Journal of Earth Science, Vol. 26, No. 2, p. 181–191, April 2015 *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-015-0527-x

The Mysterious Mid-Carnian "Wet Intermezzo" Global Event

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ABSTRACT: Approximately 230 million years ago in the middle of the Carnian stage of the Upper Triassic, the sedimentary records in different regional basins display dramatic changes. Tropical carbonate platforms abruptly ended, and engorged river systems left widespread sand-rich layers across inland basins and coastal regions. This pulse lasted less than a million years in some basins, but constituted a permanent shift in others. Following this event, the Late Carnian has the earliest record of significant dinosaurs on land and the emergence of the calcareous nannoplankton in the oceans that now govern Earth's carbon cycle. This "most distinctive climate change within the Triassic" has been interpreted by some geoscientists as a global disruption of the Earth's land-ocean-biological system. The eruption of the Wrangellia large igneous province may have been the trigger for a sudden carbon-dioxide-induced warming and associated increased rainfall in some of these regions. Indeed, some workers have proposed that this "wet intermezzo" warming event is a useful analog to aid in predicting the effects of our future greenhouse on land ecosystems and ocean chemistry. However, the understanding of the onset, duration, global impacts and relatively rapid termination of this postulated warming pulse has been hindered by lack of a global dataset with inter-calibrated terrestrial and marine biostratigraphy, precise radio-isotopic ages, stable isotope records of temperature and the carbon system, and cycle-calibrated rates of regional and global change.
KEY WORDS: Triassic, Carnian, climate, pluvial, Wrangellia, carbon, isotope, excursion, dolomite, China, LIP, Yangtze Platform, Wet Intermezzo, large igneous province.

0 THE MID-CARNIAN WRANGELLIA LARGE IGNEOUS PROVINCE AND CHALLENGE IN CARNIAN CORRELATIONS

Approximately 230 million years ago, the enormous Wrangellia Large Igneous Province, now accreted to northwestern North America, erupted in the Pacific (Greene et al., 2010). This Wrangellia LIP was an uninterrupted outpouring of up to 6 km of subaerial and submarine flows covering an estimated 25 000 km^2 in the largest igneous event (ca. 100 000 km^3) during the Triassic. The basalts erupted onto marine claystones with Ladinian (Middle Triassic) Daonella bivalves and are overlain by limestones and claystones with Late Carnian or earliest Norian *Tropites* ammonoids and *Halobia* bivalves. Radio-isotopic dates, albeit using pre-2012-standards for Ar-Ar and U-Pb methods, had indicated that the entire succession formed between 233 and 227 Ma, and that perhaps the majority of the eruption occurred in less than 2 myr (Greene et al., 2010).

The eruption of other major large igneous provinces ("LIPs") are often associated with major global climate-ocean-biological catastrophes, including the end-Permian mass extinction (Siberian Traps), end-Triassic mass extinction (Central Atlantic Magmatic Province), earliest Aptian oceanic anoxic event (Ontong Java Plateau), and Paleocene-Eocene boundary thermal maximum ("PETM"; North Atlantic Igneous Province). The huge magmatic outpourings and associated thermal heating of the underlying carbonate and organic-rich sediments release large amounts of greenhouse-forming carbon dioxide and methane, cooling sulfur dioxide, and ozone-affecting chlorine and other gasses. The initial distortions of the climate system cascade into numerous secondary effects, ranging from enhanced monsoonal precipitation and continental weathering to increased burial of organic carbon that leave records of carbon-isotope excursions (e.g., Wignall, 2001).

The recognition of the global scale and magnitude of significant climate/ecosystem events in Earth history and their coincidence with major LIP eruptions required an international program to initially standardize a reference time scale of integrated inter-calibrated biostratigraphic zonations, geologic stage definitions, radio-isotopic dating constraints, stable isotope trends and excursions, magnetic reversal patterns, and durations using orbital-climate cycles. Then these standards were applied to place the timing and rates of regional environmental facies shifts into a global framework (e.g., reviews by

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Manuscript received September 18, 2014.
Manuscript accepted January 15, 2015.

Ogg, J. G., 2015. The Mysterious Mid-Carnian "Wet Intermezzo" Global Event. *Journal of Earth Science*, 26(2): 181–191. doi: 10.1007/s12583-015-0527-x

