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The Global Stratotype Section and Point (GSSP) for the boundary between the Capitanian and Wuchiapingian Stage (Permian)

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The Global Stratotype Section and Point (GSSP) for the boundary between the Capitanian and Wuchiapingian stages, also the boundary between the Guadalupian and Lopingian Series is defined at the First Appearance Datum (FAD) of the conodont Clarkina postbitteri postbitteri *at the base of Bed 6k in the Penglaitan Section along the Hongshui River in Guangxi Province, South China. This point is within a chronomorphocline from* Clarkina postbitteri hongshuiensis *to* C. dukouensis *and nearly coincides with the Middle-Upper Absaroka Megasequence boundary and as such is documented within a continuously deposited carbonate lowstand succession with deep-water facies of the Maokou Formation below and deep-water facies of the Heshan Formation above. Furthermore, this point also coincides with a major extinction of various Permian fossils including corals, fusulinaceans, ammonoids and brachiopods. The proximity to an apparently global major sequence boundary and extinction event will serve as a means of correlation of this GSSP into other regions in which the defining taxon is not present because of profound provincialism during the Middle and Upper Permian. Carbon isotopic trends and magnetostratigraphic signatures are also provided to help correlate this GSSP into other regions, including those with continental facies successions. The Tieqiao Section near the county town of Laibin is also described as a supplementary reference section.*

Introduction

The uppermost Permian used to be referred to as a stage or a subseries, the Tatarian in the traditional standard succession. In its type locality in the Urals of Russia, the Tatarian is a terrestrial succession without marine fossils and cannot, therefore, provide a good section for defining the boundary stratotype for the Upper Permian. Marine successions of this part of the Permian have been called Lopingian (Grabau, 1923; Huang, 1932; Sheng, 1962), the Dzhulfian (Glenister and Furnish, 1961; Furnish and Glenister, 1970), the Transcaucasian or the Yichangian (Waterhouse, 1982) based on successions in South China or the Transcaucasus. The Lopingian Series is not only a name proposed relatively early, but it is also represented by a fully developed marine succession with highly diverse faunas in South China. Through a vote in 1995, the Permian Subcommission on Stratigraphy (SPS), International Commission of Stratigraphy, decided to adopt a chronostratigraphic scheme with the Lopingian Series as an international standard for the youngest series of the Permian (Jin et al., 1997).

Grabau (1923) introduced the “Loping Series” for a Late Permian lithostratigraphic unit in South China. Huang (1932) raised it to the rank of series to include all Permian deposits that overlie the Maokou Limestone. Sheng (1962) adopted the Lopingian Series as the upper series of a two-fold Permian and referred it to a series apparently higher than the Guadalupian Series, based on the fusulinacean succession. He included two units, the Wuchiaping and Changhsing formations, within the series, which were subsequently transferred into chronostratigraphic units, the Wuchiapingian (Kanmera and Nakazawa, 1973) and Changhsingian (Furnish and Glenister, 1970) Stages. Among other stage names for this time interval, the Dzhulfian (or Djhulfian) Stage is comparable with the Wuchiapingian Stage. A study on the Guadalupian-Lopingian (G/L) boundary sequence in central Iran showed that the environment of the Dzhulfian unit (Unit 5 of the Hambast Formation) was shallow and restricted with repeated erosional surfaces and shelly layers in Abadeh (The Iranian-Chinese Research Group, 1995). The unconformity between Unit 5 and Unit 6 of the Hambast Formation (Taraz, 1971) is not only marked by a distinct lithologic and depositional sequence change as well as the occurrence of gypsum-bearing shale beds in Julfa, but also by the lack of conodonts from the *Clarkina postbitteri sensu lato*, *Jinogondolella granti* to *J. xuanhanensis* Zones of pelagic facies around the base of the Dzhulfian Stage (Sweet and Mei, 1999). For these reasons, SPS agreed to adopt the Wuchiapingian Stage rather than the Dzhulfian Stage.

The base of the Wuchiapingian Stage as well as the Lopingian Series was historically designed to coincide with a global regression, that is, the boundary surface between the Middle and the Upper Absaroka Megasequences. This boundary also coincides with an important mass extinction event, or the first phase of the end-Permian extinction which was named pre-Lopingian crisis or end-Guadalupian extinction (Jin, 1993; Jin et al., 1994; Stanley and Yang, 1994; Shen and Shi, 1996, 2002; Wang and Sugiyama, 2000). This global lowstand and associated major extinction event are the very reasons why a third Permian Series has been adopted by SPS and are fundamental to the definition and correlation.

Capitanian-Wuchiapingian (C/W) boundary successions were reported from South China, Abadeh and Julfa in central Iran, SW USA, and the Salt Range, Pakistan. Extensive surveys on marine

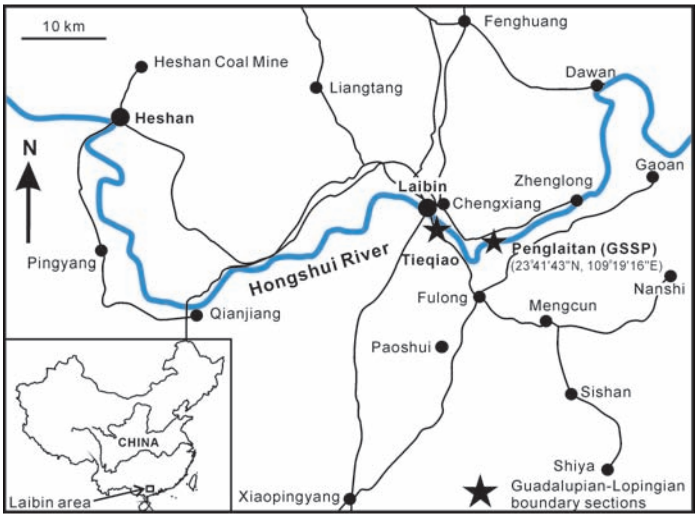

Figure 1 Location map of the Tieqiao and Penglaitan sections in the Laibin area, South China.

sections over the last decade prove that only a few sections exhibit continuous deposition across the C/W boundary and those with a complete succession of pelagic faunas are particularly rare. In the type region of the Guadalupian Series, the Capitanian Stage is overlain by evaporite deposits of the Ochoan Series. No pelagic fauna has been reported from the Capitanian strata in central Iran and the Salt Range, Pakistan. In the shallow marine successions of the C/W boundary interval in South China, there is usually a depositional gap. The Penglaitan and Tieqiao (Rail-Bridge) sections in the Laibin area, Guangxi Province, South China (Figure 1) are unique among these sections in that they contain a complete and inter-regionally correlatable succession of pelagic conodont zones and other diverse, and inter-regionally correlatable Permian fossils.

