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Synchroneity of climatic change and extinctions in the Late Triassic

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ABSTRACT

Although the Late Triassic was a time of widespread aridity, evidence exists for a significant increase in rainfall during the middle to late Carnian. Upper Triassic playa-lake sediments were interrupted by late Carnian fluviatile sandstones with erosive bases and high kaolinite/illite ratios. There was also an increase in the clastic component of marine sequences during this interval. Middle and upper Carnian marine carbonates show an extreme depletion in $\delta^{13}C$ values, consistent with increased fresh-water influx. Large-scale karstic phenomena in limestone areas subaerially exposed during the Late Triassic are a further indication of increased rainfall. Important faunal and floral changes occurred during the Carnian-Norian interval; marine invertebrate turnover was greatest at the lower/middle Carnian boundary, and terrestrial extinctions were concentrated at the Carnian/Norian boundary. The cause of this Carnian pluvial episode may have been related to the rifting of Pangea, through disruption of atmospheric and oceanic circulation patterns, eustatic changes, or the effects of volcanism associated with rifting. A change in surface ocean temperature, salinity or pH, or habitat loss may have caused the decline of many shallow-marine invertebrates at the start of the middle Carnian; a return to arid conditions at the Carnian/Norian boundary would account for the turnover among terrestrial vertebrates and plants.

INTRODUCTION

The Triassic was a time of widespread aridity, terrestrial sequences being characterized by red beds, aeolian sands, evaporites, and playa-lake deposits. The configuration of land and ocean produced higher and more equable average global temperatures and generally lower rainfall by comparison with other geologic periods (Tucker and Benton, 1982).

However, the increasing aridity through the Late Triassic and into the Early Jurassic (Hay et al., 1982; Manspeizer, 1982) was interrupted by an interval of greatly increased rainfall during the middle to late Carnian. Here, we summarize the evidence for this from terrestrial and marine sequences, karstic phenomena, and stable isotopes, and we attempt to correlate it with contemporaneous faunal and floral changes.

EVIDENCE FROM SEDIMENTARY SEQUENCES

The nonmarine sequence in the Upper Triassic of Britain and Europe typically comprises a succession of evaporitic, and largely unfossiliferous, red and green mudstones, dolomitic siltstones, and subordinate sandstones. Some degree of correlation can be achieved by using palynomorphs. The German Keuper (Upper Triassic) has been divided into widely traceable lithostratigraphic units. The most distinctive is the Schilfsandstein, up to 35 m of stacked-channel sandstones cutting down into the underlying playa-lake mudstones. It has been dated as late Carnian (Leschik, 1955; Hahn, 1984) and can be traced from Switzerland through Germany into Poland.

The Schilfsandstein can be correlated with a similar late Carnian unit in the British Triassic, termed the Arden, North Curry, Butcombe, Weston Mouth, and Dane Hills Sandstone Members in different parts of the country (Warrington et al., 1980). This unit often shows a lenticular profile, with a thick, plant-bearing, sandstone/mudstone sequence in the center passing laterally over a few kilometres into an overbank facies of calcareous nodular mudstones and siltstones (Warrington and Williams, 1984; Ruffell and Warrington, 1989). Away from upstanding Paleozoic blocks, the channel-confined sands coalesce into a laterally extensive, silty dolomitic limestone. Clay mineral analysis shows proportionally greater kaolinite/illite ratios by comparison with the sediments above and below (Fig. 1), a strong indication of warm humid conditions during this interval. The Schilfsandstein and its British equivalents are unique in the European Triassic for their scale of development and widespread occurrence. They indicate a great increase in runoff, in turn reflecting an increase in rainfall.

In southern New Brunswick, eastern Canada, red beds in the Echo Cove Formation (Upper Triassic) are interrupted by a sequence of green beds with abundant plant debris. Palynomorphs from this middle unit, the Fownes Head Member, also indicate a middle to late Carnian date for this humid interval (Nadon and Middleton, 1984).

Further evidence for such a pluvial episode comes from marine sequences. The carbonate buildups of the Middle and Late Triassic are interrupted by clastic facies in the middle and late Carnian, both in Europe and farther afield (Gobbett and Hutchinson, 1973), though this is not necessarily due to increased continental runoff but may be an effect of the mid-Carnian regression (Hallam, 1984) or tectonic activity.

