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The Carnian Humid Episode of the late Triassic: A Review

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Abstract - From 1989 to 1994 a series of papers outlined evidence for a brief episode of climate change from arid to humid, and then back to arid, during the Carnian Stage of the late Triassic. This time of climate change was compared to marine and terrestrial biotic changes, mainly extinction and then radiation of flora and fauna. Subsequently termed, albeit incorrectly, the Carnian Pluvial Event (CPE) by successive authors, interest in this episode of climatic change has increased steadily, with new evidence being published as well as several challenges to the theory. The exact nature of this humid episode, whether reflecting widespread precipitation or more local effects, as well as its ultimate cause remains equivocal. Bed-by-bed sampling of the Carnian in the Southern Alps (Dolomites), shows the episode began with a negative carbon isotope excursion that lasted for only part of one ammonoid zone (*A. austriacum*). However, that the Carnian Humid Episode represents a significantly longer period, both environmentally and biotically, is irrefutable. The evidence is strongest in the European, Middle East, Himalayan, North American and Japanese successions, but not always so clear in South America, Antarctica and Australia. The eruption of the Wrangellia Large Igneous Province and global warming (causing increased evaporation in the Tethyan and Panthalassic oceans) are suggested as causes for the humid episode.

Introduction

Abundant red-bed facies, with evaporites, aeolian sands and evidence of ephemeral lakes, rivers and extreme seasonality, has led to a long-held prevailing view that the climate through much of the Triassic was predominantly arid or semi-arid at least across Europe and North America (Crowley, 1994; Lucas & Orchard, 2013). In 1989 two of us (MJS, AR) collated evidence, from published sources as well as our own observations, for a significant increase in humidity during the early Julian to Tuvolian of the Carnian Stage. The onset and cessation of this humid episode appeared to be broadly synchronous with significant biotic changes, both as extinctions and diversifications (Simms & Ruffell 1989, 1990). Despite increased interest in palaeoclimate studies through the 1990s, this hypothesis was not immediately embraced by the geological community and aroused significant opposition in some quarters both in Europe (Visscher *et al.* 1994) and North America (P.Olsen, *pers. comm.*, 1995). However, the ensuing two decades has seen a growing body of evidence (summarised below) in support of our original hypothesis that the Carnian was significantly more humid than at other times during the Triassic.

1. Challenges to the Humid Episode Theory

Following the publication of Simms & Ruffell (1989, 1990), there have been more than twenty publications that

have supported the hypothesis (the key 12 works are included in Table 1) and one publication, and a website, that have cast doubt on the theory. The key works that were negative, positive, or modified the theory are summarised in Table 1. However, some of the publications misinterpret what Simms & Ruffell (1989) suggested this episode to be and, furthermore, the two more critical works include information that supports our hypothesis. The desire on our part to clarify some issues, drove us to write this review article. Visscher *et al.* (1994) rather provocatively entitled their paper *Rejection of a Carnian (Late Triassic) "pluvial event" in Europe*. Significantly they substituted the word 'event' in place of 'episode', as was used in Simms & Ruffell (1989) or 'phase', as in Simms & Ruffell (1990). In summary, Visscher *et al.* (1994) suggested that a widespread inundation was not necessary in order to explain the features of the late Triassic sandstone successions in northern Europe that were key evidence in the hypothesis. Instead, they suggested these humid climate deposits could be local to the river systems and a consequence of isolated, elevated water tables. On closer examination of the evidence for this humid episode (see Ruffell, 1991), namely a network of fluvial channels prograding onto the late Triassic 'Keuper' or 'Mercia' landscape, there is little difference in the two hypotheses. The main divergence of opinion would be that Visscher *et al.* (1994) perceived a River Nile situation, where a major river has penetrated an arid landscape, but without forcing a widespread change to a humid climate. Conversely, we envisaged a more extensive development of discrete river systems in numerous separate basins, much as was later developed more eloquently by Shukla *et al.* (2010) for the same stratigraphic unit, the Schilfsandstein, (syn = Stuttgart Formation) and its regional equivalents, that were discussed by both Visscher *et al.* (1994) and us (Simms & Ruffell 1989, 1990). In summary, the evidence for an increase in the volumes of water flowing through previously arid areas (especially of the northern European, or Germanic Basins) was not in dispute between Visscher *et al.* (1994) and Simms & Ruffell (1989), but the effect on local climate was, which is one reason we will review the evidence that has come forward subsequently. A second result of the work of Visscher *et al.* (1994) was their introduction of the word 'event' to describe the hypothesis, which has a bearing on subsequent criticism of the theory by Kozur & Bachmann (2008) and by Paul Olsen (*pers. comm.*, 1995). The latter is summarised very well in a scientific website article by Alan Kazlev (<http://palaeos.com/authors/MAK.html>), wherein the contradictory evidence of Carnian humid-indicator fluvial sandstones and coals being deposited at the same time as arid-indicator evaporites is examined. Kazlev provides an excellent summary of how Olsen reconciles this by observing that the main evidence for the Carnian Pluvial Event, as termed by Visscher *et al.* (1994), comes from east-west aligned deposits in the equatorial Tethyan rift that would have developed diachronously and/or with coeval evaporitic and fluvial basins along its breadth. This too has only minor disagreement with Simms & Ruffell (1989) who comment (p.267) on the coincidence of depositional evidence with the palaeo-Triassic equator, and how the rifting and breakup of Pangaea could have played a part in generating the Carnian Pluvial Episode (as they termed it). The main difference between our view and Olsen's are that he could not reconcile his rift-related origin for an 'event' and we suggested the humid episode could be more widespread than the Tethyan Rift. On the former, we never suggested this was an event as Visscher *et al.* (1994) envisaged it. Our hypothesis sits comfortably with diachroneity in deposition along the graben and basins of the rift as Olsen sees them. On the latter, whatever generated the Carnian humid episode, it did have a more widespread effect than we envisaged, as described here, making it a significant period of Earth history, but one still with an enigmatic origin. The different views of the three sets of authors (Simms & Ruffell; Visscher *et al.*; Olsen) can be resolved by examination of Dal Corso *et al.* (2012: examined in detail, below) and by examination of our Table 1. These latter authors demonstrate how the indicators of humid palaeoclimates began deposition

during what they term 'a major negative $\delta^{13}\text{C}$ spike in the Carnian'. It appears then that the humid episode lasted for most of the Carnian stage, but began with a shorter-lived isotope excursion that could be considered an event (an abrupt change), followed by a longer-lived episode of humid climates (probably a few million years after the 237Ma base of the Carnian, to somewhere into the Tuvanian, post 230Ma). To clarify, we follow Dal Corso *et al.* (2012) in terming the negative carbon isotope excursion the Carnian (Carbon) Isotope Excursion (CCIE), which best approximates an 'event' as in event stratigraphy, as opposed to the bulk of the Carnian, which we term the Carnian Humid Episode (CHE). The two must no longer be confused in the literature.

