627 m thick (Guizhou Bureau, 1987, p. 297–298). The tuffaceous basal marker of the other Anisian formations is not exposed in any of the sections. The basal contact is defined by lithology, primarily the appearance of boundstone at the base of the Poduan.

The Poduan type section is described as mostly gray or light-gray, massive, algal wackestone with many intervals of breccia or rudstone and some of bioclastic limestone (Guizhou Bureau, 1987, p. 297–298). The Poduan at Hetaoshu, Zhenfeng, is mainly massive, bioclastic, grain-supported limestone (three-fourths of the thin sections) with dolostone and terrigenous mudrock in the basal 29 m and wackestone and breccia making up about half of the formation below 180 m. Only a few intervals of boundstone were detected; the unweathered, massive rocks made such observations difficult. At Hongyan, in contrast, the lower 395 m of massive limestone is 70% boundstone; this is probably equivalent to the “massive algal wackestone” described at the type locality. About two-thirds of the boundstone samples examined in thin section could be documented as framestone. The hazards of identifying boundstone in thin section were mitigated by the large thin sections and the small framebuilders. The remainder of the massive interval at Hongyan is breccia (15%) and bioclastic limestone (15%), much of it as lenses within boundstone.

The main biotic component in the massive interval at Hongyan and at Hetaoshu is the problematic organism *Tubiphytes* (Fig. 33). Despite its diminutive size, this branching and encrusting organism appears to be the major framebuilder of the massive boundstones. It is typically intergrown with *Plexoramea cerebriformis*, a branching framebuilder described from the Qingyan Formation (Fig. 33). Arborescent corals or sponges dominate locally (Figs. 34, 35). The existence of framestones is indicated by the abundance of *Tubiphytes*, arborescent corals, and accessory framebuilders in growth position; the prominence of encrusting organisms; the unbedded character of the rock; and the abundance of constructional pores (growth-framework porosity of Choquette and Pray, 1970) that reach 75% of the volume of some samples. Downward-directed branches of some *Tubiphytes* and under-surface attachment of many encrusters indicate a cryptic biota within the cavities (cf. Wood et al., 1994). Biota observed in outcrop include *Tubiphytes*, corals, sponges, crinoids, bivalves, brachiopods, gastropods, foraminifers, ostracodes, bryozoans, and green algae. The relative abundance, from weighted estimates in thin sections, is (from greatest to least) *Tubiphytes*, foraminifers, *Plexoramea cerebriformis*, echinoderms, unidentified laminar encrusters, gastropods, green algae (both dasycladaceans and codiaceans), unidentified strictly tubular organisms, echinoid spines, *Ladinella porata* (problematic encruster; Figs. 34, 35), ostracodes, sponges, unidentified cellular encrusters, mollusk fragments, brachiopods, crinoids, stromatoporoids, corals, bryozoans, bivalves, and a problematic encruster, *Baccanella floriformis*. Minor biota are ammonoids, calcispheres, and worm tubes. Corals and perhaps sponges are underrepresented in these estimates because their relatively large size and clustered growth pattern make random sampling in thin section impractical. They rank behind only *Tubiphytes* and *Plexoramea cerebriformis* as framework components. Encrusting is the most common form of both *Tubiphytes* and foraminifers. As the variety of taxa suggests, the biodiversity in the Poduan Formation is possibly even greater than in the Qingyan, but it has received less study.

The most common “non-skeletal” components by far are peloids, irregularly shaped micritic particles derived mainly from micritization and abrasion of skeletal fragments. Lithoclasts of skeletal limestone, fecal pellets, intraclasts, and oncoids are patchily distributed.

Cement makes up 34% by volume of the Poduan at Hongyan. Isopachous crusts of cloudy, bladed or fibrous crystals with convergent optic axes are by far the most common cement. They constitute on average 31% of the rock and exceptionally 70% of *Tubiphytes* boundstone with growth-framework porosity. The petrographic characteristics indicate early marine cementation. Later coarsely crystalline, equant cement contributes 3% of the rock volume.

Biota identified from the Poduan Formation (Guizhou Bureau, 1987, p. 297–299; Xiao Jiafei et al., unpublished; foraminifers and dasyclad algae identified by Ioan I. Bucur, 2002, personal commun.; bryozoans, sponge, and problematic taxa identified by Baba Senowbari-Daryan and Ioan Bucur, 1996, personal commun.):

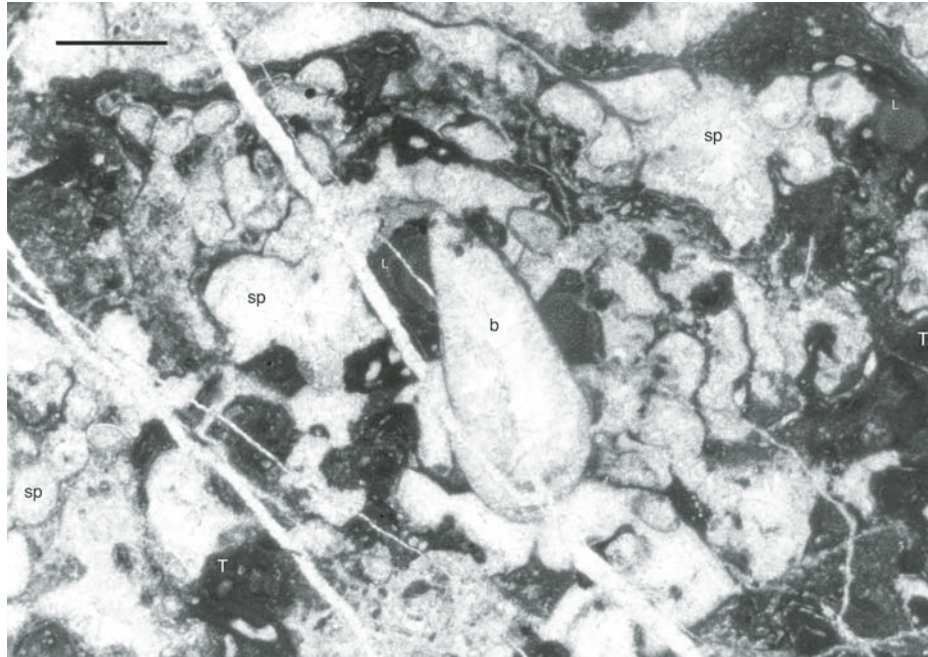


Figure 34. Poduan reef biota. Most of the larger (millimeter-size) cellular forms are probably sponges (sp), somewhat altered by dissolution, recrystallization, boring, and encrustation. *Tubiphytes* (T) are minor in this view, but are the main framework element throughout the Poduan reef. Identifiable among the myriad encrusters is *Ladinella porata* (L); two examples at center are cut by a large, rain-drop-shaped boring (b). Such borings, probably *Axothoracidae*, are attributed to barnacles. Hongyan section. Photomicrograph; scale bar is 1 mm.

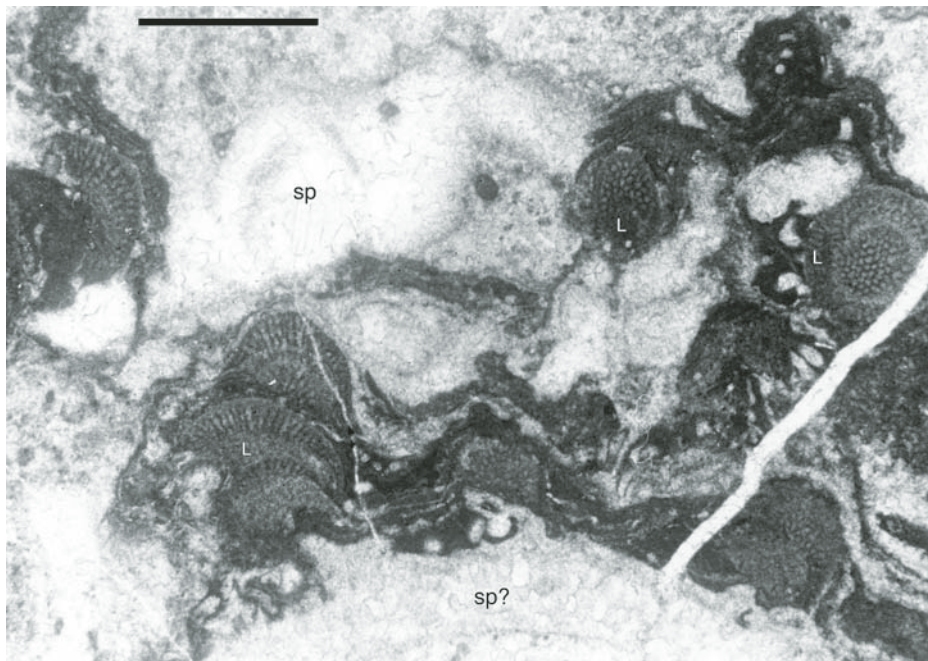


Figure 35. Biota from Poduan reef. Light, sparry areas defined by micrite rims (sp) are probable sponges. The abundant, concentrically banded encrusters are *Ladinella porata* (L). *Tubiphytes* is the encruster at the upper right. The common micritic and laminated encrusters are unidentified. Photomicrograph; scale bar is 1 mm.

Algae: Rivulariacean-like cyanobacteria, Porostromata, Solenopora, and dasyclads: *Acuculaella* sp., *Diploporella annulata* (Schaffhütl), *D. annulatissima* Pia (= *D. monregalensis* Baretto, cf. Granier 2002), *D. sinica* Bucur and Enos, *Euteutloporella triasina* (Schauroth), *Griphoporella?*/*Gyroporella?* sp., *Gyroporella maxima* Pia, *Julpiaella calicina* (Pia), *J. dissocladelloidea* (Pia), *J. subtilis* (Pia), *Macroporella alpina* Pia, *M. dinarica* Pia, *Oligoporella* sp., *O. pilosa* Pia, *Physoporella* cf. *minutula* (Gümbel), *P.* cf. *pauciforata* (Gümbel), *Physoporella?* sp., *Poncetella hexaster* (Pia), *Pseudodiploporella* sp., *P. proba* (Pia)

Foraminifers: *Agathammina austroalpina* Kristan-Tollmann, *Agathamminoides* sp., *Ammobaculites* sp., *Ammobaculites eumorphos* Kristan-Tollmann, *Aulotortus* sp. (or *Involuntina* sp.), *A. eotriassicus*, *Diplostroma* sp., *D.* cf. *astrofimbriata* Kristan-Tollmann, *Duotaxis* cf. *birmanica* Zaninetti & Broennimann, *Earlandia amplimuralis* (Pantic), *E. tintinniformis?*, *Earlandina* sp., *E.* cf. *grandis* Salaj, *E. elongata* Salaj, *Endoteba* sp., *Endotebanella* sp., *Endotriada* sp., *E. kuepperi* (Oberhauser), *Endotriadella* sp., *E.* cf. *robusta* Salaj, *E. wirzi* (Koehn-Zaninetti), *Glomospira* sp., *G. inflata* Michalik, Jendrekova & Borza, *G.* sp./*Meandrospiranella* sp., *Glomospirella* sp., *Krikoumbilica pileiformis* He, “*Lamelliconus*” (= “*Trocholina*”) sp., *Meandrospira* sp., *M. dinarica* Kochansky-Devidé & Pantic, *M.* cf. *pusilla* (Ho), *Palaeolituonella meridionalis* Luperto Sinni, *Pilamina densa* Pantic, *Pilaminella grandis* (Salaj), *P.* cf. *kuthani* (Salaj), *Reophax* sp., *R. asper* Cushman & Waters, *Tetrataxis nana* Kristan-Tollmann, *Triadodiscus?*/*Aulotortus?* sp., *Trochammina alpina* Kristan-Tollmann, *Turriplomina mesotriasica*, *Valvulina* sp., “*Valvulina*” *azzouzi* Salaj. Also Duostominae, Involutinidae, Nodosariaceae

Sponges: *Celiphia?* *minima*

Corals: *Conophylloia* sp., *Margarosmia* sp., *Pinacophylloium* sp., *Protoheterastrea* sp., *Thecosmia* sp., *T.* cf. *sublaevis*, *Zardinophyllum* sp., Fois and Schäfer (identified by B. Senowbari-Daryan)

Bryozoans: *Reptonoditrypa cantica* Schäfer and Fois, *Disstrictella?* sp.

Brachiopods: *Athyris subquadrata*, *Aulacothyris angustaeformis*, *Diholkorhynchia sinensis*, *D.* sp., *Mentzelia mentzeli*, *M. multicostata*, *Nudispiriferina minima*, *Pseudospiriferina* sp., *Rhaetina angustaeformis*, *Septaliphoria sinensis*

Bivalves: *Aequipeecten* cf. *subalternans*, *Cassianella* sp., *Daonella indica*, *D.* sp., *Entolium* cf. *lavarendanum*, *E.* cf. *tenuistriatum*, *Leptochondria* cf. *gratiosus*, *L. illyrica*, *L. subillyrica*, *L.* sp., *Neomorphotis elongatus*, *N. giganteus*, *N. intermedius*, *N. magneauritus*, *N.* sp., *Ornithopecten subarcoidea*, *Plagiostoma* cf. *striata*, *Pleuromya* cf. *elongata*, *Posidonia* sp., *Schaffhaeutlia* sp.

Ammonoids: *Japonites* sp., *Leiophyllites* sp., *Neocomides* cf. *yohi*.

Crinoids: *Traumatocrinus* sp.

Problematic taxa: *Tubiphytes* Maslov, *Plexoramea cerebriformis* Mello, *Ladinella porata* Ott, *Bulloporella irregularis*, *Baccanella floriformis* Pantic, *Olangocoelia otti* (Bechstadt and Brandner), *Radiomura cautica* Schaefer and Senowbari-Daryan.

Estimated accumulation rates for the Poduan Formation vary from 66 m/m.y., using minimum thickness and maximum duration estimates, to 205 m/m.y. at Hetaoshu (Table 2). If we consider the entire Anisian interval at Hongyan, which includes tongues of the Qingyan and Guanling Formations, the maximum rate would be 230 m/m.y. Curiously, the mean accumulation rates, 93 to 185 m/m.y., are almost identical to those for the basin-margin Qingyan Formation. Any relief inherited at the Anisian slope break was maintained, but not increased.

### Guanling Formation

Outcrops of the Guanling Formation extend over a broad area of Guizhou, west and north of the other Anisian formations described above (Fig. 22). The Guanling is summarized in the description of map units of the Geologic Map of Guizhou as “variegated shale, argillaceous limestone, and dolomite in the lower part, limestone and dolomitic limestone in the upper part, 500-912 m thick” (Guizhou Bureau, 1987). It forms a distinctive ledge-and-slope topography with low relief, owing to many intervals of terrigenous mudrock and argillaceous carbonates interspersed with more resistant limestone and dolostone, particularly in the lower part (Fig. 36).

We measured a detailed section 617 m thick at the type locality, Yongningzhen, Guanling. Published measured sections are from Longchang (814 m thick; Guizhou Team, 1980), Sanqiao, Guiyang (535 m, Guizhou Bureau, 1987, p. 296), and Gaoqiao, Zunyi, 125 km to the north (505 m, Guizhou Bureau, 1987, p. 281). Unpublished measured sections were studied at Bojishan (TB in Fig. 2), 656 m thick, and at Renrenshan, an incomplete section 297 m thick. These sections, with a total thickness of 3425, m were used in the lithologic summary below. In addition, the upper 290 m of the Poduan interval at Hongyan (Xiao et al., unpublished) is bioclastic lime packstone, best referred to the Guanling Formation (M. Minzoni, 2003, personal commun.). Two dip cross sections of the Triassic of Guizhou by Wei Jiayong et al. (1996; Fig. 13C and 13D) contained eight graphic sections through the Guanling interval, including the published sections at Longchang and Gaoqiao, as well as Bojishan and Yongningzhen. Altered tuff, the “green-bean rock,” is recognized at the base of the Guanling Formation in seven of the eight sections and at Sanqiao and Renrenshan.

Overall the Guanling is ~61.5% dolostone, 32% limestone, and only 6.5% mudrock, although argillaceous dolostone and argillaceous limestone, which also tend to weather recessive, constitute 17% and 7% of the formation, respectively. The makeup of Guanling limestones by depositional texture, based on the sections with sufficiently detailed observations



Figure 36. Interbedded carbonates and terrigenous mudrock (dark), Guanling Formation, midway between Anshun and Guanling (Fig. 22). The thick bed with irregular weathered surface (cb) includes collapse breccia, apparently from evaporite dissolution.

(Yongningzhen, Bojishan, and Renrenshan), is approximately two-thirds mudstone (64.6%), 14% wackestone, 19.5% packstone, and 2% grainstone. This excludes argillaceous limestones, which are invariably muddy. Among the dolostones, in contrast, dolopackstone is about as abundant as dolomudstone at 38%, and dolograins and dolowackestone are about equal at 12%. If one assumes that all the coarsely crystalline dolostone as well as the argillaceous dolostone was originally lime mudstone, mudstone would be twice as common as packstone. Still, the proportion of grain-support is appreciably greater among the dolostones than the limestones. This suggests dolomitization selective by permeability rather than grain size or mineralogy. It is possible that dolomitization also postdated mineralogic stabilization. On the other hand, it may be that both the grainier textures and the higher dolomite contents of the Bojishan and Renrenshan sections result from locations close to the platform margin.

At the type locality, Yongningzhen, Guanling (Fig. 2), the basal 160 m of the 617-m Guanling section is mostly dolostone. The top 223 m is almost exclusively limestone. In the middle 234 m, limestone and dolostone alternate on the scale of a few meters. Argillaceous carbonate, much of it nodular bedded, is concentrated in the middle of the section between 215 and 395 m. Cleaner carbonate is somewhat more prevalent upward in the formation, culminating in the upper 45 m, which is entirely packstone, mostly cherty. Fossils are sparse in the lower, more dolomitized part of the YN section. Bivalves are most common throughout, but ostracodes increase to dominance upward, and echinoderm fragments, first noted at 406 m, are also common. Gastropods and foraminifers are less common throughout, and brachiopods are very rare. Horizon-

tal burrows are about three times as common as vertical burrows throughout. Lamination is sparse; fenestrae and tepee structures are lacking. Peloids are the most common non-skeletal component. Oncoids and intraclasts are sparsely scattered throughout. Grapestone and ooids are rare.

The Renrenshan section, very close to the platform margin in an area where the Poduan Formation is missing, is a useful section for analysis, although the top of the Guanling is not exposed. The total thickness is 297 m, probably representing about the lower half of the formation. The section is 97% dolostone and 3% mudrock, but textural preservation is reasonably good. Depositional textures of the dolostone are mudstone 38%, argillaceous mudstone 7%, wackestone 15%, packstone 26%, and grainstone 8%; 3% is crystalline dolostone. The lower half of the interval (roughly the basal quarter of the formation) is markedly cyclic; 73 cycles were noted, with an average thickness of 1.7 m. These included well-developed cycles with grain-supported bioclastic, lithoclastic, or oolitic bases; muddier midsections with sparse gastropods, fenestrae, and local desiccation cracks; and laminated dolomudstone caps. Other cycles are simple couplets with thicker and coarser-grained bases and laminated caps. Rare but significant structures include bi-directional cross-lamination, desiccation cracks, and molds of gypsum crystals. Fossils are invariably from packstones or grainstones. Gastropods are the most common, followed by brachiopods, bivalves, and foraminifers.

The nearby Bojishan section (4 km northeast of Renrenshan, 20 km south of Guiyang; Fig. 2) is likewise 97% dolostone in a complete section 656 m thick. This dolomitic facies of the Guanling is locally mapped as the Huaxi Formation. Coarsely crystal-

line dolomite constitutes 44% of the interval and is concentrated in the lower 337 m, essentially the interval exposed at Renrenshan. Where depositional textures can be recognized in outcrop, the proportions are 21% dolomudstone, 5% wackestone, 58% packstone, and 16% grainstone. Distribution of textures is fairly uniform through the mimic-dolomitized upper part of the section, except that all the grainstone is in the middle third of the formation. Cycles similar to those described from Renrenshan are recognized only in the upper 260 m of the formation (Fig. 37). Characteristic millimeter lamination, fenestral fabric, and disruptive tepee structures (Assereto and Kendall, 1971; Dunham, 1972) are confined to caps in the cyclic intervals (Fig. 38). Intervals of brecciation, intraclasts, bioclasts, and bioturbation occur sporadically in the non-cyclic lower portion of the formation. Gastropods are the only fossils observed.

The proportions of depositional textures in 45 thin sections from Bojishan are roughly comparable to those reported from the outcrop: 36% mudstone, 2% wackestone, 44% packstone, 16% grainstone, and 2% breccia, all dolostone. Peloids and fecal pellets are by far the most common particles; they are recognized in about half the samples, and are typically common to abundant. Grapestones occur in about a third of the samples followed by intraclasts (13% of samples), ooids (9% of samples but in small numbers), mudstone intraclasts (4%), oncoids, skeletal intraclasts, and lithoclasts. Echinoderm fragments are the most widely recognized bioclasts, probably because of their relatively small size and ease of recognition in thin section. Gastropods and bivalves occur in almost as many samples, nearly a third, and are volumetrically more important. Other fossils, in order of decreasing

abundance are foraminifers, dasyclad algae, codiacean algae, echinoid spines, calcispheres, and ostracodes.

Clastic carbonates in the top 290 m of the Poduan Formation in the Hongyan section (Minzoni, unpublished, 2001) are similar to the cyclic portions of the Guanling Formation, although they are preserved as limestone rather than dolostone. This section shows that Guanling lithofacies adjacent to and overstepping the Poduan do not differ appreciably from those where the Poduan is absent at the platform margin, as at Bojishan and Renrenshan. The most significant differences are a greater abundance of grain-supported lithologies and of dasycladacean algae in the Hongyan section (Bucur and Enos, 2001; Bucur et al., 2003). Dasyclads rival gastropods as the most common biota. Hongyan, Bojishan, and Renrenshan demonstrate the prevalence of cyclicity at the platform margin in contrast to non-cyclic interior deposits, as at Yongningzhen.

The three sections with published descriptions, Sanqiao, Longchang, and Gaoqiao, are less dolomitized than the more marginal sections; dolostone constitutes ~70%, 55%, and 32% of the sections, respectively. Unfortunately, depositional textures, sedimentary structures, and cyclicity were not recorded. Terrigenous content is appreciably higher in these more interior sections, which include 8% to 10% mudrock, while argillaceous dolostone and limestone make up 23% to 55% of the sections. Brecciated dolostones are reported from all sections, most commonly at Gaoqiao, the most interior location. Biota are for the most part sparse, but widely dispersed. Bivalves dominate among the identified forms, followed by gastropods and isolated occurrences of lingulid brachiopods, crinoids, ammonoids, and bone

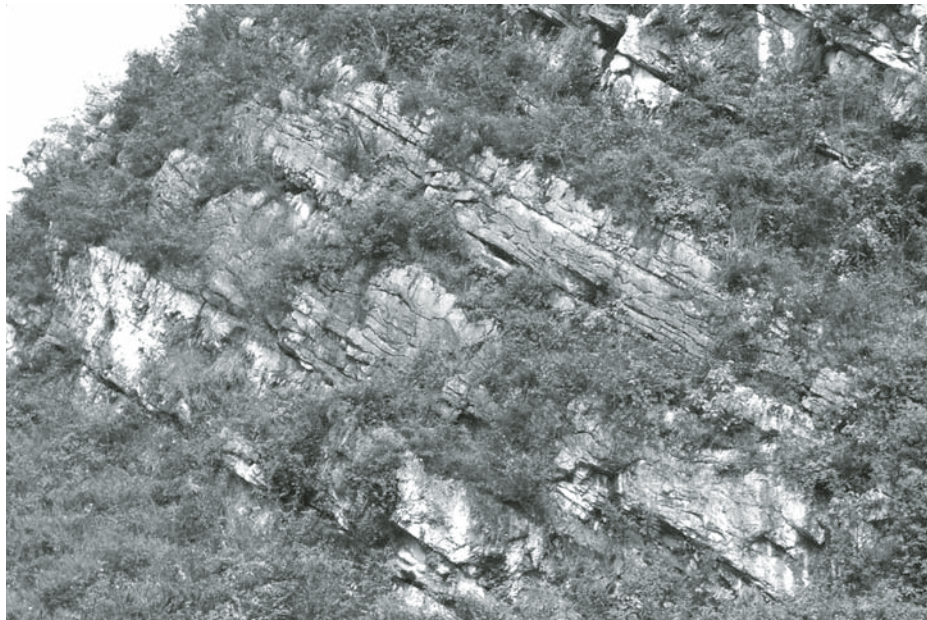


Figure 37. Shoaling-up cycles in dolostone of the Guanling Formation, also called Huaxi Formation in this dolostone facies. The fine-grained tops of middle cycles are visibly deformed by tepee structures. Prominent bed at base is ~1.5 m thick. Bojishan section (TB in Fig. 2). From Enos et al. (1997, p. 567).



Figure 38. Synsedimentary deformation within Guanling Formation, Bojishan section (TB in Fig. 2). Many beds are buckled, but not breached, as in the lower beds at left. These we called “yurt structures,” rather than true tepees.

fragments. Bipedal reptiles criss-crossed desiccation-cracked lime mud, as recorded on a bedding-plane at Shangba, 25 km north of Zhenfeng (Fig. 39). Bed thickness increases toward the top of the Guanling, accompanied by considerable brecciation and vuggy porosity, in sections from the Zhenfeng area (Longchang, Yongningzhen, Langdai; graphic logs in Fig. 13C). Halite molds are reported 60 and 170 m above the base of the Guanling at Langdai (Wei Jiayong et al., 1996), and molds of isolated or stellate clusters of gypsum crystals are widely scattered through the formation, most notably at Dulaying, 10 km north of Guiyang.

Some regional trends within the Guanling Formation are evident from the well-distributed measured sections and the correlated cross sections (Fig. 13C and 13D; Wei Jiayong et al., 1996). The formation thickens systematically from the interior of the Yangtze Platform toward the margin. An approximate north-south section of the Zhenfeng sector thickens from 250 m on the northern Guizhou border with Yunnan to a maximum of 814 m in the Longchang section, nearest the margin. In an approximately parallel section across the Guiyang sector, the Guanling is 210 m thick on the northern Guizhou border with Sichuan and thickens to 656 m at Bojishan. Dolostones make up 97% of the Guanling interval in the margin sections, except for Hongyan. Limestone abundance increases into the platform interior, culminating at 60% in the Gaoqiao, Zunyi, section, the most interior of the detailed sections. Terrigenous content in the form of mudrock interbeds and argillaceous carbonates appears highest in the most interior sections along the northern Guizhou border. Terrigenous interbeds are also prominent in the lower part of the Zhenfeng cross section, but are distributed throughout the Guanling interval farther east in the Guiyang sector.

The Guanling interval in the easternmost section, at Xiaozhang, 25 km east of Zunyi (Fig. 13), includes enough claystone and silty mudstone that it was assigned to the Badong Formation. This interval has subsequently been subdivided into Guanling and Yangliujing (Ladinian) Formations, however (Yu Youyi, 2005, personal commun.). The Badong, characterized by red mudrock and sandstone, represents the entire Middle Triassic in northeastern Guizhou (Fig. 22; Guizhou Bureau, 1987). The siliciclastics of the Badong suggest an uplifted source area in that general direction. This is almost certainly the Jiangnan Massif (“oldland”). This large Precambrian massif is evident in the paleogeography as far back as Early Sinian (late Proterozoic; Wang Hongzhen, 1985; Liu Baojun and Xu Xiaosong, 1994). At times of emergence it covered eastern Guizhou, northeastern Guangxi, Hunan, Jiangxi, southern Anhui, and possibly western Jiangsu and Zhejiang (Wang Hongzhen, 1985; Liu Baojun and Xu Xiaosong, 1994). It was submerged during most of the Permian (Liu Baojun and Xu Xiaosong, 1994; Enos, 1995, p. 247), the Induan, and possibly the Olenekian (Liu Baojun and Xu Xiaosong, 1994). The influx of siliciclastics in the Middle Triassic signals its resurrection.

Fossils from the Guanling Formation (Guizhou Bureau, 1987, p. 281–282 and 296–297; Wei Jiayong et al., 1996; foraminifers, dasyclad algae, and problematic taxa all from Hongyan section, identified by Ioan I. Bucur, 2002, personal commun.):

Algae: Rivulariacean-like cyanobacteria, dasyclads: *Diplopora annulata* (Schafhäütl), *D. annulatissima* Pia, *D. sinica* Bucur and Enos, *Euteutlopora triasina* (Schauroth), *Gyroporella?* sp., *Julpiaella* cf. *calicina* (Pia), *J.* cf. *dissocladelloidea*, *J. subtilis* (Pia), *Macroporella alpina* Pia, *M. dinarica* Pia, *Oligoporella pilosa* Pia, *Physo-*



Figure 39. Reptile tracks in desiccation-cracked platform-interior deposits provide confirmation of intermittent exposure. Impressions of the three-toed forelimb (circled) are discontinuous, indicating intermittent bipedal gait. Human feet (unbound) and pencil provide scale. Shangba, north of Zhenfeng.

*porella* cf. *pauciforata* (Gümbel), *Poncetella hexaster* (Pia), *Pseudodiplopora proba* (Pia)

Foraminifers: *Endotebanella* sp., *Endotriada* sp., *Endotriadella wirzi*, *Glomospira* sp., *Glomospirella* sp., *Meandrospira dinarica*, *Pilamina* cf. *densa*, *Trochammina* sp., Duostominidae

Ammonoids: *Progonoceratites* sp., *P. nanjiangensis*, *P. cf. robustus*

Bivalves: *Bakevella* sp., *Entolium* sp., *Eumorphotis* sp., *Gervillia* sp., *G. cf. mytiloides ornata*, *Hoernesia satibliqua*, *Leptochondria* sp., *L. alberti*, *L. illyrica*, *L. paradoxica*, *L. subillyrica*, *L. subparadoxica*, *Modiolus* aff. *minuta*, *Myophoria* sp., *Myophoria (Costatoria)* sp., *M. (Costatoria) goldfussi*, *M. (Costatoria) goldfussi mansuyi*, *M. curvirostris*, *M. (Neoschizodus) laevigata*, *Palaeolima praecepedecliva*, *P. subcostata*, *Palaeonucula* sp., *Plagio-*

*stoma radiata*, *P. striata*, *Pleuromya* sp., *P. elongata*, *P. musculoides*, *Trigonodus* sp., *T. cf. sandbergeri cuneatus*, *Unionites* sp., *U. spicatus*

Gastropods: *Loxonema* sp., *Naticopsis* sp.