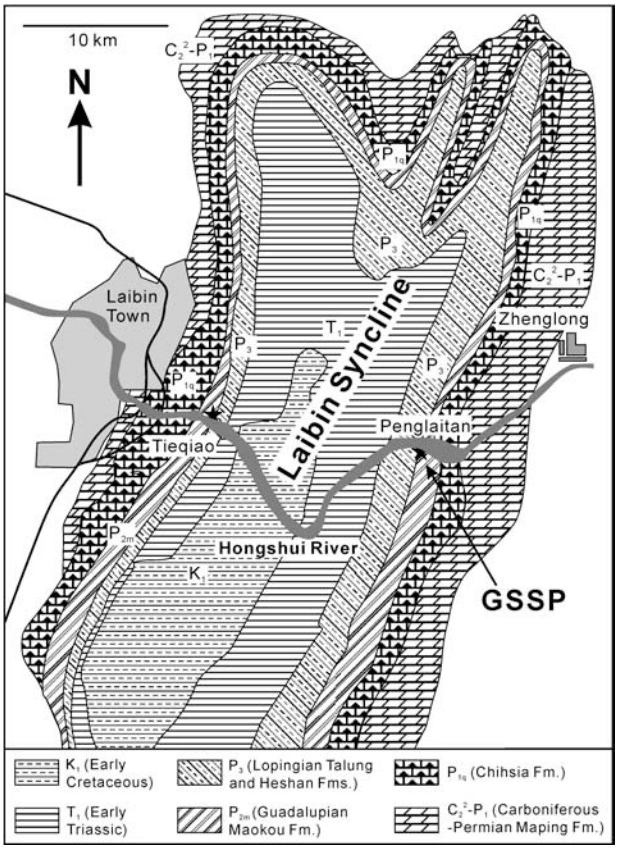

Figure 2 Geological map showing the Laibin Syncline and the positions of sections (modified from Jin et al., 1998).

The Global Stratotype Section and Point (GSSP) for the basal boundary of the Wuchiapingian Stage has been defined at the first occurrence of the conodont *Clarkina postbitteri postbitteri* Mei and Wardlaw (in Mei et al., 1994a) at the base of Bed 6k of the Penglaitan Section, with the Tieqiao Section on the western slope of the Laibin Syncline (Figure 2) as a supplementary reference section.

Description of type sections

The county town of Laibin is midway between Guilin, one of the major tourist cities in China, and Nanning, the provincial capital of Guangxi Autonomous Region. Structurally, these sections are located on the both slopes of the Laibin Syncline (Figure 2). Penglaitan is the name of a rocky islet of the Hongshui (Red-water) River, some 20 km east of Laibin. The Maokouan-Lopingian strata of the Penglaitan Section was measured on the eastern slope of the syncline along the southern bank of the Hongshui River nearby this rocky islet (23° 41' 43"N, 109° 19' 16"E). The Tieqiao (Rail Bridge) Section on the western slope of the syncline is situated on the northern bank of the Hongshui River, 5 km southeast to the county town of Laibin (Figure 2).

Permian rocks are extensively exposed along the banks of the Hongshui River, and have not suffered any substantial structural disturbance or metamorphism (Figure 3). Sha et al. (1990) divided the Guadalupian Maokou Formation into 5 members. Mei et al. (1998) defined the corresponding conodont zone of each member. Member I is composed of carbonate siltstone and sandstone of turbidite-

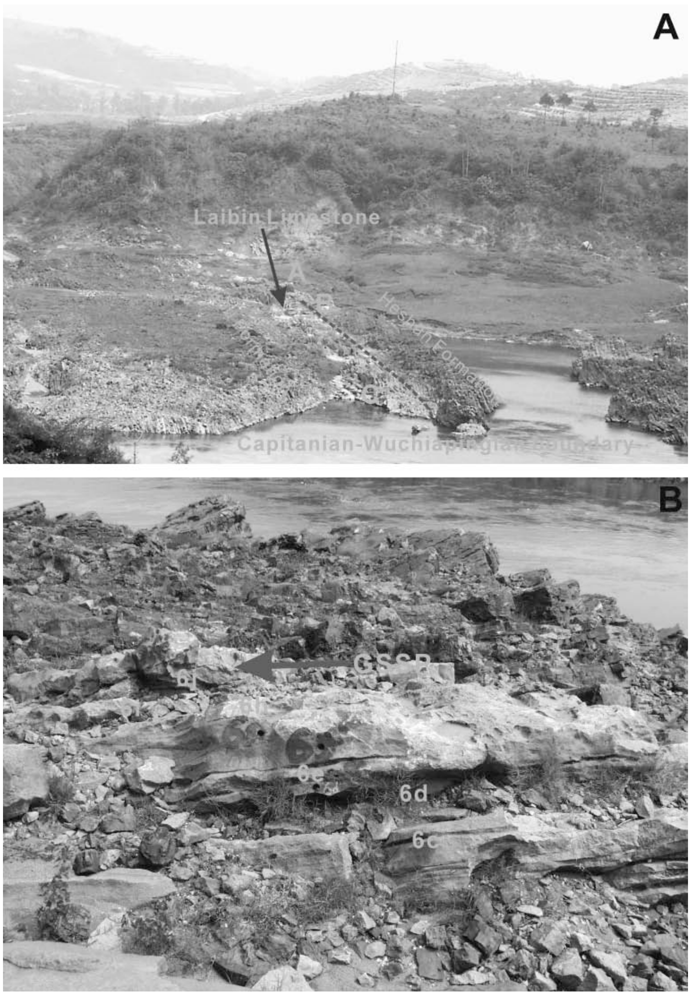

Figure 3 A. Distant view showing the Laibin Limestone and the conodont sample positions at the Tieqiao Section. B. Close view of the Penglaitan Section with bed numbers.

hemipelagic facies with allochthonous bioclasts. It is characterized by the occurrence of conodonts from the *Sweetognathus subsymmetricus* Zone. Member II, about 56 m in thickness, comprises interbedded radiolarian chert and carbonate mudstone, which are mostly basinal facies. The diagnostic conodont for the base of the Guadalupian, *Jinogondolella nankingensis,* first appears in this member. Member III consists of massive carbonate debris flow deposits with a radiolarian-rich fauna and is 26 m in thickness. Member IV (Units H115-118 of Sha et al., 1990) contains interbedded radiolarian chert and cherty carbonate mudstone and sandstone. It is 133 m thick, and comprises more than 10 cycles of turbidite deposits. Member V (Unit H119, Figure 3A) or the Laibin Limestone, is 11m in thickness and is composed of massive lime sandstone and siltstone of distal tempestite facies. The overlying Heshan Formation, 150 m in thickness, is composed of black cherty limestone of basinal facies in the lower part and white bioclastic carbonate of sponge reef facies in the upper part. Conodont samples were repeatedly collected in the C/W boundary interval along three parallel sections at the Tieqiao Section (respectively indicated as A, B and C in Figure 3A). These sections are only tens of metres apart along the same shoreline and can be well traced bed-by-bed, therefore all the fossils are plotted in one lithostratigraphic column (Figure 4A). The Permian lithostratigraphic units at the Tieqiao Section can also be well recognized in succession at the Penglaitan Section with very little change (Figures 3B, 4B). The Laibin Limestone, which is the key stratigraphic unit for the GSSP, is about 8 m thick at Penglaitan and contains thinner bedded carbonate in the middle part. The overlying Heshan Formation, 270 m in thickness at Penglaitan, is mostly composed of chert and lenticular limestone of basinal facies. The Late Wuchiapingian reefal carbonates about 91 m in thickness at the Tieqiao Section are reduced to 10 m in thickness at the Penglaitan Section.