2. Support for the Humid Episode Theory

A major consideration in evaluating what the Carnian Humid Episode was is the assessment of the palaeogeographic extent of the evidence for such a climate change. Such evidence encompasses lithofacies changes, for instance from evaporitic playas to fluvial sandstones, or from reef limestones to shales; mineral and/or element abundances; isotopes; and weathering features such as palaeosols and palaeokarst. One of the strengths of our original evidence was in its diverse sources, while the evidence for synchronicity with the biotic changes came from the independence of the climatic and biotic palaeorecords. Thus a broad geographic spread (Figure 1) of publications is included here in this review in order to facilitate discussion of the origin of the Carnian changes. These are also all post-1994, the last year in which Simms, Ruffell & Johnson (1994) and Visscher *et al.* (1994) published on the matter.

Our review examines the primary question - where is the evidence for this episode of Triassic climate change or, indeed, are there locations where no evidence exists? Due to the existence, or non-existence, of published data on the Triassic of the world we have split this review into broad, and somewhat, arbitrary, locations (Figure 1) which we use as a numbered sequence for descriptions and comment (below). Two observations have been fundamental in the development of the Carnian humid episode theory. First, in the northwest European (Germanic basins, see below), red-bed and evaporite deposition was interrupted by Carnian sandstones and blue/grey/green mudstones; secondly, throughout the Tethys Ocean, carbonate deposition ceased and Carnian siliciclastics formed, after which carbonate platforms were re-established. Thus, in some ways, pre-Carnian humid episode conditions returned, in the Ladinian but with a different biota in place. By substituting "event" for 'episode', Visscher *et al.* (1994) set in train two courses of action that have had consequences for the theory. The first was negative, in that Olsen (pers. comm., 1995) and Kozur & Bachman (2010) were led to believe that Simms & Ruffell (1989, 1990) were talking about a geological phenomena in the event stratigraphy sense (<http://www.inqua-sac.com.org/stratigraphic-guide/event-stratigraphy/>), and they could not reconcile what they saw in the diachronous deposition of some deposits and simultaneous laying down of salts and sands in other locations along the Tethyan Rift. The second effect was that Visscher *et al.* (1994) actually coined a far more appealing phrase for the humid episode than Simms & Ruffell (1989) did, causing it to be used in most of the works cited above, and often incorrectly quoted as being the correct term. It may seem trivial to concern ourselves with the change of one word, but when one examines the effect this has had on how this theory was subsequently viewed, this is no minor matter as a conception was created of an event rather than a more prolonged episode of humidity, when we consider that both may have occurred.

3. Alpine Fold Mountain Belt or Western Neotethys (Austria, Hungary, Slovenia, Italy north and south and adjacent Areas (Spain, Iberia)

It seems logical to begin this global review of publications in those locations where the first post-1994 evidence for support, or otherwise, for the Carnian Humid Episode was found.

3.a Austria

Pott, Krings & Kerp (2008) studied fossil plants, mainly gymnosperms, from a well-dated Triassic succession near Lunz, west of Vienna, in Austria. They examined plant morphology, stoma and cuticle from the plant-rich shale and associated coal of the Carnian Lunzer Sandstein, from which they concluded that, although the plants could tolerate drought, the shales and coals had been deposited under humid conditions during a sea-level lowstand. Their work did not specifically mention a Carnian humidity or event, yet it provides strong supporting evidence. Roghi *et al.* (2010) studied the late Triassic Raibler Schichten of the same Lunz area but were more explicit in their aim of investigating the palaeoclimate of the Carnian. They also highlighted the early work of Schlager & Schöllnberger (1974) that had previously identified a “Reingrabener Wende”, or Reingraben event/turnover in the Northern Calcareous Alps of Austria and Germany. Roghi *et al.* (2010) identified this as a distinct event but incorrectly ascribed the concept, and name (‘event’), to Simms & Ruffell (1989) when in fact it had been Visscher *et al.* (1994) that used the term. Like Pott, Krings & Kerp (2008), Roghi *et al.* (2010) based their interpretations primarily on the evidence from fossil plants, but used palynology instead of macrofossils. They provided a correlation between the Raibler Schichten of the Northern Calcareous Alps and the Lunz succession, and thence on to the Julian Alps and Dolomites of Italy, thereby demonstrating the widespread extent of the clastic input to the late Triassic carbonate systems that prevailed before and returned afterwards. Their pollen data provide information on the plant types of the time, with hygrophytes dominant and some rare xerophytes. They identify four episodes of siliciclastic input and indicate that they may represent four humid phases in the Julian Alps and Dolomites. This evidence led Roghi *et al.* (2010) to consider a widespread episode of humid climates in the Carnian that they correlated with similar successions in the Germanic basins (northern Europe, see below); Barents Sea and Svalbard (also see below); northern Iraq, Tunisia, Israel (for the latter, see below) and Iran.