Brachiopods: *Lingula* sp., *Rhaetina elongata*

Crinoids: *Cyclocyclicus* sp.

Conodonts: *Neogondolella constricta* (Yongningzhen section)

Problematic taxa: *Olangocoelia otti* (Bechstadt and Brandner)

Vertebrates: *Sanchiaosaurus* sp.

Calculated accumulation rates for the Guanling Formation range from 63 to 230 m/m.y., almost identical to the range for the Poduan Formation. The mean accumulation rates, however, are ~15% lower, at 80 to 160 m/m.y.

### Depositional Environments

The Anisian formations are readily grouped into dominantly siliciclastic basinal deposits of the Xinyuan and Xuman Formations, carbonate-platform deposits of the Poduan and Guanling Formations, and the basin-margin Qingyan Formation, characterized by carbonate breccias intertonguing with siliciclastics. Over most of the platform interior the Guanling Formation is bioturbated muddy carbonate with some grain-supported carbonate, both composed of bioclasts, fecal pellets, peloids, intraclasts, and grapestone. Much of the carbonate is somewhat argillaceous and mudrock interbeds or intervals are common. The biota is dominated by bivalves, with ostracodes and echinoderms common in the upper part. The only clear evidence of subaerial exposure within the platform interior is the desiccation-cracked mudflat traversed by bipedal reptiles ~14 km from the platform edge. Molds of evaporite minerals are widespread. Intervals of brecciated dolostone that could be interpreted as evaporitic solution-collapse breccias are rare; they were observed only near the base of the Guanling at Yongningzhen. No bedded evaporites are known from Guizhou, but anhydrite, halite, and potassium salts are widely distributed in coeval deposits from neighboring Sichuan, farther in the interior of the Yangtze Platform (Wu Yinglin and Yan Yangji, 1987; Wu Yinglin et al., 1989).

Several factors indicate a subtidal platform with restricted circulation and episodic elevated salinity in Guizhou during the Anisian: the non-cyclic combination of low-energy constituents, bivalve-dominated biota, and interstitial evaporites. Local occurrences of ammonoids and crinoids point to periods of normal-marine salinity; possible collapse breccias at the base of the Guanling and widespread evaporite molds signal episodes of severe restriction. An elevated rim of the carbonate platform is the probable cause of restriction in the platform interior. This is consistent with the slower accumulation rates and lesser total thickness, by ~100 m, of the Guanling rocks in comparison to the platform-margin units (Table 2). The wide fluctuations in salinity recorded in the deposits probably reflect fluctuations in sea level that alternately submerged and exposed the rim, or episodic

breaches in the rim (see below). Even extreme fluctuations in climate would be unlikely to control salinity on such a large platform; minimal inflows of seawater can maintain salinity above the threshold for evaporite deposition, even in arid climates (Lucia, 1972). A prolonged rise of relative sea level with larger amplitude is indicated by nodular-bedded argillaceous carbonate (215 to 395 m at Yongningzhen).

A general increase in terrigenous content within the Guanling toward the north and east points to a source in that general direction, probably from the Jiangnan Massif in eastern Guizhou and adjacent Hunan, which had been flooded through the Induan and possibly the Olenekian (Liu Baojun and Xu Xiaosong, 1994). In the Zhenfeng sector, the mudrock content is intermediate but is concentrated in the lower Guanling. The source was probably the Khamdian massif to the west in Yunnan, a persistent source in the Late Permian (Enos, 1995) and Early Triassic, but of declining importance by the Middle Triassic. Neither source produced a great flood of detritus, however. Total unit thickness decreases onto the platform toward the north. This suggests that a decline in carbonate production in the interior of the platform was partly responsible for the relative increase in terrigenous content. This is a predictable consequence of the restricted conditions that prevailed on the platform. In contrast, cyclic carbonates at the platform margin prograded over the boundstones of the Poduan Formation at Hongyan, suggesting progradation of that portion of the margin.

Cyclicity is marked in the Guanling deposits toward the platform margin. A typical cycle consists of a grain-supported bioclastic, intraclastic, or oolitic base; a muddier midsection with sparse mollusks, fenestrae, and local desiccation cracks; and a laminated dolomudstone cap, in some cases disrupted to form tepee structures. This is the familiar shoaling-upward pattern of platform carbonates (James, 1977; Enos, 1983), aggrading from a shallow subtidal base into the supratidal zone. Laminar and domal stromatolites, fenestrae, and desiccation cracks are reliable indicators of tidal-flat deposition (Shinn, 1983). The rare bi-directional cross-lamination, "herring-bone structures," are a further indication of tidal influence. Vertical burrows can be a response to the stress of intermittent exposure. Molds of gypsum and halite crystals and gypsum rosettes reflect concentrated pore waters, probably formed by interstitial evaporation during more prolonged periods of exposure, such as neap-tide cycles. Tepee structures, commonly superposed on the cycle caps, characteristically form by rapid displacive cementation in subaerial fresh-water or hypersaline settings (Assereto and Kendall, 1971; Dunham, 1972; Smith, 1974; Esteban and Pray, 1983), indicating longer periods of exposure, perhaps hundreds of years, for many of the cycle caps. In contrast, the subtidal portions of the cycles show a fair diversity of biota, despite the domination by gastropods and bivalves. Echinoderms and calcareous algae, in particular, reflect episodes of normal salinity. Abundant algae indicate deposition within the photic zone. Cyclic repetition of supratidal exposure on a scale of meters points to very shallow water. Repeated shoaling-upward cycles with evidence of sub-

aerial exposure are recorded only in sections near the platform-margin slope break. This distribution suggests that the rim of the platform was elevated. The low-energy cycle caps indicate some degree of shelter from waves generated in the adjacent basin, although the cycle bases are typically grain supported. The elevated margin and the consequent sheltered environment could have been formed by reefs, shoals, or islands.

The predominance of boundstone, especially framestone, within the Poduan Formation and among the platform-derived blocks within the basin-margin Qingyan Formation indicates that a narrow zone of framework reef formed the outer margin of the Yangtze Platform during the Anisian. The diminutive size and obscure appearance of the framebuilders, dominantly *Tubiphytes*, set this framestone apart from most in the geologic record and certainly stand in contrast to other Mesozoic and modern reefs with frameworks of scleractinian corals or rudist bivalves. The existence of framestone is indicated by the abundance of constructional pores framed by skeletons in growth position. As the framebuilders were small, so were the cavities; most are of centimeter to millimeter scale, but they form up to 75% by volume of some samples. The skeletons and the cavity walls were host to a myriad of encrusters and borers. In many instances the framebuilders themselves grew into the cavities from the sides and roof. Thick crusts of marine cement added rigidity to the framework. Internal sediment was washed into most of the cavities, indicating that the depositional surface was connected by an open pore network and was probably very close at hand. The boundstones and framestones form massive units typical of reef rocks, although individual reef or mound morphology could not be identified in the karstic outcrops. Without preservation of mound morphology or of stratal relationships indicating depositional relief above the lagoon floor, the configuration of the postulated reefs is conjectural. Reefs are nevertheless the prime candidates for producing restriction in the platform interior and providing a sheltered environment for tidal flats near the slope break.

The breccias associated with the platform-margin boundstones, common at Hongyan, probably reflect penecontemporaneous erosion of bound blocks, the widely accepted, albeit ironic, criterion for wave-resistant structures. Unfortunately, an overprint of brecciation from faulting and probable cave collapse obscures distinctions among the possibilities: tectonic breccia, solution-collapse breccia, and "reef talus." The spatial association of breccia with boundstone and slight rounding of some blocks are suggestive, but hardly definitive. The situation is clearer on the seaward side of the slope break at Dabang, south of Hongyan, and at Hetaoshu, Zhenfeng, where wedges of carbonate breccia containing abundant *Tubiphytes*, *Plexoremaya*, and a few arborescent corals extend from the platform margin several kilometers into the basin. More dramatic are the huge blocks of framestone within the Qingyan Formation that indicate early, in situ lithification and a basinward slope seaward of the platform margin. Large, club-shaped echinoid spines found within redeposited, platform-derived grainstones of the Qingyan are an obvious adaptation for rock-boring infauna in a wave-

agitated environment. Although they were not found in situ in the Poduan Formation, they provide another clue that the platform edge was lithified and subject to high wave energy.

The putative reef framework consisted of diminutive branching structures, *Tubiphytes* and *Plexoramea*; arborescent corals; sponges; and small domed stromatolites, all heavily encrusted and intergrown with epibionts (Figs. 33–35). Downward-directed branches of some *Tubiphytes* and undersurface attachment of many encrusters indicate a cryptic biota within the cavities (cf. Wood et al., 1994). This configuration supports the existence a true framework reef, albeit one that may not have had much relief above the seafloor.

The Qingyan Formation forms a narrow wedge along the northern margin of the Nanpanjiang Basin adjacent to Guiyang sector of the Yangtze Platform (Fig. 22). The characteristic facies association of carbonate breccia, bioclastic limestone, and lime mudstone is also recognized in outcrops, although not generally mapped, in the Zhenfeng sector of the Yangtze Platform and adjacent to the Great Bank of Guizhou (Lehrmann, 1993; Lehrmann et al., 1998). The background sedimentation of the Qingyan Formation was lime mudstone interbedded with terrigenous mudrock and shale. The lime mudstone apparently derived from fine debris shed from the platform and transported in suspension, i.e., periplatform ooze (Schlager and James, 1978; Boardman and Neumann, 1984; Mullins et al., 1984; Droxler and Schlager, 1985). Beds of lime mudstone diminish in abundance into the basin and are replaced laterally by terrigenous mudstone and shale of the Xinyuan Formation (Fig. 22), the background sedimentation deeper into the basin. Centimeter-scale dolostone and lime-mudstone interbeds at the inner edge of the Qingyan outcrop belt (Fig. 26) indicate that the transition from platform to basin was gradual at some stages of platform evolution. The dolostone with preserved traction structures is interpreted as silt-sized material derived from the platform whereas the structureless mudstone was a periplatform suspension deposit (Enos et al., 1997).

The widespread grain-supported limestones of the Qingyan Formation (Fig. 27) are inferred to be turbidity-current deposits derived from the adjacent platform margin and slope, judging from the spectrum of fossils and particles, sedimentary structures such as graded beds with scoured bases, and syndimentary deformation. The carbonate breccias of the basin margin have a matrix of carbonate mud and alternate with grainstone turbidites and periplatform mudstones. Contacts of the breccia beds are typically sharp and parallel to bedding within adjacent lime mudstone (Figs. 28, 29), but locally they truncate the mudstone, indicating channelized erosion (Fig. 30). Erosion of adjacent mudstone is an obvious source for the platy mudstone clasts within the breccias. Lithoclasts of grain-supported bioclasts within the breccias are comparable to the interbedded grainy limestones, except that they lack the muddy intraclasts that are found in the turbidites. The bioclastic lithoclasts probably derived directly from the shallow platform margin, where cementation was more rapid. The breccias are attributed to debris flows generated on

the upper slopes of the platform. Collapse of the platform margin contributed massive blocks of boundstone and triggered debris flows. Other blocks rolled or surfed down the slope where they sit isolated in muddy deposits (Figs. 31, 32).

The outcrop pattern of the Qingyan Formation, a band more than 175 km long and up to 20 km wide (Fig. 22), suggests a carbonate debris apron, typical of carbonate basin-margin deposits (cf. Enos, 1977; Crevello and Schlager, 1980; Cook and Mullins, 1983; Cook et al., 1983; Mullins et al., 1984). The detailed configuration of the platform margin, revealed by mapping near Qingyan (Qin Shourong et al., 1989) shows that the platform retreated progressively ~2.7 km during accumulation of 340 m of platform carbonates in the early Anisian (Enos et al., 1997). The retreat involved repeated episodes of collapse, which produced blocks up to 100 m long and 30 m thick within the Qingyan. Collapse of the platform margin on a much larger scale is suggested by a lunate reentrant of the Qingyan Formation into the platform 40 km southwest of Guiyang (Fig. 22) that measures 7 km wide and 10 km deep. The overall scale of collapse and retreat of the platform margin is indicated by the mapped dimensions of the Qingyan facies, more than 175 km long and up to 20 km wide. Throughout most of this distance, the platform-margin Poduan facies is missing; the Guanling Formation extends to the edge of the platform. The lack of recognizable platform-margin facies suggests that it was entirely consumed by collapse represented by breccias and isolated blocks and by erosion that fed the carbonate turbidites and periplatform mudstones. The typical width of the Poduan outcrop belt is 3 to 7 km (Fig. 22). Using the average value indicates removal of 875 km<sup>2</sup> of the platform margin. This should be a minimum figure as the collapse was not necessarily limited to the platform-margin facies. Major episodes of margin collapse may have produced gaps in the platform rim and consequent influx of normal marine water into the generally restricted platform interior, as noted in discussion of the Guanling environments.

The Xinyuan Formation is a starved-basin deposit in comparison to the Qingyan with its flux of platform-derived carbonate mud and debris and to the Xuman Formation and equivalents in Guangxi, which received up to ten times the thickness of terrigenous mud (after compaction). The mud of the Xinyuan Formation is predominately terrigenous, "hemipelagic ooze." The appreciable carbonate admixture in some of the mudrocks as well as discrete interbeds of lime mudstone reflects input from the adjacent carbonate platforms. The siltstones and few fine-grained sandstones interbedded with the mudrocks in the upper part of the Xinyuan have sharp bases with current-imposed sole marks, such as flute casts, and internal structures that include planar lamination, ripple-drift cross-lamination, and convoluted lamination. The alternation of lithologies and the suite of sedimentary structures point to distal turbidity currents in the deposition of the siltstone and sandstone.

The lithologies and sedimentary structures described from the Xuman Formation are very similar to those of the Xinyuan. They must represent the same depositional processes: distal turbidites for the siltstones and some of the muddier lithologies that

have current structures, hemipelagic suspension for the terrigenous mud, and periplatform suspension for the carbonate mud. The bioclastic limestones with graded beds appear to be more proximal turbidites from the carbonate platform.

The dramatic increase in thickness of the terrigenous rocks in southwestern Guizhou and on into western Guangxi indicates a voluminous source of fine-grained terrigenous detritus to the southwest of the Xuman outcrops, perhaps from the southern part of the Khamdian massif. On the other hand, paleocurrent directions from the Xinyuan Formation at Mengjiang, near the southwest corner of the Great Bank of Guizhou, are toward the southwest, 235° (Chaikin, 2004, p. 100). The terrigenous detritus cannot have come from the Great Bank of Guizhou, an isolated carbonate platform. It apparently was deposited by currents from the east deflected along the margins of the Great Bank. Paleocurrent data from regional studies of Middle Triassic turbidites in western Guangxi and eastern Yunnan, in part equivalent to the Xuman and Xinyuan, also indicate currents from east to west (Sun Shu et al., 1989, p. 1254, 1259; Xia Bangdong et al., 1993, p. 327; Wu Jiang et al., 1983, p. 132). The thickness trends and the paleocurrent indicators suggest at least two sources at opposite ends of the basin for the detritus. Too little is known about the petrology and paleocurrents of the terrigenous rocks to determine whether they were transported across the attached carbonate platform or derived more directly from massifs that may have bordered the basin, e.g., Khamdian Massif to the southwest and the Jiangnan Massif to the east (Wang Hongzhen, 1985; Liu Baojun and Xu Xiaosong, 1994). The Xinyuan portion of the basin was starved relative to the thicker Xuman. Nevertheless, Anisian terrigenous deposits eventually filled the basin, at least adjacent to the Guiyang sector, and provided a substrate for progradation of the carbonate platform later in the Middle Triassic, during the Ladinian (Fig. 23; Wei Jiayong and Enos, 1991).

#### LADINIAN (UPPER MIDDLE TRIASSIC) FORMATIONS

Ladinian formations in southwestern Guizhou are the Bianyang, Longtou, and Yangliujing, corresponding to basinal, platform-margin, and platform-interior settings, respectively (Table 1, Fig. 40). Contacts with the underlying and overlying formations are generally conformable (Guizhou Bureau, 1987). However, the basal Yangliujing is mapped as laterally transitional to the upper Xinyuan Formation south of Guiyang and is therefore considered upper Anisian locally (Qin Shourong and Jiao Huiliang, 1986; Qin Shourong et al., 1989). Moreover, at least the upper part of the Bianyang Formation extends into the Carnian. Facies mapping at the margin of the Yangtze Platform (Guizhou Bureau, 1987) shows the upper Bianyang as laterally transitional to the Zhuganpo and Wayao Formations, now considered Carnian (Yang Shouren et al., 1995). On the basis of conodont biostratigraphy, Lehrmann (1993; Lehrmann et al., 1998) concluded that the entire Bianyang on the north slope of the Great Bank of Guizhou is Carnian.

Some changes in the location of the platform-edge slope break are apparent between the Anisian and the Ladinian. In the Zhenfeng sector the platform edge retreated slightly; in the Guiyang sector it prograded appreciably (Fig. 23; Wei Jiayong and Enos, 1991).

#### Bianyang Formation

The Bianyang Formation is characterized by “rhythmic sedimentation in flysch pattern, composed of sandstone, claystone, and a small amount of calcilutite in bathyal ... facies. ... Can reach a thickness of ... 2764 m. ...” (Guizhou Bureau, 1987, p. 308). The total thickness of the Bianyang is problematic, as with many other flysch<sup>2</sup> formations. The contacts are typically gradational, the lithology is repetitive without key marker beds, structure is complicated, and the total thickness is great. Moreover, the top of the Bianyang is rarely exposed; younger rocks have been stripped by erosion in most parts of the basin.

A putatively complete measured section, 1976 m thick, from the type locality at the south edge of Bianyang was published by the Guizhou Bureau (1987, p. 309–310). A later measurement of the same section, perhaps with different contact concepts, gives the thickness as 1050 m (Tong Jinnan et al., 2004). D.H. Chaikin described the basal 346 m in greater detail and measured paleocurrents from this section (Chaikin, 2004). Chaikin (2004) also measured incomplete detailed sections 2 km north of Bianyang (1191 m), north of Luodian near the Great Bank of Guizhou (879 m), and near Lianhe, Zhenfeng (694 m; the total thickness of this section is ~2815 m, but it may include 200 m or more of post-Bianyang strata; Wei Jiayong et al., 1996). He measured additional paleocurrents at Mengjiang, at the southwest corner of the Great Bank of Guizhou, using an unpublished section by the Guizhou Regional Geologic Mapping Team. For this study all of the above measured sections were utilized and smaller outcrops were visited near Dabang, Ceheng, Huagaoling, Popin, Xiaoladi, Zhenfeng-Anlong road, and Baicheng, all near the platform-to-basin transition in the Zhenfeng sector (Fig. 2).

Contacts with the underlying Xinyuan or Xuman Formation are gradational, marked by the greater abundance of matrix-rich sandstone within the Bianyang compared to the mudrock, locally calcareous, and siltstone of the underlying units. Locally, as at Ceheng in southwestern Guizhou (Guizhou Bureau, 1987, p. 297) and northeast of Zhenfeng, the Bianyang overlies the Poduan Formation, forming a sharp contact with terrigenous rocks overlying platform limestones. The top of the Bianyang at Bianyang and Lianhe is a transition from terrigenous rocks to lime mudstones and calcareous mudrock, although some workers consider this a calcareous facies of the Bianyang. Bianyang, Lianhe, and Dabang are the only localities on the 1:500,000 geologic map of

<sup>2</sup>Flysch is used here in a lithofacies sense for thick sequences (hundreds of meters) of alternating thin beds of clastic rocks and intervals of shale or mudstone. The clastic rocks typically have internal and bedding structures characteristic of deposition by turbidity currents (cf. Enos, 1969. Also: Sujkowski, 1957; Hsü, 1970; Pettijohn, 1975, p. 578 ff.).

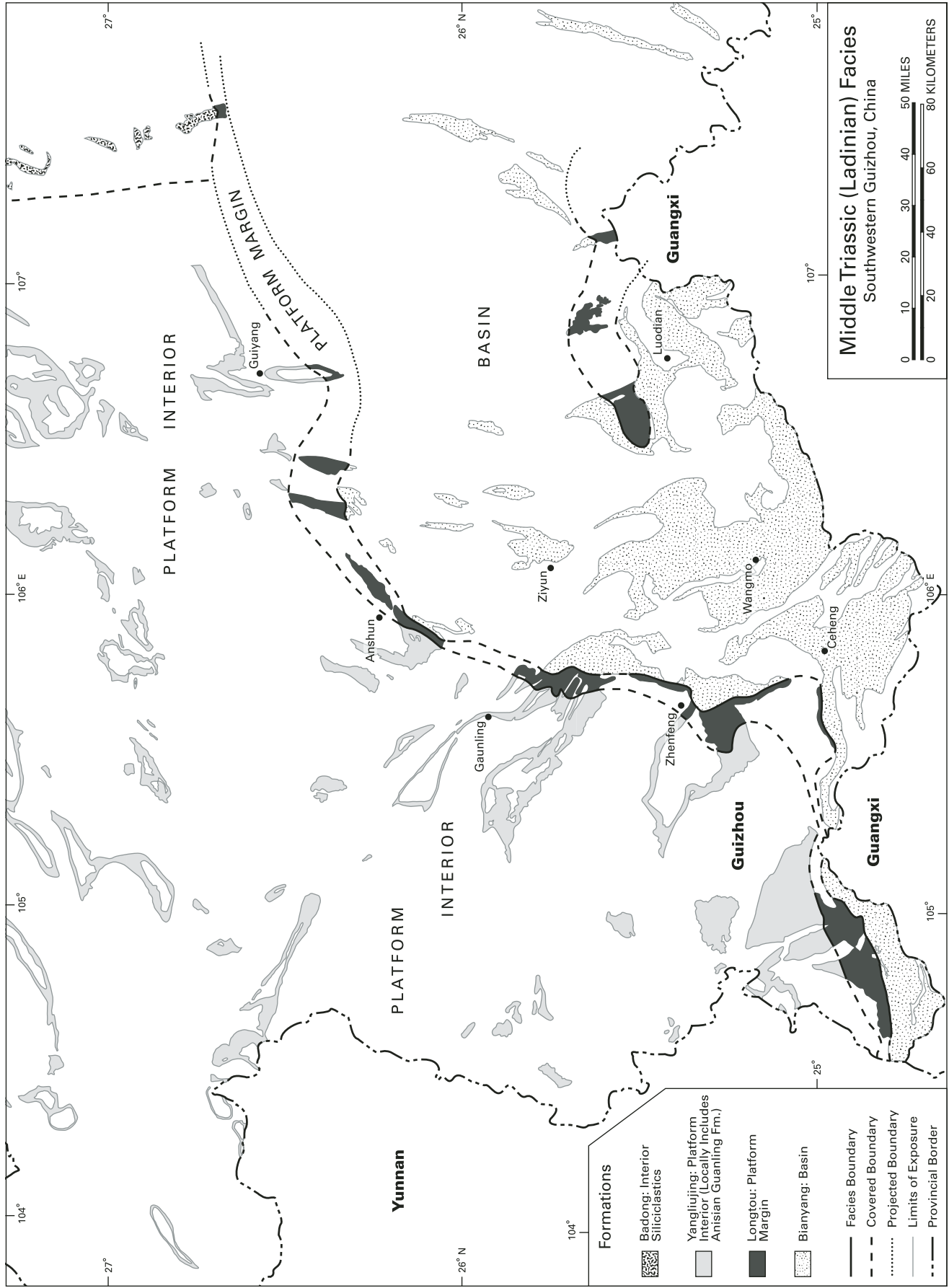


Figure 40. Ladinian (upper Middle Triassic) facies distribution in southwestern Guizhou. Compiled from the Geologic Map of Guizhou (1:500,000; Guizhou Bureau, 1987). Formations, represented by patterns on the map, are essentially time-equivalent facies. Expanded and modified from Enos et al. (1998, p. 59).

Guizhou that show a top to the Bianyang Formation (Guizhou Bureau, 1987). Each is adjacent to a carbonate platform where a syncline has preserved Upper Triassic strata. Lateral transitions from the Bianyang to platform carbonates of the Longtuo Formation are abrupt and conspicuous, because of the lithologic contrasts (Fig. 41). However, the resulting differential compaction and modern erosion commonly obscure details of the transition.

Typical Bianyang lithologies are dark-gray mudrock alternating with thin, laminated siltstone and thicker beds of very fine-grained, matrix-rich sandstone (Fig. 42). Sandstone beds are typically overlain by siltstone and in turn by mudrock. The lower 300 to 700 m of the formation contains most of the sandstone in the sections we studied, although the Guizhou Bureau reports as much as 1273 m of strata with copious sandstone



Figure 41. Lateral contact between the Bianyang Formation (right) and the Longtuo Formation. Both formations are essentially horizontal; the vertical breaks at left (vb) are joints in the massive Longtuo carbonates. Bedding in Bianyang is best seen in cuestas forming skyline at right. (Bar. Streak in middle background is a trail (tr), not bedding.) The apparent interfingering of lithologies (dotted) results largely from the perspective on slight re-entrants in the platform margin created by modern erosion; the true relationship is apparently onlap. Road in the foreground gives some notion of scale. South of Zhenfeng, near Xinchin (XN in Fig. 2). K.J. Hsü and co-workers (Hsü et al., 1988, 1990; Sun et al., 1989) postulate that such contacts represent a suture with the Bianyang overthrust onto the platform.



Figure 42. Bianyang Formation in sandy facies. Near platform edge northeast of Zhenfeng.

(1987, p. 308). The upper part is dominated by mudrock and is more calcareous toward the top. Topographically the Bianyang forms soft, rounded hills with no sharp ridges, although slopes can be very steep and the relief high, owing to intense stream dissection.

Mudrock in the Bianyang varies from partings to units 65 m thick. The mudrock is generally dark gray to black, poorly indurated, and slightly to appreciably silty. Silty mudrock is lighter gray, contains vague laminations, and is locally slightly fissile. Burrows include U-tubes up to 80 cm long with spreite (Fig. 43). Thin-shelled bivalves, such as *Daonella*, *Halobia*, and *Posidonia*, are widely dispersed.



Figure 43. Two U-tubes from Bianyang mudrock near top of the formation. Note spreite connecting the paired tubes, best seen in the (poorly exposed) burrow at lower left. The tubes are probably referable to *Diplocraterion*, although they are superficially similar to *Tisooa banyangensis* (new species), described by Wang Shangyan (1997b) from the Bianyang (cf. discussion in text). Scale bar (lower right) is 2 cm. Bianyang south section.

Siltstones form beds up to several centimeters thick, but lenses 1 to 2 cm thick are more common. Fresh siltstones are dark gray and well indurated. Lamination is ubiquitous, ripple cross-lamination and climbing ripples are common (Fig. 44). Carbonaceous fragments aligned in bedding planes are widespread. Sole marks include flute casts, prod marks, and groove casts.

Bianyang sandstone beds are 20 to 500 cm thick. The sandstones are dark gray, very well indurated, and poorly sorted with appreciable clay and silt matrix—typical graywackes in many classifications (e.g., Pettijohn, 1975, p. 224 ff.). Mudrock clasts are common. Carbonized wood fragments are widely distributed. Modal grain size is everywhere very fine sand, except for several beds of fine sand at north Bianyang. Grading is difficult to discern because of the fine grain size, but sandstone beds are commonly overlain gradationally by siltstone and, ultimately, by mudrock. This constitutes an incomplete Bouma sequence of massive sandstone grading up into laminated or rippled siltstone, capped with dark-gray, structureless mudrock. Most sandstones thicker than ~50 cm are amalgamated, as indicated by internal load casts, fluid-escape structures, or lenses of mudstone or laminated siltstone (Fig. 44). The abundant sole marks are load casts, flute casts, groove casts, and prod casts (Fig. 45). Aligned mudrock clasts on the upper surface of sandstone beds were measured for paleocurrents in a few cases (Fig. 46). In favorable exposures, clast orientation could be measured as parallel to sole marks on the bases of the same beds, confirming their utility as paleocurrent indicators. Fluid-escape structures include flame structures, dish structures, mud diapirs, and narrow, undulating clay streamers that extend upward as much as 20 cm from the base of some sandstone beds.

Sections studied by Chaikin (2004) adjacent to the Great Bank of Guizhou, near Luodian south of the bank and two at Bianyang ~2 km apart north of the bank, show a common pattern of sandstone dominance at the base and mudrock above. The most extensive section north of Bianyang consists of somewhat more than half sandstone in the lower 415 m and only ~3% in the upper 776 m. In the type section at the southwest edge of Bianyang, the basal 315 m is dominantly sandstone. The more complete section published by the Guizhou Bureau (1987, p. 309) included 200 m of claystone and siltstone at the base, which were considered part of the Xinyuan by Chaikin (2004), overlain by 305 m of predominately sandstone, 145 m of mudrock, and 60 m more of mostly sandstone. The overlying 1250 m consists of variations of mudrock with minor siltstone. The section south of Great Bank of Guizhou near Luodian included mostly sandstone in the basal 460 m, overlain by 250 m of mudrock and an additional 80 m of sandstone with minor mudrock. This basal concentration of sandstone is not so evident at Lianhe, near the eastern margin of the Yangtze Platform, where sandstone is distributed throughout 2800 m of section (Fig. 13E; Wei Jiayong et al., 1996), although it is somewhat more abundant in the basal 1280 m.

