Chapter 2
Stratigraphy of Studied Area Across the Permian–Triassic Boundary, South China

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The research area lies in eastern Yunnan–western Guizhou, southwest of China (Fig. 2.1), in the eastern part of the Yunnan–Guizhou plateau, where highland accounts to over 90% of the land with an average altitude of more than 1,000 m. The area is rather complicated in geology with widespread karsts with unique mountainous relief and climate, as described by the Chinese saying, "There is never a sunny day for three days and there is never a level land for three meters." However, its particular relief of natural beauty holds over 10 minority groups, namely Miao, Buyi, Tujia, Yi, Hui, Zhuang, Yao, etc., who have developed their own ethnic culture and institutions. It hence provides rich and colorful tourism resources groups with many national-level scenic sites. However, it was just this relief that made the area most inaccessible in history and hence its economy most underdeveloped. With the improvement of its economy in recent years, highways are building in the area and so make it more convenient for section observation and description and also for sample collection for all the surveyed sections can be found on the new ways.

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J. Yu et al. (eds.), *Plants and Palynomorphs around the Permian-Triassic Boundary of South China*, New Records of the Great Dying in South China,
https://doi.org/10.1007/978-981-19-1492-8_2

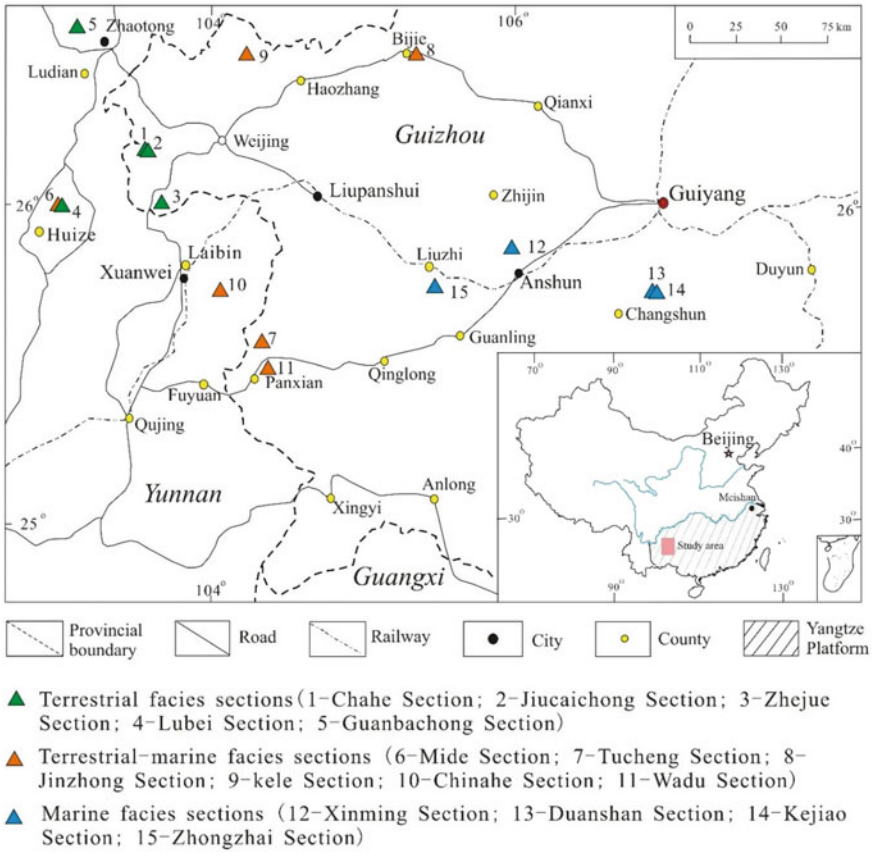

Fig. 2.1 Distribution of studied sections in Western Yunnan and Eastern Guizhou

2.1 Lithostratigraphy Units Across Permian–Triassic Boundary in Research Area

The research area is situated on the western margin of the Yangtze Platform, i.e. the border area between western Guizhou and eastern Yunnan on the eastern side of the Kangdian Massif (Oldland) (Fig. 2.2). As the stratigraphic units in the area are named, modified and even supplemented by different researchers, the terms are confused in the definition of the layer or even name of the same units (Table 2.1). The lithostratigraphy across the non-marine Permian–Triassic boundary, dealt with in this research, include Late Permian coal-bearing Xuanwei Formation, Early Triassic variegated clastic rocks of the Kayitou Formation (Table 2.1).

