3 Depositional Sequences, Biotic Assemblages and Review on Changhsingian (or Late Changhsingian) Palaeo-Water Depths of Studied Sections

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3.1 Depositional Sequences and Biotic Assemblages

The Permian–Triassic depositional sequences at Hushan include the upper Talung Formation and Lower Chinglung Formation (Fig. 3.1; see He et al. 2011). The upper Talung Formation is dominated by dark grey thin-bedded cherts and siliceous mudstones, intercalated with medium-bedded grey argillaceous limestones, thin-bedded calcareous mudstones and volcanic ash. The siliceous mudstones abundantly yield horizontal beddings. The upper Talung Formation contains abundant radiolarians, ammonoids, conodonts, small brachiopods, bivalves, and a small number of ostracods and foraminifers. The lower Talung Formation at Hushan is covered by Quaternary sediments. The basal part of the Lower Chinglung Formation mainly comprises yellowish calcareous mudstones, thin- to medium-bedded argillaceous limestones, interbedded with volcanic ash, and contains ammonoids and bivalves.

The Permian–Triassic interval at Majiashan includes the upper Talung Formation and the basal part of the Yinkeng Formation (Fig. 3.1; see He et al. 2008a). The upper Talung Formation is characterized mainly by grey to greyish-black, thin-bedded, carbonaceous mudstones, siliceous mudstones and cherts. The upper Talung Formation yields a few small foraminifers, bivalves and brachiopods, microgastropods, ostracods, and abundant ammonoids, radiolarians. The basal part of the Yinkeng Formation is characterized by greyish green thin-bedded calcareous mudstones interbedded with argillaceous limestone, with ammonoids and bivalves.

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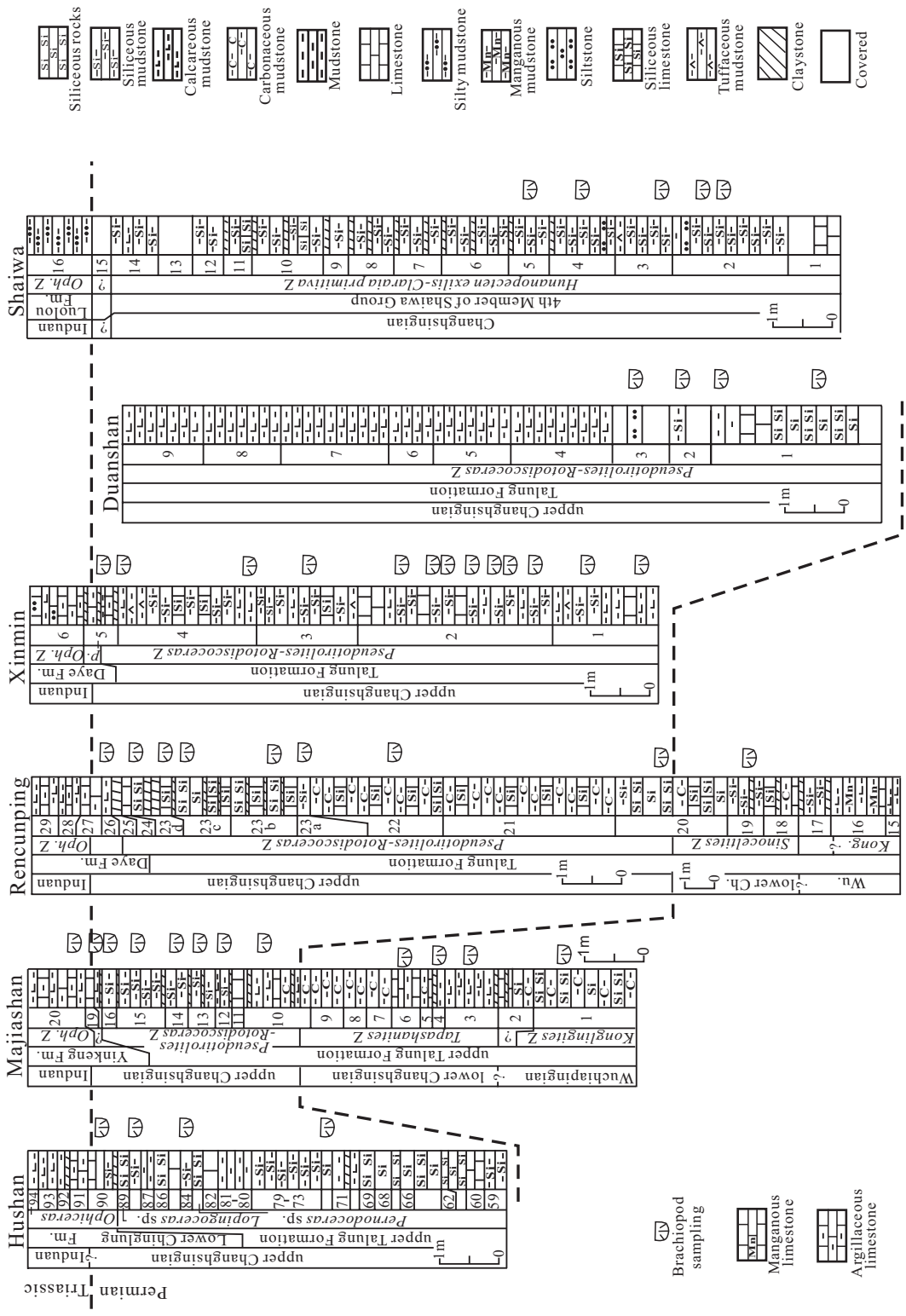

