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Palynological record across the Norian-Rhaetian boundary at Pignola-Abriola (Southern Apennines, Italy): implications for marine-continental correlation

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KEY WORDS - Rhaetian, palynostratigraphy, sporomorphs, Newark Supergroup, GSSP.

ABSTRACT - The formal definition of the base of the Rhaetian Stage remains unresolved, and correlation of the Norian-Rhaetian boundary (NRB) between marine and continental successions is complicated by the use of different biostratigraphic frameworks and by pronounced floral provincialism. Here we present the first detailed palynological record across the NRB from the Pignola-Abriola section (southern Apennines, Italy), a candidate Global Stratotype Section and Point (GSSP) for the base of the Rhaetian. Of 33 samples investigated, 16 yielded identifiable palynomorphs, allowing recognition of three terrestrial (T1-T3) and three marine (M1-M3) assemblages. Their stratigraphic distributions are calibrated against the established conodont and radiolarian biostratigraphy, $\delta^{13}C_{org}$ record and magnetostratigraphy of the section. A key result is the first observed occurrence of Rhaetipollis germanicus *within the upper Norian, below the independently constrained NRB, demonstrating that its first occurrence does not coincide with the base of the Rhaetian at Pignola-Abriola. Conversely,* Patinasporites densus*,* Vallasporites ignacii*,* Enzonalasporites *sp. and* Duplicisporites granulatus *have their last observed occurrences within the Norian part of the succession. Comparison with European palynostratigraphic schemes and the Newark Supergroup reveals substantial regional differences in the observed ranges of several key Late Triassic sporomorph taxa, consistent with strong palaeogeographic and climatic control on floral distributions. Because the Pignola-Abriola magnetostratigraphy is independently correlated with the Newark Astrochronostratigraphic Polarity Time Scale, its palynological record provides a direct link between the marine western Tethyan chronostratigraphic framework and continental North American palynofloras. The integration of terrestrial sporomorphs with independently calibrated marine stratigraphic proxies therefore adds an important correlation tool to Pignola-Abriola as a candidate GSSP and extends the correlation potential of the proposed NRB to continental successions lacking marine biostratigraphic markers.*

INTRODUCTION

The Late Triassic was characterized by major climatic, environmental and biotic changes that affected both marine and terrestrial ecosystems. These include the Carnian Pluvial Episode (CPE), associated with major perturbations of the global carbon cycle, enhanced hydrological cycling, changes in sea level and carbonate production, and substantial faunal and floral turnover (Rigo et al., 2007; Dal Corso et al., 2018; Jin et al., 2022), as well as the environmental deterioration culminating in the end-Triassic mass extinction, when carbon-cycle perturbations, climatic change, marine deoxygenation, changes in carbonate production and widespread terrestrial ecosystem stress accompanied major biological turnover (Todaro et al., 2018; Zaffani et al., 2018; He et al., 2020, 2022; Fox et al., 2022; Rigo et al., 2024). The intervening Norian-Rhaetian interval was itself characterized by significant environmental and biological changes, including carbon-cycle perturbations, changes in continental weathering, marine redox conditions and major evolutionary turnovers among pelagic organisms (Trotter et al., 2015; Zaffani et al., 2017; Karádi et al., 2020; Rigo et al., 2020, 2024; Maron et al., 2024). The Upper Triassic succession of the Lagonegro Basin records several of these environmental changes from the Carnian to the Triassic-Jurassic transition (Reggiani et al., 2005; Rigo et al., 2007), making it particularly suitable for investigating the relationships among climatic, environmental and biotic changes within an integrated stratigraphic framework.

Despite considerable progress in Upper Triassic stratigraphy, the base of the Rhaetian Stage, corresponding to the Norian-Rhaetian boundary (NRB), still awaits formal definition by the International Commission on Stratigraphy. Two sections have been proposed as candidate GSSPs for the base of the Rhaetian: Steinbergkogel in Austria and Pignola-Abriola in southern Italy (Rigo et al., 2016). The Pignola-Abriola section exposes approximately 63 m of hemipelagic to pelagic deposits of the Lagonegro Basin spanning the middle-upper Norian to lower Rhaetian. The section is continuously exposed, fossiliferous and characterized by limited structural deformation, and its stratigraphic framework integrates conodont and radiolarian biostratigraphy, magnetostratigraphy and carbon-isotope stratigraphy (Bazzucchi et al., 2005; Giordano et al., 2010; Maron et al., 2015; Bertinelli et al., 2016; Rigo et al., 2016; Zaffani et al., 2017; Maron et al., 2024).

At Pignola-Abriola, the proposed base of the Rhaetian is placed at the first occurrence (FO) of *Misikella posthernsteini* Kozur & Mock, 1974, the biomarker selected by the Subcommission on Triassic Stratigraphy for definition of the base of the stage (Krystyn, 2010; Rigo et al., 2016). Recent taxonomic revision has clarified the evolutionary succession within *Misikella* across the boundary interval. Specimens previously referred to as *M. posthernsteini* s.l., *M. hernsteini/posthernsteini*

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transitional forms or *M. posthernsteini* morphotype A are now assigned to the distinct species *Misikella onouei* Takemura & Rigo, 2026, which represents the morphologically transitional form between *M. hernsteini* (Mostler, 1967) and *M. posthernsteini* (Takemura et al., 2026). The resulting evolutionary succession *M. hernsteini-M. onouei-M. posthernsteini* provides a refined biostratigraphic framework across the upper Norian-lower Rhaetian interval. The evolutionary radiation of *Misikella* across this interval forms part of the final major phase of conodont evolution during the Late Triassic (Karádi et al., 2020). The conodont event is closely associated with the base of the *Proparvicingula moniliformis* radiolarian Zone and occurs near a prominent negative $\delta^{13}C_{org}$ excursion that has been recognized in geographically distant marine successions (Maron et al., 2015; Bertinelli et al., 2016; Rigo et al., 2016, 2020). The Pignola-Abriola section is furthermore subdivided into ten magnetozones, and correlation of its magnetostratigraphic record with the Newark Astrochronostratigraphic Polarity Time Scale (APTS) places the proposed NRB within Newark Chron E20r at approximately 205.7 Ma (Maron et al., 2015). This astrochronological age estimate is independently supported by high-precision U-Pb zircon geochronology from the Pucará Basin of northern Peru. There, bivalve biochronology constrains an ash-bearing interval to the uppermost Norian-lowermost Rhaetian, and U-Pb ages bracket the NRB between 205.70 ± 0.15 and 205.30 ± 0.14 Ma, with a best estimate of 205.50 ± 0.35 Ma (Wotzlaw et al., 2014). The agreement between these independent astrochronological and radioisotopic constraints provides a robust numerical calibration for the Norian-Rhaetian boundary.

Correlating this marine chronostratigraphic framework with continental successions remains one of the principal challenges in Late Triassic stratigraphy. Marine successions are commonly constrained by marine biostratigraphy, including conodonts, radiolarians, ammonoids and bivalves, integrated with chemostratigraphy and magnetostratigraphy (Muttoni et al., 2004; Hounslow & Muttoni, 2010; Ogg, 2012; Maron et al., 2015; Rigo et al., 2016). Continental successions, in contrast, are generally correlated using sporomorph assemblages, vertebrate faunas, magnetostratigraphy and cyclostratigraphy (Cornet, 1977, 1993; Fowell et al., 1994; Kent & Olsen, 1999; Olsen & Kent, 1999; Olsen et al., 2011). Direct calibration between these two depositional realms is therefore difficult because their biostratigraphic frameworks are largely based on different fossil groups.