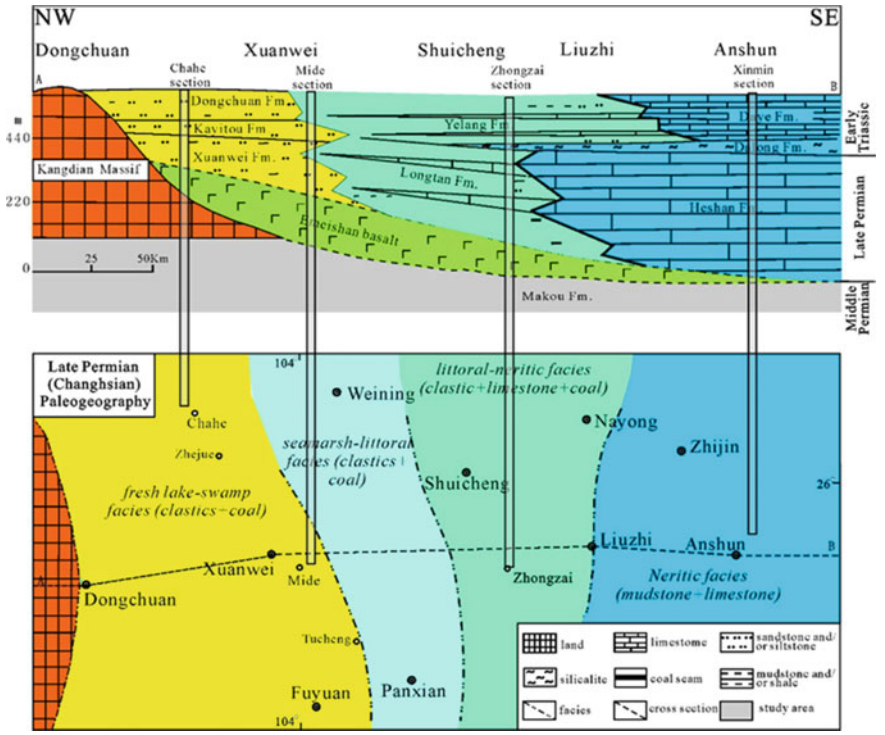

Fig. 2.2 Late Permian Changhsingian paleogeography and lithostratigraphy of western Guizhou and eastern Yunnan (modified after Wang and Yin 2001; Yao et al. 1980)

Table 2.1 Stratigraphic classification near the non-marine Permian–Triassic boundary in western Guizhou–eastern Yunnan (words in Italic is indicate stratigraphic period in the book)

Stage		Deep-water carbonate and silicolite facies	Shallow sea carbonate facies	Neritic clastic facies	Nearshore facies	Terrestrial facies
T 1	*Induan*	*Luolou Formation*	*Daye Formation*	*Yelang Formation*	Feixianguan Formation	Dongchuan Formation
					Kayitou Formation	*Kayitou Formation*
P3	*Changhsingian*	*Dalung Formation*	*Wujiaping Formation*	*Lungtan Formation*	*Xuanwei Formation*	*Xuanwei Formation*
	Wuchiapingian	Lungtan Formation	Lungtan Formation			
P2	Capitanian	Dongwu Movement			Emeishan Basalt	Emeishan Basalt
	Wordian	Maokou Formation	Maokou Formation	Maokou Formation	Maokou Formation	Maokou Formation