Fig. 3.1 Stratigraphic columns of Hushan, Majiashan, Rencunping, Xinmin, Duanshan and Shaiwa sections. Fm.- Formation, Wu.- Wuchiapingian, Ch.- Changhsingian, *Oph.- Ophiceras, Kong.- Konglingites* Zone, *p.- Hindeodus parvus* Zone, Z- Zone

The Permian–Triassic interval at Rencunping includes the Talung Formation and basal part of Daye Formation (Fig. 3.1; see Xiao et al. 2017). The Talung Formation is dominated by greyish-black thin-bedded cherts, siliceous mudstones, siliceous limestones and carbonaceous mudstones, intercalated with volcanic ash. The Talung Formation abundantly yields ammonoids, radiolarians, small brachiopods and a few small bivalves. The basal part of the Daye Formation is characterized by greyish green thin-bedded calcareous mudstones interbedded with argillaceous limestone, with abundant ammonoids and bivalves.

The Permian–Triassic transition at Xinmin spans the Changhsing, Talung and Daye Formations (Wu et al. 2018). This study focuses on the Talung Formation (Fig. 3.1). 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, spongy spicules and spherical radiolarians (Xiang et al. 2013), as well as transported plant fragments (Song et al. 2015). Bouma Sequence is commonly observed in siliceous and argillaceous limestone beds. The Daye Formation is composed of thin-bedded calcareous mudstones, argillaceous limestones (namely marls in the basal part) and silty limestones (overlying marls) (Fig. 3.1), with graded bedding and hummocky cross bedding in silty limestones.

The uppermost part of the Permian at Duanshan comprises the Talung Formation (Fig. 3.1; see Wu et al. 2018) and the Permian–Triassic boundary sequence is covered by the Quaternary sediments. The Talung Formation at Duanshan is dominated by light grey calcareous mudstones, with cherts in the lower part of the formation, and intercalated with limestones, siliceous mudstones and siltstones. Ammonoids have been found throughout the formation and a mixed brachiopod fauna (dominated by warm-water elements, but associated with cool-water elements, e.g., *Attenuatella* and *Costatumulus*) found in the lower part of the formation (Zhang and He 2009; He et al. 2014).

