An integrated biostratigraphy (conodonts and foraminifers) and chronostratigraphy (paleomagnetic reversals, magnetic susceptibility, elemental chemistry, carbon isotopes and geochronology) for the Permian-Upper Triassic strata of Guandao section, Nanpanjiang Basin, south China

Daniel J. Lehrmann^{a*}, Leanne Stepchinski^a, Demir Altiner^b, Michael J. Orchard^c, Paul Montgomery^d, Paul Enos^e, Brooks B. Ellwood^f, Samuel A. Bowring^g, Jahandar Ramezani^g, Hongmei Wang^h, Jiayong Wei^h, Meiyi Yuⁱ, James D. Griffiths^j, Marcello Minzoni^k, Ellen K. Schaal^{l**}, Xiaowei Li^l, Katja M. Meyer^{l++}, Jonathan L. Payne^l

^a*Geoscience Department, Trinity University, San Antonio, TX, 78212, USA*

^b*Department of Geological Engineering, Middle East Technical University, Ankara, 06531, Turkey*

^c*Natural Resources Canada-Geological Survey of Canada, Vancouver, British Columbia, V6B 5J3, Canada*

^d*Chevron Upstream Europe, Aberdeen, Scotland, UK*

^e*Department of Geology, University of Kansas, Lawrence, Kansas 66045, USA*

^f*Louisiana State University, Baton Rouge, Louisiana 70803, USA*

^g*Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*

^h*Guizhou Geological Survey, Bagongli, Guiyang 550011, Guizhou Province, China*

ⁱ*College of Resource and Environment Engineering, Guizhou University, Caijiaguan, Guiyang, 550003, Guizhou Province, China*

^j*Chemostrat Ltd., 2 Ravenscroft Court, Buttington Cross Enterprise Park, Welshpool, Powys, SY21 8SL, UK*

^k*Shell International Exploration and Production, 200 N. Dairy Ashford, Houston, TX, 77079*

^l*Department of Geological and Environmental Sciences, Stanford University, Stanford, California 94305, USA*

*Corresponding author. Tel.: 210-999-7654. E-mail address: dlehrmann@trinity.edu

**Current address: Lawrence University, Geology Department, 711 E Boldt Way, Appleton, WI 54911

++ Department of Environmental & Earth Sciences, Willamette University, Salem, OR 97301

ABSTRACT

The chronostratigraphy of Guandao section has served as the foundation for numerous studies of the end-Permian extinction and biotic recovery in south China. Guandao section is continuous from the Permian-Triassic boundary to the Upper Triassic.

Conodonts enable broad delineation of stage and substage boundaries and calibration of foraminifer biostratigraphy as follows. Changhsingian- Griesbachian: first *Hindeodus parvus*, and first appearance of foraminifers *Postcladella kalhori* and *Earlandia* sp. Griesbachian-Dienerian: first *Neospathodus dieneri*, and last appearance of foraminifer *P. grandis*. Dienerian-Smithian: first *Novispathodus waageni* and late Dienerian first appearance of foraminifer *Hoyenella* ex gr. *sinensis*. Smithian-Spathian: first *Nv? crassatus* and last appearance of foraminifers *Arenovidalina* n. sp. and *Glomospirella* cf. *vulgaris*. Spathian-Aegean: first *Chiosella timorensis* and first appearance of foraminifer *Meandrospira dinarica*. Aegean-Bithynian: first *Nicoraella germanica* and first appearance of foraminifer *Pilammina densa*. Bithynian-Pelsonian: after last *Neogondolella regalis*, prior to first *Paragondolella bulgarica* and first appearance of foraminifer *Aulotortus eotriasicus*. Pelsonian-Illyrian: first *Pg. excelsa* and last appearance of foraminifers *Meandrospira ? deformata* and *Pilamminella grandis*. Illyrian-Fassanian: first *Budurovignathus truempyi*, and first appearance of foraminifers *Abriolina mediterranea* and *Paleolituonella meridionalis*. Fassanian-Longobardian: first *Bv. mungoensis* and last appearance of foraminifer *A. mediterranea*. Longobardian-Cordevolian: first *Quadralella polygnathiformis* and last appearance of foraminifers *Turriglomina mesotriasica* and *Endotriadella wirzi*.

The section contains primary magnetic signature with frequent reversals occurring around the Permian-Triassic, Olenekian-Anisian, and Anisian-Ladinian boundaries. Predominantly

normal polarity occurs in the lower Smithian, Bithynian, and Longobardian-Cordevolian. Predominantly reversed polarity occurs in the upper Griesbachian, Induan-Olenekian, Pelsonian and lower Illyrian. Reversals match well with the GPTS. Large amplitude carbon isotope excursions, attaining values as low as -2.9‰ $\delta^{13}\text{C}$ and high as $+5.7\text{‰}$ $\delta^{13}\text{C}$, characterize the Lower Triassic and basal Anisian. Values stabilize around $+2\text{‰}$ $\delta^{13}\text{C}$ through the Anisian to Carnian. Similar signatures have been reported globally. Magnetic susceptibility and synthetic gamma ray logs show large fluctuations in the Lower Triassic and an overall decline in magnitude of fluctuation through the Middle and Upper Triassic. The largest spikes in magnetic susceptibility and gamma ray, indicating greater terrestrial lithogenic flux, correspond to positive $\delta^{13}\text{C}$ excursions. High precision U-Pb analysis of zircons from volcanic ash beds provide a robust age of 247.28 ± 0.12 Ma for the Olenekian-Anisian boundary at Guandao and an age of 251.985 ± 0.097 Ma for the Permian-Triassic boundary at Taiping. Together, the new U-Pb geochronology from the Guandao and Taiping sections suggest an estimated duration of 4.71 ± 0.15 Ma for the Early Triassic Epoch.

Keywords: Permian-Triassic, biostratigraphy, conodonts, foraminifera, carbon isotopes, paleomagnetic, geochronology, China.

1. Introduction

Guandao section occurs on the northern flank of an isolated carbonate platform, the Great Bank of Guizhou (GBG) in the center of the Nanpanjiang Basin in southern Guizhou Province (Fig. 1). The GBG and Guandao section hold importance as a key reference for correlation in

the basin because the GBG is the best exposed and has the longest history among isolated carbonate platforms within the basin. The basin center position of the GBG, far from terrestrial influence, the high subsidence rates yielding a continuous record of marine sedimentation, and the presence of continuous exposures across the platform to basin profile make this area ideal for studies of platform evolution, the end-Permian mass extinction and Triassic biotic recovery.

Guandao section is composed primarily of deep-marine pelagic carbonates with abundant microfossils punctuated by carbonate turbidite and debris-flow breccia beds that contain shallow-marine biota shed from the adjacent platform. Physical and carbon isotope correlations tie the deep-marine record at Guandao with shallow-marine record of the GBG (Payne et al., 2004; Meyer et al., 2011; Kelley et al., 2014). Further advantages of Guandao section for chronostratigraphy include the presence of numerous volcanic ashes, preservation of magnetic reversals, and record of high-magnitude carbon isotope excursions (Lehrmann et al., 1998, 2005; 2006; Payne et al., 2004).

Guandao has served as a key section for age calibration supporting a wide range of studies on carbonate platform evolution (Lehrmann et al., 1998, 2005; Kelley et al., 2014) patterns of reef evolution (Payne et al., 2006a), patterns of abundance, diversity and size of fossils during Permian extinction and recovery (Payne et al., 2006b; 2011; Tong et al. 2007; Song Haijun et al., 2011), and geochemical studies of carbon isotopes, strontium isotopes, and redox sensitive elements (Payne et al., 2004; Tong et al., 2007; Meyer et al., 2011, 2013; Schaal et al., 2011; Lau et al., 2013; Song Huyue et al., 2011, 2013). The section has been resampled several times for conodonts, and portions of the biostratigraphic data, magnetostratigraphy and geochronology have been published as a contribution to stage boundary definition (Lehrmann, 1993, Lehrmann et al., 1998, 2005, 2006; Payne et al., 2004; Wang et al., 2005; Orchard et al.,

2007). Much of the available data however, has been published only in schematic form or remains unpublished. The purpose of this paper is to present the integrated conodont and foraminifer biostratigraphic data for the entire Guandao section and to provide integration with available paleomagnetic reversal, magnetic susceptibility and carbon isotope data. In addition to graphic plots the data is presented in a database in an online repository (<http://dx.doi.org/10.1594/PANGAEA.836206>). The calibration of the benthic foraminifer biostratigraphy with conodont stage/ substage age assignment promises to improve age definition with foraminifers elsewhere. The integrated dataset provides new magnetostratigraphic data to supplement the GPTS especially for the Anisian-Ladinian portion of the section. Finally, publishing the entire Guandao data set should be a significant benefit to future studies of the Permian-Triassic history of the Guandao section and south China.

2. Geologic Setting

The Guandao section occurs on the basin-margin slope on the northern flank of a Permian-Triassic platform, the Great Bank of Guizhou in the Nanpanjiang Basin of south China. The GBG is the northernmost of several isolated carbonate platforms within the basin (Fig. 1). The Nanpanjiang Basin was a deep-marine embayment in the southern margin of the south China tectonic block and is bordered by the Yangtze Platform, a vast shallow-marine carbonate platform that stretched across south China (Fig. 1). The south China block existed in the equatorial eastern Tethys during the Late Permian, and drifted northward crossing the equator and reaching approximately 12° north latitude by the Late Triassic (Enkin et al., 1992, Van-der-Voo, 1993). The GBG is dissected by two synclines that have exposed continuous cross-sections

across the paleobathymetric profile from the shallow-marine platform top, margin, basin-margin slope and basin (Fig. 2). Guandao section occurs at the basin-margin slope position in the western syncline, on the north flank of the GBG, immediately south of the town of Bianyang (Fig. 2).

The GBG was initiated as a carbonate platform in the latest Permian during a major transgression that drowned much of the Yangtze Platform bordering the eastern Nanpanjiang Basin in the area from Luodian to Guiyang (Fig. 1). This drowning expanded the eastern part of the basin, as shallow-marine sedimentation persisted near the former margin of the Yangtze Platform and developed into an isolated carbonate platform (Lehrmann et al., 1998, 2005). During the Early Triassic the GBG developed a low-relief ramp like profile with oolite shoals developed at the margin, shallow-subtidal to peritidal interior and slopes dominated by pelagic carbonate mud deposition punctuated by thin carbonate turbidites and debris flows shed from the margin (Fig. 2). In the Middle Triassic, Anisian *Tubiphytes* reefs developed at the margin, peritidal conditions continued in the interior and basin margin slopes steepened (Fig. 2). By the Middle Triassic, Ladinian the platform margin had developed approximately 400 m of relief above the base of slope at Guandao and slope deposition shifted to grainstone breccia as slopes reached the angle of repose (Fig. 2). Finally, the platform developed a high-relief escarpment during the late Ladinian, with breccia shed to the base of the escarpment as the platform was drowned and the basin filled with siliciclastic turbidites of the Bianyang Formation in the Carnian (Lehrmann et al., 1998; Fig. 2).

3. Stratigraphy

Guandao section spans 774 m from the Upper Permian through the Upper Triassic, Carnian (Fig. 2, 3). The section begins in the cherty skeletal limestone of the Upper Permian Wuchiaping Formation (Fm.). The Wuchiaping represents shallow-marine deposition on the Yangtze Platform prior to the Late Permian drowning in the region north of the GBG. The Wuchiaping is a cherty bioclastic packstone containing a diverse assemblage of shallow-marine fossils including articulate brachiopods, mollusks, echinoderms, bryozoans, corals, calcareous sponges, calcareous algae and foraminifers (Lehrmann et al., 1998). The Wuchiaping is overlain by silicious lutite (chert) of the uppermost Permian Talung Fm. (Fig. 2, 3). The Talung represents drowning of the Yangtze Platform in the latest Permian. The Talung is a black, nodular-bedded radiolarian siliceous lutite (chert) containing the ammonoids *Rotodiscoceras*, *Pseudotirolites*, and *Pleurondoceras* (Guizhou Bureau, 1987).

The Permian-Triassic boundary occurs within a black shale interval 28 m thick overlying the Talung Fm. (Fig. 3). The bivalve *Claraia* occurs in the upper part of the shale interval marking the basal Triassic. Although the PTB occurs within a black shale interval at Guandao, additional sections in the interior of the GBG preserve the PTB within a limestone succession (Lehrmann et al., 2003, Payne et al., 2004; Krull et al., 2004; Chen et al., 2008).

The Lower Triassic succession at Guandao has been mapped regionally as the Luolou Fm. (Guizhou Bureau, 1987). The succession is 264 m thick and consists predominantly of platy thin-bedded pelagic lime mudstone to wackestone with occasional thin shale interbeds and punctuated by carbonate packstone-grainstone turbidite and debris flow breccia beds (Fig. 3). Pelagic lime mudstone beds are horizontally laminated or rarely burrowed. Carbonate turbidite beds are composed of oolite, peloids and intraclasts. Debris-flow breccias are matrix-rich and contain a mix of oolite clasts derived from the platform margin and lime-mudstone clasts derived

from the slope. At the base of debris-flow breccia beds, lime mudstone is commonly contorted by soft-sediment deformation into wavy or overturned folds; however, there is no evidence of significant erosion beneath the debris flow units. Between 187-224 m there is a conspicuous dolomitized interval that includes two thick debris flow breccias beds (Fig. 3). Several thin volcanic ash units occur in the Lower Triassic succession and bracketing the Lower-Middle Triassic (Olenekian-Anisian) boundary (Fig. 3).

The Middle Triassic succession at Guandao is regionally mapped at the Xinyuan Fm. (Guizhou Bureau, 1987), however the Xinyuan Fm. elsewhere in Guizhou is restricted to the Anisian and consists of a mixed carbonate-clastic basin margin facies. The lithofacies succession at Guandao is significantly different from the stratigraphy adjacent to the Yangtze Platform where most Triassic formations were defined. At Guandao the Middle Triassic succession is entirely carbonate and includes the Anisian and Ladinian (Fig. 2, 3).