Quartz constitutes 74% of the sand-sized components (Chaikin, 2004). About 17% of the quartz is polycrystalline, mostly metasiltstone. Feldspars and lithic fragments average 11

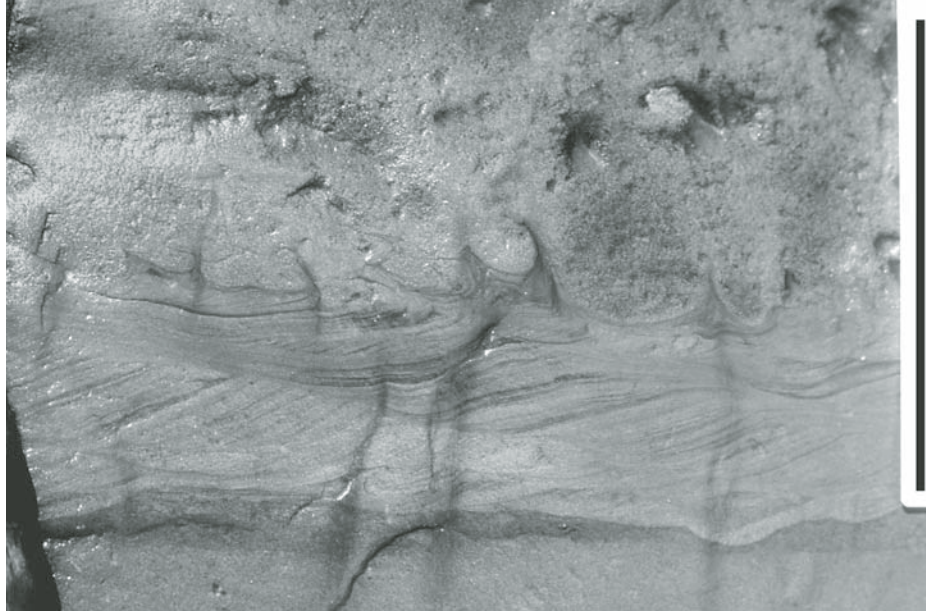


Figure 44. Sedimentary structures in amalgamated bed, Bianyang Formation. Climbing ripple-drift cross-lamination is prominent in siltstone bed that caps a sandstone interval at base. Flame structures formed by fluid escape mark the base of the superjacent sandstone. Luodian section.

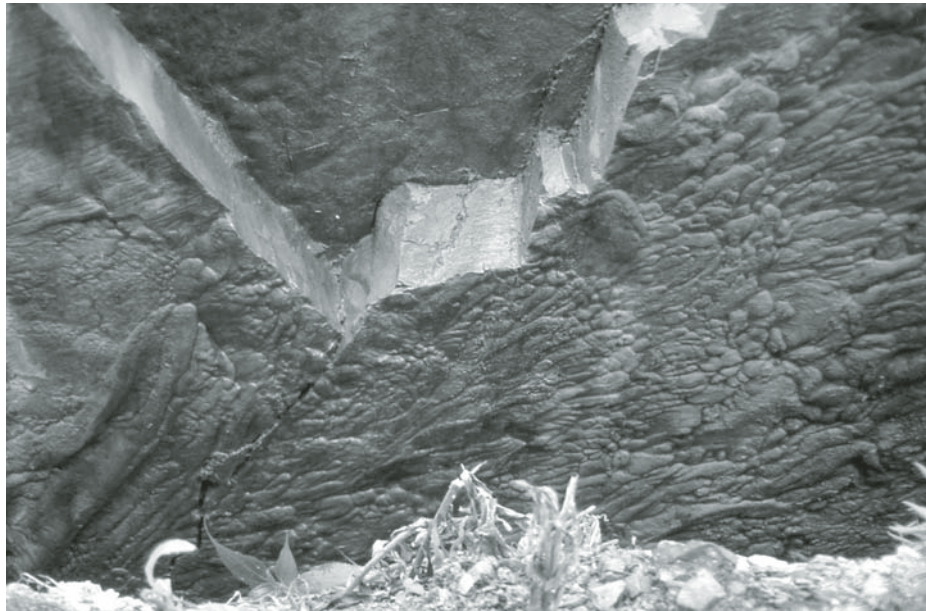


Figure 45. Flute casts on the sole of a sandstone bed in Bianyang Formation. Thickness of bed is ~25 cm. Near Anlong.

and 16% of the sand-sized components, respectively. Potassium feldspar is generally more abundant than plagioclase. Lithic fragments are varied, but altered siltstone and claystone are the most common. Micas are a persistent accessory. The heavy-mineral suite, based on only five samples, is decidedly mature; zircon, tourmaline, rutile, and opaques constitute 95%. Matrix consisting

of clay, mica, and fine quartz averages 7.5% of the bulk volume. Diagenesis, especially calcite replacement, has clearly altered the abundance of matrix; the original content may have been as high as 17% (Chaikin, 2004). Matrix volume has been reduced significantly by calcitization, but alteration of feldspars and lithic fragments to clay may have increased the apparent matrix content.



Figure 46. Oriented clasts of mudrock eroded from top of sandstone bed leave concave-up depressions that provide a paleocurrent lineation. Long and short axes have been marked to facilitate measurement. Elongation parallels orientation of sole marks, where visible, on the base of the same bed. Wing span of scale (below center) is 4.0 cm. Luodian section.

Calcitization of quartz, feldspar, and lithic fragments is also pervasive, making the sandstones distinctly calcareous. Carbonized plant fragments, disseminated pyrite, and chlorite, probably also diagenetic, combine to give the rock its shades of gray. Evidence of compaction is ubiquitous. Grains are commonly oriented, fitted, embayed, sutured, or crushed.

Limestones are absent from the measured Bianyang sections, even those measured as close as a kilometer to the escarpments of carbonate platforms. However, multiple wedges of lime breccia many meters thick are locally interspersed in the lower Bianyang immediately adjacent to the Yangtze Platform and on both flanks

of the Great Bank of Guizhou. Micritic limestones up to 50 m thick are reported at the base of the Bianyang locally in southwestern Guizhou (Guizhou Bureau, 1987, p. 308). In contrast, bioclastic limestones found near the top of the Xuman Formation in the same area are used to differentiate it from the overlying Bianyang. Carbonates do occur at or above the top of the Bianyang near the Yangtze Platform margin south of Zhenfeng and north of the Great Bank of Guizhou in the form of black “marls,” calcareous mudrock, and argillaceous lime mudstone interspersed with calcareous or matrix-rich sandstone (Fig. 13E). This characteristic facies, 359 to 582 m thick, has been locally mapped as the Heimiaowan Member. The name comes from an alternative name for the town of Lianhe (LH in Fig. 2). Some workers have mapped this facies as the top of the Bianyang; others as the base of the Laishike Formation. The choice depends largely on whether the map area lies mainly in the Nanpanjiang Basin or on the Yangtze Platform. An important point is that the Heimiaowan is virtually the only unit that can be recognized in both basin and platform—if the correlations are correct. The locally abundant ammonoids and sparse conodonts are reportedly Carnian in age (Wei Jiayong, 10 August 1999, personal commun.). The dark color and carbonate content, as well as the putative Carnian age, suggest a correlation with the Zhuganpo Formation, a deeper-water limestone that covered the Zhengfeng sector of the Yangtze Platform at the beginning of the Carnian, and possibly with the overlying Wayao Formation, a condensed interval. (See “Carnian Formations” below.) The geologic map of Guizhou (Guizhou Bureau, 1987) shows a lateral transition of the uppermost Bianyang to Zhuganpo at the platform edge near Lianhe and Dabang, presumably based on such a correlation and on stratigraphic succession.

Paleocurrent measurements within the Bianyang (Chaikin, 2004) include “lineations” from structures such as groove casts and oriented particles that give the axis of flow, but not a unique direction, and true current vectors from flute casts and current ripples. The north Bianyang section provided 91 vectors and 87 lineations. The dominant current direction was south. The vector mean is  $202^\circ$  and the dominant mode is  $175^\circ$ . The mean of lineations is north-south. South Bianyang yielded only 22 measurements with a mean of  $162^\circ$ . The trend of the south-adjacent margin of the Great Bank of Guizhou is approximately northeast-southwest in this sector (Fig. 47). Measurements from the Luodian section, south of Great Bank of Guizhou, included 80 lineations and 56 vectors. The dominant mode is  $316^\circ$ . A secondary mode is toward the south ( $185^\circ$ ) and eight current-ripple marks give a mean direction of  $266^\circ$ . The mean of lineations is  $325^\circ$ . The trend of the escarpment of the Great Bank of Guizhou varies near this locality, but is approximately east-west (Fig. 47). Twenty measurements from Mengjiang at the southwest corner of the Great Bank of Guizhou showed considerable scatter; the mean is  $54^\circ \pm 74^\circ$ . Paleocurrents in the underlying Xuman Formation, in contrast, were directed away from the bank ( $235^\circ$ ) and showed little scatter ( $\pm 23^\circ$ ). Current vectors at Lianhe are to the west,  $259^\circ$  from 47 measurements. The mean of 58 polymodal lineation measurements is  $309/129^\circ$ ; with a signifi-

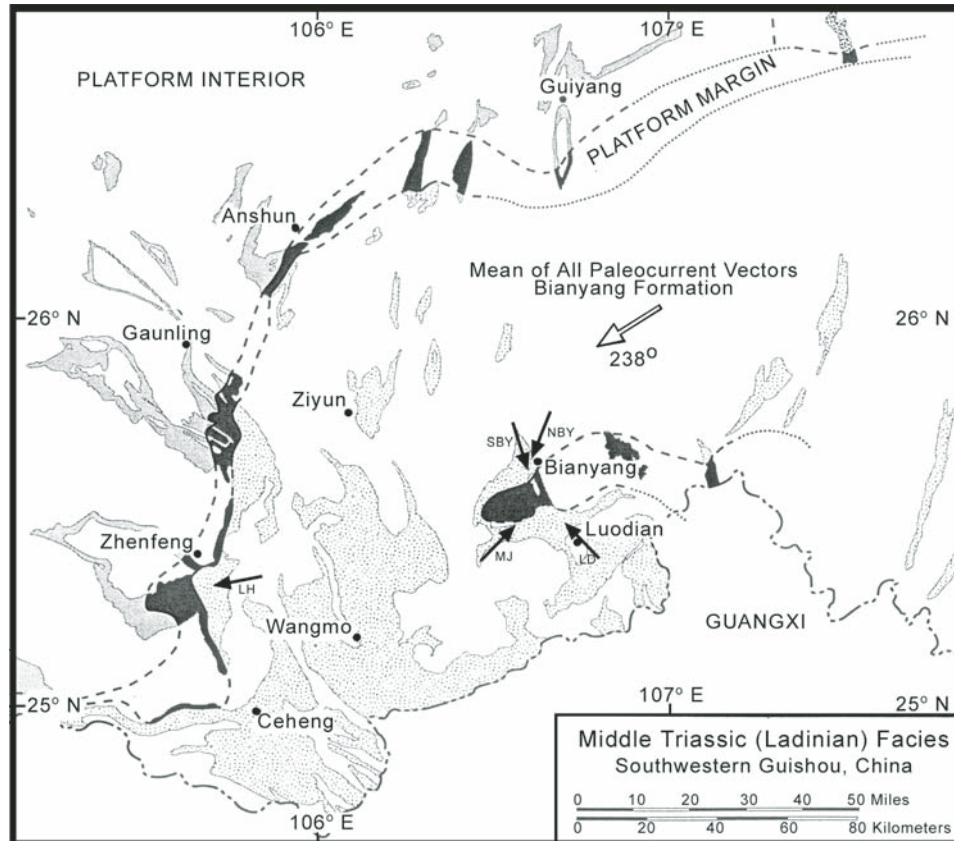


Figure 47. Paleocurrent measurements from the Bianyang Formation (modified from Chaikin, 2004, p. 117). Arrows are vector means from measured sections. (The dominant mode is shown at Luodian because the data are trimodal.) No extensive sections are available that are not close to, and possibly influenced by, an adjacent carbonate platform. Ladinian facies patterns are the same as in Figure 40; the stippled pattern is the Bianyang Formation. For locality abbreviations, see Fig. 2. SBY and NBY are south and north Bianyang sections, respectively.

cant mode at  $245^\circ$ . The trend of the Yangtze Platform margin in this sector is north-south. A startling pattern from each locality is a strong component of flow toward the local platform margin (Chaikin, 2004, p. 115). The regional paleoflow direction during Bianyang deposition appears to have been from east-northeast ( $238^\circ$ ; Fig. 47). Paleocurrent studies of Middle Triassic flysch, in part equivalent to the Bianyang, in southern Guizhou, northwestern Guangxi, and eastern Yunnan also indicate generally west-flowing paleocurrents with appreciable local variation (Sun Shu et al., 1989, p. 1259; Xia Bangdong et al., 1993, p. 327; Wu Jiang, 1993, p. 132). Further south in western Guangxi, where the entire Middle Triassic flysch is reportedly 9000 m thick, transport directions are toward the north (Zhang Jiyan, 1986).

The biota of the Bianyang is dominated by thin-shelled bivalves and ammonoids. The bivalve fauna is more varied than from any other Triassic unit except the Banan. Conodonts have been reported from the carbonate breccias (Lehrmann, 1993; Lehrmann et al., 2002) and from the calcareous Heimiaowan facies (Wei Jiayong, 10 August 1999, personal commun.; Lehrmann, unpublished data, 2002). Megafossils from the breccias have not

been systematically studied. Published faunal lists do not discuss any lithologic associations of the fossils. Wang Shangyan (1997b) reported cylindrical burrows, *Tisoa banyangensis* [sic] (new ichnospecies), up to a meter long, from the sandy lower member of the Bianyang at the type locality. Paired tubes ~5 mm in diameter are encased in sand and surrounded by a cylinder of concentric mud ~6 cm in diameter. Wang attributed the burrows to suspension-feeding bivalves, but *Tisoa* is generally regarded as an arthropod burrow (Häntzschel, 1975). We observed subvertical U-tubes with spreite in sandstones of the lower member as well as mudrocks near the top of the Bianyang (Fig. 43). The tubes are ~8 mm in diameter, spaced 1.5 to 4 cm apart, and up to 80 cm long. The dimensions are similar to those of *Tisoa banyangensis*, but the presence of spreite and absence of the sand and mud haloes indicate that they are distinct. They are probably referable to *Diplocraterion*.

The Bianyang has long been considered to represent most or all of the Ladinian and nothing but the Ladinian, based on ammonoid and bivalve biostratigraphy (Guizhou Bureau, 1987). However, lateral transitions of the uppermost Bianyang into the

Zhuganpo and Wayao Formations mapped at the basin margin near Lianhe and Dabang (Guizhou Bureau, 1987) indicate a Carnian age for at least this part of the Bianyang, as the Zhuganpo and Wayao contain Carnian conodonts (Yang Shouren et al., 1995). Moreover, Carnian conodonts (*Metapolygnathus polygnathiformis* and *Cornudina* or *Misikella* cf. *longidentata*) were collected from the upper half of the Bianyang in basin-margin exposures at Dabang (Lehrmann, unpublished data, 2002). Samples from a basal breccia of the Bianyang at the top of the Hetaoshu (HT) section yielded both upper Ladinian and Carnian forms (*Metapolygnathus polygnathiformis*, *M. tadpole*, *Paragondolella inclinata*, *Budurovignathus mungoensis*). A breccia near the base of the Bianyang south of Zhenfeng (25°21.226'N 105°39.366'E) contains upper Ladinian conodonts (*Gladiogondolella budurovi?*, *Paragondolella inclinata*). On a more extreme note, Lehrmann found Carnian conodonts in carbonate breccias beneath and within basal Bianyang turbidites north-adjacent to the Great Bank of Guizhou (Lehrmann, 1993; Lehrmann et al., 1998, 2002). These indicate that the entire Bianyang Formation here, in the type area, was deposited after the beginning of the Carnian. A possible explanation is that the Bianyang turbidites onlap the carbonate slope to the extent that only the youngest portion is represented there, despite the apparent steepness of the slope (Lehrmann, 1993; Lehrmann et al., 1998) and great thickness of the turbidites. In part these conflicts reflect international disagreement among biostratigraphers regarding placement of the Ladinian-Carnian boundary. Conodont workers generally place the boundary appreciably lower than do ammonoid aficionados. Nevertheless, the Bianyang Formation appears to be diachronous.

Fossils from the Bianyang Formation (Guizhou Bureau, 1987, p. 308–309; Wei Jiayong, 1996, from Lianhe section; conodonts from D.J. Lehrmann, 2002, personal commun.):

Brachiopods: *Konnickina*, *Lingula* sp.

Bivalves: *Bakevella* sp., *Burmisia* sp., *Cassianella* sp., *C.* cf. *gryphaeatoides*, *Catella* cf. *latisulcata*, *Daonella* sp., *D. banchangensis*, *D. bifurcata*, *D. bulogensis*, *D. bulogensis bifurcata*, *D. densisulcata*, *D. indica*, *D. jilongensis*, *D. lommeli*, *D. paucicostata*, *D. tripartita*, *D.* cf. *tyrolensis*, *D. varifurcata*, *Halobia* sp., *H. küi*, *H. rugosoides*, *H. subcomata*, *Hoernesia* sp., *Nuculana* sp., *N. alpina*, *Palaeocardita* sp., *Palaeoneilo* sp., *P.* cf. *tyrolensis*, *Pinna* sp., *P. pteriformis* (subsp. nov.), *P. subcarinata*, *Plagiostoma* cf. *limeata*, *Pleuonectites* sp., *Posidonia* sp., *P. bakevellaformis*, *P.* cf. *elliptica*, *P. idriana*, *P. wengensis*, *P. wengensis robusta*, *Pteria cortinensis*, *Quadratia* sp.

Ammonoids: *Anolcites* sp., *Leiophyllites* sp., *Monophyllites* sp., *Protrachyceras* sp., *Trachyceras* sp.

Conodonts: *Budurovignathus mungoensis*, *Gladiogondolella budurovi?*, *Gondolella ramiformis*, *G. tethysides*, *Metapolygnathus polygnathiformis*, *Paragondolella inclinata*, *P. inclinata-foliata*, *P. tadpole*

Ichnofossils: *Tisoa banyangensis* Wang Shangyan (1997b); U-tubes with spreite (*Diplocraterion?*)

Plant fragments

Accumulation rates for the Bianyang Formation are problematic. The duration of sedimentation is uncertain, as outlined above. It may have occupied the entire Ladinian or only a small part of the Carnian or both. It is probably diachronous within Guizhou. The total thickness is also questionable, owing to structural complications and the absence of overlying units. The only recognized “complete” sections are at the basin margin, where the total thickness might be expected to be reduced by onlap. If we assume, for simplicity, that deposition of the Bianyang spanned the entire Ladinian and no more, accumulation-rate estimates range from 220 to 555 m/m.y. (Table 2), among the highest in the entire Triassic. Decompacted rates would be appreciably higher because most of the upper Bianyang is mudrock. If the entire Bianyang was deposited early in the Carnian, as indicated for the type area (Lehrmann, 1993; Lehrmann et al., 1998, 2002), accumulation rates were extremely high.

### Longtou Formation

The Longtou Formation formed a broad margin, up to 15 km wide, of the Yangtze carbonate platform during the Ladinian, bounded by the basinal, terrigenous Bianyang Formation to the southeast and the platform-interior Yangliujing Formation, mostly dolostone, to the northwest (Fig. 40). The platform-margin facies represented by the Longtou are predominately grain-supported peloidal, intraclastic, and grapestone limestones. Cyclicity is marked (cf. Wu Yinglin et al., 1989). The Longtou thickness reportedly ranges from 174 to 1254 m (Guizhou Bureau, 1987, map legend). Some of the apparent variation is owing to vertical transitions with the Yangliujing Formation. The Longtou and Yangliujing form the most prominent topographic ridges in the landscape of Guizhou (Fig. 48).

The type section near Huaxi (526 m thick; Guizhou Bureau, 1987, p. 299) was studied in the some detail, including 72 polished slabs and 26 thin sections. The Hongyan section of Xiao Jiafe, Huang Xunhua, and Kuang Shunda (unpublished, 1992) includes 1242 m of Longtou Formation; Marcello Minzoni measured 930 m in a more detailed section in 2001. The discrepancy arises from different interpretations of some structural deformation and placement of the base of the Longtou. The Beila section, midway between Zhenfeng and Longchang, includes 690 m of dolostone at the base referable to the Yangliujing Formation, overlain by 625 m of cyclic limestone with dolomitic caps, the Longtou Formation. Transitions from the Longtou platform margin to the basinal Bianyang Formation in the Zhenfeng area (Dabang, Huagaoling, Popin, Panlong, and Xinchin; Fig. 41) were reconnoitered.

The mapping criterion for the Longtou Formation is the occurrence of limestone in contrast to dolostone of the platform-interior Yangliujing Formation. This change generally parallels a more subtle change in depositional facies from high-energy cyclic carbonates in the Longtou to lower-energy cyclic carbonates of the Yangliujing. The diagenetic transition is also somewhat gradational and occurs vertically as well as horizontally. Thus placement of the contact may vary in detail. For example, Wei Jiayong



Figure 48. Longtou Formation forms a prominent ridge at Beila section, as elsewhere in Guizhou. The prominent bedding reflects meter-scale cyclicality. Road lower left provides scale.

et al. (1996; cf. Fig. 13) refer 180 m of limestone at the top of the Longchang section to the Longtou Formation, but the Guizhou Team (1980, p. 154) and the Guizhou Bureau (1987, p. 292) consider the entire section Yangliujing.

The Longtou is distinguished from the underlying Poduan Formation by a much higher proportion of non-skeletal grains (Fig. 49), a general higher-energy aspect, marked cyclicality, and a paucity of boundstone. The contact appears conformable in most places. Where the Guanling Formation oversteps the reef facies of the Poduan, as in the Hongyan area, the base of the Longtou is difficult to establish. Although the Guanling is generally muddier than the Longtou, grain composition is quite similar. Field geologists have used a cluster of thinner beds (<1 m) as the base of the Longtou in this area (Xiao Jiafe, 1999, personal commun.). Minzoni used a possible paleokarst horizon ~100 m higher as the base of Longtou. These picks are ~200 m and 100 m, respectively, below the Anisian-Ladinian boundary, as determined by I.I. Bucur (2002, personal commun.), based on benthic foraminifers and dasyclad algae. This stage boundary is traditionally considered coincident with the base of the Longtou (Guizhou Bureau, 1987). In many areas a considerable thickness of dolomitic Yangliujing Formation intervenes above the Poduan or Guanling and beneath the Longtou. As mapped by the Guizhou Bureau (1987), the Longtou Formation is conformably overlain by the Gaicha Formation in the Guiyang sector of the Yangtze Platform and by the Zhuganpo Formation in the Zhenfeng sector. The nature and implications of these relations are considered below.

The upper third of the Longtou is extensively brecciated in both the Hongyan and Huaxi sections. The stratiform brec-

cias were formed in situ by diagenesis that produced conspicuous tepee structures (Fig. 50) and, rarely, diagenetic pisolites (Dunham, 1969; Esteban and Pray, 1983). Approximately half of the afflicted interval was brecciated beyond reliable recognition of the original lithology; thus breccia totaled ~16% of each section. The surviving recognizable lithologies of the entire Longtou at Hongyan are 32% lime mudstone, 16% wackestone, 29% packstone, and 23% grainstone. Lithologies were divided somewhat more finely, and probably more accurately, at Huaxi with the aid of polished slabs and thin sections. Exclusive of breccias, the section is 5% mudstone, 11% wackestone, 17% filled packstone (i.e., all of the interparticle space is filled with mud), 37% washed packstone, 18% grainstone, 10% rudstone, and 1.4% dolostone. Some, probably small, part of the apparent difference in mudstone content between the two sections is the presence of initially soft fecal pellets that appear to be matrix in the field, but are in grain support as seen in thin section or polished slab. Nevertheless, although grain-supported lithologies predominate in the Hongyan section (52%), they are appreciably more abundant in the Huaxi section (82%). This difference is noteworthy because the Huaxi section is located considerably farther from the slope break than is Hongyan (Fig. 2). The most common sedimentary structures within the Longtou (Fig. 51) are lamination, fenestrae, stromatolites, and cross-lamination, in order of decreasing abundance. Cross-lamination is more abundant at Huaxi than at Hongyan. Relatively rare, but diagnostic, sedimentary structures are desiccation cracks (Fig. 52), oscillation ripples, herringbone cross-lamination, and domal stromatolites.



Figure 49. Longtou packstone with oncoids, grapestones, and peloids. Hongyan section.



Figure 50. Tepee structures distort bedding in Longtou Formation at Beila. Through-going layers at bottom and beneath hammer probably delineate depositional cycles.

Abundance estimates of various components in thin sections and slabs (71 samples) from the Huaxi section may be taken as a rough volumetric estimate of the composition of the formation. Non-skeletal grains constitute 56% of the volume (Fig. 49), skeletal grains 7%, muddy matrix 21%, and cement-filled primary porosity 16%. About half of the non-skeletal component, 27% of the total volume, is peloids. Many peloids may be micritized

skeletal grains, but other possibilities include micritized coated grains, unrecognized fecal pellets, mud lumps, etc. Recognizable fecal pellets, many of them soft at the time of deposition, contribute 14% of the volume. Various intraclasts form 7.2% of the rock and grapestone 3.85%. Intraclasts include 4.1% aggregates that are presumed to have been lithified at deposition, because they consist of non-cohesive grains and have abraded margins

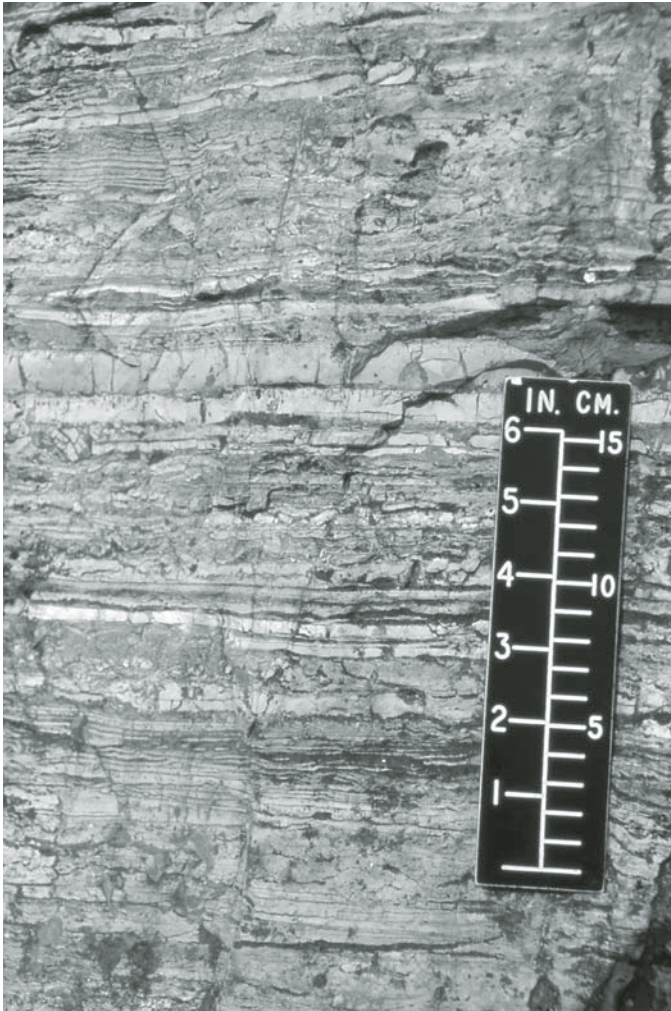


Figure 51. Laminated and fenestral dolomitic limestone in Longtou Formation, Beila section.

(but lack the distinctive features of grapestones). Minor non-skeletal grains are oncoids (Fig. 49), 0.7%; coated grains, 0.6%; ooids, 0.06%; and pisoids, 1.7%. Note that our categories of non-skeletal grains do not strictly adhere to R.L. Folk's (1959, 1962) definitions. Folk's intraclasts include grapestones, pellets or peloids larger than 0.2 mm, and probably oncoids. The lithified intraclasts are judged not to have been "reworked from ... much older carbonate beds," and thus would be proper intraclasts (Folk, 1962, p. 65). The pisoids are probably diagenetic in origin (as in Dunham, 1969), but those included in the estimates show signs of reworking before deposition, which should qualify them as intraclasts.

It is surprising that the various categories of coated grains contribute so little (~1.4%) to the rock in what is clearly a high-energy margin, as evidenced by the well-washed, grain-supported, coarse-grained, current-bedded rocks. The portion of coated grains might have been somewhat higher had the Hongyan section been sampled in more detail. Several oolite

units, ~10 m thick in aggregate, crop out 70 to 110 m above the base of the Longtou.

The small volume of skeletal grains (7%) consists of, in approximate order of decreasing abundance: gastropods, dasyclad algae, foraminifers, bivalves, codiacian algae, mollusk fragments, and ostracodes. In outcrop the most commonly recognized fossils are gastropods, dasyclads, and bivalves. Although field estimates are influenced by size and ease of recognition, this much larger sampling agrees with the petrographic observations. Dasyclad algae are particularly abundant in the basal Longtou and upper Guanling Formations in the Hongyan section; some represent new species (Bucur and Enos, 2001; Bucur et al., 2003). Minor skeletal constituents are echinoderm fragments, calcispheres, echinoid spines, *Tubiphytes*, corals, and brachiopods. The large component of peloids (27%) is probably related to the low abundance of skeletal grains; the majority were micritized beyond recognition. This degree of alteration also warns that relative abundances may have been significantly altered by differential micritization.

Lithologies that could be considered reef facies are virtually absent from the outcrops. Exceptions are small bioherms of arborescent corals or *Tubiphytes* near the slope crest southeast of Zhenfeng and near Hongyan. Resedimented blocks containing bouquets of arborescent corals, probably derived from the Longtou Formation, were observed in the basin margin Bianyang Formation at Huagaoling, Popin, and Panlong, all southeast of Zhenfeng and near Dabong, southeast of Hongyan (Fig. 2).

Meter-scale cycles are a prominent feature of the Longtou Formation (Fig. 48). Although cycles were not logged in detail in the published measured sections, units noted as cyclic constitute 53% of the Hongyan section and 30% of Huaxi section. In our detailed measured section at Beila, 95% of the undolomitized (Longtou) part is cyclic. Cycles range from 40 cm to 20 m thick. Calculated average cycle thicknesses are 6.1, 3.5, and 3.7 m respectively. This estimate is clearly skewed toward thicker cycles; many cycles of centimeter to decimeter scale, observed at the base of the Hongyan section, for example, were not recorded in enough detail to use in the calculations.

