

Terrestrial environmental change across the Permian-Triassic boundary in the Karoo Zambezi Basin, Mozambique: Integrating palynological, sedimentological and carbon isotope evidence

P. Fernandes^{a,*}, Z. Pereira^b, J.E. Spangenberg^c, M. Mendes^b, G. Lopes^d, R.C.G.S. Jorge^e, L. Albardeiro^f, E. Font^g, T. Adatte^c, T. Vennemann^c, J. Marques^h

^a Centro de Investigação Marinha e Ambiental (CIMA), Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

^b Laboratório Nacional de Energia e Geologia, Rua da Amieira, Apartado 1089, 4466-901 São Mamede de Infesta, Portugal

^c Institute of Earth Surface Dynamics, University of Lausanne, Géopolis, 1015 Lausanne, Switzerland

^d Plants, Photosynthesis and Soil, School of Biosciences, University of Sheffield, Alfred Denny Building, Western Bank, Sheffield S10 2TN, UK

^e Universidade de Lisboa, Departamento de Ciências da Terra e Energia da Faculdade de Ciências, Instituto Dom Luiz, Campo Grande, Edifício C6, Piso 4, 1749-016 Lisboa, Portugal

^f Laboratório Nacional de Energia e Geologia, Bairro da Val d'Oca. Ap. 14, 7601-909 Aljustrel, Portugal

^g Departamento de Ciências da Terra, Universidade de Coimbra, Rua Sílvio Lima, 3030-790 Coimbra, Portugal

^h Gondwana Empreendimentos e Consultorias, Limitada, Rua 1.335, No. 233, Bairro da COOP, Maputo, Mozambique

ARTICLE INFO

Editor: S Shen

Keywords:

Palynology
Carbon stable isotopes
Gondwana
Permian-Triassic boundary
Mozambique

ABSTRACT

The Permian-Triassic boundary (PTB; ca. 252 Ma) marks the most severe biotic crisis in Earth history, yet high-resolution terrestrial records from southeastern Gondwana, outside the Main Karoo Basin of South Africa, remain scarce. We present a multidisciplinary investigation of borehole CIMT-014 from the N'Condédzi Coalfield, Mozambique, which preserves a near-continuous continental succession spanning the PTB within the Karoo Zambezi Basin. Sedimentological, palynological, palynofacies, total organic carbon (TOC), and organic carbon isotope ($\delta^{13}\text{C}_{\text{org}}$) analyses were integrated to reconstruct environmental, ecological, and carbon-cycle changes across the transition.

The uppermost Permian Matinde Formation comprises organic-rich floodplain mudstones, siltstones, and thin coal seams deposited under warm, humid conditions and dominated by *Glossopteris*-associated gymnosperm floras. Crossing the PTB, these deposits are abruptly replaced by conglomeratic, lacustrine, and fluvial sediments of the Cádzi Formation. Palynological data document a marked decline of glossopterid and other gymnosperm pollen, followed by a short-lived increase in opportunistic lycopphyte and fern spores. Concurrently, palynofacies shift from assemblages rich in non-opaque phytoclasts to assemblages dominated by opaque phytoclasts, while TOC values decline from >40 wt% in coal-bearing intervals to <0.2 wt% in the earliest Triassic succession.

A pronounced negative $\delta^{13}\text{C}_{\text{org}}$ excursion of approximately 5.4‰ occurs across the boundary interval, with values decreasing from −25.0‰ to a minimum of −30.4‰. The magnitude, stratigraphic coherence, and association with floral turnover, cessation of peat formation, and fluvial reorganisation indicate that the isotopic carbon excursion records a major perturbation of the global carbon cycle rather than local diagenetic effects. The isotopic signal is consistent with widespread carbon-cycle disruption linked to Siberian Traps magmatism and associated greenhouse-gas emissions.

Our results demonstrate that terrestrial ecosystems in southeastern Gondwana experienced profound ecological and environmental disruption during the end-Permian crisis and establish the Karoo Zambezi Basin of Mozambique as a key archive for correlating continental records of the PTB in Gondwana.

* Corresponding author.

E-mail addresses: pfernandes@ualg.pt (P. Fernandes), zelia.pereira@lneg.pt (Z. Pereira), jorge.spangenberg@unil.ch (J.E. Spangenberg), marcia.mendes@lneg.pt (M. Mendes), gilda.lopes.geo@gmail.com (G. Lopes), rjorge@fc.ul.pt (R.C.G.S. Jorge), luis.albardeiro@lneg.pt (L. Albardeiro), efont@uc.pt (E. Font), thierry.adatte@unil.ch (T. Adatte), Torsten.Vennemann@unil.ch (T. Vennemann), joamarques@gondwana.co.mz (J. Marques).