Among marine biostratigraphic tools, conodonts have played a particularly important role in the subdivision and correlation of sedimentary successions, providing biostratigraphic constraints throughout much of the Palaeozoic and Triassic and contributing to the temporal calibration of major events recorded in the geological record and the interpretation of exceptional fossil occurrences (e.g., Bagnoli et al., 1998; Liu et al., 2017; Rigo et al., 2018; Karádi et al., 2020; Jin et al., 2022). Their rapid evolutionary turnover and widespread distribution have allowed the development of detailed biozonations that provide an important framework for regional and interregional correlation. In the Upper Triassic, conodont biostratigraphy is particularly relevant to the definition and correlation of stage boundaries, including the Norian-Rhaetian boundary considered here (Krystyn, 2010; Rigo et al., 2016).

Palynomorphs provide a particularly useful means of bridging this gap because terrestrial sporomorphs can be preserved in both continental and marine sedimentary successions. Their value for integrated stratigraphy is well illustrated elsewhere in the Upper Triassic, where palynological records have been combined with marine biostratigraphy and other stratigraphic proxies to constrain environmental and biotic events (Rigo et al., 2007; Zaffani et al., 2018). In continental basins, sporomorph assemblages constitute one of the principal biostratigraphic tools and underpin the palynostratigraphic framework of several reference successions. This is particularly important in the Newark Supergroup of eastern North America, where successive palynofloral assemblages occur within a succession independently constrained by high-resolution magnetostratigraphy and cyclostratigraphy (Cornet, 1977, 1993; Fowell et al., 1994; Kent & Olsen, 1999; Olsen & Kent, 1999; Olsen et al., 2011).

The use of sporomorphs for long-distance chronostratigraphic correlation is nevertheless complicated by pronounced Late Triassic floral provincialism. The stratigraphic distributions of many sporomorph taxa were controlled not only by evolutionary appearances and disappearances but also by palaeolatitude, climate and regional environmental conditions (Cornet, 1977; Litwin & Skog, 1991; Kürschner & Herngreen, 2010). Low-palaeolatitude assemblages may therefore differ substantially from approximately coeval assemblages at middle and higher palaeolatitudes. Consequently, first and last occurrences established within one palaeogeographic province cannot necessarily be transferred directly to another without independent stratigraphic calibration. This problem is especially relevant for the Norian-Rhaetian transition, for which many established palynostratigraphic schemes derive from continental, paralic or shallow-marine successions of Europe and North America (Lund, 1977; Schuurman, 1977; Orłowska-Zwolińska, 1983; Litwin & Skog, 1991; Kürschner & Herngreen, 2010; Fijałkowska-Mader et al., 2015).

Despite the extensive chronostratigraphic framework available for Pignola-Abriola, its palynological record across the Norian-Rhaetian transition has not previously been characterized in detail. The occurrence of terrestrial sporomorphs within this pelagic succession provides an opportunity to calibrate palynological events directly against conodont and radiolarian biostratigraphy, carbon-isotope stratigraphy and magnetostratigraphy. Moreover, because the Pignola-Abriola magnetostratigraphic succession is independently correlated with the Newark APTS, its palynological record provides a direct means of comparing western Tethyan marine assemblages with continental North American palynofloras without assuming their equivalence on the basis of sporomorph composition alone.

Here we present the first detailed palynological study of the Pignola-Abriola section across the Norian-Rhaetian transition. We document the taxonomic composition and stratigraphic distribution of terrestrial and marine palynomorph assemblages and integrate their first and

last observed occurrences with the established conodont, radiolarian, carbon-isotope and magnetostratigraphic framework. Particular attention is given to the stratigraphic position of *Rhaetipollis germanicus* (Schulz) Schuurman 1977, and other taxa widely used in Upper Triassic palynostratigraphy and to comparison with established European and North American palynological schemes. The main objective is to provide an independently calibrated palynological framework that extends the correlation potential of the Pignola-Abriola candidate GSSP from marine to continental Upper Triassic successions.

GEOLOGICAL SETTING

The Pignola-Abriola section is exposed along the SP5 road between the villages of Pignola and Abriola, on the western flank of Monte Crocetta in the Southern Apennines of Italy (40°33′23.5″N, 15°47′1.7″E) (Fig. 1). During the Late Triassic, this area formed part of the Lagonegro Basin, a deep-water basin that developed along the southwestern branch of the western Tethys Ocean between the Apenninic and Apulian carbonate platforms (Şengör et al., 1984; Stampfli et al., 1991; Catalano et al., 2001; Ciarapica & Passeri, 2005).

The Upper Triassic succession of the Lagonegro Basin is represented by the Calcari con Selce and Scisti Silicei formations, recording the long-term evolution of the basin from carbonate-dominated pelagic sedimentation to biosiliceous deposition (Scandone, 1967; Amodeo, 1999; Bertinelli et al., 2005a; Passeri et al., 2005; Giordano et al., 2010; Rigo et al., 2012). This transition reflects the progressive deepening of the basin and the diachronous onset of deposition below the carbonate compensation depth (CCD), although its timing varied according to palaeogeographic position within the basin (Amodeo, 1999; Giordano et al., 2010; Bertinelli et al., 2016).

The Pignola-Abriola section comprises approximately 63 m of hemipelagic to pelagic sediments spanning the middle-upper Norian to the lower Rhaetian (Maron et al., 2015; Rigo et al., 2016). Rather than recording abrupt lithological changes, the succession documents a progressive environmental evolution from carbonate-dominated sedimentation towards mixed carbonate-siliceous deposition. This long-term trend is accompanied by increasing terrigenous input, enhanced biosiliceous productivity, and the deposition of organic-rich shale intervals that indicate repeated episodes of dysoxic to anoxic bottom-water conditions during the latest Norian and earliest Rhaetian (Amodeo, 1999; Giordano et al., 2010; Bertinelli et al., 2016; Maron et al., 2024). Thin calcarenitic beds, derived from episodic gravity flows sourced from the adjacent carbonate platforms, punctuate the otherwise continuous pelagic succession without