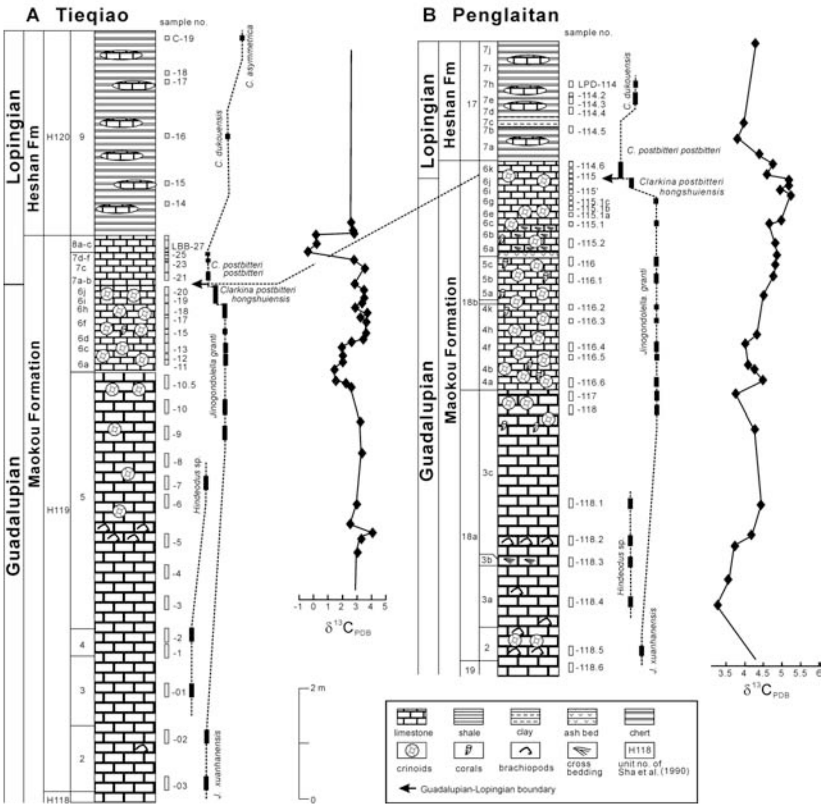

Figure 4 Lithological columns and key conodonts around the C/W boundary interval in the Tieqiao and Penglaitan sections (biostratigraphy modified from Mei et al., 1998; carbon isotope excursions after Wang et al., 2004). Various unit/bed numbers refer to different authors.

Depositional sequence of the C/W boundary interval

The base of the Wuchiapingian Stage coincides with the boundary surface between the Middle and the Upper Absaroka Megasequences that is caused by a distinct event of global sea-level change. The Jiangnan Basin in South China consistently subsided during the Late Paleozoic and Early Triassic between the Yangtze and Cathaysian Blocks and extended southward into the Laibin area in eastern Guangxi (Wang and Jin, 2000). The Laibin Limestone represents a lowstand systems tract deposited continuously on the slope setting during the G/L boundary interval. This interval is largely characterized by an unconformity in shelf or platform sections as well as in many other areas globally (Figure 5).

From Member IV of the Maokou Formation to the Laibin Limestone (Member V), chert and cherty carbonate mudstone of outer shelf to basinal facies change into grainstone and packstone of distal tempestite facies. This marks a rapid shallowing as several transitional facies units are missing between. The lower part of the Laibin Limestone (Units 2–5 in Tieqiao; Units 2–3 in Penglaitan; Figures 4, 5) is characterized by packstone of tempestite facies and wackestone with algal laminae that exhibit continuous shallowing. Well-developed stylolites in Unit 5 of the Tieqiao Section may have formed at a level indicating submarine erosion or nondeposition. The conodont faunas of the C/W succession are dominated by gondolellids that inhabited deeper environments as a whole, but was interrupted briefly by the dominance of a shallow water conodont fauna, the *Hindeodus* sp. interval, in Units 3 and 4, and most of Unit 5 at the Tieqiao Section and Unit 3 (except the topmost part) at the Penglaitan Section (Figure 4). Brachiopods, corals and other shallow-water benthic fossils are common in these beds. Accordingly, a conformable sequence boundary or surface of maximum regression lies on the top of Unit 5 at Tieqiao, and near the top of Unit 3 at Penglaitan (Figure 5). The GSSP at Penglaitan occurs nearly 5 m above this point of maximum regression within the late lowstand or early transgressive systems tract.

The top of the uppermost shallowing-upward cycle of the "lowstand" unit represents a transgressive surface (Van Wagoner et al., 1990). The late lowstand or early transgressive systems tract (from Bed 5f to Bed 6j in the Tieqiao Section and from uppermost Bed 3c to Bed 6k in the Penglaitan Section, Figures 4, 5) contain thick-bedded crinoidal grainstone and lenticular packstone that mark the beginning of an overall deepening. These rocks consist of high frequency cycles of deposition. Each cycle is dominated by hummocky, cross-stratified crinoid grainstone in the lower portion and lenticular packstone in the upper, often with vertical burrows at the top of beds. The facies change is interpreted to range from fine-grained deposits of relatively deeper below-wave-base facies to shallow subtidal environments near the intertidal zone. The conodonts of the *Jinogondolella granti* and *Clarkina postbitteri sensu lato* Zones are associated with deposition of the latest lowstand and earliest TST at Penglaitan, and occur mostly in the lenticular packstone.

The last two high-frequency cycles of the Laibin Limestone in the Penglaitan Section are respectively composed of Bed 6g to 6i-lower and Bed 6i-upper to 6k. Beds 6h and 6i-lower are coarse crinoidal grainstone, which contain very rare conodont fragments, but fish remains and small gastropods are common. Bed 6i-upper comprises mostly packstone with some carbonate mudstone intraclasts. Bed 6j contains abundant mudstone intraclasts and numerous small solitary corals. This bed is variable in thickness and consequently Bed 6k may contact directly with Bed 6i-upper locally. The intraclasts are interpreted as consolidated intertidal carbonate brec-

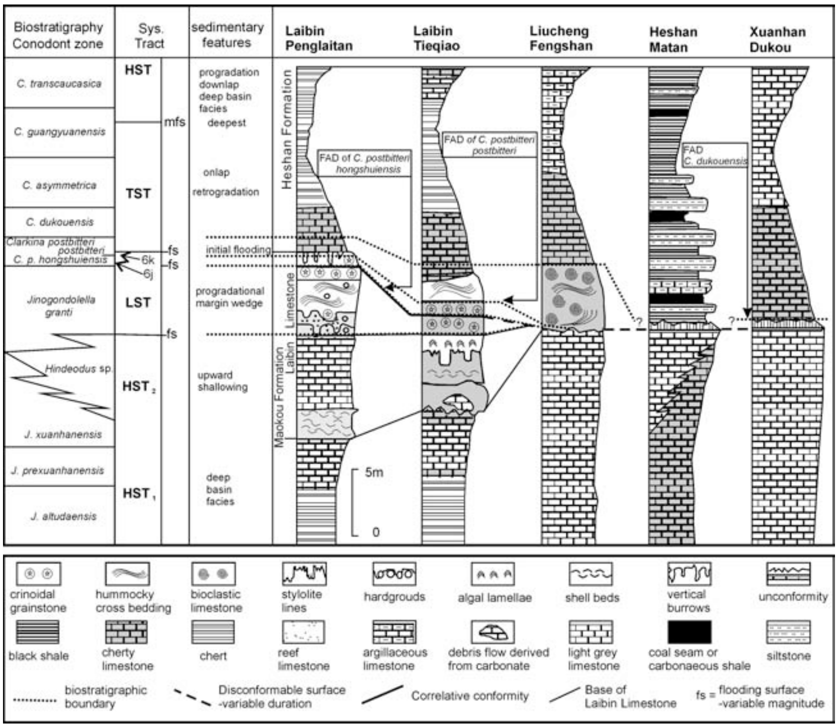

Figure 5 Sequence biostratigraphic diagram showing lithology, key sequence stratigraphic surfaces and biozonal boundaries for five key sections. The figure highlights the complete nature of the succession at Penglaitan and the hiatus at shelf sections like Matan and Dukou (provided by Z.Q. Chen and Yugan Jin). The symbol Bed 6k with the GSSP level looks like a hardground, but is actually a standard symbol in China to represent extensive burrowing throughout a bed (soft sediment bioturbation). The GSSP level occurs between two flooding surfaces and the upper one is a major flooding surface that brings deepwater radiolarian-rich facies into the area.

cia that were reworked by storms and introduced into the Penglaitan deposits during sea-level rise. Bed 6k shows soft-sediment burrows throughout, with the top dominated by vertical burrows.