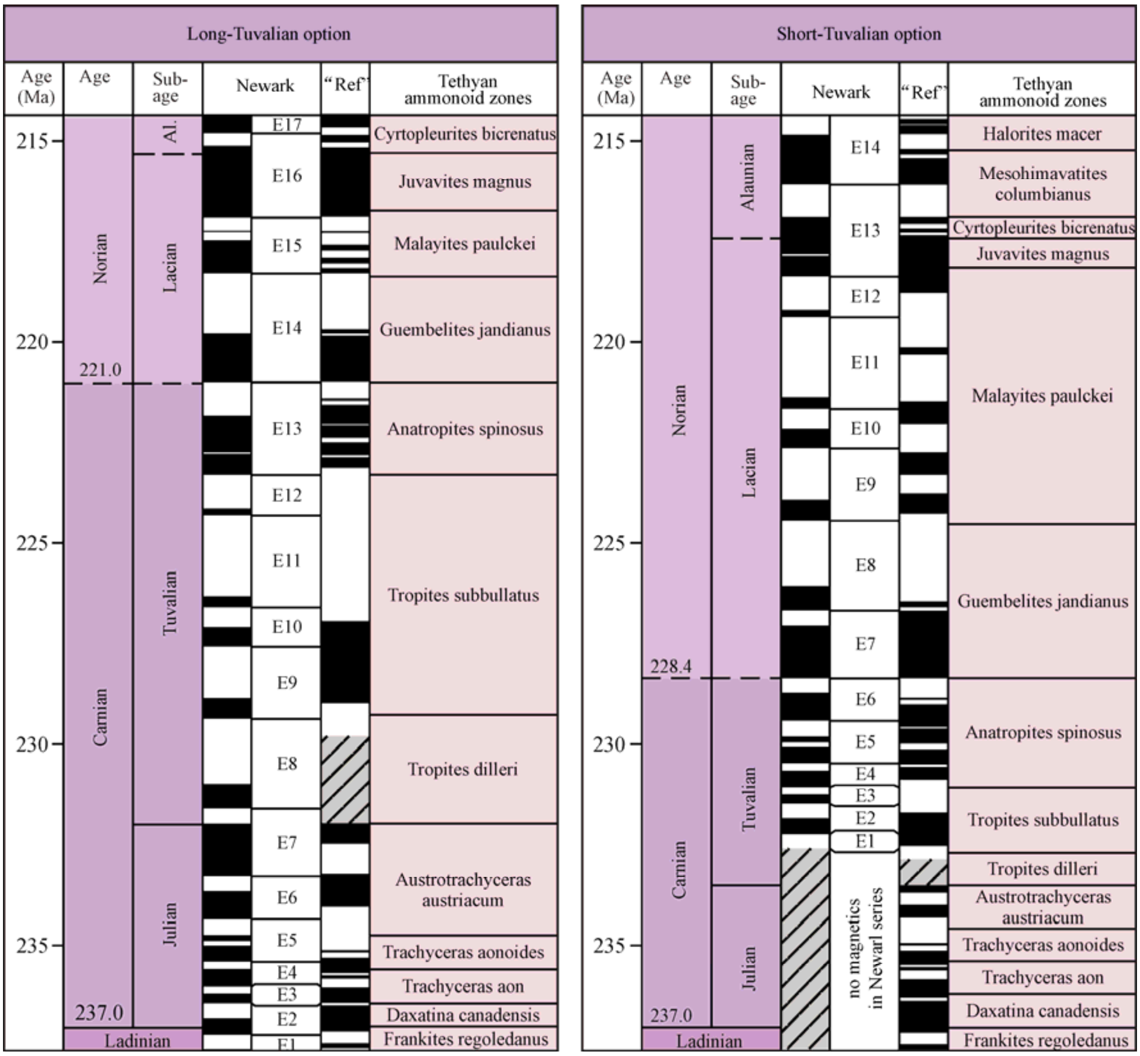

Figure 1. The Carnian time-scale puzzle. Comparison of two end-member age models based on different options for correlating the "reference" magnetic polarity scale derived from a synthesis of ammonite- or conodont-dated outcrops to the astronomical orbital-climate cycle-scaled magnetic polarity zones of the Newark Group. Left option: a "Long-Tuvalian substage" (and absence of Rhaetian) in the Newark cyclo-magnetostratigraphy. Right option: a Short-Tuvalian substage that is not present in the lower Newark succession, because a "Long-Rhaetian" spans the upper Newark cyclo-magnetostratigraphy. In each case, the ages for the top of the Triassic (201.3 Ma) and base of the Carnian (237.0 Ma) are the same. See Hounslow and Muttoni (2010), Ogg et al. (2014) and Ogg (2012) for details on the full Norian-Rhaetian correlation possibilities and debate. In each option, the potential definition of the Norian stage boundary is indicated by a dashed line; the final decision will be made by the International Commission on Stratigraphy. In GTS2012 and in Fig. 3, the numerical age scale of the second option ("Short-Tuvalian") was selected for scaling the Upper Triassic in other diagrams.

Hesselbo et al., 2002, for the end-Triassic event; and by Yin et al., 2007, 2001, and by Kozur, 1998, for the end-Permian event).

Even through the "Mid-Carnian" Wrangellia LIP should have caused a major disruption in global climate and ecosystems, its recognition has been hindered by many factors. The Late Triassic currently lacks a high-precision integrated time scale. Indeed, the range of estimates of the span of the Carnian stage range between 16 myr (the "Long-Tuvalian substage" option; e.g., Lucas et al., 2012) and 8.5 myr (the "Short-Tuvalian substage" option) (e.g., reviews in Ogg et al., 2014; Ogg, 2012; Hounslow and Muttoni, 2010). The inter-calibrations of regional biostratigraphic scales, especially between terrestrial and marine realms, remain uncertain or are hindered by long ranges of key palynology and conodont marker taxa. Most exposed fossiliferous marine Carnian successions are in discontinuous slices within collisional mountain belts (e.g., the historical reference sections in the Carnic Alps, Himalayas and Canadian Rockies) or are interrupted by major hiatuses or non-fossiliferous beds within the "Mid-Carnian" interval. These aspects of Carnian geology, coupled with diagenetic overprints, have hindered the establishment of a verified magnetostratigraphy or orbital-cycle-derived durations of chrons and biozones.

Ideally, the 20-myr Ma Late Triassic pattern of cycle-scaled magnetostratigraphy from the fluvial-lacustrine Newark Supergroup of eastern North America should provide a reference standard, similar to the cycle-scaled C-sequence that underpins the Cenozoic time scale. But correlations to the magnetic stratigraphy derived from Late Triassic ammonite- or conodont-zoned strata are difficult in the absence of reliable cyclostratigraphy stratigraphy of those strata or consistent terrestrial-to-marine biostratigraphic correlations. Lucas et al. (2012) concluded "Given the dearth of biostratigraphic tie-points, establishing any unambiguous correlation to the Newark magnetostratigraphy is highly unlikely." The situation is indeed challenging; but the correlation puzzle will probably be solved in the coming decade with focused interdisciplinary studies.

The significance, magnitude and apparent global signature of this Mid-Carnian episode were not recognized until recently. However, the Mid-Carnian Event that is expected from the Wrangellia LIP is suggested by several anomalous sedimentary levels in different basins. Initially, each of its manifestations in these various regions was interpreted as a local tectonic or climatic anomaly. Therefore, this Mid-Carnian Episode was given a plethora of names, e.g., the "Reingraben Event" in Austrian Alps, the "Raibl Event" in the Italian Dolomites, the "Carnian Pluvial Event" in Britain-northern Europe, and the "Carnian Wet Intermezzo" in Germanic Basin. With improved dating and inter-regional correlation, it was gradually realized that this anomalous climatic episode extended beyond basins within present-day Europe (e.g., Simms and Ruffell, 1990, 1989); and it is now suspected within many diverse regions (Fig. 2). Indeed, if verified, then as has happened with other LIP-induced climate-ecosystem events at the end-Triassic and PETM, this Mid-Carnian Event will provide the much-needed global correlation horizon for all regional basins from terrestrial to deep-marine settings.