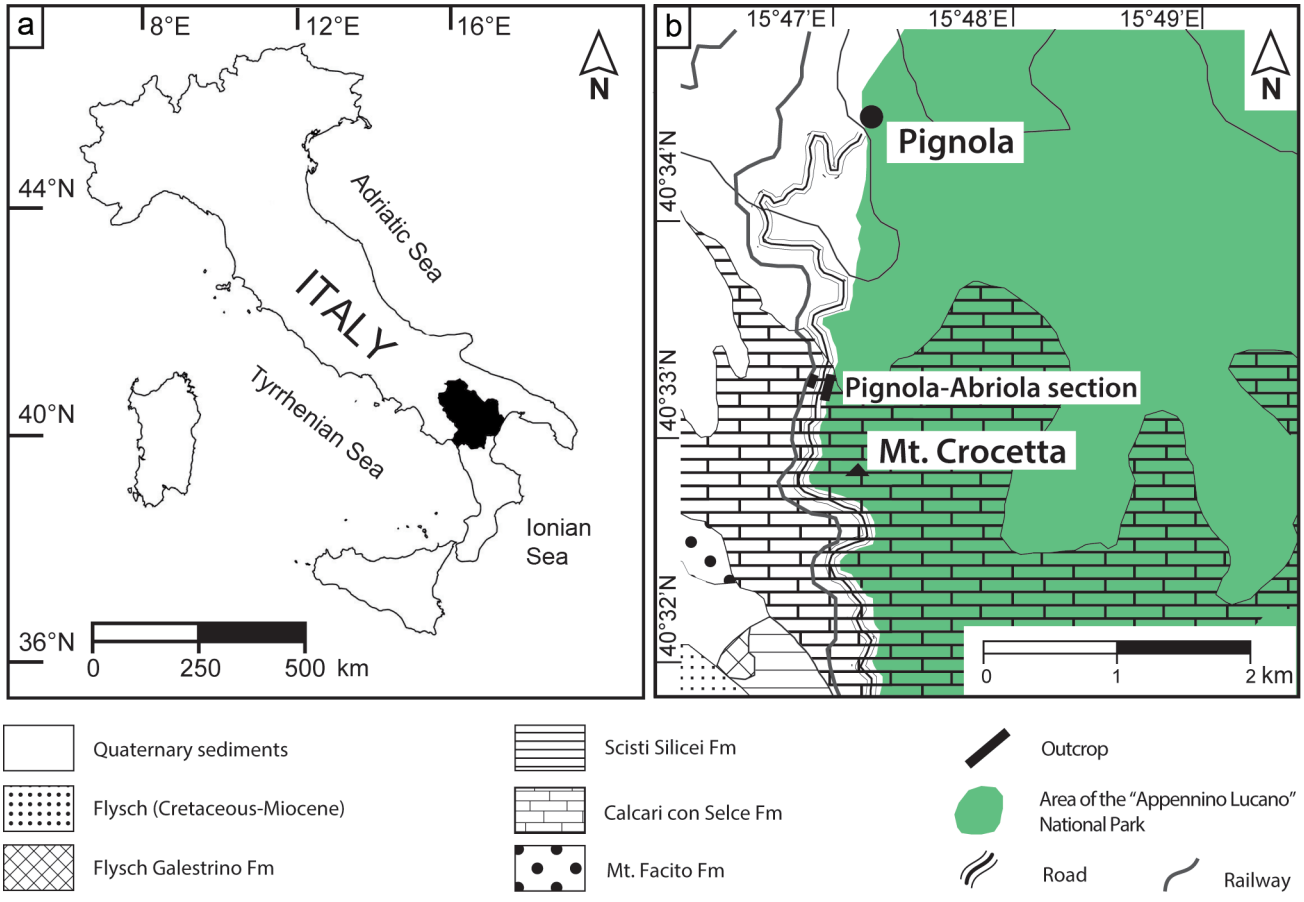


Fig. 1 - (color online) Location and geological setting of the Pignola-Abriola section. a) Location of the study area in southern Italy. b) Simplified geological map of the Pignola-Abriola area, showing the location of the studied section near Mt. Crocetta and the main lithostratigraphic units exposed in the area.

significantly disrupting its stratigraphic continuity (Bertinelli et al., 2005a; Giordano et al., 2010).

The Pignola-Abriola section has been extensively investigated using an integrated stratigraphic approach (Fig. 2). Its chronostratigraphic framework is constrained by conodont and radiolarian biostratigraphy, magnetostratigraphy and carbon-isotope stratigraphy, complemented by geochemical and rock-magnetic investigations (Bazzucchi et al., 2005; Rigo et al., 2005, 2016, 2020, 2024; Giordano et al., 2010; Maron et al., 2015, 2024; Bertinelli et al., 2016; Zaffani et al., 2017). Conodonts display a low Colour Alteration Index (CAI ≈ 1.5), indicating maximum burial temperatures below approximately 100 °C (Bazzucchi et al., 2005; Giordano et al., 2010). This integrated marine stratigraphic framework provides the independent chronostratigraphic control used here to calibrate the terrestrial and marine palynological events across the Norian-Rhaetian transition.

MATERIALS AND METHODS

A total of 33 rock samples, each weighing approximately 20 g, were collected from the Pignola-Abriola section across the Norian-Rhaetian interval. Of these, 16 yielded identifiable palynomorph assemblages, whereas the remaining samples were barren or contained only poorly preserved organic residues.

Palynological preparation followed standard acid-maceration procedures. Each sample was treated with 37% hydrochloric acid (HCl) to dissolve the carbonate fraction, followed by 40% hydrofluoric acid (HF) to remove the silicate fraction. The resulting residues were repeatedly washed to neutral pH and mounted on microscope slides. No heavy-liquid separation or oxidation treatments were applied. Palynomorphs were examined and photographed using a Leica DMLB transmitted-light microscope at magnifications of ×400

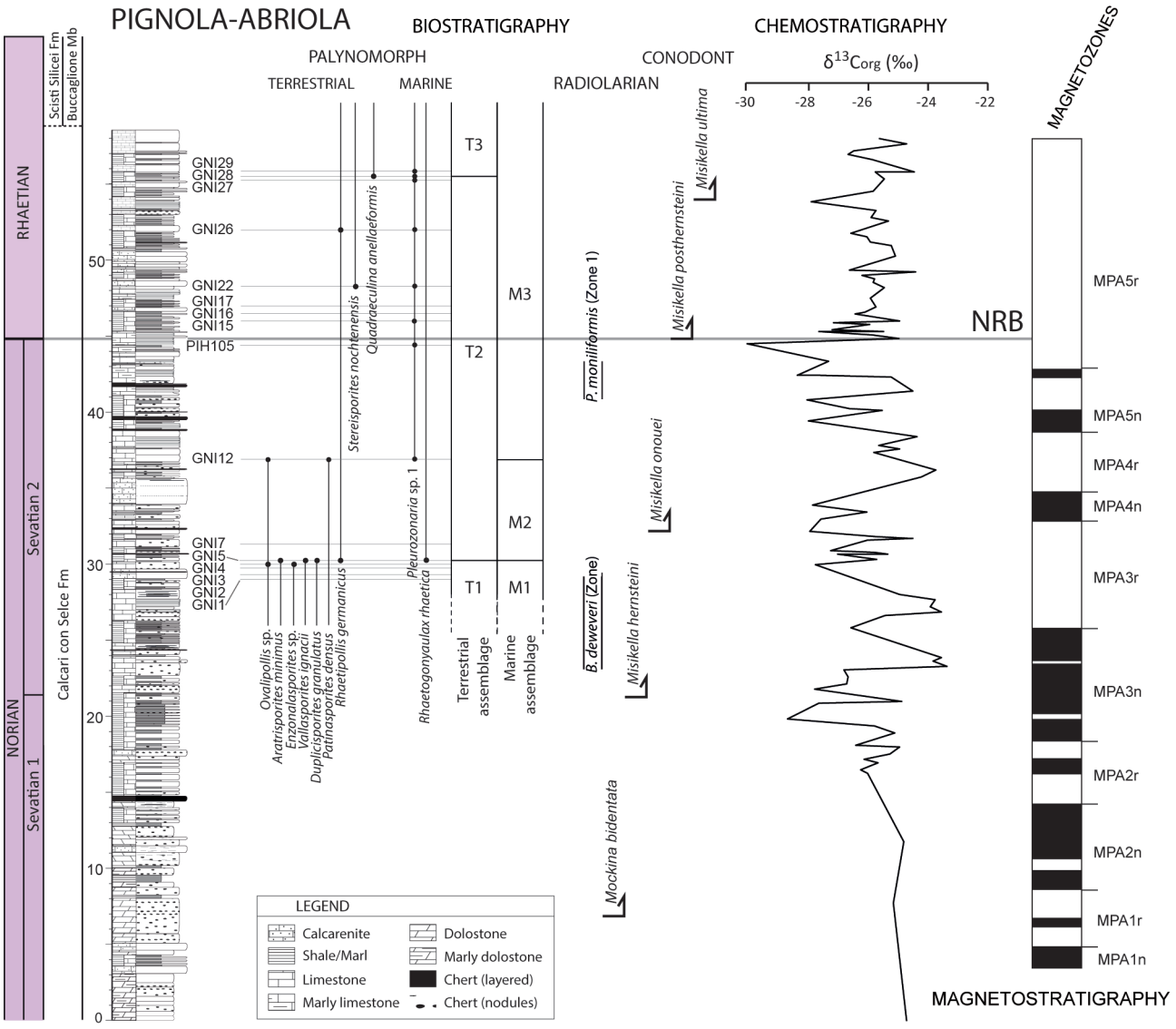


Fig. 2 - (color online) Integrated stratigraphic framework of the Pignola-Abriola section across the Norian-Rhaetian boundary (NRB). The stratigraphic log shows lithology and sample positions together with the distribution of selected terrestrial and marine palynomorphs and the terrestrial (T1-T3) and marine (M1-M3) assemblages identified in this study. Published radiolarian and conodont biostratigraphy, the $\delta^{13}C_{org}$ record, and magnetostratigraphy are shown for comparison. The NRB is placed at the first occurrence (FO) of *Misikella posthernsteini*.

and ×640. Taxonomic identification followed Klaus (1960), Schulz (1967), Praehauser-Enzenberg (1970), Orłowska-Zwolińska (1983), Van der Eem (1983), Roghi (2004), and Fijałkowska-Mader et al. (2015).