Stronger evidence comes from stable isotopes. Systematic $\delta^{13}C$ profiles through a marine carbonate and evaporite sequence in Israel, the Saharonim Formation (Ladinian to lower Carnian) and the Mohilla Formation (middle to upper Carnian) (Druckman et al., 1982), show an extreme $\delta^{13}C$ depletion in the Mohilla Formation, indicating an influx of fresh water during the middle to late Carnian (Magaritz and Druckman, 1984).

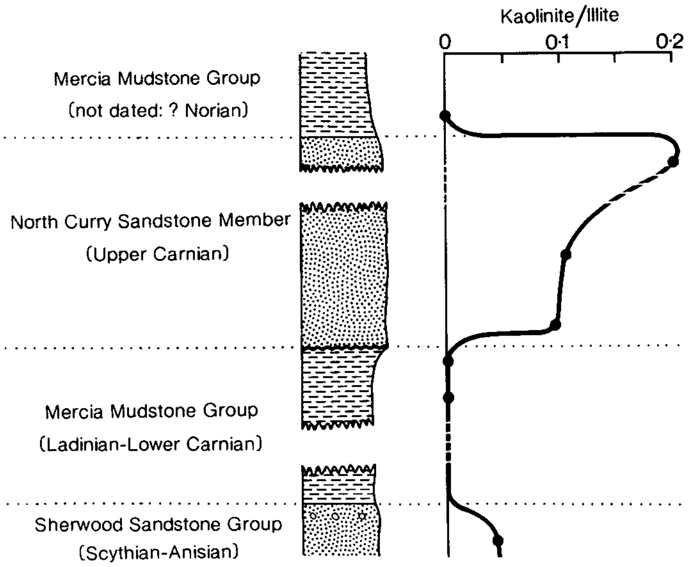

Figure 1. Variation in kaolinite-illite proportions through North Curry Sandstone Member and adjacent strata.

KARSTIC PHENOMENA

Ancient cave systems are a well-documented feature of the Carboniferous limestone in southwest England and South Wales (Ford, 1984; Fraser, 1985; Whiteside and Robinson, 1983), though precise dating has proved problematic. The infilling sediments in some have yielded Jurassic marine faunas (Duff et al.,1985) or Rhaetian palynomorphs (Marshall and Whiteside, 1980); others can be proven as pre-Rhaetic in that they underlie the Rhaetic transgression surface. Vertebrates have been used for dating these cave sediments, though they share few taxa with normal terrestrial sequences. Two genera, *Kuehneosaurus* and *Tricuspisaurus*, are closely allied to forms from the upper Carnian of North America (Crush, 1984). Thus, the sediment fills of these cave systems vary from late Carnian to Jurassic in age.

Watercourse cave systems have important paleoclimatic implications. Their present abundance in limestone areas reflects high rainfall and meltwater runoff associated with the glacials and interglacials of the past million years. Although cave systems are known from desert regions, they are infrequent, are strongly dependent upon geologic structure, and probably developed during earlier, wetter conditions (Waltham et al., 1985). The geographic distribution of Triassic caves in Britain directly reflects the exposure of potentially cavernous limestones during the Late Triassic. Their areal density is comparable with that of recent cave systems in parts of England and Wales, judging by the frequency with which the latter are exposed during quarrying operations, and is considerably higher than for recent desert regions such as Oman (Waltham et al., 1985). Carey (1984) has noted Carnian paleokarst on earlier Triassic carbonates in northwestern Nevada, and the lead/zinc mineralization of parts of the Alpine Triassic also appears to have been strongly influenced by a period of karstification, probably in the early middle Carnian (Bechstadt and Dohler-Hirner, 1983).

Constraints on cave formation and the age range of sediments in these Triassic caves suggest that they were formed during the pluvial episode in the middle to late Carnian. Infilling may have commenced soon after their formation and continued over an extended period of time. The Rhaetic transgression may have led to the infilling of lower altitude systems, those at higher altitudes remaining open considerably longer, leading to altitude-linked diachroneity of the cave sediments at different sites. Thus, it may not be purely fortuitous that Rhaetian fills occur at a present altitude of about 40 m ordnance datum (Marshall and Whiteside, 1980); fills of undoubted Jurassic age are at about 200 m ordnance datum (Duff et al., 1985).