In the Anisian the Guandao succession continues with facies and interpreted depositional environments similar to those of the Lower Triassic; namely deep-marine slope sedimentation consisting of pelagic lime-mudstone punctuated by carbonate packstone-grainstone turbidite and debris flow breccia beds. The composition of shallow-marine clasts and biota within intraclasts delivered to the slope, however changes dramatically reflecting the development of *Tubiphytes* reefs at the platform margin (Fig. 2, 3). Grains in the carbonate turbidite beds are dominated by *Tubiphytes* fragments and crinoid ossicles with subordinate bivalves, gastropods, echinoids and brachiopods. Clasts in the debris-flow breccias include *Tubiphytes* and sponge boundstone derived from the margin reef. Breccia beds in the Anisian are substantially thicker (reaching a maximum of 50 m) reflecting steepening basin-margin slopes (Fig. 3). Like the Lower Triassic, pelagic lime mudstone intervals beneath the debris-flow breccia beds are commonly contorted by

soft-sediment deformation but there is no evidence of significant erosion beneath the debris-flow units.

In the upper Ladinian there is a significant shift in facies to lithoclastic grainstone breccia with *Tubiphytes* boundstone clasts and fragmented *Tubiphytes* debris. The shift coincides with steepening of the slope past 30° and reflects a shift to grainflow deposition (Fig. 3). In the Carnian there is yet another major shift in deposition with the introduction of siliciclastic turbidites of the Bianyang Fm. that ultimately filled the basin and buried the platform (Fig. 2). The base of the turbidite sandstone and shale of the Bianyang Fm. was logged at the top of Guandao section (Fig. 3). Breccia tongues within the lower Bianyang Fm. contain carbonate boundstone clasts with a diverse reef biota of *Tubiphytes*, scleractinian corals, sphinctozoan and inozoan sponges and solenoporacean algae (Fig. 3). These breccias were interpreted to have been eroded from the high-relief escarpment of the GBG as siliciclastic turbidites were infilling the basin (Lehrmann et al., 1998).

4. Conodont succession and boundary definition

Stage boundaries of the Triassic have been formally defined with a Global Stratotype Sections and Point (GSSP) only for the base of the Griesbachian, Ladinian, and Carnian. Hence, the following discussions of boundary placement for the remaining stages may be regarded as tentative.

4.1 Permian-Triassic boundary

In Guandao section the Permian-Triassic boundary (PTB) is placed at 17 m within a black shale interval at the first appearance of the Early Triassic bivalve *Claraia*. Although conodonts were not extracted from the shale, siliceous lutites of the Talung immediately beneath the Shale contain the Late Permian ammonoids *Rotodiscoceras*, *Pseudotirolites* and *Pleurondoceras* (Guizhou Bureau, 1987). The underlying limestone of the Wuchiaping Fm. contains upper Permian conodonts of the genus *Clarkina* (0.2-3 m; Figs. 4, 5.22,23), and the overlying limestone of the basal Luolou Fm. contains *Hindeodus parvus*, the index for the basal Triassic Griesbachian (45-57m; Fig. 4, 5.3,4), and *H. anterodentatus* (55-56.6m; Fig. 4, 5.2). The GSSP of the PTB at Meishan section was defined at the First Appearance Datum (FAD) of *H. parvus* (Yin et al., 2001; Jiang et al., 2007). *H. latidentatus*, *H. praeparvus*, and *H. eurypyge*, the precursors to *H. parvus* (Nicoll et al., 2002; Orchard, 2010), have not yet been identified at Guandao, although they have been recognized in the PTB succession at Bianyang in the basin north of Guandao (Yan et al., 2013), and on the platform to the south at Dawen (Chen et al., 2009).

4. 2 Griesbachian-Dienerian boundary

In Guandao section the Griesbachian-Dienerian substage boundary is placed at 68.8 m on the basis of the first occurrence of *Neospathodus dieneri* (Fig. 4, 5.5,6). The placement of the boundary is also supported by the last occurrence of *Hindeodus parvus* in the underlying Griesbachian preceding the first occurrence of *Ns. dieneri* (Fig. 4). The Griesbachian-Dienerian boundary is classically defined on the basis of ammonoids such as *Meekoceras*, and *Proptychites candidus* (Tozer, 1974; Balini et al., 2010; Orchard, 2008). *Ns. dieneri* was first reported from

the Salt Range in Pakistan (Sweet, 1970). It has been reported from a wide variety of localities and is commonly cited as an indicator for the Dienerian (Sweet, 1988; Metcalf, 1990; Orchard and Tozer, 1997; Paul and Paul, 1997; Orchard and Krystyn, 2007; Zhao et al., 2008; Orchard, 2010).

4. 3 Induan-Olenekian (Dienerian-Smithian) boundary

The Induan-Olenekian boundary is placed at 131.9 m on the basis of the first occurrence of *Novispathodus waageni*, *Nv. posterolongatus* and the genus *Eurygnathodus* (Fig. 4, 5.7-9). Additional taxa that help constrain the boundary are the occurrences of *Neospathodus cristigalli* and *Ns. peculiaris* below the boundary (Fig. 4, 5.10-12), and the occurrence of *Discretella discreta* above the boundary (Fig. 4, 5.14,15). Interestingly *Nv. waageni* was not recovered from the nearby basinal section at Bianyang (Yan et al., 2013), although this species has a widespread distribution in Asia. The FAD of *Nv. waageni* sensu lato (including its morphological variants such as *Nv. waageni eowaageni*, *Nv. waageni waageni* and *Nv. posterolongatus*; Zhao et al., 2004) occur along with ammonoids such as *Flemingites*, *Euflemingites*, and *Gyronites* that are considered to characterize the base of the Olenekian (Smithian) in potential GSSP sections in Chaohu, Anhui, China and Spiti, India (Tong et al., 2004; Orchard and Krystyn, 2007; Orchard, 2007a; Krystyn et al. 2007). Recently, Goudemand (2015) has refined the succession around the boundary in both China and India and identified a succession of taxa that serve as indicators of the boundary interval, including further variants on the aforementioned *Novispathodus* species, *Eurygnathodus* spp., and *Borinella nepalensis*; the latter taxon occurs in neither Chaohu nor

Guandao. *D. discreta* has wide geographic distribution and makes its first appearance later in the early Olenekian (Orchard, 2010).

4. 4 Smithian-Spathian boundary

In Guandao section the Smithian-Spathian substage boundary is placed at 190.1 m on the basis of the first occurrence of *Novispathodus? crassatus* (Fig. 4, 5.16, 17). Additional conodonts supporting the placement of the boundary are the slightly higher occurrences of *Gladigondolella carinata*, *Cornudina*, and *Spathicuspis spathi* (Fig. 4, 5.13, 20, 21, 28). *Novispathodus? crassatus* characterizes early Spathian strata in North America (Orchard and Tozer, 1997). *Nv. pingdingshanensis* is now also considered an important indicator for the Smithian-Spathian boundary in south China (Zhao et al., 2008; Goudemand et al., 2012); however this distinctive form with its strongly posteriorly-curved denticles has not yet been found at Guandao section.

4. 5 Olenekian-Anisian boundary

The Olenekian-Anisian boundary is placed at 267.3 m at Guandao section on the basis of the first occurrence of *Chiosella timorensis* (Fig. 4, 6. 1,2). The Olenekian-Anisian boundary at Guandao includes a major faunal turnover from assemblages dominated by *Triassospathodus ex gr. homeri*, *Novispathodus triangularis*, *Nv. abruptus*, and *Spathicuspis spathi* in the Olenekian (Fig. 4, 5. 19, 24, 25, 28) to *Cs. timorensis*, *Neogondolella ex gr. regalis*, and *Gladigondolella tethydis* in the basal Anisian (Fig. 4, 6.1-5, 13-16, 27, 28). *Ts. ex gr. homeri*, *S. spathi*, and *Gd. carinata* range across the boundary into the Aegean (Fig. 4). *Cs. gondelloides*, the evolutionary

precursor to *Cs. timorensis*, begins slightly below the boundary, and *Ng. regalis* and *G. tethydis* first appear in the Aegean after the first appearance of *Cs. timorensis* (Fig. 4; Orchard et al., 2007).

In the proposed GSSP at Desli Caira, Dobrogea, Romania the Olenekian-Anisian boundary is placed on the basis of the ammonoids *Deslicairites* below and *Paracrochordiceras* and *Japonites* above, with the boundary closely corresponding to the first appearance of *Cs. timorensis* (Gradinaru et al., 2006, 2007). Goudemand et al. (2012) reported an occurrence of *Cs. timorensis* associated with ammonoids of the late Spathian *Neopopanoceras haugi* Zone in Nevada, and therefore questioned the usefulness of the FAD of *Cs. timorensis* as an index for the Olenekian-Anisian boundary. However, the appearance of *Cs. timorensis* in combination with the major turnover of conodont faunas as described above (see also Orchard et al., 2007) provide a significant constraint on the boundary position. The Olenekian-Anisian boundary at Guandao is considered to be an important reference section to supplement the GSSP (Orchard et al., 2007).

4. 6 Aegean-Bithynian boundary

The Aegean-Bithynian boundary is placed at 279.7 m based on the first occurrence of *Nicoraella germanica* (Fig. 4, 5.26). The base of the Bithynian substage is defined in its type area of the Kocaeli peninsula of Turkey by the first appearance of the ammonoid *Nicomedites osmani* (Assereto, 1974). There, the first occurrence of *Ni. germanica* occurs 5 m below the base of the *Osmani* Zone(?), thus its appearance approximates the boundary placement defined with ammonoids. The conodont succession from Chios, the Germanic Basin, and Sicily also support the use of *Ni. germanica* for definition of the base Bithynian. In these areas the Bithynian strata

contain *Ni. germanica* whereas strata of the underlying Aegean substage lack *Ni. germanica* but contain *Cs. timorensis* (Nicora, 1977; Kozur, 1974a, 1974b, 2003).

4. 7 Bithynian-Pelsonian boundary

The Bithynian-Pelsonian boundary is loosely constrained at Guandao section as occurring somewhere between the last occurrence of *Ng. ex gr. regalis* (336.2-390.4 m; Fig. 4, 5.13-16) and the first occurrence of *Paragondolella bulgarica* (432.2 m; Fig. 4, 6.6-8). Uncertainty in boundary placement derives from need for taxonomic revision of the high-bladed conodonts here referred to the *Ng. ex gr. regalis* group. This group is typically considered to range within the lower to middle Anisian (cf. Orchard and Tozer, 1997) although examples are known from the late Spathian: revision of the group into several taxa promises to provide greater biostratigraphic resolution. The ammonoid *Balatonites balatonicus* is used to define the base of the Pelsonian stage in the type area of the Balaton Highlands of Hungary (Voros, 2003). The first occurrence of *B. balatonicus* is accompanied by the conodont *Pg. bulgarica* supporting its use as a proxy for the Pelsonian (Voros, 2003).

4.8 Pelsonian-Illyrian

The Pelsonian-Illyrian boundary at Guandao is defined at 473.9 m based on the first occurrence of *Paragondolella ex gr. excelsa* (Fig. 4; 6.11). Additional support for the boundary placement comes from the first occurrence of *Neogondolella constricta*, which first appears slightly lower than *Pg. excelsa* (fig. 4, 6. 9,10). *Pg. excelsa* and *Ng. constricta* are considered

typical upper Anisian (Illyrian) taxa (Sweet, 1988; Orchard and Tozer, 1997; Brack et al. 2005; Orchard, 2010). On the basis of ammoniods, the boundary is typically placed at the transition from *Bulogites zoldianus* to *Rieppelites ciméganus* or at the somewhat later FAD of *Paraceratites* (Monnet et al., 2008, Balini et al., 2010), which is approximated by the first occurrence of *Ng. constricta* and the later occurrence of *Pg. excelsa* (cf. Muttoni et al., 1998).

4. 9 Anisian-Ladinian (Illyrian-Fassanian)

In Guandao section the Anisian-Ladinian boundary is placed at 559.8 m on the basis of the first occurrence of *Budurovignathus truempyi* (Fig. 4, 6.16-18). The Anisian-Ladinian boundary is defined in a GSSP in the dolomites of northern Italy based on the first appearance of the ammonoid *Eoprotrachyceras curionii* (Muttoni et al., 2004; Brack et al., 2005). Orchard (2010) noted that the conodont *Bv. praeungaricus*, which appears in the top of the underlying *Nevadites secadensis* zone, forms a useful conodont proxy for the Anisian-Ladinian boundary. The successor species *Bv. truempyi* first appears within the *E. curionii* zone (Muttoni et al., 2004) and therefore also is a useful proxy for the boundary.

4. 10 Fassanian-Longobardian

The Fassanian-Longobardian boundary at Guandao is defined at 579.2 m based on the first occurrence of *Budurovignathus mungoensis* and *Paragondolella inclinata* (Fig. 4; 6.19-22). The upper Ladinian embraces the *Frankites regoledanus* and *F. sutherlandi* ammoniod zones (Balini et al., 2010), and associated conodont proxies that occur in both the Longobardian of

Tethys and in North America include *Bv. mungoensis* and *Pg inclinata* (Orchard and Tozer, 1997; Muttoni et al., 2004; Orchard, 2007b).

4. 11 Ladinian-Carnian (Longobardian-Cordevolian)

The Ladinian-Carnian boundary is placed at 630.9 m based on the first occurrence of *Quadralella polygnathiformis* (Fig. 4, 6.24,25). The Ladinian-Carnian boundary has been defined in a GSSP in the Dolomites of northern Italy on basis of the first appearance of the ammonoid *Daxatina canadensis* (Manco et al, 2004; Mietto et al., 2007). In North America the base of the Carnian was defined by the *Trachyceras desatoyense* zone, although *Daxatina* has also found to co-occur with ammonoids in the upper part of the underlying *F. sutherlandi* zone in Nevada (Balini et al., 2007; Orchard, 2010). In northern Italy, Spiti, and North America, *Q. polygnathiformis* co-occurs or slightly preceeds the ammonoids used in definition of the Ladinian-Carnian boundary, thus forming a useful proxy for identifying the boundary (Orchard, 2010). In the Guanling area of Guizhou, facies of the Wayao Formation that mark the drowning of the Yangtze Platform contain conodont *Quadralella polygnathiformis* and the Carnian ammonoid *Trachyceras multituberculatum* (Yang et al., 1995; Enos et al., 2006; Hao et al. 2010).