However, one must be careful to avoid a "conspiracy theory" bias. Any particular regional feature can have different interpretations other than an over-arching Mid-Carnian Event hypothesis. However, it is the temporal consistency of anomalous features that may eventually lead to a global understanding. Plus, the Wrangellia LIP effects and feedbacks have other predicted responses in geochemical and environmental signals that can provide powerful tests of the Mid-Carnian Event.

Let us briefly examine some of the interpreted identifications of this episode through the lens of some expected Wrangellia-induced impacts, starting with the original "Wet Intermezzo" within the Germanic Basin.

1 A WARMER AND WETTER WORLD

During the Carnian, the majority of the present continents were assembled in a Pangea super-continent. In many of these Pangean settings, the typical Middle through Late Triassic environments consisted of relatively arid to monsoonal-type ecosystems in terrestrial basin and extensive carbonate reefs adjacent to the Tethys seaways (e.g., Preto et al., 2010; Parrish, 1993). This general climate regime was interrupted by a distinctive Mid-Carnian Episode of more humid conditions and associated increased delivery of coarser clastic sediments into the basins. This "Carnian Wet Intermezzo" (Kozur and Bachmann, 2010) was first recognized in the basins of present-day North Europe; but other regions are reported to have similar responses.

A predicted response of the global climate system to increased greenhouse gasses, such as those resulting from the Wrangellia LIP eruptions, is a warmer atmosphere with more

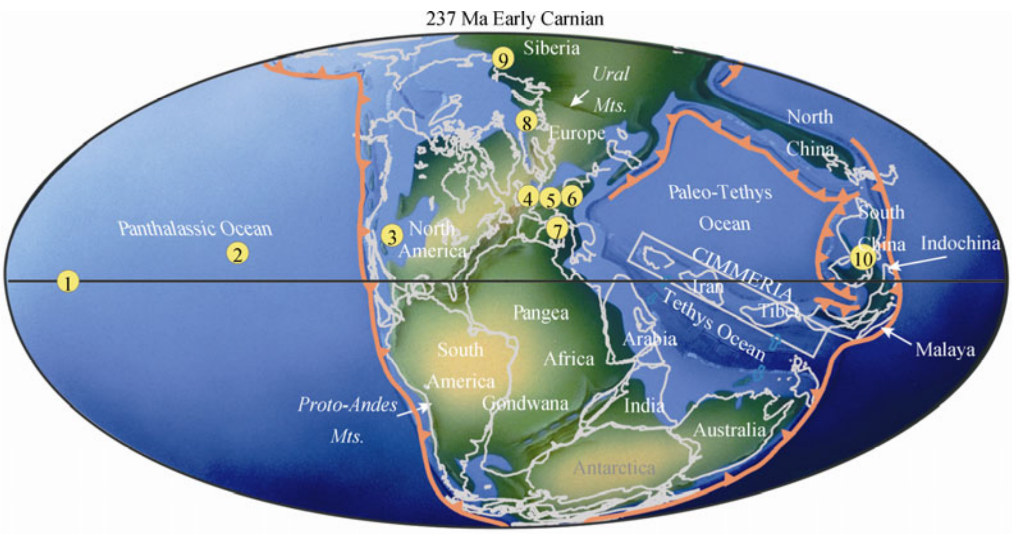

Figure 2. Some Mid-Carnian Event localities with selected references (concept modified from Nakada et al, 2014, and placed on Carnian paleogeography from Chris Scotese, http://www.scotese.com). 1. Pacific cherts with schematic location, now accreted to Japan (Nakada et al., 2014); 2. Wrangellia Large Igneous Province with schematic location, now accreted to British Columbia and Alaska (Greene et al., 2010); 3. Chinle Group of southwestern USA (Lucas et al., 1997); 4. Mercia mudstone group of Britain (Simms and Ruffell, 1989); 5. Schilfsandstein (Stuttgart) Formation of Germanic Basin (Kozur and Bachmann, 2010); 6. Reingraben Turnover event in Austrian hallstatt facies (Hornung and Brandner, 2005); 7. Heiligkreuz Formation into Carnian platforms of Italian dolomites (e.g., Preto and Hinnov, 2003); 8. prograding Carnian deltas in Barents Sea (Hochuli and Vigran, 2010); 9. increased rainfall and fluvial influx in strata at Kotel'nyi Island of Siberia (Bragin et al., 2012; as summarized in Nakada et al., 2014); 10. Yangtze Platform of South China (Enos et al., 2006; Lehrmann et al., 2005). Mts. Mountains.

evaporation and, depending upon the regional situation, more seasonal precipitation. In particular, the magnitude of monsoon-associated summer rainfall and flooding may increase with greater land-surface heating drawing in oceanic moisture. The increased greenhouse conditions would further enhance the Pangean "mega-monsoons" (e.g., Parrish, 1993; Kutzbach and Gallimore, 1989). The combination of increased atmospheric carbon dioxide and moisture content will increase the rates of continental weathering. Basins and margins near exposed silicate-rich uplifts will receive an enhanced delivery of clastic-rich sediments (e.g., Algeo and Twitchett, 2010, and references therein). Similar to the glacial-to-Holocene transitions, the warmer and more humid conditions will shrink the extent of global deserts, hence the flux of wind-borne dust into the ocean basins. For those oceanic and shelfal settings, a warmer more equable climate, when coupled with the additional carbon released into the Earth system, can lead to deposition of organic-rich "black shales" under expanded "oceanic anoxic event" (OAE) minimum-oxygen zones. All of these effects have been reported in different regions in deposits that are assigned to the middle of the Carnian stage.

The most striking example is in the Germanic Basin, where the semi-playa-like facies of evaporite-bearing clay-rich Keuper formations were temporarily disrupted by a sand-rich braided-river system depositing the thick Stuttgart (Schilfsandstein) Formation (e.g., Kozur and Bachmann, 2010; Shuckla et al., 2010). These fluvial sands of the "Wet Intermezzo" are correlated by conchostracan and megaspore assemblages to marine deposits of the uppermost Julian substage (upper *Austrotrachyceras austriacum* ammonite Zone) (e.g., Kozur and Bachmann, 2010; Kozur, 1975). The playa-lacustrine-evaporitic fine-grained sediments of the Keuper facies resume at the Julian/Tuvalian boundary (see Fig. 3).