Wu Yinglin et al. (1989) presented an idealized cycle from the Longtou at Qingyan (p. 37) and typical cycles from Huaxi (p. 126), which they termed "loferite cycles" in analogy to cycles from the Norian Dachstein Limestone around Lofer, Austria, described and interpreted by A.G. Fischer (1964). Their idealized Longtou cycle has an erosional base overlain by cross-bedded calcarenite, followed by a fining-upward interval of calcirudite (Wu Yinglin et al., 1989, p. 37). This portion of the cycle was attributed to deposition in tidal channels. The overlying interval is wavy to hemi-spheroidal stromatolites, ascribed to algal mediated sedimentation in the intertidal zone. The cycle is capped by dolomitic calcarenite or calcilitite with gypsum molds, desiccation polygons, and sheet cracks with "agate-like veins" (these are likely isopachous cement crusts) reflecting supratidal deposition (Wu Yinglin et al., 1989, p. 37). Such cycles are reported along the margin of the Yangtze

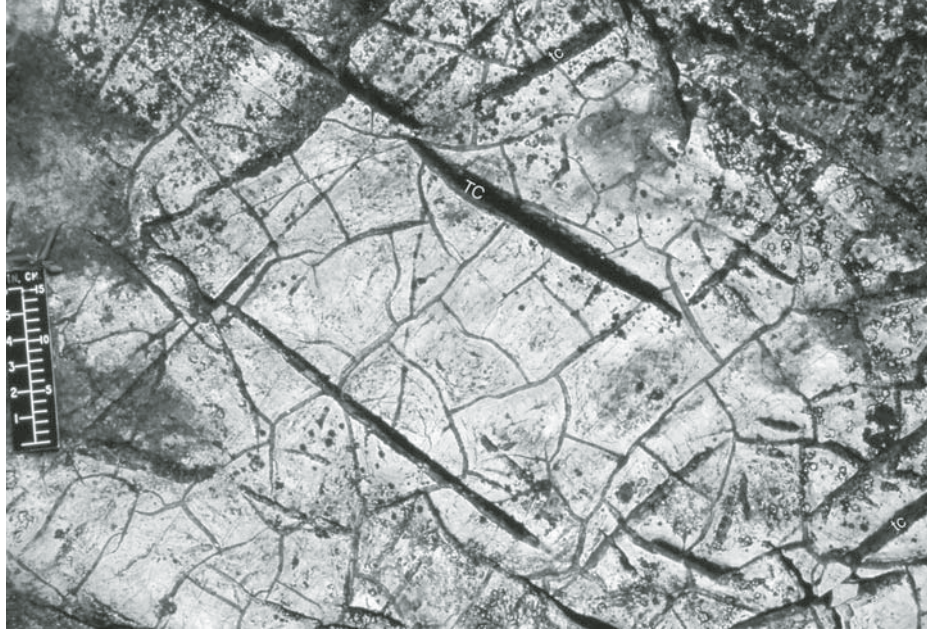


Figure 52. Polygonal and concentric desiccation cracks in dolomudstone of Longtou Formation near Huangpingzhai (PZ in Fig. 2). Large linear cracks oriented northwest-southeast (TC) are solution-enlarged tectonic fractures; a less prominent set is oriented northeast-southwest (tc).

Platform from east of Guiyang southwest into Yunnan, a distance of 600 km (Wu Yinglin et al., 1989, p. 38).

A notable contrast with cycles of other formations of the Yangtze Platform, as well as the original Lofer cycles, is the dominance of high-energy lithologies—rudstones, grainstones, and packstones—in the Longtou cycles (Fig. 49). Many cycles, including two sampled for detailed petrographic study, have grainstone caps that are finer grained but better washed than the packstone or filled packstone found lower in the cycle. The paucity of cohesive mud in the dominant lithologies undoubtedly reduced the incidence of fenestrae, desiccation cracks, and domal stromatolites and favored the development of current lamination and cross-lamination. Some laminated cycle caps consist of grainstone or packstone interlaminated with mudstone, indicative of repeated variations in energy during deposition. Cycle caps in the more interior section at Beila are laminated, fenestral dolomudstone, typical of many cycle caps worldwide. We did not observe any signs of evaporites in the Longtou cycles, in contrast to Wu Yinglin et al. (1989).

Diagenetic disruption of the depositional fabric is common in cyclic Longtou rocks, manifested as intervals with tepee structures, sheet cracks, diagenetic pisolites, and auto-brecciation (Fig. 50). These features are superposed on horizons with fenestrae, stromatolites, and desiccation cracks (Figs. 51, 52) in the upper portions of cycles. Some intervals tens of meters thick, e.g., 311 to 361 m in the Huaxi section, are apparently amalgamated intervals of diagenetic disruption. Such structures have been widely documented as characteristic of subaerial exposure (cf. Dunham, 1972; Assereto and Kendall, 1971; Smith, 1974). In the abundant Longtou examples,

the cements that accompany and amplify the volume expansion associated with tepees and auto-brecciation are invariably banded, isopachous, radial fibrous crusts or botryoidal clusters. These cement fabrics are indicative of precipitation from marine rather than meteoric waters. Thus it appears that the dominant fluids during the episodes of exposure presumably responsible for the disruptive structures were marine. However, we have observed scant evidence of the formation of evaporites that might be expected in such settings, although Wu Yinglin et al. (1989) included gypsum molds in their idealized cycles.

Most of the cycles clearly shoaled upward as indicated by upward increases in the abundance of fenestrae, domal stromatolites, and lamination within typical cycles and occasional desiccation cracks in cycle caps. This conclusion is reinforced by the concentration of subaerial diagenetic disruption in the upper portions of cycles. A few cycles are symmetrical. Three successive cycles totaling 6.5 m thick in the Huaxi section grade up from laminated fenestral wackestone to interlayered fenestral wackestone and packstone with peloids, grapestone, and oncoids, overlain with a sharp transition by peloid wackestone with gastropods, followed by a reversed succession of packstone to laminated fenestral wackestone.

Our observations indicate that the cycle described by Wu Yinglin et al. (1989) is highly idealized. The cycle bases are generally sharp but rarely show signs of erosional relief or appreciable reworking of the underlying bed. Cross-bedding is rare, although smaller-scale cross-lamination is not uncommon, generally in the upper units of cycles. Cycle bases rarely fine upward, as expected in channel deposits; in some instances the basal lithologies reflect

lower energy than the capping units, as mentioned above. We interpret the typical cycle base as level-bottom, shallow subtidal deposits, rather than tidal-channel deposits. The high depositional energy recorded throughout most cyclothems likely owes more to wave action than to tidal currents, at least in the basal units. The definitive structures, oscillation ripples for waves and herringbone cross-lamination for tides, are both present in a few locations, but are extremely rare. Rounding, sorting, and winnowing of fines, the ubiquitous indicators of high energy in the cycle bases, are more efficiently achieved by wave action than by tidal reworking. The upper units of the cycles are clearly tidal-flat deposits as indicated by fenestrae and stromatolites, as well as by the sparse desiccation cracks, rare herringbone cross-lamination, and domal stromatolites. The common lamination, mudstone-grainstone interlayering, and ripple cross-lamination probably reflect tidal currents. Evidence for formation of evaporite minerals is lacking.

It should be remembered that the Lofer cyclothem, as figured by Fischer (1964, p. 113) and widely reproduced in detailed and generalized papers on cyclic carbonates, is deepening upward, with a microkarst surface bearing vestiges of a paleosol at the base. Although shoaling-upward and symmetrical cycles are also present in the Lofer type area (Enos and Samankassou, 1998), Fischer's illustration of an upward-deepening cycle is universally "the Lofer cyclothem." These defining characteristics are not present in the Longtou cycles. Coincidentally, tepee structures, the disrupted cycle caps so common in the Longtou cycles, are virtually absent in Lofer cyclothems (Goldhammer et al., 1990; Satterley, 1996; Enos and Samankassou, 1998). On the other hand "loferite," defined by Fischer (1964, p. 124) as "limestones or dolomites which are riddled by shrinkage pores," is certainly applicable to the capping units of typical Longtou cycles.

The Longtou cycles with well-washed, "high-energy" lithologies do not correspond precisely with the high-energy, shoaling-upward models proposed by James (1977) and Pratt et al. (1992) that are predicated on beach progradation or tidal-channel migration. Wu Yinglin et al. (1989) postulated tidal-channel deposits in their idealized cycle, but in our more limited study we found very few of the hallmarks of channel deposits, such as scoured bases, lag deposits, or cross-bedding (as opposed to ripple-scale cross-lamination, which is not uncommon). Moreover, the cycles rarely fine upward, as expected in channel deposits. The characteristic features of shoreface and beach deposition are also lacking, e.g., low-angle inclined bedding, systematic upward increases in grain size and washing, or upward increases in the dominance of hydrodynamic structures over biogenic structures (cf. Inden and Moore, 1983). Cemented intraclasts do not exhibit the characteristics of beach-rock cementation, such as radial fibrous crusts, pendant and meniscus cement distribution, or keystone vugs. Intraclasts are sparsely distributed throughout the rocks, rather than concentrated in layers or lenses characteristic of lag deposits. A scenario consistent with the collective characteristics and setting of the Longtou cycles would be platform-margin sand flats (cf. Harris, 1979; Halley et al., 1983) that repeatedly shoaled upward through rapid sediment production and accumu-

lation. In this slightly irregular constructional topography, grains alternately lay dormant for extended periods to be micritized into peloids and cemented into grapestone and were reworked into well-washed sand sheets. Local high-energy, storm-swept tidal flats developed in the lee of areas that accreted above sea level.

The southern margin of the Ladinian Yangtze Platform has been removed by modern erosion in the Guiyang sector, but the Longtou Formation oversteps the Anisian platform edge along the east limb of the syncline that extends south from Guiyang and overlies the Anisian basin fill of the Xinyuan Formation to the limit of Longtou outcrop 5 km to the south (Qin Shourong et al., 1989; Wei Jiayong and Enos, 1991). This produces an apparent progradation by the Longtou of at least 5 km along the strike of the present outcrop, but it is only ~0.6 km measured perpendicular to the local trend of the Anisian margin. In contrast, east of Zhenfeng and at Ceheng in southwestern Guizhou (Fig. 2), Bianyang turbidites overlie the Poduan Formation, which formed the Anisian platform margin, indicating retreat of the Ladinian platform margin in the Zhenfeng sector.

Fossils from the Longtou Formation (Liu Yuzhou, 1996, p. 358; Yang Shouren et al., 1995, p. 167; Wei Jiayong et al., 1996; Xiao Jiawei et al., unpublished Hongyan section. Foraminifers and algae identified by Ioan Bucur, 2002, personal commun.):

Algae: Porostromata, dasyclads: *Diplopora annulatissima* Pia, *D. annulata* (Schafhäütl), *Gyroporella* cf. *ampleporata* Gumbel, *Oligoporella*, *Poncetella*

Foraminifers: *Diploremina* cf. *astrofimbriata* Kristan-Tollmann, *Earlandita?* sp., *Endotriada* sp., *E.* cf. *elegans* Salaj, *Endotriadella robusta* Salaj, *E.* cf. *pentacamerata* Salaj, *E. wirzi* Koehn-Zaninetti.

Corals: *Montilivaltia capitata*, *Pinacophyllum* sp., *Thamnastraea* sp., *Thecosmilia* sp.

Brachiopods: *Adgyella* sp., *Lissorhyncia pygmaea*, "*Maxillirynchia*" *sinensis*, *Mentzelia* sp., *Rhaetina* sp., *Sanqiaothyris elliptica*, *S. subcircularis*

Bivalves: *Chlamys* sp., *Daonella* sp., *Entolium lavaredanum*, *E. tenuistriatum*, *Lima* sp., *Montilivaltia* sp., *Palaeolima* sp., *Pamilelodon* sp., *Plagiostoma striata*, *Unionites* sp.

Ammonoids: *Flexoptychites* sp.

Conodonts: *Neogondolella polygnathiformis*, *N. foliata inclinata*.

Accumulation rates calculated for the Longtou Formation range from 58 to 265 m/m.y. (Table 2). Physical compaction was probably minimal in these largely grain-supported carbonates. There is likewise little evidence of chemical compaction. In fact, the great abundance of tepee structures suggests that the total thickness may have been expanded slightly by early diagenesis.

### Yangliujing Formation

The platform-interior deposits of the Ladinian in Guizhou are the Yangliujing Formation (Fig. 40). It consists of dolostone and dolomitic limestone; thickness ranges up to 1200 m (Guizhou Bureau, 1987). Locally a limestone member is reported at the top,

but more commonly such limestone is considered a tongue of the Longtou Formation, even at considerable distance from the shelf edge, as at Longchang (Fig. 13C). The Yangliujing continues the prominent topographic ridge of the Longtou formation without diminution. We measured the Yangliujing interval at Beila, near Zhenfeng, as 690 m of crystalline dolomite with poor fabric retention. The overlying 635 m of limestone is referred to the Longtou Formation. The Yangliujing in the familiar section at Longchang is 1000 m thick, including 180 m of limestone (Longtou?) at the top, as described by the Guizhou Team (1980). The type section west of Guanling, the Yongningzhen section (Fig. 2), is unsatisfactory because of severe dolomitization, structural deformation, and inadequate exposure. Other measured sections are from Sanqiao, Guiyang (318 m thick; Guizhou Bureau, 1987, p. 296–297), Langdai (502 m; Guizhou Team, unpublished), and Gaoqiao, Zunyi (250 m; Guizhou Bureau, 1987, p. 281). The Yangliujing at Gaoqiao is overlain disconformably by the uppermost Triassic Erqiao Formation and may be truncated by Late Triassic erosion. The top 24 m of the Yangliujing was included in a detailed section measured on the Gui-Huang highway at the west edge of Guiyang (GH, Fig. 2). The basal 273 m of the Yangliujing is included in the Bojishan section (Guizhou Team, unpublished), which we reconnoitered.

In the Zhenfeng sector the Yangliujing Formation is overlain conformably by deeper-water limestone of the Zhuganpo Formation. In the Guiyang sector the Gaicha Formation, shallow-water carbonate with an appreciable siliciclastic component, overlies the Yangliujing and the Longtou Formations. In northern Guizhou, as at Gaoqiao, most of the Upper Triassic is missing, so that the Erqiao Formation (Rhaetian?) rests disconformably on the Yangliujing. The Yangliujing itself is missing farther north near the Sichuan border, apparently because of Late Triassic erosional truncation. In northeastern Guizhou, the Yangliujing interval is represented by the upper part of the Badong Formation, described as “purplish red shale and sandstone in upper ... parts ...” (Guizhou Bureau, 1987, description of map units). The field distinction of the lateral transition from the Yangliujing to the Longtou Formation is based primarily on a rather sharp diagenetic transition from dolostone to limestone, although the Yangliujing is also generally more muddy than the platform-margin Longtou facies. The basal contact of the Yangliujing with the Guanling Formation in the interior of the platform in northern Guizhou is defined by the ridge-forming dolostone of the Yangliujing overlying dominantly limestone with significant terrigenous interbeds. In practice, however, the two formations are undifferentiated in many areas (Guizhou Bureau, 1987), either because of map scale or the lack of a well-defined contact. Both formations become more terrigenous eastward and grade into the Badong Formation toward the Jiangnan Massif. Toward the platform margin where the Guanling Formation becomes more dolomitic (Huaxi facies), especially in the Guiyang sector, the topographic contrast with the Ladinian ridge formers persists. In the well-studied syncline that extends south from Guiyang, dolostone, mapped as Yangliujing (Qin Shourong et al., 1989),

oversteps the Xinyuan Formation and extends basinward beneath Longtou limestone to the limit of outcrop, ~0.6 km perpendicular to depositional strike. An underlying unit of Yangliujing dolostone passes laterally into terrigenous clastics of the Xinyuan. Thus the base of the Yangliujing is diachronous, at least locally.

In common with some of the underlying platform-interior units and the correlative Longtou Formation, the Yangliujing Formation is characterized by meter-scale, shoaling-upward cycles, at least near the platform margin. The published measured sections are, unfortunately, too general to address the character, number, or, in some cases, even the presence of such cycles. Thus observations on the cycles and of the component lithologies are limited to the detailed sections at Gui-Huang (24 m only) and at Beila, within the limestones in the upper half of the section, which are best referred to the Longtou Formation, although they were mapped as Yangliujing by the Guizhou Bureau (1987). The cyclic character of much of the rest of the formation is obvious, even through the overprint of dolomitization, and the original depositional textures appear to have been similar. The bulk of the rocks at Gui-Huang and Beila are light-gray peloidal or skeletal packstone, wackestone, and minor grainstone that weather almost white (Fig. 53). Bedding thickness is typically 1 to 2 m; the range observed is 40 cm to 5.5 m. The dominant grains are peloids, micritized bioclasts, fecal pellets, grapestone aggregates, and muddy lithoclasts. Other types of intraclasts and coated grains are relatively rare. The sparse biota includes gastropods, bivalve fragments, dasycladacian and codiacian algae, echinoderms, and foraminifers. Brachiopods and conodonts are reported from the top of the Yangliujing at Longchang (Yang Shouren et al., 1995, p. 166). A few burrows and fenestral voids are the only sedimentary structures. This is the range of lithologies of the lower, thicker, portion of a typical cycle that is decimeters to a few meters thick. Fenestral voids increase in abundance toward the top of a cycle. The capping unit of a cycle is generally thinner; centimeters to a few decimeters of dolomitic lime mudstone or dolomudstone. Primary structures are laminar or domal stromatolites, fenestral pores, and desiccation cracks (Fig. 54). These structures are commonly overprinted by buckled layers in the form of “tepees” and by sheet cracks with extensive isopachous cement.

Elsewhere the Yangliujing is mostly non-cyclic, light-gray to slightly yellowish dolostone in thick, meter-scale, beds with a few thinner-bedded intervals. The few non-dolomitic intervals include bioclastic wackestone and grainstone. A few shale layers or argillaceous dolostones occur near the base in all sections except Langdai. Preserved fossils are mostly gastropods and bivalves. Plant fragments, fish scales, and reptile bones are reported from near the base of the formation. Gypsum molds and probably the vugs in the most updip section at Gaoqiao, Zunyi, reflect dissolved evaporites. The updip Langdai section also has numerous vugs and minor breccias likely caused by dissolution of evaporites. Brecciated dolostone is widespread in the upper part of the Yangliujing. Some of it may result from collapse with dissolution of evaporites, but most appears related to diagenetic disruption that forms tepee structures at the top of cycles.



Figure 53. Proximal Yangliujing Formation in Longchang section. The Yangliujing is vaguely cyclic, generally on the scale of the prominent bedding breaks. Many laminated and fenestral intervals alternate with structureless, peloidal wackestone.



Figure 54. Laminated dolomudstone and dolowackestone alternate with intraclastic doloredstone in upper Yangliujing Formation, GH section. Disruption of bedding is probably incipient tepee formation, but it is heavily overprinted by stylolites.

Fossils from the Yangliujing Formation (Guizhou Bureau, 1987, p. 281, 292, 296; Yang Shouren et al., 1995, p. 166; Wei Jiayong et al., 1996; Guizhou Team, 1980, unpublished):

Brachiopods: *Mentzelia* sp., *Nudispiriferina* sp., *Lingula* sp., *L. deitersensis*

Bivalves: *Astarte* sp., *Bakevella* sp., *B. cf. substriata*, *Costatoria* sp., *Curionia* sp., *Entolium* sp., *E. cf. discites*, *Gervillia cf. mytiloides ornata*, *Leptochondria* sp., *L. cf. paradoxica*, *L. subillyrica*, *Modiolus* sp., *Myophoria* (*Costatoria*) *goldfussi*, *M. (C.) cf. submultistriata*, *Myophoria* (*Neoschizodus*) sp., *Myophoriopsis* sp., *Pleuromya*

sp., *P. elonata*, *Pteria cassiana*, *Unionites* sp., *U. alberti*, *U. muensteri*, *U. spicatus*, oysters

Gastropods: *Neritaria* sp.

Crinoids: *Traumatocrinus hsüi*

Conodonts: *Neogondolella polygnathiformis*, *Proniodella decrescens*

Vertebrates: *Sauropterygia*

Plants: *Carpdithus* sp., *Equisetum* sp.

Yangliujing accumulation rates range from 28 to 265 m/m.y. (Table 2). This does not take into account that the lower part of the Yangliujing may be Anisian, as indicated by lateral transition

to the Xinyuan Formation south of Guiyang. This would extend the duration of Yangliujing sedimentation by an unknown amount and thus reduce average accumulation rates. Compactional features are not apparent, but the presence of significant mud in some intervals suggests the possibility of some compaction.

### Depositional Environments

The meter-scale cycles of the Yangliujing and Longtou Formations are interpreted as shoaling-upward, subtidal to supratidal deposits, as discussed at length with the Longtou Formation. The bases of the cycles lack structures other than a few burrows and contain some open-marine biota including dasyclad algae, corals, ammonoids, and a variety of brachiopods, as well as bivalves. Fenestrae appear in the upper parts and are abundant in cycle caps. Other distinctive structures in the typically dolomitic caps are laminar stromatolites, rare domal stromatolites, desiccation cracks, and ripple-drift cross-lamination. Tepee structures, commonly overprinted on the cycle caps and locally obliterating entire cycles, indicate extended subaerial exposure (Dunham, 1972; Assereto and Kendall, 1971), possibly in a hypersaline environment (Esteban and Pray, 1983). The preponderance of high-energy facies in these cycles is striking. Grainstones, rudstones, and packstones predominate in the subtidal portions. Cycle caps are finer grained, but in some cases, even more devoid of mud. Cycles in the Yangliujing Formation, farther into the platform interior, are somewhat muddier than those of the Longtou, particularly in the cycle caps, typically dolomudstone. It is not clear that the peritidal cycles are confined to the platform margin, as is typical in underlying Triassic units, because of a dearth of detailed sections from the interior and the heavy dolomitic overprint in the Yangliujing Formation. However, the area with extensive development of tepees is much wider than in underlying units and includes all detailed sections of the Yangliujing as well as the Longtou. Certainly there was a wide, flat top at the margin of the platform, if not across the entire platform.

Peritidal cycles also extend to or very close to the platform margin in the Longtou. The subtidal facies is dominated by non-skeletal components—peloids, fecal pellets, intraclasts, and grapestones. This is in distinct contrast to the underlying Poduan Formation, dominated by massive reef facies and the attendant skeletal debris. Reef assemblages present within the Longtou in the Zhenfeng sector, which include corals and *Tubiphytes*, are very limited in lateral extent, suggesting that they represent patch reefs (Minzoni et al., 2003). The dominance of non-skeletal components in the Longtou points to platform-margin sand shoals as the main depositional environment. Coated grains are rare, so the ultimate source of the carbonate may have been biogenic mud and clasts, now degraded beyond recognition. Level-bottom communities, patch reefs, and possibly unrecognized reefs could have contributed. The lack of a facies changes near the margin raises the question of whether the margin may have been truncated by extensive collapse, as proposed for the Poduan Forma-

tion, where most of the reef margin in the Guiyang sector collapsed to form the Qingyan Formation (Enos et al., 1997). The answer seems to lie in the paucity of carbonate breccia derived from the Longtou in the adjacent basin. A few such breccias are recognized, including some with reef biota, but their volume is trivial (Minzoni et al., 2003). The lack of evidence for collapse is particularly striking at the northern margin of the Great Bank of Guizhou where exceptional exposures allow reconstruction of a precipitous escarpment up to 1700 m high without significant basin-margin debris accumulation (Lehrmann, 1993; Lehrmann et al., 1998). The Longtou platform margin prograded basinward at least 0.6 km beyond the Anisian margin in the Guiyang sector (Wei Jiayong and Enos, 1991; Enos et al., 1998, p. 73; both estimates of 5 km of progradation failed to take into account the acute angle between the trend of the shelf margin and the strike of the exposures near Mengguan; see Figs. 2 and 40). Progradation could have been much greater; the seaward portion of the Ladinian margin has been removed by modern erosion. In contrast the Longtou platform margin retreated relative to the Poduan margin in the Zhenfeng sector. This is documented by overstep of the basinal Bianyang Formation on Poduan reefs near Zhenfeng and Ceheng and by successive small stepbacks of the Longtou margin mapped south of Zhenfeng (Minzoni, 2003a, 2003b).

Replacement of Ladinian carbonate-platform deposits to the northeast by more coarse grained, probably continental, siliciclastics of the Badong Formation suggests an uplifted source area in that general direction, namely the Jiangnan Massif.

Fan Jiansong (1980) and Yang Zunyi et al. (1986) have characterized the Ladinian sequence on the Yangtze Platform as “regressive.” Tong Jinnan (1998, p. 298) shows relative sea level falling steadily throughout Longtou deposition, except for the uppermost 75 m. In contrast, a steadily rising curve is shown for the time-equivalent Yangliujing Formation (Tong, p. 299) and an erratic curve for the Bianyang Formation (p. 297). We interpret the record in Guizhou as essentially one of highstand vertical accretion with appreciable progradation in the Guiyang sector. A thick amalgamated-tepee interval in the upper part of the Longtou and Yangliujing Formations (e.g., 577 to 787 m above base at Hongyan) has been identified as a sequence boundary (Wei Jiayong and Enos, 1991; Wei Jiayong et al., 1996; Minzoni et al., 2003), although this horizon cannot be correlated into the basin. Following this presumed fall in relative sea level, peritidal sedimentation was reestablished on the platform, necessitating a relative rise in sea level.

Regional correlations (Guizhou Bureau, 1987) show the Bianyang Formation as the basinal equivalent of the Ladinian platform deposits represented by the Longtou and Yangliujing Formations. These terrigenous rocks fringe the Yangtze Platform and the isolated Great Bank of Guizhou (Fig. 40). Some interbeds and wedges of carbonate breccia, probably slope deposits, interfinger with the terrigenous clastics locally. Lehrmann (1993, Lehrmann et al., 1998, 2002) found Carnian conodonts in platform-derived carbonate breccias below the base of the Bianyang at the north margin of the Great Bank of Guizhou,

near the Bianyang type area. Equivalent conodonts occur near the top of the platform carbonates on the Great Bank. By Lehrmann's reconstruction, based on mapping as well as biostratigraphy, the Ladinian platform margin developed a very steep profile with 1700 m of relief above a starved basin. Nearly all of the Bianyang appears to be younger than the platform-margin buildup, Carnian in fact. This would represent an extreme case of reciprocal sedimentation (Meissner, 1972; Wilson, 1975) with the carbonate platform accreting to high relief above the starved basin followed by very rapid filling of the basin while the adjacent platform was dormant, because of either subaerial exposure or drowning. A sequence-stratigraphic framework for western Guizhou by Wei Jiayong et al. (1996) places all but the basal few meters of the Bianyang within a sequence that includes the uppermost Longtuo and Yangliujing Formations, as well as the overlying Zhuganpo and Wayao, essentially splitting the difference between the traditional stratigraphy and Lehrmann's reconstruction.

The Bianyang Formation is a typical flysch deposit (Chaikin, 2004). It has the sedimentologic attributes of great thickness, alternation of thin, matrix-rich clastic beds with hemipelagic background deposits, and abundant sole marks on the clastic beds. The spectrum of sedimentary structures in the clastic beds is diagnostic of turbidity-current deposition. On the other hand, some aspects of the Bianyang are unusual for flysch. The very fine grain size and small range of modal sizes are remarkable—scarcely a “Wildflysch” (cf. Jackson, 1997, p. 715). Turbidity-current transport is not good at sorting, even in the distal portions. The explanation presumably lies in the source area. The source rocks were not coarse grained and the area was not likely to have been one of high relief, unless it was in sand dunes. Recycling of grains that had been sorted and stabilized through previous sedimentary cycles is indicated. This is consistent with the dominance of siltstone clasts among the lithic fragments and the paucity of igneous rock fragments, which are generally harder to overlook in point counting. In the depositional process, hemipelagic mud from the slope was mixed in to form a matrix. Not unusual, except in abundance and exquisite detail, are the fluid-escape structures. This may reflect unusually rapid deposition, consistent with Lehrmann's corollary of extremely rapid filling of the Nanpanjiang Basin surrounding the Great Bank of Guizhou in the early Carnian (Lehrmann, 1993; Lehrmann et al., 1998).

Paleocurrents within the Bianyang are generally directed from east to west (Hou Fanghao and Huang Jixiang, 1984; Sun Shu et al., 1989; Xia Bangdong et al., 1993; Chaikin, 2004), with apparent local interaction with the carbonate platforms (Chaikin, 2004). Paleocurrent data from regional studies of Middle Triassic flysch in western Guangxi and eastern Yunnan, in part equivalent to the Xuman and Xinyuan, also indicate currents from east to west (Sun Shu et al., 1989, p. 1254, 1259; Xia Bangdong et al., 1993, p. 327; Wu Jiang et al., 1993). An obvious eastern source terrain would be the Jiangnan Massif, which was largely exposed during Ladinian (Liu Baojun and Xu Xiaosong, 1994,

p. 158) and possibly merged with the Yunkai massif to the south to form the entire eastern border of the Nanpanjiang Basin. Much of the rock currently exposed in the Jiangnan Massif is low-grade, siliciclastic metasedimentary rocks. Volcanoclastics, glacial-marine deposits, and granitic intrusions are also well represented (Guizhou Bureau, 1987). The fine-grained quartz, siltstone clasts, K-feldspar, and mature heavy-mineral suite of the Bianyang could derive from such a source area. This vast terrain could have readily provided the voluminous deposits of the Bianyang without necessitating extensive or rapid uplift. Delivering the sediment to the basin rapidly enough to fill it, however, would have required huge volumes of fine-grained, unconsolidated sediment be stored in large, mature drainage basins and then rapidly flushed out with rejuvenation. No vestige of such deposits survives within the massif, which has been stripped of virtually all Phanerozoic sedimentary cover. The Middle Triassic Badong Formation in northeastern Guizhou is a candidate for such a deposit, but much of it appears too coarse grained to have been a source for the Bianyang in a single cycle. It may represent a catchment area for the coarser-grained sediment from the Jiangnan Massif as the finer fractions were swept down into the basin. The upper part of the Bianyang Formation, well over half the total volume, consists of mudrock and siltstone, with virtually no sandstone. Thus, the source area ceased to deliver sand, but some source then supplied mud at a prodigious rate.