The Permian–Triassic transition at Shaiwa includes the Changhsingian Shaiwa Group and the Lower Triassic Luolou Formation. The Fourth Member of the Shaiwa Group is focused in this study (Fig. 3.1). It comprises greyish black thin-bedded siliceous mudstones, intercalated with greyish green thin-bedded siliceous limestones and pale volcanic ash. It yields abundant ammonoids, radiolarians and a few brachiopods, bivalves and foraminifers (Chen et al. 2006). The top part of Shaiwa Group and the Permian–Triassic boundary have been covered by the Quarternary sediments. The basal part of the Luolou Formation is composed of greyish yellow thin-bedded silty mudstones. It yields ammonoids and bivalves.

The Permian–Triassic intervals at Xiejiaping and Dengcaoba include the Talung Formation and basal part of the Daye Formation (Fig. 3.2). The Talung Formation at Xiejiaping is dominated by greyish black thin-bedded carbonaceous mudstones, siliceous mudstones and limestones, intercalated with cherts, calcareous mudstones and volcanic ash. It yields abundant ammonoids and a few brachiopods and conodonts. The basal Daye Formation comprises thin-bedded limestones and calcareous mudstones, with volcanic ash intercalations. It yields ammonids, conodonts and bivalves. The Talung Formation at Dengcaoba is dominated by greyish black thin-bedded cherts, carbonaceous mudstones and calcareous mudstones, with ammonoids in the lower part and small brachiopods, ammonoids and bivalves in the upper part. The basal Daye Formation comprises thin-bedded argillaceous limestones and calcareous mudstones, with ammonoids and brachiopods.

The Permian–Triassic interval at Shangname includes the Talung Formation and basal part of Luolou Formation (Fig. 3.2). The Talung Formation comprises greyish green thin-bedded tuffceous mudstones, with ammonoids and abundant (monospecific) brachiopods. The Lower Triassic Luolou Formation overlies the Upper Permian Talung Formation by a fault. The Luolou Formation comprises yellowish green thin-bedded calcareous mudstones, with a few ammonoids.

The Permian–Triassic transitional sequence at Dongpan is continuous and includes the Talung Formation and basal part of the Luolou Formation,