<https://doi.org/10.1016/j.palaeo.2026.114049>

Received 25 April 2026; Received in revised form 25 June 2026; Accepted 5 July 2026

Available online 8 July 2026

0031-0182/© 2026 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The Permian-Triassic boundary (PTB; ca. 252 Ma) marks the most severe biotic crisis of the Phanerozoic and a major perturbation of the Earth system that profoundly affected marine and terrestrial ecosystems (Zhang et al., 2023; Dal Corso et al., 2022; Shen et al., 2022; Aftabuzzaman et al., 2021; Hochuli et al., 2016; Benton and Newell, 2014; Looy et al., 2001; Erwin, 1994). The End-Permian Mass Extinction (EPME) resulted in the loss of more than 90% of marine species, accompanied by ecosystem collapse and delayed recovery that extended well into the Early Triassic (Raup and Sepkoski Jr., 1982; Raup and Sepkoski, 1984; Stanley, 2016; Song et al., 2013). This interval is widely associated with rapid climatic warming, widespread oceanic anoxia and acidification, and major disturbances to the global carbon cycle, commonly linked to greenhouse-gas emissions from Siberian Traps large igneous province magmatism and associated thermogenic degassing (Wignall, 2001; Svensen et al., 2009; Beerling et al., 2007; Black et al., 2018).

The EPME was equally severe for terrestrial ecosystems, with approximately 70% of tetrapod genera disappearing, and plant communities also underwent significant restructuring (Sahney and Benton, 2008). Nonetheless, due to the discontinuous sedimentological characteristics of terrestrial environments, which frequently experience episodes of non-deposition, active erosion, and the removal of existing sediments or rock layers, phenomena that occur at varying time scales, the terrestrial Permian-Triassic Boundary (PTB) remains one of the most contested stratigraphic intervals in the geological record. Some aspects of this controversy concern whether the EPME was a catastrophic event for terrestrial ecosystems overall or a gradual one, and the exact timing relative to the marine PTB remains debated. For example, in the Main Karoo Basin of South Africa, a stepwise pattern of faunal turnover is observed, with a first event, the “dinocephalian extinction event”, occurring at the end of the Guadalupian, and the “PTB tetrapod extinction event” occurring just before the end of the Permian (Lucas, 2009; Lucas, 2017). Some workers interpret this as evidence that terrestrial extinctions started before the globally recognised marine event, challenging the idea that catastrophic events caused synchronous PTB extinctions on land and at sea, and prompting reconsideration (Lucas, 2009; Gastaldo et al., 2026).

The plant communities add another layer of complexity to the PTB in terrestrial environments. The flora restructuring resulted from: 1) long-term taxonomic shifts from Paleophytic to Mesophytic floras, primarily driven by successive ecological disturbances rather than abrupt biodiversity loss (Nowak et al., 2019; Nowak et al., 2020), and 2) short-term changes in plant communities linked to the ecological and environmental changes caused by the EPME event (e.g. Liu et al., 2020; Xiong et al., 2021; Schneebeli-Hermann and Galasso, 2025). Palynological records indicate, initially, the loss of pollen assemblages, followed by lycopsid and, later, gymnosperm-dominated assemblages in the Triassic (Schneebeli-Hermann et al., 2017). In several continental successions, terrestrial ecosystem disruption appears to have preceded the main marine extinction event, with the disappearance of the *Glossopteris* occurring up to ~370 kyr earlier (Fielding et al., 2019). This suggests that marine and terrestrial ecosystems did not respond synchronously to the EPME, and that the expression of the terrestrial crisis varied regionally (Bond and Wignall, 2014; Dal Corso et al., 2022; Lu et al., 2022; Liu et al., 2023). However, whether this plant turnover was truly instantaneous or preceded, accompanied, or slightly lagged the vertebrate extinction pulse remains contested.

Across Gondwana, terrestrial PTB records document environmental disruptions, including the decline of *Glossopteris*-dominated ecosystems, and turnovers in palynological and macrofloral assemblages in the Main Karoo Basin of South Africa (Retallack et al., 2003; Gastaldo et al., 2005, 2015, 2020, 2026; Gastaldo and Bamford, 2023; Botha et al., 2020), Pakistan (Hermann et al., 2011; Schneebeli-Hermann et al., 2015), India (Jha et al., 2018; Bhattacharya et al., 2021; Saxena et al., 2025),