2.1.1 Non-Marine Facies Depositional Area

Xuanwei Formation: changed from the named Xuanwei coal series by Xie et al. (1941) in Dasuopo of Xuanwei City, Yunnan Province. It originally referred to the series of yellowish-green shale, coarse-grained sandstone, coal beds and sandy shale, over the basalt and under the red sandstone and shale (Table 2.1), bearing rich gigantopterid flora. Sheng (1962) changed it into Xuanwei Formation. After their systematic generalization and study of the Late Permian terrestrial coal-bearing formation in western Guizhou and eastern Yunnan, specialists from Nanjing Institute of Geology and Paleontology of the Chinese Academy of Science (1980) put all the late Permian coal-bearing strata (including some sea-flooding layers locally) in the area into Xuanwei Formation. Wang and Yin (2001) also take this terminology. This formation is made up of a series of terrestrial coal-bearing deposits, yellowish green, greyish-green and brownish-yellow fine-grained sandstone, siltstone, claystone, shale with coal-seams, and siderite in some parts, with rich gigantopterid flora (Fig. 2.2).

Kayitou Formation: is the overlying Xuanwei Formation, changed from the term "Kayitou Sand-shale Bed" given by Wang and Biqingchang (1940) when they investigated Dasuopo Coal Field in Xuanwei City. In lithology, the Kayitou Formation is similar to that of the Xuanwei Formation, mainly consisting of yellowish green, greyish-green and brownish-yellow siltstone, conglomerate, claystone and shale in the lower part, while its upper part contains an assemblage of yellowish-green, grayish-green and brownish-yellow siltstone, claystone and shale (Fig. 2.3). This formation is in a progressive transition with the overlying Dongchuan Formation consisting of purple-red clastics and underlying Xuanwei Formation in conformity. The widespread appearance in south China of the lycopod *Tomiostrobus* (=*Annalepis*), accompanied with bivalves, ostracodas and conchostraca has been suggested to coincide with the end of the EPPC and the beginning of Triassic (Yu et al. 2015).

Generally, the two series of the deposits across the non-marine Permian–Triassic boundary in western Guizhou and eastern Yunnan are easy to distinguish by their colors. The Xuanwei Formation is composed of a series of gray or grayish-white clastic rocks intercalated with coal beds and seams, the upper Kayitou Formation, variegated (gray, yellowish-green and purple), no coal beds or seams.

2.1.2 Shallow-Water Facies (Neritic Clastic Facies) Depositional Area

The Permian–Triassic interval in the facies area includes the Lungtan and the Yelang Formations (Fig. 2.2). The Changhsingian Lungtan Formation is dominated by fine sandstones, muddy siltstones and calcareous mudstones, intercalated with coal seam,