The Carnian-Norian Mercia Mudstone Group of Britain was also interrupted by an influx of the Arden sandstone/North Curry sandstone member beginning in the middle of the Carnian (Simms and Ruffell, 1989). Similar influxes of sandy sediments occur in basins of Spain, Portugal, France, and Morocco-Algeria (Arche and López-Gómez, 2014). The braided-river deposits that began to fill the newly-formed succession of rift basins of present eastern North America (e.g., Stockton Formation of the Newark Basin, New Haven Arkose of the Hartford Basin, etc.) have yielded a cycle-scaled magnetostratigraphy "E-series", which if projected onto the "Short Tuvalian" age model suggests an onset in the middle of the Carnian.

The accumulation of these sandy fluvial deposits was not continuous in some basins. The facies oscillations in these continental deposits have been interpreted to imply that the Mid-Carnian "Wet Intermezzo" spanned either two or three 400-ka cycles (hence 0.8 or 1.2 myr), depending on location (e.g., Kozur and Bachmann, 2010, 2008; Roghi et al., 2010).

Further west into the Laurasian sectors of Pangea, the Chinle Group of southwestern USA began with a sudden influx of crossbedded sandstones and conglomerates (Shinarump Formation) onto a former widespread soil-covered exposure surface (e.g., Lucas et al., 1997). The Shinarump Formation sands of latest Julian are overlain by Tuvalian mudstone-dominated units (Kozur and Weems, 2010).

The cascading effects of this temporary global shift in terrestrial climate appear to have been a major factor in the appearance of early dinosaurs. It is thought that these earliest dinosaurs were possibly more adaptable to shifts from arid to humid and back to arid conditions (Benton et al., 2014). Therefore, in these terrestrial settings, the Mid-Carnian Event may have been the trigger for the development of the dinosaurs, which would later dominate the Jurassic and Cretaceous world.

Even in the middle of the mega-Pacific Ocean (called "Panthalassa", meaning "all seas"), this shift in climate recorded by the characteristics of the pelagic sediments that were later accreted to Japan. A sudden and temporary shift from a relatively drier-cooler arid climate with extensive deserts and dust storms to a wetter-humid world is reflected in a reduction in atmospheric dust fallout into those oceanic sediments (Nakada et al., 2014). This reduction in land-derived dust was accompanied by a reduction in the essential iron-nutrients needed for the productivity of plankton, therefore a slowdown in the rate of silica-rich deposition from radiolarian tests. The anomalous interval of low-dust and low-silica was followed by resumption of "normal" Carnian bedded radiolarites. Cyclostratigraphy using precession cycles of this episode in these bedded cherts suggests a duration close to 0.9 myr (Nakada et al., 2014), which is similar to the duration estimated in the Germanic Basin for the Stuttgart Formation (Kozur and Bachmann, 2010).

2 CARBONATE PLATFORMS SUFFER

Carbonate platforms flourish in shallow depths under warm, clear marine waters that are free of influxes of clay-rich sediment and of elevated nutrient levels. Two other common conditions are that the temperatures should not be excessively hot and that the water pH will enable preservation of the precipitated carbonate. The Wrangellia LIP eruptions and increased seasonal runoff from the land masses will have several negative impacts on carbonate platforms on the margins of the Tethyan seaways and even the reefs that were isolated within the oceans-increased seasonal runoff from the adjacent landmasses could smother the carbonate platform ecosystems, high nutrient content within those pulses of runoff would encourage algae to outcompete some of the carbonate-precipitating colonial organisms, the increased carbon dioxide content of the atmosphere and ocean would elevate the ocean acidity, and the warmer greenhouse conditions might locally exceed the optimal conditions for the major reefal organisms. As with today's greenhouse world causing slowing or termination of many modern reef systems, the Mid-Carnian Event should be marked by a widespread disruption of earlier Carnian platforms. Indeed, this predicted effect is widely recorded throughout the Carnian world; although alternate interpretations of major sea-level falls or of regional tectonic activity have been proposed for each individual region. For example, the global sequence-stratigraphy synthesis for Mesozoic by the Exxon Group (e.g., Hardenbol et al., 1998) and the interpreted Triassic events of Haq and Al-Qahtani (2005) both assign a major sea-level