5. Foraminifer succession and calibration with conodonts

5.1 Permian-Triassic boundary

In Guandao section neither the Permian-Triassic boundary shales nor limestones at the base of the Luolou Formation have yielded any foraminifera. However, despite the fact that

characteristic lowermost Triassic foraminiferal assemblages are absent in deep-marine lithologies of the Guandao section, foraminifers are present in the platform-interior succession of the Great Bank of Guizhou. In Dawen and Dajiang sections, very close to the Permian-Triassic boundary, a population of disaster taxa, *Postcladella kalhori* and *Earlandia* spp., as described in Groves & Altiner (2005), make their first appearances in the thrombolite facies directly overlying the Changhsingian carbonates containing *Paleofusulina* and advanced species of *Colaniella* (Lehrmann et al. 2005; Payne et al., 2004). Known nearly from the entire western Tethyan domain including Hungary, Italy, Austria, Serbia, Greece, Turkey, Caucasus, Iran (Brönnimann et al., 1972; Zaninetti, 1976; Altiner et al., 1980; Rettori, 1995; Groves et al., 2005, 2007; Krainer and Vachard, 2011), *Postcladella kalhori* has been previously reported from the Nanpanjiang Basin and the Great Bank of Guizhou by Song et al. (2009) and Payne et al. (2011) immediately above the Permian-Triassic boundary calibrated by the occurrence of earliest Triassic conodonts.

5. 2 Griesbachian-Dienerian boundary

Foraminifers have not been recorded around this boundary in Guandao section due to the unfavorable facies. In Dawen and Dajiang sections from the platform interior of the Great Bank of Guizhou both *Postcladella kalhori* and *Postcladella grandis* make their last appearances close to the Griesbachian-Dienerian boundary, correlated with the Guandao section on the basis of carbon isotope and conodont data (Payne et al., 2004). *P. grandis*, previously introduced by Altiner & Zaninetti (1981) as a „forma“ of *P. kalhori* has been raised to the species rank in this study and the last appearance of this form nearly coincides with the Griesbachian-Dienerian

boundary. However, the last appearance of *P. kalhori* postdates the boundary and this species makes its last appearance both in the Dawen and Daijiang sections in the early Dienerian. Although the data related with the last occurrence of *P. grandis* is totally new, the last appearance of *P. kalhori* has already been reported in the Tethyan domain from the early Dienerian (Rettori, 1995) or late Induan (Krainer & Vachard, 2011).

5. 3 Induan- Olenekian (Dienerian-Smithian) boundary

Foraminifers are still absent in the Induan-Olenekian boundary beds of the Guandao section which are primarily composed of breccias layers. In Dawen and Daijiang sections, from the platform interior, foraminifers are not diagnostic to delineate the Induan-Olenekian boundary. Following the extinction of Griesbachian-early Dienerian disaster forms, *Hoyenella* ex gr. *sinensis* makes its first appearance toward the late Dienerian and ranges into the Anisian. In the Tethyan realm some foraminiferal taxa whose first appearances are reported to be close to the Induan-Olenekian boundary (Rettori, 1995) are either absent (*Arenovidalina chialingchiangensis*, *A. amylovolutum*, *Gandinella silensis*) in Guandao section or appear in the Olenekian (*Krikoumbilica pileiformis*).

5. 4 Smithian-Spathian boundary

In Guandao section foraminifers appear for the first time in the Smithian. *Hoyenella* ex gr. *sinensis*, already appeared in the Dienerian of the inner platform succession of the Great Bank of Guizhou, occurs frequently in the Smithian of Guandao section and ranges higher up into the

Anisian by crossing the Smithian-Spathian boundary (Fig. 4, 7.3-4). In the upper half of the Smithian substage a new *Arenovidalina* species, probably the ancestor of *A. chialingchiangensis* and *A. amylovolutum*, makes its first appearance and this form disappears very close to the Smithian-Spathian boundary (Fig. 4, 7.1). Another form, which disappears slightly below the Smithian-Spathian boundary, is *Glomospirella* cf. *vulgaris* (Fig. 4, 7.18). In the Tethyan domain this form ranges from Dienerian to Spathian (Rettori, 1995). However, in Guandao material it seems to be confined to the upper Smithian strata. The first appearance of involutinid foraminifera, probably the ancestor of triadodiscids occurs slightly below the Smithian-Spathian boundary (Fig. 4, 7.37). It should also be noted that some species like *Meandrospira cheni* (Fig. 7.5), *Endoteba bithynica* (Fig. 7.26), whose first appearances are reported to be close to the Smithian-Spathian boundary in the Tethyan domain (Rettori, 1995), occur for the first time above the Smithian-Spathian boundary in Guandao section (Fig. 4). The reason for these late appearances might be due to the presence of unfavorable facies in the lower Spathian strata, mainly composed of dolomites and breccias (Fig. 3).

5. 5 Olenekian-Anisian boundary

In Guandao section *Meandrospira dinarica* (Fig. 7.6-7) and *Arenovidalina abriolense* (Fig. 7.2) make their first appearances at or slightly above the Olenekian-Anisian boundary (Fig. 4). Although the first appearances of *Endotebanella kocaeliensis* (Fig. 7.32) and *Endotriadella wirzi* (Fig. 7.30-31) were reported previously at this boundary in the Tethyan realm (Dağ, 1980; Zaninetti, 1976; Rettori, 1995) these forms first occur in the late or latest Spathian in Guandao material. Several forms known from the Anisian of the Tethyan realm successively appear

above the Olenekian-Anisian boundary in the Aegean [*Tolypammmina gregaria*, *Turrispirillina* sp.(Fig. 7.34), *Pilamminella grandis* (Fig. 7.19), *Pilammmina densa* (Fig. 7.20)]. The Lazarus taxon *Endoteba controversa* (Fig. 7.25) with its recognizable sections occurs for the first time in the latest Aegean (Fig. 4). We also note that true triadodiscids make their first appearance close to the Aegean-Bithynian boundary. Nearly coincident with the first appearance of the stage boundary indicator, *Chiosella timorensis*, *Meandrospira dinarica* seems to be the best foraminiferal marker to delineate the Spathian-Anisian boundary although it has been considered for a long time as the zonal marker of Pelsonian in western Tethys (Salaj, 1969; Zaninetti et al., 1972). Recently, in the study of Song et al. (2011), illustrating the stratigraphic ranges of Late Permian to Middle Triassic foraminifera from South China including the data from Guandao section, stratigraphic distribution of *M. dinarica* has been shown to be ranging from Olenekian to Anisian. We consider that this confusing stratigraphic range given for *M. dinarica* is most probably related with incorrect interpretation of the limits of the taxon. *M. dinarica* population of Song et al. (2011) most probably comprises, in addition to the proper sections of *M. dinarica*, the sections of *M. pusilla* and *M. cheni* from the Olenekian.

5. 6 Aegean-Bithynian boundary

Neither the first nor the last appearances of foraminiferal species perfectly coincide with this boundary defined on the basis of the first appearance of the conodont marker, *Nicorella germanica*. Among the species recognized in the Chinese material, *Pilammmina densa* (Fig. 7.20), appearing slightly below the boundary (Fig. 4) could be the most diagnostic species approximating the Aegean-Bithynian boundary. Considered as the marker of Pelsonian-Illyrian

in the Tethyan realm (Salaj, 1969; Zaninetti, 1976; Rettori, 1995) the first occurrence of *P. densa* is definitely earlier in the Chinese material. The two species, *Endoteba bithynica* (Fig. 7.26) and *Meandrospira pusilla* (Fig. 7.13) appeared previously in the Olenekian, make their last appearances in the Bithynian, well above the Aegean-Bithynian boundary. The other species which make their first appearances above the Aegean-Bithynian boundary in this substage are *Planinvoluta ? mesotriasica* (Fig. 7.14-15), *Endotebanella ? n. sp.* (Fig. 7.35) and *Paleolituonella reclinata*. Among these forms, *Endotebanella ? n. sp.*, representing a new trend in the evolution of endotebid foraminifera with spine-bearing chamber corners, probably belongs to a new genus. *Paleolituonella reclinata*, previously placed in synonymy under *Paleolituonella meridionalis* by Rettori (1995) is definitely a valid taxon with a smaller test and a thinner wall and appears much earlier than the latter species in the Anisian (Fig. 4).

5. 7 Bithynian-Pelsonian boundary

Despite the fact that the Bithynian-Pelsonian boundary is not reliably drawn on the basis of conodont data two foraminiferal species occur close to the lower boundary of the questionable interval below Pelsonian s. s. (Fig. 4). *Aulotortus eotriasicus* (Fig. 7. 38), known from Pelsonian in the Tethyan realm (Zaninetti et al., 1994; Rettori, 1995), occurs for the first time slightly below the Bithynian-Pelsonian boundary. *Endoteba obturata* (Fig. 7.27) whose first appearance is known from the late Anisian (Rettori, 1995) occurs for the first time just at this boundary. Well above the Bithynian-Pelsonian boundary but still within this questionable Pelsonian interval, while *A. eotriasicus*, *Endotebanella ? sp.* and *Turrispirillina sp.* make their last

appearances the genus *Ophthalmidium* with its characteristic sections (Fig. 7.16) and *Endotriada thyrrhenica* (Fig. 7.29-30) appear for the first time.

5.8 Pelsonian-Illyrian boundary

The Pelsonian-Illyrian boundary, clearly identified by conodont data, coincides with the last occurrences of two foraminifera species, *Meandrospira* ? *deformata* (Fig. 7.11) and *Pilamminella grandis*, which already appeared in Pelsonian s.s.. From these forms, *M.* ? *deformata* seems also limited at the Pelsonian-Illyrian boundary in the western Tethys (Rettori, 1995). Three Anisian species, *Meandrospira dinarica* (Fig. 7.6-7), *Pilamina densa* (Fig. 7.20) and *Pilamminella grandis* (Fig. 7.19) make their last appearances slightly below the Pelsonian-Illyrian boundary. In the Tethyan realm, stratigraphic ranges of *M. dinarica* and *P. grandis* do not extend further into the late Anisian (Rettori, 1995; De Bono et al., 2001) as it has been recorded in Guandao section, however, *P. densa* is known from the late Anisian. The other species which make their first appearances below the Pelsonian-Illyrian boundary are *Trochammina almtalensis* (Fig. 7.21-22), *Turriglomina mesotriasica* (Fig. 7.9), *Turriglomina* cf. *magna* (Fig. 7.10) and *Malayspirina* sp. (Fig. 4). The first appearance of the genus *Turriglomina* in the upper Pelsonian s.s. of Guandao section is perfectly in accord with the ranges given in the phylogenetical model of Rettori (1995) illustrating the evolutionary derivation of *Turriglomina* in the late Pelsonian from the *M. dinarica* ancestor.

5. 9 Anisian-Ladinian (Illyrian-Fassanian) boundary

Many of the foraminifera species recognized in Guandao section cross the Anisian-Ladinian boundary identified on the basis of the first appearance of the conodont *Budirovinathus truempyi* (Fig. 4). The last appearances of *Hoyenella* ex gr. *sinensis* (Fig. 7.3-4), *Turriglomina* cf. *magna* (Fig. 7.10), *Planinivoluta* ? *mesotriasica* (Fig. 7.14-15) and *Endotriada tyrrhenica* (Fig. 7.28-29) at or below the boundary are possibly local or facies controlled since these forms are known from higher levels of Triassic (Rettori, 1995). Foraminifers which appear close to the boundary seem to be more significant (Fig. 4). First appearances of *Abriolina mediterranea* (Fig. 7.36) and *Paleolituonella meridionalis* slightly below the boundary are quite comparable with ranges given from western Tethyan domain (Zaninetti et al., 1992; Rettori, 1995). Although their identifications are problematic, the first appearance of *Agathammina*-like forms also coincides with the Anisian-Ladinian boundary.

5. 10 Fassanian-Longobardian boundary

Although foraminifers are mostly nondiagnostic for the characterization of the Fassanian-Longobardian boundary in the Ladinian (Zaninetti, 1976; Rettori, 1995) the last appearances of several foraminiferal species are recognized slightly below or above this boundary in Guandao section. Slightly below the boundary, *Abriolina mediterranea* (Fig. 7.36) and *Malayspirina* sp. (Fig. 4) make their last appearances. Above the boundary, progressive disappearances of *Paleolituonella meridionalis*, *Ophthalmidium exiguum* (Fig. 7.17), *Krikoumbilica pileiformis*, *Endoteba obturata* (Fig. 7.27), *Endoteba controversa* (Fig. 7.25) and *Endotebanella kocaeliensis* (Fig. 7.32) might be significant to constrain the Fassanian- Longobardian boundary in future studies. Involutinid foraminifera (*Aulotortus*, *Lamelliconus*, *Trocholina*) which could be

potential markers to delineate this boundary (Zaninetti, 1976; Piller, 1978; Rigaud et al., 2013) are remarkably absent or very rare in basinal Guandao section because of paleoecological restrictions.

5. 11 Ladinian-Carnian (Longobardian-Cordevolian)

The boundary delineated by the first appearance of the conodont, *Quadralella polyanthiformis* is also firmly constrained by the successive last appearances of two foraminifera species, *Turriglomina mesotriasica* (Fig. 7.9) and *Endotriadella wirzi* (Fig. 7.30-31) occurring close to the boundary. These last appearances (Fig. 4) are perfectly in accord with the data in Dağ (1980) and Rettori (1995) from the western Tethys. In addition, although its last appearance datum is not well known *Paleolituonella reclinata* makes its last appearance at this boundary. Several species comprising *Triadodiscus* sp., *Tolypammina gregaria*, *Trochammina almtalensis* (Fig. 7.21-22), *Ophthalmidium* spp. (Fig. 7.16), *Arenovidalina abriolense* (Fig. 7.2) progressively disappear above the boundary in the Carnian (Fig. 4). We note that also in the Carnian of Guandao section some populations representing new steps in the evolution of Triassic foraminifera make their sporadic appearances. *Galeanella* sp. might be one the most ancient records of galeanellid foraminifers widely known from the Upper Triassic Tethyan reef belts (Zaninetti and Martini, 1993). *Turriglomina carnica* (Fig. 7.8), *Piallina bronnimanni* ? (Fig. 7.23), *Austrocolomia marschalli* are the other Carnian forms (Fig. 4) known from the Tethyan realm (Dağ, 1980; Martini et al., 1995; Rettori et al., 1998).