In the Tieqiao Section, Bed 6i can be correlated with Bed 6j in the Penglaitan Section since both beds comprise abundant mudstone intraclasts, abundant small solitary corals and the conodont *Clarkina postbitteri hongshuiensis*. It is possible that the corresponding part of Bed 6h to 6i-lower of the Penglaitan Section is missing at the Tieqiao Section where Bed 6i with abundant *C. postbitteri sensu lato* lies directly over Bed 6h that contains abundant *Jinogondolella granti* just as Bed 6g of the Penglaitan Section does (Henderson et al., 2002). The contact between Bed 6k and Bed 7a at Penglaitan represents a major flooding surface, which is overlain by radiolarian-rich, deep-water facies of the Heshan Formation. Applying the transgressive-regressive sequence model of Embry (1988, 1990), this point could be viewed as the beginning of a new sequence within a conformable succession. The Heshan Formation is composed of high-frequency cycles that rapidly deepen upward; the cycles consist of lenticular lime mudstone deposited below storm-wave-base to chert of outer shelf to basinal facies, with or without clay beds at the base. This transgressive unit is a response to the very rapid sea-level rise occurring during the interval represented by the conodont *Clarkina dukouensis* Zone.

In summary, the Laibin Limestone could be referred to as an "intersequence", in which a continuously deposited succession of shallow water facies are found with relatively deep water facies on either side (Member IV of the Maokou Formation and the lower part of the Heshan Formation) as a result of the major lowstand of sea level associated with this boundary interval. The Laibin Limestone was deposited during the late parts of relative sea-level fall and early parts of relative sea level rise. The correlative conformable surface associated with the G/L unconformable sequence boundary as seen on shallow carbonate platforms can be placed within this "intersequence" interval, but there are several potential positions at each of the high-frequency cycle boundaries. The bases of Bed 6i-upper and Bed 7a (Figures 4, 5) at Penglaitan are important flooding surfaces within the widespread transgression starting near the top part of the Laibin Limestone. The interval between the two flooding surfaces includes the conodont *C. postbitteri sensu lato* Zone at the Penglaitan Section, which might extend northward to the Chenzhou Basin of southern Hunan, far beyond the distribution of the underlying *Jinogondolella granti* Zone.

Fossil successions

Composite ranges of key fossils from both the Tieqiao and Penglaitan sections in the Laibin area are given in Figure 6.

Conodonts

Conodonts from the Laibin Limestone (Figures 4, 7) in both Tieqiao and Penglaitan sections are exclusively dominated by *Jinogondolella* species in the basal part (Unit 2 at both Tieqiao and Penglaitan) and by *Clarkina* species in the uppermost part (Bed 6i to Unit 8 at Tieqiao Section and Bed 6i-upper to 6k at Penglaitan). The lower part of the Laibin Limestone is dominated by *Hindeodus*. Rare specimens of shallow water elements including *Sweetognathus fengshanensis* and *Iranognathus erwini* were also recovered respectively within lower Unit 3 at Tieqiao and Bed 6k at Penglaitan. *Jinogondolella* and *Clarkina* species also dominate conodonts from equivalent beds at the Fengshan Section near Liuzhou, but contain more common to abundant nearshore shallow water elements including *Hindeodus, Sweetognathus fengshanensis, Iranognathus erwini,* and *Sweetina*. Based on the stratigraphic range and evolution of species of *Jinogondolella* and *Clarkina*, four phylogenetic conodont zones are recognized around the C/W boundary in the Tieqiao and Penglaitan sections (Figures 4, 6): the *Jinogondolella granti* Zone ranges from upper part of Unit 5 through Bed 6h in the Tieqiao Section, and from the uppermost Unit 3 through 6i-lower (4.8 m thick) in the Penglaitan Section; the *Clarkina postbitteri hongshuiensis* Subzone ranges through Beds 6i-upper and 6j; the *Clarkina postbitteri postbitteri* Subzone ranging from Beds 6k through 7b and the *Clarkina dukouensis* Zone that starts at Bed 7e in the Penglaitan Section. The middle two subzones can be collectively regarded as the *Clarkina postbitteri sensu lato* Zone. *Clarkina postbitteri hongshuiensis* is transitional between *Jinogondolella granti* and *Clarkina postbitteri postbitteri*. It is usually close to *Jinogondolella granti* in its denticulation with closely spaced to fused middle denticles and sometimes with a gradually narrowing anterior platform (Figure 7). It is close to *Clarkina postbitteri postbitteri* with a high anterior blade and sometimes with an abruptly narrowing anterior platform as well as the lack of anterior platform serration (Henderson et al., 2002). Figure 7 shows some elements of *Jinogondolella granti, Clarkina postbitteri hongshuiensis,* and *C. postbitteri postbitteri* as illustrated by Henderson et al. (2002).

The FAD of both subspecies of *C. postbitteri sensu lato* is at or close to the conformable boundary surface between the Middle and the Upper Absaroka Megasequences. The latter horizon can be traced in different lithofacies and onto the shelf or platform by the recognition of either the major sequence boundary or a remarkable changeover from conodont faunas dominated by *Jinogondolella* below in the Guadalupian to those dominated by *Clarkina* above with total absence of *Jinogondolella* in the Wuchiapingian.

Clarkina postbitteri hongshuiensis has recently been documented from the Lamar Limestone in the Apache Mountains of West

Texas immediately below the first evaporites of the Castile Formation (Lambert et al., 2002). It appears that conodont evolutionary trends within the Jiangnan Basin in South China and the Delaware Basin in USA were similar and that species of *Clarkina* appear in both areas as the Delaware Basin became evaporitic and the southern part of the Jiangnan Basin was represented by the lowest stand of sea-level. Henderson et al. (2002) suggested that *Clarkina postbitteri hongshuiensis* evolved from *Jinogondolella granti* in the near continuous marine environments of the southern Jiangnan Basin. Lambert et al. (2002) proposed a different lineage for the origin of *Clarkina postbitteri hongshuiensis* in the Delaware Basin. Both interpretations have merit and it is a difficult question to ultimately resolve. If the Lambert's et al. (2002) scenario is correct, then the first occurrence of *C. postbitteri hongshuiensis* in the Jiangnan Basin is a result of migration and the FAD in the two regions may be diachronous. They did not dispute the origin of the distinctive *Clarkina postbitteri postbitteri* in the Jiangnan Basin, which makes the FAD of this subspecies the most suitable for GSSP definition.