#### CARNIAN (LOWER UPPER TRIASSIC) FORMATIONS

The Carnian Stage is represented in Guizhou by the Zhuganpo, Wayao, Laishike, and Banan Formations in the Zhenfeng sector and the Gaicha and Sanqiao Formations, with very different lithologies, in the Guiyang sector (Table 1). Until recently the Zhuganpo and Wayao were considered members of the Falang Formation (Guizhou Bureau, 1987), but they are now considered separate formations, making the Falang obsolete (Yang Shouren et al., 1995). Because of stratigraphic position, the Zhuganpo and Gaicha Formations were formerly thought to be uppermost Middle Triassic and correlative, despite the differences in lithofacies (Guizhou Bureau, 1987). Recent conodont biostratigraphy indicates, however, that the Zhuganpo is basal Carnian (Yang Shouren et al., 1995). The Gaicha Formation is now better substantiated as correlative with the Zhuganpo, and therefore Carnian in age, based on magnetostratigraphy and magnetic susceptibility of the two formations (A. K. Berry, unpublished data; Montgomery et al., 2003; Enos et al., 2003). At least the upper part of the Bianyang Formation is also Carnian, as it is laterally transitional with the Zhuganpo and Wayao Formations at two locations in the Zhenfeng sector. (See details in Ladinian chapter.) Lehrmann (1993) concluded from conodont biostratigraphy that the entire Bianyang is Carnian near the type locality. Because of the uncertainty, we discussed the Bianyang with the Ladinian formations, in accordance with traditional Guizhou stratigraphy.

## Gaicha Formation

The Gaicha Formation is mapped only in the southern part of the Guiyang sector of the Yangtze Platform (Fig. 55). It conformably overlies platform carbonates of the Longtou and Yangliujing Formations and is overlain paraconformably or disconformably by siliciclastics of the Sanqiao Formation. The base of the Gaicha is defined by the first appearance of siliciclastics, generally thin claystones. Argillaceous lithologies are totally lacking in the underlying Longtou and are essentially confined to the base of the Yangliujing. In fact, the Gaicha would probably not be differentiated from the underlying units except for the influx of terrigenous clastics in the form of thin interbeds of claystone, siltstone, and minor calcareous sandstone. Carbonate, mostly dolostone, is the predominant lithology, constituting up to 87% of the unit in southern exposures (Fig. 56). The top of the Gaicha is marked by a few meters of bioclastic limestone in several sections and lime mudstone in others. The overlying Sanqiao Formation contains more and coarser siliciclastics; sandstone is a major component.

Detailed sections measured at Hauxi, Gui-Huang Highway at the west edge of Guiyang, and Lingjiawan (Fig. 2; measured by A.K. Berry and P. Enos) essentially span the north-south extent of Gaicha outcrops (Fig. 55). A reconnaissance section measured along the Gui-Huang Highway 1.5 km east of Pingba is the westernmost exposure of the Gaicha. Published sections are from Sanqiao (the type section near Gui-Huang) and Hauxi (Guizhou Bureau, p. 295, 299). Thickness is remarkably consistent at ~100 m, but a southward thinning trend is suggested by measured thicknesses of 119 m at Lingjiawan; 108 m at Gui-Huang, 7 km to the south; and 87 m at Hauxi, 18 km farther south. A wedge of siliciclastics near the base of the formation accounts for this amount of thinning and more, even without decompaction. Shale and sandstone with appreciable breccia and minor carbonates form an interval 57 m thick at Lingjiawan and 31 m thick at Gui-Huang, but are represented only by one or several shale or sandstone intervals at Hauxi, none thicker than 60 cm. The breccias appear to represent dissolution of evaporites, so the initial thickness contrasts would have been somewhat greater. Siliciclastics are virtually absent in the westernmost Gaicha exposure at Pingba, which is 95 m thick. It is apparent that the carbonates thicken toward the platform margin concomitant with the thinning of the siliciclastics.

Most of the Gaicha carbonates are grain supported, but contain some muddy matrix of lime mud, dolomitic mud, clay, or silt. Peloids are the most common component, although some beds contain numerous fecal pellets, intraclasts, oncoids, coated bioclasts, or ooids. Recognizable bioclasts constitute ~5% of the carbonates. Bivalves predominate over gastropods, echinoderms, brachiopods, and green algae.

The marked meter-scale cyclicity of the underlying Yangliujing and Longtou Formations is subdued, but evident, in the Gaicha Formation. The lower Gaicha is marked by siliciclastic-carbonate couplets with prominent desiccation cracks at the top of the carbonate to indicate a shoaling-upward vector. Gray-green,

red, or purple shale or claystone with a few marine bivalves or plant fragments and thin siltstone or sandstone interbeds form several decimeters of a couplet, arbitrarily considered the base. Carbonates, mostly dolostone, marked by fenestral pores and planar lamination, aggregate to several meters thick. Vertical burrows and bioclasts are sparse. Clay-filled burrows, root casts, or desiccation cracks mark the tops of some carbonate intervals. Higher in the formation, siliciclastic intervals are reduced, and bioturbated peloidal carbonates, some with a considerable quartz-sand admixture, form cycle bases several meters thick. These carbonates, which contain gastropods and bivalves, are interpreted as shallow subtidal deposits. The upper parts of cycles contain lenses of intraclasts and oncolites, suggesting somewhat higher energy, within laminated, fenestral carbonates. Some of the laminations are domal stromatolites. Tepee structures are reported from a section near Hauxi (Wei Jiayong et al., 1996), and a probable microkarst surface was observed at Pingba. Thus shoaling and ultimately exposure terminate the cycles.

Breccias in the lower half of the Gaicha are not confined to the siliciclastic intervals; they also occur sporadically among dolostones in the lower 40% to 60% of the northern sections (GH and LJW, respectively, in Fig. 2). The breccias are sharp stones in an earthy matrix, indicating an origin from evaporite dissolution and collapse. Large, irregular vugs in a few of the overlying dolostones likely represent nodular evaporites. Evaporites apparently were common in platform-interior locations.

Sandstones in the Gaicha are locally cross-bedded, burrowed, or contain oscillation ripples.

The south-thinning wedge of siliciclastics in the lower Gaicha may be an extension of the Badong Formation, mapped farther to the east and north (Fig. 55). The age of the Badong is poorly constrained; it is thought to span the entire Middle Triassic (Guizhou Bureau, 1987), but may extend into the Late Triassic by virtue of its tentative correlation with the Zhuganpo and Gaicha Formations. In any case, the presence of this predominately siliciclastic unit along the margin of the Jiangnan Massif suggests a source for the Gaicha siliciclastics to the north and east, either directly from the Proterozoic metasedimentary rocks of the massif or recycled through erosion of the Badong Formation.

A unique interval within the Gaicha overlies a possible paleo-karst surface 4 m above the base at Pingba. The evidence for paleo-karst is an irregular surface with ~25 cm of relief that cuts a shelly limestone. The limestone contains many large, irregular vugs filled with mud similar to the overlying decimeter-thick shale. Nodular-bedded muddy limestone, 2.4 m thick, with appreciable pyrite overlies the shale. This suggests that somewhat deeper water followed subaerial exposure, apparently incipient drowning of the platform margin, before shallow-water carbonate deposition resumed.

Fossils from the Gaicha Formation (Guizhou Bureau, 1987, p. 295; Wei Jiayong et al., 1996; unpublished Dulaying section): Bivalves: *Astarte* sp., *Bakevella* cf. *yunnanensis*, *Leptochondria* cf. *subillyrica*, *Laxonema* sp., *Myophoriopsis*? sp., *Naticopsis* sp., *Ostrea* sp., *Pleuromya elongata*, *Trigonodus* sp., *Unionites spicatus*

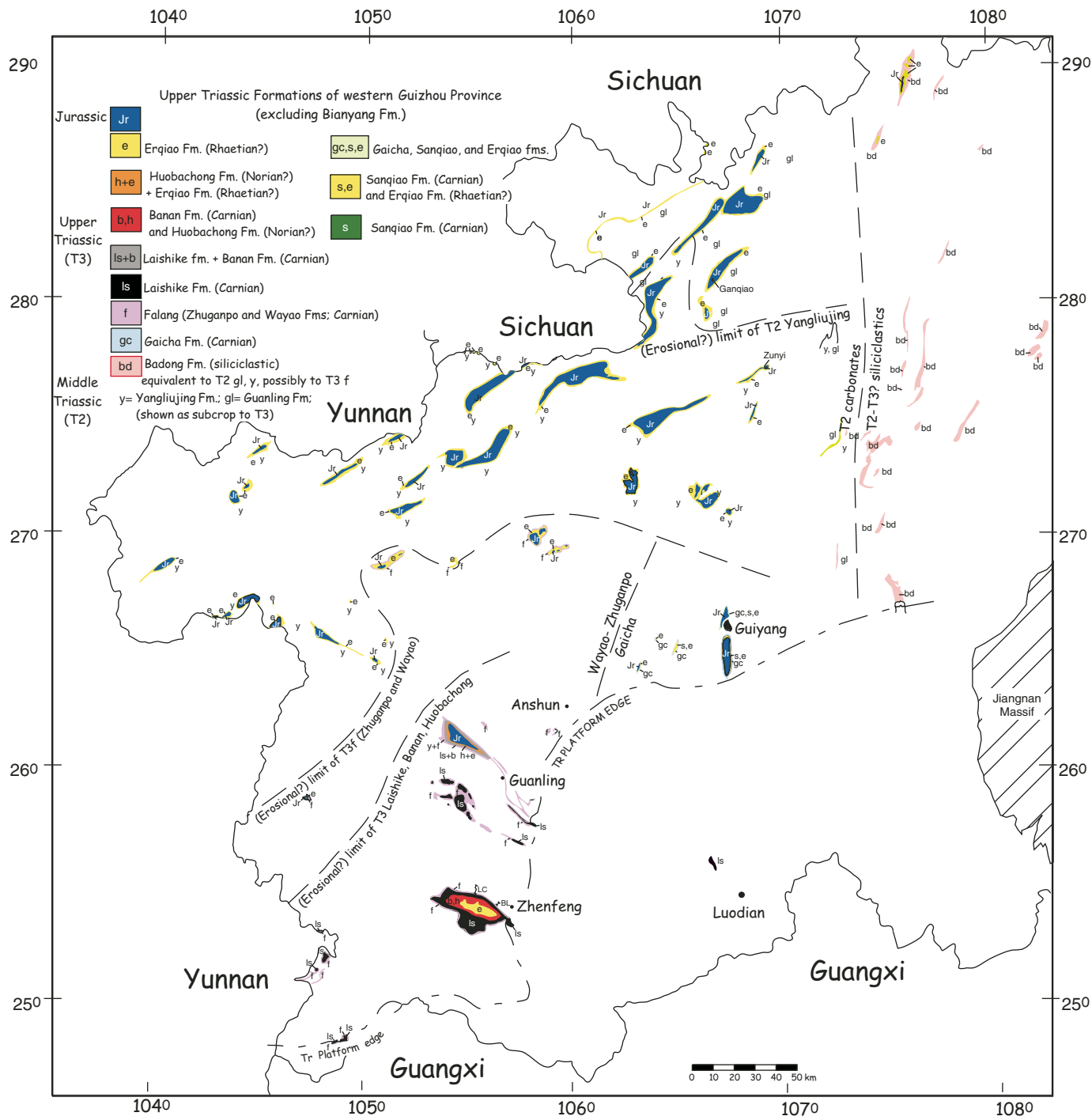


Figure 55. Distribution of Upper Triassic formations in Guizhou Province. Unlike earlier Triassic series, facies differentiation is primarily by vertical succession rather than lateral transitions. This reflects both the termination of the Yangtze Platform as the dominant paleogeographic element and the limited area of preservation of all formations except the Rhaetian? Erqiao Formation. The Badong Formation, mostly Middle Triassic but possibly extending into Late Triassic (Guizhou Bureau, 1987), defines the eastern limit of Upper Triassic deposition or preservation. Small Badong outcrops at 108°28'E 28°0'N and 108°38'E 28°35'N (continuing into Sichuan Province) are outside the map area. Distribution of formations underlying the Upper Triassic, indicated by lowercase letters, illustrates the northwestward bevel beneath the Erqiao Formation. Distribution of the overlying formation, everywhere Lower Jurassic, demonstrates the essential conformity between the uppermost Triassic and the basal Jurassic. Note the virtual absence of recognized Upper Triassic formations in the Nanpanjiang Basin area, southeast of the drowned Yangtze Platform. The Laishike outcrop north of Luodian is mostly within the drowned Great Bank of Guizhou.



Figure 56. Gaicha Formation from measured section at Huaxi. This section, near the southern limit of exposure, is dominated by dolostone, but thin beds of shale (SH) and sandstone distinguish the Gaicha from the underlying Longtou Formation.

Unidentified ammoid (Pingba)

Plants: *Equisetum* sp.

Although the Gaicha Formation represents only part of the Carnian, tentative magnetostratigraphic correlations with the Newark Basin (USA) chronology provide estimated accumulation rates of only 11 to 15 m/m.y. (Montgomery et al., 2003). This is based on a duration of 15 m.y. for the Carnian (Kent and Olsen, 2000). An early Carnian (Julian) duration of 4.0 m.y. from Haq et al. (1988) would increase these rates to 22 to 30 m/m.y. (Table 2), still very low for platform carbonates. Presumably the Gaicha contains hiatuses of considerable duration, in addition to the several desiccated surfaces and a possible paleokarst surface observed and the reported tepee interval. Compaction was probably too minor to affect sedimentation rates in the sandstones and the shallow-water carbonates, which are commonly grain supported and possibly cemented early. Considerable compaction of the mudrocks is assumed, but they are too minor to affect rates, except in the northern sections.

### Sanqiao Formation

The Sanqiao Formation continues the trend of increasing siliciclastics that began in the Gaicha; it comprises ~100 m of sandstone and mudrock with 25 to 30% limestone reported in some sections. The preserved Sanqiao is confined to the margin of the Yangtze Platform in the Guiyang sector (Fig. 55). It was probably stripped by pre-Rhaetian erosion to the north and differs in facies from Carnian units (described below) to the west and south. It was formerly mapped on the Great Bank of Guizhou and in the north-adjacent basin (Guizhou Bureau, 1987), but these outcrops are referred to the Laishike Formation in recent mapping (Yu Youyi, 2000, unpublished maps). A complete section was published from Sanqiao, the type locality northwest of Guiyang

(Guizhou Bureau, 1987, p. 301). Graphic sections from Dulaying and near Bojishan (Fig. 13D; Wei Jiayong et al., 1996) and reconnaissance observations at Huaxi and Lingjiawan provide additional information. The Sanqiao is 94 m thick at Sanqiao, ~100 m at Dulaying, and 40 m in an incomplete section at Bojishan. It overlies the Gaicha Formation paraconformably or disconformably. The top is beveled by an erosional disconformity beneath the Erqiao Formation.

At the Sanqiao section (Guizhou Bureau, 1987, p. 301), two siliciclastic members are interlayered with two limestone members. The basal member is predominately mudrock with thin sandstone beds in the basal 11 m and sandstone with subordinate mudrock in the upper 19 m. Limestone lenses at the top are transitional to the overlying limestone member. Marine bivalves are abundant throughout and include shallow-water forms such as *Pinna*. Crinoids and lingulid brachiopods are found in the upper, sandier unit. Plant fragments and unspecified trace fossils occur at the base. The mudrocks are yellowish-green or dark-gray, sandy, calcareous mudstone and shale. The sandstone is grayish yellow, micaceous, calcareous, and locally argillaceous. It forms thin interbeds in the lower unit and thick beds in the upper. The overlying limestone member, 17 m thick, is medium-to-thick-bedded skeletal limestone that becomes argillaceous toward the top. Brachiopods abound. The upper sandstone member is 36 m of yellowish quartzose to argillaceous sandstone with intercalations of sandy mudstone and shale. Bivalves are common. The top 11 m of the Sanqiao is limestone, varying from dark-gray, thin-bedded, cherty lime mudstone at the base to gray, oolitic and skeletal limestone at the top. Fossils include bivalves, brachiopods, and corals.

The Sanqiao succession a short distance to the north at Dulaying, although reported in little detail, is clearly rather different. The basal 20 m are thick-bedded sandstone that overlies shelly limestone at the top of the Gaicha Formation. The succeeding

43 m are interbedded mudrock and sandstone with the proportion of sandstone increasing upward. Five genera of marine bivalves are reported from the muddy portion and plant fragments from the upper sandstone. Thin-bedded, shelly limestone, 25 m thick with six genera of marine bivalves, overlies the sandstone. The top 12 m are interbedded sandstone and mudrock. The Dulaying section thus contains a single, thick limestone unit rather than two as at Sanqiao. Sandstone is less abundant than mudrock and more concentrated in the lower part of the formation. The fauna appears to be less varied and less abundant. No limestone was observed in incomplete sections of the lower Sanqiao at Bojishan, Huaxi, and Lingjiawan. Mudrock alternates with thin beds of sandstone for several tens of meters at the base. Carbonaceous fragments, vertical and horizontal burrows including *Cruziana*, and oscillation ripples with crests oriented east-west occur in this interval at Lingjiawan. Massive beds of sandstone form the upper parts of the outcrops at Huaxi and Lingjiawan (Fig. 57).

Fossils from the Sanqiao Formation (Guizhou Bureau, 1987, p. 301; Wei Jiayong et al., 1996, unpublished Dulaying section):

Corals: "*Thamnastraea*" sp.

Brachiopods: *Lingula* sp., *Rhaetionopsis* sp., *R. ovata*, *Sanquiaothyris* sp., *S. elliptica*

Bivalves: *Adygella* sp., *Bakevellia* sp., *Burmesia* cf. *drumbecki*, *B.* cf. *lirata*, *Cuspidaria* sp., *Entolium* sp., *E. tenuistriatum rotundum*, *Halobia* sp., *Leptochondria* sp., *Liostraea* sp., *L. zhenfengensis*, *Myophoriopsis* sp., *Naticopsis* sp., *Nuculana* cf. *perlonga*, *Pinna* aff. *lima*, *P. subcarinata*, *Plagiostoma* sp., *P. laevigata*, *P.* cf. *nuitoense*, *Palaeneilo* sp., *P. praecata*, *P. elliptica*, *Pleuronectites* sp., *Plicatula* cf. *tripartita*, *Pteria elegans*, *Quadratia* sp., *Rhaetina* sp., *Rhaetionopsis ovata*, *Unionites guizhouensis*

Crinoids: *Cyclocyclicus* sp.



Figure 57. Massive sandstone beds in lower part of Sanqiao Formation at top of Lingjiawan section.

The age of the Sanqiao is poorly known; it is presumed to be Carnian. Accumulation rates can be roughly estimated by assuming that it occupies the rest of the Carnian not represented by the underlying Gaicha Formation. Using the 15-m.y. duration for the Carnian of Kent and Olsen (2000) gives a rate of 13 m/m.y. The estimate for the Tuvalian of 4.0 m.y. by Haq et al. (1988) gives 23 m/m.y. (Table 2). These estimates ignore the reported disconformity at the base of the Sanqiao (Guizhou Bureau, 1987, p. 301) and probable truncation by an unconformity at the top as well as any effects of compaction. Accurate evaluation of any of these effects could significantly increase the accumulation rate. Given, in addition, the uncertainty about the duration of the Carnian, these rate estimates are very rough indeed.

### Zhuganpo Formation

The Zhuganpo Formation extends throughout the Zhenfeng sector, the western part of the Yangtze Platform, except in the north, where it was apparently stripped by erosion in the Late Triassic (Fig. 55). It disconformably overlies the Yangliujing or Longtuo Formation with an abrupt transition (Fig. 58; Minzoni, 2003a, 2003b, Enos et al., 1997, p. 65) and conformably underlies the Wayao Formation. Complete sections were measured at Beila, Huangpingzhai, and Yongningzhen (Wayao), the type locality. Only the top 3 m at Longchang and the basal 38 m at Hongyan were measured, because of poor exposure. Thirty-six samples and 15 thin sections were studied from these outcrops. The Zhuganpo interval was examined in passing at Langdai and Duanqiao. Complete sections of the Zhuganpo were published by Guizhou Bureau (1987, p. 292) from Longchang and by Yang Shouren et al. (1995, p. 165–167) from Longchang and Yaojiawan, Zhenfeng.

The Zhuganpo is fairly consistent in thickness and lithology. It is 55 m thick at Huangpingzhai, 62 m at Beila, 73 or 78.5 m at Longchang (Guizhou Bureau, 1987, p. 292; Yang Shouren et al., 1995, p. 165, respectively) and 130 m at Yaojiawan, Zhenfeng (Yang Shouren et al., 1995, p. 167). Farther north it is generally thicker: 107 m (Wei Jiayong et al., 1996) or 155 m thick (our measurement) at Yongningzhen, 120 m at Duanqiao, 22 km to the southeast, 88 m at Hongyan, ~10 km farther east, and 212 m at Langdai (Guizhou Team, unpublished). The characteristic lithology is medium-gray, nodular-bedded, muddy limestone with an average bedding thickness of ~25 cm. The limestones appear to have little clay content, except in the very incomplete, weathered section at Longchang. An exception to the lithic uniformity is a shelf-margin section at Yaojiawan, Zhenfeng, where Yang Shouren et al. (1995, p. 167) reported light- to medium-gray, medium- to thick-bedded, bioclastic and oolitic limestone. The other measured sections were generally molluscan wackestones, floatstones, or mudstones (e.g., 99% of Langdai section). In thin sections, however, the ultra-thin-shelled bivalves are not uncommonly seen to be in contact to form a packstone, although the muddy matrix constitutes as much as 60 to 75% of the volume because of loose packing. Thin-shelled bivalves such as *Halobia* are the domi-



Figure 58. Contact of Zhuganpo Formation (ZGP) on Longtou Formation (LT), Hongyan section (2569 m). The Zhuganpo is darker with thinner and slightly wavy bedding. The uppermost bed of the Longtou is capped by peritidal laminites. The contact is disconformable as shown by syndimentary faulting and erosion of the uppermost Longtou in nearby exposures (Minzoni, 2003a, 2003b).

nant skeletal component. Other megafossils, in order of decreasing abundance, are ammonoids, crinoids, gastropods, brachiopod fragments, fish bones, and the diminutive aquatic reptile *Kweichousaurus*. Gastropods decrease in abundance upward; ammonoids and crinoids, including long, articulated stems, increase markedly. Microfossils include conodonts, many calcispheres, a few ostracodes, foraminifers, and problematic calcareous tubes. Isolated occurrences are sponges, sponge spicules, possible stromatoporoid and bryozoan debris, and *Tubiphytes* fragments in the lower part of Huangpingzhai section.

Pellets are a significant component in the basal 10 m of the Zhuganpo Formation. Intraclasts, a few millimeters to centimeters in size, increase in abundance upward and are the dominant non-skeletal component in the upper part (Fig. 59). These intraclasts result from light cementation in situ, establishing incipient hardgrounds. Most clasts are indistinct with vague boundaries, even in thin section (Figs. 60, 61). A somewhat darker, denser aspect of the intraclasts, both in outcrop and thin section (Figs. 59, 60, 61), is emphasized by differential compaction to delineate them from the surrounding, slightly argillaceous, mud. Truncated grains, borings, fractures, and encrustation, features indicative of reworked lithoclasts, are present but quite rare. A few intraclasts contrast with the surrounding matrix, either by greater concentration of fossils or contrasts in fossil type. This indicates either some transportation or cement nucleation around inhomogeneities, or both. Cement most commonly nucleated in matrix adjacent to bivalve shells. A few intraclasts apparently nucleated in and around small, lined burrows (Fig. 61) or ammonoids. The intraclasts are on a much smaller scale than the nodular bedding, but differential cementation may have been a factor in the

bedding configuration as well, as has been suggested in other examples (Wanless, 1979; Ricken, 1986; McNeice, 1987). Pyrite constitutes an estimated 2% of the volume of some samples in the form of disseminated microcrystals, framboidal clusters, and rare millimeter-scale crystals. Chert nodules are reported from the Longchang section (Guizhou Bureau, 1987, p. 291; Yang Shouren et al., 1995, p. 166), but silicification in our samples was confined to very local replacement of bivalve shells by microcrystalline quartz and a fragment of silicified wood.

Fossils from the Zhuganpo Formation (Guizhou Bureau, 1987, p. 292; Wei Jiayong et al., 1996; modified from Yang Shouren et al., 1995):

Brachiopods: *Koninckina* sp., *Neoretzia* sp., *Mentzelia* sp.

Bivalves: *Halobia* cf. *subcomata*, *Leptochondria* sp.

Ammonoids: *Protrachyceras* sp., *P. deprati*, *P. dowillei*

Crinoids: *Traumatocrinus* *hsüi*

Conodonts: *Cypridodella conflexa*, *C. medioceras*, *C. spengleri*, *C. subsymmetrical*, *C. venusta*, *Didymodella alternata*, *Enantiognathus ziegleri*, *Gladiogondolella* cf. *tethydis*, *G. sp.*, *Gondolella jiangyouensis*, *G. navicula*, *Hibbardella triassica*, *H. cf. lautizima*, *H. sp.*, *Hindeodella* sp., *Lonchodina muelleri*, *Metapolygnathus polygnathiformis*, *Neogondolella maantangensis*, *N. navicula navicula*, *N. tadpole*, *N. sp. indet.*, *Ozarkadina tortilis*, *Paragondolella foliata foliata*, *Pg. foliata inclinata*, *Prioniodella ctenoides*, *P. decrescens*, *Prioniodina petraeviridis*, *P.(Flabelignathus) latidentata*, *P.(Flabelignathus) sp.*, *Roundya* sp., *Xaniognathus elongatus*.

Vertebrates: *Kweichousaurus hui* Young (a long-necked aquatic reptile, only a few centimeters in length).

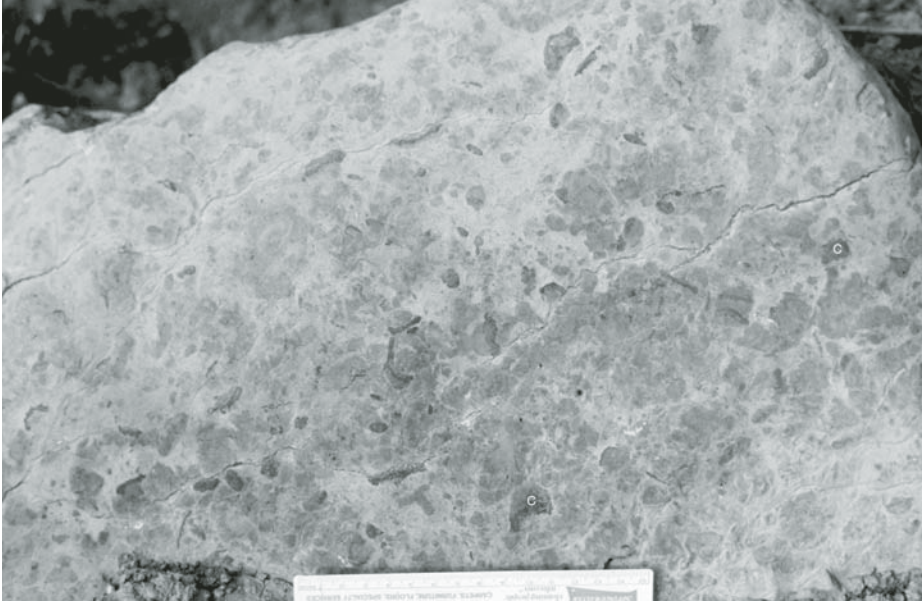


Figure 59. Bedding surface near top of Zhuganpo, Huangpingzhai section (PZ in Fig. 2). Darker domains are intraclasts and a few burrows with incipient cementation. Some of the darkest clasts (c), apparently the best cemented, have sharp corners, encrustations, and bored margins. Scale is 15 cm. Modified from Enos et al. (1998, p. 63).

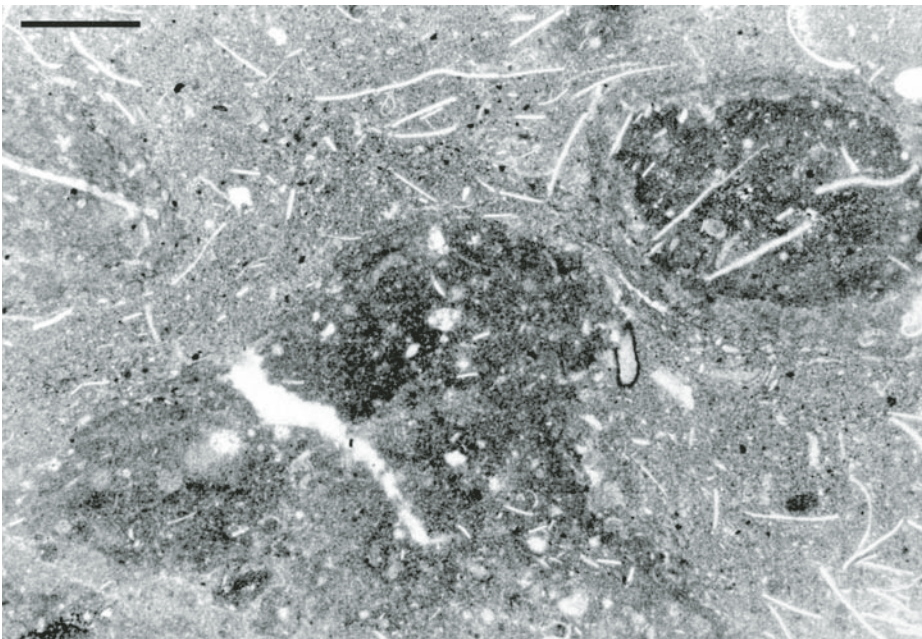


Figure 60. Photomicrograph of wackestone from the Zhuganpo Formation, Beila section. The darker, denser areas are lightly cemented intraclasts, probably cemented in situ in this case. Note the spar-filled fracture that terminates at the clast margin at lower left. This indicates the relative rigidity of the clasts. The subtle alignment of shell fragments around the cemented nodes is interpreted as a result of compaction following early cementation. Scale bar is 0.5 mm.

Yang Shouren considers this conodont assemblage to represent the early Carnian Cordevolian and Julian stages (Yang Shouren, 1995; Yang Shouren et al., 1995). However, ammonoid specialist Hugo Bucher states, “From the Zhuganpo, I have a clear Ladinian association containing the diagnostic [ammonoid] genus *Anolcites*. This was found a few meters below the *Kweichousaurus* main horizon” (letter 27 January 2003). This contradiction reflects an ongoing controversy between conodont and ammonoid specialists; the “ammonoid Ladinian-Carnian boundary” is significantly higher stratigraphically.