BIOTIC CHANGES DURING THE CARNIAN-NORIAN INTERVAL

Although the Triassic/Jurassic boundary is regarded as a time of considerable biotic turnover, Benton (1986a) has also identified extinction peaks in the Carnian—an earlier one among marine invertebrates at the base of the mid-Carnian (Julian) and a second, for nonmarine tetrapods, at the Carnian/Norian boundary (Fig. 2).

Ceratitid ammonoids reached a peak of about 150 genera in the Carnian but declined to about 100 genera by the Norian, much of this decline occurring close to the Cordevolian/Julian boundary (Benton, 1986a). A smaller sample of 35 species from the Langobardian-Julian interval shows an extinction rate of only 6 out of 29 species (21%) between the lower and upper Cordevolian, whereas between the upper Cordevolian and Julian, it is 13 out of 25 species (52%) (Urlichs, 1974).

The major extinction peak among bivalve molluscs was at the Triassic/Jurassic boundary (Hallam, 1981), although there is some evidence for increased turnover among the Pectinidae between the Carnian and Norian (A.L.A. Johnson, 1987, personal commun.).

Triassic bryozoa are poorly known, but recent work shows a peak of 22 species in the lower Carnian (Schäfer and Fois, 1987). Only 13 species survived into the late Carnian (their table does not distinguish a middle Carnian), an extinction rate of 41%; only 2 species survived into the Norian, an extinction rate of 85%.

Among conodonts, the stenothermic *Gladigondolella* fauna disappeared at the end of the Cordevolian and was replaced by more eurythermic genera such as *Epigondolella*, *Metapolygnathus*, and *Ancyrogondolella* (Budarov et al., 1985; Kozur, 1976). There was also a marked decrease in the species origination rate from the early Carnian onward (Aldridge, 1988); Norian conodonts have a lower degree of endemism than older Triassic faunas (Sweet et al., 1971).

Carbonate reefs, a major feature of Tethyan Triassic sequences, changed significantly between the early Carnian and the Norian (Flügel and Stanley, 1984). Anisian to early Carnian reefs were very similar to the Permian calcisponge/algal and *Tubiphytes*/algal crust reefs. Scleractinian corals, though often abundant, never achieved reef-building status. In contrast, scleractinans were major framework builders in Norian reefs, though it is unclear how climatic change may have influenced this change.

Crinoids reached a Triassic peak in the early Carnian but subsequently declined. At least two major groups became extinct before the end of the Triassic (Simms, 1989). Noticeably absent from post-Cordevolian faunas were the encrinids, a prominent element of earlier Triassic marine faunas. The Isocrinina also declined greatly in post-Cordevolian Triassic faunas and did not rediversify significantly until the Early Jurassic (Simms, 1988). In contrast, the minute somphocrinids maintained high levels of abundance throughout the Carnian and into the lowermost Lacian (early Norian) before declining rapidly and finally disappearing by the late Norian (Leo Krystyn, 1988, personal commun.).

A faunal turnover of comparable magnitude has also been documented among nonmarine tetrapods (Benton, 1986a, 1986b; Olsen and