6. Integrated chronostratigraphy

6. 1 Paleomagnetic reversal stratigraphy

The Triassic geomagnetic polarity time scale (GPTS) has been developed largely through integration of measurement of remnant magnetic field reversals in strata calibrated with biostratigraphy of ammonoids and conodonts. Longer and more continuous magnetostratigraphic records with good biostratigraphic control and relatively steady sedimentation rates are most advantageous for constraining magnetic reversal patterns. Guandao section, spanning continuous deep-marine sedimentation through the Upper Permian through Carnian is one of the longest sections available for the Triassic. Details regarding the sampling methods, magnetic mineralogy, reliability of paleomagnetic data and reversal stratigraphy for the lower portion of Guandao section are presented in the data repository item #2006229 (Lehrmann et al., 2006). The reversal stratigraphy for the entire section is presented in Fig. 3.

The Upper Permian through Lower Triassic reversal stratigraphy at Guandao correlates reasonably well with other marine sections and provides support for construction of the GPTS (Hounslow and Muttoni, 2010). In the Upper Permian, Changhsingian at Guandao there is a shift from normal to reversed polarity in the uppermost Wuchiaping to Talung Fm. (Fig. 3). Reversed polarity in the uppermost Permian is similar to sections in Shangsi, China (Steiner et al., 1989) and Abadeh, Iran (Gallet et al., 2000) although it differs from the GSSP at Meishan which exhibits normal polarity across the PTB (Yin et al., 2001). Hounslow and Muttoni (2010) suggested that the normal polarity of the basal Triassic magnetozone LT1 extends down into the uppermost Permian, Changhsingian consistent with the pattern at Meishan, and that the apparent reversed polarity in the uppermost Permian of other sections such as Abadeh, Iran, results from a hiatus in sedimentation and gap in the paleomagnetic record. At Guandao, the PTB occurs within

a shale interval that was too friable to sample, thus the missing normal polarity zone likely exists within this gap in sampling (Fig. 3).

The Induan-Olenekian reversal stratigraphy at Guandao integrates well with other sections (Hounslow and Muttoni, 2010). The normal to reversed couplet within the Griesbachian (Fig. 3) correlates to LT1 and a normal polarity interval spanning the Griesbachian-Dienerian boundary followed by a longer reversed polarity interval within the Dienerian (Fig. 3) correlates to LT2 of the GPTS (Hounslow and Muttoni, 2010). Although there is a gap in the reversal record near the base of the Smithian (breccia and shale) at Guandao (Fig. 3), the two short reversals in the lower Smithian followed by a longer normal polarity zone in the upper Smithian and lower Spathian are similar to other sections and correspond to LT-4 through LT-6 (Muttoni et al., 2000; Hounslow and Muttoni, 2010).

The Olenekian-Anisian boundary at Guandao, like that found in other sections, is defined by a longer predominantly reversed polarity interval in the Upper Olenekian (LT9r) followed by a predominantly normal polarity with several short reversed intervals in the basal Anisian, Aegean to Bithynian (MT1-4) (Fig. 3; Hounslow and Muttoni, 2010).

Although the base of the Pelsonian is poorly constrained biostratigraphically at Guandao section, placement at 390.4 m (Fig. 3) would be most consistent with the GPTS yielding a Pelsonian that is dominantly of reversed polarity (MT4r) followed by a short normal to reversed couplet in the uppermost Pelsonian and basal Illyrian (MT5) (Fig. 3; Hounslow and Muttoni, 2010).

The Anisian-Ladinian boundary at Guandao, as recognized herein by the first occurrence of the conodont *Bv. truempyi*, correlates to a level slightly higher than the ammonoid *E.*

curionii that is used to define the boundary (Muttoni et al., 2004; Orchard, 2010). Using the ammonoid for boundary placement the boundary falls at the base of magnetozone MT8 with a reversed interval at the base of the Ladinian (Hounslow and Muttoni, 2010). The slightly higher placement of the boundary at Guandao puts it within a normal polarity interval at the base of MT9 (Fig. 3; Muttoni et al., 2004; Hounslow and Muttoni, 2010).

The Upper Ladinian at Guandao is predominantly normal in polarity with several short reversals each represented by only one sample (half bar, Fig. 3). This pattern is similar to the pattern of predominantly normal and several short reversed polarity intervals integrated in the GPTS (M-9 to M-13; Hounslow and Muttoni, 2010). Finally, the Ladinian-Carnian boundary at Guandao follows the last short reversed interval in the Longobardian and a long normal polarity above the boundary followed by two reversals in the Cordevolian (Fig. 3). This corresponds to the pattern in the GPTS (UT-1, 2; Muttoni et al., 2000; Hounslow and Muttoni, 2010).

6. 2 Magnetic susceptibility

Magnetic susceptibility in marine carbonate successions is a function of detrital and aeolian mineral concentration controlled by fluctuations in influx of terrestrial lithogenic (siliciclastic) material which responds both to changes in climate and continental weathering and sea level fluctuations (Ellwood et al., 2000; 2013). Magnetic susceptibility samples were taken at intervals of approximately 0.5 – 1 m from the Guandao section and were measured with the susceptibility bridge at Louisiana State University, using the techniques described in Ellwood et al. (2013).

Magnetic susceptibility ranges from $<1 \times 10^{-10}$ to $>1 \times 10^{-7} \text{ m}^3/\text{kg}$. The magnetic

susceptibility curve shows a great deal of character especially in the Lower Triassic portion of the section, which also contains the greatest variability in $\delta^{13}\text{C}$ (Fig. 3). To some extent there magnetic susceptibility is correlated with $\delta^{13}\text{C}$, yielding high magnetic susceptibility anomalies corresponding to positive carbon isotope excursions in the Griesbachian, in the upper Dienerian, and Lower Spathian (Fig. 3). The positive $\delta^{13}\text{C}$ spikes, indicating a greater burial of isotopically light carbon, are believed to be climate-change effects that also drive the flux of detrital and aeolian particles into the marine environment, resulting in higher magnetic susceptibility values. The Anisian-Ladinian shows lesser variability in magnetic susceptibility, but includes fluctuations that do not correlate with $\delta^{13}\text{C}$ excursions. Spikes in magnetic susceptibility in the Carnian near the top of the section reflect increased detrital flux as the siliciclastic turbidites of the Bianyang Fm. began infilling the basin in this area (Lehrmann et al., 1998).

The prominent spikes in magnetic susceptibility in the Griesbachian and upper Dienerian and Lower Spathian closely correspond to the three greatest positive carbon isotopic excursions of the Lower Triassic, but show no systematic correspondence to lithologic variability in the section (Fig. 3). Large fluctuations in carbon isotopes have been interpreted to result from massive release of isotopically light carbon into atmosphere/ocean systems perhaps from thermogenic carbon release from Siberian traps volcanism and associated changes in continental weathering, riverine input of increased lithogenic nutrient into the oceans and associated changes in oceanic primary productivity (Payne and Kump, 2007; Meyer et al., 2011). The large magnetic susceptibility spikes indicate significantly greater lithogenic influx into the Nanpanjiang Basin as would be expected to correlate with increased continental weathering and riverine flux increased burial of organic carbon associated with the carbon cycle perturbations (Fig. 3).

6. 3 Elemental Geochemistry (Chemostrat GR log)

A synthetic chemical gamma ray log has been calculated for Guandao section, with the calculation based on the concentrations of elemental potassium, thorium and uranium (Ellis and Singer, 2007): $\text{Chemical gamma ray} = (\text{K} \times 16.32 \times 0.83) + (\text{Th} \times 3.93) + (\text{U} \times 8.09)$

Calculated chemical gamma ray mimics the natural gamma ray (GR) log which is commonly used in subsurface exploration to characterize the rock or sediment in a borehole or drill hole. As with a GR log, a chemical gamma ray log may be used to distinguish between different lithologies based on the amount of natural gamma radiation emitted by certain rock types. Particularly, shale emits more radiation than other sedimentary rock types such as sandstone or limestone, because radioactive potassium is more prevalent in the clay mineral fraction of shale; and additionally the cation exchange capacity of clay minerals in shale causes them to absorb more radioactive thorium and uranium.

In Guandao section the chemical gamma ray log shows lower values in the packstone/grainstone intervals higher in the sequence. The log shows a higher response in mudstone/wackestone intervals (which will contain higher amounts of clay minerals), and the greatest response in the chemical gamma ray log is to the shaly interval in the Griesbachian. The spikes in Chemostrat gamma ray profile in the Griesbachian, upper Dienerian and Lower Spathian mimic the magnetic susceptibility curve and positive carbon isotope excursions suggesting a similar driving mechanism (Fig. 3).

6. 4 Carbon isotope excursions

Guandao section and correlative sections in the shallow-marine strata of the adjacent carbonate platform interior of the GBG contain large magnitude carbon isotope excursions at the PTB and through the Lower Triassic and basal Anisian followed by stable values in the overlying Anisian through Carnian (Fig. 4; Payne et al., 2004). Similar high magnitude carbon isotope excursions have been reported for the Lower Triassic in multiple sections in south China, Europe, the Middle East, and Japan indicating that they reflect perturbations in the global carbon cycle and therefore should be useful in chemostratigraphic correlation (Atudorei and Baud, 1997; Korte et al., 2005; Payne and Kump, 2007; Tong et al., 2007; Horacek et al., 2007; Galfetti et al., 2007, Tanner, 2010).

The negative shift of -3‰ $\delta^{13}\text{C}_{\text{carb}}$ at the PTB (Fig. 3) was measured in shallow-marine carbonate strata in the GBG at Dajiang and Heping sections (Payne et al., 2004; Krull et al., 2004). The excursion is not represented in Guandao because the PTB is developed in a black shale horizon, which has not yet been analyzed for carbon isotopes. The excursion has been recorded in the equivalent basin margin north of Guandao at Bianyang section (Meyer et al., 2013).

Additional significant excursions that can be calibrated to the integrated chronostratigraphy at Guandao (Fig. 3) include: a $+3\text{‰}$ shift to $+4.9\text{‰}$ $\delta^{13}\text{C}$ in the Upper Dienerian, a -7.8‰ shift to -2.9‰ $\delta^{13}\text{C}$ in the upper Smithian, a $+5.1\text{‰}$ shift to $+2.2\text{‰}$ $\delta^{13}\text{C}$ in the basal Spathian, a -3.2‰ shift to -1.0‰ $\delta^{13}\text{C}$ in the Middle Spathian, a $+5.7\text{‰}$ shift to $+4.7\text{‰}$ $\delta^{13}\text{C}$ in the Aegean, followed by a shift back to baseline values of 2‰ in the basal Bithynian and one last $+1\text{‰}$ excursion in the middle Bithynian followed by stable values around 2‰ in the succeeding Anisian through Carnian (Fig. 3).

6.5 Geochronology

6.5.1 Olenekian – Anisian boundary in Guandao

The age of the Olenekian – Anisian (O-A) boundary at the Guandao section was constrained by U-Pb ID-TIMS analyses on single zircons from five interstratified volcanic ash interlayers that straddle the boundary (Lehrmann et al. 2006; Ramezani et al., 2007). The resulting chronostratigraphy placed the O-A boundary at 247.2 ($\pm$ 0.4) Ma, which suggested a total duration of 5.4 ($\pm$ 0.6) m.y. for the Early Triassic Epoch when compared to the contemporaneous estimates of the PTB age from the GSSP section at Meishan, eastern China (e.g., Mundil et al., 2004; Shen et al., 2011). The analyzed Guandao zircons had been pre-treated some by the air abrasion method (Krogh, 1982), and others by the modern chemical abrasion technique (CA-TIMS: Mattinson, 2005), to mitigate the effects of Pb loss. In addition, weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates were calculated from statistically coherent clusters of data after excluding “outlier” analyses interpreted as xenocrystic zircon or having suffered persistent Pb loss.

Advances made in high-precision U-Pb geochronology since the publication of the Guandao geochronological data have allowed for improved accuracy and precision of zircon dates. Improvements include production, calibration and community-wide use of the EARTHTIME mixed U-Pb tracers, a more accurate estimate for the present-day isotopic composition of natural U (Hiess et al., 2012), and new algorithms and software for more rigorous statistical treatment of ID-TIMS data and date uncertainties (McLean et al., 2011; Bowring et al., 2011). These have been a major step in eliminating interlaboratory bias and in moving towards a more robustly calibrated geologic time scale. Here we present new zircon CA-TIMS analyses

from three previously analyzed Guandao ash beds reported in Lehrmann et al. (2006), using state-of-the-art U-Pb analytical procedures, in order to assess the accuracy of the published O-A boundary age. Our new analyses utilize the EARTHTIME ET535 mixed ^{205}Pb - ^{233}U - ^{235}U tracer, as well as a more aggressive CA-TIMS zircon pre-treatment, and follow the detailed analytical procedures described in Ramezani et al. (2011; 2014). Complete U-Pb isotopic data and calculated dates are presented in Table S1 (<http://dx.doi.org/10.1594/PANGAEA.836206>). New geochronologic constraints on the O-A boundary age are illustrated in Figure 8.

Six new single-zircon analyses from sample PGD Tuff-1 that occurs 4.20 meters below the O-A boundary in the lower Guandao section (Lehrmann et al., 2006; 2007) form a highly coherent cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $247.458 \pm 0.053/0.12/0.29$ Ma (see Table S1 for notation) and mean square of weighted deviates (MSWD) of 0.55 (Fig. 8). The weighted mean date is interpreted as the age of eruption and deposition of the ash. It is 75 k.y. (0.3‰) older and 46% more precise than the previously reported date, although well within the reported internal uncertainties.

Sample PGD Tuff-3 from 4.90 meters above the O-A boundary in the lower Guandao section (Lehrmann et al., 2006; 2007) produced six new zircon analyses, four of which form a coherent cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $247.08 \pm 0.11/0.17/0.31$ Ma (Table S1 and Fig. 8) and a MSWD of 0.39. Two older and significantly discordant analyses (z3 and z6) are evidently of detrital/xenocrystic origin. The above weighted mean date which represents the best estimate for the age of ash deposition is fairly comparable (0.02% younger, similar precision) to the previously published date for this sample.

A subset of six CA-TIMS analyses from previously reported data from sample GDGB Tuff-110 (Lehrmann et al., 2006) was re-reduced from the stage of raw mass spectrometric data, with state-of-the-art parameters and algorithms (see above). This ash bed occurs 17.25 meters above the O-A boundary. In addition, we augmented these data with three additional new analyses (Table S1 and Fig. 8) in order to evaluate the reproducibility of older U-Pb analyses that were produced before adoption of the EARTHTIME tracers. The new analyses exhibit more scatter that can be accounted for by analytical uncertainties alone, similar to that exhibited by the old data. A group of four old and two new analyses form a coherent cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $246.939 \pm 0.090/0.13/0.29$ Ma and a MSWD of 0.37 (Fig. 8). However two data points are slightly younger with $^{206}\text{Pb}/^{238}\text{U}$ dates of 246.57 ± 0.15 Ma and 246.40 ± 0.17 Ma (Table S1 and Fig. 8). As the former “young” analysis was produced using the latest protocols, the latter data cannot be readily excluded on account of persistent Pb loss. Therefore, the two youngest dates with a weighted mean date of 246.50 ± 0.11 Ma should be considered as the closest estimate for the age of deposition of the corresponding ash bed.