3.b Hungary

Two papers summarise the evidence from Hungary. In the first, Rostasi, Rausick & Varga (2011) provided a background that is similar to that of Roghi *et al.* (2010), summarising the widespread nature of Carnian humidity. The authors went further, however, in considering whether this palaeoclimate change was due to uplift in the margins of the Palaeotethys, as Pangaea coalesced and then broke up (Dubiel *et al.*, 1991), or instead was due to a large igneous province such as Wrangellia (Greene, Scoates & Weiss, 2008; Furin *et al.*, 2006). Rostasi, Rausick & Varga (2010) used clay mineral analysis in order to understand the nature of sediment input during an episode of clastic, mainly shale, deposition during the late Triassic carbonate-dominated successions of the Hungarian Transdanubian Range. The inputs of illite-smectite, smectite and variable kaolinite observed, especially in the Menschely Marl Member, were taken by Rostasi [Rausick & Varga \(2010\)](#) as evidence for more humid hinterland climates in the Carnian of this part of Hungary. They explain lateral variations in clay mineralogy as a consequence of the complex palaeogeography of the time, including rift and graben systems that were intermittently active through changing palaeoclimatic conditions, much as Olsen (pers. comm., 1995) and Ruffell & Shelton (1999) envisage for the North Atlantic successions. In the second key paper, Haas *et al.* (2012) used samples from the Balatoneederics Bet-1 borehole with a consideration of a similar succession of the

Transdanubian Range that [Rostasi, Rausick & Varga \(2010\)](#) analysed. Haas *et al.* (2012) considered the shallow groundwater conditions necessary for early dolomite formation, and concluded that the diagenetic conditions necessary were caused by increased freshwater inputs in Carnian times. Haas *et al.* (2012) compared this interpretation to clay mineral contents, which like Roghi *et al.* (2010) showed a change from arid-indicator illites to semi-humid smectites through much of the Julian Substage (Carnian). Both Hungarian works confirmed the presence of humid climates in Carnian hinterland throughout much of Europe - the Germanic Basin, Mecsek Mountains of southern Hungary, Northern Alps, Transdanubian Range and Dolomites - as well as a similar, earlier (poorly dated, but early Triassic) 'Campil Event'. Fijalkowka-Mader (1999) describes analogous successions from Poland, with good palynological records of palaeoclimate change: further work on the clay mineralogy and stable isotope stratigraphy of these successions will yield interesting results for the Carnian climate story.

3.c Slovenia

In Slovenia, Kolar-Jukovsek & Jukovsek (2010) identified three shale and silt-dominated intervals as a 'Carnian clastic interval', equivalent to the Raibl Beds (below the Hauptdolomit) of the Southern Alps (see the above descriptions from Roghi *et al.*, 2010, who recognized four such intervals). They ascribe the term 'Carnian Pluvial Event' to Hornung, Krystyn & Brandner (2007). Unlike some other publications reviewed here, which used palynology or sporomorphs, their approach was to use conodonts to elucidate whether the age of this episode can be resolved in Slovenia. No new evidence of palaeoclimatic conditions was presented although the mere presence of this siliciclastic interval, dated to within the Carnian Stage, is taken by these authors to be evidence of humid climates in this area.

3.d Italy

Triassic successions in northern Italy formed much of the original evidence for a Carnian humid episode and, while many subsequent papers have confirmed this, two papers stand out in contrast. The first, by Roghi (2004) on the succession at Cave del Predi in the Julian Alps, was published 10 years after the controversy concerning whether this was an 'event' as interpreted by Visscher *et al.* (1994), or a longer-lasting and possibly diachronous 'episode' as originally argued by Simms & Ruffell (1989, 1990). Roghi (2004) incorrectly stated that Simms & Ruffell 'suppose a Carnian "pluvial event" briefly interrupting the prevalent arid climate of the late Triassic'. Roghi used palynomorphs as the basis for analysis. This confirmed a more or less complete Carnian succession at the Cave de Predi, with a major change at the Julian - Tuvanian Boundary, thus defining the age of the evolution to humid hinterland climates in this area of northern Italy. Roghi (2004) also commented on the presence of humid indicator materials in the putative Carnian of Nova Scotia, the Colorado Plateau (see below), China, Bear Island in Norway, and the North Sea [and showed the widespread nature of the humid episode.](#)

The second paper we highlight here, also based on the northern Italian successions, forms a complete contrast. Dal Corso *et al.* (2012) sampled two of the well-dated late Triassic successions of the Dolomites, specifically the Carnian type section at Stuares Wiesen and Milieres-Dibona, for stable isotope ($\delta^{13}\text{C}$) analysis. The $\delta^{13}\text{C}$ record shows a positive trend towards heavier carbon through the Carnian, punctuated by a negative shift, towards lighter carbon, in the mid-Julian (see their Figure 2 for details). This coincides with parts of the stratigraphy where no fossil wood was recorded, followed by an influx of wood where the authors place the start of their Carnian Pluvial Event. This, they conclude coincides with the onset of eruptions in the Wrangellia Large

Igneous Province or LIP of the northern Pacific and offshore Alaska, which could have injected CO₂ and other gases into the atmosphere. This would have caused both acidification of the oceans and [warming](#), thereby increasing weathering and runoff and exerting a major influence on carbonate reef platforms and the CCD (as recorded by Rigo *et al.* 2007).

Furin *et al.* (2006) made a similar comparison between the rise of Carnian humidity and the Wrangellia LIP. The latter authors, working in the Lagonegro Basin of the southern Apennines, showed the absence of limestones through the Julian- Tuvalian Boundary, which they interpreted as a rise in the Carbonate Compensation Depth (CCD). The significance of their work is that this absence of carbonates is here recorded in a deep water setting, thus expanding the extent of the event environmentally, if not geographically. Rigo *et al.* (2007) state that the Carnian input of green clays, which are [more](#) organic-rich [than](#) the clays and silts above and below, is unprecedented in the successions. This change could be ascribed solely to increased terrigenous input, although this would have to contain significant [terrestrial](#) organic matter as well. [Rigo *et al.* \(2007\) anticipated the work of Dal Corso *et al.* \(2012\) in conjecturing that increased CO₂ could be responsible for the Carnian climate change.](#)

4. Spain and Portugal – The Iberian Peninsula

The main work concerning this area is by Arche & Gomez-Lopez (2014), who [undertook](#) detailed analysis of the Carnian Manuel Formation of the southern regions of Spain and Portugal. Like Hornung *et al.* (2007) on the Himalayas and Nakada *et al.* (2014) on Japan, Arche & Gomez-Lopez (2014) were critical in their global assessment of Carnian palaeoenvironmental events. This was due primarily to the palaeogeographic location of Iberia in Triassic times, as the deposits here provide something of the missing link between the deposits in eastern North America and both northern ('Germanic') and central ('Tethyan') successions. The remarkable aspect of the Manuel Formation is the coarse nature of the clastic deposits compared with the generally finer clastics found in the Tethyan or Germanic Carnian. These conglomerates are found between evaporite-dominated successions above and below, broadly comparable with the clays and salts of the Germanic successions and the limestones of the Tethyan sequences. As such the Carnian Manuel Formation is a high-sediment load deposit. Arche & Gomez-Lopez (2014, p.196) were correct in their assessment that we assumed a Carnian wet episode but they then introduced the term "Middle Carnian Pluvial Event" in parentheses, although unasccribed to any specific authors. The Middle Carnian is used informally by Arche & Gomez-Lopez (2014), when either Carnian (in poorly dated successions) or Julian (plus any biozone identified) is preferred, where the succession is better-dated.

