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TRIASSIC MICRO-CHARCOAL AS A PROMISING PUZZLE PIECE IN PALAEOCLIMATE RECONSTRUCTION: AN EXAMPLE FROM THE GERMANIC BASIN

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Abstract: Fossil charcoal is the primary source of evidence for palaeo-wildfires and has gained increasing interest as a proxy in the reconstruction of past climates and environments. Today, increasing temperatures and decreasing precipitation/humidity appear to correlate with increases in the frequency and intensity of wildfires in many regions worldwide. Apart from appropriate climatic conditions, sufficient atmospheric oxygen (>15%) is a necessary precondition to sustain combustion in wildfires. The Triassic has long been regarded as a period without evidence of wildfires; however, recent studies on macro-charcoal have provided data indicating their occurrence throughout almost the entire Triassic. Still, the macro-palaeobotanical record is scarce and the study of micro-charcoal from palynological residue is seen as very promising to fill the gap in our current knowledge on Triassic wildfires. Here, the authors present the first, verified records of micro-charcoal from the Triassic of the Germanic Basin, complementing the scarce macro-charcoal evidence of wildfires during Buntsandstein, Muschelkalk and Keuper (Anisian–Rhaetian). The particles analysed by means of scanning electron microscopy (SEM) show anatomical features typical of gymnosperms, a major element of the early Mesozoic vegetation following the initial recovery phase after the PT-boundary event. From the continuously increasing dataset of Triassic charcoal, it becomes apparent that the identification of wildfires has a huge potential to play a crucial role in future studies, deciphering Triassic climate dynamics. The first SEM study of micro-charcoal from palynological residue spanning the entire Triassic period, presented here, is a key technique to further unravel the charcoal record as a puzzle piece in palaeoclimate reconstruction.

Key words: Wildfire, palaeoclimate, Triassic, Peri-Tethys, Germany.

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INTRODUCTION

Wildfires are an integral part of modern, terrestrial ecosystems and at the same time, increasing temperatures and changing precipitation patterns, related to ongoing global change, strongly affect global fire regimes (e.g., Jolly *et al.*, 2015; Veraverbeke *et al.*, 2017; Turco *et al.*, 2018; Halofsky *et al.*, 2020). Increases in the frequency, extent, and severity of wildfires appear to correlate with a warming climate, highlighting the fire-climate relationship. From this background, the study of fossil charcoal, the primary source of evidence for wildfires in the geological record, is seen as a powerful tool in the reconstruction of past climates (e.g., Whitlock and Larsen, 2001; Hu *et al.*, 2006; Vannière *et al.*, 2008; Cardoso *et al.*, 2018; Xu *et al.*, 2020; Lu *et al.*, 2021). Although the oldest records known so far date from the mid- to late Silurian (Glasspool *et al.*, 2004; Glasspool and Gastaldo, 2022), it is not until the Late Devonian when extensive charcoal deposits document globally widespread wildfires (Lu *et al*., 2021). At that time, certainly sufficient fuel was available in the form of the first lignophytic forests (e.g., Decombeix *et al*., 2005; Gerrienne *et al*., 2010) and the atmospheric oxygen reached a level to sustain combustion in wildfires (Scott and Glasspool, 2006; Scott, 2010). The Permian and Triassic have long been regarded as periods without considerable evidence of wildfires (cf. Scott, 2000); however, over the past two decades the increasing number of reports of Permian and Triassic charcoal (e.g., Uhl and

Kerp, 2003; Uhl *et al*., 2004, 2007, 2012; Abu Hamad *et al*., 2012; Mahesh *et al*., 2015; Yan *et al*., 2016; Arzadún *et al*., 2017; Shivanna *et al*., 2017; Pole *et al*., 2018; Kubik *et al*., 2020; Murthy *et al*., 2020; Jasper *et al*., 2021; Wan *et al*., 2021; Murthy *et al*., 2022) has changed this view of a late Palaeozoic-early Mesozoic fire gap. Likewise, as more robust datasets have been published integrating geochemical, palaeontological, and sedimentological proxies, our understanding of the climate of the Triassic period changed from a stable hot-house world (e.g., Frakes, 1979) to a dynamic system, punctuated by numerous oscillations to and from humid conditions (e.g., Trotter *et al*., 2015; Sun *et al*., 2020; Forte *et al*., 2022). In contrast, the patchy published record of charcoal still hampers the use of this terrestrial proxy to further refine the Triassic climate history. In this regard, the study of micro-charcoal from palynological residue is seen as very promising to complement the still scarce macro-palaeobotanical record of Triassic wildfires. Although a number of palynological studies have reported the occurrence of putative Triassic micro-charcoal (cf. Abu Hamad *et al*., 2012), none of these studies has verified the charcoal nature of such material based on techniques such as SEM analyses of homogenized cell walls, which are widely accepted as standard in the analysis of macro-charcoal (e.g., Scott, 2000, 2010; Jasper *et al*., 2021). In fact, such an approach has only very rarely been used for the analysis of micro-charcoal from palynological samples (e.g., Martill *et al*., 2012; Pole *et al*., 2018), whereas most studies tried to identify micro-charcoal by means of transmitted light microscopy (e.g., Mangerud and Rømuld, 1991).