The age of the O-A boundary at Guandao can be constrained by linear extrapolation from the new U-Pb zircon dates corresponding to the nearest bracketing ash beds PGD Tuff-1 and PGD Tuff-3. This yields an age estimate of 247.28 ± 0.12 Ma for the O-A boundary, which is statistically indistinguishable from – and further refines – the previously reported boundary age of $247.2 (\pm 0.4)$ Ma in Lehrmann et al. (2006; 2007).

6.5.2 Permian – Triassic boundary in Taiping

The duration of the Early Triassic Epoch (combined Induan and Olenekian stages) is crucial to our understanding of ecosystem reorganization and biotic recovery in the wake of the global end-Permian extinction. Previous estimates for the Early Triassic duration were based on U-Pb geochronology of Olenekian/Spathian – Anisian sections in South China (e.g., Lehrmann et al., 2006; Ovtcharova et al., 2006) and that of the extensively studied PTB sections in eastern (Meishan) and central (Shangsi) China (e.g., Bowring et al., 1998; Mundil et al., 2004; Shen et al., 2011). However, these geographically distant, deep basin, PTB sections are highly distinct from the O-A shallow platform sections in terms of depositional facies and accumulation rate.

An expanded section of the PTB occurs at Taiping as part of the Pingguo Platform of the Nanpanjiang Basin in South China (Lehrmann et al., 2003). In addition to its proximity (within the same basin), the Taiping section shares the same Permo-Triassic depositional facies with Guandao, to which it is correlated via carbon isotope chemostratigraphy (Krull et al., 2004; Payne et al., 2004). The earliest Triassic strata directly overlying the PTB are characterized by calcimicrobial framestones that mark the first appearance of conodont *Hindeodus parvus* (Lehrmann et al. 2003). Seven distinctive volcanic ash beds occur on both sides of the PTB interval at Taiping (Fig. S1: <http://dx.doi.org/10.1594/PANGAEA.836206>), which provide the necessary material for high-precision U-Pb geochronology. Here we report new U-Pb CA-TIMS zircon dates from two ash beds that are closest to, and straddle, the PTB boundary at Taiping. The use of latest analytical protocols (e.g., ET535 tracer) makes these dates internally consistent with those from the O-A boundary interval at Guandao described above.

Sample TP Tuff-3 is from a ca. 0.2 meters-thick ash bed that occurs approximately 0.5 meters below the PTB at the Taiping section. Four youngest zircon grains analyzed from this sample overlap within 2 σ analytical uncertainties with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of

$252.002 \pm 0.072/0.13/0.30$ Ma and a MSWD of 0.84 (Table S1 and Fig. 8). Two slightly older analyses (z4 and z6) with $^{206}\text{Pb}/^{238}\text{U}$ dates of 252.19 ± 0.13 Ma and 252.17 ± 0.13 Ma are interpreted as detrital/xenocrystic and excluded from date calculation. Sample TP Tuff-4 is from a ca. 1.6 meters-thick ash bed, the base of which occurs approximately 4.7 meters above the PTB. Four zircon analyses from this sample yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $251.835 \pm 0.065/0.13/0.30$ Ma and a MSWD of 1.0. Linear extrapolation gives an age estimate of 251.985 ± 0.097 Ma for the PTB at Taiping. The latter is consistent with the most recent age constraint of 251.902 ± 0.024 Ma for the PTB at the GSSP in Meishan (Burgess et al., 2014). Together, the new U-Pb geochronology from the Guandao and Taiping sections suggest an estimated duration of 4.71 ± 0.15 Ma for the Early Triassic Epoch.

7. Importance and potential of Guandao Section

Guandao section is a key section in south China for biostratigraphy and chronostratigraphy. Guandao section occurs on the deep-marine basin margin slope of an isolated carbonate platform in the middle of the Nanpanjiang Basin. The long section is continuously exposed from the Upper Permian through lower Upper Triassic and occurs within a cross section that is physically correlated to the adjacent shallow-marine carbonate platform. The section spans the end-Permian extinction and the Early to Middle Triassic interval of biotic recovery.

Charts showing regional correlation of conodont and foraminifer biostratigraphic zonations with Guandao section are shown in figures 9 and 10. Guandao section clearly has the advantage over other sections in south China and elsewhere of being a very long, continuously

exposed section without significant unconformities spanning the Upper Permian through Carnian. Studies of conodont biozonation in sections on south China (cf. Bianyang, Jiarong, Chaohu; Fig. 9) have extensive data from the Upper Permian and Lower Triassic, but are lacking in the Middle and Upper Triassic. Guandao section contains a world class Lower to Middle Triassic (Olenekian-Anisian) boundary succession with high-resolution biostratigraphy, geochronology and chronostratigraphic data that will serve as an important reference section to supplement that of the GSSP candidate at Desli Cairn (Lehrmann et al., 2006; Orchard et al., 2007). Other stage boundaries in the Guandao section are approximated by the occurrences of key conodont species, but precise placement of boundaries will require additional sampling. As conodonts are abundant throughout the section, nearly all of the other stage boundaries have potential for refined bed-by bed sampling for conodonts and biostratigraphic analysis. The Permian-Triassic boundary section at Guandao is occupied by a black shale interval that thus far has not been sampled for conodonts. Additional detailed study of conodonts in this interval promises to provide an important complement to the Permian-Triassic boundary sections in the adjacent GBG and the GSSP at Meishan section.

Likewise the Guandao section is important for foraminifer biostratigraphy as it is a long uninterrupted section in comparison to the various sections in the Tethyan realm that are used to develop a foraminiferal biostratigraphy for the Triassic. Furthermore, Guandao has the advantage of having the foraminifer distributions calibrated to biostratigraphically important conodonts and other chronostratigraphic data sets. If the selected species of foraminifera are plotted against the Triassic chronostratigraphy firmly fixed by the conodont zonation in Guandao section, it is clearly seen that the stepwise first appearances of many foraminiferal taxa (Fig. 10) have a great potential for the construction of a detailed biostratigraphic scheme in the Tethyan

realm. The Guandao section, particularly in the Olenekian-Carnian interval, contains many foraminiferal species whose stratigraphic ranges are comparable to those given in the literature by Zaninetti (1976), Dağer (1980), He (1980), Salaj et al. (1988), Vachard and Fontaine (1988), Altiner and Koçyiğit (1993), Rettori (1995), De Bono et al. (2001), Márquez (2005) and Krainer and Vachard (2011). With these taxa, it is possible to recognize or approximate not only stage or substage boundaries but also establish a detailed biostratigraphic subdivision within the substages which would make the chronostratigraphic resolution based on foraminiferal zonation comparable with that provided by the conodont zonation. One should also note that first appearances of taxa during a recovery period following a major extinction event are always biostratigraphically significant because as the fauna recovers itself, like the foraminiferal fauna recovering Olenekian through Middle Triassic, diversity increases by the stepwise appearances of taxa. Recently, Song et al. (2011) produced a high-resolution foraminifer biostratigraphy by integrating data from several sections in south China (Guandao, Bianyang, Qingyan, Chaohu, Shangxi). However the data set is focused on the interval of recovery from the end-Permian extinction and spans only up into the Anisian. The new foraminifer data from Guandao presented herein spans up into the Carnian and presents potential for additional high-resolution biostratigraphic studies in the younger Triassic succession.

8. Conclusions

A detailed biostratigraphy at Guandao section is based on the occurrence data of 48 species of conodont and 42 species of foraminifer. The conodont biostratigraphy helps constrain the ranges of important foraminifers, in many cases improving upon the constraints in range

recognized from previous studies on sections from the western Tethys. The combined conodont and foraminifer biostratigraphy provides a robust age calibration at the substage level and is integrated with paleomagnetic reversal stratigraphy, magnetic susceptibility, and chemostratigraphy.

Reversals match well with the GPTS. Intervals containing numerous reversals span the Permian-Triassic, Olenekian-Anisian, and Anisian-Ladinian boundaries. Predominantly normal polarity intervals occur in the Lower Smithian, Bithynian, Longobardian-Cordevolian. Predominantly reversed polarity intervals occur in the upper Griesbachian, Induan-Olenekian, Pelsonian and Lower Illyrian.

Several large magnitude carbon isotope excursions characterize the Lower Triassic and basal Anisian. Stable values around +2‰ $\delta^{13}\text{C}$ characterize the Anisian to Carnian. Similar signatures have been reported globally. Magnetic susceptibility and synthetic gamma ray logs show large fluctuations in the Lower Triassic with an overall decline in magnitude of fluctuation through the Middle and Upper Triassic. The largest positive spikes in magnetic susceptibility and gamma ray values correspond to positive $\delta^{13}\text{C}$ excursions in the Lower Triassic indicating a link between atmospheric carbon release, terrestrial weathering, lithogenic flux to the marine environment and organic carbon burial. High precision U-Pb analysis of zircons from volcanic ash beds provide a robust age of 247.28 ± 0.12 Ma for the Olenekian-Anisian boundary at Guandao and an age of 251.985 ± 0.097 Ma for the PTB at Taiping. Together, the new U-Pb geochronology from the Guandao and Taiping sections suggest an estimated duration of 4.71 ± 0.15 Ma for the Early Triassic Epoch.

Acknowledgements

This research is based upon work supported by the National Science Foundation (EAR-9804835), by the Petroleum Research Fund of the American Chemical Society (40948-B2 and 33122-B8), and Shell International Exploration and Production (46000572). The authors wish to acknowledge the logistical and geological support of the Guizhou Bureau of Geology and Guizhou University. Orchard's contribution was made possible through support from the Geoscience for Energy and Minerals Program of the Geological Survey of Canada. Shuzhong Shen and Yukio Isozaki are acknowledged for reviews that substantially improved the manuscript.

References

- Altiner, D., Baud, A., Guex, J., and Stampfli, G., 1980, La limite Permien-Trias dans quelques localités du Moyen Orient: recherches stratigraphiques et micropaléontologiques. *Rivista Italiana di Paleontologia* 85 (3-4), 683-714.
- Altiner, D., and Zaninetti, L., 1981, Le Trias dans la region de Pinarbasi, Taurus oriental, Turquie: unités lithologiques, micropaléontologie, milieux de dépôt. *Rivista Italiana di Paleontologia* 86 (4), 705-760.
- Altiner, D., and Koçyiğit, A., 1993, Third remark on the geology of Karakaya Basin. An Anisian megablock in northern central Anatolia : micropaleontologic, stratigraphic and tectonic implications for the rifting stage of Karakaya Basin, Turkey. *Revue de Paléobiologie* 12 (1), 1-17.

- Assereto, R., 1974, Aegean and Bithynian, proposal for two new Anisian substages:
Schriftenreihe der Erdwissenschaftlichen Kommissionen. Österreichische Akademie der
Wissenschaften 2, 23-39.
- Atudorei, V., Baud, A., 1997, Carbon isotope events during the Triassic. *Albertiana* 20, 45-49.
- Balini, M., Jenkys, J., McRoberts, C., and Orchard, M. J., 2007, The Ladinian-Carnian boundary
succession at South Canyon (New Pass Range, central Nevada), In Lucas, S. G., (Ed.) *The
Global Triassic*, New Mexico Museum of natural History and Science Bulletin 41, 127-138.
- Balini, M., Lucas, S. G., Jenks, J. F., Spielmann, J. A., 2010, Triassic ammonoid biostratigraphy:
an overview, In Lucas, S. G. (Ed.), *The Triassic Timescale: Geological Society special
Publications* 33, 221-262.
- Bowring, J.F., McLean, N.M., Bowring, S.A., 2011. Engineering cyber infrastructure for U-Pb
geochronology: Tripoli and U-Pb_Redux. *Geochem. Geophys. Geosyst.* 12, Q0AA19.
- Brack, P., Rieber, H., Nicora, A., Mundil, R., 2005, The global stratotype section and point
(GSSP) of the Ladinian stage (Middle Triassic) at Bagolino (southern Alps, northern Italy)
and its implications for the Triassic time scale. *Episodes*, 28 (4), 233-244.
- Brönnimann, P., Zaninetti, L. and Bozorgnia, F., 1972, Triassic (Skythian) smaller Foraminifera
from the Elike formation of the central Alborz, northern Iran, and from the Siusi formation
of the Dolomites, northern Italy. *Mitt. Ges. Geol. Bergbaustud* 21, 861-884.
- Brosse, M., Bucher, H., Bagherpour, B., Baud, A., Frisk, A., M., Goudun, K., Goudemand, N.,
2015, Conodonts from the Early Triassic microbialite of Guangxi (south China):
implications for definition of the base of the Triassic system: *Paleontology, Early View*, p.
1-22, doi: 10.1111/pala.12162.