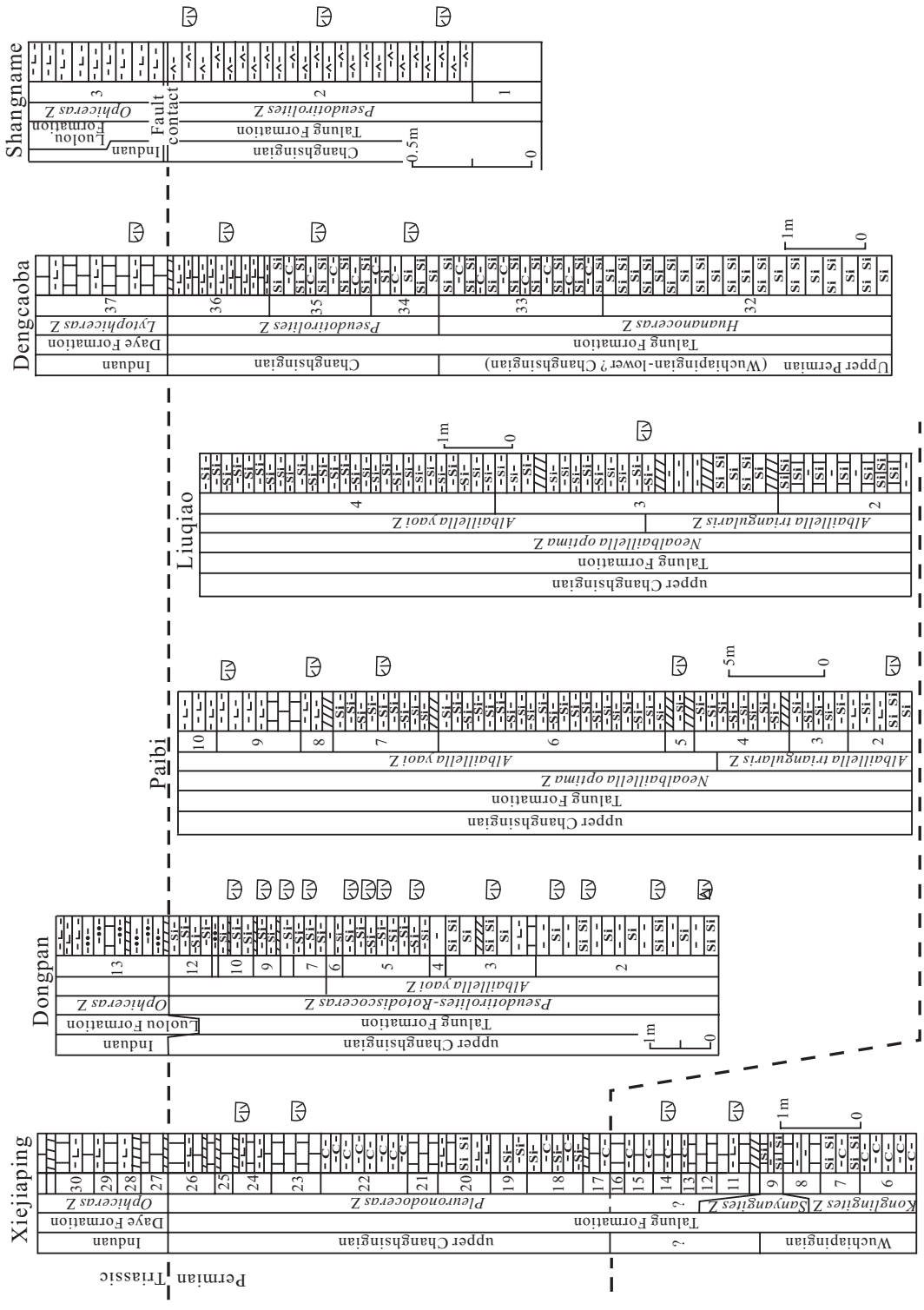

Fig. 3.2 Stratigraphic columns of Xiejiaping, Dongpan, Paibi, Liuqiao, Dengcaoba and Shangname sections. *Z*- Zone. Legends are same to Fig. 3.1

but the top part of Permian and the Lower Triassic at Paibi and Liuqiao are covered by the Quaternary sediments (Fig. 3.2). The Talung Formation is dominated by greyish green thin-bedded siliceous mudstones and cherts, intercalated with yellowish green thin-bedded mudstones, calcareous mudstones and manganous limestones at Dongpan, Paibi and Liuqiao. It yields abundant ammonoids, pelagic radiolarians and cool-water brachiopods, and a few bivalves, foraminifers and palaeopsychrospheric ostracods (He et al. 2005, 2007a; Bu et al. 2006; Feng et al. 2007; Gu et al. 2007; Yuan et al. 2007; Yang et al. 2015). The basal Luolou Formation comprises yellowish brown silty mudstones and calcareous mudstones, intercalated with light gray thin-bedded limestones. It yields abundant ammonoids and bivalves.

The Permian–Triassic interval at Zhongzhai includes the Lungtan Formation and basal part of Yelang Formation (Fig. 3.3). The Lungtan Formation is dominated by fine sandstones, muddy siltstones and calcareous mudstones, intercalated with limestones or lens-shaped limestones, with fine laminations in calcareous mudstones (Zhang et al. 2014). It yields abundant brachiopods (forming shell beds) and a few conodonts, bivalves, gastropods, foraminfers and ostracods. 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. 2008b; Gao et al. 2009; Zhang et al. 2013).