This paper presents the first SEM study on micro-charcoal from the Germanic Basin to fill the gap in our current knowledge on the fossil record of Triassic wildfires, both on a regional and global scale. The Germanic Basin is proposed as an excellent field lab for the study of the taphonomic processes of micro-charcoal in a well-established sedimentological and stratigraphical context (Fig. 1; Bachmann *et al*., 2021; Franz and Barnasch, 2021; Franz *et al*., 2021; Paul, 2021a). Moreover, this study aims to highlight the potential of pre-Quaternary micro-charcoal as a palaeoclimate proxy and to motivate further integrated palynological-palaeobotanical studies of charcoal in research on early Mesozoic palaeoclimates.

GEOLOGICAL SETTING

During Triassic times, the western Tethys Ocean was bordered northwards by the peripheral Germanic Basin, the so-called northern Peri-Tethys (Szulc, 2000; Feist-Burkhardt *et al*., 2008). This type region of the Triassic reflects the tripartition of the system, including the Lower Triassic continental, fluvial-aeolian deposits of the Buntsandstein, the Middle Triassic shallow-marine carbonates and evaporites of the Muschelkalk, and the fluvial, playa and deltaic to shallow-marine deposits of the Upper Triassic Keuper (Fig. 1). The well-established bio- and lithostratigraphic framework enables the genetic interpretation of depositional sequences across the basin (Aigner and Bachmann, 1992; Geluk and Röhling, 1997; Szulc, 2000; Pöppelreiter and Aigner, 2008; Götz and Lenhardt, 2011; Franz *et al*., 2014, 2015) that is the basis for regional and global correlation.

A generally arid to semi-arid climate predominated during the entire Triassic, though fluctuations in response to warming, induced by volcanic events, as well as recurrent marine flooding, have been recognized (Sellwood and Valdes, 2007; Preto *et al*., 2010; Trotter *et al*., 2015; Paul, 2021b). Isotopic data indicate extremely hot conditions in the Early Triassic, dropping slightly in the remainder of the Triassic (e.g., Scotese *et al*., 2021). However, the timing of climate trends is still in flux and continuously improving with new geochronological data becoming available, as reflected in the recently updated Triassic timescale (Ogg and Chen, 2020) and the most recent version, 2022/02, of the International Chronostratigraphic Chart (Cohen *et al*., 2013; updated 2022).

MATERIALS AND METHODS

The palynofacies of Triassic deposits of the Germanic Basin is characterized by high amounts of opaque phytoclasts (e.g., Hauschke and Heunisch, 1990; Fijałkowska, 1994; Götz, 1996; Götz *et al*., 2001), which represent oxidized plant debris and in parts micro-charcoal (Fig. 2; particles smaller than 180 μm, as defined by Scott, 2010). However, so far none of the palynofacies studies carried out in the Germanic Triassic has addressed the identification of phytoclasts as charred particles, providing evidence of wildfire activity. Therefore, palynological residue of 62 samples from outcrops and wells, previously studied in detail with regard to stratigraphy (including palynology) and depositional environment (Tab. 1), and yielding phytoclasts of various sizes and shapes, was reanalysed by means of scanning electron microscopy to identify pyrogenic particles. These samples, housed at the Geozentrum Hannover, were processed using standard palynological preparation techniques (Wood *et al*., 1996; Traverse, 2007). For each sample, palynological residue was mounted on a glass disc, which was then fixed on a standard stub with an adhesive tab. After drying, the residue was platinum/palladium-coated for analysis under a FEI Sirion 200 scanning electron microscope at the Geozentrum Hannover. The identification of micro-charcoal is based on the presence of homogenized cell walls of phytoclasts, which are anatomically interpretable as originating from (woody) plant tissues (e.g., Jones and Chaloner, 1991; Scott, 2000, 2010). Anatomical details can be seen on a "sub-cellular" level, e.g., on tracheid fragments exhibiting pits. Already early studies in the 1970s and 1980s point to the need for SEM analysis to identify charcoal (Komarek *et al*., 1973; Patterson *et al*., 1987) and since then numerous SEM studies on fossil and modern charcoal have demonstrated that homogenized cell walls are a reliable feature to identify fossil charcoal fragments (e.g., Scott and Jones, 1991; Heinz and Barbaza, 1998; Rowe and Jones, 2000; Thevenon and Anselmetti, 2007; Tanner *et al*., 2012; El Atfy *et al*., 2019; Huang *et al*., 2021; Cai *et al*., 2021; Li *et al*., 2022).

RESULTS

The palynological residue of 62 samples, reanalysed for the present study, reveals equidimensional and lath-shaped