Australia (Mishra et al., 2019; Wheeler et al., 2020), Antarctica (McLoughlin et al., 1997; Retallack et al., 2005; Lindström and McLoughlin, 2007) and Tibet (Liu et al., 2020). They are accompanied by major shifts in fluvial depositional systems, including transitions from coal-forming environments to fluvial high-energy siliciclastic sedimentation in Australia and Antarctica (Tabor et al., 2017; Fielding et al., 2019, 2021; Cornamusini et al., 2023) and in the Main Karoo Basin of South Africa (Hiller and Stavrakis, 1984; Smith, 1995; Ward et al., 2005). Evidence of increasing aridification and enhanced aeolian activity across Gondwana further indicates climate-driven environmental stress (Ward et al., 2005; Smith and Botha-Brink, 2014). In several continental successions, the terrestrial ecosystems appear to have preceded or closely coincided with the marine extinction event (Fielding et al., 2019). These patterns are interpreted within the broader context of global climatic disturbances linked to the Siberian Traps volcanism (Dal Corso et al., 2022; Shen et al., 2023), and the Main Karoo Basin in particular remains one of the key archives for understanding PTB ecosystems on land (Viglietti et al., 2021; Gastaldo et al., 2020, 2026).

Despite these advances, high-resolution, integrated terrestrial records of the PTB from southeastern Gondwana remain comparatively scarce. In particular, the eastern African Karoo basins, and the Karoo Zambezi Basin of Mozambique (KZBM), are much less well documented than the Main Karoo Basin in South Africa. This limits our ability to assess the spatial variability of terrestrial ecosystem, fluvial reorganisation and carbon-cycle perturbations across Gondwana.

In the KZBM, borehole CIMENT-014 from the N'Condédzi Coalfield (NCC) preserves a rare, nearly continuous continental sedimentary succession spanning the PTB (Galasso et al., 2019b). This sequence provides an opportunity to document environmental changes in Gondwana's terrestrial ecosystems during this critical interval. Here we present a multidisciplinary study integrating high-resolution palynostratigraphy and palynofacies analysis with sedimentology and bulk organic geochemistry, including stable carbon isotope ($\delta^{13}\text{C}_{\text{org}}$) and total organic carbon (TOC) analyses. Within this framework, our study aimed to:

- 1) refine the location of the PTB in borehole CIMENT-014 using quantitative palynostratigraphy, and relate it to lithostratigraphic boundaries within the Matinde and Cádzi formations; 2) characterise changes in terrestrial vegetation and organic matter assemblages across the PTB, documenting the timing and nature of *Glossopteris* decline-spore-dominated floras; 3) reconstruct the evolution of depositional environments across the boundary, from the late Permian coal-bearing floodplain systems to Early Triassic lacustrine and braided-fluvial deposits, and assess the relative roles of climate forcing and rift-related tectonics in driving these changes; and lastly, 4) document and interpret the $\delta^{13}\text{C}_{\text{org}}$ and TOC trends through the PTB interval, evaluate the extent to which they record primary carbon-cycle perturbations versus local fluctuations and compare the magnitude and structure of the excursion with other Gondwana PTB records.

By addressing these objectives, we provide a new, high-resolution PTB record from southeastern Gondwana that contributes to understanding the spatial variability of the environment and ecosystem.

2. Geological setting

The NCC is situated approximately 50 km NE of Tete city (Fig. 1A) and is one of several coalfields in the Moatize-Minjova Sub-Basin, which is part of the major Karoo Zambezi Basin of Mozambique (KZBM) (Fernandes et al., 2024a, 2024b) (Fig. 1A). The development of the KZBM is related to the brittle reactivation of high-strain shear zones (e.g., the Sanangóé and Mzarabani shear zones) of the Zambezi Belt (Fig. 1A), formed during the Pan-African Orogeny (620–530 Ma) (Carvalho, 1977; Afonso, 1984; Pinna et al., 1993; Jamal, 2005; GTK-Consortium, 2006; Norconsult Consortium, 2007; Grantham et al., 2008; Viola et al., 2008). Tectonic reactivation of these high-strain