Arche & Gomez-Lopez (2014) use the superb evidence of the Manuel Formation, which they date convincingly as Carnian, to compare to many of the successions considered here in Europe and, most critically, north African successions in Morocco, Algeria and Tunisia and further south into the Sahara. How much further south in central Africa this evidence can be traced becomes difficult as the next known Carnian successions that can be used to develop the story are in Kenya, Mozambique and South Africa. Arche & Gomez-Lopez (2014) provide very useful summaries of the marine deposits of Western Neotethys (Italy, Hungary, Austria, see above) as well as eastern North America. Two aspects stand out from their work as critical for our discussion. First, some papers (e.g. Dal Corso *et al.*, 2012) have linked the Carnian episode to volcanic activity, specifically the Wrangellia LIP (offshore Alaska): Arche & Gomez-Lopez (2014) show evidence of Carnian volcanics within and close to the area of Manuel Formation deposition and are one of the few papers to show this direct comparison.

Secondly, they describe in detail their interpretation of the depositional conditions of the Manuel Formation, specifically 'a series of fluvial networks disposed in a radial pattern ... as a laterally continuous apron, at the subsiding rifted margins of the Iberian Massif' (p.21). This interpretation, together with the lithostratigraphical context of coarse clastics sandwiched between evaporites, makes interpretation of the Manuel Formation critical to the debate between our original concept of a widespread humid phase, and Visscher *et al.*'s (1994) 'Nile vallies in a Carnian Sahara' as quoted by Arche & Gomez-Lopez (2014, p.196). A final observation in this work is intriguing: the authors comment that in some locations, evidence for humid-related Carnian deposits is absent (e.g. the Aquitaine Basin), a phenomenon we have also encountered in examining the South African and Antarctic successions.

5. Israel

In comparison with the Alpine foldbelt, the Triassic of Israel has limited outcrop but is significant for two reasons. Firstly, this was the first location where a significant negative $\delta^{13}\text{C}$ excursion was recorded (Druckman, Hirsch & Weissbrod, 1982; Magaritz & Druckman, 1984) and related to the Carnian episode (Simms & Ruffell, 1989). Subsequently Bialik, Korngreen & Benjamini (2013) have related the Triassic stratigraphy of the Makhtesh region of Israel to the Carnian humid interval on the basis both of this isotope excursion and the changing facies patterns of carbonates and evaporites. The second reason that the Israeli successions are important is that palaeogeographic reconstructions suggest the area would have been on the margins of Pangaea, with the Tethys Ocean to the east. This is significant because, should the Carnian humid episode be a tectonically-driven event related to the mid-Atlantic Rift and Alpine belts, a record of increased humidity on the [far-distant](#) eastern margin of Pangaea would be anomalous and require [alternative](#) explanation (see Hornung *et al.*, 2007, below). Major changes in early – mid Triassic pollen are recorded in the subsurface of north-east Libya (Brugman & Visscher, 1988) as well as other circum-Mediterranean locations (Buratti & Cirilli, 2007).

6. Germanic Basins (northern Germany, Paris Basin, southern England)

Although much of the initial evidence for the Carnian humid episode came from the Italian successions, the late Triassic non-marine record in northern Europe was equally important in development of the theory. In exploiting the idea of a humid climate phase within the otherwise mainly arid late Triassic, Simms & Ruffell (1990) cited Wurster's (1964) seminal work on the sedimentology of the Schilfsandstein of the German non-Alpine Triassic. However, Angermeier *et al.* (1963) had previously made a connection between the pale sandstones and green mudstones of the Schilfsandstein (within the evaporite- and red bed dominated Keuper Marl) and a major change in palaeoenvironments. Unlike the Italian, Austrian, Hungarian and contiguous deposits that have been the focus of significant subsequent work, relatively little work specific to palaeoclimate reconstructions has occurred in the Germanic, and related, non-marine basins, with Kozur & Bachmann (2010); McKie (2014) and Shukla *et al.*, (2010) being the exceptions. By 'Germanic' we imply that some or the entire classic three-fold Triassic lithostratigraphy - Bunter, Muschelkalk and Keuper stratigraphy - can be applied to the area under study. Some papers have improved our knowledge of the already-known Carnian sandstones, the Schilfsandstein and its equivalents, such as Peron *et al.* (2005) on the Chaunoy Sandstones of the Paris Basin, and the equivalent Gres a Roseaux (Goggin & Jacquin, 1998) and Porter & Gallois (2008) on the UK Keuper-equivalent Mercia Mudstone Formation sandstones. These confirm previous records of a change in depositional conditions from arid-dominated to a greater influence of fluvial deposition. Three publications in particular are