Fusulinaceans

Fusulinaceans are rich in the C/W boundary succession of the Laibin area. The lower part of the Laibin Limestone in the Tieqiao Section comprises the fusulinaceans of the *Metadoliolina* Zone (Figure 6). It contains *Metadoliolina douvillei, M. spheroidea, Lepidolina parasuschanica, Schwagerina pseudocompacta, Chusenella zhonghuaensis, Kahlerina sinensis, Lantschichites minima* and *Reichelina changanchiaoensis*. The upper part of this member is correlated with an acme zone, the *Lantschichites minima* Zone; and this zone is 2 m in thickness. Specimens of *Lantschichites minima* first occur in the middle part of the Maokou Formation and become dominant in Unit 5 in association with the conodont *Jinogondolella granti* in the Tieqiao Section. Other fusulinaceans of this zone include *Lepidolina* sp. sparse *Metadoliolina* sp. and schwagerinids. The *Codonofusiella kueichowensis* Zone is recognized in the beds with the conodont *Clarkina postbitteri postbitteri* (Beds 8a–c) in the Tieqiao Section, which contains monotonous *Codonofusiella* and *Reichelina*. The newly proposed *Palaeofusulina jiangxiana* Zone occurs in the lower part of the Heshan Formation, which also contains the *Clarkina asymmetrica* conodont Zone (Figure 6) and ranges upward to the conodont *Clarkina guangyuanensis* Zone (Wang and Jin, 2006).

Evolution of fusulinaceans around the C/W boundary is characterized by a drastic extinction. Fusulinaceans are very abundant and diverse in the Guadalupian Series. In South China, some 40 genera of 6 families have been recorded from the Guadalupian rocks. Only 5 genera, including *Codonofusiella, Dunbarula, Reichelina, Nankinella* and *Staffella,* extend upward through the C/W boundary, which means, that a more than 85% genus level extinction of fusulinaceans occurs below the boundary. Schubertellids were never dominant elements in fusulinacean communities during the Guadalupian, except for the genus *Lantschichites*. This genus was very abundant in the *Lantschichites minima* Zone, while most keriotheca-walled fusulinaceans disappeared, and then became extinct beneath the C/W boundary. *Codonofusiella, Reichelina* and the other three schubertellid genera persisted into the Wuchiapingian and became the dominant fusulinaceans of the stage. In terms of the conodont zones, this change occurs in the upper part of the *Jinogondolella granti* Zone and in the *Clarkina postbitteri hongshuiensis* Subzone because no fusulinacean fossils have been found from this interval in the Tieqiao Section. This biotic change may serve as a critical feature in recognizing C/W boundary units elsewhere in the Tethyan sections with fusulinaceans. Also, the *Lantschichites minima* Zone can be correlated with the *Lantschichites splendens* Zone from the Altuda Formation of the Latest Capitanian in Texas, USA, which occurs above the highest occurrence of keriotheca-walled fusulinaceans (Yang and Yancy, 2000).

Ammonoids

Ammonoids referred to *Shengoceras* (Zhou et al., 2000) previously identified as *Waagenoceras* have been found in Bed 6k in the topmost part of the Maokou Formation at the Penglaitan Section (Figure 6). This fact implies that the Maokouan ammonoids extend upward into the *Clarkina postbitteri sensu lato* Zone as do the ammonoids from the same zone in southern Hunan, South China.

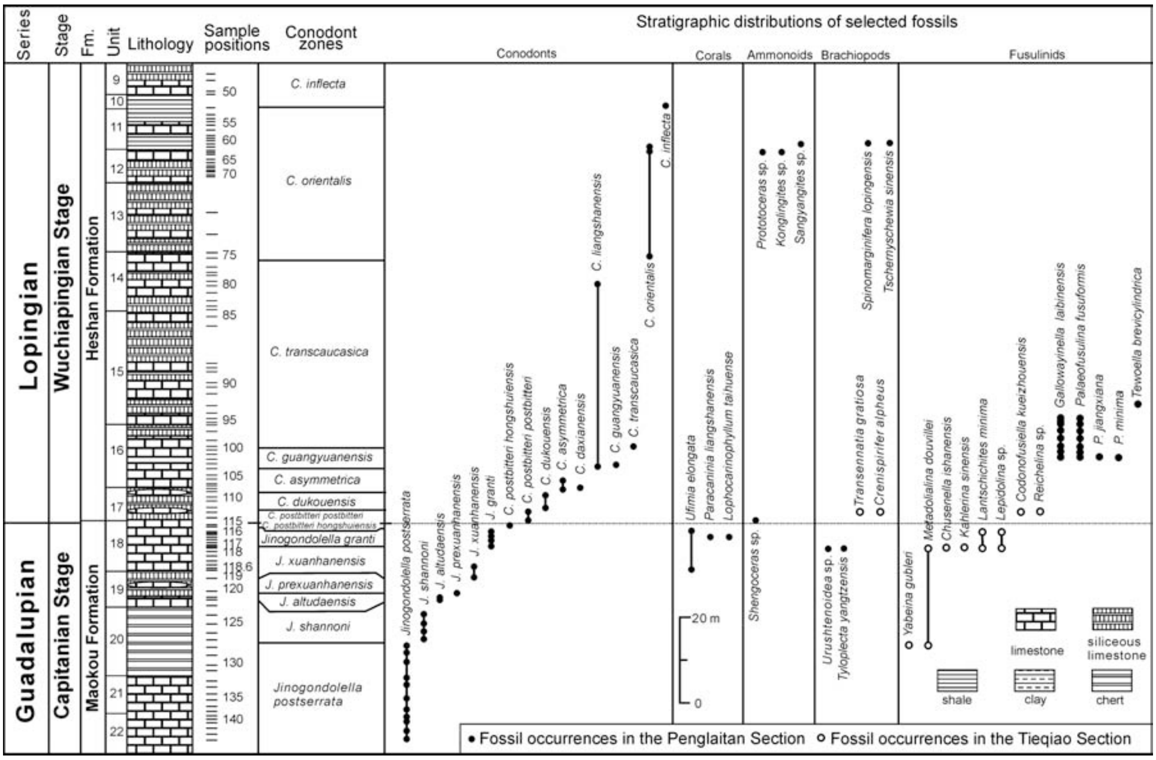

Figure 6 The C-W boundary sequence at the Penglaitan and Tieqiao sections (composite) and the distribution of various fossil groups (modified from Jin et al., 1998).