The occurrence of terrestrial and marine palynomorph taxa was recorded in each productive sample and their stratigraphic distributions were used to distinguish successive palynological assemblages. Because the recovered assemblages are generally sparse and only 16 samples yielded identifiable palynomorphs, the present study focuses on taxonomic composition, stratigraphic distribution and biostratigraphic correlation rather than quantitative palaeoecological reconstruction.

PALYNOLOGICAL ASSEMBLAGES

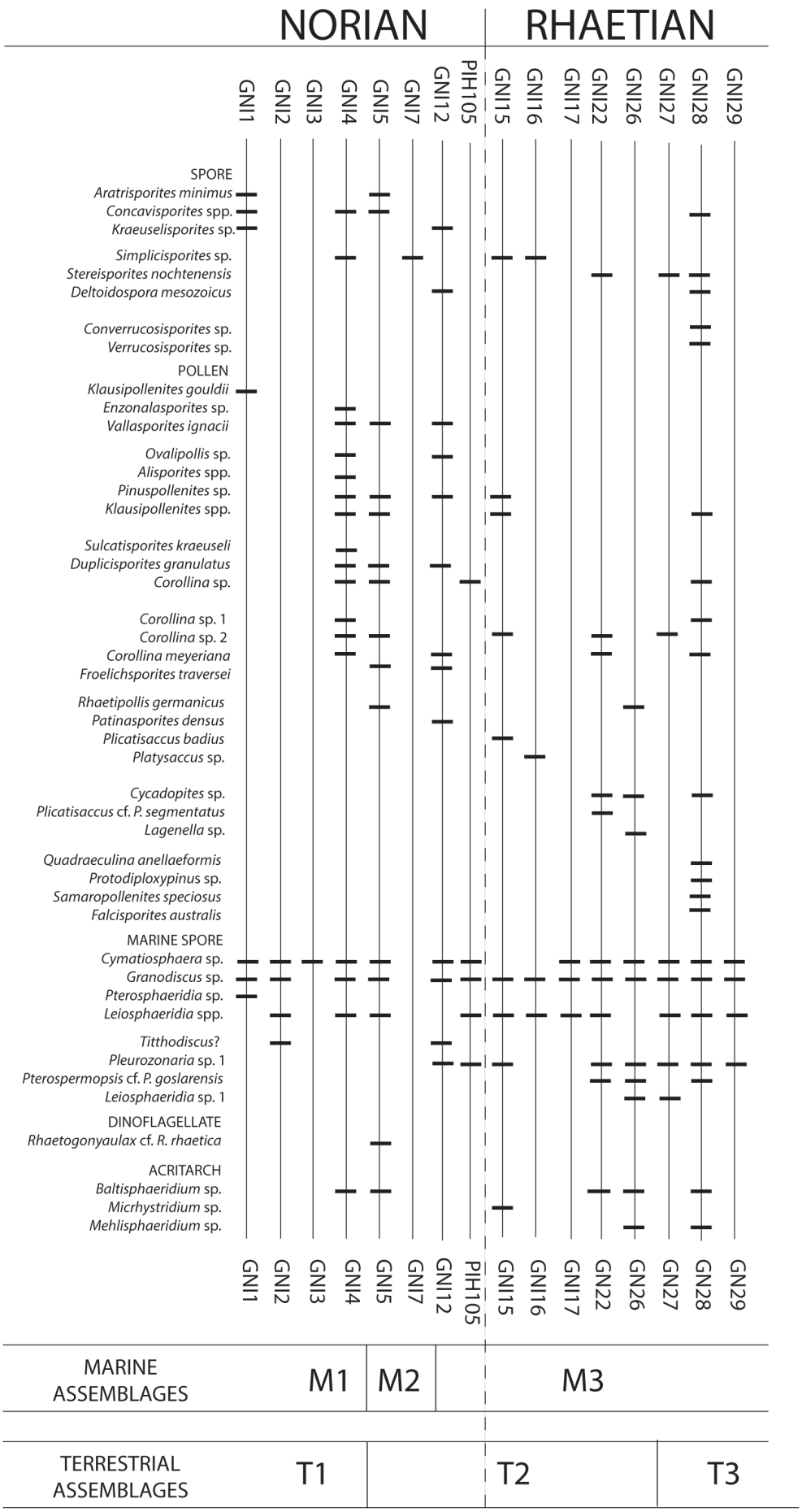
Palynological analysis identified 33 terrestrial taxa, comprising 8 spore and 25 pollen taxa, together with 12 marine palynomorph taxa represented by prasinophytes, acritarchs and dinoflagellates (Figs 2, 3). Palynomorph preservation ranges from moderate to poor. Terrestrial palynomorphs range in colour from pale yellow to brown, whereas marine palynomorphs are generally better preserved and range from yellowish-brown to dark brown.

Despite the pelagic marine depositional setting of the Pignola-Abriola section, the terrestrial palynomorph assemblage is relatively diverse and includes taxa attributed to bryophytes, pteridophytes, lycophytes and several gymnosperm groups. Bryophytes are represented by *Stereisporites*. Fern spores include *Deltoidospora*, *Concavisporites*, *Converrucosisporites* and *Verrucosisporites*, whereas lycophytes are represented by *Simplicisporites* and *Kraeuselisporites* (Fig. 3, Pl. 1). Gymnosperm pollen includes monosaccate, bisaccate and Circumpolles forms. Monosaccate pollen is represented by *Enzonalasporites*, *Vallasporites* and *Patinasporites*, whereas bisaccate pollen includes *Alisporites*, *Pinuspollenites*, *Klausipollenites*, *Plicatisaccus*, *Platysaccus* and *Sulcatisporites*. Circumpolles are represented by *Corollina*, *Duplicisporites* and *Rhaetipollis*. Additional gymnosperm pollen includes *Protodiploxypinus*, *Lagenella* and *Cycadopites*. *Froelichsporites* and *Ovalipollis* are retained here without assignment to a specific botanical affinity (Fig. 3). Marine palynomorphs are dominated by prasinophytes represented by *Cymatiosphaera*, *Granodiscus*, *Pterosphaeridia*, *Leiosphaeridia*, *Tytthodiscus*, *Pleurozonaria* and *Pterospermopsis*. Acritarchs include *Baltisphaeridium*, *Micrhystridium* and *Mehlisphaeridium*, whereas the dinoflagellate *Rhaetogonyaulax* cf. *R. rhaetica* (Sarjeant) Loeblich & Loeblich 1968 is also present (Fig. 3, Pl. 1).

The stratigraphic distribution of palynomorphs from sample GNI1, the lowermost productive sample of Norian age, to sample GNI29, the uppermost productive sample of Rhaetian age, records a series of first and last observed occurrences of terrestrial and marine taxa. Based primarily on first observed occurrences, three terrestrial assemblages (T1-T3) and three marine assemblages (M1-M3) are distinguished. The proposed Norian-Rhaetian boundary in the Pignola-Abriola candidate GSSP section lies between samples PIH105 and GNI15 (Figs 2, 3).