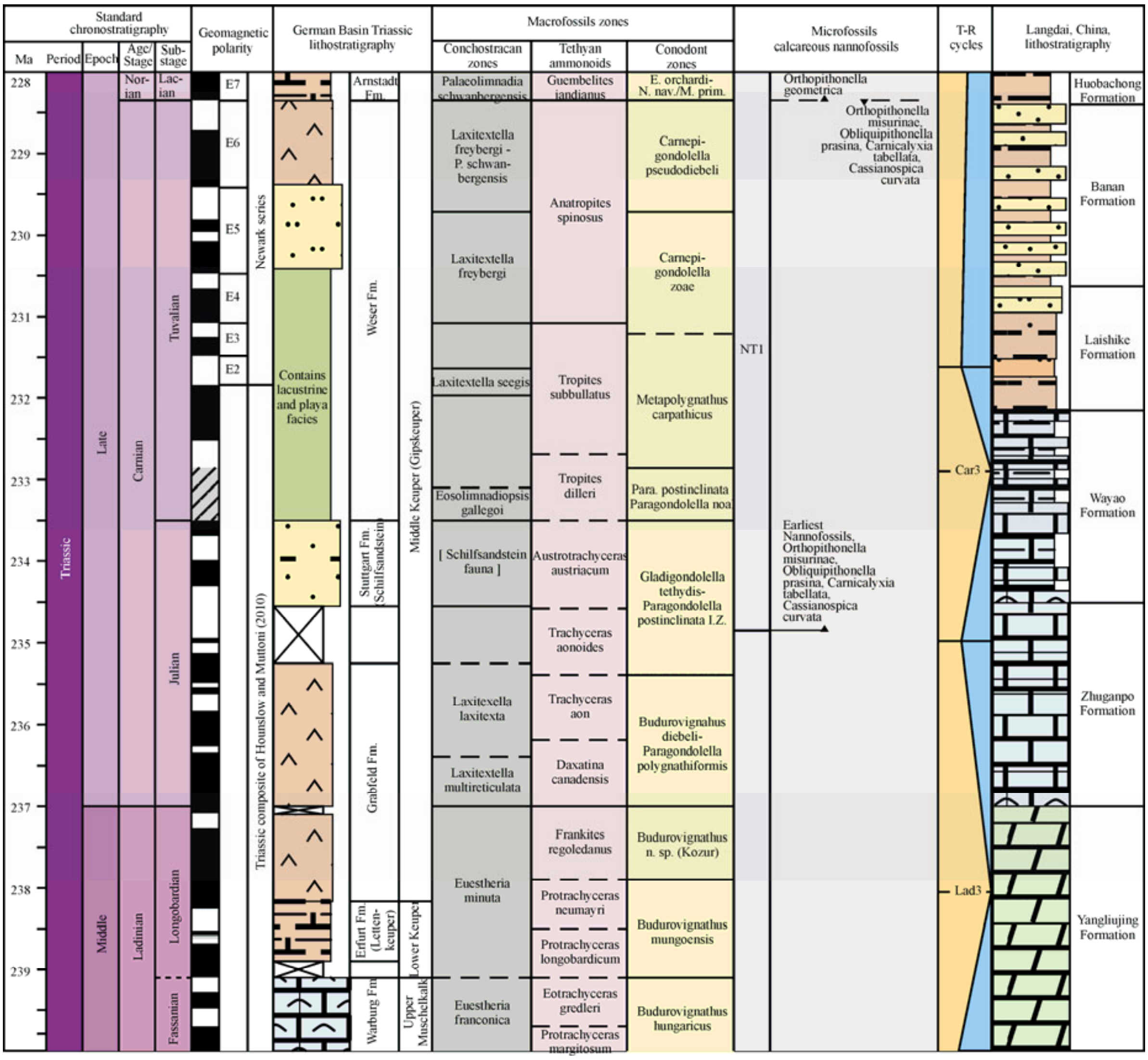

Figure 3. Selected scales of Carnian stratigraphy. The Mid-Carnian Event is during the latest Julian. Geomagnetic polarity is "Short-Tuvalian" option of Fig. 1. Germanic Basin lithostratigraphy and conchostracan zones are schematic from Kozur and Bachmann (2008), Kozur and Weems (2010) and Kozur (pers. comm., 2010). Generalized Tethayn ammonite zones and conodont zonation for Tethyan realm is modified from Kozur (2003, and pers. comm., 2010) and Balini et al. (2010). Calcareous nannofossil events from Bown (1998). Major sea-level transgression-regression cycles modified from Hardenbol et al. (1998) and Haq and Al-Qahtani (2005). Lithostratigraphy of southern margin of Yangtze Platform is modified from Enos et al. (2006). However, inter-calibration of these different columns is only approximate, pending detailed correlations that use common stratigraphic events.

lowstand to the Mid-Carnian followed by a major Mid-Carnian flooding event; although the reference sections for their interpretations and age assignments are not detailed.

Massive reefal buildups and atolls within the northern calcareous Alps of Austria-Hungary and the famous dolomite region of the Italian Southern Alps had prograded during the Ladinian through Early Carnian. These stable carbonate systems were dramatically terminated by an influx of clay-rich to sandy-carbonate sediments that filled the deep inter-platform basins and eventually capped the former platforms (e.g., Bosellini et al., 2003; Preto and Hinnov, 2003; Gianolla et al., 1998). In the Austria region, the latest-Julian influx into the basinal Hallstatt facies of black-shale-rich facies of the "Reingraben Turnover is one of the most conspicuous stratigraphic changes, which is mirrored in all facies belts of the entire NW Tethyan continental margin (Schlager and Schöllnberger, 1974). "Shallow-water carbonate production resumed slowly during the Tuvalian (Late Carnian)..." (Hornung and Brandner, 2005). This episode is assigned to the uppermost Julian substage (upper *Austrotrachyceras austriacum* ammonite zone) (e.g., Hornung et al. 2007; Hornung and Brandner, 2005). In the dolomites, the end-Julian Heiligkreuz Formation (locally formerly called "Raibl Beds") completely filled the basins and created a striking horizon as it flooded onto the terminated platforms (Fig. 4) and created a flat coastal tide-dominated plane. The demise of the carbonate platforms might have been caused by either a major change in climate, a change in regional subsidence rates, a sea-level drop causing exposure followed by highstand influx of terrigenous clastics, or combination of all these factors (summarized in Gattolin et al., 2013). During the Early Tuvalian, the regional environment changes to more arid conditions followed by the establishment of the extensive Dolomia Principale cyclic-carbonate lagoonal-platform facies that continued without an apparent significant break for over 20 myr until near the end of the Triassic.

In South China, the vast Yangtze Platform that had accumulated shallow-water carbonates through nearly the entire Late Proterozoic through Middle Triassic ended during the Carnian (e.g., Enos et al., 2006; Lehrmann et al., 2005). Unlike in the dolomites region, the Yangtze Platform carbonates never resumed, and the overlying Norian deposits are typically braided river systems emptying into coastal swamps. This termination of the southern edge of Yangtze Platform in Guizhou Province passes through a series of stages with variable characteristics among subregions (Enos et al., 2006). For example, in the region near the town of Guanling, the ca. 1 000 m of Anisian-Ladinian shallow-water dolomitic limestones of the Guanling and Yangliujing formations are followed by 70–170 m of biomicritic limestone facies of the Zhuganpo Formation that is assigned to the Early Carnian (based on the conodont *Metapolygnathus polygnathiformis*, with *Metapolygnathus nodosus* of mid-Carnian appearing in the uppermost beds) (Wang et al., 2008). The Zhuganpo Formation has a sharp transition to dark grey clayey laminated carbonates of the mid-Carnian Wayao Formation (Enos et al., 2006; but now called lower member of Xiaowa Formation by Wang et al., 2008). The thin (ca. 12 m) lower member contains organic-rich horizons with well-preserved marine reptiles and clusters of spectacular enormous floating crinoids attached to driftwood (Wang et al., 2008). The lowermost Xiaowa (Wayao) Formation has an overlap of the occurrences of *Protrachyceras* ammonites that are considered restricted to Late Ladinian–Early Carnian and of *Metapolygnathus nodosus* conodonts that are typically considered to mark the onset of Late Carnian (Wang et al., 2008), therefore the sharp basal transition is probably latest Early Carnian and a candidate for the Mid-Carnian Event. Combined magnetostratigraphy and cyclostratigra of the type Wayao Section indicates that the lower half of the Zhuganpo Formation is mixed polarity, followed by a ca.1.3 myr dominance of reversed polarity that continues into the lower member of the Xiaowa (Wayao) Formation (Montgomery et al., 2005) followed with mixed-polarity (Zhang et al., submitted) —a pattern that when coupled with cycle stratigraphy in the same sections is consistent with "Short-Tuvalian" synthesis of the Julian to lowermost Tuvalian magnetic polarity scale of Hounslow and Muttoni (2010) (Figs. 1 and 3). Therefore, the timing of termination and initial influx of terrigenous clastics in at least this portion of the Yangtze Platform seems coincident with the Mid-Carnian Event; although there are probably other regional factors that were operating.