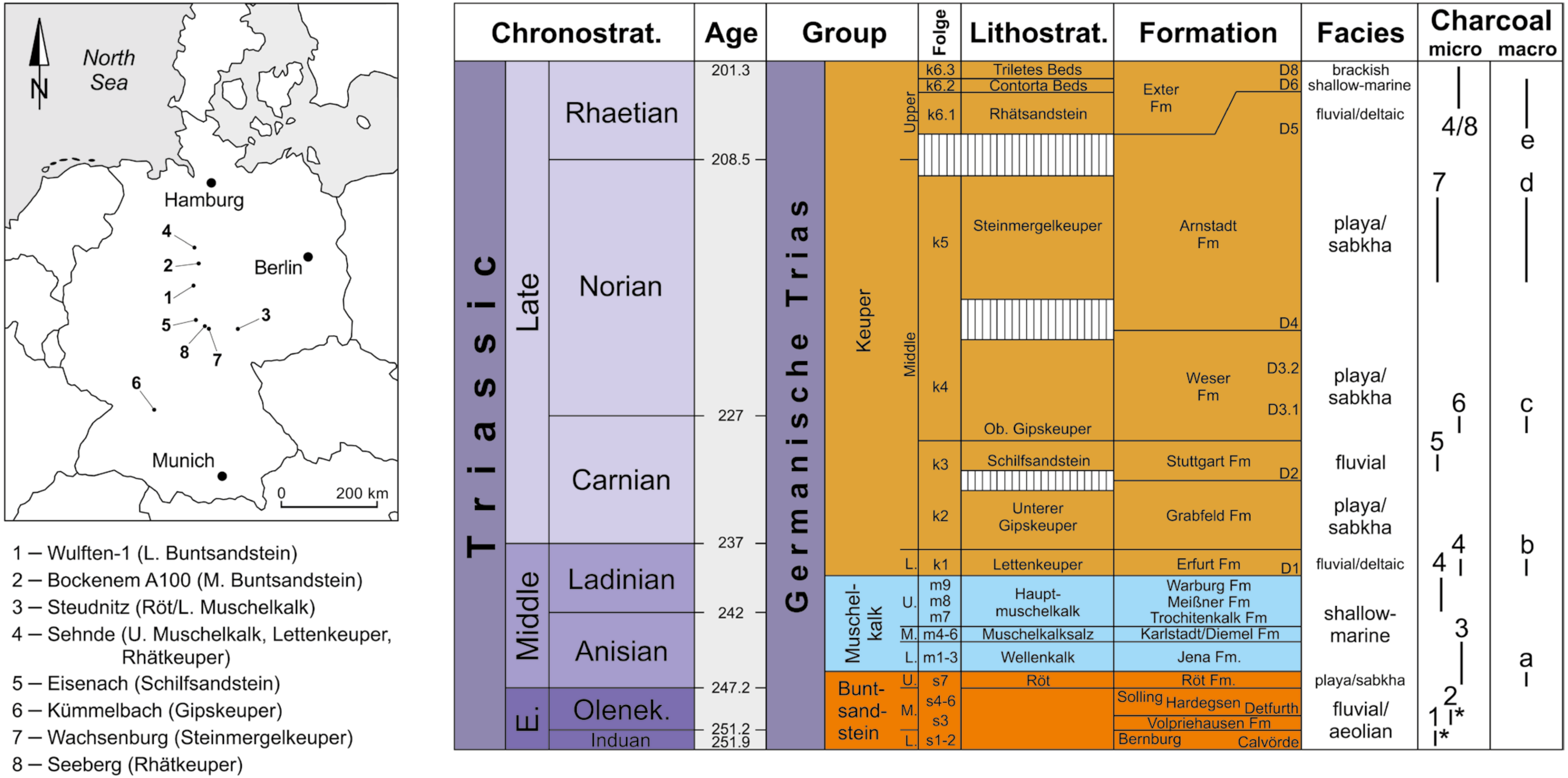

Fig. 1. Locality map (left) and stratigraphic framework of charcoal discoveries in the Germanic Basin (right). Chronostratigraphy after Cohen *et al.* (2013, updated 2022), lithostratigraphy and facies from German Stratigraphic Commission (2016). Charcoal discoveries (right column): micro-charcoal occurrence (this study) with numbers of the sample localities provided on the locality map (stars indicate discoveries of solely oxidised phytoclasts; see results); macro-charcoal discoveries (literature review): a – Uhl *et al.* (2010); b – Kelber (2021); c – Kelber (2007); d – Havlik *et al.* (2013), Kubik *et al.* (2015); e – Kelber (2007, 2021), Uhl and Montenari (2011). Abbreviations used: E. – Early; L. – Lower; M. – Middle; U. – Upper; Fm. – Formation; D1-D8 – Late Triassic unconformities.