- Burgess, S. D., Bowring, S., and Shen, S., 2014, High-precision timeline for Earth's most severe extinction. *Proceedings of the National Academy of the United States of America* 111 (9), 3202-3204.
- Chen, J., Beatty, T., Henderson, C.M., and Rowe, H., 2009, Conodont biostratigraphy across the Permian-Triassic boundary at the Dawen section, Great Bank of Guizhou, Guizhou Province, South China: Implications for the Late Permian extinction and correlation with Meishan: *Journal of Asian Earth Science*, 36, 442-458.
- Chen, Y., Jiang, H., Lai, X., Yan, C., Richoz, S., Liu, X., Wang, L., in press, Early Triassic conodonts of Jiarong, Guizhou Province, south China, *Journal of Asian Earth Sciences*.
- Dağ, Z., 1980, Les Foraminifères du Trias de la Péninsule de Kocaeli-Turquie. Thèse, Université de Genève, Département de Géologie et de Paléontologie 1857, 1-69.
- De Bono, A., Martini, R., Zaninetti, L., Hirsch, F., Stampfli, G., and Vavassis, I., 2001, Permian-Triassic stratigraphy of the pelagonian zone in central Evia island (Greece). *Eclogae Geologicae Helveticae* 94, 289-311.
- Ellis, D.V. and Singer, M., 2007, *Well logging for Earth Scientists*. Springer Science & Business Media B.V., pp. 692.
- Ellwood, B.B., Crick, R.E., El Hassani, A., Benoist, S. and Young, R., 2000. MagnetoSusceptibility Event and Cyclostratigraphy (MSEC) in Marine Rocks and the Question of Detrital Input Versus Carbonate Productivity. *Geology*, 28, 1135 – 1138.
- Ellwood, B.B., Wang, W.-H., Tomkin, J.H., Ratcliffe, K.T., El Hassani, A., Wright, A.M., 2013. Testing high resolution magnetic susceptibility and gamma gradation methods in the

- Cenomanian–Turonian (Upper Cretaceous) GSSP and near-by coeval section. *Palaeogeography, Palaeoclimatology, Palaeoecology* 378, 75-90.
- Enkin, R.J., Yang Zhenyu, Chen Yan, and V. Courtillot, 1992, Paleomagnetic constraints on the geodynamic history of the major blocks of China from the Permian to the present. *Journal of Geophysical Research* 97 (B10), 13953 - 13989.
- Enos, Paul, D. J. Lehrmann, Wei Jiayong, Yu Youyi, Xiao Jiafei, D. H. Chaikin, M. Minzoni, A. K. Berry, and P. Montgomery, 2006, Triassic evolution of the Yangtze Platform in Guizhou Province, P. R. C., Geological Society of America, Special Paper 417, 105 p.
- Galfetti, T., Hochuli, P. A., Brayard, A., Bucher, H., Weissert, H., Vigran, J. O., 2007, Smithian/Spathian boundary event : evidence for global climate change in the wake of the end-Permian biotic crisis. *Geology* 35, 291-294.
- Gallet, Y., Krystyn, L., Besse, J., Saidi, A., Ricou, L., E., 2000, New constraints on the Upper Permian and Lower Triassic geomagnetic polarity time scale from the Abadeh section (central Iran); *Journal of Geophysical Research*, 105, 2805-2815.
- Goudemand N., 2015, Note on the conodonts from the Induan-Olenekian boundary: Albertiana, 42, 49-51.
- Goudemand N., Orchard M., Bucher H., Jenks J., 2012. The elusive origin of *Chiosella timorensis* (Conodonts, Triassic). *Geobios* 45, 199-207.
- Gradinaru, E., Kozur, H. W., Nicora, A., Orchard, M. J., 2006, The *Chiosella timorensis* lineage and correlation of the ammonoids and conodonts around the base of the Anisian in the GSSP candidate at Desli Caira (North Dobrogea, Romania). *Albertiana* 34, 34-38.

- Gradinaru, E., Orchard, M. J., Nicora, A., Gallet, Y., Besse, J., Krystyn, L., Sobolev, E., Atudorei, B. V., Ivanov, D., 2007, The global boundary startotype section and point (GSSP) for the base of the Anisian Stage, Desli Caira Hill, North Dobrogea, Romania. *Albertiana* 36, 54-71.
- Groves, J. R., and Altiner, D., 2005, Survival and recovery of calcareous foraminifera pursuant to the end-Permian mass extinction. *Comptes Rendus Palevol* 4, 487-500.
- Groves, J. R., Altiner, D., and Rettori, R., 2005, Extinction, survival, and recovery of lagenide foraminifers in the Permian-Triassic boundary interval, central Taurides, Turkey. *Journal of Paleontology* 79 (4), 1-38.
- Groves, J. R., Rettori, R., Payne J. L., Boyce M. D., and Altiner, D., 2007, End-Permian mass extinction of lagenide foraminifers in the southern Alps (northern Italy). *Journal of Paleontology* 81 (3), 415-434.
- Guizhou Bureau of Geology and Mineral Resources, 1987, Regional Geology of Guizhou Province. Geological Memoir, Serial 1(6), pp.700 [Geologic map 1:500,000].
- Hao, W., Sun, Y., Jiang, D., Yang, S., Wang, X., 2010, Cephalopods of the "Falang Formation" (Triassic from Guanling and Zhenfeng counties, Guizhou Province, China. *Acta Geologica Sinica* 7, 430-439.
- He, Y., 1980, Sketch of the Triassic foraminiferal biostratigraphy of northwestern Sichuan (Szechuan), China. *Rivista Italiana di Paleontologia* 85 (3-4), 1167-1174.
- Hiess, J., Condon, D.J., McLean, N., Noble, S.R., 2012. $^{238}\text{U}/^{235}\text{U}$ Systematics in Terrestrial Uranium-Bearing Minerals. *Science* 335, 1610-1614.

- Horacek, M., Wang, X., Grossman, E. L., Richoz, S., and Cao, Z., 2007, The carbon-isotope curve from the Chaohu section, China: different trends at the Induan-Olenekian boundary or diagenesis? *Albertiana* 35, 41-45.
- Hounslow, M. W., and Muttoni, G., 2010, The geomagnetic polarity timescale for the Triassic: linkage to stage boundary definition, in Lucas, S. G. (ed.), *The Triassic Timescale*. Geological Society special Publications, 33, 61-102.
- Jiang, H., Lai, X., Luo, G., Aldridge, R., Zhang, K., and Wignall, P., 2007, Restudy of the conodont zonation and evolution across the P/T boundary at Meishan section, Changxing, Zhejiang, China. *Global and Planetary Change* 55, 39-55.
- Kelley, B. M., 2014, Physical, chemical, and biological controls on the temporal and spatial variability of a Late Permian to Late Triassic isolated carbonate platform in the Nanpanjiang Basin of south China, Unpublished PhD Thesis, Stanford University, pp. 193.
- Korte, C., Kozur, H. W., and Veizer, J., 2005, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of brachiopods and carbonate rocks as proxies for coeval seawater and paleotemperature. *Palaeogeography, Palaeoclimatology, Palaeoecology* 226, 287-306.
- Kozur, H., 1974 a, Biostratigraphie der germanischen Mitteltrias. Teil I. *Freiberger Forsch.-H.*, Leipzig C 280, 1-56.
- Kozur, H., 1974 b, Biostratigraphie der germanischen Mitteltrias. Teil II: *Freiberger Forsch.-H.*, Leipzig, v. C 280, 1-70.
- Kozur, H. W., 2003, Integrated ammonoid, conodont and radiolarian zonation of the Triassic: *Hellesches Jahrbuch Geowissenschaften*, v. B25, p. 49-79.

- Krainer, K., and Vachard, D., 2011 The Lower Triassic Werfen Formation of the Karawanken mountains (Southern Austria) and its disaster survivor microfossils, with emphasis on *Postcladella* n. gen. (Foraminifera, Miliolata, Cornuspirida). *Revue de Micropaléontologie* 54 (2) 59-85.
- Krogh, T.E., 1982. Improved Accuracy of U-Pb Zircon Ages by the Creation of More Concordant Systems Using an Air Abrasion Technique. *Geochim Cosmochim Acta* 46, 637-649.
- Krull, E.S., Lehrmann, D.J., Druke, D., Kessel, B., Yu, Y.Y. and Li, R., 2004, Stable carbon isotope stratigraphy across the Permian-Triassic boundary in shallow marine carbonate platforms, Nanpanjiang Basin, South China. *Palaeogeography, Palaeoclimatology, Palaeoecology* 204 (3-4), 297-315.
- Krystyn, L., Richoz, S., Bhargava, O. N., 2007, Induan-Olenekian boundary (IOB) in Mud – an update on the candidate for the GSSP section MO4. *Albertiana* 36, 33-45.
- Lau, K. V., Maher, K., Kelley, B. M., Yu, M., Lehrmann D. J., Payne, J. L., 2013, Prolonged and recurrent global seafloor anoxia in the Early Triassic from uranium isotope evidence. *Geological Society of America Abstracts with Programs* 45 (7), 884.
- Lehrmann, D. J., 1993, The Great Bank of Guizhou, birth evolution of a Triassic carbonate platform, Guizhou Province, south China: unpublished PhD thesis, University of Kansas, pp. 457.
- Lehrmann, D.J., Enos, Paul, Payne, J. L., Montgomery, P., Wei, Jiayong, Yu Youyi, Xiao Jiafei and Orchard, M. J., 2005, Permian and Triassic depositional history of the Yangtze

platform and Great Bank of Guizhou in the Nanpanjiang basin of Guizhou and Guangxi, south China. *Albertiana* 33, 147-166.

Lehrmann, D. L., Payne, J. L., Felix, S. V., Dillett, P. M., Wang Hongmei, Yu Youyi, and Wei Jiayong, 2003, Permian-Triassic boundary sections from shallow-marine carbonate platforms of the Nanpanjiang Basin, south China: Implications for oceanic conditions associated with the end-Permian extinction and its aftermath. *Palaaios* 18 (2) 138-152.

Lehrmann, D. J., Pei, D., Enos, p., Ellwood, B. B., Zhang, J., Wei, J., Dillett, P., Koenig, J., Steffen, K., Druke, D., Gross, j., Kessel, B., Newkirk, T., 2007, Impact of differential tectonic subsidence on isolated carbonate platform evolution: Triassic of the Nanpanjiang basin, south China: *American Association of Petroleum Geologists Bulletin*, v. 91, no. 3, p. 287-320.

Lehrmann, D.J., Ramezani, J., Bowring, S.A., Martin, M.W., Montgomery, P., Enos, P., Payne, J.L., Orchard, M.J., Hongmei, W., Jiayong, W., 2007. Timing of recovery from the end-Permian extinction: Geochronologic and biostratigraphic constraints from south China: COMMENT AND REPLY: REPLY. *Geology* 35, e136-e137.

Lehrmann, D. J., Ramezani, J., Bowring, S. A., Martin, M. W., Montgomery, P., Enos, Paul, Payne, J. L., Orchard, M. J., Wang, H., Wei, J., 2006, Timing of recovery from the end-Permian extinction: Geochronologic and biostratigraphic constraints from south China. *Geology* 34, 1053-1056.

Lehrmann, D. J., Wei Jiayong, and Paul Enos, 1998, Controls on facies architecture of a large Triassic carbonate platform: the Great Bank of Guizhou, Nanpanjiang Basin South China: *Journal of Sedimentary Research, Section B*, 68 (2), 311-326.

- Manco, S., Mietto, P. Nicora, A., Preto, N. Rigo, M., and Tognon, M., 2004, Conodont fauna at the Ladinian/ Carnian boundary interval in the southern Alps. *Albertiana* 30, 9.
- Martini, R., Rettori, R., Urosevic, D., and Zaninetti, L., 1995, Le genre *Piallina* Rettori et Zaninetti (Foraminifère) du Trias (Carnien) de Serbie orientale (domaine Carpato-Balkanique). *Revue de Paléobiologie* 14 (2) 411-415.
- Márquez, L., 2005, Foraminiferal fauna recovered after the Late Permian extinctions in Iberia and the westernmost Tethys area. *Palaeogeography, Palaeoclimatology, Palaeoecology* 229 (1-2), 137-157.
- Mattinson, J.M., 2005. Zircon U/Pb chemical abrasion (CA-TIMS) method; combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. *Chemical Geology* 220, 47-66.
- McLean, N.M., Bowring, J.F., Bowring, S.A., 2011. An algorithm for U-Pb isotope dilution data reduction and uncertainty propagation. *Geochem. Geophys. Geosyst.* 12, Q0AA18.
- Metcalf, I., 1990, Triassic conodont biostratigraphy of the Malay Peninsula. *Geological Society of Malasia Bulletin* 26, 133-145.
- Meyer KM, Jost AB, Yu Y, and Payne JL., 2011, $\delta^{13}\text{C}$ evidence that high primary productivity delayed recovery from end-Permian mass extinction. *Earth and Planetary Science Letters* 302, 378-384.
- Meyer, K. M., Yu, M., Lehrmann, D., van de Schootbrugge, and Payne, J. L., 2013, Constraints on Early Triassic carbon cycle dynamics from paired organic and inorganic carbon isotope records. *Earth and Planetary Science Letters* 361, 429-435.

- Mietto, P., Andretta, R. et al., 2007, A candidate for the global stratotype and point for the base of the Carnian stage (Upper Triassic): GSSP at the base of the Canadensis subzone (FAD of Daxatina) in the Prati de Stuores Wiesen section (southern Alps, NE Italy). *Albertiana* 36, 78-101.
- Monnet, C., Brack, P., Bucher, H., Rieber, H., 2008, Ammoniods of the middle/late Anisian boundary (Middle Triassic) and the transgression of the Prezzo Limestone in eastern Lombardy-Giudicarie (Italy). *Swiss Journal of Geoscience* 101, 61-84.
- Mundil, R., Ludwig, K.R., Metcalfe, I., Renne, P.R., 2004. Age and timing of the Permian mass extinctions; U/Pb dating of closed-system zircons. *Science* 305, 1760-1763.
- Muttoni, G., Gaetani, M., Budurov, K., Zagorchev, I., Trifonova, E., Ivanova, D., Petrounova, L. and Lowrie, W. 2000, Middle Triassic paleomagnetic data from northern Bulgaria; constraints on Tethyan magnetostratigraphy and paleogeography. *Palaeogeography, Palaeoclimatology, Palaeoecology* 160, (3-4), 223-237.
- Muttoni, G., Kent, D. V., Meco, S., Balini, M., Rettori, R., Gaetani, M., Krystyn, L., 1998, Towards a better definition of the Middle Triassic magnetostratigraphy and biostratigraphy in the Tethyan realm. *Earth and Planetary Sciences* 164, 285-302.
- Muttoni, G., Nicora, A., Brack, P., Kent, D. V., 2004, Integrated Anisian-Ladinian boundary chronology. *Palaeogeography, Palaeoclimatology, Palaeoecology* 208, 85-102.
- Nakrem, H. A., Orchard, M. J., Weitschat, W., Hounslow, M. W., Beatty, T., and Mork, A., 2008, Triassic conodonts from Svalbard and their Boreal correlations: *Polar Research*, v. 27, p. 523-539.