In the Longmen Mountains region of Sichuan, China, the Middle Triassic platform carbonates culminate in a lower Carnian oolitic and calcareous sponge facies that is suddenly truncated by a mid-Carnian black shale, followed by a Upper Carnian to Norian succession of calcareous siltstone and fine sandstone. The magnetostratigraphy of the mid-Carnian black shale through lower portion of the Upper Carnian calcareous siltstones is identical to the pattern in the Xiaowa Formation (Zhang et al., submitted). The arrival of this "black shale event" and similar levels in adjacent areas (e.g., Songpan-Ganzi, Changdu, Hoh Xil) has been proposed as both the cause of the local shallow-water carbonate termination and the regional response to the mid-Carnian warming (Zhiqiang Shi, pers. commun., 2013-14; Shi et al., 2009). However, the termination of this portion of the carbonate platform and influx of clastic sediments has also been interpreted as a Longmen

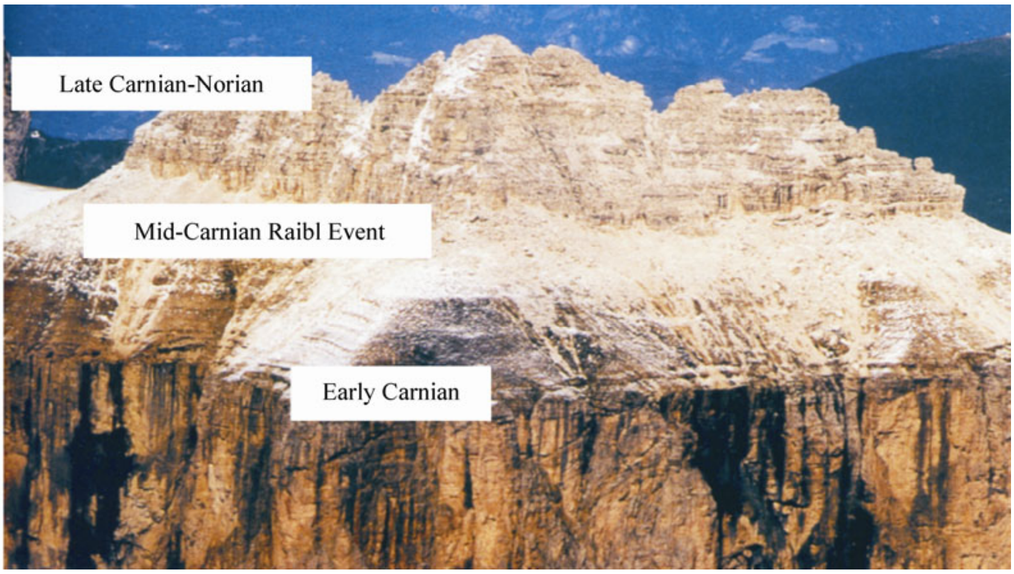

Figure 4. Mid-Carnian event in Italian dolomites. An influx of clay- and sand-rich sediments of the Mid-Carnian "Raibl Event" (Heiligkreuz Formation) terminated the prograding Early Carnian reef systems and was followed by a new reef-platform of the Late Carnian through Norian (photo provided to Jim Ogg by Marco Franceschi for their joint summer' 2013 field course guide).

Mountain foreland basin development or a "Late Longmen Mountain" tectonic phase of the general Indosinian collision history as China blocks and other mini-continents accreted to southern Asia (e.g., Li et al., 2014, 2003; Bradley, 2008). As with all the regional records of the Mid-Carnian event; a more precise stratigraphy is required to resolve the multiple interpretations of local versus global factors.

3 CARBON-12 ENRICHED ATMOSPHERE AND A CARBONATE CRISIS IN OCEANS

Nearly all episodes of catastrophic environmental change and mass extinctions that have been interpreted as cascading effects of major LIP eruptions are also characterized by a negative excursion in carbon isotopes (e.g., end-Permian, end-Triassic, basal Toarcian, Paleogene-Eocene boundary). The explanation of the timing and magnitude of these negative excursions is debated. There was probably a combination of the emissions of carbon-12-enriched magmatic degassing ($\delta^{13}C$= -7‰), heating of organic-rich sediments by intrusions associated with the surface eruptions, destabilization of deep-sea methane hydrates upon greenhouse-induced warming of oceanic water and perhaps increased upwelling of previously stratified waters that had become enriched in carbon-12. The Wrangellia Ocean Plateau was emplaced onto and intruded strata that include organic-rich claystones (Greene et al., 2010). The thermal heating of these deposits and the other major LIP-induced effects should have produced a typical negative excursion in carbon isotopes. The onset of such LIP-induced negative excursions is often quite rapid, therefore serves as a powerful tool for global high-resolution correlation, including between marine and terrestrial realms (e.g., the base of the Eocene is defined to coincide with the onset of the $\delta^{13}C$ excursion). Therefore, as with the other episodes, carbon-isotope stratigraphy should enable unambiguous correlation of the Mid-Carnian Event.