The Permian–Triassic interval at Huangzhishan includes the top part of the Changhsing Formation and lower part of the Yinkeng Formation (Fig. 3.3). The top part of the Changhsing Formation comprises light gray medium- to thin-bedded bioclasitic limestones, with abundant corals, brachiopods, crinoids, sponges, gastropods, bryozoans, ostracods, foraminifers, algae and a few conodonts (Chen et al. 2008, 2009). The Yinkeng Formation comprises greyish green thin-bedded argillaceous mudstones and calcareous mudstones (He et al. 2015), with abundant brachiopods (forming shell beds) and a few bivalves, conodonts and foraminfers (Chen et al. 2008, 2009; He et al. 2015, 2017).

The Permian–Triassic interval at Daoduishan includes the Changhsing Formation and basal part of the Yinkeng Formation (Fig. 3.3). The Changhsing Formation comprises gray to light gray thin- to medium-bedded bioclastic limestones, occasionally intercalated with gray thick-bedded bioclastic limestones and black cherty nodules, with hummocky cross-stratification, parallel stratification, or wavy cross-bedding (He et al. 2016). It yields conodonts, brachiopods, foraminifers, algae, ostracods, fusulinids, sponges and crinoids. The basal Yinkeng Formation is composed of dark gray thin-bedded calcareous mudstones and dark gray thin- to medium-bedded argillaceous limestones, intercalated with pale volcanic ash, with fine laminations in calcareous mudstones (He et al. 2016). It yields conodonts, bivalves and a few foraminifers and brachiopods.

3.2 Palaeo-Water Depths of Studied Sections During the Changhsingian (or Late Changhsingian)

Lithological and biotic features are key and basic aspects for the analysis of sedimentary environments. Generally, carbonate deposits accumulate above the lysocline, siliceous carbonate accumulates between the lysocline and the carbonate compensation depth (CCD), and opal or siliceous sediments form below the CCD (Weber and Pisias 1999; Weber and von Stackelberg 2000; Dittert and Henrich 2000; Edmond and Huh 2003). As the position of the CCD is deeper than the lysocline (Weber and Pisias 1999), siliceous (opaline) mudstone will accumulate in deeper water than limestone and siliceous limestone. Additionally, the fine-grained sediments (e.g., siliceous mudstone) with weak bioturbation could have accumulated in a setting from outer shelf to basin, with >120 m water depths (Immenhauser 2009) and therefore indicates a deeper water setting.