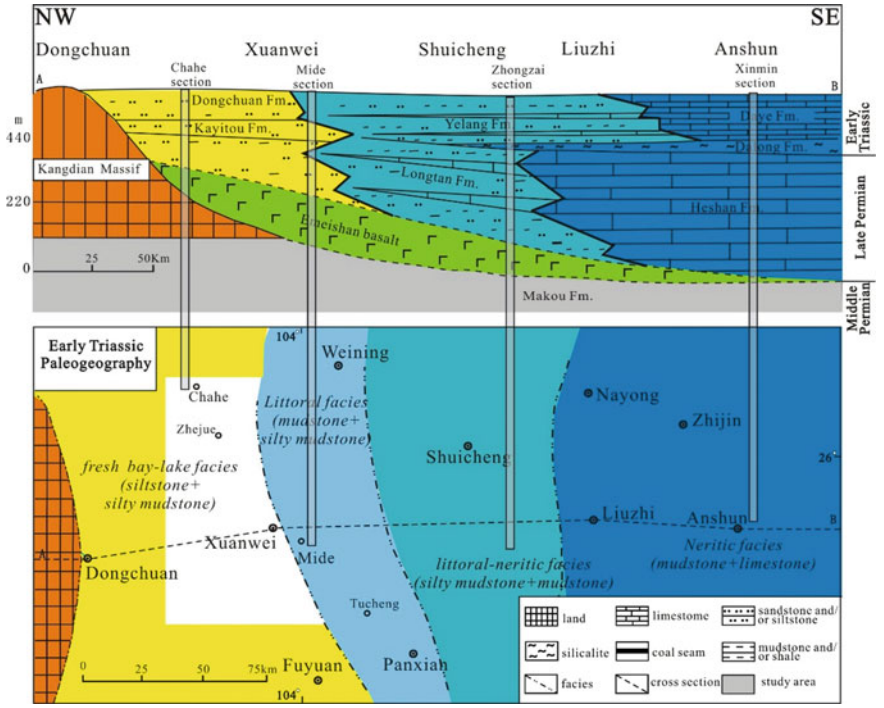

Fig. 2.3 Early Triassic Induan paleogeography and lithostratigraphy of western Guizhou and eastern Yunnan (modified after Wang and Yin 2001; Yao et al. 1980)

limestones or lens-shaped limestones, with fine laminations in calcareous mudstones (Zhang et al. 2014). It yields abundant marine fauna and plant fossils.

The Induan Yelang Formation comprises light gray thin-bedded argillaceous limestones, yellowish green calcareous mudstones and silty mudstones, intercalated with pale volcanic ash, with conodonts, bivalves, gastropods and brachiopods (Fig. 2.3) (Peng et al. 2007; He et al. 2008a; Gao et al. 2009; Zhang et al. 2013), no plant fossils.

2.1.3 Deep-Water Facies (Shallow Marine Carbonate Facies) Depositional Area

The Changhsingian Talung Formation is distributed in the western part of the Yangtze sea and is laterally equivalent to the Heshan Formation in eastern areas (Fig. 2.2). The Talung Formation mainly comprises dark grey siliceous mudstones, siliceous limestones and calcareous mudstones, intercalated with volcanic ash (Wu et al. 2018). It has abundantly yielded ammonoids and small brachiopods, and a few

bivalves, foraminifers, radiolarians (Xiang et al. 2013) and Plant fossils, which mainly comprise *Lepidostrobophyllum*, *Paracalamites*, *Pecopteris*, *Gigantopteris*, *Cordaites*, *Sphenobaiera* and large conifer with good cuticle (Li et al. 2019).

The Induan Daye Formation is composed of thin-bedded calcareous mudstones, argillaceous limestones (namely marls in the basal part) and silty limestones (overlying marls) (Fig. 2.3), with graded bedding and hummocky cross bedding in silty limestones.

2.2 Permian–Triassic Deposition Environmental Changes in Research Area

2.2.1 Carbonates Terrace Stage in Early-Middle Permian

In Late Devonian-Early Permian, western Guizhou-eastern Yunnan was in an environment of marine carbonates terrace. While in Middle Permian early Qixian, the area was a tidal flat-lagoon, when the sediments form terrestrial coal-bearing clastics (Liangshan Formation). It turned into a semi-limited terrace in Middle Permian middle-late Qixian, when series of dark gray and grayish-black medium-thick micrites and micritic bio-clastic limestone interbedded with carbonaceous shale. In Late-middle Middle Permian Maokouan, the paleogeographic pattern and deposition characteristics of the Qixian were inherited. However, the terrace was considerably wider in this stage, where medium-thick to thick massive carbonates assemblages were developed, dominated by bio-clastic limestone and limestone bearing dolomite masses.

2.2.2 Continent and Littoral-Neritic Sea Stage in Late Permian-Early Late Triassic

The Early Permian paleogeographic framework was changed by Dongwu movement (see Table 2.1). With the large-scale eruption of Emeishan basalt in the bordering area of Sichuan–Guizhou–Yunnan, most of the area was uplifted to lead to disconformable contact between Middle and Upper Permian, and thus formed Kangdian Oldland with its long axis of the main body extending approximately South to North in Yunnan Province. The research area is just located on the eastern side of this oldland (Figs. 2.2 and 2.3).