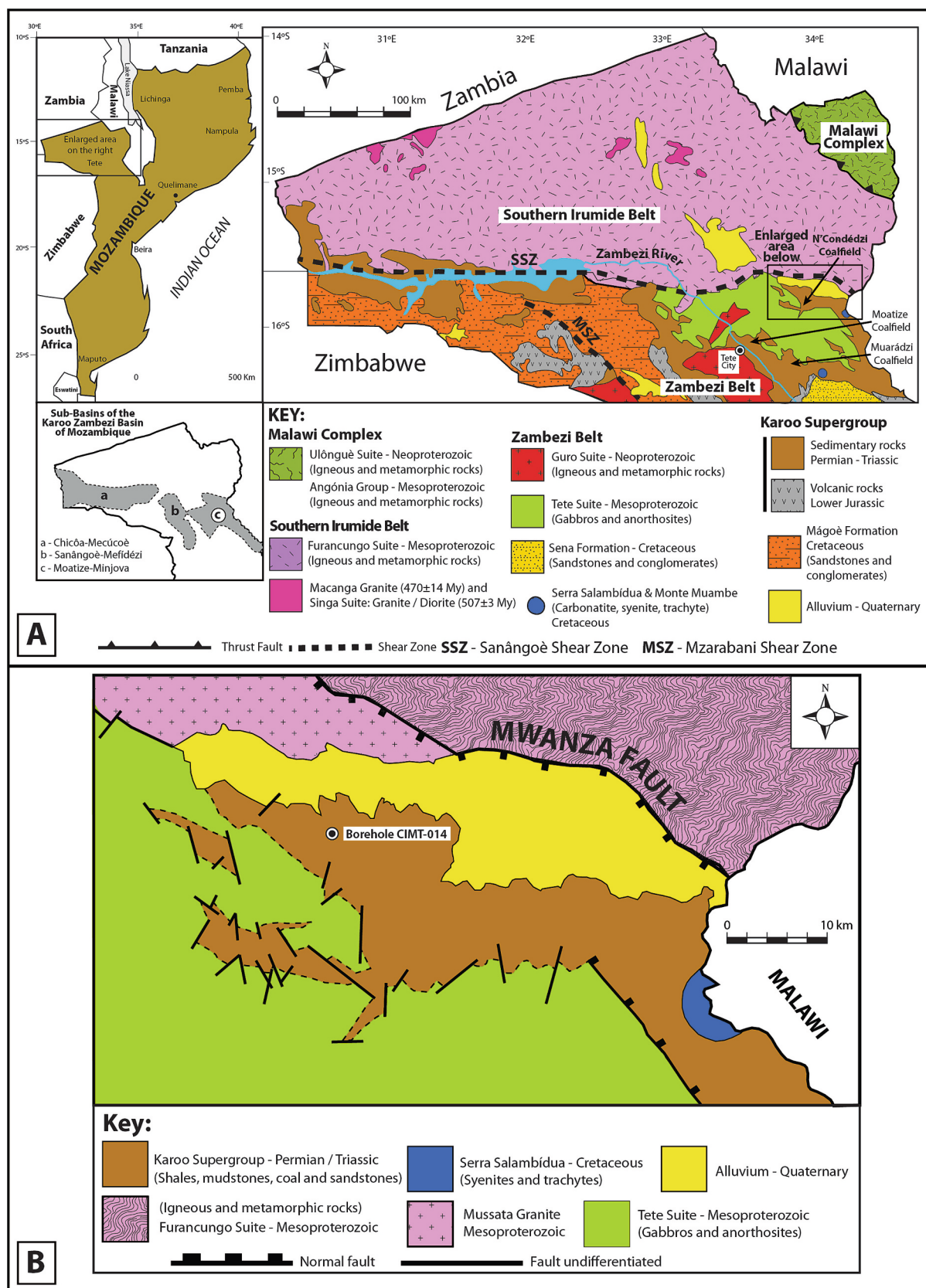


Fig. 1. A. Simplified geological map of the Tete Province, Mozambique, showing the location of Sub-Basins of the Karoo Zambezi Basin and the N'Condédzi, Moatize and Muarâdži coalfields. Adapted from Geological Map of Mozambique, Direcção Nacional de Geologia, Maputo (2006). B. Detailed geological map of the N'Condédzi Coalfield, showing the location of the borehole CIMT-014.

shear zones began in the Permian (Cisuralian), creating an extensional tectonic regime that progressively developed, forming intracontinental rift basins.

The northern boundary of the NCC is marked by the Mwanza Fault (Fig. 1B), a normal fault resulting from the reactivation of the Sanangôe Shear Zone (SSZ) associated with the early tectonic phases of this coalfield's development. On the southern margin of this sub-basin, Karoo sedimentary rocks either rest unconformably over the Mesoproterozoic gabbros-anorthosites of the Tete Suite or are faulted against later lithologies (Fig. 1B).

The general stratigraphic sequence of the lower Karoo in the Moatize-Minjoia Sub-Basin (MMSB) comprises four clastic units arranged from oldest to youngest: the Vúzi, Moatize, Matinde, and Cádzi formations (Fig. 2). The Permian-Triassic boundary (PTB) in the NCC was determined from palynological data corresponding to the boundary between the Matinde and Cádzi formations (Galasso et al., 2019b). A brief description of these clastic formations is provided below. Additional information on the geology and lithostratigraphy of the MMSB can be found in the studies by GTK-Consortium (2006), Fernandes et al. (2024a, 2024b), Fernandes et al. (2015); Fernandes et al. (2024a), Pereira et al. (2016), and Galasso et al. (2019a).

The Vúzi Formation unconformably overlies Precambrian basement rocks and comprises an alternating succession of conglomerates, sandstones, siltstones, mudstones, and rare thin coal seams, with a thickness of ca. 100 m (GTK-Consortium, 2006). The deposition of the Vúzi Formation was interpreted as a result of fluvial-to-lacustrine processes in a periglacial setting (Achimo et al., 2014; Pendkar et al., 2014; Fernandes et al., 2023). A recent palynological revision indicates that the Vúzi Formation is Kungurian to Lower Roadian in age (Lopes et al., 2021a, 2021b; Fernandes et al., 2023).