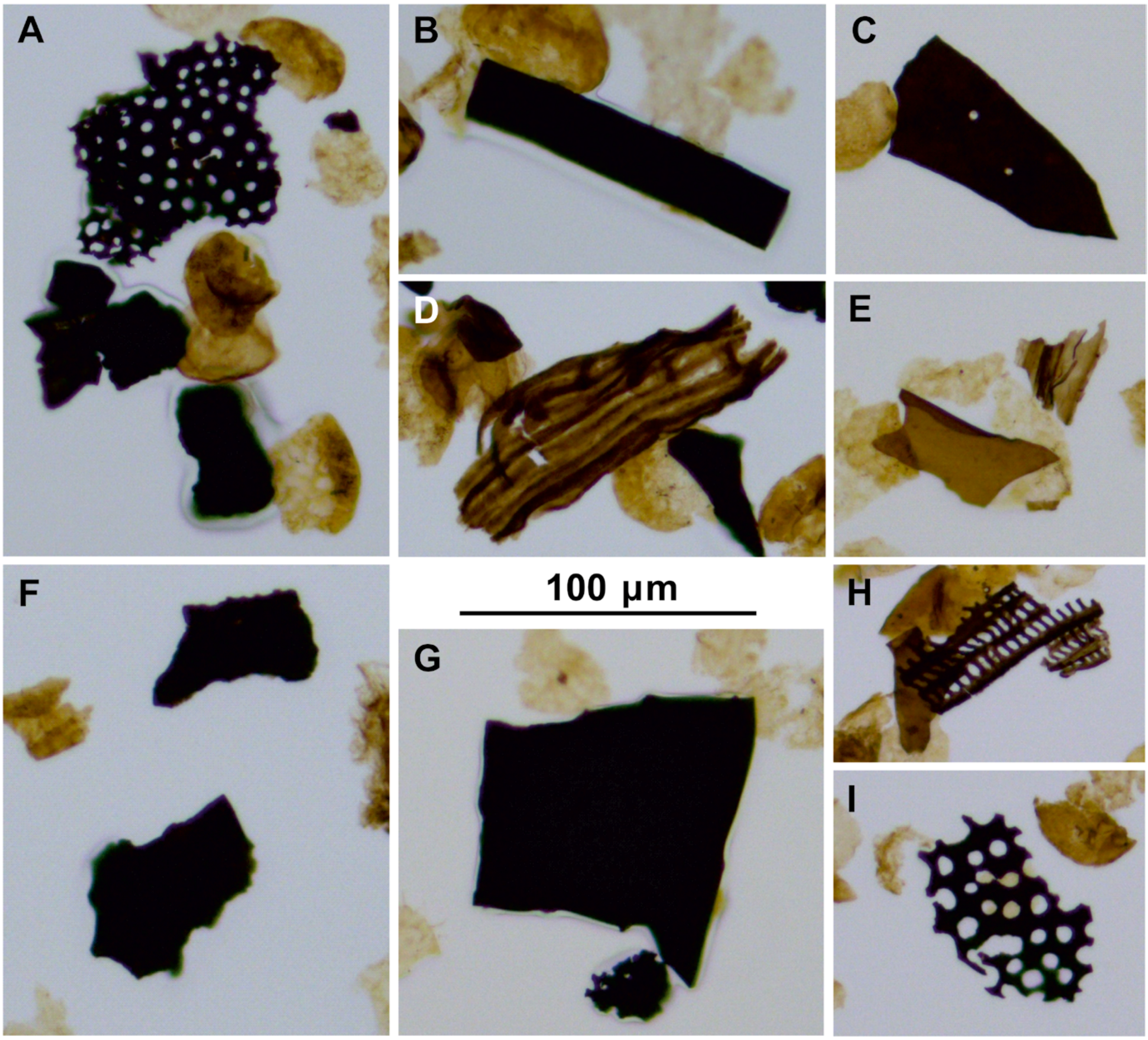

Fig. 2. Palynofacies of the Germanic Basin, characterized by phytoclasts of different sizes, shapes, and preservation (Muschelkalk, Steudnitz). **A.** Opaque tracheid fragment (top) and equidimensional, angular-subrounded phytoclasts (below). **B.** Opaque, lath-shaped phytoclast (? charcoal). **C.** opaque phytoclast with bordered pits (? charcoal). **D.** Translucent wood remain. **E.** Translucent plant tissue. **F.** Opaque, subangular phytoclasts. **G.** Opaque, angular phytoclast (? charcoal). **H.** Translucent tracheid fragment. **I.** Opaque tracheid fragment.

(elongate), charred particles in the range of 30–120 µm length, exhibiting homogenized cell walls and well-preserved anatomical details, such as bordered pits (Fig. 3). The particles mainly represent fragments of tracheids displaying anatomical features typical of gymnosperms, a major element of the early Mesozoic vegetation, following the initial recovery phase of the PT-boundary event (e.g., Grauvogel-Stamm and Ash, 2005). However, the taxonomic affinity remains unknown owing to the small size of phytoclasts.

The micro-charcoal studied occurs in terrestrial and shallow-marine deposits (Fig. 1), stratigraphically covering the early Anisian claystones of the Röt Formation (4 samples), the Anisian mud- and wackestones of the Lower Muschelkalk (7 samples), the late Anisian–early Ladinian mudstones of the Upper Muschelkalk (6 samples), the Ladinian clay- and siltstones of the Lettenkeuper (5 samples), the Carnian siltstones of the Schilfsandstein (6 samples) and Gipskeuper (7 samples), the Norian claystones of the Steinmergelkeuper (6 samples), and the Rhaetian clay- and siltstones of the Rhätkeuper (15 samples). All opaque phytoclasts of the Lower and Middle Buntsandstein siltstones (6 samples), analysed so far by means of SEM, lack diagnostic features of charcoal and are thus classified as oxidised particles.

Fluvial deposits (Buntsandstein, Lettenkeuper, Schilfsandstein) show abundant equidimensional particles, whereas shallow-marine and sabkha deposits (Röt, Muschelkalk, Gipskeuper, Steinmergelkeuper) reveal a wider spectrum of sizes and shapes (elongate to equidimensional).

Table 1

Selected samples for SEM analysis from outcrop
and well sections located in the central part of the Germanic Basin, Germany.