- Nicoll, R. S., Metcalf, I., and Wang, C., 2002, New species of the conodont *Hindeodus* and the conodont biostratigraphy of the Permian-Triassic boundary interval. *Journal of Asian Earth Sciences* 20, 609-631.
- Nicora, A., 1977, Lower Anisian platform conodonts from the Tethys and Nevada: Taxonomic and stratigraphic revision. *Palaeontographica A* 157, 88-107.
- Orchard, M. J., 2007a, Report on 2007 conodont collections from Mud, Spiti. *Albertiana*, 36, 46-49.
- Orchard, M. J., 2007b, New conodonts and zonation, Ladinian-Carnian boundary beds, British Columbia, Canada, In Lucas, S. G., (Ed.) *The Global Triassic*. New Mexico Museum of Natural History and Science Bulletin 41, 321-330.
- Orchard, M. J., 2008, Lower Triassic conodonts from the Canadian Arctic, their intercalibration with the ammonoid-based stages and a comparison with other North American Olenekian faunas. *Polar Research* 27, 393-412.
- Orchard, M. J., 2010, Triassic conodonts and their role in stage boundary definition, In Lucas, S. G. (Ed.), *The Triassic Timescale*. Geological Society Special Publications 33, 139-161.
- Orchard, M. J. and Krystyn, L., 2007, Conodonts from the Induan-Olenekian boundary at Mud, Spiti. *Albertiana* 35, 30-34.
- Orchard, M. J., and Tozer, E. T., 1997, Triassic conodont biochronology, its calibration with the ammonoid zonation standard, and a biostratigraphic summary for the western Canada sedimentary basin. *Bulletin of Canadian Petroleum Geology* 45 (4), 675-692.

- Orchard, M. J., Lehrmann, D. J., Wei, J., Wang H., Taylor, H. J., 2007, Conodonts from the Olenekian-Anisian boundary beds, Guandao, Guizhou Province, China. *New Mexico Museum of Natural History and Science Bulletin* 41, 347-354.
- Ovtcharova, M., Bucher, H., Schaltegger, U., Galfetti, T., Brayard, A., Guex, J., 2006. New Early to Middle Triassic U-Pb ages from South China: Calibration with ammonoid biochronozones and implications for the timing of the Triassic biotic recovery. *Earth Planet Sc Lett* 243, 463-475.
- Paull, R. K., and Paull, R. A., 1997, Conodont biostratigraphy of the Lower Triassic Mackenzie Dolomite Lentic, Sulfur Mountain Formation in the Cadomin area, Alberta. *Bulletin of Canadian Petroleum Geology* 44 (4), 706-714.
- Payne J. L. and Kump, L. R., 2007, Evidence for recurrent Early Triassic massive volcanism from quantitative interpretation of carbon isotope fluctuations. *Earth and Planetary Science Letters* 256, 264-277.
- Payne, J. L., Lehrmann, D. J., Christensen, S., Wei, J., and Knoll, A. H., 2006a, Environmental and Biological Controls on the Initiation and Growth of a Middle Triassic (Anisian) Reef Complex on the Great Bank of Guizhou, Guizhou Province, China. *Palaaios* 21, 325-343.
- Payne, J. L., Lehrmann, D. J., Wei, Jiayong; Knoll, A. H., 2006b, The pattern and timing of biotic recovery On the Great Bank of Guizhou, Guizhou Province, China. *Palaaios* 21, 63-85.
- Payne, J. L., Lehrmann, D. J., Wei, Jiayong, Orchard, M. P., Schrag, D. P., Knoll, A. H., 2004, Large Perturbations of the Carbon Cycle During Recovery from the End-Permian Extinction. *Science* 23, 506-509.

- Payne, J. L., Summers, M. Rego, B. L., Altiner, D., Wei, J., Yu, M., and Lehrmann, D. J., 2011, Early and Middle Triassic trends in diversity, evenness, and size of foraminifers on a carbonate platform in south China: implications for tempo and mode of biotic recovery from the end-Permian mass extinction. *Paleobiology* 37 (3), 409–425.
- Piller, W., 1978, Involutinacea (Foraminifera) der Trias und des Lias: Beiträge zur Paläontologie von Österreich 5, 1-164.
- Ramezani, J., Bowring, S. A., Martin, M. W., Lehrmann, D. J., Montgomery, P., Enos, P., Payne, J. L., Orchard, M. J., Hongmei, W., Jiayong, W., 2007. Timing of recovery from the end-Permian extinction: Geochronologic and biostratigraphic constraints from south China: COMMENT AND REPLY: REPLY. *Geology* 35, e137-e138.
- Ramezani, J., Fastovsky, D. E., Bowring, S. A., 2014. Revised chronostratigraphy of the Lower Chinle Formation strata in Arizona and New Mexico (USA): High-precision U-Pb geochronological constraints on the Late Triassic evolution of dinosaurs. *American Journal of Science* 314, 981-1008.
- Ramezani, J., Hoke, G. D., Fastovsky, D. E., Bowring, S. A., Therrien, F., Dworkin, S. I., Atchley, S. C., Nordt, L. C., 2011. High-precision U-Pb zircon geochronology of the Late Triassic Chinle Formation, Petrified Forest National Park (Arizona, USA): Temporal constraints on the early evolution of dinosaurs. *Geological Society of America Bulletin* 123, 2142-2159.
- Rettori, R., 1995, Foraminiferi del Trias inferior e medio della Tetide: revision tassonomica, stratigrafia ed interpretazione filogenetica. *Université de Genève, Publications du Département de Géologie et Paléontologie* 18, 1-147.

- Rettori, R., Loriga, C. and Neri, C., 1998, Lower Carnian foraminifers from the type locality of the Calcare del Predil (Raibl Group, northeastern Italy). *Rivista Italiana di Paleontologia e Stratigrafia* 104, (3), p. 369-380.
- Rigaud, S., Blau, J., Martini, R. and Rettori, R., 2013, Taxonomy and phylogeny of the Trocholinidae (Involutinina). *Journal of Foraminiferal Research* 43, 4, 317-339.
- Salaj, J., 1969, Essai de zonations dans le Trias des Carpates occidentals d'après les Foraminifères. *Geol. Prace* 42, 123-128.
- Salaj, J., Trifonova, E., and Gheorghian, D., 1988, A biostratigraphic zonation based on benthic foraminifera in the Triassic deposits of the Carpatho-Balkans. *Revue de Paléobiologie*, Vol. Spéc. No. 2, 153-159.
- Schaal, E. K., Paytan, A., and Payne, J. L., 2011, Strontium isotope constraints on Permian-Triassic global Change. *Geological Society of America Abstracts with Programs* 43 (5), 506.
- Shen, S., Crowley, J. L., Wang, Y., Bowring, S. A., Erwin, D. H., Sadler, P. M., Cao, C., Rothman, D. H., Henderson, C. M., Ramezani, J., Zhang, H., Shen, Y., Wang, X., Wang, W., Mu, L., Li, W., Tang, Y., Liu, X., Liu, L., Zeng, Y., Jiang, Y., Jin, Y., 2011. Calibrating the End-Permian Mass Extinction. *Science* 334, 1367-1372.
- Song, Haijun, Tong, J., Chen, Z. Q., Yan, H., and Wang, Y., 2009, End-Permian mass extinction of foraminifers in the Nanpanjiang Basin, South China. *Journal of Paleontology* 83 (5), 718-738.

- Song, Haijun, Wignall, P. B., Chen, Z. Q., Tong, J., Bond, D. P. G., Lai, X., Zhao, X., Jiang, H., Yan, C., Niu, Z., Chen, J., Yang, H., Wang, Y., 2011, Recovery tempo and pattern of marine ecosystems after the end-Permian mass extinction. *Geology* 39 (8), 739-742.
- Song, Huyue, Tong, J., Algeo, T. J., Horacek, M., Qiu, H., Song, H., Tian, L., Chen, Z. Q., 2013, Large vertical ^{13}C DIC gradients in Early Triassic seas of the South China Craton; implications for oceanographic changes related to Siberian Traps volcanism. *Global and Planetary Change*, v. 105, p. 7-20.
- Song, Huyue., Tong, J., Song, H., Algeo, T. J., 2011, Large seawater sulfur isotope perturbations during the early Mesozoic. *Record - Geological Survey of Western Australia*, 117.
- Steiner, M., J. Ogg, Z., Zhang, and S. Sun, 1989, The late Permian/early Triassic magnetic polarity time scale and plate motions of South china. *Journal of Geophysical Research* 94, 7343-7363.
- Sweet, W. C., 1970, Uppermost Permian and Lower Triassic conodonts of the Salt Range and Trans-Indus Ranges, west Pakistan, in Kummel, B., and Teichert, C., (eds.) *Stratigraphic boundary problems: Permian and Triassic of west Pakistan*. University of Kansas Department of Geology Special Publication 4, 207-275.
- Sweet, W. C., 1988, The conodonts, morphology, taxonomy, paleoecology, and evolutionary history of a long-extinct animal phylum. *Oxford Monographs on Geology and Geophysics* 10, Claredon Press, Oxford, pp. 212.
- Tanner, L., 2010, The Triassic isotope record, In Lucas, S. G. (Ed.), *The Triassic Timescale*. Geological Society Special Publications, 33, 103-118.

- Tong, J. Zakharov, Y. D., Orchard, M. J., Yin, H. and Hassan, H. J. 2004, Proposal of Chaohu section as the GSSP candidate of the Induan-Olenekian boundary: *Albertiana*, 29, 13-28.
- Tong, J. Zuo, J., Chen, Z. Q., 2007, Early Triassic carbon isotope excursions from south China; proxies for devastation and restoration of marine ecosystems following the end-Permian mass extinction. *Geological Journal* 42 (3-4), 371-389.
- Tozer, E. T., 1974, Definition of the limits of Triassic stages and substages: suggestions prompted by comparison between North America and the Alpine-Mediterranean region. *Schriftenreihe der Erdwissenschaftlichen Kommissionen Österreichische akademie der Wissenschaften* 2, 195-206.
- Vachard, D., and Fontaine, H., 1998, Biostratigraphic importance of Triassic foraminifera and algae from South-East Asia. *Revue de Paléobiologie* 7 (1), 87-98.
- Van-der-Voo, R., 1993, *Paleomagnetism of the Atlantic, Tethys and Iapetus oceans*: Cambridge, U.K., Cambridge University Press, pp. 411.
- Vörös, A., 2003, The Pelsonian Substage on the Balaton Highland (Middle Triassic, Hungary). *Geologica Hungarica, Series Palaeontologica* 55, pp.195.
- Wang H., Wang, X., Li, R., and Wei, J., 2005, Triassic conodont succession and stage subdivision of the Guandao section, Bianyang Luodian. *Acta Palaeontologica Sinica*, 44, 611-626.
- Yan, C., Wang, L., Jiang, H., Wignall, P. B., Sun, Y., Chen, Y., and Lai, X., 2013, Uppermost Permian to Lower Triassic conodonts at the Bianyang section, Guizhou Province, south China. *Palaeo*, 28, 509-522.

- Yang, S., Liu J., Zhang, M., 1995, Conodonts of the Falang Formation of southwestern Guizhou and their age. *Journal of Stratigraphy* 19, 722-732.
- Yin, H., Zhang, K., Tong, J., Yang, Z., Wu, S., 2001, The global stratotype section and point (GSSP) of the Permian-Triassic boundary: Episodes, v. 24, n. 2, p. 102-114.
- Zaninetti, L., 1976, Les Foraminifères du Trias. Essai de synthèse et corrélation entre les domaines mésogéens européen et asiatique. *Rivista Italiana di Paleontologia* 82 (1), 1-258.
- Zaninetti, L., and Martini, R., 1993, *Bispiranella* et *Orthotrinacria* (Foraminifères, Trias), nouvelle description et regroupement dans la famille des Orthotrinacriidae (Milioliporacea). *Bollettino della Società Paleontologica Italiana* 32, (3), 385-392.
- Zaninetti, L., Brönnimann, P., and Baud, A., 1972, Essai de zonation d'après les foraminifères dans l'Anisien moyen et supérieur des Préalpes médianes rigides (Préalpes romandes, Suisse, et Préalpes du Chablais, France). *Eclogae Geologicae Helveticae* 65, (2), 343-353.
- Zaninetti, L., Rettori, R. and Martini, R., 1994, *Aulotortus ? eotriasicus*, n. sp., un nuovo foraminifero del Trias medio (Anisico) delle Dinaridi ed Ellenidi. *Bollettino della Società Paleontologica Italiana* 33 (1) 43-49.
- Zaninetti, L., Rettori, R., Martini, R., Cirilli, S., and Ciarapica, G., 1992, il foraminifero *Abriolina* Luperto, 1963 (Trias medio, Appennino meridionale): ridefinizione, tassonomia, nuovi dati sulla distribuzione stratigrafica. *Revue de Paléobiologie* 11, (1), 197-204.
- Zhao, L., Orchard, M. J., and Tong, J., 2004, Lower Triassic conodont biostratigraphy and speciation of *Neospathodus waageni* around the Induan-Olenekian boundary of Chaohu, Anhui Province, China. *Albertiana*, 29, 41-43.

Zhao, L., Tong, J., Sun, Z., and Orchard, M. J., 2008, A detailed Lower Triassic conodont biostratigraphy and its implications for the GSSP candidate in the Induan-Olenekian boundary in Chaohu, Anhui Province. *Progress in Natural Sciences*, 18, 79-90.

Figure Captions:

Fig. 1. Lower Triassic paleogeography of the Nanpanjiang basin and Yangtze Platform and isolated carbonate platforms in parts of Guizhou, Guangxi, and Yunnan. GD = Guandao section.

Fig. 2. (A) Landsat image of the Great Bank of Guizhou (GBG). The Bianyang syncline (area between Bianyang and Bangun) is asymmetric and faulted on the east. Strata dip gently on west limb of the syncline and are steeply dipping ($60\text{--}70^\circ$) on the east limb. The east limb of the syncline displays a complete, uncomplicated cross-section through the platform. (B) High resolution, worldview image of the natural cross-section of northern margin of GBG exposed on the east limb of the Bianyang syncline. GD = Guandao section. Area of high-resolution image is shown in yellow rectangle on landsat image (A). Platform interior to the left, basin is to the right. (C) Detailed geological map of northern margin of GBG on the east limb of the Bianyang syncline. Same area as B. GD = Guandao section.

Fig. 3. Integrated lithofacies and chronostratigraphy of Guandao section. Data sets are available in the online data repository (<http://dx.doi.org/10.1594/PANGAEA.836206>). Location is shown in Figure 2. Age boundaries (stage and substage boundaries are based on biostratigraphic ranges shown in figure 4. Other chronostratigraphic data sets

(paleomagnetic reversal stratigraphy, magnetic susceptibility, synthetic gamma ray, and carbon isotopes are discussed in the text. The lower portion of the carbon isotope curve shown in red is from the Permian-Triassic boundary succession at Dajiang section (Fig. 2).