significant to the Carnian climate story from the Germanic basins. First, Shukla *et al.* (2010) carried out facies and sandbody geometric analysis of the Stuttgart Formation (Schilfsandstein) and compared their observations with the modern Ganga Plain of the Ganges. Their descriptions are remarkably similar to those of correlative Carnian sandstones in the Paris Basin and southern UK. The analogy with the Ganges, if correct, suggests that significant volumes of water were carried by the Schilfsandstein fluvial system. This however, is still not at odds with the original objection of Visscher *et al.* (1994) to the Carnian Pluvial Episode, which suggested that such a large river system could flow through an essentially arid landscape (the Nile analogue). What is significant for our argument is that this river system appeared at, and existed during a specific interval. The second major contribution from the Germanic successions to discussions concerning the Carnian palaeoclimate is the comprehensive synthesis of Kozur & Bachmann (2010). This encompasses all of the evidence for the humid episode, both from the Germanic series and adjacent areas, and also spells out much of the terminology for the same episode - Northern Alpine Raibl Event (Angermeier *et al.*, 1963); "middle Carnian wet interval" (Kozur, 1972, 1975); Reingraben turning point/Riengraben Event (Schlager & Schollnberger, 1974); Carnian Pluvial Episode (correctly cited - Simms & Ruffell, 1989), Carnian Crisis (Hornung, *et al.*, 2007) and "Middle Carnian Wet Intermezzo" (Kozur & Bachmann (2008). The use of Middle Carnian is not strictly accurate, Julian being preferred (Dal Corso, *et al.* 2014). The earlier naming of this siliciclastic influx to a carbonate system, demonstrates that the dramatic intercalation of grey mudstones, siltstones and plant fossil-bearing sandstones in the predominantly red mudstones of the Keuper has long been recognized as something other than an isolated event. Kozur & Bachmann (2010) go on to make an interesting point "Ever since the careful studies by Hornung (2008) in the Northern Alps and other parts of the Tethys (summarized in Hornung, 2008), it generally has been accepted that there was a real Carnian Wet 'Intermezzo' in the sense of Kozur & Bachmann (2010) in the Germanic Basin and in the adjacent northwestern Tethys region and not just a strong influx of outside fresh water into an otherwise arid region. But often a pluvial event is automatically assumed, even though this cannot be demonstrated anywhere within the Germanic Basin or in the adjacent northwestern Tethys region". This apparently contradictory statement is predicated on the use of yet another name to describe Carnian humidity - here 'intermezzo', or a musical term meaning a short movement, often inserted in a longer piece of music. The Carnian episode as seen here, could be considered an intermezzo for the Germanic basins, should its duration be accurately determined. We consider that Kozur & Bachmann (2010) are stating that the 'event' (a rapid, more or less geologically instant) part of the Carnian episode cannot be demonstrated in the Germanic successions: below we show how the rise in humidity may well have begun (geologically) quickly, but led to a prolonged period of humid climates. The third work we wish to highlight on the Germanic successions is that of McKie (2014), who presents a comprehensive examination of the Triassic of the North Sea. McKie's (2014) figures 18, 19 and 21 show four wet climate phases (Olekenian; late Ladinian; early Carnian and Rhaetian), the Carnian and Rhaetian are associated with warmer temperatures (from oxygen isotopes), and only the Carnian is associated with volcanics (in the Alpine successions in McKie, but also known from Iberia, see Arche & Lopez-Gomez, 2014). McKie (2014) shows the effect the development of the Ladinian and Carnian fluvial systems had on the palaeogeography of the North Sea Basin, and ascribes this to an increase in the summer monsoon from Tethys and a southern migration of the northern (higher) latitudinal precipitation.

Comparing Dal Corso *et al.*'s (2012) record of a carbon isotope spike, to the sedimentary record of the Germanic basins, we see that in the carbonate successions, the humid interval lasted for some millions of years, but started, coincidentally with a quite sudden event. Examining the sedimentary log of Ruffell & Warrington

(1988), we see that the Carnian influx of sands and muds began with an erosional event, marked by rip-up clasts and a vertebrate-bone conglomerate, suggestive of a rapid erosional change. Thus the sudden start to the Carnian humid phase maybe reconcilable in both the clastic Germanic and carbonate Tethyan successions as starting abruptly, but lasting for some time as an episode of humid climates.

7. Svalbard (Norwegian North Sea)

The work of Xu *et al.* (2014) is highlighted in this review since it provides an accurately dated record of pre- and post-Carnian events from a Boreal marine succession, unlike all the other articles considered here. This succession would have been located well north of any influence from circum-equatorial events or Pangean rifting. Xu *et al.* (2014) based their analyses on Re-Os geochemical ages and $^{187}\text{Os}/^{188}\text{Os}$ ratios. The osmium ratios show late Carnian excursions that Xu *et al.* (2014) compare to the strontium isotope (seawater) curve. They concluded that the Wrangellian LIP episode is of the same age, and would have had the required effect on ocean chemistry, to be a prime candidate for the cause of the Carnian climatic events.

8. North America - Western United States

8.a Eastern Seaboard

The eastern seaboard of North America has historical analogues to how the Germanic basins played a role in the development of the Carnian Pluvial Episode theory. These locations extend from the New York/ New Jersey, Connecticut palaeovalley successions, to the critical Milankovitch-calibrated successions of the Newark Rift Basin (Olsen & Kent, 1999) and the basins of New Brunswick. Many show evidence of major changes in the Carnian, although generally neither as dramatic as the 'intermezzo' of the Germanic successions nor as well dated as the type Italian sections. However, as Olsen (1980) pointed out, determining the cause of this rise in palaeohumidity will not be determined by examining the circum-Atlantic successions, since they were dominated by the same equatorial climate and Pangean breakup mechanisms. An excellent summary of the eastern seaboard basins is provided by Arche & Gomez-Lopez (2014, see above), who stress the palaeogeographic connections between the basins around the Bay of Fundy and those in Morocco, thereby reinforcing the fact that, although now separated by the Atlantic, these basins were adjacent from a palaeoclimatic perspective and thus provide only confirmatory local evidence of changing humidity. The Stockton Formation (Chatham Group) provides important evidence for the Carnian humid episode (Arche & Gomez-Lopez 2014), as it comprises a braided fluvial and lacustrine set of environments (Olsen *et al.*, 1996), with minimal aeolian influence on deposition. Further south on the United States eastern seaboard, Triassic deposits are mainly covered, although Driese & Mora (2002) use combined palaeopedology and stable isotope geochemistry to demonstrate similar late Triassic climate changes to those to the north and west (see below).

8.b West and Southwestern USA

Unlike the circum-Atlantic basins, local controls on palaeoclimate are harder to envisage further to the west, where evidence for the Carnian episode in the southwestern and western USA Chinle Formation was identified during the initial (Dubiel, 1989) and later confirmatory publications on the Carnian strata (Cleveland, Atchley & Nordt, 2007). Prochnow *et al.* (2006) made a significant contribution to the debate concerning the nature of the Carnian humid event through their application of a multi-proxy approach to the analysis of Lower Chinle Formation soils in Utah. From this they gained abundant information on changing rainfall rates, atmospheric

temperatures and CO₂ contents, compared to palaeobotanical communities. Their Figure 7 contains a summary of this information, with convincing correlation of pedogenic interpretations of precipitation, palaeoCO₂ (from C isotopes), palaeotemperature (from O isotopes) and changing plant communities (palaeobotanical reconstruction). Interestingly, the world-famous Petrified Forest Member was deposited as the Carnian humid episode became established (see Fig. 7 of Prochnow *et al.* 2006). Cleveland, Atchley & Nordt (2007) found evidence that increased rainfall occurred not only in the paleosols of the Lower Chinle Formation but in an associated palynological association which could be correlated with the hygrophytic associations described in Roghi (2004) and Litwin, Traverse & Ash (1991).