The Moatize Formation conformably overlies the Vúzi Formation and includes workable coal seams in the Moatize Coalfield (GTK-Consortium, 2006). The Moatize Formation contains coal seams of variable thickness intercalated with sandstones, siltstones, mudstones, and rare conglomerates, attaining a maximum thickness of ca. 340 m. It was deposited in various environments ranging from post-glacial lacustrine at the base to alluvial in the middle and upper parts of the

formation. Stratigraphically, it spans from the lower Roadian to the upper Wuchiapingian (Lopes et al., 2021a, 2021b; Fernandes et al., 2023).

The Matinde Formation is a ca. 2 km-thick sedimentary succession that conformably overlies the Moatize Formation. The Matinde Formation comprises coarse to fine-grained sandstones, siltstones, mudstones, coal beds, and conglomerates. The sandstone beds exhibit sedimentary features suggesting deposition in fluvial channels. In contrast, the floodplain deposits of these fluvial systems are primarily composed of siltstones, mudstones, and coal beds of varying thickness. The Matinde Formation can reach a maximum thickness of up to 2 km at its maximum extent (GTK-Consortium, 2006). The Matinde Formation is most likely of Wuchiapingian to uppermost Changhsingian age (Galasso et al., 2019b; Götz et al., 2017; Lopes et al., 2021a; Pereira et al., 2016, 2019; Fernandes et al., 2023).

The youngest geological unit, the Cádzi Formation, consists of red arkosic conglomerates and coarse- to medium-grained sandstones showing cross-stratification. In the NCC, the minimum thickness of the Cádzi Formation is 1.2 km. These lithologies were intercalated with reddish to green mudstones and siltstones. Silicified tree logs of *Rhexoxylon* sp. and *Dadoxylon* sp. have been found in this formation (GTK-Consortium, 2006). The Cádzi Formation was deposited in fluvial environments characterised by braided river systems. The NCC was dated from the Induan (Early Triassic) to the Carnian (Upper Triassic) (Galasso et al., 2019b). No Middle Triassic palynomorphs were identified in the NCC, suggesting a significant hiatus related to a regional Middle Triassic uplift described by Fernandes et al. (2015) from the Muarádzi Coalfield (Fig. 1A).

3. Materials and methods

3.1. Borehole and stratigraphic framework

This study is based on borehole CIMENT-014, drilled for coal exploration in the NCC to a total depth of 500 m (Fig. 3). The borehole was previously investigated for organic maturation and palynology by Galasso et al. (2019a, 2019b), who identified the PTB in the upper part of the Matinde Formation. Based on their palynostratigraphy, the PTB was placed within a 42 cm-thick interval between the last Permian (Changhsingian) L3 - *Osmundacidites senectus* assemblage at 489.42 m (sample MQ148) and the first Triassic (Induan) T1 - *Densioisporites neiburgii* assemblage at 489.00 m (sample MQ147). The PTB coincides with major lithological changes, namely the disappearance of coal and the onset of coarse clastic and red- to green-mottled siltstones and mudstones assigned to the Cádzi Formation. The Matinde-Cádzi formation boundary is placed at the base of the first conglomerate bed at 489.0 m (Galasso et al., 2019b).

Higher in the borehole, Galasso et al. (2019b) recognised Induan (T1) assemblages at 466.22 m (MQ141), Olenekian (T2, *Platysaccus queenslandi*) assemblages between 323 and 148.8 m, and an Upper Triassic Carnian assemblage (T3 - *Samaropollenites speciosus*) at 132.12 m. These data provide the chronostratigraphic framework for the present study.

3.2. Sampling strategy

For this work, we focused on the lower part of CIMENT-014, from 500.0 to 462.0 m depth, encompassing the upper Matinde Formation and the lowermost Cádzi Formation, which includes the PTB interval identified by Galasso et al. (2019b). This interval is dominated by mudstones and siltstones, which are suitable for palynological, palynofacies and geochemical analyses.