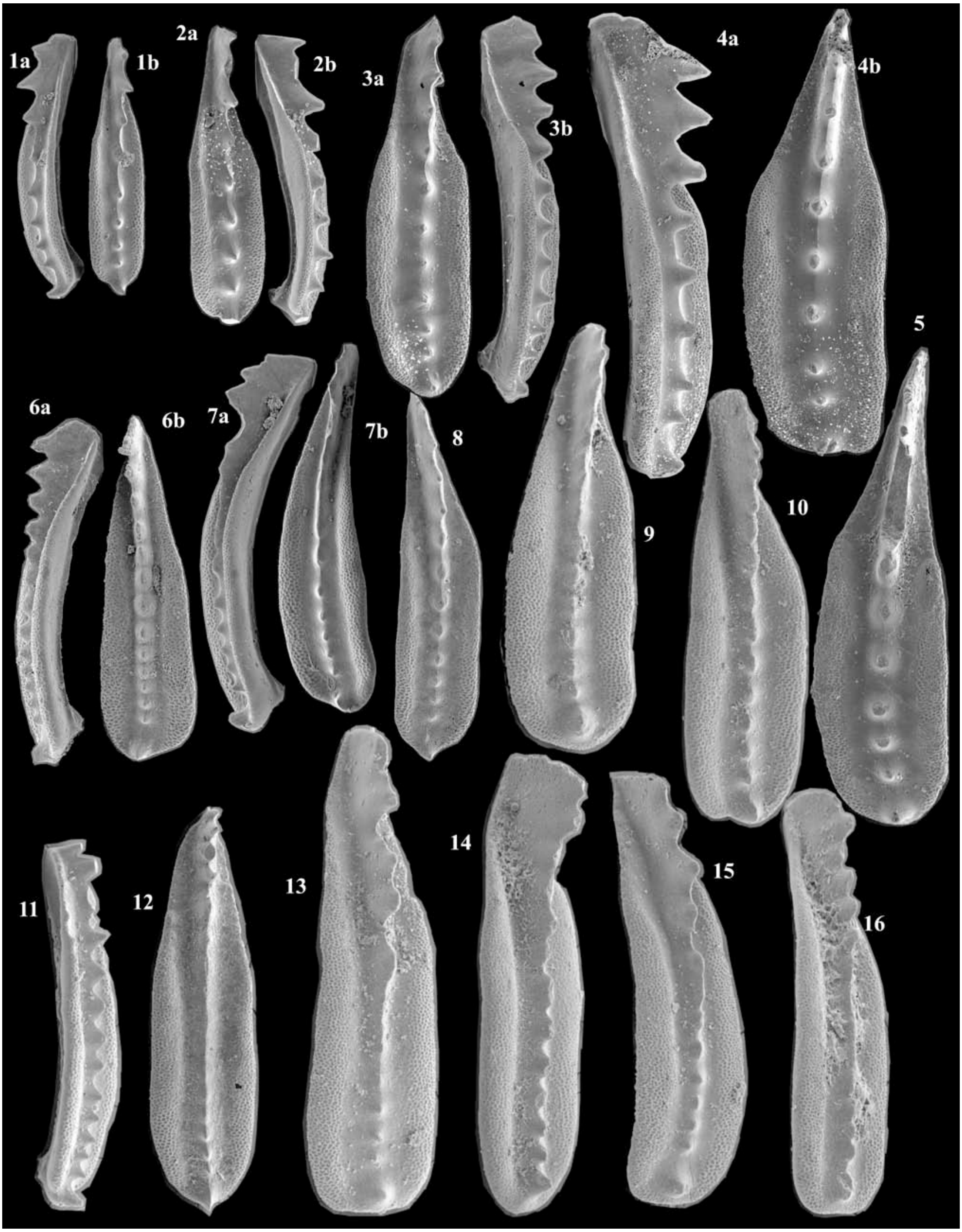

Figure 7 Key conodonts from the Tieqiao and Penglaitan sections. All specimens are SEM photos magnified the same amount (for scale specimen 9 is exactly 1 mm in length). Letters a and b designate different views of the same specimen. 1, 6–10, 13–16, **Clarkina postbitteri hongshuiensis** *Henderson et al., 2002 showing the specimens with closely spaced and often fused denticles, especially in adult specimens. Specimens 1, 6, 8, 13–16 are from Bed 6i-upper and 7, 9, 10 are from Bed 6j at the Penglaitan Section. 2–5,* **Clarkina postbitteri postbitteri** *Mei and Wardlaw in Mei et al., 1994a showing the specimens with more widely spaced and consistently discrete denticles and abruptly narrowing anterior (top in figure) platform. All specimens are from Bed 6k at the Penglaitan Section. 11–12,* **Jinogondolella granti** *Mei and Wardlaw in Mei et al., 1994a from Bed 6h at the Tieqiao Section.*

From the top part of the Douling Formation in the Xiaoyuanchong Section, Chenxian County of Hunan Province, specimens of *Clarkina postbitteri sensu lato* have been reported (Mei et al., 1998), which now can be identified as *C. postbitteri postbitteri*. Ammonoids associated with this earliest Wuchiapingian conodont zone were referred to the *Roadoceras–Doulingoceras* Zone, which contains such newcomers as *Roadoceras, Doulingoceras, Strigogoniatites* and *Cebolites* (Zhou, 1987). It also includes *Altudoceras* and *Paraceltites,* the dominant genera of the *Altudoceras-Paraceltites* Zone of Late Guadalupian, and therefore, shows a close relationship with Guadalupian ammonoids. The sutural pattern of *Doulingoceras* shows that it represents an advanced stock in the phylogenetic lineage of the paraceltid ammonoids (Zhou, 1987).

Ammonoid faunas suffered a dramatic change around the G/L boundary as well, where 90.7% of Guadalupian ammonoid genera disappeared (Yang and Wang, 2000). Wuchiapingian ammonoids were dominated by forms of the Superfamily Otoceratoidea and 92.1% of the ammonoid genera originated in the Wuchiapingian. The turning point is coincident with the change of conodont faunas from *Jinogondolella* to *Clarkina,* but slightly later than that for fusulinaceans, corals and brachiopods. In terms of the conodont zones, the extinction timing probably corresponds to the *Clarkina dukouensis* Zone because otoceratacean ammonoids occur in the *Clarkina asymmetrica* Zone.

Corals

The corals from the Guadalupian beds in the Tieqiao and Penglaitan sections have been described by Wang and Sugiyama (2001). Those occurring in Member V of the Maokou Formation (Figure 6) are all solitary corals; colonial rugose corals of the Capitanian such as *Ipciphyllum* and *Paracaninia* do not extend upward from Member III, which approximately correlates with the Wordian-Capitanian boundary. The species listed in Figure 6 can extend into the Wuchiapingian beds, but they are restricted to the Guadalupian in the Laibin area. There is a dramatic change of coral faunas around the G/L boundary. Family and generic-level extinctions reach respectively 75.6% and 77.8% of the total Guadalupian corals (Wang and Sugiyama, 2000). However, the extinction level of corals varies within different facies at various sections. The Guadalupian above Member III of the Maokou Formation in the Tieqiao and Penglaitan sections are mostly slope facies and thus, the extinction level coincides with the boundary between Members III and IV.

Brachiopods

Among the brachiopod genera from the Tieqiao and Penglaitan sections, *Urushtenoidea* is a characteristic Guadalupian brachiopod genus and *Tyloplecta yangtzeensis* appeared in the Capitanian, but is dominant in the Lopingian. *Transennatia gratiosa, Hustedia remota* and *Crenispirifer alpheus*, all of which are dominant forms of Wuchiapingian brachiopod faunas in the Tethyan regions, were recently found from Beds 8b and 8c (around the *C. postbitteri postbitteri* Subzone) in the Tieqiao Section. In the Penglaitan Section, the Lopingian common brachiopods such as *Tyloplecta yangtzeensis, Spinomarginifera lopingensis, Transennatia gratiosa* etc. occur in Units 2 and 3. In the Xiaoyuanchong Section, Chenxian County of Hunan Province, the brachiopods occurring in the *C. postbitteri postbitteri* Subzone include *Orthothetina regularis, Oldhamina* sp., *Spinomarginifera lopingensis, Tschernyshewia sinensis* etc. All the above mentioned information suggests that brachiopods more or less experienced a changeover around the G/L boundary interval. Statistical analysis shows about 87% of the Guadalupian brachiopod species became extinct around the G/L boundary in South China (Shen and Shi, 1996) although it is probably much less profound in a broad scale (Shen and Shi, 2002). Given the extinction level of Guadalupian brachiopod faunas, it is evident that brachiopods of the *C. postbitteri postbitteri* Subzone are dominated by Wuchiapingian forms.

Magnetostratigraphic investigation and Geochronology

Manfred Menning and Shu-zhong Shen collected 640 oriented cylinders from the Chihsia, Maokou and basal part of the Heshan formations at the Tieqiao Section and from the G/L boundary sequence at the Penglaitan Section for a major magnetostratigraphic investigation. Partial or total remagnetization complicates the magnetostratigraphic research (Menning et al., 1996). Isotopic age of the tuff beds around the C/W boundary at the Penglaitan Section has been studied since 1995 by Samuel Bowring and others, but no reliable age has been identified so far.