In addition, the temporary increase in the acidity of the oceans and other waters from the release of the magmatic carbon dioxide should have caused a "crisis" in precipitation of carbonate by pelagic organisms. For example, there was a "nannoconid crisis" during the earliest Aptian (Middle Cretaceous) caused by the enormous Ontong Java oceanic plateau formation (Erba, 2004, 1994). The gradual return to pre-eruption "normal" conditions as the excess carbon dioxide is removed through carbon burial should yield an alkaline ocean that is rich in dissolved calcium that accumulated when carbonate precipitation was hindered. This transitional alkaline-enhanced oceanic environment could encourage the evolution of more forms of carbonate-precipitating organisms in both pelagic and shallow-water environments.

All three potential responses—a negative carbon-13 excursion, a carbonate-precipitation crisis, and a following surge in new forms of oceanic carbonate-precipitating organisms —have been reported or interpreted for the Mid-Carnian Event.

Carbon-isotope stratigraphy using bulk-carbonate analyses and some shell material through the Ladinian-Carnian-Norian indicate that broad background trends are broken by either one or two brief Mid-Carnian negative isotope spikes with magnitude of about -2% to -3% (Korte et al., 2005; Muttoni et al., 2014). A slight negative excursion of -1% is also reported from bulk rock analyses from the lowermost Xiaowa (Wayao) Formation of Guzhou, China (Xia et al., 2013). The ranges of conodont taxa in these sections help to constrain the correlation between studies and the general timing relative to the Julian–Tuvalian substages. However, bulk-carbonate analyses in deep-water sections prior to the advent of abundant pelagic nannofossils and foraminifers in the Late Triassic can be distorted by diagenesis of platform-derived microspar (Preto et al., 2013a). Therefore, use of organic carbon extracts from the sediments is considered by some workers to be a more reliable method for high-resolution carbon-isotope stratigraphy. There is a sharp negative excursion in carbon isotopes observed in both total organic-carbon (of -2%) and extracts of alkane molecules (of -4%) in the mid-Carnian of the dolomites of northern Italy (Dal Corso et al., 2012). The brief but pronounced excursion is in the lowest portion of the Heiligkreuz Formation clastic influx at the base of *Austrotrachyceras austriacum* ammonoid Zone (latest Julian).

4 AFTER THE CARBONATE CRISIS, THE OLDEST PELAGIC CALCAREOUS NANNOFOSSILS APPEAR

From the Jurassic to the modern world, deep-sea sediments include carbonates formed from the calcareous tests of pelagic plankton, especially nannoplankton. The earliest calcareous nannofossils are calcispheres, probably from calcareous dinoflagellates, reported from lower Carnian strata in the southern Alps of Italy (e.g., Bown, 1998). This earliest calcareous nannofossil zone NT1 is from these first appearances of calcispheres *Orthopithonella misurinae* and *Obliquipithonella prasina* and nannoliths *Carnicalyxia tabellata* and *Cassianospica curvata* to the first appearance of *Prinsiosphaera triassica* (base of zone NT2) in the Norian; and *P. triassica* became a major contributor to deep-sea micrites during the latest Triassic (Preto et al., 2013a). Why did the pre-Carnian oceans lack plankton which precipitated carbonate tests?

An interesting speculation is that the elevated carbon-dioxide levels during Mid-Carnian Event enhanced delivery of calcium and bicarbonate ions through terrestrial weathering, but also simultaneously hindered preservation of calcium carbonate under the increased acidity of the marine waters (Preto et al., 2013b). Therefore, when the CO_2 levels of the Mid-Carnian Event began to subside, the marine waters became supersaturated with respect to carbonate minerals and "facilitated precipitation of carbonate from pelagic organisms in the open ocean, and may have triggered a significant calcification of nannoplankton for the first time" (Preto et al., 2013b).

5 INCREASED WEATHERING RATES CAUSE STRONTIUM AND OSMIUM EXCURSIONS

Weathering products of newly erupted mantle-derived volcanics are enriched in non-radiogenic ^{86}Sr and ^{188}Os; whereas weathering products of ancient continental cratons are relatively enriched in the accumulated ^{87}Sr and ^{187}Os from radioactive decay of ^{87}Rb and ^{187}Re. The ratios of $^{87}Sr/^{86}Sr$ and $^{187}Os/^{188}Os$ in seawater are recorded in marine carbonates and in organic-rich claystones and metalliferous marine sediments, respectively. The relative residence times implies that

$^{187}Os/^{188}Os$ ratios are a more sensitive recorder of the short-term response to immediate surface weathering of major magmatic eruptions, whereas $^{87}Sr/^{86}Sr$ trends reflect the longer-term weathering rates of the continental crust relative to the rates of eruption and alteration of oceanic ridge basalts. Therefore, the eruption of a major LIP might cause an initial brief negative excursion in $^{187}Os/^{188}Os$ from the short-term surge in delivery of ^{188}Os from the exposed volcanics; followed by increased rates of chemical weathering of continental material from the sustained warmer humid climate that would produce a global trend towards increased $^{87}Sr/^{86}Sr$ ratios from the enhanced ^{87}Sr influx. This initial magmatic influence followed by greatly increased continental weathering has been interpreted for the changing strontium and osmium ratios during the Early and Middle Toarcian associated with the eruption of the Karoo-Ferrar volcanic province in Gondwana (e.g., Jenkyns, 2010; McArthur et al., 2008; Kemp et al., 2005). Preliminary strontium-isotope syntheses for the Triassic indicates the long-term decline in $^{87}Sr/^{86}Sr$ ratios that began in Anisian was suddenly reversed in Early Carnian to an increasing trend that continued into Late Norian; which is a pattern that resembles the signature during earliest Toarcian (McArthur et al., 2012; Korte et al. 2003). A possible brief negative excursion in $^{187}Os/^{188}Os$ near the Boreal assignment of the Ladinian-Carnian boundary is interpreted as a release of ^{188}Os from the initial phase of the Wrangellia LIP eruptions (Xu et al., 2014). Even though the features of strontium- and osmium-isotope curves are not a direct proof of volcanic-induced global warming, they provide an indicator of the degree of global climate change. Additional detail and more precise stratigraphic controls for inter-regional correlation of these studies is required, and the establishment of detailed strontium-isotope and osmium-isotope excursions for the Carnian will enable an additional means of correlating marine strata during this event and providing estimates of relative durations.