During a second sampling campaign, we collected 59 new core samples (prefix H) for high-resolution sedimentological logging, palynology, palynofacies analysis, and bulk organic geochemistry ($\delta^{13}\text{C}_{\text{org}}$ and TOC). In addition, 16 aliquots (prefix MQ) from the earlier study by

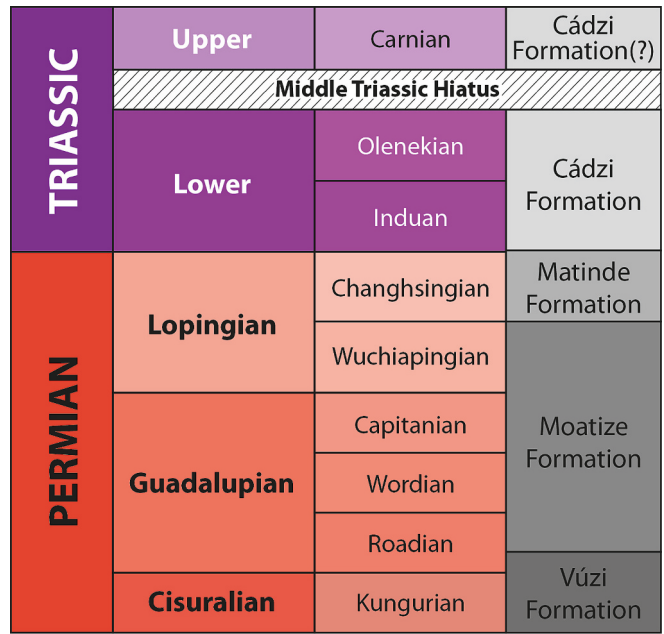


Fig. 2. General stratigraphy of the lower Karoo in the Moatize-Minjoia Sub-Basin (MMSB), including the N'Condédzi Coalfield (NCC). For the location of the MMSB and NCC, see Fig. 1A. After Galasso et al. (2019b) and Fernandes et al. (2024a).