The terrestrial assemblage T1 occurs in the Norian part of the section and is characterized by the presence of the monosaccate pollen taxa *Enzonalasporites* sp. and *Vallasporites ignacii* Leschik 1955, associated with the Circumpolles taxon *Duplicisporites granulatus* (Leschik) Scheuring 1970. The assemblage also includes *Klausipollenites*, *Alisporites*, *Pinuspollenites*, *Corollina* spp. and *Corollina meyeriana* (Klaus) Venkatachala & Góczán 1964, whereas spores include *Concavisporites*, *Aratrisporites minimus* and *Simplicisporites* (Fig. 3). Assemblage T2 is defined by the first observed occurrences of *Rhaetipollis germanicus* (Schulz) Schuurman 1977 and *Froelichsporites traversei* (Dunay & Fisher 1979) Litwin, Smoot & Weems 1993 in sample GNI5 and spans the Norian-Rhaetian boundary. Importantly, the first observed occurrence of *R. germanicus* lies within the upper Norian, below the independently constrained Norian-Rhaetian boundary. The lower part of T2 records the last observed occurrences of *Enzonalasporites* sp., *Vallasporites ignacii*, *Patinasporites densus* Leschik 1955 and *Duplicisporites granulatus*, all of which are restricted to the Norian part of the studied succession. In contrast, *Corollina*, *Klausipollenites* and other bisaccate pollen persist across the boundary. *Rhaetipollis germanicus* has a discontinuous occurrence in the studied succession and is recorded again in sample GNI26. The upper part of T2 records the occurrence of the trilete spore *Stereisporites nochtenensis* (Krutzsch 1963) Schuurman 1977, associated with *Cycadopites*, *Plicatisaccus* cf. *P. segmentatus* Fisher & Dunay 1984 and *Lagenella* sp., whereas *Corollina meyeriana* persists into the lower Rhaetian (Fig. 3). Assemblage T3 occurs in the upper Rhaetian part of the studied succession and is characterized by the first observed occurrences of *Quadraeculina anellaeformis* Maljavkina 1949, *Samaropollenites speciosus* Goubin 1965, *Falcisporites australis* (De Jersey) Stevens 1981 and *Protodiploxypinus* sp. This interval also records an increase in spore diversity, including the first observed occurrences of *Deltoidospora mesozoicus* (Thiergart 1949) Schuurman 1977, *Converrucosisporites* sp. and *Verrucosisporites* sp., whereas *Corollina meyeriana* and *Cycadopites* sp. remain present. Several taxa show relatively persistent occurrences throughout the studied succession, particularly *Corollina* spp. and the bisaccate pollen genera *Klausipollenites* and *Pinuspollenites*, which represent the most consistently recorded components of the terrestrial palynoflora (Fig. 3).

Marine assemblage M1 is characterized by the persistent occurrence of the prasinophytes *Cymatiosphaera*, *Granodiscus* and *Leiosphaeridia*, which are the dominant marine components in the lower part of the studied succession. Assemblage M2 is defined by the first observed occurrence of *Rhaetogonyaulax* cf. *R. rhaetica* in sample GNI5, within the upper Norian. Assemblage M3 is defined by the first observed occurrence of *Pleurozonaria* sp. 1 in sample GNI12. This taxon becomes a prominent component immediately below the proposed Norian-Rhaetian boundary, particularly in sample PIH105. The overlying succession records *Pterospermopsis* cf. *P. goslarensis* Mädler 1963 and *Leiosphaeridia* sp. 1, together with the acritarchs *Baltisphaeridium*, *Micrhystridium* and *Mehlisphaeridium*, which occur discontinuously in the upper part of the section (Fig. 3).


NORIAN
RHAETIAN
GNI1
GNI2
GNI3
GNI4
GNI5
GNI7
GNI12
PIH105
GNI15
GNI16
GNI17
GN22
GN26
GN27
GN28
GN29
SPORE
Aratrisporites minimus
Concavisporites spp.
Kraeuselisporites sp.
Simplicisporites sp.
Stereisporites nochtenensis
Deltoidospora mesozoicus
Converrucosisporites sp.
Verrucosisporites sp.
POLLEN
Klausipollenites gouldii
Enzonalasporites sp.
Vallasporites ignacii
Ovalipollis sp.
Alisporites spp.
Pinuspollenites sp.
Klausipollenites spp.
Sulcatisporites kraeuseli
Duplicisporites granulatus
Corollina sp.
Corollina sp. 1
Corollina sp. 2
Corollina meyeriana
Froelichsporites traversei
Rhaetipollis germanicus
Patinasporites densus
Plicatisaccus badius
Platysaccus sp.
Cycadopites sp.
Plicatisaccus cf. P. segmentatus
Lagenella sp.
Quadraeculina anellaeformis
Protodiploxypinus sp.
Samaropollenites speciosus
Falcisporites australis
MARINE SPORE
Cymatiosphaera sp.
Granodiscus sp.
Pterosphaeridia sp.
Leiosphaeridia spp.
Titthodiscus?
Pleurozonaria sp. 1
Pterospermopsis cf. P. goslarensis
Leiosphaeridia sp. 1
DINOFLAGELLATE
Rhaetogonyaulax cf. R. rhaetica
ACRITARCH
Baltisphaeridium sp.
Micrhystridium sp.
Mehlisphaeridium sp.
MARINE ASSEMBLAGES
M1
M2
M3
TERRESTRIAL ASSEMBLAGES
T1
T2
T3

DISCUSSION

Comparison with established palynological zonations across the Norian-Rhaetian boundary

First and last occurrences of sporomorph taxa have traditionally been used to subdivide Upper Triassic successions and to establish regional palynostratigraphic schemes. However, many of these schemes were developed in continental, paralic or shallow-marine settings without direct calibration against independent marine biostratigraphic markers. This is particularly relevant across the Norian-Rhaetian transition, where the stratigraphic occurrence of taxa such as *Rhaetipollis germanicus* has been widely used for correlation (e.g., Kürschner & Herngreen, 2010). At Pignola-Abriola, the palynological succession can instead be positioned within an independently established chronostratigraphic framework based on conodont biostratigraphy and magnetostratigraphy and directly compared with the $\delta^{13}C_{org}$ record (Fig. 2). This provides an opportunity to evaluate the stratigraphic position of the main palynological events relative to the independently constrained Norian-Rhaetian boundary.

The terrestrial palynological succession at Pignola-Abriola broadly resembles the pattern recognized in established late Norian-Rhaetian European palynostratigraphic schemes, including the persistence of characteristic Norian monosaccate pollen, the appearance of *Rhaetipollis germanicus*, and an increase in palynomorph diversity during the Rhaetian (Lund, 1977; Schuurman, 1977; Bonis et al., 2010; Kürschner & Herngreen, 2010; Fijałkowska-Mader et al., 2015) (Fig. 4). Nevertheless, several taxa occurring in Rhaetian continental and marginal-marine successions, including *Ricciisporites tuberculatus* Lundblad 1954, *Granuloperculatipollis rudis* (Venkatachala & Góczán) Mostler et al. 1978 and *Limbosporites lundbladii* Nilsson 1958, were not identified in the Pignola-Abriola assemblages. These differences are not unexpected because most of the palynostratigraphic schemes used for comparison were established in the Germanic Basin and northwestern Europe, whereas Pignola-Abriola represents a pelagic marine succession of the western Tethys (Rigo et al., 2016). Differences in assemblage composition therefore need to be considered in relation to depositional setting and palaeogeographic and palaeoclimatic controls, in addition to their possible chronostratigraphic significance.

The lower terrestrial assemblage T1 is characterized by the co-occurrence of monosaccate pollen and Circumpolles. Its composition shows similarities with latest Norian assemblages assigned to the *Granuloperculatipollis rudis* Zone of Kürschner & Herngreen (2010), the *Corollina meyeriana* assemblage (*meyeriana* Subzone) of Orłowska-Zwolińska (1983), as subsequently revised by Fijałkowska-Mader et al. (2015), and the upper part of the *Corollina-Enzonalasporites* Zone of Lund (1977). A precise correlation of assemblages T1 and T2 with phases 2 and 3 recognized by Schuurman (1977) in the Grès à Roseaux and Grès et Schistes à *Avicula contorta* is more difficult because of differences in the occurrence of monosaccate pollen and the gradual appearance of *Rhaetipollis* documented in the French successions (Fig. 4).