The biostratigraphic assignment of the Zhuganpo to the Cordevolian and Julian (early and middle Carnian; Yang Shouren, 1995) and tentative magnetostratigraphic correlations with the Newark basin (Montgomery et al., 2003) allow calculation of approximate sedimentation rates for the Zhuganpo of 6 to 18 m/m.y. (Table 2). These are the slowest of all Triassic formations. The somewhat less generous estimates of Haq et al. (1988) for duration of the Julian gives rates of 14 to 39 m/m.y. (Table 2). Decompaction would increase the rates appreciably, perhaps severalfold, in these muddy limestones that were only patchily cemented before burial.

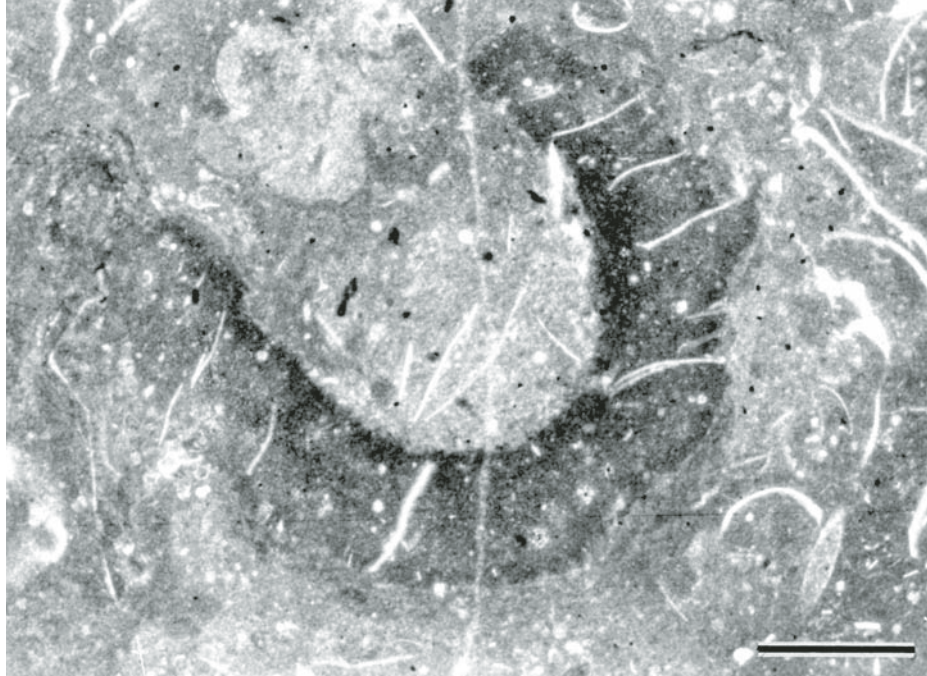


Figure 61. Intraclast formed by incipient cementation within and around a burrow lining. The incomplete burrow and the apparent truncation of shell fragments (right margin) suggest that the clast has been displaced after cementation. Top of Zhuganpo Formation, Beila section. Photomicrograph; plane light. Scale bar is 1 mm. Modified from Enos et al. (1998, p. 64).

### Wayao Formation

The Wayao Formation is confined to the Zhenfeng sector of the Yangtze Platform in Guizhou (Fig. 55), where it overlies the Zhuganpo Formation and underlies the Laishike Formation with apparently conformable contacts (Fig. 62). The onset of deposition of black shale, typically interbedded with nodular, gray limestones over several meters, marks the base of the Wayao (Enos et al., 1998, p. 66). The top is not well defined in some areas, as demonstrated by a relocation of the contact 75 m higher in the Longchang section between 1980 (Guizhou Team, 1980, p. 171) and 1987 (Guizhou Bureau, 1987, p. 291) and then 90 m lower in 1995 (Yang Shouren et al., 1995, p. 164). The very dark shales of the Wayao gradually become lighter in shading and more silty upward. Thick sandstone beds that characterize the Laishike first appear 178 m above the base of the Wayao Formation in this section (Guizhou Team, 1980, p. 171). In contrast, sandstone beds were used to define the base of the Laishike overlying thin Wayao intervals at the nearby Beila and Huangpingzhai sections.

The Wayao was measured at Beila, Huangpingzhai (Wei, unpublished section, 1995), and at Longchang (basal 25 m) and examined at Duanqiao, Langdai, Xiaowa, and Yongningzhen, the type locality (Fig. 2). Nine samples and two thin sections were studied. Available section descriptions of the Wayao include Longchang (Guizhou Bureau, 1987, p. 292; Yang Shouren et al., 1995, p. 164); Ganlongdong, Zhenfeng (Yang Shouren et al., 1995, p. 166; very near Beila); Langdai (Guizhou Team, unpub-

lished); and incomplete sections at Yongningzhen (Yang Shouren et al., 1995, p. 163) and Duanqiao (Yang Shouren et al., 1995, p. 164). The Wayao is 48.5 m or 138 m thick at Longchang (Yang Shouren et al., 1995, p. 164; Guizhou Bureau, 1987, p. 291, respectively), 30.4 m at Beila, 26.4 m at Huangpingzhai, 22.3 m at Ganlongdong, Zhenfeng (Yang Shouren et al., 1995, p. 166), greater than 70 m at Yongningzhen (Wei Jiayong et al., 1996), 207 m at Langdai (Guizhou Team, unpublished), and missing at Yaojiawan, Zhenfeng, a platform-edge section (Yang Shouren et al., 1995, p. 167). An anomalous limestone and marl section over 93 m thick at Duanqiao was described as Wayao by Yang Shouren et al. (1995, p. 164).

Typical Wayao lithology is dark-gray to black, fissile, calcareous shale, especially prominent near the base. At Xiaowa and Wayao black, laminated lime mudstone predominates at the base. Gray shale and silty shale are more common upward in the formation. Muddy, dark-gray, nodular to laminated limestone with planktonic biota, similar to the Zhuganpo, forms beds up to ~20 cm thick. These occur mostly in the lower Wayao and tend to become thinner and fewer upward. Limestone is limited to the basal 8.5 m at Huangpingzhai, but extends sporadically through 70 m of section without an exposed top at Yongningzhen (Wei Jiayong et al., 1996). Limestone is confined to two lenses of laminated argillaceous lime mudstone, each ~30 cm thick, in the condensed 30-m section at Beila. In contrast the entire section at Langdai is limestone or argillaceous limestone (10%), except for the uppermost 30 m, which is mudrock and



Figure 62. Contact of Zhuganpo and Wayao Formations in the Yongningzhen section, near Wayao. This is the type locality for both formations. The contact, at the feet of the geologist (W.J.Y.), appears conformable, best seen to the right. The apparent truncation of Zhuganpo beds at lower left results from the perspective. The Wayao Formation (above) is darker, thinner bedded, and shalier. In the Beila and Longchang sections farther south, shale is more dominant; limestone is confined to a few nodular beds or isolated nodules. Staff is 2 m long.

sandstone better referred to the Laishike Formation. Moreover, the upper third of the limestone interval includes numerous light-gray, fine-grained, meter-scale beds of pellet packstone and a few of ooid grainstone.

Thin-shelled pectinacean bivalves, mainly *Halobia* and *Daonella*, are abundant throughout the Wayao (Fig. 63). Many of the bivalves are less than 2 mm across and have only a few growth lines, indicating juvenile forms. Ammonoids are abundant at the base of the Wayao (Fig. 64), but few toward the top. The ammonoids are as large as 20 cm in diameter, although the modal size is ~5 cm. The limestones also contain brachiopods and patchy concentrations of crinoid columnals. Microfossils are abundant conodonts (Yang Shouren et al., 1995), few foraminifers, calcispheres, sponge spicules, and rare worm tubes. “Algal lumps” of unspecified character are reported from the basal Wayao (Yang Shouren et al., 1995, p. 164, 166), but none were observed in this study.

A fossil lagerstätte bearing the “Guanling fauna” of Yin Gongzheng et al. (2000, p. 23) occurs 7 to 10 m above the base of the Wayao Formation in outcrops and dedicated quarries at Xiaowa (Fig. 2), west of the type Wayao near Yongningzhen (Fig. 65; Yu Youyi et al., 2000, 2001; Yin Gongzheng et al., 2000). Spectacular clusters of crinoids and complete skeletons of aquatic reptiles are the highlights (Figs. 66, 67). Ammonoids are also common and well preserved, although the assemblage is essentially monospecific (Fig. 64; Hugo Bucher; letter 27 January 03). The crinoids apparently joined the nektonic ammonoids

and reptiles by attaching to floating logs; holdfasts are preserved on fossilized wood fragments. These fossils are receiving worldwide recognition through recent publications, but also through commercial sales, now on the black market as commercial exploitation and exportation of these exquisite fossils have been banned by the People’s Republic of China.

Black, nodular chert and microquartz replacement of bivalves are rare in the Wayao. Pyrite is common in the limestone as bands and as clusters of crystals that may reflect burrows. The black shale weathers rapidly to reddish brown or yellow brown through oxidation of the pyrite. The sooty appearance of the fresh limestone and a pungent hydrocarbon smell from the shale and limestone indicate a high content and maturity of organic carbon. The weathered limestones are draped with dendrites or stained black with pyrolusite, reflecting a high manganese content.

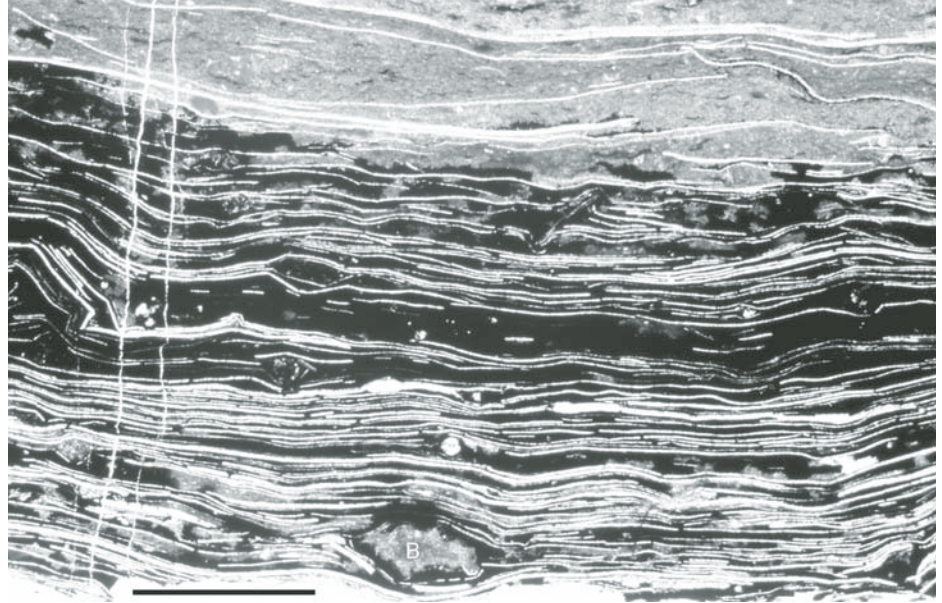
Fossils from the Wayao Formation (Guizhou Bureau, 1987, p. 291; Liu Yuzhou, 1991, p. 356; crinoids are from Yu Youyi et al., 2000; conodonts modified from Yang Shouren et al., 1995; vertebrates from Yin Gongzheng et al., 2000):

Brachiopods: *Rhaetinopsis ovata*

Bivalves: *Daonella bulongensis bifurcata*, *D. acutiforminata*, *D. bifurcata*, *Halobia brachyotis*, *H. comatoides*, *H. kui*, *H. cf. planicosta*, *H. rugosoides*, *H. subeomata*, *H. subplanicosta*, *Posidonia* sp.

Ammonoids: *Analcites* sp., *Carnites?* sp., Carnitidae cf. *Pseudocarnites* sp., *Cyrtoleurites socius*, *C. bicrenatum*, *Joannites* sp., *Protrachyceras* sp., *P. costulatum*, *P.*

Figure 63. Halobiid bivalves from the Wayao Formation, Longchang section. The dense packing of the thin shells reflects slow sedimentation rates of the lime-mud matrix. The marked horizontal orientation results partly from compaction. Draping of layering around the burrow at the base (B) and fracturing of the bivalves at left margin center also evince compaction. Manganese oxides produce the dark stain of the matrix in layers across the middle. Photomicrograph; plane light. Scale bar is 1 mm.



*deprati*, *P. yongningensis*, *P. douvillei*, *Trachyceras* sp., *T. multituberculatum*

Crinoids: *Traumatocrinus hsüi* Mu, *T. hsüi enormis* Mu, *T. guanlingensis* Yu et al., *T. cf. candax*

Conodonts: *Enantiognathus ziegleri*, *Gondolella* sp., *G. navicula*, *Hindeodella nevadensis*, *Metapolygnathus polygnathiformis*, *Neogondolella navicula navicula*, *N. sp. indet.*, *N. aff. tadpole*, *Ozarkadina tortilis*, *Paragondella foliata foliata*, *Pg. foliata inclinata*, *Prioniodella ctenoides*, *P. decrescens*, *P. "prioniodelloides,"* *P. sp. indet.*

Vertebrates, Class Reptilia: Order Sauropterygia: *Sinasaurus hoangi*, *Wayaosaurus geei*, *W. bellus*. Order Placodontia: *Placochelys? minutus*, Order Ichthyosauria: *Guanlingsaurus liangae*, *Guizhouichthyosaurus tangae*, *Mixosaurus guanlingensis*, *Qianichthyosaurus zhoui* Li, *Typicusichthyosaurus tsaihuae*, *Xinpusaurus suni*. Six of the nine genera and nine of the ten species identified are newly coined (Yin Gongzheng et al., 2000), suggesting a high degree of endemism.

According to Yang Shouren, the conodont assemblage is late Carnian (early Tuvlian, Yang Shouren et al., 1995; Yang Shouren, 1995). The ammonoid *Trachyceras multituberculatum* is considered a general Carnian marker (Guizhou Bureau, 1987, p. 316). In contrast, Hugo Bucher observed, "The reptile-bearing beds [the lagerstätte] are bounded at the top by a nodule horizon yielding a typically early Carnian trachyceratid (aon group)" (letter 27 January 2003). Given the age uncertainty and the likelihood that the Wayao does not represent an entire stage, it is not feasible to estimate accumulation rates. If the lowermost Wayao is a condensed interval as concluded by Enos et al. (1998, p. 67), very low accumulation rates would be expected for this interval. If the Wayao does not occupy an entire stage, the formation-averaged accumulation rate would be significantly higher than

for underlying Zhuganpo, which may represent two stages (Yang Shouren et al., 1995). This differential would be increased even more by decompaction of the shale-dominated Wayao. Thickness contrasts between the "typical" sections dominated by black shale (mean 32 m) and limestone-dominated sections (up to 207 m) would result in highly variable accumulation rates, albeit damped by the greater compaction expected in shale intervals.

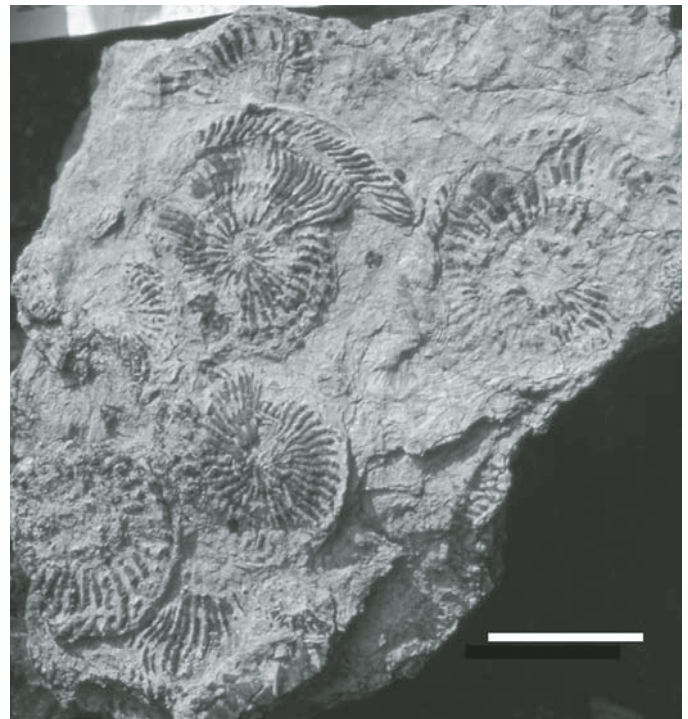


Figure 64. Ammonoids from mudrock interbed of Wayao Formation at Xiaowa (cf. Fig. 65). Scale bar is 2 cm.



Figure 65. Quarry near base of Wayao Formation at Xiaowa, opened to extract fossils from the Wayao lagerstätte. Limestone is exceptionally dominant in this area. Height of quarry wall is ~3 m.

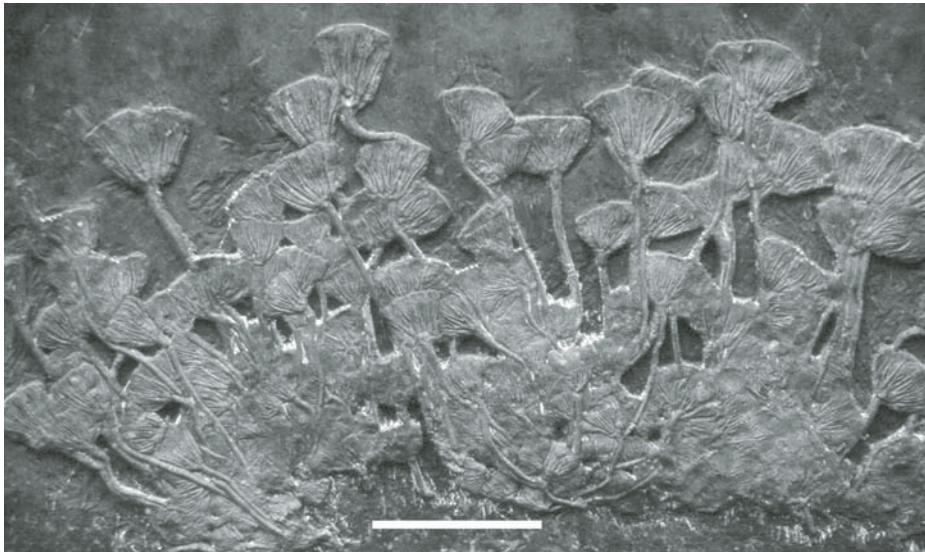


Figure 66. Crinoids from Wayao near Xiaowa. These specimens of *Traumatocrinus guanlingensis* (Yu Youyi et al., 2000) were probably attached to a floating log. Prepared sample was purchased by Yu Youyi from a local farmer. Scale bar is 10 cm.

### Laishike Formation

Outcrops of the Laishike Formation are confined to the southern Zhenfeng sector of the Yangtze Platform (Fig. 55). Three of these outcrop belts, in the axes of major synclines, are mapped for a few kilometers into the adjacent Nanpanjiang Basin, near Guanling, Zhenfeng, and the Great Bank of Guizhou. The Laishike may well be preserved in other parts of the basin, but it is lithologically indistinguishable from the underlying Bianyang Formation, so it may not have been recognized. It is quite possible that the present erosion level has cut into older formations everywhere else in the basin; the more distinctive upper-

most Triassic and Jurassic terrestrial formations are nowhere preserved within the basin. To the north the Laishike, along with the younger formations, was stripped by Late Triassic erosion prior to deposition of the Erqiao Formation, probably in the Rhaetian. Older formations, the Wayao and Zhuganpo, extend appreciably farther north to define a beveled margin of the Upper Triassic Formations (Fig. 55).

The only published measured section of the Laishike is from Longchang (Guizhou Team, 1980, p. 170–171; Guizhou Bureau, 1987, p. 291), large parts of which are now overgrown. Rather different lithofacies were described in a complete section at Duanqiao (Guizhou Team, unpublished; also partly overgrown)

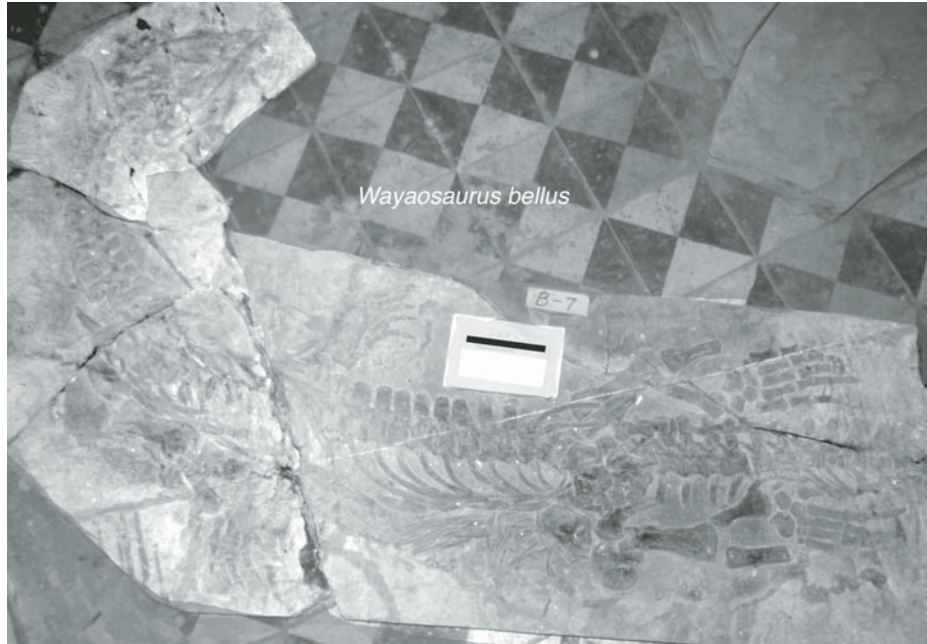


Figure 67. *Wayasaurus bellus* Zhou (Yin Gongzhen et al., 2000), one of nine genera and ten species of aquatic reptiles from the basal Wayao lagerstätte. Scale bar is 15 cm.

and at Langdai (Guizhou Team, unpublished; basal 96 m only). The basal 45 m of the Laishike was measured in good exposures at Beila. The lowermost Laishike is poorly exposed at the top of the Huangpingzhai section; higher portions crop out well in intermittent exposures along the nearby Zhenfeng-Anlong road (Fig. 68). Paleocurrent directions were measured along the Z-A road, at Longchang, and at Beila. As noted above, the contact between the underlying Wayao Formation and the Laishike is gradational and not precisely defined. The upper contact with the Banan Formation is also gradational and subject to varying interpretations. The thickness of the Laishike at Longchang may be 789 m (Guizhou Team, 1980, p. 170–171) or 732 m (Guizhou Bureau, 1987, p. 291). By matching the different top and base picks of the 1980 and 1987 interpretations, the thickness could be as great as 809 m or as little as 712 m. The Duanqiao section is 520 m thick.

The Laishike Formation is predominately gray, yellowish-weathering claystone and mudstone, bearing ammonoids and thin-shelled bivalves, with thin interbeds of siltstone (Guizhou Bureau, 1987, p. 291). The defining lithology of the Laishike, however, is thick beds of fine-grained, matrix-rich sandstone (Fig. 68). The sandstone beds form clusters several tens of meters thick that crop out as prominent ridges. Four such ridges are evident at Longchang; the uppermost is 135 m below the top of the formation. Many of the sandstone beds are amalgamated; maximum observed bed thickness was 3.3 m. The sandstones contain quartz of fine-sand size, small lithic fragments, white mica, and intraclasts of mudstone with soft-sediment folds. A few ammonoids, bivalves, and *Zoophycos* feeding traces are present. The

bases of sandstone beds are commonly sharp and the tops gradational to mudstone, but any graded beds are obscured by the fine grain size. Frondescant casts (scour marks; ten Haaf, 1959, p. 30; Potter and Pettijohn, 1963, p. 126) are abundant on the bases of some beds, particularly at Longchang (Fig. 69). Sparse sole marks, including flutes, grooves, and prod marks, were observed in all exposures. Small-scale current ripples are prominent on large exposures of bed tops above the Huangpingzhai section. Larger-scale cross-beds are lacking. Paleocurrents were generally toward the southwest, but with considerable variation:  $248^\circ$  from five flute-cast soles at Longchang,  $156^\circ$  from six flute casts and grooves above the Huangpingzhai section,  $242^\circ$  from seven current ripples slightly farther above Huangpingzhai, and a trend of  $80/260^\circ$  on five groove casts from Beila. The mean of these and several isolated measurements ( $n = 26$ ) is  $222^\circ \pm 52^\circ$ .

The composition of the Laishike Formation at Duanqiao, some 45 km to the north (Fig. 2), is quite different. The 520-m section is now poorly exposed, but the Guizhou Regional Geological Survey Team (unpublished) described the basal quarter as skeletal lime wackestone and mudstone, probably better referred to the Zhuganpo Formation (Enos et al., 1998). The overlying rocks are mostly silty calcareous shale with some silty lime mudstone. Thus, they are considerably more calcareous and lack sandstones or any other coarser-grained clastics. They might be deeply weathered Wayao mudrocks, at least in part. Carbonate is also prominent in exposures of the basal Laishike at Langdai, as cement in quartzose and lithic sandstones, but also as “limestone sands” (Guizhou Team, unpublished), probably calciturbidites.



Figure 68. Laishike Formation on Zhenfeng-Anlong road, south of Huangpingzhai section (PZ in Fig. 2). This is typical flysch lithology: mudrock alternating repeatedly with matrix-rich sandstone bearing abundant current sole marks.

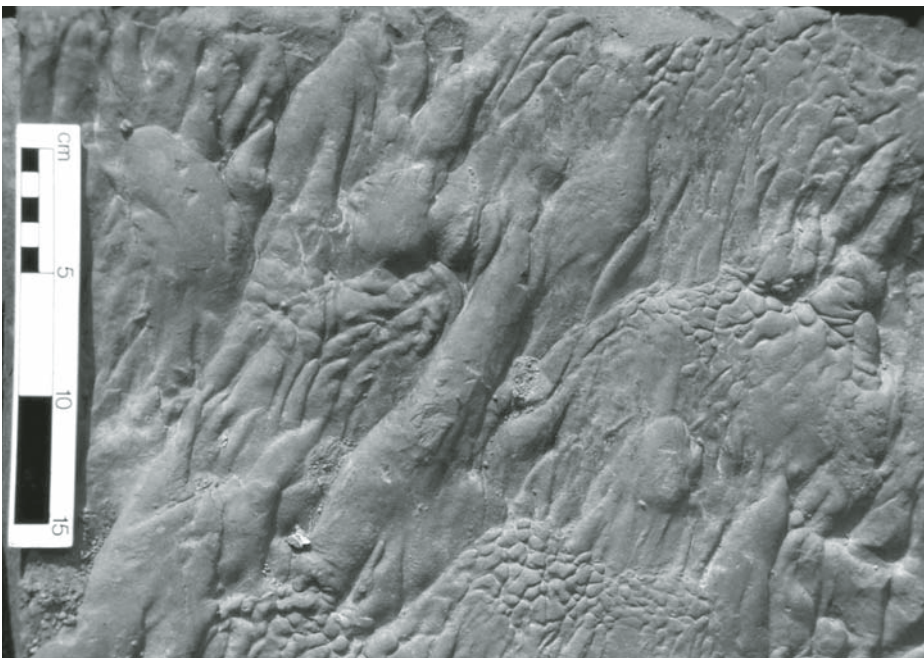


Figure 69. Sole marks, primarily flutes and frondescant casts, on the base of a sandstone bed, Laishike Formation. Float block, Longchang section.

Fossils from the Laishike Formation (Guizhou Bureau, 1987, p. 291; Yang Shouren et al., 1995):

Bivalves: *Chlamys* sp., *Halobia* aff. *miesenbachensis*, *H.* cf. *rugosa*, *H. rugosoides*, *Palaeoneilo elliptica*, *Palaeonucula* sp., *Posidonia* sp.

Ammonoids: *Cyrtopleurites* sp., *C. bicrenatus*, *Monophyllites?* sp., *Paratibetites clarkei*, *Protrachyceras* sp., *Sirenites* sp., *Trachyceras* sp., *T. multituberculatum*, *T. sinensis*, *Traskites?* sp.

Very approximate accumulation rates for the Laishike may be calculated by combining it with the overlying Banan Formation, also siliciclastic, and assuming that together they occupy the entire Tuvlian. Duration of the Tuvlian was estimated at ~6 m.y. by Kent and Olsen (2000) and 6.2 m.y. by Ogg (2004). An estimate of ~4 m.y. can be derived from Haq et al. (1988) by interpolation. The resulting estimates range from 205 to 320 m/m.y.,

somewhat less than the Bianyang, but among the highest in the Triassic. Using a more likely assumption—that the Wayao may have occupied as much as half of the Tuvlian—would double these rates, to as high as 640 m/m.y. Decompaction of the many shales, especially common in the Laishike, could increase these rapid rates severalfold.

### Banan Formation

The Banan Formation crops out only in the axes of two deep synclines in the Zhenfeng sector of the Yangtze Platform (Fig. 55). Only older formations are exposed to the south and southeast in Guizhou and northern Guangxi, on the former Yangtze Platform and the Nanpanjiang Basin. To the north the Banan was probably stripped by Late Triassic erosion, along with the immediately older and younger formations. Judging



Figure 70. Banan Formation at Duanqiao. The sandstone, siltstone, and mudstone interbeds are arranged in upward-coarsening and -thickening cycles (cf. Fig. 71). The tops of two cycles are marked (1 and 2). The ridges on the skyline at far right are the topographic expression of repeated cycles (cf. Fig. 72)

from stratigraphic position and general lithologic similarities, the Banan Formation is probably correlative with the Sanqiao Formation in the Guiyang sector of the Yangtze Platform.

A Banan measured section, 463 m thick, from Longchang in the southern syncline is published (Guizhou Team, 1980, p. 174–176; Guizhou Bureau, 1987, p. 290–291). We examined this section and exposures in the northern syncline at Duanqiao. The Banan differs significantly from the underlying, finer-grained Laishike and the overlying, coarser-grained Huobachong, but the contacts are gradational and somewhat arbitrary, as discussed with those respective formations.