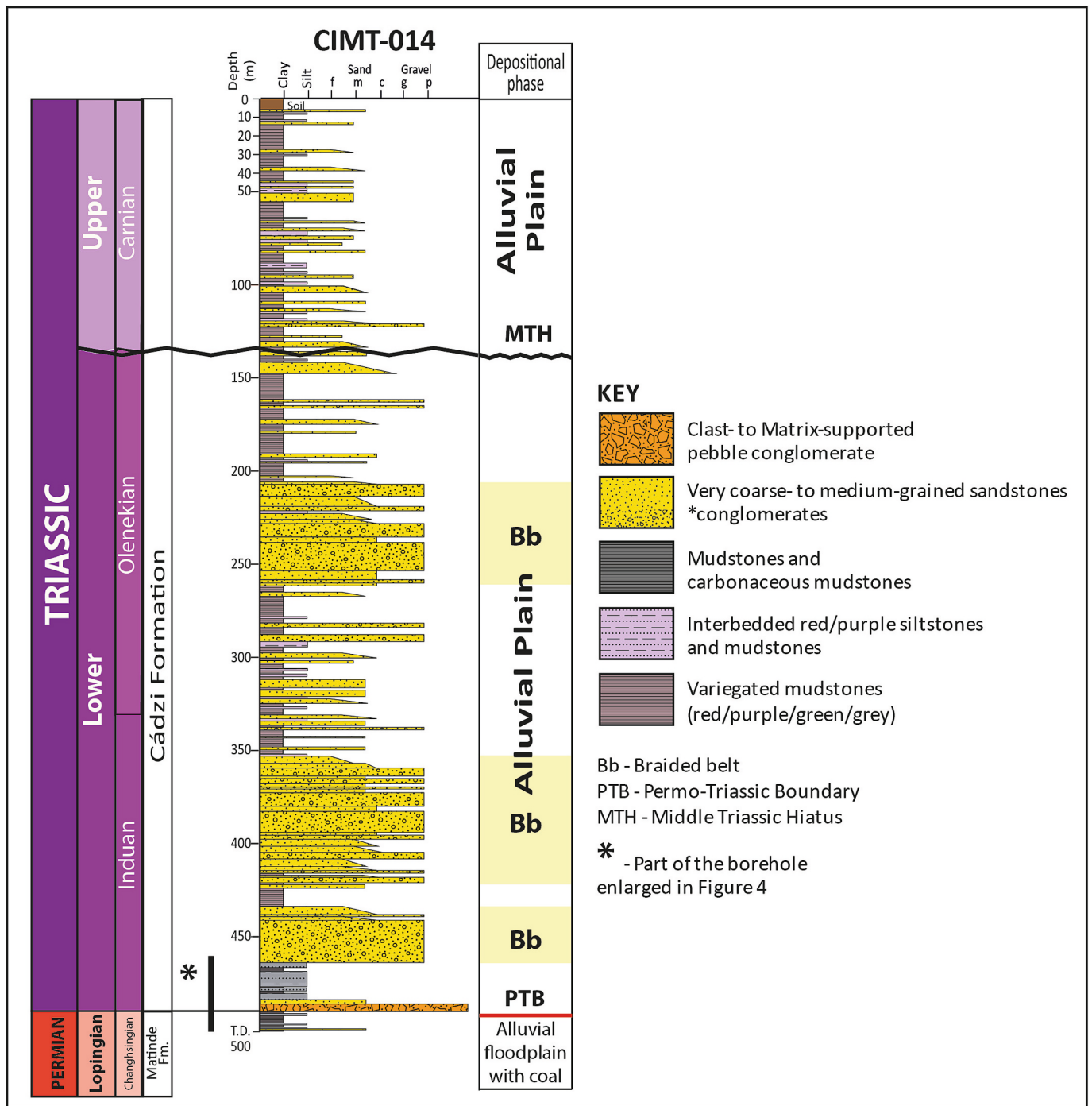


Fig. 3. Borehole CIMT-014 chronostratigraphic column, showing (*) in the lower part, which corresponds to the PTB section described in this study (after Galasso et al., 2019b and Fernandes et al., 2024b).

Galasso et al. (2019a, 2019b) were re-analysed to improve vertical resolution across the PTB (Fig. 4 and Table 1). Our sampling targeted fine-grained lithologies (mudstones and siltstones); coal seams and coarse sandstones/conglomerates were not analysed for bulk organic geochemistry and palynology.

A complete lithological and sedimentological description of CIMT-014 was provided by Galasso et al. (2019a, 2019b) and Fernandes et al. (2024b). Here, we present new palynological, palynofacies and geochemical data for the 500–462 m interval.

3.3. Palynology and palynofacies

Palynological and palynofacies methods follow standard procedures. Briefly, approximately 50 g of each sample was processed at the National Laboratory of Energy and Geology (LNEG, Portugal) using HCl and HF acid digestion to concentrate organic matter. For palynostratigraphic analysis, oxidised residues were sieved at 20 µm and mounted on glass slides using Entellan®. At least 250 palynomorphs were counted per productive sample, with additional scanning for rare taxa. Relative abundances were classified as rare (<5%), common (6–10%), frequent (11–20%), abundant (21–40%) and super-abundant (>40%). Local sporomorph assemblages were correlated with established Gondwanan