A particularly relevant feature of the Pignola-Abriola record is provided by assemblage T2. Its base is defined by the first observed occurrences of *Rhaetipollis germanicus* and *Froelichsporites traversei* at sample GNI5, well below the independently constrained Norian-Rhaetian boundary. Consequently, *R. germanicus* first occurs within the upper Norian at Pignola-Abriola, and assemblage T2 extends from the upper Norian across the Norian-Rhaetian boundary. Within the lower part of T2, *Enzonalasporites* sp., *Vallasporites ignacii*, *Patinasporites densus* and *Duplicisporites granulatus* show their last observed occurrences, whereas *Corollina*, *Klausipollenites* and other bisaccate pollen persist across the boundary. The position of these events is independently constrained by the conodont biostratigraphic and magnetostratigraphic framework of the section and can be compared directly with the $\delta^{13}C_{org}$ record. The occurrence of *R. germanicus* below the Norian-Rhaetian boundary is therefore not inferred from palynological correlation but is established from its position within this independent stratigraphic framework (Fig. 4). The occurrence of *R. germanicus* in T2 nevertheless allows comparison with several European palynostratigraphic schemes. The assemblage shows similarities with the transition from the *Granuloperculatipollis rudis* Zone to the *Rhaetipollis germanicus* Zone of Kürschner & Herngreen (2010). Likewise, the *meyeriana* c Subzone of Orłowska-Zwolińska (1983), as revised by Fijałkowska-Mader et al. (2015), records the appearance of *R. germanicus* together with the progressive disappearance of *Enzonalasporites* and other characteristic Norian elements. Assemblage T2 can also be compared with the assemblage of the Twyning Mudstone Formation of the Mercia Mudstone Group, which contains *R. germanicus*, *Ovalipollis pseudoalatus* (Thiergart 1949) Schuurman 1976 and different Circumpolles morphotypes (Hounslow et al., 2004), with the *Perinopollenites-Ricciisporites-Rhaetipollis* (PRRh) Zone of the Danish Basin (Lindström et al., 2023), and with Zone GTr 18 of Heunisch (1999). However, the independently calibrated occurrence of *R. germanicus* in the upper Norian at Pignola-Abriola indicates that its first occurrence should not be assumed to coincide with the base of the Rhaetian in different palaeogeographic settings (Fig. 4).

The upper terrestrial assemblage T3 occurs entirely within the Rhaetian part of the studied succession and is characterized by the first observed occurrences of *Quadraeculina anellaeformis*, *Samaropollenites speciosus*, *Falcisporites australis* and *Protodiploxypinus* sp., together with an increase in spore diversity. Its composition is broadly comparable with Rhaetian assemblages recognized in European palynostratigraphic schemes. However, the stratigraphic distribution of *Q. anellaeformis* is geographically variable. In the Norwegian

Fig. 3 - Stratigraphic distribution of palynomorph taxa in the productive samples from the Pignola-Abriola section. Occurrences are grouped into spores, pollen, marine spores, dinoflagellates, and acritarchs. The resulting terrestrial (T1-T3) and marine (M1-M3) assemblages are shown at the base of the diagram. The dashed vertical line indicates the Norian-Rhaetian boundary.

Arctic succession, the *Quadraeculina anellaeformis* Zone begins in the upper Norian and is followed by a *Ricciisporites* spp. Zone (Paterson & Mangerud, 2020). At Pignola-Abriola, *Q. anellaeformis* first occurs in the Rhaetian, whereas *Ricciisporites tuberculatus* was not recorded in the studied interval. Accordingly, the *R. tuberculatus* Zone of Orłowska-Zwolińska (1983) and Fijałkowska-Mader et al. (2015) cannot be recognized in the present material (Fig. 4).

A markedly different palynological pattern is documented in western North America. Litwin et al. (1991) recognized three informal palynological assemblage zones in the Chinle Formation, which they interpreted as ranging from the late Carnian to the early Norian. In the upper part of the Chinle succession, monosaccate and non-striate bisaccate pollen remain important components of the assemblages, whereas *Corollina* (= *Classopollis*), *Rhaetipollis germanicus*, *Ricciisporites tuberculatus* and other taxa commonly associated with European Rhaetian assemblages are absent (Litwin et al., 1991). Litwin & Skog (1991) subsequently emphasized that low-palaeolatitude North American Norian assemblages commonly retain several "holdover" Carnian elements, including *Alisporites*, *Patinasporites*, *Klausipollenites*, *Pityosporites* and *Ovalipollis*, whereas characteristic Rhaetian taxa such as *Rhaetipollis*, *Ricciisporites*, *Triancoraesporites* and *Zebrasporites* are preferentially represented at middle to higher palaeolatitudes (Fig. 4). They interpreted this contrast as evidence for pronounced latitude-controlled floral provincialism during the Late Triassic. This palaeogeographic control on sporomorph distribution provides an important context for comparison with the Newark Supergroup.

Comparison with the Newark Supergroup palynofloras

The Late Triassic palynological succession of the Newark Supergroup provides a particularly relevant comparison with the Pignola-Abriola assemblages. The Newark succession was subdivided by Cornet (1977) and subsequent authors into successive palynofloral assemblages defined primarily by changes in their overall taxonomic composition (Cornet & Traverse, 1975; Cornet, 1977, 1993; Cornet & Olsen, 1985). The Lower Passaic-Heidlersburg palynoflora is characterized by abundant gymnosperm pollen, including bisaccate forms, together with the continued occurrence of *Vallasporites ignacii*, *Patinasporites densus* and other characteristic Late Triassic taxa (Cornet, 1977, 1993; Cornet & Olsen, 1985). The overlying Upper Balls Bluff-Upper Passaic palynoflora (ex Manassas-Upper Passaic palynofloral zone of Cornet [1977]), also contains *P. densus* and *V. ignacii*, together with *Classopollis torosus* (Reissinger) Klaus 1960 and *Granuloperculatipollis rudis* (Cornet, 1977; Litwin et al., 1991). The persistence of these taxa in the North American succession is noteworthy because several elements traditionally regarded as characteristic of older European assemblages persist into stratigraphically higher low-palaeolatitude North American palynofloras.

Cornet (1977) already emphasized that the stratigraphic ranges of terrestrial palynomorphs may be strongly influenced by geography and climate and that geographically restricted relict taxa may persist beyond their ranges documented elsewhere. This interpretation is consistent with the latitude-controlled floral provincialism subsequently documented by Litwin & Skog (1991), including the persistence of several "holdover" Carnian elements in low-palaeolatitude North American Norian assemblages.

The comparison with Pignola-Abriola is particularly informative because it does not rely exclusively on palynological similarity. The magnetostratigraphic succession of Pignola-Abriola was correlated with the Newark Astrochronostratigraphic Polarity Time Scale (APTS) by Maron et al. (2015), providing an independent basis for comparison between the two successions. In this correlation, magnetozone MPA5r at Pignola-Abriola, which contains the proposed Norian-Rhaetian boundary, is correlated with Newark magnetozone E20r.2r at approximately 205.7 Ma (Maron et al., 2015, 2019; Rigo et al., 2016). This provides an independent

EXPLANATION OF PLATE 1

(color online) Selected palynomorphs from the Pignola-Abriola section.

Fig. 1 - *Stereisporites nochtenensis* (Krutzsch 1963) Schuurman 1977, GNI22, P28/2, diameter 34 µm.

Fig. 2 - *Enzonalasporites* sp., GNI4, K46/1, diameter 37 µm.

Fig. 3 - *Patinasporites densus* Leschik 1955, GNI12, S34, diameter 45 µm.

Fig. 4 - *Ovalipollis* sp., GNI4, F45/3, length 40 µm.

Fig. 5 - *Sulcatisporites kraeuseli* Mädler 1964, GNI4, J49, length 80 µm.