9. Indian Himalayas

Although the publications on the European Tethyan successions, Germanic Basins, and NE North American deposits were critical in helping develop theories of climate change in the Carnian, it is data from beyond these 'central Pangaean' locations that will really provide further evidence as to what happened in the Carnian. Just as the successions in Israel, Svalbard, South America, China and Japan assist in this manner, so the work of Hornung *et al.* (2007) provides data for the Indian Himalayan successions. The critical point is the palaeogeographic location of the succession in late Triassic times, which [was Perigondwanan](#), on the southern shores of the Tethyan Ocean ([Hornung *et al.* 2007](#)). This removes the Himalayan succession from the central Pangean and western Tethyan area of influence and shows the Carnian episode as occurring away from the equatorial Tethyan/Germanic/North Atlantic area. Hornung *et al.* (2007) recorded a shift to siliciclastic deposition following a cut-off in carbonate production, as the Carnian change takes place, and suggested that this occurred throughout the exposed Triassic of the Himalayas. They also documented a $\delta^{13}\text{C}$ excursion comparable with that seen at a similar level in other regions. The shift to siliciclastic deposition, the isotope record, and the correlation to the 'Reingraben Event' or Carnian Humid Episode forced Hornung *et al.* (2007) to conclude that this climatic change was a global event that could have caused a complete shut-down in platform carbonate production. They suggest a reinforcement of the mega-monsoonal system as a possible cause.

10. China

The Triassic successions of China contain a wealth of data with great potential for contributing to the Carnian climate change debate, but they remain relatively poorly documented. There are non-marine (aeolian, fluvial and lacustrine) basins such as Junggar (Tang, Parnell & Ruffell, 1994) that can be compared to many of the North American and Germanic basins, as well as extensive carbonate platforms comparable with the Italian, Hungarian and other Tethyan Platform successions (Hornung *et al.*, 2007). In southwest China Shi *et al.* (2010) described the complete cessation of sponge reef limestones in the Carnian, and the onset of deposition dark shales with tuffs. In the eastern, non-marine successions, Liming & Meng (2006) described the palynology of Eastern Gansu Province and the dramatic changes to Carnian floras in this area, commensurate with a major climatic change. Lehrmann *et al.* (2005) describe the Triassic of the Yangtze platform and Great Bank of Guizhou in the Nanpanjiang Basin of Guizhou and Guangxi, south China, where an influx of clastic material ????????. This clastic influx appears very similar to that described from the Austrian Alps (Raibl Schichten: see Hochuli & Frank, 2000), with Banan Formation sandstones and siltstones, followed by Huobachong Formation mixed clastics with coals: the last deposits of the Triassic on the Yangtze Platform comprise Erqiao Formation sandstones. Lehrmann *et al.* (2005) show clastics occurring above the Carnian on the Yangtze Platform, suggesting that this was not a

discrete clastic input in this area, more a wholesale change from carbonate to clastic sedimentation. While the sand and gravel input continues after the Carnian in many areas of China (e.g. continued Huobachong Formation deposition and Rhaetian Erqiao Formation), coals are restricted to the Carnian, suggesting increased humidity at this time and perhaps an 'intermezzo' of less discrete nature than the Himalayan and Alpine Tethys to the west. More work is required on these successions to pin down mid- to late Triassic events in these areas of China.

11. Indonesia

Two papers with Martini as lead author are of value here, if providing some enigmatic results. Martini *et al.* (2000) examined the sequences of West Timor by deconstructing the significant tectonic overprint. Clastic-rich successions, mainly shales, observed in the Carnian have been dated using radiolaria, pollen, conodonts and ammonoids and compared to similar successions on the Australian margin. No rocks are observed underlying the Carnian shales, thereby precluding any conjecture that this is a discrete clastic input, as opposed to a change in sediment supply. What is significant is the observation of late Triassic fluvio-deltaic successions in Papua New Guinea and Middle to Late Triassic delta and non-marine clastics in the Exmouth Plateau successions (Malita Formations). Martini *et al.* (2000) stressed the tectonic differences between Timor, Papua New Guinea and areas closer to mainland Australia, yet considered the Carnian black shales and clays of the High Londonderry Formation to be equivalent to the Timor succession. Martini *et al.* (2004) found a similar pattern of Triassic sedimentation in their work on Seram (Indonesia), as well as on Buru and Misool, often with Mesozoic clastic (shales, calcareous mudrocks) sedimentation commencing in the late Triassic, but with little or no earlier Triassic to provide context. Rao (1998) describes the Permian – Triassic succession of Malaysia, where no obvious evidence of a Carnian humid phase can be observed, albeit that his detailed carbon isotope records are from the Permian succession and do not extend up into the Triassic Koding Limestone, where further work may prove fruitful.

12. Gondwana Successions (Antarctica, southern Africa, southern South America, Australia, non-Himalayan India)

Triassic deposits are known from many areas of Antarctica (Beardmore Glacier; Transantarctic Mountains, Shackleton Glacier) but none are sufficiently well dated to allow the kind of analyses required to obtain a comparable picture of Late Triassic changes here. Numerous publications have addressed aspects of the Triassic of Antarctica, but some observations are intriguing as regards to what happened in the Carnian. For instance, the sedimentological analysis by McLoughlin & Drinnan (1997) of the Flagstone Bench Formation in the Prince Charles Mountains recognised three units. The lower, sandstone-dominated Richie Member (early Triassic) they suggested was deposited in a [paralic](#) environment yet with evidence of increasing aridity and seasonality [as no coals are present](#). The succeeding Jetty Member showed signs of greater arid influence, whilst the McKelvey Member at the top of the formation, probably Carnian or Norian in age, contains plant-rich beds indicative of more humid conditions. Should the Jetty Member be Carnian, which is possible but not proven, then this succession is the reverse (shows evidence of arid climates) of the situation elsewhere. This is not an isolated occurrence, with McLoughlin, Lindstrom & Drinnan (1997) suggesting that the base of the Carnian is in the topmost Jetty Member, when coal deposition ceased and sand influx waned, which again is the reverse of what is seen in some other successions. A similarly intriguing situation was described by Retallack & Alonso-Zarza (1998) from humid-indicator palaeosols in the Lashly Formation of the Allan Hills in Victoria Land. Awatar *et al.*