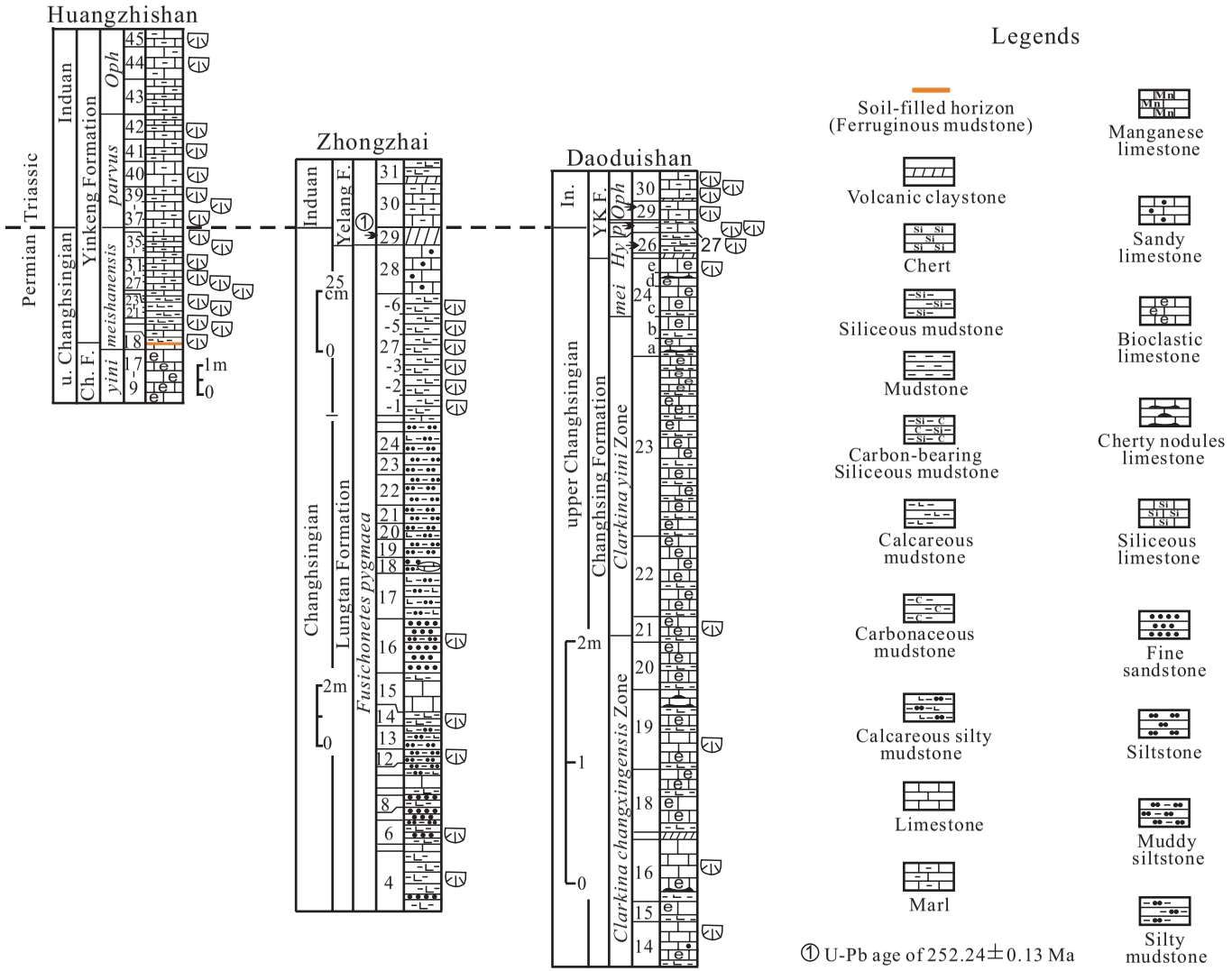

Fig. 3.3 Stratigraphic columns of Huangzhishan, Zhongzhai and Daoduishan sections. u.- upper, Ch.- Changhsing, F.- Formation, *yini- Clarkina yini* Zone, *meishanensis/mei- Clarkina meishanensis* Zone, *parvus/p- Hindeodus parvus* Zone, *Oph- Ophiceras* Zone, *Hy- Hypophiceras* Zone, In.- Inudan, YK- Yinkeng

The research on radiolarian palaeo-water depths revealed that the presence of spherical radiolarians (Entactinaria or Spumellaria forms), lack of Latentifistularia (excluding *Ishigaum obesum* and *Quadricaulis inflata*) and lack of Albaillellaria forms together are generally taken to indicate water depths <200 m (outer shelf), the presence of Latentifistularia or Albaillellaria forms generally indicates water depths of approximately 200 m or deeper. If Latentifistularia and Albaillellaria forms dominated a radiolarian fauna (especially the abundant presence of *Neoalbaillella* forms), it would mean that water depths were more than 500 m (Kozur 1993; He et al. 2008a, 2011; Xiao et al. 2017).

At Hushan, the upper Talung Formation is overwhelmingly dominated by cherts and siliceous mudstones, with abundant presence of radiolarian Albaillellarians and Latentifistularians in a few horizons and abundant presence of ammonoids and conodonts in most beds (He et al. 2011). Therefore, the water depths would have reached about 200 m or deeper when the maximum transgression took place during the late Changhsingian at Hushan (Fig. 3.4).

At Majiashan, the upper Talung Formation is dominated by carbonaceous mudstones, siliceous mudstones and cherts, with the presence of radiolarian Latentifistularians (*Ishigaum obesum*, *Quadricaulis inflata* and *Foremanhelena robusta*) in a few horizons (He et al. 2008a; Gui et al. 2009), abundant presence of ammonoids and a few presences of small benthonic invertebrates. Therefore, the water depth was 100–200 m when the maximum transgression took place during the late Changhsingian (Fig. 3.4; He et al. 2008a; Xiao et al. 2017).