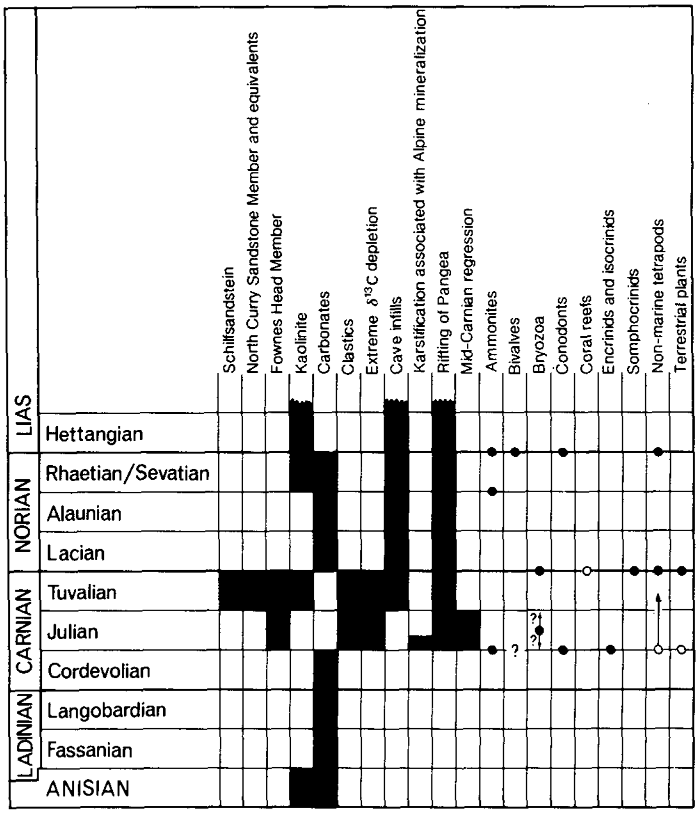

Figure 2. Timing of events in Late Triassic. Solid circles represent periods of high extinction rates; open circles indicate times of significant origination rates. Precise dating between lower and upper Carnian of earlier bryozoa turnover is unspecified in literature. Among nonmarine tetrapods there was extended period of diversification from early middle Carnian into late Carnian.

Sues, 1986; Tucker and Benton, 1982). The timing of this event was at the Carnian/Norian boundary, with no significant turnover at the Cordevolian/Julian boundary, though several different groups diversified during the Julian and Tuvalian. Particularly striking was the decline of labyrinthodont amphibians at the end of the Carnian and the rapid diversification of dinosaurs during the Norian. The proportional composition of nonmarine tetrapod faunas in the German Keuper (late Ladinian to late Norian) shows a similar pattern (Benton, 1986b). Labyrinthodonts dominate the lower and middle Keuper, constituting 97% of the total in the Schilfsandstein (late Carnian), but declined rapidly thereafter. They are absent from the upper Stubensandstein (middle Norian), which is dominated by the prosauropod dinosaur *Plateosaurus*, constituting 77% of the total. The overwhelming dominance of labyrinthodont amphibians in the Schilfsandstein indicates deposition during an unusually wet period of the Triassic. Their subsequent decline reflects a return to arid conditions in the Norian, whereas the uricotelic dinosaurs were able to diversify in the Late Triassic despite the increasing aridity.

Changes in Upper Triassic floras closely parallel those of the fauna. Boulter et al. (1988) recognized two periods of major floral turnover in the Late Triassic record; one around the middle Carnian, at which originations significantly exceed extinctions, and a larger one around the Carnian/Norian boundary. where extinctions predominate (Olsen and Sues, 1986). Van der Eem (1983) and Visscher and Van der Zwan (1981) recognized hygrophytic palynomorphs in the Schilfsandstein and the marine Lunzer Schichten but attributed this to the influence of extensive river systems rather than increased climatic humidity.

There have been no suggestions as to the cause of the Carnian extinction peaks or the reason for the nonsynchroneity between terrestrial and marine faunas. Raup and Sepkoski (1986) attributed the Carnian peak in their data to sampling error; hence, an extraterrestrial cause is not implicated. The coincidence between the onset and cessation of the Carnian pluvial episode and the timing of major faunal and floral turnover suggests a direct link. Shallow-marine invertebrates were affected more at the beginning of the middle Carnian, perhaps through a change in surface ocean temperature, a change in salinity or pH, or the loss of shallow-water carbonate habitats. The terrestrial flora and vertebrate faunas were relatively unaffected at this lower boundary; many groups actually showed a considerable increase in diversity through the middle and late Carnian before experiencing a major turnover at the Carnian/Norian boundary. Clearly, the more humid climate during this interval benefited many terrestrial groups, though only some could thrive when arid conditions returned in the Norian.