Stratigraphy	Locality	No. of samples	Reference
Lower Buntsandstein (Induan)	Wulften-1 (Lower Saxony)	3	Backhaus *et al*. (2013)
Middle Buntsandstein (Olenekian)	Bockenem A100 (Lower Saxony)	3	Backhaus *et al*. (2013)
Röt (early Anisian)	Steudnitz (Thuringia)	4	Rameil *et al*. (2000)
Lower Muschelkalk (Anisian)	Steudnitz (Thuringia)	7	Rameil *et al*. (2000)
Upper Muschelkalk (Ladinian)	Sehnde (Lower Saxony)	6	Beutler *et al*. (1996)
Lettenkeuper (Ladinian)	Sehnde (Lower Saxony)	5	Beutler *et al*. (1996)
Schilfsandstein (Carnian)	Eisenach (Thuringia)	6	Franz *et al*. (2014)
Gipskeuper (Carnian)	Kümmelbach (Baden-Wurttemberg)	7	Heunisch and Nitsch (2011)
Steinmergelkeuper (Norian)	Wachsenburg (Thuringia)	6	Schulz (1996)
Rhätkeuper (Rhaetian)	Sehnde (Lower Saxony), Seeberg (Thuringia)	7 8	Beutler *et al*. (1996) Schulz (1962, 1967)

DISCUSSION

Refining the Triassic charcoal record

After two decades of collection of charcoal data, the previously assumed "Triassic tranquillity" with regard to wildfires (Scott, 2000) is no longer valid. To date, the record of Triassic charcoal is based on macro-charcoal findings from Central Europe (Kelber, 1999, 2007; Uhl *et al*., 2008, 2010; Uhl and Montenari, 2011; Havlik *et al*., 2013; Kubik *et al*., 2015; Philippe *et al*., 2015), the Southern Alps (Uhl *et al*., 2014), the Middle East (Abu Hamad *et al*., 2013, 2014), Russia, China, Greenland, USA, Argentina, Brazil, Australia and Antarctica (review in Abu Hamad *et al*., 2012; Kumar *et al*., 2013; Cardoso *et al*., 2018), indicating stratigraphic occurrence throughout almost the entire Triassic (Jasper *et al*., 2021). The so far oldest known, verified Triassic record was only recently reported from the uppermost Lower Triassic of China (Wan *et al*., 2021). Regionally, the scarce charcoal record of the Early Triassic, with findings mainly from localities at higher latitudes, might be explained by the central Pangaean "dead zone" (Sun *et al*., 2012), lacking sufficient vegetation as fuels. However, a marked increase in drought-tolerant plant taxa took place in central Pangaea during the early Permian (Marchetti *et al*., 2022), documenting the potential of certain plant groups for adaptation to increased temperature and aridity.

Macro-charcoal discoveries in the Germanic Basin are so far known from southern Germany and Poland (Kelber, 1999, 2007; Uhl *et al*., 2008, 2010; Uhl and Montenari, 2011; Havlik *et al*., 2013; Kubik *et al*., 2015; Philippe *et al*., 2015). Stratigraphically, these findings include the Anisian Voltzia Sandstone, the Ladinian Lettenkeuper, the Carnian Coburg Sandstone, the Norian Patoka Member and the Rhaetian Rhät-Sandstein.

The micro-charcoal discoveries presented in this study complement the macro-charcoal record of the Germanic Basin, highlighting certain times of extensive wildfire activity. In addition, the new data in the present study even provide a more nearly complete record (Fig. 1), especially in depositional settings, where macro-charcoal has not been reported so far, e.g., in shallow-marine Muschelkalk (Anisian–early Ladinian) deposits. On the other hand, the Germanic Basin is stratigraphically limited by the presence of Carnian/Norian unconformities. Thus, a global dataset is required to fill this missing stratigraphic record.

The single mention of late Olenekian–Anisian micro-charcoal in palynological slides from samples of the Barents Sea (Mangerud and Rømuld, 1991), studied by means of transmitted light microscopy, is questionable as the present authors showed that SEM analysis is imperative for distinguishing between oxidised phytoclasts and pyrogenic particles. So far, the data of the authors from the Germanic Basin reveal the oldest micro-charcoal within the early Anisian (Röt), confirming the previously recognized Early Triassic charcoal gap (cf. Abu Hamad *et al*., 2012). The question remains, whether the Early Triassic charcoal gap reflects an Early Triassic wildfire gap or has to be seen as an artefact due to various taphonomic biases, as discussed in Abu Hamad *et al*. (2012).

Deciphering regional *vs.* local signals

Iversen (1941) was the first to realize that micro-charcoal in palynological slides could be used as a fire proxy. However, this method holds limitations with regard to size and source, as larger charcoal particles can break during transport, creating a high abundance of small particles (smaller than 100 μm). Quantification of micro-charcoal is also extremely difficult, especially in deposits, which also contain macro-charcoal. Owing to the compaction of sediments, larger specimens of macro-charcoal are often shattered *in situ* to smaller pieces (e.g., Uhl *et al*., 2010: see fig. 5 therein; Kubik *et al*., 2015: see fig. 7 therein). Although macro-charcoal can be transported by water over large distances (e.g., Scott *et al*., 2014), it is usually interpreted as a signal for local fires. In contrast, micro-charcoal documents