At Rencunping, the Talung Formation is dominated by cherts, siliceous mudstones, siliceous limestones and carbonaceous mudstones, with abundant presences of Entactinaria, Spumellaria and Latentifistularia elements (e.g., *Ishigaum trifustis*, *Foremanhelena robusta*, *Nazarovella scalae*, *Latentifistula similicutis*) and a few presences of Albaillellaria elements (*Albaillella triangularis*, *Albaillella yaoi yaoi*, *Albaillella yaoi longa*, *Albaillella protolevis*, *Albaillella angusta* and *Albaillella excelsa*) in some intervals (Xiao et al. 2017) and small benthonic invertebrates. Therefore, the water depths would have reached deeper than 200 m (or deep to 300 m) during the Changhsingian at Rencunping (Fig. 3.4; see Xiao et al. 2017).

At Xinmin, the Talung Formation is dominated by siliceous limestones and siliceous mudstones. The biotic association in this formation is mainly composed of planktonic cephalopods, associated with spherical radiolarians (Xiang et al. 2013) and small benthonic invertebrates, indicating the water depths would have been <200 m in an outer shelf (Fig. 3.4; see Xiao et al. 2017).

At Duanshan, the Talung Formation is dominated by siliceous limestones and siliceous mudstones. The biotic association in this formation is mainly composed of planktonic cephalopods,

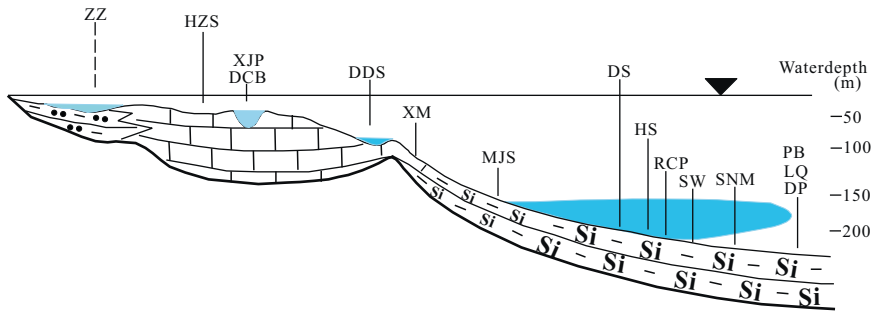

Fig. 3.4 Sketch diagram showing the palaeogeographic setting and palaeo-bathymetry of studied section (revised after He et al. 2017). Blue represents anoxic and light blue represents dysoxic. ZZ- Zhongzhai, HZS- Huangzhishan, XJP- Xiejiaping, DCB- Dengcaoba, DDS- Daoduishan, XM- Xinmin, MJS- Majiashan, DS- Duanshan, HS- Hushan, RCP- Rencunping, SW- Shaiwa, SNM- Shangname, PB- Paibi, LQ- Liuqiao, DP- Dongpan

associated with mixed brachiopods (warm- and cool-water elements). Radiolarian Latentifistularia and Albaillellaria elements have been found in a few horizons of the Talung Formation from the other section nearby Duanshan. Therefore, the water depths would have reached about 200 m when the maximum transgression took place during the Changhsingian at Duanshan (Fig. 3.4).

At Shaiwa, the Fourth Member of Shaiwa Group is dominated by siliceous mudstones, with pelagic radiolarians, bathyal trace fossil *Nereites*, small invertebrates and deep-water sedimentary structures (e.g., Bouma Sequence) (Chen et al. 2006). All these features indicate a bathyal setting (deeper than 200 m; see Chen et al. 2006) during the Changhsingian at Shaiwa (Fig. 3.4).