The Banan Formation consists of mudstone, siltstone, and sandstone. The gray to greenish-gray sandstone is coarse grained and matrix poor relative to the sandstone of the underlying Laishike Formation. It is carbonate-cemented, medium- to fine-grained quartz arenite and lithic arenite with locally abundant feldspar, mica flakes, and dark grains, presumably heavy minerals. Some pebbly lenses are made up exclusively of mudstone intraclasts; others contain lithoclasts of limestone or crystalline rocks. Bivalve fragments, carbonaceous grains, and plant fragments occur sporadically. Sandstone beds are as thick as 1.7 m; thicker packages of amalgamated beds are common. In contrast, some intervals with rhythmic argillaceous breaks are distinctly flaggy. Sandstone-dominated intervals aggregate 3 to 20 m thick, with somewhat coarser grain size and thicker beds toward the tops (Figs. 70, 71). Mudrock interbeds are concomitantly less common upward in these coarsening-and-thickening-upward cycles. Repeated cycles form parallel topographic ridges that are readily identifiable as the Banan Formation (Fig. 72). At least 14 ridges are visible at Longchang, 11 at Duanqiao, and 16 near the Zhenfeng-Anlong road south of Huangpingzhai.

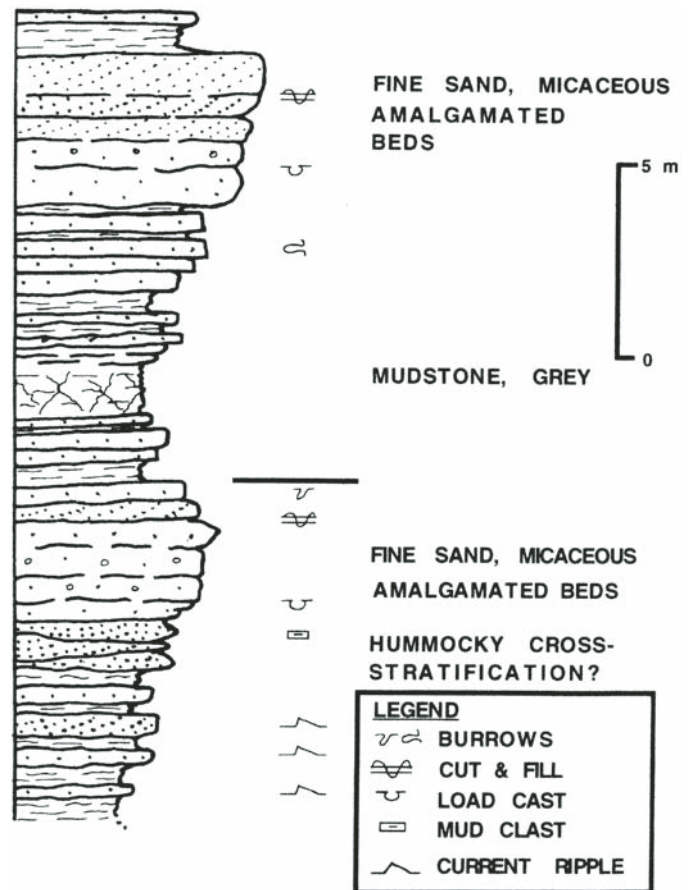


Figure 71. Two coarsening- and thickening-upward cycles within the Banan Formation in a road cut at Duanqiao (cf. Fig. 70). Lower cycle is incomplete; the base is covered. From field sketch and photographs. Scale is approximate. From Enos et al. (1998, p. 68).



Figure 72. Ridges formed by upward-coarsening and -thickening cycles within the Banan Formation near Duanqiao (cf. Fig. 70). Similar topography marks the Banan outcrop belt at Longchang (cf. Enos *et al.*, 1998, p. 69) and other localities.

Planar or sigmoidal cross-bed sets up to 50 cm thick with dips up to  $25^\circ$  are common (Fig. 73). Some sandstone and siltstone beds have ripple-drift cross-lamination throughout. Limited paleocurrent measurements on cross-beds ( $n = 6$ ) and ripple marks ( $n = 3$ ) from Longchang give a mean vector of  $210^\circ \pm 15^\circ$ . An even smaller set of measurements ( $n = 4$ ), from one of the same beds and from adjacent cycles, gives a mean of  $360^\circ \pm 46^\circ$ , suggesting current reversals during Banan deposition. Shallow cut-and-fill structures (reactivation surfaces) and large load casts are widely distributed. A combination of reactivation surfaces and gently inclined bedding with variable dips suggests hummocky cross-stratification in some

thinner-bedded intervals (Fig. 71). This raises the possibility that measured paleocurrent directions may reflect local currents more than regional provenance. Vertical burrows, U-shaped burrows, and extensive bioturbation are locally prominent in all lithologies.

Mudstone of the Banan is generally gray, gray-green, or yellow-green; it is dark gray at the top of the formation and in an interval near the middle (Guizhou Bureau, 1987, p. 290). Bed thickness ranges from partings to decimeters within the sandstone intervals and up to 30 m thick in mudrock intervals that include interlaminated siltstone. The mudrock is generally calcareous claystone, with carbonate content that increases toward the top



Figure 73. Cross-bedding in the Banan Formation, Longchang section. Sigmoidal surface that appears to be on the geologist's back is a cross-bedding plane. Cross-bedding is visible by the hammers at the right and in the underlying beds (marked by Xs). Top of a coarsening- and thickening-upward cycle.

of the formation. Weathered surfaces are blocky or spheroidal, except where bioturbation produces a rough surface texture. Siltstones are mostly ripple-laminated lenses or thin beds, exceptionally to 20 cm thick, within the mudrock. The bivalve fauna, more varied than in any other Triassic formation, is mostly small, thick-shelled forms (e.g., *Myophoria*, *Unionites*, *Bakevella*, *Mytilus*). Halobiid bivalves, ammonoids, and conodonts occur only in the basal beds (Guizhou Bureau, 1987, p. 291–292). A few plant remains are reported (Guizhou Bureau, 1987, p. 290–291). Several thin coal seams and associated gleyed claystone were observed within the Banan at Longchang. A thin coal seam at the top (Guizhou Team, 1980, p. 174) would more logically be included in the overlying Huobachong Formation, which contains considerable coal.

Fossils from the Banan Formation (Guizhou Bureau, 1987, p. 290):

Bivalves: *Artica* sp., *Bakevella* cf. *arguta*, *B.* cf. *modiolaeformis*, *B.* cf. *intermedia*, *Costatoria guizhouensis*, *Casianella* sp., *C.* cf. *beyrichii*, *Entolium* sp., *E.* cf. *subsecutum*, *E. tenuistriatum rotundum*; *Gervillia* (*Odontoperna*) *bouei*, *Halobia* sp., *Heminajas forulata*, *Hoernesia* sp., *H.* cf. *bifornicata*, *Homomya zhenfengensis*, *Liostraea zhenfengensis*, *Modiolus plana*, *Myophoria* (*Costatoria*) *kweichowensis*, *M.* (*Costatoria*) *kweichowensis* (subsp. nov.), *M.* (*Elegantinia*) sp., *M.* (*Elegantinia*) *venusta*, *Myophoria* (*Neoschizodus*) sp., *M.* (*Neoschizodus*) sp. (sp. nov.), *Myophoriopsis guizhouensis*, *M. nucaliformis*, *M.* (*Pseudocorbula*) sp., *Mytilus* sp., *Nuculana* cf. *alpina*, *Palaoneilo* sp., *Plagiostoma* sp., *P.* cf. *laevigata*, *Placunopsis* sp., *Schafhaeutlia* sp., *S. plana*, *Trigonodus keuperinus*, *Unionites* sp., *U. myophoriodes*, *U.* cf. *guizhouensis*, *U.* cf. *trapeziodelis*, *Waagenoperna* sp., *W. aviculaeformis*

Ammonoids: *Trachyceras* sp., cf. “*Trachyceras*” *sinensis*

Plants: *Equisetum sarrani*.

Estimates of accumulation rates for the Banan are feasible only by combining it with the Laishike, as outlined above. Rates range from 205 m/m.y. to as high as 640 m/m.y. without decompaction.

## Depositional Environments

The Gaicha Formation continues the pattern of deposition that was established on the Yangtze Platform during the Middle Triassic: high-energy, cyclic, shallow-marine carbonate sedimentation with episodes of subaerial exposure. A significant difference is influxes of siliciclastics, particularly in the lower Gaicha, which may have been cyclic as well. A marked southward thinning of at least the thickest wedge of siliciclastics suggests a southerly component to transport. North-south alignment of the Gaicha outcrops (Fig. 55) precludes identification of other vector components, except that siliciclastics are minimal in the westernmost exposure. Areal distribution of siliciclastics (Figs. 40, 55) and paleogeographic maps (Wang Hongzhen, 1985; Liu Baojun

and Xu Xiaosong, 1994) suggest that the source was the Jiangnan Massif, exposed to the east and north. The influx of siliciclastics increased, after an apparent lull in the upper Gaicha, to constitute about three-quarters of the overlying Sanqiao Formation. Sandstone is a minor component of the Gaicha but makes up over half of the Sanqiao in the type section. A locally abundant and fairly diverse fauna indicates shallow-marine deposition for both the carbonates and siliciclastics of the Sanqiao Formation. No signs of subaerial exposure were reported. No Norian deposition is recorded in the Guiyang sector of the Yangtze Platform; the Sanqiao is overlain by the Rhaetian(?) Erqiao Formation. Both the Gaicha and Sanqiao are lacking north of Lingjiawan (7 km north of Guiyang), probably because of pre-Erqiao erosion (Fig. 55). This apparent uplift to the north is consistent with a postulated southerly component of siliciclastic transport in the early Carnian formations. The beveling, however, truncates Norian strata and has a northwesterly vector (Fig. 55). Thus, it must postdate the early Carnian, when siliciclastics were apparently derived from the east and north.

In the Guiyang sector the demise of the Yangtze carbonate platform was played out in shallow water with an influx of siliciclastics and subsequent erosion. In stark contrast, the more complete sequence in the Zhenfeng sector records the death of the platform by drowning, followed by burial under siliciclastic debris that eventually accreted to sea level and above (Enos et al., 1998). This sequence was also beveled toward the northwest by erosion prior to deposition of the Rhaetian(?) Erqiao Formation (Fig. 55).

The initial Carnian unit in the Zhenfeng sector, the Zhuganpo Formation, is interpreted as a fairly deep-water deposit, based on the dominance of planktonic and nektonic biota and the fine grain size, dark-gray shades, and nodular bedding of the limestone. The common conodont *Metapolygnathus polygnathiformis* (formerly *Neogondolella polygnathiformis*; Yang Shouren et al., 1995) is not found in shallow-marine deposits, so it is considered to represent basinal biofacies (Kozur, 1976). The sparse brachiopod and bivalve fauna indicates normal bottom water at depths below the photic zone, but above the aragonite compensation depth, as the bivalves and ammonoids are reasonably well preserved. The general lack of reworking suggests depths below storm wave base. The scarcity of burrows and benthos, as well as the darker shades of the Zhuganpo limestones, indicates dysaerobic conditions at or very near the sediment surface (cf. Byers, 1977). Intraclasts were largely cemented in situ near the sediment surface, as indicated by sparse borings and encrustations. This indicates slow sedimentation to allow for cementation of the low-permeability muds before burial.

The transition from the Yangliujing Formation to the Zhuganpo Formation is of particular interest because this change to deep-water sedimentation represents the termination of shallow-water carbonate deposition on the Yangtze Platform for all time. The transition is well exposed in the Huangpingzhai, Beila, and Hongyan sections and less so at Duanqiao and Longchang. At Huangpingzhai the contact is abrupt; thin, nodu-

lar bedding and darker shades appear at a bedding contact that also marks a sharp reduction in the number of gastropods, thick-shelled bivalves, reworked intraclasts and coated grains, and an increase in mud, incipient intraclasts, thin-shelled bivalves, and crinoids. The uppermost supratidal cap is only 4.5 m below this contact. In the Beila section, the change from thick-bedded, very light-gray limestone to thin-bedded, medium-gray limestone is equally abrupt. In detail, however, the change to markedly mud-dier limestone is 1 m higher, and the onset of nodular bedding, as distinct from thin, planar and, finally, wavy bedding, is 4 m higher. The uppermost shoaling-upward cycle with a supratidal cap is 25 m below the contact, although a 40-cm interval of whitish, laminated dolomudstone with reworked intraclasts occurs 3.2 m above the contact. The contact is also very sharp at Hongyan where thin, wavy beds of medium-gray lime mudstone immediately overlie laminated dolomudstone with fenestrae and desiccation cracks. Lateral tracing of this contact, however, reveals several small faults that cut the top of the Yangliujing and were leveled by erosion prior to Zhuganpo deposition (Minzoni, 2003a, 2003b).

The black-shale interval of the Wayao marks the total cessation of carbonate deposition on the Yangtze Platform in southern Guizhou. This interval is highly condensed, judging from the concentrations of planktonic and nektonic fossils, of manganese and iron, and of organic carbon in an environment that had little or no bottom life. The shale probably accumulated below the photic zone and certainly in an anoxic environment, as indicated by the concentration of organic matter, fine lamination, and absence of bioturbation. It was, however, above the aragonite compensation depth, as the ammonoids and bivalves are exquisitely preserved and are still carbonate within centimeters of highly weathered outcrop surfaces. The general paucity of limestone deposition resulted from a cessation of the influx of carbonate mud exported from the moribund Yangtze Platform, rather than from sea-floor dissolution. The "algal lumps" reported from the basal Wayao (Yang Shouren et al., 1995, p. 164, 166) may be limestone lenses observed at Beila. We are skeptical concerning the presence of algae in the inferred depositional setting of the Wayao, except for the calcispheres, probably secreted by algal plankton.

Subsequent deposits in southern Guizhou are entirely siliciclastic except for a few limestone beds in the northern Laishike exposures at Duanqiao and Langdai. The Laishike sandstones are interpreted as turbidity-current deposits, based on a diagnostic suite of sedimentary structures, especially sole marks; muddy textures; and a hint of graded bedding. The siltstones are probably more distal turbidity-current deposits. The claystone and mudstone represent the background hemipelagic sedimentation, as indicated by the fine grain size and the assemblage of planktonic and nektonic fossils. The Laishike Formation can be readily characterized as flysch (cf. Tercier, 1947; Sujkowski, 1957; Enos, 1969), although it is rather thin at 800 m or less.

The anomalous finer-grained and carbonate-rich rocks at Duanqiao assigned to the Laishike (Guizhou Team, 1980) are interpreted as slope deposits isolated from turbidity-current

input (Enos et al., 1998). The Laishike turbidity currents, which generally flowed from this northeasterly direction, apparently bypassed the slope and deposited on the basin floor or had a local point source between Longchang and Duanqiao, such as a submarine canyon incised into the drowned platform. The sandy carbonates at Langdai were not studied. They possibly include calciturbidites derived from the longer lived northern part of the Yangtze Platform in the Guiyang sector or Sichuan.

The siliciclastics of the overlying Banan Formation are interpreted as deposits of a storm- and current-swept, shallow-marine shelf. The thick-walled benthic fauna; thick-bedded, well-washed, cross-bedded sandstone; vertical burrows; and possible hummocky cross-stratification indicate high energy. Ripples, particularly those in thin siltstones, could form in a variety of settings from terrestrial to abyssal. However, entirely rippled cosets with probable reversals in paleocurrent direction reflect tide- or wind-driven currents. The dominant transport direction may have been toward the south-southwest, but north-directed paleocurrents are also recorded. The coarsening- and thickening-upward sandstone packages suggest deltaic or coastal sequences. These sand bodies are laterally continuous in outcrop (Fig. 72), but their geometry has not been mapped in detail. Interlayered muds presumably accumulated in deeper or more sheltered portions of the shelf; they were the substrate for most of the molluscan fauna.

Accumulation rates in the Carnian, although not well constrained in some cases, fluctuated widely. They include the slowest calculated rates for the entire Triassic in the Zhuganpo Formation and the fastest in the combined Laishike and Banan Formations. In this regard, too, the Carnian was a time of change.

## NORIAN (MIDDLE UPPER TRIASSIC) FORMATION

### Huobachong Formation

The Huobachong Formation is preserved only in the two synclines in the Zhenfeng sector of the Yangtze Platform, co-extensive with the underlying Banan Formation (Fig. 55). The Huobachong is 687 m thick in the Longchang section (Guizhou Team, 1980, p. 180–182; Guizhou Bureau, 1987, p. 289–290) and ~300 m at Langdai (Wei Jiayong et al., 1996). It is appreciably coarser grained than the underlying Banan Formation, but the contact is rather arbitrary. The uppermost Banan is a unit 54 m thick of "marl ... thick-bedded ... quartz sandstone, calcareous claystone with thin coal seam at top." (Guizhou Team, 1980, p. 174). The basal Huobachong, above a conformable contact, is 84 m of "calcareous claystone; thick- to very thick-bedded lithoclastic sandstone; grayish-black carbonaceous shale with thin coal seam" (Guizhou Team, 1980, p. 182). A more workable definition of the contact would seem to be at the *base* of lowermost coal, thus placing all of the coal in the Huobachong, which contains numerous other coals. The overlying Erqiao is much coarser grained and thicker bedded (Fig. 74), but has many lithologies comparable to those of the Huobachong and appears



Figure 74. Aspect of Huobachong (HBC) and Erqiao Formations (EQ) at Longtoushan (Dragon-head Mountain), Longchang section. The contact, at the foot of the cliffs in the upper third of the picture, is described as conformable (Guizhou Bureau, 1987, p. 289). The Huobachong is completely missing north of Langdai, however, and successively older formations are beveled beneath the Erqiao to the northwest (Fig. 55), so the contact is regionally disconformable. Coal is extensively mined from the Huobachong at the foot of the mountain; note smoke at the right.

conformable at Longchang, so the contact can also difficult to define. Units both above and below the contact identified by the Guizhou Team (1980; Guizhou Bureau, 1987) are lithoclastic quartz sandstone and black or carbonaceous mudrock with coal seams ~30 cm thick. The lowermost Erqiao unit is 9 m thick and contains a single coal seam 35 cm thick. If this coal seam is taken instead as the top of the Huobachong, all of the coal at Longchang would be assigned to the Huobachong to make a more workable field distinction. This may, however, be too simplistic. Regionally the basal Erqiao contact is an unconformity that bevels the Huobachong and many underlying formations, although the plane of unconformity cannot be reliably recognized at Longchang. Beyond the recognized limits of preservation of the Huobachong, the overlying Erqiao contains carbonaceous shales in the basal 11 m (Guizhou Bureau, 1987, p. 281, near Guiyang, and at Panshui, Zunyi, p. 293) or two thin coal beds some tens of meters above the contact (Guizhou Bureau, 1987, p. 281, Gaoqiao, Zunyi). These carbonaceous units cannot, of course, be precisely correlated with any coal at Longchang, but they provide a rational basis for assigning the uppermost coal to the Erqiao. We prefer the equally rational assignment of all coals near the contact to the Huobachong. This would expand the thickness of the formation by only a few meters and would not include a demonstrable unconformity. If this definition were applied throughout Guizhou, it would extend the limits of the Huobachong Formation into Zunyi County, well beyond the presently mapped extent (Fig. 55).

Many of the coal seams in the Longtoushan area near Longchang are exploited commercially, although they are of low grade with considerable impurities. Eleven coal beds up to 1 m thick have been identified (Guizhou Team, 1980, p. 181–182; Guizhou Bureau, 1987, p. 289). Sandstone and conglomerate are the dominant lithologies of the Huobachong (Fig. 75). They are light-gray to white, lithic and arkosic arenites that form amalgamated beds up to 18 m thick. Grain size and composition show considerable variation. Modal size ranges from fine sand to pebble conglomerate. Quartz is everywhere the principal component, with up to an estimated 15% chert or quartzite fragments. Feldspar content ranges up to 25% in some beds, arkose by most classifications. One interval of pure quartz arenite with extensive euhedral overgrowths is so friable that outcrops are mantled by white, angular quartz sand. Sedimentary structures include conspicuous lenticular beds, planar beds, festoon and tabular cross-beds, and ripple marks. Paleocurrent measurements on six cross-bed sets from a single locality (Fig. 75) give  $302^\circ \pm 45$ . Finer-grained intervals include, in addition to coal, gray-green, gray, or black thin-bedded, calcareous claystone, silty claystone, and carbonaceous mudstone. Most of the sandstone and conglomerate is packaged in fining- and thinning-upward cycles that terminate with coal, carbonaceous mudstone, or dark-gray claystone; 25 such cycles from ~8 to 47 m thick can be recognized in the section measured by the Guizhou Team (1980, p. 179–182). A variety of plant fossils abound in the mudrocks and coals of the Huobachong. Numerous bivalves include (1) marine, (2)



Figure 75. Outcrop Huobachong sandstone at Longchang section. Tabular cross-beds, measured from each layer ( $n = 6$ ) give a paleocurrent vector of  $302^\circ \pm 45$ . Dips range from 13 to  $23^\circ$ , averaging  $17.5$ . Height of exposure is 5.2 m.

euryhaline, possibly intertidal (e.g., *Mytilus*), (3) brackish-water (e.g., *Ostrea*, *Liostraea*), and (4) fresh-water forms (e.g., *Unio*). A fresh-water ostracode, a gastropod, and an inarticulate brachiopod (*Lingula*) occur in the lower Huobachong (Guizhou Bureau, 1987, p. 290). Plant root traces were observed beneath one of the few coal seams exposed at the surface.

Fossils from the Huobachong Formation (Guizhou Team, 1980, p. 179–182; Guizhou Bureau, 1987, p. 289; Liu Yuzhou, 1996):

Plants: *Anomozamites* cf. *gracilis* Nathorst, *A.* cf. *minor* Nathorst, *Cladophlebis* sp., *Cycadites saladini* Zeiller, *Dicthyophyllum nathorsti*, *Equisetum* sp., *E. sarrani* (Zeiller), *Ferganiella* sp., *Geichenites yipinglangensis* Li and Tsao, *Neocalamites* sp., *N. carrerei*, *N. carcinoides* Harris, *Nilssonia* sp., *N.* cf. *furcata*, *Nilssoniopteris* sp., *N. jouzdyi* (Zeiller) Flozin, *Podozamites* sp., *P. lanceolatus* (Lindley and Hutton), *P.* cf. *schrenki*, *Pterophyllum* sp., *P. aequale* (Brongniart), *P.* cf. *longifolium* Brongniart, *P. nathorsti*, *P. pinnatifidum* Harris, *P.* cf. *ptilum* Harris, *P.* cf. *schrenki* Zeiller, *Taeniocladopsis rhizomoides* Sze, *Taeniopteris minuscula*, *Thoumatopteris* sp., *Todites shensiensis*

Brachiopods: *Lingula deitersensis* Pflucker

Bivalves: *Badiotella guizhouensis*, *Bakevellia* sp., *Burmesia lirata*, *Heminajas forulata* Chen, *Liostraea zhenfengensis*

Yin, *Modiolus* sp., *M.* cf. *plana* Yin, *Myophoria* (*Elagantina*) *venusta* Chen, *Myophoriopsis acyrus* Liu, *M.* cf. *nuculiformis* (Zenker), *Mytiloperma* sp., *Mytilus* sp., *Ostrea* sp., *Placunopsis* sp., *Prolaria sollasi*, *Trigonodus* sp., *T. keuperinus* (Berger), *T. keuperinus* (subsp. nov.), *Unio* sp., *U. guizhouensis* Yin, *Unionites* sp., *U.* cf. *griesbachi* (Bittner), *Waagenoperma* (sp. nov.?), *Yunnanophorus* sp., *Y. boulei* (Patte)

Ostracodes: *Darwinula contracta* Mandelstam.

Accumulation rates for the Huobachong Formation can be calculated on the basis of the assumption, unlikely as it may be, that it spans the entire Norian (Table 2). Rates range from 17 to 86 m/m.y. for the various sections, depending on the duration assigned to the Norian. Decompaction would not change the calculated rates appreciably for sandstones and conglomerates, but coals and mudrock intervals, with initial water contents of 90 and 75% respectively (cf. Enos and Sawatsky, 1981, p. 967), would be greatly expanded. The cumulative thickness of Huobachong coals is ~5 m in 11 beds at Longtoushan, Longchang (Guizhou Team, 1980, p. 181–182; Guizhou Bureau, 1987, p. 289). This would represent ~50 m of initial sediment. A conservative estimate of the thickness of claystone and other mudrocks at Longchang is 340 m, out of a total thickness of 687 m. This would decompact to ~1350 m of sediment. This additional sediment would increase the minimum and maximum calculated accumulation rates to 135 and 220 m/m.y., respectively. This is within the range calculated for fluvial environments over periods of a million years (Enos, 1991, p. 78), albeit without decompactation.

### Depositional Environments

Coarse-grained, cross-bedded sandstones and conglomerates of the Huobachong form thinning- and fining-upward cycles with little fine-grained material. Braided streams are the most likely depositional setting. Thick coal seams would be remarkable in such an environment, however. Swamps within or adjacent to a braid plain are uncommon, typically small, and quite short lived, thus unlikely to produce commercial coal deposits. Repeated occurrences of brackish to fully marine bivalves and inarticulate brachiopods interspersed with occurrences of plants and fresh-water bivalves point to a coastal setting with numerous marine incursions. Coastal swamps that were episodically overwhelmed by encroaching braided streams are the likely habitat of coal deposition. Unfortunately, we lack details about what parts of the cyclic units contain specific types of fossils and about the contact relations and lateral continuity of the coal beds. Areal distribution of the Huobachong is so limited that thickness or grain-size trends cannot be used to deduce source area. The limited and local paleocurrent directions are toward west-northwest, essentially at right angles to those of all underlying units. They may be a clue that the Jiangnan Massif, the apparent source of siliclastics in the Middle–Upper(?) Triassic Badong Formation as well as the Bianyang Formation, continued as a source area.

## RHAETIAN? (UPPERMOST TRIASSIC) FORMATION

### Erqiao Formation

The Erqiao Formation appears almost entirely nonmarine. Its age is consequently rather problematic, but is thought to be Rhaetian (Guizhou Bureau, 1987, p. 676). The Erqiao is coarser grained and thicker bedded than the underlying Huobachong (Fig. 74), but the range of lithologies is similar. The contact was described as conformable at Longchang (Guizhou Bureau, 1987, p. 289). The Erqiao covers most of the Yangtze Platform in Guizhou, however, in the Guiyang as well as the Zhenfeng sector, and overlies units as old as Anisian (Fig. 55; Guizhou Bureau, 1987), indicating a major unconformity at its base. There is no indication of active folding during the Late Triassic. The sub-Erqiao unconformity appears rather to bevel the underlying formations uniformly, starting with the Huobachong, Banan, and Laishike northward from the syncline at Guanling and reaching the level of the Anisian Guanling Formation near the northern border of Guizhou (Fig. 55). A sharper bevel is evident in the northwestward extension of the syncline from Guanling toward the Yunnan border where the unconformity drops from the level of the Huobachong to the Wayao or Zhuganpo Formation in a distance of not more than 43 km. The only exposures of possible Upper Triassic rocks east of 107°35'E are of the Badong Formation, predominately Middle Triassic but possibly lowermost Upper Triassic in part. The only units overlying the Badong are Upper Cretaceous red conglomerates and sandstones in angular unconformity. This may mean that the Erqiao (and Jurassic strata) was stripped off before the Late Cretaceous or that it pinched out depositionally toward eastern Guizhou, as suggested by the paleogeography of Wang Hongzhen (1985, p. 94) and Liu Baojun and Xu Xiaosong (1994, p. 166).

Published measured sections of the Erqiao are from Longchang, where an incomplete section 446 m thick “conformably” overlies the Huobachong Formation (Guizhou Team, 1980, p. 179); from Houwu-Moshichong, Qingzhen (QZ, Fig. 2; 30 km west-southwest of Guiyang), where 67 m of Erqiao disconformably overlies the Sanqiao Formation (Guizhou Bureau, 1987, p. 300); at Panshui, Zunyi, 175 m overlying the Yangliujing Formation (Guizhou Bureau, 1987, p. 293), and at Gaoqiao, Zunyi, 124 m overlying a thin (125 m) Yangliujing interval (Guizhou Bureau, 1987, p. 281). In the last three sections, which lie far to the east and north of Longchang, the Erqiao is thinner, but apparently complete, as it is overlain conformably or paraconformably by the Lower Jurassic Ziliujing Group.

Deposition of coarse-grained siliciclastics continued from the Huobachong into the overlying Erqiao Formation, but coal in the Erqiao is confined to near the base of the formation, as it is presently defined, or is absent as we would define it (see Huobachong above). The basal unit of the Erqiao in the thick, but incomplete, Longchang section is ~34 m thick—or 43 m if the coal unit is included in the Erqiao rather than in the Huobachong. This unit consists of claystone, siltstone, and thin- to medium-bedded sandstone. The overlying unit is 133 m of white, very

thick bedded, coarse-grained, lithic arenite with up to 20% quartzose rock fragments and, from personal observations, of light-gray pebble conglomerate (Fig. 76). The uppermost 29 m includes some intercalated siltstone, suggesting a fining-upward trend. The overlying units include similar coarse-grained sandstones (Fig. 77), but intervals of gray siltstone and silty claystone define three thinning- and fining-upward cycles, 79, 75, and 46 m thick, respectively. Lenticular bedding and cross-bedding with general easterly dips are prominent throughout the sandy intervals of the Erqiao. These units terminate the deposition of coarse-grained siliciclastics in the preserved section; the upper cycle ends with carbonaceous shale. The final 79 m of exposure are gray claystone with some silty claystone, for a total exposed thickness of 446 m. All fossils reported from this exposure are of plants, except for three bivalve genera (*Modiolus*, *Myophoriopsis*, and *Indosinion*, a brackish-water form) found in the basal, middle, and top units, respectively (Guizhou Team, 1980, p. 179–180). Fossils from sections elsewhere in Guizhou are mostly plants, but include a branchiopod (*Howellites*) and a bivalve (*Siberconcha*) that indicate fresh-water deposition.