Chemostratigraphy

A carbon isotope study of carbonate rocks from the Kungurian (Early Permian) to the Induan (Early Triassic) in the Tieqiao Section shows carbon isotopic values fluctuating between +2.0 per mil and +3.5 per mil during the Guadalupian interval. Values for $\delta^{13}C$ drop from + 3.2 per mil in the Laibin Limestone to -0.5 per mil at the base of the Heshan Formation (in Beds 8a to 8c at the Tieqiao Section; i.e. the upper part of the *C. postbitteri sensu lato* Zone), return to an average value in Unit 9, and jump to the highest value +5 per mil $\delta^{13}C$ in the reef carbonate of the Heshan Formation (Wang et al., 2004). Strontium isotope of $^{87}Sr/^{86}Sr$ is consistent with the carbon isotopic trend showing a dramatic drop in Bed 8a to Bed 8c (Wang et al., 2004). In the Penglaitan Section, values of $\delta^{13}C$ range from +4.0 per mil to +5.3 per mil in the Laibin Limestone except for the dolomitized Unit 2. The values decrease rapidly from +5.3 per mil at Beds 6g, 6h and 6i drop to +3.6 per mil at Bed 7a, and then recover gradually to +4.5 per mil at Unit 8. This carbon isotope curve has been largely confirmed by Kaiho et al. (2005) and coincident with that of the Tieqiao Section with a rapid decrease across the G/L boundary and the lowest value located within the upper part of the *C. postbitteri sensu lato* Zone (Figure 4).

Selection of GSSP for base-Wuchiapingian Stage and the base-Lopingian Series

The Penglaitan and Tieqiao sections are excellent sections in which to establish a finely resolved chronology and both meet the requirements for serving as GSSP. However, the Penglaitan Section (Figure 8) is preferred as the GSSP for the G/L boundary because of excellent outcrops of both Wuchiapingian and Changhsingian beds and because this section appears to be somewhat more distal and complete compared with the Tieqiao Section.

Three potential points, namely the respective FADs of *Clarkina postbitteri hongshuiensis, C. postbitteri postbitteri,* and *C. dukouensis* have been considered (Figures 4, 8). The FADs of both *C. postbitteri hongshuiensis* and *C. postbitteri postbitteri* are at or close to the boundary surface between the Middle and the Upper Absaroka Megasequences. These horizons can be traced in different lithofacies by the recognition of either the major sequence boundary or a remarkable changeover from conodont faunas dominated by *Jinogondolella* below in the Maokouan to those dominated by *Clarkina* above, with total absence of *Jinogondolella* in the Wuchiapingian. Two questions were raised by these options. The first was the reported occurrences in Texas of *Clarkina postbitteri* (Wardlaw pers. comm., 2002) and transitional morphotypes between *Jinogondolella crofti* and *Clarkina postbitteri hongshuiensis* (Lambert et al., 2002) were in dispute. Wardlaw et al. (2001) referred this taxon to "*Clarkina*" sp. and indicated that this taxon in West Texas, USA occurred with *Jinogondolella* spp., including *J. granti*. This question was answered with the documentation of *Clarkina postbitteri hongshuiensis* from the Lamar Limestone in the Apache Mountains of

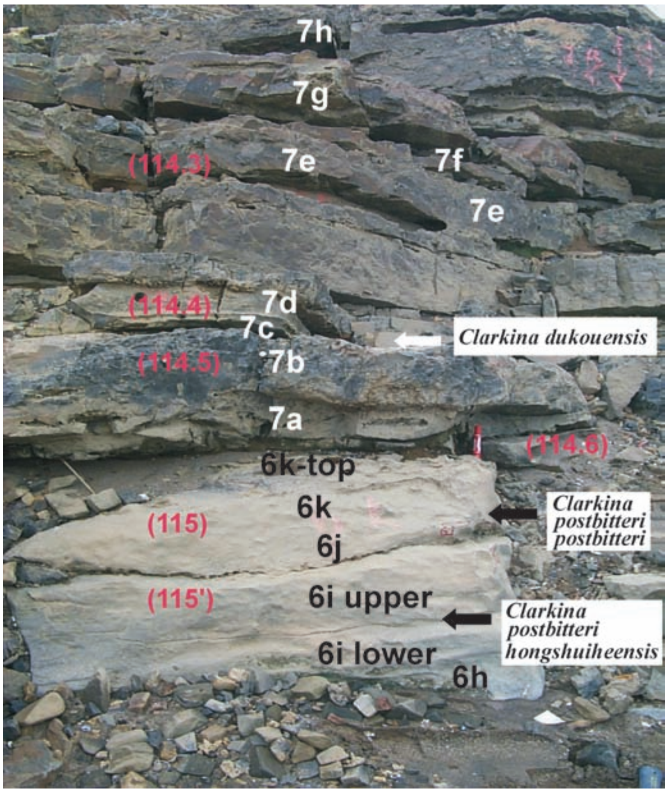

***Figure 8** A photo of the Penglaitan Section in Laibin, Guangxi, South China showing the different options for the GSSP of the Guadalupian-Lopingian boundary. The FAD of Clarkina postbitteri postbitteri represents the GSSP ratified by IUGS. Different bed/sample numbers used before are indicated.*

West Texas immediately below the first evaporites of the Castile Formation (Lambert et al., 2002). As pointed out previously in the discussion on conodonts, Lambert et al. (2002) indicate a different evolutionary lineage, which leaves some doubt regarding the synchroneity of the FAD of *C. postbitteri hongshuiensis* between the Delaware Basin in USA and the Jiangnan Basin in South China. This leaves the distinctive and easily recognized *Clarkina postbitteri postbitteri* as the best option for the Penglaitan GSSP.

The second question was that a depositional hiatus had been suggested below Bed 6i-upper, in part because conodonts are absent or very rare below this surface suggesting very shallow water deposition. As described in the section on depositional succession, the upper part of the Laibin Limestone consists of high frequency cycles. Both Bed 6i-lower and Bed 6k form the upper parts of the uppermost two cycles and are fairly gradational and continuous with the lower parts of each cycle. Though depositional gaps might occur between cycles, they seem no more than those at normal bedding planes; that is, they are insignificant in terms of the resolution of conodont chronostratigraphy. A conodont zone usually comprises many cycles. Furthermore, these concerns are addressed by choosing a point within a cycle at the base of Bed 6k.

The proposal for the FAD of *Clarkina dukouensis* at Bed 6k was not regarded as an acceptable choice for selection because the basal boundary of the *Clarkina dukouensis* Zone, after further study by conodont experts, is recognized at Bed 7e of the Penglaitan Section, which is above a clay bed (Bed 7c) that may indicate considerable environmental change (Jin, 2000a, 2000b). Furthermore, the morphologic differences between *Clarkina dukouensis* and *C. postbitteri postbitteri* are very subtle and this FAD would be very difficult to pick consistently. A detailed study demonstrates that specimens of *Clarkina* from Bed 6k belong to *Clarkina postbitteri postbitteri* rather than to early forms of *Clarkina dukouensis* (Henderson et al., 2000; Henderson, 2001) and therefore Bed 6k was reported to contain the first appearance of *Clarkina postbitteri postbitteri* (Henderson et al., 2002).

The selected point is at the base of Bed 6k of the Penglaitan Section (Figures 3B, 4, 8) defined by the FAD of *Clarkina postbitteri postbitteri* within an evolutionary lineage from *C. postbitteri hongshuiensis* to *C. dukouensis*. The FAD of *C. postbitteri sensu lato* could also be used to approximate this boundary, as it is only 20 cm below the defining point at the base of Bed 6i-upper at the Penglaitan Section (Figure 8).