In the early Late Permian Lungtan stage, alluvial plain, littoral and neritic sea were formed successively eastward with progressive transition. The alluvial plain is dominated by rivers and lakes, forming the deposition of sandstone, siltstone, mudstone and coal-bearing series. Whereas the marine-terrestrial transition off-shore environment contained mainly tidal flats and lagoons, accompanied by the small

deltas with the coal-bearing deposition of off-shore-plain, dominated by sandstone, siltstone, mudstone, limestone and coal. The neritic sea was a semi-limited carbonates terrace, consisting mainly of micrites and bio-clastic limestone intercalated with few terrestrial clastics.

The Lungtan paleogeographic framework was then inherited during the Changhsingian except that the transgression expanded westward and the continent reduced relatively. However, the area along Xuanwei and Weining (Fig. 2.2) contained deposition from fresh-water lakes, swamps and rivers, composed mainly of sandstone, mudstone and coal. The plants were mainly dominating in the biome. In the late Changhsingian, the continent expanded to some extent and the coast shifted a little eastward.

In the Early Triassic Induan, the transgression again expanded with the coast moving westward. However, the area east to the Kangdian Massif still contained terrestrial sediments, some areas in Xuanwei of Yunnan and Weining of Guizhou (Fig. 2.3) still existed as continental. A series of grayish-green and yellowish-green sandy mudstone interbedded with purple-red ones, containing a few plant fossils with absence of coal were deposited in early Induan. In the Middle-Late Induan, the environment changed into seasonal rivers and lakes, where a series of purple-red sandy mudstone was deposited. The main characteristic in lithology is dominant to purple-red, rare organisms and development of cross-beddings.

In Panxian–Shuicheng area (Fig. 2.3) on the eastern side of the area occur late Induan nearshore tidal clastics deposits bearing limestone with abundant marine fossils dominated by bivalves and ostracodas. This environment then is changed in a gradual transitional style into marine carbonates terrace eastward.

In Olenekian, there was the similar environment as the Induan except that the coast moved further westward, causing further decrease of the continent. The rocks deposited are dominated by tidal facies sandstone, siltstone and mudstone intercalated with argillaceous limestone, oolitic limestone and dolomites. Tidal beddings are well developed in the clastic rocks. Eastwards, the carbonates take up a bigger proportion. In the deposition area predominated by clastics, few fossils are found with the exception of a few bivalves and plant fragments.

Sum up, the Permian–Triassic transition (Late Permian and Early Triassic) in the research area falls into three lithofacies zones, from east to west, respectively marine facies (clastics and carbonates facies), marine-terrestrial alternation facies (clastics facies) and terrestrial facies (clastic facies). Hence, many clear and complete Permian–Triassic boundary sections of these facies are well developed in western Guizhou and eastern Yunnan, which provide ideal area for proposing a precise locality of the Marine and terrestrial Permian–Triassic boundary strata and for correlating between the marine and terrestrial boundaries. Vertically, from Late Permian to latest Induan we can observe:

(1) Late Permian: deposited marine facies strata in Nayong–Liuzhi area, standing for the beginning of the westward transgression;
(2) Early Induan: deposited marine facies strata in Tucheng and Mide areas, standing for the other transgression reached this western area;

(3) Middle-Late Induan: deposited terrestrial strata in Tucheng area;
(4) Latest Induan: occurred marine facies deposition again in Tucheng area.

A typical terrestrial Permian–Triassic boundary section is situated in the area to the west of Xuanwei-Fuyuan (Figs. 2.2 and 2.3), where there are other P–T boundary sections ever reported, such as Laibing section (Fig. 2.1) in Xuanwei, Yunnan (Nanjing Institute of Geology and Paleontology of the Chinese Academy of Science 1980), Zhejue section and Chahe section in Weining, Guizhou (Wang and Yin 2001). To its east, there are sections of marine-terrestrial transition facies, such as Mide section in Xuanwei, Yunnan, and Tucheng section in Panxian, Guizhou and so on (Fig. 2.1).