Fig. 6 - *Froelichsporites traversei* (Dunay & Fisher 1979) Litwin, Smoot & Weems 1993, GNI5, M39/3, diameter 76 µm.

Fig. 7 - *Rhaetipollis germanicus* (Schulz) Schuurman 1977, GNI5, D23, diameter 40 µm.

Fig. 8 - *Corollina meyeriana* (Klaus) Venkatachala & Góczán 1964, GNI4, L34/4, diameter 26 µm.

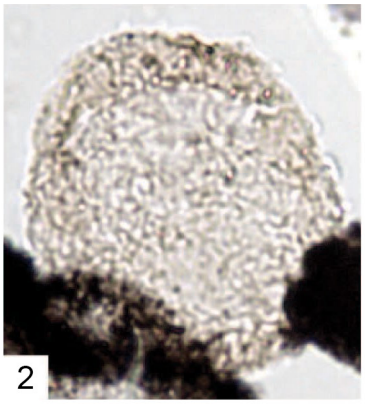
Fig. 9 - *Granodiscus* sp., GNI15, V51/1, diameter 45 µm.

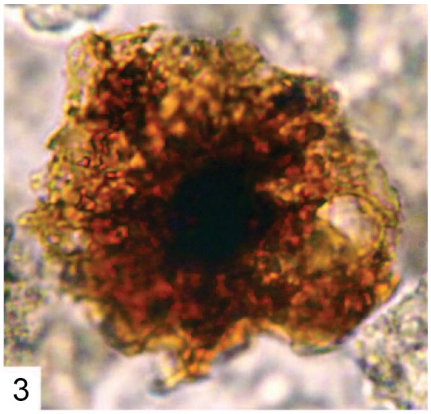
Fig. 10 - *Cymatiosphaera* sp., GNI1, E47/2, diameter 40 µm.

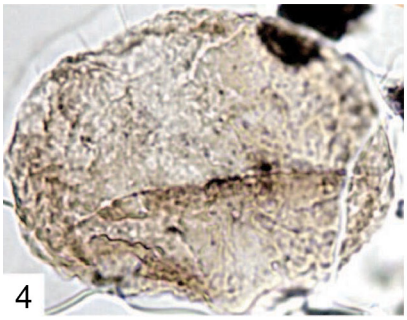
Fig. 11 - *Leiosphaeridia* sp., GNI5, D29, diameter 42 µm.

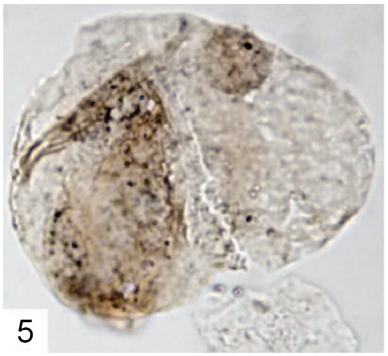
Fig. 12 - *Pleurozonaria* sp. 1, GNI26, D34, length 140 µm.


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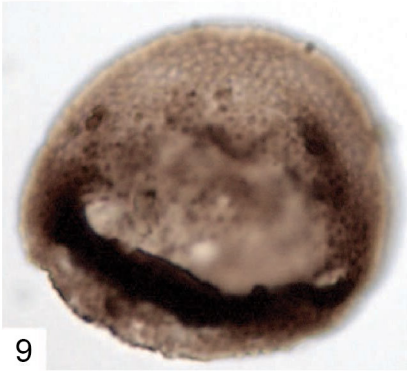

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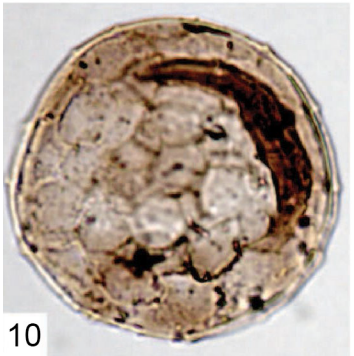

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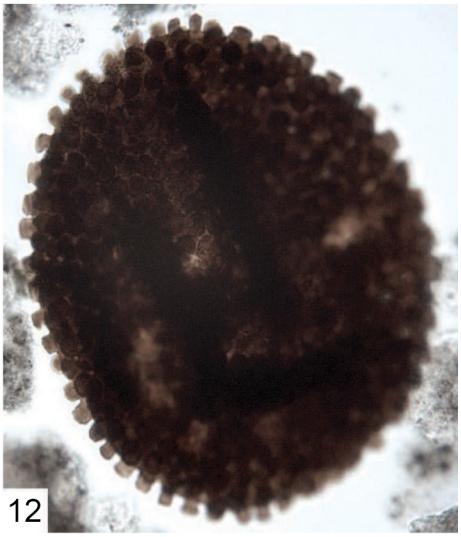

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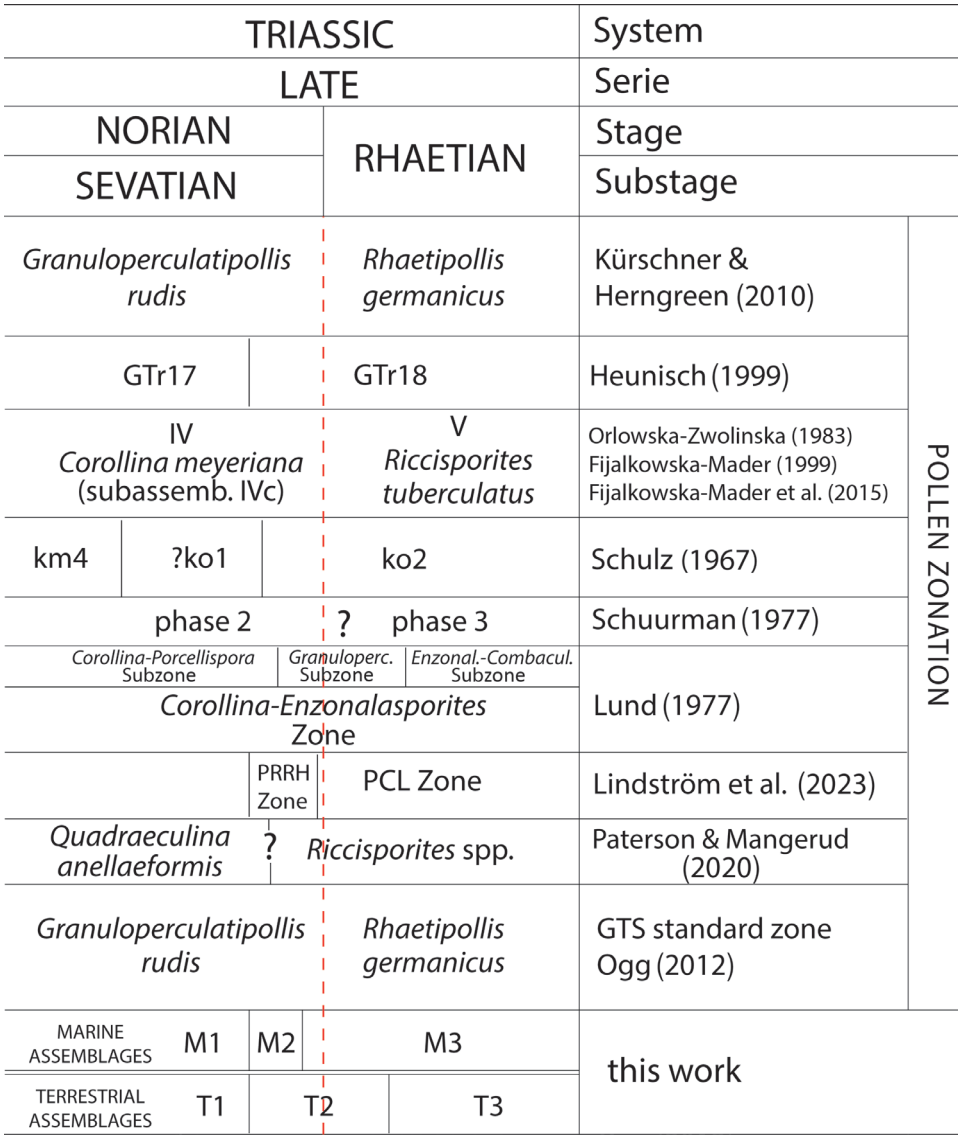