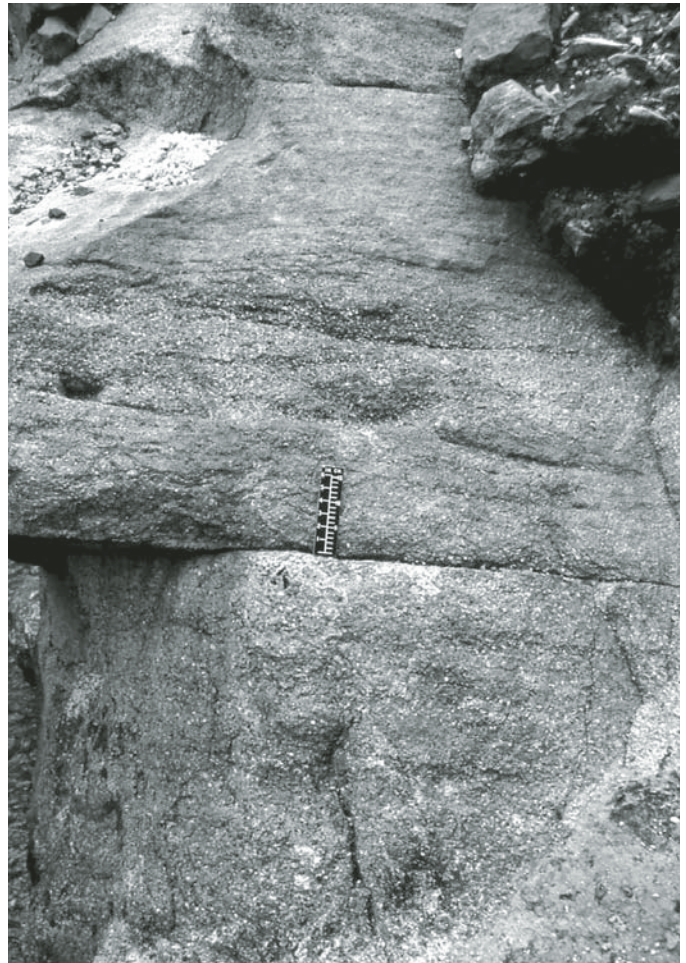


Figure 76. Quartz-pebble conglomerate (clasts to 2 cm) near base of Erqiao Formation, Longtoushan, Longchang section. Scale is 15 cm.



Figure 77. Thick beds of coarse-grained sandstone form the base of a fining-upward unit in the middle part of the Erqiao Formation, Longtoushan, Longchang section.

All Erqiao exposures east and north of Longtoushan (Longchang section) that we observed or the Guizhou Bureau reported (Guizhou Bureau, 1987) lack the conspicuous conglomerates, except for a basal conglomerate figured by Wei Jiayong et al. (1996) in the Songkan, Tongzi, section near the Sichuan border (Fig. 13D, section 10). For example, at Gaoqiao, Zunyi, the basal 9 m of the Erqiao is gray claystone alternating with fine-grained silty sandstone and intercalations of very dark gray, sandy claystone with plant fragments. The overlying 89 m is moderately thick-bedded, fine- to medium-grained, quartzose sandstone with two thin coal seams and interbeds of silty claystone and muddy sandstone in the upper part. The uppermost 26 m is thick-bedded, medium- to coarse-grained, gray, quartzose sandstone. This sandstone has no apparent counterpart in the truncated Longchang section, which ends with 79 m of claystone.

Fossils from the Erqiao Formation (Guizhou Team, 1980, p. 179–180; Guizhou Bureau, 1987, p. 281, 289, 293; Liu Yuzhou, 1996, p. 374–376):

Plants: *Calamites* sp., *Cladophlebis* sp., *C. cf. asiatica*, *C. kaoiana*, *Clathropteris* sp., *C. meniscioides* Brongniart, *C. platyphylla* (Goepfert), *Coniopteris* sp., *Czekanowskia* cf. *rigida*, *Dictyophyllum* sp., *D. nathorsti*, *Equisetum* sp., *E. sarrani* (Zeiller), *E. ferganensis*, *Hyrcaopteris sevenensis* Kryshtofovich and Prynada, *Lepidopteris ottonis*, *Neocalamites* sp., *Otozamites* sp., *Pityophyllum* sp., *Podozamites* sp., *P. lanceolatus* (Lindley and Hutton), *Pterophyllum minutum* Li and Tsao, *Radicitis* sp., *Sphenopteris* sp., *Stenorachis?* sp., *Taeniopteris* sp., *Thinnfeldia* sp., *Thoumatopteris* sp.

Bivalves: *Costatoria kweichowensis*, *Indosinion* sp., *Modiolus* sp., *Myophoriopsis* sp., *Sibireconcha* sp., *Utschamilla* sp.

Branchiopods (conchostracan): *Howellites* sp.

Fish scales.

If the Erqiao Formation is assumed to represent the entire Rhaetian, calculated accumulation rates range from 11 to 112 m/m.y. (Table 2). The mean rate, depending on the duration assumed for the Rhaetian, is 34 to 51 m/m.y. The very low rates are from the thin distal sections to the east where the duration of sedimentation was likely much less. The prevailing finer grain sizes in these sections indicate, however, that accumulation rates were in fact appreciably slower. Decompaction would be insignificant in this sandstone-dominated unit, except in the Longchang section. Although Longchang includes the coarsest-grains rocks observed, it also includes ~155 m of claystone. Decompaction of these rocks, assuming initial water content of 75%, would result in sedimentation rates of 150 to 230 m/m.y. These are very close to rates for the underlying Huobachong Formation which has similar lithologies, but finer grain sizes.

### Depositional Environments

Braided-stream deposition apparently continued from the Huobachong into the Erqiao Formation, but with rejuvenation to give a more proximal character and reverse the transport direction toward the east. Marine incursions ceased or were rare; no fossils or diagnostic structures were observed in the poorly exposed, thick, upper claystone at Longchang in the southwest.

The brackish-water mollusks indicate that the sea had not yet retreated permanently and suggest a low-relief, perhaps coastal setting. The sparse occurrences of coal or dark, carbonaceous shales, mainly toward the base of the formation and in the east, could reflect coastal or flood-plain swamps.

The Erqiao and the Huobachong Formations constitute a typical molasse<sup>3</sup> sequence, which could also include the underlying, shallow-marine Banan Formation (as in the “marine molasse” of the peri-Alpine basin). The logical development of the three formations as a genetic sequence is contradicted by the paleo-current data, albeit very limited. These indicate bimodal flow toward the south-southwest and north for the Banan, toward the west-northwest for the Huobachong, but generally eastward for the Erqiao. This three-formation interval thins from 1600 m in the Longchang area, where the top is eroded, to only 161 m thick in the Guiyang area (Guizhou Bureau, 1987, p. 300–301). The lower part of the interval at Guiyang is the finer-grained Sanqiao Formation, apparently a more distal facies and possibly older (Carnian?). The Banan and Huobachong are missing entirely in the Guiyang sector. The Erqiao is both thinner and finer grained eastward, as outlined above. No Erqiao or other Upper Triassic rocks are recognized in Guizhou east of 107°35'E. Only the Erqiao Formation is preserved north of 27°05'. It is 175 m thick at Panshui, Zunyi, and 124 m at Gaoqiao, compared to 446 m in the incomplete section at Longchang.

The thinning and fining northward and, more dramatically, eastward point to a source terrain in the west or southwest. Beveling of the units beneath the Erqiao is rapid toward the west and more gradual northward. This indicates regional uplift without local folding to the west and north with cannibalism of pre-Erqiao deposits. A likely western source for the coarse terrigenous material would be the Khamdian Massif (“oldland”), which supplied siliciclastic debris to the southwestern margin of the Yangtze Platform intermittently during the Permian and Triassic (Sheng Jinzhang et al., 1985; Wang Hongzhen, 1985; Liu Baojun and Xu Xiaosong, 1994). The Longmenshan forms the northwestern boundary of the Yangtze Plate and reflects a probable Triassic suture zone (Şengör, 1987). Uplift in this area may have begun in the Rhaetian with debris being shed onto the western margin of the Yangtze Platform.

## SUMMARY AND CONCLUSIONS

Deposition of carbonates on the Yangtze Platform in Guizhou during the Early and Middle Triassic totaled 3140 m in the interior at Longchang and 2610 m near the edge at Hongyan. These are the most complete sections; both are from the Zhenfeng sector. A composite section from the Guiyang sector at Gaimao and Tongmuling-Bojishan on the platform margin would be 2030 m

thick. A complete section of the interior at Dulaying, Guiyang, is 1525 m thick. The section at Gaoqiao in northern Guizhou is 1450 m thick, but was probably truncated by Late Triassic erosion. A composite of the thickest sections of each formation would total 4125 m; composite mean thickness would be 2740 m (Table 3). Time-equivalent basinal deposits of Early and Middle Triassic age reach a composite mean thickness of 3315 m and a composite maximum thickness of 4925 m. No complete basinal section is recognized and unit thickness is in general poorly known, so these numbers are gross approximations. After shallow-water carbonate deposition ceased on the Yangtze Platform at the beginning of the Carnian, an additional 2540 m of mostly siliciclastic rocks accumulated at Longchang, in the Zhenfeng sector. Upper Triassic deposits are an order of magnitude thinner in the Guiyang sector, e.g., 250 m at Dulaying (Fig. 13D).

Average accumulation rates for the platform carbonates would be 130 m/m.y. using mean formation thickness or 200 m/m.y. using maximum formation thickness (Table 3). Accumulation rates of the Early and Middle Triassic apparently differed by ~50%, but which epoch was faster depends on whether the estimates of Haq et al. (1988) or Ogg (2004) are used for duration of the epochs. These authors partitioned time quite differently, although their totals for the two epochs are similar (Table 3). Haq et al. would have Middle Triassic accumulation rates for mean formation thickness exceed those of Early Triassic, with 163 versus 117 m/m.y., respectively. Ogg would reverse the contrast: 86 m/m.y. for Middle Triassic and 196 m/m.y. for Early Triassic. New dates for the Scythian-Anisian boundary from the Nanpanjiang Basin (Martin et al., 2001; Lehrmann et al., 2002, 2006b) would shorten the duration of the Early Triassic to ~5.0 m.y. This would increase the Early Triassic platform accumulation rate to 235 m/m.y., appreciably higher than either of the calculated Middle Triassic rates. This introduces an apparent paradox. Biotic recovery of shallow-water biota from the end-Permian mass extinction was delayed until the Anisian in south China, as elsewhere (Payne et al., 2004, 2006). Moreover, the total skeletal content of the platform carbonates is less in the Lower Triassic rocks than in the Middle Triassic (Payne et al., 2006; Lehrmann et al., 2005). Nevertheless, accumulation rates apparently decreased in the Middle Triassic. The contribution of oolites and calcimicrobialites to Early Triassic sedimentation clearly exceeded that in the Middle Triassic, although it is unlikely that they overcompensated for the low biotic production. A more likely explanation to the paradox lies in the time sequestered in hiatuses. Induan sedimentation was on a ramp with no evidence for periods of exposure, even in updip sections. By the Olenekian the configuration had changed to a platform with a low rim. The Anshun Formation near the platform margin is characterized by fining-upward cycles with supratidal caps. Numerous tepee structures toward the top of the formation indicate more prolonged periods of exposure. Evidence of exposure with gaps in the sedimentary record is also evident in the upper and seaward part of the Anisian Guanling Formation, although it is less prevalent. In both the Olenekian and Anisian, platform-interior rocks appear

<sup>3</sup>Molasse is used as a lithofacies term for “... partly marine, partly continental ... sedimentary facies consisting of a very thick sequence of ... conglomerates, sandstones, shales, and marls, characterized by [large-scale cross-bedding] and sometimes by coal and carbonate deposits.” (Jackson, 1997, p. 415. See also Pettijohn, 1975, p. 580 ff.)

to be entirely subtidal in origin, indicating a deeper lagoon with continuous sedimentation, but probably at reduced rates. The most impressive evidence of exposure is in the Ladinian rocks. Both the Longtou and the Yangliujing Formations have extensive intervals of amalgamated tepees, signaling extended periods of subaerial exposure. It must be noted, however, that accumulation rates for the Ladinian platform carbonates are nearly identical to those in the Anisian (Table 2), despite much more impressive evidence of subaerial exposure and thus of gaps in sedimentation.

Basinal sedimentation contemporaneous with platform growth in the Early and Middle Triassic was at rates of 160 m/m.y., if mean formation thickness is used, and 235 m/m.y. if maxima are used. These are ~20% greater than the platform rates. Middle Triassic rates of basinal sedimentation were unequivocally much higher than those of the Early Triassic, despite major differences in the duration assigned to the two epochs (Table 3). Early Triassic rates range from 38 m/m.y. for mean formation thickness to 93 m/m.y. for maximum thickness (average values of 3 estimates in Table 3). Corresponding Middle Triassic rates are 260 and 367 m/m.y. The basin deepened by starvation in the Induan and by differential sedimentation in the Olenekian, but eventually filled up by the end of Middle Triassic or early in the Carnian (Lehrmann et al., 1998; Wei Jiayong and Enos, 1991), as reflected in the accelerated accumulation rates.

Deposition of platform carbonates was widespread throughout most of the Permian in south China (Enos, 1995), but platform configuration was appreciably different than in the Triassic (Figs. 3, 4). A transgression in the Late Permian, perhaps 2 m.y. before the end of the Permian (Haq et al., 1988), produced a thin, cherty, pelagic blanket, the Dalong Formation, over much of the former platform and reconfigured the stage for Triassic deposition. When carbonate deposition resumed in the mid-Induan, the margin of the Yangtze Platform had retreated ~100 km northward in the Guiyang sector and was a low-relief ramp overlying the flat Permian platform. Limited exposures of Permian and Lower Triassic margin facies in the Zhenfeng sector suggest little shift in location.

The initial Triassic deposits across most of Guizhou were terrigenous mud with ammonoids and thin-shelled bivalves. No hiatus is detectable between the Permian and Triassic rocks at most localities. Volcanic ash is present at the contact on the Great Bank of Guizhou (Martin et al., 2001; Lehrmann et al., 2002) and at Pingba and Hongyan, in the Guiyang and Zhenfeng sectors, respectively (Fig. 13A and 13B). At this juncture, the southern margin of the Yangtze Platform was a deep, flat seafloor over the drowned Permian platform. Hemipelagic mud was supplied mainly from the persistent Khamdian Massif to the west in Yunnan. Carbonate deposition gradually resumed throughout the area in the Induan with attenuated transitions from deeper environments in the south and east to shallower in the north and west, defining a carbonate ramp. Carbonates of the Luolou Formation to the southeast are characterized by thin, commonly laminated beds of dark-gray lime mudstone with ammonoids and thin-shelled bivalves. Interspersed lime breccias with mixtures

of muddy intraclasts and oolite lithoclasts reflect intrabasinal slumping and debris flows originating in shallower water to the northwest. At the updip end of the spectrum, the Yelang is about four times as thick and has three or more intervals of thick-bedded oolite, representing intermittent ooid shoals. Interbeds of terrigenous mudstone thicken toward the west to dominate the interval, reflecting continued input of detritus from the Khamdian massif. Thin-bedded lime mudstones with prominent burrowed horizons form a broad belt between the ooid shoals and the dark, laminated mudstones. Burrowed intervals without benthic biota indicate dysaerobic conditions. Thin laminated interbeds reflect encroachment of anaerobic conditions that prevailed deeper in the basin. The laminated mudstones in the basin are a generally condensed interval, but a corresponding maximum flooding surface is not recognized on the platform. Conversely, the thick oolite intervals in the Induan platform deposits probably represent three or more highstand intervals, but these do not have recognized basinal equivalents. The best-studied platform-margin section at Hongyan has six prominent breccia intervals as well as several thinner beds (Minzoni, unpublished data). Only two of the intervals show significant concentrations of oolite clasts, so possible correlations with the platform oolite intervals are not obvious. No evidence of persistent subaerial exposure was noted in a brief reconnaissance of the platform-interior deposits.

An approximation of the configuration of the ramp over the Permian platform top at the end of the Induan is provided by mean thickness figures: 580 m for the updip Yelang Formation, 300 m for the mid-ramp Daye, and 145 m for the basinal Luolou (Table 3). The apparent depth differential of 435 m on the distal ramp could have been increased by basin subsidence or reduced by isostatic sinking of the platform. By the end of the Early Triassic, mean thickness of platform-interior deposits totaled 1175 m, the platform-margin total was 750 m, and basin was 250 m (Table 3). Facies distributions indicate the development of a rimmed platform in the Olenekian. The platform-to-basin relief may have been 500 m or more. Maintenance of an interior subtidal lagoon despite much greater sediment accumulation there suggests active isostatic depression as part of the cause. Isostasy could also have reduced the relative depth of the basin.

The locations of the Olenekian facies tracts parallel those of the Induan, but the predominance of peritidal cycles in the intermediate Anshun Formation signals the evolution from ramp to platform. Non-cyclic mudstones in the platform interior were deposited in a subtidal lagoon behind a rimmed platform margin. Equivalent basinal deposits are mixed terrigenous and lime mudstones with sparse lime breccia and turbiditic siltstone totaling only ~100 m thick. The scarcity of benthic fossils and alternations of laminated and burrowed beds indicate fluctuations between anaerobic and dysaerobic bottom water in a starved basin. Toward the end of the Olenekian, severe restriction of circulation in the interior of the platform is evidenced by molds of gypsum crystals and widespread solution-collapse breccias.

A prominent zone of amalgamated tepees in the upper part of the Anshun Formation is a likely a sequence boundary within

the Olenekian. It has been tentatively correlated with a red, auto-brecciated horizon, a likely paleosol, in the platform interior of the Guiyang sector (Wei Jiayong and Enos, 1991), but precise correlations are not yet feasible. No evidence of subaerial exposure was noted in the type Yongningzhen Formation in the Zhenfeng sector.

The transition from Olenekian (Early Triassic) to Anisian (Middle Triassic) is marked by a layer of altered acidic tuff, recognized in most outcrops in Guizhou as well as in the adjacent provinces, although some ambiguity results from multiple tuffs near the contact in several locations. Conodont biostratigraphy from the north slope of the Great Bank of Guizhou (Lehrmann et al., 1998, 2002), supported by magnetostratigraphy (Montgomery et al., 2000), places the contact between ash beds at that locality. Concordant U/Pb dates from zircons give an age of  $247.21 \pm 0.1$  m.y. for the Early-Middle Triassic boundary (Lehrmann et al., 2006b).

The trend from carbonate dominance to siliciclastic dominance in the basinal deposits that began in the Early Triassic and would culminate in the Ladinian continued through the Anisian. The laterally equivalent Xinyuan and Xuman Formations are overwhelmingly siliciclastic mudrocks, although some calcareous intervals and a few beds of lime mudstone indicate some periplatform input. The Xuman Formation, which lies generally south of the Zhenfeng sector of the Yangtze Platform, is an order of magnitude thicker than the Xinyuan. Near the platform margin, an apron of carbonate blocks, grains, and mud dramatically changed the character of the basin deposits; these are mapped as the Qingyan Formation. For the first time in the Triassic, the platform margin was formed by a narrow band of boundstone, the Poduan Formation, interpreted as organic reefs. The framebuilders were *Tubiphytes*, *Plexoramea*, sponges, arborescent corals, and skeletal stromatolites, assisted by myriad encrusters. This marginal facies is missing throughout most of the Guiyang sector, coincident with the extent of the Qingyan facies. The blocks and skeletal grains of the basin-margin apron were derived from the collapse of the platform-margin reefs (Enos et al., 1997). Successive collapse led to retreat of the margin in the early Anisian by 2.7 km at Qingyan and by 10 km at a platform re-entrant 30 km farther west (Fig. 12). In contrast, platform-interior deposits overlie the Poduan reef in the Hongyan section, suggesting some progradation of the margin in that area. Peritidal cycles are evident in the Guanling Formation only near the platform margin, or at the actual slope break where collapse has removed the reef that presumably provided a sheltered environment for these accumulations. The reef rim also probably caused some restriction of the platform-interior subtidal lagoon to allow accumulation of lime mud and some interstitial gypsum, recorded by molds of crystals and of rosettes. Episodes of better circulation that allowed crinoids and ammonoids to flourish may have followed collapse events that breached the reef barrier. Argillaceous interbeds, common within the Guanling, probably extend from the Badong Formation in eastern Guizhou, characterized by red mudrock and sandstone adjacent to the Jiangnan Massif.

Ladinian platform sedimentation is characterized by high-energy deposits of grapestone, bioclasts, and ooids and by repetitive peritidal cycles. The peritidal cycles were not confined to near the platform margin, as in underlying Triassic units, but apparently stretched far into the interior to define a flat-topped platform. Tepees structures are common as cycle caps or amalgamating successive cycles, indicating extended periods of subaerial exposure. A thick, intensely deformed, amalgamated tepee interval in the upper part of the succession is probably a sequence boundary, although it cannot be correlated into the basin. At the beginning of the Ladinian, the platform prograded at least 0.6 km in the Guiyang sector, but retreated in the Zhenfeng sector, another indication of differential subsidence between adjacent sectors of the platform. Typical flysch deposits of the Bianyang Formation filled the Nanpanjiang Basin, either during the Ladinian (Guizhou Bureau, 1987) or following demise of the Great Bank of Guizhou and the Zhenfeng sector of the Yangtze Platform at the onset of the Carnian (Lehrmann, 1993; Lehrmann et al., 1998). The fine sand and coarse silt of the Bianyang, as well as continental siliciclastics on the eastern part of the platform, were apparently derived from the Jiangnan Massif immediately to the east.

In the Carnian and Norian, contrasts between the Guiyang and Zhenfeng sectors became sharper. We attribute these differences to tectonics that produced greater rates of subsidence and syndepositional faulting in the Zhenfeng sector (Enos et al., 1998; Minzoni, 2003a). Several hints of tectonic intervention throughout the Triassic were cited above, in thickness variations and in contrasts between platform-margin retreats and advances in the two sectors. Tong Jinnan (1998) invoked tectonics, without citing specific structural features, to explain regional correlations across facies gradients in the Anisian through early Carnian in Guizhou. In contrast, we invoke tectonic variations, and cite some relevant evidence, to explain stratigraphic differences across the region, i.e., lack of correlation.

The Carnian began in the Guiyang sector with the same old thing—deposition of cyclic peritidal carbonates. Mudrock and sandstone are interspersed, however, most prominently in a southward-thinning wedge at the base of the Gaicha Formation. Siliciclastics, especially sandstone, predominate in the overlying Sanqiao Formation, also deposited in shallow water, judging from the biota. Both units are truncated toward the north, apparently by erosion during the Norian, which has no recognized deposits in this sector.

In the Zhenfeng sector, shallow-water carbonate deposition ended abruptly at the beginning of the Carnian. The ensuing nodular-bedded, ammonoid-bearing, dark-gray lime mudstone of the Zhuganpo Formation documents the drowning of the Yangtze Platform (Enos et al., 1998). Carbonate deposition ceased altogether with the Wayao Formation, a condensed sequence characterized by black shale with concentrations of manganese, iron, and organic carbon. The accommodation space created during drowning was subsequently filled by up to 800 m of turbiditic sandstone and mudrock and 465 m of shallow-shelf sandstone dur-

ing the later Carnian. Thinning- and fining-upward cycles of cross-bedded sandstones and conglomerates in the Norian are interpreted as braided-stream deposits with interspersed paralic coals and mudrocks bearing fresh-water, brackish, or marine fossils.

Still coarser grained deposits of the Rhaetian indicate rejuvenation and reorientation of braided streams to form a clastic wedge. The wedge became thinner and finer grained to the east and north as it spread across a surface that beveled deposits as old as Anisian. The bevel resulted from tilting, rather than folding, with the greatest uplift toward the west and intermediate toward the north.

The Upper Triassic succession in Guizhou is typical of foreland-basin lithofacies sequences, in which flysch sedimentation is followed by molasse (cf. Pettijohn, 1975; Allen and Homewood, 1986; Enos et al., 1998). The upper Carnian Laishike Formation has all the sedimentologic characteristics of flysch. Its predecessor, the Bianyang Formation is an even better example, primarily because of its greater thickness (2800 m versus 800 m). However, neither formation can be directly linked to a local orogeny, a prerequisite for tectonic definitions of flysch preferred by some authors. Paleocurrents indicate that both were derived from the east. The Bianyang, at least, appears to derive from the Jiangnan Massif, a long-stabilized Proterozoic craton. K.J. Hsü and co-workers would readily accept these units as the syntectonic deposits of their proposed Triassic suture in southeast China (Hsü et al., 1988, 1989, 1990; Sun Shu et al., 1989); however, serious objections have been raised to this concept (Rowley et al., 1989; Gupta, 1989; Rodgers, 1989; Gilder et al., 1996). The molasse sequence, in a strictly lithofacies sense, includes the Banan ("marine molasse"), Huobachong, and Erqiao Formations. These comprise a logical filling sequence from shallow marine to continental and from distal to proximal. The sandstones are petrographically similar enough, under the hand lens, to suggest common genesis. However, this relationship and the possible "post-orogenic" credentials of this sequence are called into question by the limited paleocurrent data. Banan paleocurrents are directed south-southwest ( $210^\circ$ ) with a second mode to the north ( $360^\circ$ ). Cross-bedding in the Huobachong dips west-northwest ( $300^\circ$ ), essentially perpendicular to those in the underlying Banan. The Erqiao, the culmination of the general upward increase in grain size and emergence, thins and fines toward the east, consistent with qualitative observations on cross-beds. Thus these units were probably derived from different directions. Paleocurrent directions in the underlying flysch sequences consistently indicate an easterly source. The more distal character eastward and the mature sand and pebble composition of the Erqiao Formation point to provenance from the Khamdian Massif in Yunnan. Transport direction and composition point to the Jiangnan Massif as the source of the Bianyang Formation (Chaikin, 2004) and probably of the Laishike. Not only are the sedimentologic flysch and molasse derived from opposite directions, and thus genetically unrelated, but both also are apparently derived from exposed Proterozoic massifs rather than active orogens. They emphatically do not qualify as flysch and molasse in the tectonic definitions favored by some authors.

The tectonic disqualification is significant because the Late Triassic is generally considered the prime time of suturing of the various terranes that make up China and southeast Asia. In most chronologies it marks the onset, if not the culmination, of these events, the Indosinian orogeny (cf. Ridd, 1980; Zhang Zhimeng et al., 1984; Şengör, 1984, 1987; Ji Xiong and Coney, 1985; Yang Zunyi et al., 1986). It is remarkable that the only evidence of regional tectonism in the Late Triassic throughout Guizhou is the beveling unconformity beneath the Erqiao Formation and a marked increase in grain size above the unconformity. The contact between the Erqiao and various underlying formations is a paraconformity (Dunbar and Rodgers, 1957, p. 119); beds above and below are parallel on outcrop scale. Regional mapping shows that this innocuous surface truncates units ranging in age from Norian to Anisian. The depth of truncation increases toward the west and north. No folding was involved in forming this surface, only regional tilting or perhaps uplift and differential erosion. The abrupt increase in grain size and change in transport direction from the underlying Huobachong to the Erqiao indicates uplift of a new source area. Regional trends in thickness and grain size within the Erqiao point to a westerly source. The relative textural and mineralogic maturity of the Erqiao sandstones and conglomerates points to a cratonic source, probably a rejuvenated Khamdian massif, rather than a new orogen at the plate boundary. The tectonic forces that were crumpling several or all of the margins of the Yangtze Plate did not penetrate into the interior.

The prominent fold ridges in the Guizhou landscape reflect a remarkable structural pattern. The major folds east of  $106^\circ30'E$  are narrow, steep-sided ( $60^\circ$  or  $70^\circ$  dips) synclines oriented roughly north-south. The intervening rocks are flat lying or gently folded. Thus anticlines are virtually absent; exceptions are a few slightly older, east-northeast-trending structures, e.g., at Guiyang and Luodian, that produce rhombic outcrop patterns (Figs. 3, 12). North of the latitude of Guiyang the synclines are broader, so the intervening structural plateaus are less conspicuous, but the pattern is still discernible. Long, narrow anticlines commonly result from ramping of bedding thrusts, but thin-skinned tectonics cannot account for this pattern in synclines. The basement is apparently involved, most likely through reactivation of older structures. In this case, the maximum stress is not necessarily perpendicular to fold axes; it may be at high angles.

When did these structures form, if not in the Indosinian orogeny? The first Mesozoic structural deformation in Guizhou occurred in the mid Cretaceous. The many scattered Jurassic outcrops in Guizhou (Fig. 55) conformably overlie the Erqiao Formation and are interpreted to represent each Jurassic series; i.e., there are no major gaps in the succession. In northernmost Guizhou, Lower Cretaceous rocks overlie the Jurassic paraconformably on the rim of the Sichuan Basin (Guizhou Bureau, 1987). Elsewhere scraps of coarse-grained Upper Cretaceous conglomerates hundreds of meters thick overlie Mesozoic and Upper Paleozoic rocks with angular unconformity. Thus the major orogeny in Guizhou, by whatever name, was a mid-Cretaceous

event. The timing, but not the location, corresponds to the middle (Yang Zunyi, 1986) or late (Ren Jishun et al., 1987) Yanshanian Orogeny of Chinese tectonics. (Yanshan translates roughly to “rocky mountain.”)

In western Guizhou, the structural pattern is less regular. To the southwest the dominant structural grain is northwest-southeast, with a hint of the syncline-and-plateau style. It is not very marked, however, and a few isolated anticlines are present, e.g., at Ziyun (Fig. 3). Weak north-northeast folds (Fig. 12) may represent the north-south trend that dominates farther east. To the northwest a series of northeast-southwest trending folds, once again with narrow synclines, forms the border of the Sichuan Basin (Fig. 55). Very few patches of Cretaceous conglomerates are preserved in western Guizhou, but Jurassic rocks are folded parallel with older rocks, so Cretaceous deformation is indicated. The varied fold trends make the stress field conjectural. The probable involvement of the basement in folds throughout Guizhou suggests that contrasts in the structural grain of an amalgamated basement, rather than a variety of stress directions, may be responsible. The trends of some structures, juxtaposition of fold belts, and the mid-Cretaceous age of folding, as documented by the stratigraphy, suggest that the deformation may be linked to early Himalayan tectonics rather than to the assembly of south-eastern Asia.

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