2.3 Brief Descriptions of Sections Across Permian–Triassic Boundary

To propose an accurate accessory terrestrial Permian–Triassic section and point, three sections had been selected (Fig. 2.1) to be investigated in detail. We have performed more detailed paleontological (especially paleobotanical) and stratigraphical studies on the different facies sections in Guizhou and Yunnan Provinces, corresponding to terrestrial, terrestrial-marine alternative, shallow-water facies and deep-water facies respectively. The focus is hence on the biostratigraphy, the evolution of the paleofloras through time in relation with the sedimentary environments of these sections in this monograph. The following will present a brief introduction of these selected representative sections.

2.3.1 Terrestrial Chahe Section in Weining, Guizhou Province

The Chahe Section in Weining County, western Guizhou Province (Figs. 2.1 and 2.4a) has been studied in numerous previous investigations (Yu et al. 2015; Chu et al. 2016). The bottom of this section is about 2 km away from exposures of the Emeishan basalt. After loose sediments, this section exposes the Xuanwei Formation (Beds 1–70) and overlying Kaiyitou Formation (Beds 71–89) (Fig. 2.4), then conformably overlies the Dongchuan Formation. According to a zircon U–Pb date of 252.30 ± 0.07 Ma from volcanic ash in Bed 68 of the Xuanwei Formation (Shen et al. 2011), the Permian–Triassic boundary (PTB) may be higher than the lithological boundary between the Xuanwei and Kaiyitou formations in this section.

The Xuanwei Formation at the Chahe section contains numerous plant fossils including the Cathaysian wetland genera *Lepidodendron*, *Pecopteris*, *Fascipteris* and *Gigantopteris*. Plant fossils are not only abundant in each layer, but also this section contains at least 31 plant-bearing layers with their vertical distributions shown in

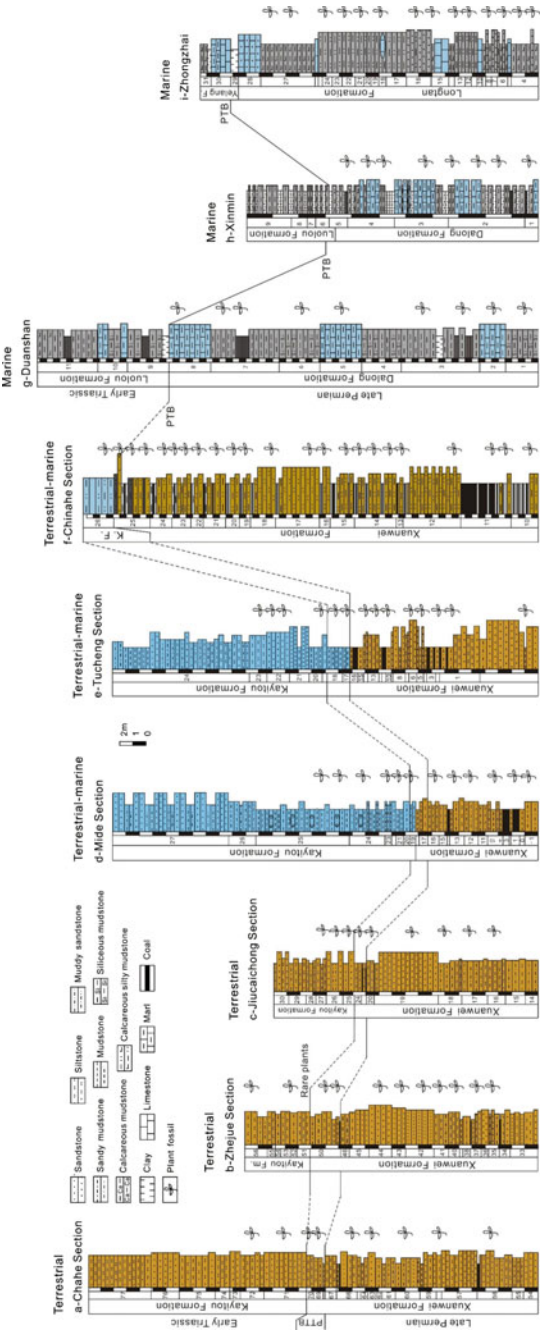

Fig. 2.4 Lithological Column, Fossil plants and palynomorphs sample localities of different facies Permian–Triassic transitional representative sections in South China