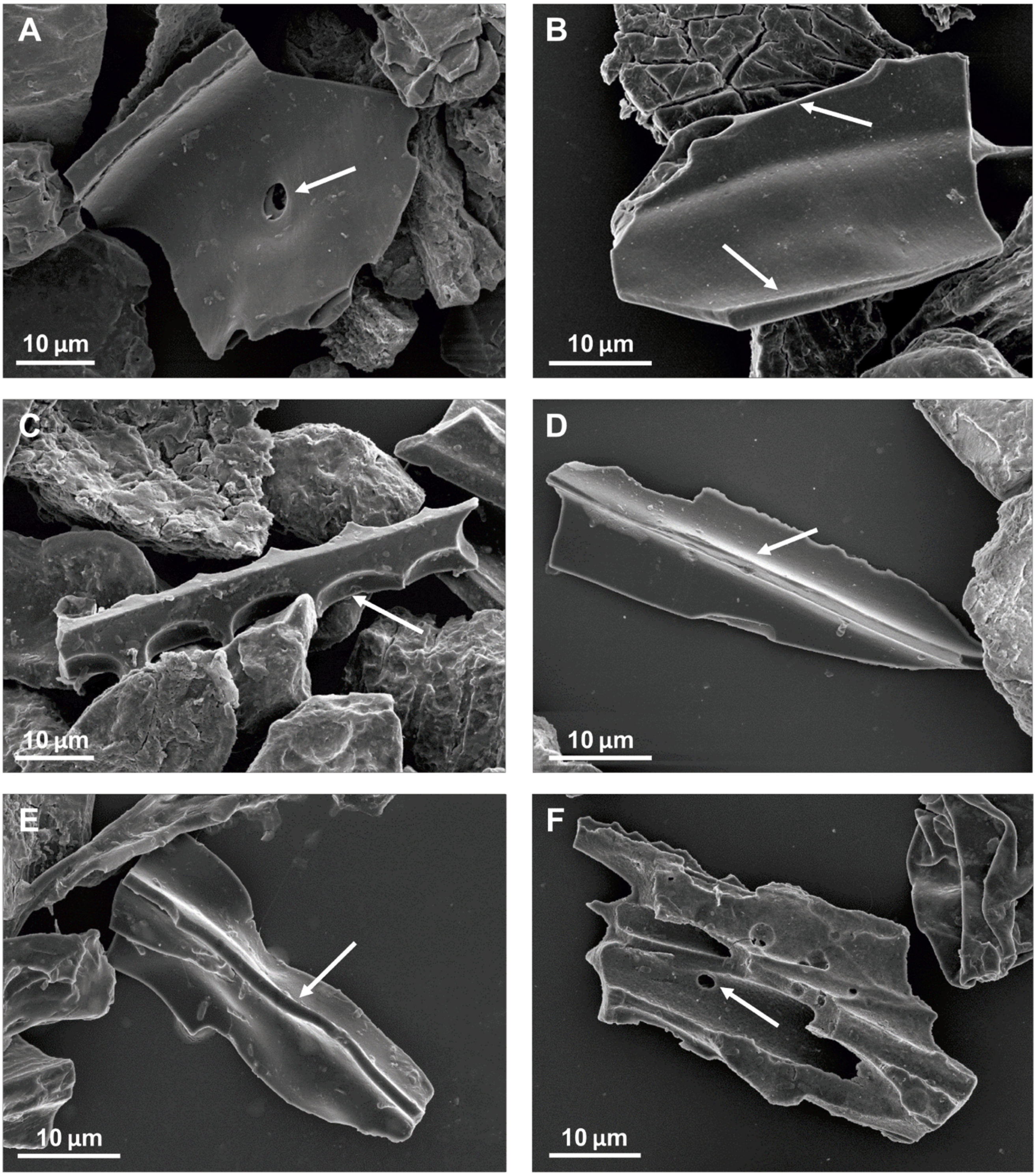

Fig. 3. Examples of micro-charcoal of the Germanic Basin. **A.** Tracheid fragment with a bordered pit (Röt, Steudnitz). **B.** Tracheid fragment with homogenized cell walls (Muschelkalk, Steudnitz). **C.** Tracheid fragment with homogenized cell walls (Lettenkeuper, Sehnde). **D.** Tracheid fragment with homogenized cell walls (Schilfsandstein, Eisenach). **E.** Tracheid fragment with homogenized cell walls (Steinmergelkeuper, Wachsenburg). **F.** Tracheid fragment with bordered pits (Rhätkeuper, Seeberg).

ongoing distribution during widespread fires and is thus considered as a regional signal. The knowledge of the exact source area remains generally vague, owing to possible transport (see discussion in Whitlock and Larsen, 2001).

For the Triassic period, the above-mentioned limitations with regard to distinguishing between regional and local signals can be overcome by an integrated palynological-palaeobotanical-sedimentological study within a distinct sedimentary basin. Here, the Germanic Basin, representing an intra-cratonic basin, is well suited to analysis of the transport and taphonomic processes of charred particles. Different fluvial styles (meandering, straight, braided, anastomosing), well documented in the Early Triassic Buntsandstein and Late Triassic Keuper deposits (Feist-Burkhardt *et al.*, 2008; Paul, 2021a; Franz and Barnasch, 2021), enable the study of the effect of different hydrodynamic regimes on fragmentation of charred particles during transport. Different bed load is another aspect to consider, when interpreting size and shape of these particles. Moreover, sorting and fragmentation of organic particles within a shallow-marine setting is well documented in Middle Triassic Muschelkalk carbonates (Rameil *et al.*, 2000) and needs to be assessed with regard to potential source areas. Furthermore, taphonomic biases, as previously discussed in detail by Abu Hamad *et al.* (2012), have to be considered, especially the low preservation potential of charcoal in typical red beds, which predominate in the Early Triassic Buntsandstein of the Germanic Basin.