(2014) place the Lashly Formation as middle late Triassic, which could be Ladinian, Carnian or Norian. These are not the only examples and, while refinement of the Antarctic Triassic chronology continues, perhaps another approach to understanding Carnian events in the Southern Hemisphere Gondwanaland might be to look at the wider temporal and spatial picture. One temporal aspect is to examine Retallack's pioneering work on the end Permian 'coal gap', recovery from which is most likely to be around the Carnian period, when plant-eating dinosaurs experienced their initial evolutionary radiation (Retallack, [Veevers & Morante](#), 1996). Perhaps the Permian-Triassic mass extinction, and subsequent rapid warming with its often arid climates, suppressed land floras until sufficient humidity had spread to areas where plants could thrive and coal deposition could be established. A spatial approach to the Gondwana successions might compare Figure 1 of Retallack, [Veevers & Morante](#) (1996) with Figure 8 of McLoughlin *et al.* (1997), wherein the idea of the end of the coal gap, and the rise of the dinosaurs, appears coincident. Retallack *et al.* (1996) showed Carnian red-beds to be coeval with some coals in South America, the Karoo Series of Southern Africa, the Transantarctic Mountains, the Topper and metamorphosed Torlesse of New Zealand, and east (Ipswich), central and western Australia (Mungaroo). They suggested that some red beds in East Antarctica could extend into the earliest late Triassic. Retallack, [Veevers & Morante](#). (1996) also show Carnian coals in parts of India, North America and the Lunz of Europe (Austria, as above). Finally, they showed coal formation being initiated during the Carnian, but not restricted to it, as in parts of the Russian Federation (their 'Former Soviet Union') and in China.

Retallack *et al.*'s (1996) spatial view of Gondwanan events, [combined with](#) examination of McLoughlin *et al.* (1997), confirms the presence of Carnian coals in southern Africa (Molteno Formation) and eastern Australia (Bowen, Callide basins, Callide Coal Measures). Dolby & Balme (1976) provide an account of the Triassic palynology of the Carnarvon Basin (NE Australia) that could yield further information on Triassic palaeoclimates in this area. McLoughlin *et al.* (1997) show the southwestern USA as predominantly Chinle Formation red beds, when there is evidence of the Carnian humid episode here (see above). Their analysis of the South American Parana Basin (Brasil) is enigmatic, with [plant fossils](#) recorded but no coals (see below). In their Figure 8, India has neither coals nor red beds and parts of Antarctica (Lambert Graben, Prince Charles Mountains, including the Jetty Member) are recorded as red beds. Retallack *et al.* (1996) also show the Eastern Antarctic successions developed as red beds into the early Carnian. Other evidence from Australia for Carnian events comes from the Wombat Plateau where ODP Leg 122 records indicate a Carnian–Norian delta dominated siliciclastic sequence succeeded by Rhaetian shallow-water reefal carbonates.

13. South America

13.a Argentina

Some evidence for humid climates in the Carnian comes from the work of Tabor *et al.* (2006) on the Ischigualasto Formation of San Juan, in north-west Argentina, where a multidisciplinary study, much like that of Prochnow *et al.* (2006) in the southwest of the USA, suggested a humid climate and/or elevated water tables in the Carnian, becoming drier or with lower water tables subsequently. Some of the earliest dinosaur-type remains occur in these wetter, Carnian deposits (Prochnow *et al.*, 2006). Many Triassic successions in Argentina and Brazil include a Carnian succession that records [a vertical succession from](#) alluvial plain, lacustrine deltaic, fully lacustrine and [repeated](#) back again (Zerfass *et al.*, 2003). In this respect they resemble the red bed to lacustrine transition, and back again, seen in the Cow Branch Formation of the Newark Supergroup (Simms & Ruffell 1989, 1990). Further work on the palynology and clay mineralogy of these sequences at outcrop and subsurface, such

as in the Potrerillos, Cacheuta, Rio Blanco formations of the Curo Basin, could prove useful.

13.b Chile

Much of central Chile contains Upper Triassic (Ladinian – Carnian) volcanic successions [in rift basins](#) (Mercedario Rift, Atuel Rift, Malargue Rift, Alumine, Cerro Chacil). These often felsic lavas and pyroclastic units are intercalated with coarse clastics, some of which were water-lain or reworked, but they provide minimal information on changing palaeoclimates. The Santa Juana Formation of south central Chile is a mixed fluvial, lacustrine, playa and alluvial succession of proven Carnian age (Nielsen, 2005). It was previously interpreted by a number of workers (see Nielsen, 2005 for details) as reflecting a change from semi-arid to more temperate climates, which would be in line with global models for the Carnian, but possibly not for [elsewhere in South America](#).

14. Japan

The most revolutionary evidence concerning the nature and extent of the Carnian Humid Episode comes from Japan. Like the Himalayan successions, the palaeogeographic context for Japan in the Triassic is critical (Figure 1), with the ocean sediments and volcanics, now often metamorphosed, that now form Japan being deposited [on the Panthalassic Ocean floor](#) some 8-10,000km west of the western Pangaean seaboard, probably in an equatorial location. Nakada *et al.* (2014) used X-ray absorption to analyse the mineralogical composition [the presumed aeolian component of pelagic](#) chert in the Triassic successions of Inuyama in central Japan. Although deposited on the ocean floor and/or in an accretionary prism, these sediments have a low illite crystallinity, suggesting minimal post-depositional alteration. The [study revealed an influx of smectite \(and loss of chlorite\) during an interval](#), constrained by radiolarian biostratigraphy, [to belong to](#) the early Julian to Tuvalian: Nakada *et al.* (2014) suggested [that this change reflects a humid episode in the far-distant source areas of Pangea](#).