Fig. 2.4. In the Chahe section, most of the plants stop at Bed 69 with after the EPPC only *Peltaspermum* sp. occurring in Bed 70. Fossil plants are absent in the Kaiyitou Formation in the Chahe section (Fig. 2.4a).

In the overlying Kayitou Formation, the plant fossils surviving from the Late Permian disappear above Bed 71, whilst plants of the genus *Peltaspermum* occur in association with conchostracans in the middle-upper part of Bed 71, which is a conchostracan-rich horizon. A total of 45 conchostracan specimens were collected in an approximately 8 m-thick interval between Bed 71 and 78, including the genera *Euestheria* and *Palaeolimnadia* (Liao et al. 2020). In the red-purple Dongchuan Formation, except in the basal part, neither conchostracans nor any other fossils have been observed but few plant fragments.

2.3.2 Terrestrial-Marine Transitional Chinahe Section in Xuanwei, Yunnan Province

The Chinahe Section in Haidai town, Xuanwei district of eastern Yunnan Province (Figs. 2.1 and 2.4f) is reported for the first time in this book. This section starts from the Emeishan Basalt (Bed 0) that is unconformably overlain by the upper terrestrial facies of the Xuanwei Formation (Beds 1–25). Marine, grayish green mudstone facies of the Kaiyitou Formation (Bed 26) which in turn overlain by the purple-red Dongchuan Formation conformably overly the Xuanwei Formation (Fig. 2.4f).

The Xuanwei Formation in the Chinahe Section commences with a thick layer of grayish black mudstone (Bed 1), that contains large amounts of well-preserved plant fossils. In Bed 1 *Lobatannularia*, *Pecopteris* and *Gigantopteris* are common, but the flora in this bed is diverse and also contains a range of sphenopsids (*Lobatannularia cathaysiana*, *L. heianensis*, *Paracalamites stenocostatus and Schizoneura amnchuriensis*), *Marattialean ferns* (*Pecopteris* (*Asterotheca*) *guizhouensis*, *P.* (*A.*) *orientalis*, *P.* (*A.*) *hemotelioides*, *P. sahnii, Fascipteris sinensis* and *F. hallei*), gigantopterids (*Gigantonoclea guizhouensis*, *G. rosulata*, *Gigantopteris dictyophylloides and Gigantopteris nicotianaefolia*), ferns (*Cladophlebis permica*, *C. ozakii*) and occasional gymnosperm leaves (*Neuropteridium* sp., *Peltaspermum* sp.,*Taeniopteris multinervis*, *Rhipidopsis panii*). Above Bed 1, the lithology changes into cycles of grayish yellow or grayish green thin-bedded siltstone to pelitic siltstone and thin coals, as well as pale gray or grayish blue thin-bedded clay or mudstone (Bed 2–25). Usually thin-bedded mudstones on coals [in Beds 3, 12, 16, 25] contain some plants fragments that are not identifiable to species level, including fragments of *Lepidostrobophyllum*, gigantopterids, *Compsopteris*, *Pecopteris* and *Taeniopteris*. Until Bed 25 there are more grayish black, medium bedded, pelitic siltstones mixed with paper coals as well as grayish yellow or green silty-mudstone. Above Bed 25, there are two gray, thin-bedded mudstones together with a black mudstone layer, which may be comparable with the sandwich-like lithologies in the Chahe Section at the boundary of the Xuanwei and Kaiyitou formations. Above this "sandwich-like" mudstone layer,

a layer of grayish yellow, thin-bedded sandstone occurs and upon a layer of black siltstone contains numerous of fragmentary specimens of *Peltaspermum*, *Lepidopteris*, *Pecopteris* and *Gigantopteris*. In the boundary of the Xuanwei and Kaiyitou formations (boundary-Bed 26), there is a monotypic layer of dispersed *Tomiostrobus* in the dark grayish black thin-bedded siltstone (in the bottom of bed 26). After the layer of *Tomiostrobus* comes the grayish blue to greenish blue thick-bedded siltstones of Kaiyitou Formation, which contains no plant fossil but abundant conchostraca and bivalves.