Implications for palaeoclimate reconstruction

An important factor, influencing the occurrence of palaeo-wildfires, is atmospheric oxygen concentration (e.g., Scott, 2000). Some studies related the absence of wildfires during the Early Triassic to extremely low oxygen concentrations and the subsequent increase of evidence for wildfires during the Middle and Late Triassic with increasing oxygen concentrations (e.g., Tanner *et al.*, 2006). However, different geochemical models differ considerably regarding the development of atmospheric oxygen during the Triassic (e.g., Berner and Canfield, 1989; Bergman *et al.*, 2004; Berner, 2005, 2006, 2009; Glasspool and Scott, 2010). Notably, more recent models reconstructed oxygen levels above 15% O_2 for the Early Triassic, which is in accordance with palaeontological evidence other than charcoal, such as the occurrence of large-bodied amphibians (e.g., Schroeder, 1913; Schoch, 1999; Damiani, 2001), which definitely require relatively high oxygen levels to breathe through both their lungs and through their skin (see discussion in Abu Hamad *et al.*, 2012). At such a concentration (>15%), oxygen would not necessarily be the limiting factor for the ignition and spread of wildfires (e.g., Belcher and McElwain, 2008; Abu Hamad *et al.*, 2012).

Another factor, which may influence the amount of charcoal that is initially produced and, after transport, preserved in sedimentary deposits, is the source vegetation. Besides the amount of biomass produced in different ecosystems (e.g., Early Triassic *Pleuromeia* and fern-dominated vegetation *versus* Middle/Late Triassic conifer-dominated vegetation) that can be consumed by fires as fuel, also the morphology and anatomy of different plant taxa of the source vegetation greatly influence wildfires and the amount of charcoal that can be produced during a fire (e.g., Abu Hamad *et al.*, 2012; Scott *et al.*, 2014; Belcher, 2016; Crawford *et al.*, 2018; Hudspith *et al.*, 2018). However, this problem can probably be overcome by combining charcoal analysis with traditional palynological and macro-palaeobotanical data. In the case of the Germanic Basin, palynofloras were dominated by bisaccate pollen-producing conifers (cf. Grauvogel-Stamm and Kustatscher, 2021; Heunisch and Wierer, 2021; Kelber, 2021).

Ultimately, for Triassic climate reconstruction, micro-charcoal can be added as a vital terrestrial proxy for wildfires (Fig. 4). From the continuously increasing dataset of Triassic charcoal, it becomes apparent that the identification of wildfires will play a crucial role in future studies, deciphering Triassic climate dynamics, as it seems at first sight that the occurrence of wildfires correlates with warming phases. This observation is supported by the conclusions drawn from a recent review of the published records of combustion products and inferred wildfire activity across major episodes of greenhouse-gas-induced global warming (Baker, 2022), demonstrating the striking link between periods of increased wildfire activity and phases of major climatic change in Earth's past. For the Triassic, multiple warming phases were first highlighted by Trotter *et al.* (2015). At the same time, Whiteside *et al.* (2015) argued that variations in $\delta^{13}C_{org}$, pointing to rapidly fluctuating extreme climatic conditions during the Late Triassic, seem to correlate with elevated and increasing pCO_2 and pervasive wildfires. The link of wildfire occurrence to warming phases and palaeoenvironmental perturbation as well as the potential role of fire-climate-vegetation interactions and feedbacks as discussed by Baker (2022) is the next research goal to detect a possible Triassic fire-climate relationship. As recent models indicate that climate change affects fire activity differently in different biomes (Harris *et al.*, 2016) and ecosystems with positive fire-vegetation feedbacks are vulnerable to climate-change-driven increases in fire activity (Tepley *et al.*, 2018), the understanding of vegetational patterns of the past becomes even more vital in palaeoclimate research. Here, palynology and palaeobotany are key disciplines. Additionally, the Germanic Basin is well suited to study the potential role of additional nutrients from wildfires on marine phytoplankton production during the Middle Triassic, as recently documented from modern fire-prone coastal regions (Liu *et al.*, 2022). Finally, our understanding of deep time data will benefit from studies of the Quaternary (cf. Seddon *et al.*, 2014), especially the Holocene, as processes and ecological patterns in a warming world should be comparable to those of the Triassic period.

CONCLUSIONS

Various Triassic deposits of the Germanic Basin yield micro-charcoal in terrestrial and shallow-marine environments. Their stratigraphic distribution provides additional information on wildfire occurrence and complements the scarce macro-palaeobotanical record. The nature of opaque phytoclasts – whether oxidised particles or micro-charcoal – as prominent organic components in palynological slides, needs to be verified by scanning electron microscopy. The unambiguous identification of pyrogenic particles is best based on the presence of homogenized cell walls, one of the diagnostic features of charcoal. Comparison with the global record indicates that charcoal occurrence corresponds to warming phases and thus is vital in Triassic climate reconstruction. Ultimately, quantitative studies are needed to capture frequency and intensity of wildfires and to detect whether these events correlate with warming phases or periods of environmental instability.