At Xiejiaping and Dengcaoba, the Talung Formation is dominated by carbonaceous mudstones, siliceous mudstones and limestones, with planktonic cephalopods and small benthonic invertebrates and lack of radiolarians, indicating a setting of interplatform basin (water depths slightly deeper than a carbonate platform) (Fig. 3.4).

At Shangname, the Talung Formation is uniquely composed of tuffceous mudstones, with abundant and monospecific brachiopiod *Martinia liuqiaoiensis* which commonly occurred in the Talung Formation of the deep-water Dongpan section (see below). Outlines of Radiolarian shells have been observed in the rocks and most of shells have not been preserved because of weathering. These features probably indicate a deep-water setting (probably similar to the Dongpan section) during the Changhsingian at Shangname (Fig. 3.4).

At Dongpan, Paibi and Liuqiao, the Talung Formation is overwhelmingly dominated by cherts and siliceous mudstones, with quite abundant presence of deep-water radiolarian Albaillellarians (e.g., *Neoalbaillella grypa*, *Albaillella levis*, *Albaillella triangularis*) in most beds and presences of ammonoids, small bivalves and foraminifers, mixed brachiopods (warm-water and cool-water elements), siliceous sponges and cold-water ostracods (He et al. 2005, 2007a, b; Feng et al. 2007; Gu et al. 2007; Yuan et al. 2007; Liu et al. 2013; Yang et al. 2015). The research on radiolarians and palaeo-bathymetry at Dongpan revealed that the water depths were commonly deeper than 200 m and even deeper than 500 m through some intervals of the Talung Formation (Fig. 3.4; He et al. 2007c; Xiao et al. 2017).

At Zhongzhai, the upper part (Beds 4–26) of the Lungtan Formation is dominated by fine-grained sandstones and muddy siltstones, representing a littoral setting (Zhang et al. 2014). The top part (Bed 27) of the Lungtan Formation is dominated by calcareous mudstones, with fine laminations (see Zhang et al. 2014). The fauna from Bed 27 at Zhongzhai mainly comprises densely-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, see Immenhauser 2009; Shen et al. 2011) (Fig. 3.4; He et al. 2017).

At Huangzhishan, the basal part (Beds 19–36) of the Yinkeng Formation is dominated by calcareous mudstones and marls, abnormally with abundant brachiopods and lacks radiolarians. The microfacies and palaeontological features suggest these intervals were mainly deposited in a shallow, low-energy setting just below the fair-weather wave-base (slightly deeper than 50 m deep; see Chen et al. 2009; Immenhauser 2009) (Fig. 3.4; He et al. 2017).

At Daoduishan, the upper part (Beds 14–24) of the Changhsing Formation is dominated by bioclastic limestones, with tempestite-related structures (He et al. 2016), and with abundant conodonts and benthonic invertebrates, together with a few spherical radiolarians. The presence of tempestite-related structures suggests that the palaeo-water depth was near the storm wave base (50–250 m deep, see Immenhauser 2009), while the presence of spherical radiolarians indicates a water depth deeper than Huangzhishan or Zhongzhai but <100 m. Therefore, the water depths would have been 50–100 m during the late Changhsingian at Daoduishan (Fig. 3.4; He et al. 2017).

In summary, the depth-related palaeoenvironments in South China are further classified into three types in this chapter, based on the above bathymetric analysis, in order to discuss on the relationship between body-size changes and palaeobathmetry. Type 1 is of shallow-water settings (i.e., *ca* 0–50 m deep, including Zhongzhai, Huangzhishan, Xiejiaping, Dengcaoba) (Fig. 3.4). Type 2 is of moderately deep-water setting (i.e., 50–100 m, including Daoduishan). Type 3 is of deep-water settings (i.e., *ca* 100–500 m or even deeper than 500 m, represented by Xinmin, Majiashan, Duanshan, Hushan, Rencunping, Shaiwa, Shangname, Dongpan, Paibi, Liuqiao) (Fig. 3.4).

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