2.3.3 Shallow-Water Zhongzhai Section, Liupanshui, Guizhou Province

The Permian–Triassic interval at Zhongzhai includes the Lungtan Formation and basal part of Yelang Formation. The Zhongzhai section is situated about 1 km northeast of Zhongzhai Village, Liuzhi County, south-western Guizhou Province (Figs. 2.1 and 2.4i). At Zhongzhai section, the lower part (Beds 1–3) of the Lungtan Formation is dominated by fine-grained sandstones and muddy siltstones with coal beds and seams. Lithology of the upper part of this formation (Beds 4–26) is the same as that of the lower part, but there is no coal seam in the upper part, representing a littoral setting (Zhang et al. 2014). The plant fossils that standing for the typical Cathaysian Flora are abundant. The top part (Bed 27) of the Lungtan Formation is dominated by calcareous mudstones, with fine laminations (Zhang et al. 2014). The fauna from Bed 27 at Zhongzhai mainly comprises dense-populated, well-preserved brachiopods (forming shell beds) and lacks radiolarians. These features suggest that this interval represents a low-energy back-barrier shallow-marine setting above the fair-weather wave-base (generally shallower than 50 m deep) (Shen et al. 2011; He et al. 2017, 2019).

The basal Yelang Formation comprises light gray thin-bedded argillaceous limestones, yellowish green calcareous mudstones and silty mudstones, intercalated with pale volcanic ash, with conodonts, bivalves, gastropods and brachiopods (Peng et al. 2007; He et al. 2008; Gao et al. 2009; Zhang et al. 2013; He et al. 2019), no plant fossil.

2.3.4 Deep-Water Xinmin Section in Anshun, Guizhou Province

The Xinmin Section is located at Xinmin valley, Puding County, Guizhou Province (Figs. 2.1 and 2.4h) and is easily accessible, well exposed, and displays a continuous sedimentation from the thin-bedded siliceous mudstone in the Talung Formation and

mudstone in the Luolou Formation, indicating a deep water basinal facies. Previously, primary works have been carried on the adjacent area of this section. Yao et al. (1980) have found abundant ammonoids, gastropods, brachiopods and foraminifers at the Jiaozishan Section, which is about 4 km south to Xinmin. Research on Guizhou stratigraphy (Dong 1997) showed that ammonoid *Pseudotirolites* is common in the Talung Formation in this area, associated with brachiopods, bivalves, gastropods, trilobites and fossil plants which mainly come from black, thin-bedded mudstone interlayers in the middle of Bed 2 and the top of Bed 4. These comprise *Lepidostrobophyllum*, *Paracalamites*, *Pecopteris*, *Gigantopteris*, *Taeniopteris* leaves with good cuticle, *Cordaites*, *Sphenobaiera* and a large number of fossil conifers with secondary or tertiary branches and well-preserved cuticles have been identified as *Anshuncladus xinminensis*, *A. contiguous*, *A. aduncatus*, *Pseudoullmania frumentarioides* and *Szecladia multinervis*.

Recently, many researches related to the end-Permian event were focused on the Xinmin Section. Feng et al. (2011) first described the strata across the PTB and reported trilobite *Pseudophillip* sp. from the top of Changhsingian at this section. Based on geochemistry works, Shen et al. (2013) discussed the volcanism records at this section. Conodont *Hindeodus parvus* in the upper part of Bed5-3 firstly occurred suggests that the PTB should be placed in Bed 5–3 (Fig. 2.4h) (Zhang et al. 2014).

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