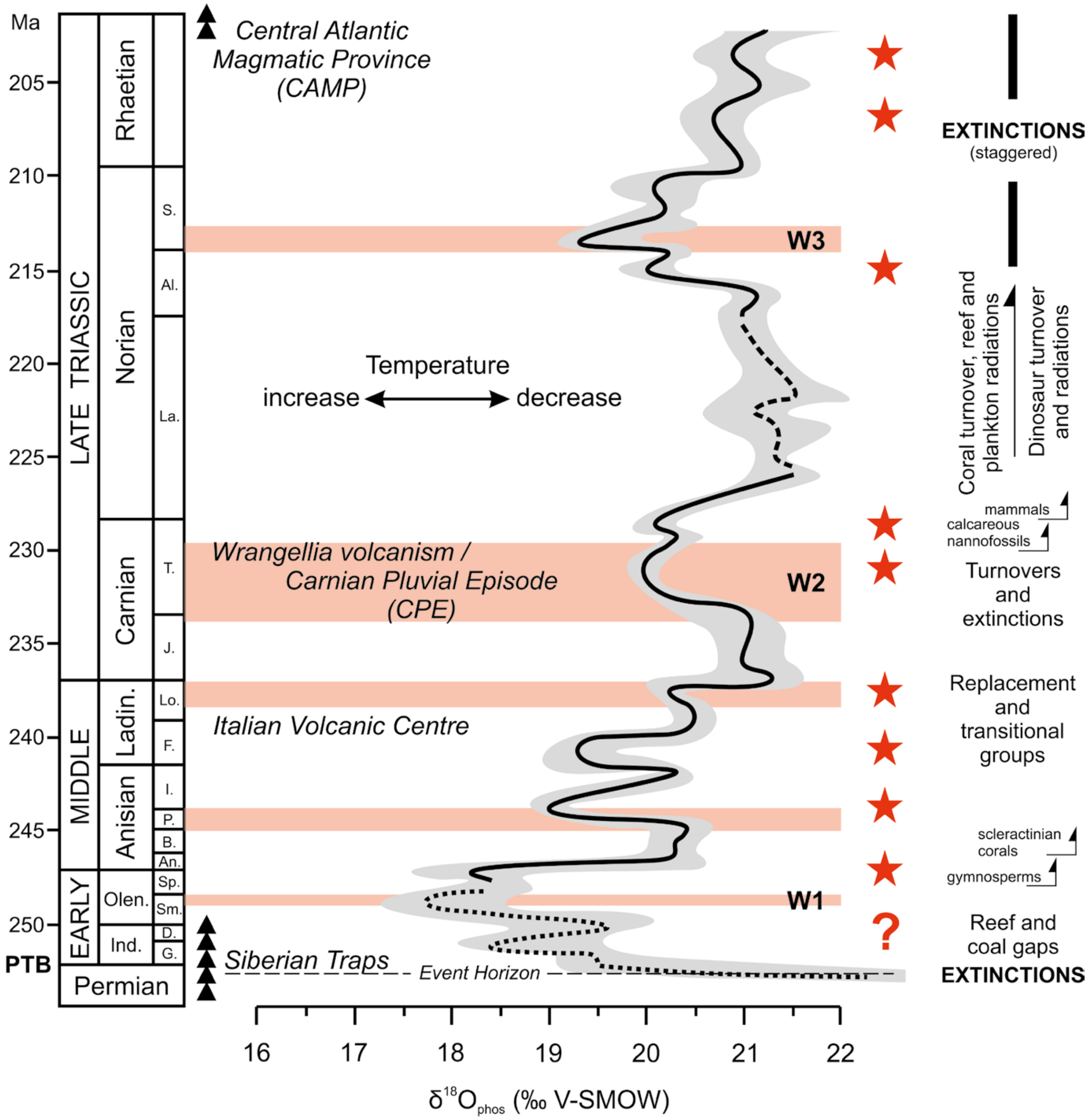

Fig. 4. First-order warming cycles (W1-3) based on Tethyan surface open-marine temperatures inferred from the conodont $\delta^{18}O_{phos}$ record of stratigraphic sections of the central and western Tethyan realm (modified from Trotter *et al*., 2015). Major biotic events of the Triassic period (right column; compiled by Trotter *et al*., 2015) and occurrence of micro- and macro-charcoal in the Germanic Basin (this study and literature review, highlighted by red stars) as source of evidence for wildfires. The question mark indicates the recognized Early Triassic wildfire gap. Abbreviations used: PTB – Permian-Triassic boundary, Ind. – Induan, Olen. – Olenekian, G. – Griesbachian, D. – Dienerian, Sm. – Smithian, Sp. – Spathian, An. – Aegean, B. – Bithynian, P. – Pelsonian, I. – Illyrian, F. – Fassanian, Lo. – Longobardian, J. – Julian, T. – Tuvalian, La. – Lacian, Al. – Alaunian, S. – Sevatian.

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