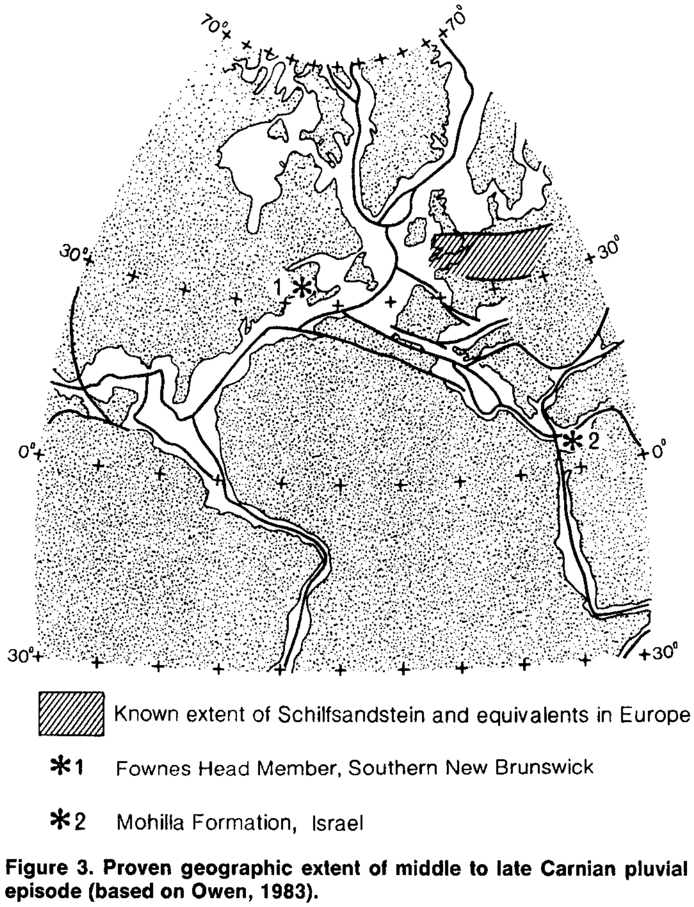

Figure 3. Proven geographic extent of middle to late Carnian pluvial episode (based on Owen, 1983).

GEOGRAPHIC EXTENT AND CAUSES OF THE CARNIAN PLUVIAL EPISODE

Terrestrial sequences show that the geographic extent of this Carnian climatic change extended through at least 50° of longitude. Inclusion of the isotopic evidence from Israel gives a latitude range from about 5° to almost 40° north of the Triassic equator (Fig. 3), comparing favorably with the position of the subtropical arid belt at other times in the Triassic (Tucker and Benton, 1982). Further work may resolve whether this climatic change was on a global or regional scale.

Although a general model can be presented linking the widespread Late Triassic aridity with the configuration of land and ocean, the ultimate factors responsible for shorter term climatic perturbations are more difficult to identify. Recognition that the rifting of Pangea, prior to opening of the North Atlantic, was initiated in the middle Carnian (Cousminer and Manspeizer, 1976; Nadon and Middleton, 1984) raises the distinct possibility that the Carnian pluvial episode was in some way precipitated by the rifting.

Basaltic volcanism associated with this rifting was widespread during the Late Triassic (Dewey et al., 1973) and may account for the climatic and faunal changes seen during the Carnian/Norian, as suggested for the Cretaceous/Tertiary boundary by Officer et al. (1987). Armstrong and Besançon (1970) obtained dates, ranging from 220 to 244 Ma, for dolerite dikes along the eastern coast of North America; there is a concentration at about 225 to 230 Ma, the Carnian of Palmer's (1983) time scale. Their dates for the Newark Group flood basalts are younger, around 200 Ma, but they consider these suspect, suggesting an age of about 225 Ma as more probable.

Alternatively, changes in topography, or the configuration of land and sea, or the effects of the mid-Carnian regression and ensuing transgression may have altered oceanic and atmospheric circulation patterns to bring moisture-laden air over large areas of the previously arid eastern side of Pangea.

A global temperature change, an increase in rainfall, and perhaps a change in the salinity or pH of the surface ocean might account for the changes in the shallow-marine fauna but would have less effect on terrestrial vertebrates. Instead, these would be more susceptible to the change from humid back to arid conditions. Hence, the nonsynchroneity of the marine and terrestrial faunal turnovers may reflect different environmental factors associated with the start and finish of the Carnian pluvial episode.

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