Clarkina postbitteri postbitteri is a distinctive form within the chronomorphocline represented by *C. postbitteri hongshuiensis* to *C. dukouensis*. Therefore, the FAD of *C. postbitteri postbitteri* is defined within a gradational lineage that is recognized within a succession of continuous deposition. The event occurs between two flooding surfaces, with the upper one marking the onset of major transgression following a major sea level lowstand.

Correlation of the GSSP

The FAD of *Clarkina postbitteri postbitteri* is clear in the Penglaitan and Tieqiao sections and throughout the Jiangnan Basin in South China. *Clarkian postbitteri sensu lato* has been reported from scattered sections in the western Tethys (Sweet and Mei, 1999; Kozur, 2003). Kozur (2003) has reported *Clarkina postbitteri sensu lato* in Oman in the western Tethys. His forms have the consistently discrete denticulation typical of *Clarkina postbitteri postbitteri* and he stated that the first occurrence of this taxon in Oman is associated with a strong biotic change in radiolarians and other faunal groups; a major biotic shift that is fundamental to recognition of this boundary. Proximity to the boundary can be further recognized by the lowest occurrence of *Clarkina postbitteri hongshuiensis*, which is 20 cm below the defining point and is the lowest occurrence of the species *Clarkina postbitteri sensu lato* as well as of the genus *Clarkina* at the Penglaitan Section. Regardless of the disputed origin of *Clarkina postbitteri hongshuiensis,* the occurrence of *C. postbitteri hongshuiensis* indicates that the boundary level should be somewhere very close to the base of the first evaporites of the Castile Formation in the Apache Mountains of West Texas (Lambert et al., 2002). In the shelf or platform successions in South China and elsewhere in the Tethys where the boundary is unconformable, overlying strata will contain younger species of *Clarkina* (e.g., *Clarkina dukouensis* at the Dukou Section in Sichuan, South China, Mei et al., 1994b); in each case it will be the first species of *Clarkina* in that section and will as such be very distinctive. This horizon can be recognized by a rapid change from *Sweetognathus* to *Iranognathus* for shallow water conodonts. Since the boundary level falls within an interval represented by a major turnover of biota, it can be recognized by faunal changes of ammonoids, fusulinaceans, brachiopods, corals etc. Such changes include the rapid extinction of verbeekinid fusulinaceans, the appearance of an acme zone of *Lantschichites* species in the topmost Capitanian and a dominance of the highly diverse fusulinaceans *Codonofusiella* and *Reichelina* in the lower Wuchiapingian. The co-occurrence of the *Codonofusiella kueichowensis* Zone with the conodont *Clarkina postbitteri postbitteri* in the Tieqiao Section implies the lowest occurrence of *Codonofusiella* and *Reichelina* is right at or just above the boundary. The Wuchiapingian brachiopods such as the *Araxilevis–Orthothetina* Assemblage occurring beneath the *Clarkina dukouensis* Zone in Iran (Sweet and Mei, 1999) and the brachiopods from the beds of the *C. postbitteri postbitteri* Subzone in the Douling Formation in South China are closely related.

Clarkina is not present in presumed Wuchiapingian strata of western and northwestern Pangea because of biogeographic restriction by profound provincialism; in these areas *Clarkina* (or *Neogondolella*) does not occur until near the very end of the Permian. Some conodont workers prefer to attribute these species to the genus *Neogondolella* (Orchard pers. comm., 2003), but resolution of this question will require detailed assessment of apparatuses from the Middle Permian to Middle Triassic (Henderson et al., 2006); this problem does not, however, affect species-level assignments. Lack of a directly applicable worldwide biostratigraphic mark for the boundary level implies the importance of using other means, such as major sequence boundaries and maximum flooding surfaces, significant reversals of polarity, and remarkable isotopic fluctuations to establish a reliable correlation in some regions. In these regions recognition of the Lopingian strata is in part related to recognizing a distinct post-Guadalupian depositional sequence because the boundary level falls within an interval represented by one of the lowest stands of sea-level in the Phanerozoic. Among the chemostratigraphic fluctuations, a substantial negative shift of carbon isotopic values occurring near the G/L boundary may serve as a distinct marker (Wang et al., 2004; Kaiho et al., 2005). It has been traced around the boundary between Members 3 and 4a in the Salt Range, Pakistan (Baud et al., 1995), which is below the *Clarkina dukouensis* Zone (Wardlaw and Mei, 1999). The corresponding depletion of carbon isotopes occurs between Units 5 and 6 in Abadeh, central Iran where it coincides with the base of the *Clarkina dukouensis* Zone (Wang et al., 2004). Studies of sulfur isotope are limited. A rapid shift in sulfur isotopes from -25‰ to about -15 ‰ was reported near the base of the Lopingian Series in Japan (Kajiwara et al., 1994).

Though Mesozoic overprinting prevents establishing a reliable magnetostratigraphic succession based in the Tieqiao and Penglaitan sections (Menning et al., 1996), magnetostratigraphic data with adequate biostratigraphic constraints are important in defining the boundary level as well. It has been shown that a normal polarity zone extends from the uppermost Wordian into the Capitanian. The C/W boundary appears to approximately correspond with the change from this normal polarity zone to a reversed polarity zone in the lower Wuchiapingian. In the Wulong Section of South China, the lower 50 m of the Wuchiapingian strata essentially shows reversed polarity (Chen et al., 1992; Heller et al., 1995). Since the upper part of the Wargal Formation is dominated by reversed polarity in the Salt Range, Pakistan, it is reasonable to refer to this interval as part of a reversed polarity zone (Haag et al., 1991). The lower boundary of this polarity zone is below the occurrence of the conodont *Clarkina dukouensis* and thus, it correlates with the Early Wuchiapingian (Wardlaw and Mei, 1998). The magnetostratigraphic sequence of the Middle and Late Permian in the Urals, Russia contains a normal polarity zone in the lower part of the Sverodvinsk Horizon. The stratigraphic range of this zone appears to be correlative with the Late Guadalupian normal polarity zone. The upper part of the Sverodvinsk Horizon with mainly reversed polarity is separated as a revised polarity zone (Molostovsky, 1992). It is widely referred to as an equivalent of the Early Wuchiapingian reversed polarity zone and therefore, the C/W boundary in this continental succession could be located between the lower and upper parts of the Sverodvinsk Horizon (Burov et al., 1996; Kotlyar and Pronina-Nestell, 2005).

The above discussion clearly demonstrates that several reliable and practical means for establishing a sound global correlation of the GSSP level are available for both marine and non-marine successions.

Summary

Worldwide investigations by the International Working Group on the Lopingian Series prove that the G/L (also C/W) boundary succession at the Penglaitan and Tieqiao sections appear to be unique sections with a complete conodont succession and numerous other fossil groups.

The boundary level between the Capitanian and Wuchiapingian Stages, the FAD of *Clarkina postbitteri postbitteri,* is defined within a lineage of *Clarkina* species based on a population concept. Several other relevant event markers occur within a short interval that straddles this biostratigraphic marker. Consequently, this GSSP can satisfy both the requirements for depositional completeness and correlation potential.

The GSSP for the C/W boundary is marked by excellent exposures, continuous deposition, diverse and abundant fossils, favorable open marine facies for long distance correlation, and chemostratigraphic signatures. It has not been subjected to major tectonic disturbances or strong diagenetic alteration and it is free from vertical facies changes and accessible. It meets all basic GSSP requirements.

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