Fig. 4 - (color online) Comparison of the terrestrial palynomorph assemblages identified at Pignola-Abriola (T1-T3) with selected Late Triassic pollen zonation schemes. The position of the Norian-Rhaetian boundary is compared with the zonations of Schulz (1967), Schuurman (1977), Lund (1977), Orłowska-Zwolińska (1983), Lindström et al. (2023), Heunisch (1999), Kürschner & Herngreen (2010), Fijałkowska-Mader (1999), Fijałkowska-Mader et al. (2015), and Paterson & Mangerud (2020), as well as the standard zonation reported by Ogg (2012). Question marks indicate intervals for which the correlation remains uncertain. The marine (M1-M3) and terrestrial (T1-T3) assemblages recognized in this study are shown at the base.

chronostratigraphic link between the marine western Tethyan succession and the continental Newark record, allowing their respective palynological assemblages to be compared without assuming equivalence on the basis of sporomorph composition.

This independent calibration allows the marked differences between the two palynofloral records to be evaluated within a common chronostratigraphic framework. At Pignola-Abriola, *Vallasporites ignacii* and *Patinasporites densus* have their last observed occurrences in the upper Norian, whereas *Rhaetipollis germanicus* first occurs below the independently constrained Norian-Rhaetian boundary and therefore has a demonstrably Norian occurrence in this succession. In contrast, *P. densus* and *V. ignacii* persist within stratigraphically higher Newark palynofloral assemblages, whereas *R. germanicus* and other characteristic European Rhaetian sporomorphs have not been reported from the Newark Supergroup (Cornet, 1977, 1993; Cornet & Olsen, 1985). These contrasting distributions are consistent with the strong palaeogeographic and palaeoclimatic control on Late Triassic sporomorph assemblages proposed by Cornet (1977) and subsequently discussed by Litwin & Skog (1991).

Alternative chronostratigraphic interpretations of the upper Newark Supergroup further illustrate the difficulties inherent in correlating continental palynofloras directly with the marine chronostratigraphic scale. Kozur &Weems (2005), using conchostracan biostratigraphy, assigned most of the upper Passaic Formation and the *Patinasporites densus* palynoflora to the Sevatian (upper Norian), rather than to the Rhaetian, and placed only the overlying Midland Formation within the upper Rhaetian on the basis of the occurrence of *Euestheria brodieana* Jones 1862.

They also emphasized that the *P. densus* palynoflora lacks several sporomorph taxa commonly regarded as characteristic of the European Rhaetian, including *Rhaetipollis germanicus*, *Triancoraesporites ancorae* Schulz 1962, *Limbosporites lundbladii*, *Zebrasporites laevigatus* (Schulz) Schulz 1967 and *Cingulizonates rhaeticus* (Reinhardt 1962) Schulz 1967 (Kozur & Weems, 2005).

The independently calibrated Pignola-Abriola record provides additional constraints for evaluating this problem. Most notably, the first observed occurrence of *Rhaetipollis germanicus* at Pignola-Abriola lies within the upper Norian, below the independently constrained Norian-Rhaetian boundary. Conversely, *Patinasporites densus* and *Vallasporites ignacii* have their last observed occurrences within the upper Norian at Pignola-Abriola, whereas these taxa persist within stratigraphically higher palynofloral assemblages of the Newark Supergroup. The stratigraphic ranges of these taxa therefore differ between the western Tethyan and eastern North American records and cannot, by themselves, provide an unambiguous basis for interregional chronostratigraphic correlation.

These differences are consistent with the palaeogeographic provincialism discussed by Cornet (1977) and Litwin & Skog (1991) and indicate that the absence of typical European Rhaetian taxa from the Newark Supergroup cannot alone be used to establish a Norian age for its palynofloras. Conversely, the occurrence of taxa traditionally regarded as characteristic of older assemblages cannot necessarily be interpreted as evidence of an older age, because their observed stratigraphic ranges may differ among palaeogeographic and climatic provinces. Independent stratigraphic calibration is therefore essential when terrestrial palynological assemblages are used for long-distance correlation.

In this respect, Pignola-Abriola provides an important link between marine and continental Upper Triassic successions. Its terrestrial palynological record is directly integrated with conodont and radiolarian biostratigraphy, carbon-isotope stratigraphy and magnetostratigraphy, while the latter provides an independent correlation with the Newark APTS (Maron et al., 2015; Rigo et al., 2016). The stratigraphic position of terrestrial sporomorph events can therefore be calibrated against an independently constrained marine chronostratigraphic framework and compared, through magnetostratigraphy, with continental successions such as the Newark Supergroup. The occurrence of this calibrated terrestrial palynological record adds an important correlation tool to Pignola-Abriola as a candidate GSSP for the base of the Rhaetian, providing a means of extending correlation of the proposed Norian-Rhaetian boundary to continental successions in which marine biostratigraphic markers are absent.

CONCLUSIONS

The palynological record of the Pignola-Abriola section documents a succession of terrestrial and marine palynomorph assemblages across the Norian-Rhaetian transition. Despite the moderate to poor preservation and relatively sparse occurrence of palynomorphs, three terrestrial (T1-T3) and three marine (M1-M3) assemblages can be distinguished and integrated with the independently established conodont and radiolarian biostratigraphy, carbon-isotope stratigraphy and magnetostratigraphy of the section.

A significant result is the first observed occurrence of *Rhaetipollis germanicus* in the upper Norian, below the independently constrained Norian-Rhaetian boundary. The T2 assemblage therefore spans the boundary, whereas the overlying T3 assemblage occurs within the Rhaetian and records the appearance of *Quadraeculina anellaeformis*, *Samaropollenites speciosus*, *Falcisporites australis* and *Protodiploxypinus* sp. Conversely, *Patinasporites densus*, *Vallasporites ignacii*, *Enzonalasporites* sp. and *Duplicisporites granulatus* have their last observed occurrences within the Norian part of the studied succession. These results show that the first and last occurrences of individual sporomorph taxa do not necessarily coincide with the Norian-Rhaetian boundary.

Comparison with European palynostratigraphic schemes and North American continental records indicates substantial regional differences in the observed stratigraphic ranges of several Late Triassic sporomorph taxa. In particular, the persistence of *P. densus* and *V. ignacii* in stratigraphically higher assemblages of the Newark Supergroup contrasts with their disappearance in the upper Norian at Pignola-Abriola, whereas *R. germanicus*, already present in the upper Norian at Pignola-Abriola, is absent from the Newark palynofloral framework. These differences are consistent with the palaeogeographic and climatic control on Late Triassic floral distributions previously proposed for low- and higher-palaeolatitude assemblages and emphasize the need for independent stratigraphic calibration when sporomorphs are used for long-distance correlation.

The significance of the Pignola-Abriola palynological record lies particularly in this independent calibration. The terrestrial sporomorph succession is directly integrated with marine biostratigraphic, chemostratigraphic and magnetostratigraphic records, while magnetostratigraphic correlation of Pignola-Abriola with the Newark APTS provides an independent link to continental North American successions. The addition of a calibrated terrestrial palynological record therefore provides a further correlation tool for Pignola-Abriola as a candidate GSSP for the base of the Rhaetian Stage, allowing the proposed Norian-Rhaetian boundary to be correlated with continental successions in which marine biostratigraphic markers are absent.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to improve the language and reduce verbosity. The authors reviewed and edited all AI-generated content as necessary and take full responsibility for the content of the published work.

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