15. Conclusions

Our original investigations more than two decades ago (Simms and Ruffell 1989, 1990) established the existence of a significant episode of climatic change, from arid to humid, during the Carnian Stage of the Triassic and identified evidence for this in both marine and non-marine successions across Europe and eastern North America. These papers acted as a catalyst for others to confirm or refute our conclusions based on new data from the area that we originally covered, and from additional locations further afield. Although in the ensuing years some have rejected our suggestion of climatic change in the Carnian, in general there has been strong support for it from diverse sources of evidence, across a much larger area than we had identified originally, and with perhaps some consensus on its possible cause. As in the original papers (Simms and Ruffell 1989, 1990), one of the main lines of evidence from many of the newly documented locations is the occurrence of widespread siliclastic units that interrupt the predominantly marine carbonate successions, with aspects of their clay mineralogy also used as evidence for climate humidity (Rhogi *et al.* 2010, Haas *et al.* 2012). In most instances this can be attributed to enhanced weathering and erosion, with a resultant increase in terrigenous runoff, but in one instance the switch from deep-water limestones to clays has been attributed to the effects of ocean acidification and a rise in the Carbonate Compensation Depth (Rigo *et al.* 2007). Data published since 1994 indicates that, with the exception of certain locations, specifically Malaysia and parts of South America and Antarctica, evidence for the Carnian Humid Episode appears to be more or less global in extent (Figure 1). This

might seem to contradict what is observed with present-day climatic belts, which generally shift north and south during episodes of climate change. However, the configuration of land and ocean in the Triassic world was very different from today and, should some trigger have affected Panthalassa and Tethys, it is possible that this could have caused a global climate change. Price (1999) considered that Icehouse climate changes are [mostly temperature trends](#), whilst Greenhouse changes are arid to humid. The Carnian represents the peak of the post-Permian Greenhouse, such that one might expect extreme climate changes at this time.

At the time of our original work little had been published on the Triassic isotope record, although what was available appeared to support the thesis of increased Carnian humidity. Recent years have seen the publication of carbon isotope curves for several locations. These indicate a significant but brief negative carbon isotope excursion in the mid-Julian interrupting a positive isotope trend through the Carnian (Dal Corso et al. (2012), with negative carbon isotope excursions also recorded in sections in the Southern Hemisphere (Graphite Peak of Retallack *et al.*, 1996) Austria (Hornung, 2008) and the Himalayas (Hornung *et al.*, 2007). The Carbon Isotope Excursion (CIE) in the Southern Alps (Dal Corso *et al.* 2014) lasts for a far shorter period of time than the Carnian Humid Episode (CHE), being confined to Palynological Assemblage B of the earliest *Austrotrachyceras austriacum* Zone. In contrast the sedimentological evidence for the Carnian Humid Episode (CHE) here extends from the base of the *Austrotrachyceras austriacum* Zone into the Tuvalian *dilleri* or *subblatus* zones. An intriguing aspect the double negative carbon isotope excursion of Retallack *et al.* (1996) is apparent when comparison is made with McKie's (2014) comprehensive review of the North Sea Triassic (especially his Figs 18 and 21C). McKie (2014) identified a late Ladinian humid episode and then the Carnian Humid Episode discussed here. Could the earlier carbon isotope shift of Retallack et al. (1996) and the Campil Event of Roghi *et al.* (2010) be reflecting these two humid phases? If so, why then did the earlier (?Ladinian) humid episode of the North Sea not have the dramatic effect on the biota that the CHE did? The answer may also lie in McKie's (2014) Figure 18, where the oxygen isotope data of Korte, Kozur & Veizer, 2005, indicates coincidentally warmer temperatures and wetter conditions for the Carnian, yet no similar warming for the earlier Ladinian.

As to the possible cause of the CHE, we alluded to the possible role of volcanism in our original papers (Simms and Ruffell 1989, 1990; Simms, Ruffell and Johnson 1994) but we were unable to identify occurrences that were of appropriate scale or age. In addition to the localised occurrences we identified, subsequent publications have identified volcanics associated with Carnian successions in Indonesia, South America and Iberia although none on a scale commensurate with the CHE. However, Xu et al. (2014) noted the synchronicity between the onset of the CHE and the eruption of the Wrangellia Large Igneous Province in the north-eastern Pacific region (Green et al. 2005, 2008) while Del Corso *et al.*, 2012 specifically linked the carbon isotope excursion, and subsequent period of climate change, to this same event. The global negative carbon isotope excursion, suggestion of ocean acidification, and the subsequent period of global warming, could all be ascribed to the effects of flood volcanism. The global warming episode may have increased evaporation from the Tethyan and Panthalassic oceans, and generated anticyclonic storms feeding moisture-laden air across Pangaea. The apparent absence of humid-climate indicators in some areas of the world, such as parts of South America, Antarctica, China and northern Siberia, may perhaps reflect a failure of this moisture-laden air to penetrate these regions (Figure 2). The Carnian Humid Episode may thus be a global event, but its effects are masked in some locations and have yet to be resolved in others.

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Figure captions

Figure 1. Global distribution of the main data sources used in this review that show evidence for humidity in the Carnian (or early late Triassic in some poorly-dated locations). The palaeogeographic map of Golonka (2007) is used as a template. Solid black denotes the continental shelf of Pangaea; grey lines denote supposed island masses (both continental and volcanic arc) and the shape of the continents following Mesozoic breakup and sea floor spreading.

1: Austria, Dolomites, Hungary, Slovenia, Sicily, Spain (Dal Corso *et al.* [2012]; Furin *et al.* [2006]; Haas *et al.* [2014]; Kular-Jurgensick & Jukovsek [2010]; Pott *et al.* [2008]; Rostasi *et al.* [2011].

2: Iberia (Arche & Lopez-Gomez [2014].

3: Israel (Magaritz & Druckman, 1984).

4: North Sea, Germany, UK (Kozur & Bachmann [2010]; McKie [2014]; Shukla *et al.* [2010]; Porter & Gallois [2008]).

5: Svalbard (Xu *et al.*, 2014).

6: Eastern North America (Arche & Lopez-Gomez, 2014); Utah (Prochnow *et al.*, 2006).

7: Indian Himalayas (Hornung *et al.*, 2007)

8: China (Lehrman *et al.*, 2005).

9: Indonesia (Martini *et al.*, 2004).

10: Australia (McLoughlin *et al.*, 1997).

10: Antarctica (Retallack & Alonzo-Zarza; Retallack *et al.*, 1996.)

11: Argentina (Tabor *et al.*, 2006).

Chile (Nielsen, 2005).

12: Japan (Nakada *et al.*, 2014).

Figure 2. A model of how warming of the Carnian oceans may have increased precipitation in many (but possibly not all) of the areas studied. Palaeogeography redrawn after Golonka (2007) and possible climate scenarios after McKie (2014).

Table 1. Key publications that supported, did not support, or modified the original Carnian Pluvial Episode of Simms & Ruffell (1989).