6 TANTALIZING CAUSE-EFFECT HYPOTHESES, BUT CAN THEY BE PROVEN?

The eruption of the massive Wrangellia Igneous Province at about 230 Ma in the Early Carnian should have produced an array of global climate and geochemical anomalies. There are indeed Mid-Carnian records of brief changes to warmer and more humid climates in some regions, increased weathering of continental lands and surge in coarser clastics into basins, demise of carbonate platforms or temporary influx of terrestrial-derived clastics onto these platforms, and excursions in carbon-strontium-osmium isotope ratios. However, each local or regional record can be interpreted in other ways. It is probable that sea-level changes, regional tectonic events and local changes in sediment facies are superimposed on the global signals expected from the Wrangellia LIP.

Our understanding of the end-Triassic, basal-Toarcian, end-Cretaceous, Paleocene-Eocene boundary, and other major events in Earth history required bringing other arrays of hazy records into sharp focus by improved high-resolution inter-regional correlations and measuring durations and rates of change. A similar international to collect and share information, re-evaluate legacy data, and apply new tools is required to understand the extent and causes of the Mid-Carnian Event.

(a) Wrangellia LIP—Improved radio-isotope dating of the initiation, main pulses, and termination may resolve the questions on whether it spanned nearly 5 myr or was mainly centered during a very brief major outpouring. Dating of other biostratigraphic-constrained volcanic ash beds in Carnian and basal Norian strata is needed to indicate the relative placement of the Wrangellia LIP in a global context. Magnetostratigraphy of the pulses may further constrain correlation to potential records in different basins.

(b) Biostratigraphy—Detailed conodont, ammonoid, bivalve, palynology, radiolarian and conchostracan ranges and intercalibrations using a database of multiple reference sections are required to establish both regional scales and global first/last appearances. Uncertainties must be included, because many reports merely draw a simple line to designate the base of a zone (or even substage) without indicating the spacing of the reliable datums.. Taxonomy, diachroneity and facies issues need to be considered and quantified. The first appearances of calcareous nannofossils should be examined in different regions relative to improved regional stratigraphy.

(c) Non-biostratigraphic stratigraphic methods—Magnetostratigraphy through the Carnian is known in a general sense, but rarely has been applied to the postulated local records of Mid-Carnian events. If preserved, the magnetic reversals coupled with biostratigraphic constraints will allow correlation between terrestrial basins (e.g., the Germanic "Wet Intermezzo" sands), carbonate platforms (e.g., the clastic Heiligkreuz Formation influx that caps the Early Carnian atolls in the dolomites) and deeper basins. Carbon-isotope excursions in both bulk carbonate and in organic-carbon compounds may eventually provide the best inter-regional correlation method and should be cross-correlated to changes in strontium and osmium isotope ratios.

(d) Cyclostratigraphy—Earth's orbital-climate cycles recorded by periodic facies alternations enabled estimates of the durations and rates-of-change within the Permian-Triassic boundary, basal Toarcian, end-Cretaceous, Paleocene-Eocene boundary and other major episodes. Cyclostratigraphy of multiple reference sections will not only provide verification of durations of biozones and magnetic polarity zones, but will also allow compilation of a reliable time scale for the Carnian.

(e) Publicly available full documentation—The recognition of the global significance of the Paleocene-Eocene boundary, the effects in different basins and in terrestrial environments, and its association with the voluminous eruptions of the North Atlantic Igneous Province was only possible through open sharing of ocean drilling, outcrop and other data. Many of the Carnian publications cited in this overview lacked detailed appendices of their data and a full explanation of the logic behind age assignments. Applying industry-or geologic survey-type standards to the archiving of reference data with appropriate lithology, imagery, biostratigraphic assemblages and other information on reproducible meter scales will greatly enhance the future usefulness of such scholarly studies.

7 SUMMARY

An unusual climatic/oceanographic event in the Mid-Carnian has various regional names including "Carnian

Pluvial Episode", "Reingraben Turnover", "Raibl Event", and "Middle Carnian Wet Intermezzo". This Mid-Carnian Event was initially recognized within the Germanic Basin by an influx of fluvial to brackish-water sands and within the Alpine region by the termination of the prograding reefs of the Earlier Carnian. Only in the past few years has there been evidence that there was a simultaneous climate/oceanographic excursion, biotic crisis and anomalous facies package on a global scale. The recovering world saw the first known dinosaurs on land and the emergence of the calcareous nannoplankton in the oceans that now govern much of Earth's carbon cycle. The trigger for the onset of this Mid-Carnian Event is postulated to be the eruption of the immense Wrangellia flood basalt province at ca. 230 Ma. The end to this "Wet Intermezzo" interval in the Germanic-Alpine region coincides with the substage boundary between Lower and Upper Carnian. This "most distinctive climate change within the Triassic" (Preto et al., 2010) has been suggested as an analog for understanding how excessive carbon-dioxide releases can affect different ecosystems and the ocean-climate system. The assembly of the global and regional responses to the Wrangellia large igneous province requires a precise integrated Carnian time scale.

ACKNOWLEDGMENTS

This Mid-Carnian Event overview was invited by Zhong-Qiang Chen, who also enabled field work in important Carnian sections in Guizhou Province. The details and significance of this event was largely acquired during a 3-day stay at the home of Heinz Kozur (Budapest, Hungary), who was an unbiased font of knowledge on all aspects of Triassic and Permian, and a field excursion to the Triassic stratigraphy of the Dolomites led by Marco Franceschi (Univ. Padova, Italy). Field work at Carnian sections in Sichuan was facilitated by Zhiqiang Shi (Chengdu Univ. Technology, China). Preliminary magnetostratigraphy and cyclostratigraphy analysis of the Guizhou and Sichuan sections is by Yang "Wendy" Zhang and Mingsong Li (China Univ. Geosciences, Wuhan) and with the generous use of the paleomagnetic laboratory facilities at Australian National University. Gabi Ogg prepared the graphics, and drafts were reviewed by Mingsong Li and Maureen Steiner. Support for this Mid-Carnian preparation was provided by a visiting professorship at the State Key Laboratory of Geobiology and Environmental Geology of the China University of Geosciences at Wuhan, China, and by a visiting-scholar sabbatical hosted by the Geosciences Australia in Canberra, Australia.

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