Fig. 4. High-resolution biostratigraphic plot and age boundary assignments (stage and substage boundaries). Data is available in spread-sheet form in the online data repository (ref). Lithologic column and other chronostratigraphic data are shown in figure 3. Diamonds indicate fossil occurrences. Blue are conodont species. Red are foraminifer species. Bv. = *Budurovignathus*, Cl. = *Clarkina*, Cn. = *Conservatella*, Cs. = *Chiosella*, D. = *Discretella*, G. = *Gladigondolella*, H. = *Hindeodus*, Ng. = *Neogondolella*, Ni. = *Nicoraella*, Ns. = *Neospathodus*, Nv. = *Novispathodus*, Pg. = *Paragondolella*, S. = *Spathicuspis*, Ts. = *Triassospathodus*, Q. = *Quadralella*.

Fig. 5. Scanning electron microphotographs of conodonts from Guandao section. Scale bar is 200 microns. 1) *Hindeodus typicalis* (Sweet), GSC-131510, sample GDL-2. 2) *Hindeodus anterodentatus* (Dia, Tian & Zhang), GSC-131511, sample GDL-7. 3, 4) *Hindeodus parvus* (Kozur & Pjatakova), GSC-131512, sample WG-8, GSC-131513, sample WG-4. 5, 6) *Neospathodus dieneri* (Sweet), GSC-131514, sample GDL-16. 7) *Eurygnathodus* sp., GSC-131515, sample WG-88. 8) *Novispathodus posterolongatus* (Zhao & Orchard), GSC-131516, sample GSL-19. 9) *Novispathodus waageni* (Sweet), GSC-131517, sample WG-47. 10, 11) *Neospathodus cristagalli* (Huckriede), GSC-131518, sample GDL-16, GSC-131519, sample WG-35. 12) *Neospathodus peculiaris* (Sweet), GSC-131520, sample WG-33. 13) *Cornudina* sp., GSC-101549, sample UGD-19. 14,15) *Discretella discrete* (Muller), GSC-131521, sample WG-49. 16,17) *Novispathodus? Crassatus*

(Orchard), GSC-131522, sample WG-88. 18) *Guangxidella bransoni* (Muller), GSC-131523, sample WG-82. 19) *Novispathodus? Triangularis* (Bender), GSC-101550, sample O-3. 20, 21) *Gladigondolella carinata* (Bender), GSC-101544, sample O-33. 22, 23) *Clarkina* sp., GSC-131524, sample GDL-3, GSC-131525, sample GDL-1. 24, 25) *Triassospathodus homeri* (Bender & Stoppel), GSC-101545, sample O-33. 26) *Nicoraella germanica* (Kozur), GSC-131526, sample GD-29. 27) *Nicoraella kockeli* (Tatge), GSC-131527, sample UGD-30. 28) *Spathicuspus spathi* (Sweet), GSC-101557, sample O-39.

Fig. 6. Scanning electron microphotographs of conodonts from Guandao section. Scale bar is 200 microns. 1-3) *Chiosella timorensis* (Nogami), 1-2 from GSC-101557, sample OU-3, 3 from GSC-101588 sample GDL-50. 4-5) *Chiosella gondolelloides* (Bender), GSC-101554, OU-2. 6-8) *Paragondolella bulgarica* (Budurov & Stefanov), 6 from GSC-131528, sample UGD-52, 7 from GSC-131529, sample UGD-53, 8 from GSC-131530, sample UGD-67. 9, 10) *Neogondolella* ex gr. *constricta* (Mosher and Clark), GSC-131531, sample UGD-94. 11) *Pg.* ex gr. *excels* (Mosher), GSC-131532, sample UGD-72. 12-15) *Ng.* ex gr. *regalis* (Mosher), 12 from GSC-131533, sample GDL-21, 13-15 from GSC-131534, sample UGD-34. 16-18) *Budurovignathus truempyi* (Hirsch), GSC-131535, sample UGD-94. 19, 20) *Budurovignathus mungoensis* (Diebel), GSC-131536, sample GDL-100. 21, 22) *Paragondolella inclinata* (Kovacs), GSC-131537, sample UGD-118. 23-25) *Quadralella polygnathiformis* (Budurov & Stefanov), GSC-131538, sample UGD-127. 26, 27) *Gladigondolella tethydis* (Huckreide) GSC-131539, sample UGD-105, GSC-131540, sample UGD-121.

Fig. 7. Foraminifers from Guandao section. Scale bars are 100 microns. 1) *Arenovidalina* n. sp., PGD-112. 2) *Arenovidalina abriolense* (Luperto), PUG-051. 3-4) *Hoyenella* ex gr. *sinensis* (Ho), PGD-176, PGD-168. 5) *Meandrospira cheni* (Ho), PGD-157. 6-7) *Meandrospira dinarica* (Kochansky-Devidé & Pantic), PUG-037, PGD-215. 8) *Turritlomina carnica* (Dağ), PUG-145. 9) *Turritlomina mesotriasica* (Koehn-Zaninetti), PUG-089. 10) *Turritlomina* cf. *magna* (Urosevic), PUG-075. 11) *Meandrospira* ? *deformata* (Salaj), PUG-054. 12) *Meandrospira* n. sp., PGD-176. 13) *Meandrospira pusilla* (Ho), PUG-012. 14-15) *Planinivoluta* ? *mesotriasica* (Baud, Zaninetti & Brönnimann), PUG-085, PUG-065. 16) *Ophthalmidium* sp., PUG-143. 17) *Ophthalmidium exiguum* (Koehn-Zaninetti), PUG-109. 18) *Glomospirella* cf. *vulgaris* (Ho), PGD-132. 19) *Pilammina grandis* (Salaj), PUG-027. 20) *Pilammina densa* (Pantic), PUG-063. 21-22) *Trochammina almtalensis* (Koehn-Zaninetti), PUG-054, PUG-091. 23) *Piallina brönnimanni* (Martini, Rettori, Urosevic & Zaninetti ?), PUG-145. 24) *Galeanella* sp., PUG-139. 25) *Endoteba controversa* (Vachard & Razgallah), PUG-037. 26) *Endoteba bithynica* (Vachard, Martini, Rettori & Zaninetti), PGD-220. 27) *Endoteba obturata* (Brönnimann & Zaninetti), PUG-063. 28-29) *Endotriada thyrrenica* (Vachard, Martini, Rettori & Zaninetti), PUG-043, PUG-089. 30-31) *Endotriadella wirzi* (Koehn-Zaninetti), PUG-014, PUG-016. 32) *Endotebanella kocaeliensis* (Dağ), PUG-101. 33) Duostominid foraminifera (*Variostoma* sp.), , PUG-063. 34) *Turrispirillina* sp., PUG-043. 35) *Endotebanella* ? n. sp., PUG-029. 36) *Abriolina mediterranea* (Luperto), PUG-093. 37) Involutinid foraminifera (*Triadodiscus* ? sp.), PGD-131. 38) *Aulotortus eotriasicus* (Zaninetti, Rettori & Martini), PUG-045.

Fig. 8. Date distribution plot of analyzed ash bed zircons of this study. Bar heights are proportional to 2σ analytical uncertainty of individual analyses; solid bars are analyses used in age calculation. Horizontal lines and bars signify the calculated weighted mean dates and their uncertainties (light shading = 1σ ; dark shading = 2σ), respectively. Analyses denoted by “a” are recalculations of previously published data in Lehrmann et al. (2006). Arrows point to older analyses falling outside the plot area. See Table S1 and text for complete analytical data and calculated dates.

Fig. 9. Correlation of Upper Permian and Triassic conodont zonations including Guandao section, various sections from south China and other areas. *British Columbia Canada is a composite of many sections. †Conodont succession at Wuzhuan, Guangxi is similar to succession described from Permian-Triassic at Dawen section in the GBG by Chen et al. (2009). Substage abbreviations: G. = Griesbachian, D. = Dienerian, Sm. = Smithian, Sp. = Spathian, A. = Aegean, B. Bithynian, P. = Pelsonian, I. = Illyrian, F. = Fassanian, L. = Longobardian, C. = Cordevolian. Abbreviations for genus names same as those in figure 4 with the addition of the following: I. = *Isarcicella*; Ic. = *Icriospathodus*; Nc. = *Neoclarkina*; Eu. = *Eurygnathodus*; Bo. = *Borinella*; Sc. = *Scythogondolella*.

Fig. 10. Range chart showing ranges of foraminifer species from Guandao section with ages calibrated by conodont age assignments and plotted in order of first occurrences. Substage abbreviations: G. = Griesbachian, D. = Dienerian, Sm. = Smithian, Sp. = Spathian, A. = Aegean, B. Bithynian, P. = Pelsonian, I. = Illyrian, F. = Fassanian, L. =

Longobardian, C. = Cordevolian. Abbreviations for genus names: A. = *Arenovidalina*,
Ab. = *Abriolina*, Au = *Aulotortus*, Aus. = *Austrocolomia*, E. = *Endoteba*, Ella. =
Endotebanella, En. *Endotriada*, Enlla. = *Endotriadella*, Glla. = *Glomospirella*, H. =
Hoyenella, M. = *Meandospira*, O. = *Opthalmidium*, P. = *Postcladella*, Pa. =
Paleolituonella, Pi. = *Pilamina*, Pilla. = *Pilamminella*, Pia. = *Piallina*, Pl. =
Planiinvoluta, T. = *Trochammina*, Tu. = *Turriglomina*.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Triassic	Carnian		Guandao, Guizhou this paper	Bianyang, Guizhou Yan et al., 2013	Jiarong, Guizhou Chen et al., in press	Wuzhuan, Guangxi πBrosse et al., 2015	Chaohu, Anhui Zhao et al., 2008	Spiti, India Orchard and Krystyn, 2007; Goudemand, 2015	Spitzbergen, Svalbard Nakrem et al., 2008	*British Columbia, Canada Orchard and Tozer, 1997
		C.	<i>Q. polygnathiformis</i>						<i>Q. polygnathiformis</i>	<i>Q. polygnathiformis</i>
		L.	<i>Pg. inclinata</i> <i>Bv. mungoensis</i>							<i>Pg. inclinata</i> <i>Bv. mungoensis</i>
	Ladinian	F.	<i>Ng. trammeri</i> <i>Ng. alpina</i> <i>Bv. hungaricus</i> <i>Bv. truempyi</i>							<i>Pg. foliata</i>
		I.	<i>Pg. excelsa</i> <i>Ng. constricta</i>						<i>Ng. constricta</i>	<i>Pg. ex gr. excelsa</i> <i>Ng. constricta</i>
	Anisian	P.	<i>Pg. bulgarica</i>						<i>Ng. constricta</i>	<i>Pg. bulgarica</i>
		B.	<i>Ni. kockeli</i> <i>Ni germanica</i>							<i>Ns. ex. gr. regalis</i>
		A.	<i>Ns. ex. gr. regalis</i> <i>Cs. timorensis</i>						<i>Cs. timorensis</i>	<i>Ns. ex. gr. regalis</i> <i>Cs. timorensis</i>
		S p.	<i>Cs. gondolelloides</i> <i>Ts. ex. gr. homeri</i> , <i>Ts. triangularis</i> , <i>Nv. abruptus</i>	<i>Ts. homeri</i> <i>Ic. collinsoni</i>	<i>Ts. triangularis</i> <i>Ts. homeri</i> <i>Ic. collinsoni</i> <i>Nv. pingdingshanensis</i>		<i>Ns. anhuiensis</i> <i>Ts. homeri</i> <i>Nv. pingdingshanensis</i>	<i>Cs. gondolelloides</i> <i>Ic. collinsoni</i>	<i>Ns. ex. gr. regalis</i>	<i>Ns. ex. gr. regalis</i> <i>Ts. ex. gr. homeri</i> <i>Ng. aff. sweeti</i>
	Induan	S m.	<i>G. bransoni</i> <i>D. discreta</i> <i>Nv. waageni</i>	<i>Pachycladina</i> , <i>Parachirognathus</i> <i>D. discreta</i>	<i>Pachycladina</i> , <i>Parachirognathus</i> <i>D. discreta</i> <i>Nv. waageni</i>		<i>Nv. waageni</i> <i>Nv. waa. eowaageni</i>	<i>Sc. milleri</i> <i>Nv. waageni</i> <i>Nv. waa. eowaageni</i> <i>Bo. nepalensis</i> <i>Nv. ex. gr. waageni</i>	<i>Sc. milleri</i> <i>Sc. mosheri</i> <i>Nv. waageni</i>	<i>Sc. milleri</i> <i>Nv. waageni</i> <i>Ns. pakistanensis</i>
		D.	<i>Ns. cristagalli</i> <i>Ns. dieneri</i>	<i>Ns. cristagalli</i> <i>Ns. dieneri</i> <i>Ns. kummeli</i>	<i>Ns. cristagalli</i> <i>Eu. costatus</i>		<i>Ns. cristagalli</i> <i>Ns. dieneri</i> <i>Ns. kummeli</i>	<i>Ns. cristagalli</i> <i>Ns. dieneri</i> <i>Ns. kummeli</i>	<i>Bo. aff. nepalensis</i> <i>Ns. pakistanensis</i> <i>Ns. cristagalli</i> <i>Ns. dieneri</i>	<i>Ns. dieneri</i>
		G.	<i>H. parvus</i> , <i>H. anterodentatus</i>	<i>H. parvus</i>	<i>Nc. discreta</i> <i>H. sosioensis</i> <i>H. parvus</i>	<i>H. postparvus</i> <i>I. isarcica</i> <i>H. parvus</i> <i>H. eurypyge</i> <i>H. praeparvus</i>	<i>Cl. krystyni</i> <i>H. typicalis</i>	<i>Cl. krystyni</i> <i>Nc. discreta</i> <i>Cl. meishanensis</i> <i>H. parvus</i>	<i>Cl. carinata</i>	<i>Cl. carinata</i>
Perm.	Ch.		<i>Cl. changxingensis</i>	<i>Cl. changxingensis</i> <i>Cl. yini</i>		<i>H. typicalis</i>				

Figure 10

* occurrence in Dajiang section, interior strata of Great Bank of Guizhou. $\perp$ First and last occurrences $\frac{?}{\perp}$ Incomplete stratigraphic ranges