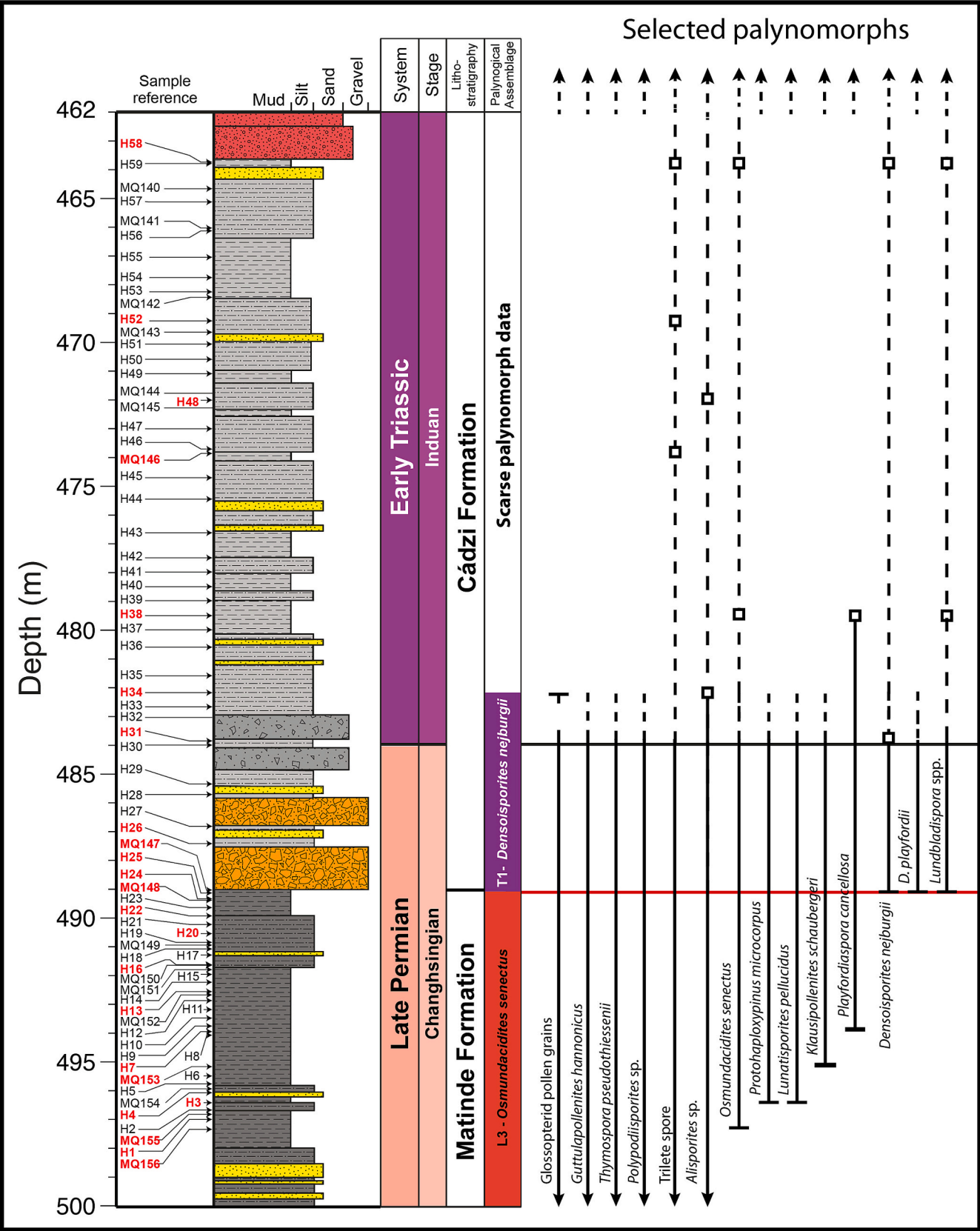


Fig. 4. Lithostratigraphy and palynology of borehole CIMT-014 from 500 m to 462 m depth. The log indicates the depths at which samples were collected. Samples marked in red were positive for palynology; on the right, the range of selected palynomorphs with age values and the scarce occurrence (white squares) of palynomorphs with only 1 occurrence or less than 5% of all particulate organic matter are shown. The horizontal red line marks the position of the palynologically defined PTB. The Permian-Triassic chronostratigraphy is based on the $\delta^{13}\text{C}_{\text{org}}$ curve (see [Section 5.3](#)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1The list of analysed samples and the results obtained for $\delta^{13}\text{C}_{\text{org}}$ and TOC.

Sample reference	Lithology	Depth (m)	TOC	$\delta^{13}\text{C}_{\text{org}}$
H58	Mudstone	463.37	0.15	−27.82
H59	Mudstone	463.42	0.08	−26.33
MQ140	Siltstone	464.85	0.07	−26.32
H57	Siltstone	465.32	0.11	−27.67
MQ141	Siltstone	466.22	0.17	−27.81
H56	Siltstone	466.32	0.17	−27.65
H55	Mudstone	467.22	0.13	−28.83
H54	Mudstone	467.92	0.12	−27.06
H53	Mudstone	468.42	0.12	−27.32
MQ142	Mudstone	468.6	0.11	−26.23
H52	Siltstone	469.42	0.13	−27.56
MQ143	Siltstone	469.72	0.11	−28.20
H51	Siltstone	470.22	0.10	−26.94
H50	Siltstone	470.75	0.07	−27.77
H49	Mudstone	471.25	0.11	−26.01
MQ144	Siltstone	471.92	0.09	−27.00
H48	Siltstone	472.15	0.07	−27.71
MQ145	Siltstone	472.42	0.09	−27.99
H47	Siltstone	473.15	0.09	−27.54
H46	Siltstone	473.85	0.06	−27.28
MQ146	Mudstone	474	0.11	−26.82
H45	Siltstone	474.85	0.08	−27.93
H44	Siltstone	475.85	0.09	−27.30
H43	Mudstone	476.6	0.10	−25.99
H42	Mudstone	477.6	0.09	−27.67
H41	Siltstone	478.1	0.11	−27.50
H40	Mudstone	478.6	0.16	−28.19
H39	Mudstone	479.1	0.14	−26.31
H38	Mudstone	479.6	0.16	−28.28
H37	Mudstone	480.1	0.14	−28.53
H36	Siltstone	480.7	0.2	−29.16
H35	Siltstone	481.67	0.18	−28.65
H34	Siltstone	482.25	0.20	−29.34
H33	Siltstone	482.75	0.17	−28.03
H32	Siltstone	483.12	0.19	−28.19
H31	Siltstone	484.25	0.15	−29.15
H30	Siltstone	484.4	0.22	−30.40
H29	Siltstone	485.42	0.13	−28.01
H28	Siltstone	485.8	0.09	−27.08
H27	Siltstone	486.9	0.18	−27.64
H26	Siltstone	487.5	0.19	−26.62
MQ147	Carbonaceous mudstone	489	4.98	−24.67
H25	Carbonaceous mudstone	489.09	13.72	−25.84
H24	Carbonaceous mudstone	489.39	2.16	−25.00
MQ148	Carbonaceous mudstone	489.42	1.84	−25.86
H23	Carbonaceous mudstone	489.69	1.58	−25.71
H22	Carbonaceous mudstone	489.99	2.37	−25.46
H21	Carbonaceous siltstone	490.29	1.71	−25.27
H20	Carbonaceous siltstone	490.59	3.21	−25.24
H19	Carbonaceous siltstone	490.89	2.14	−25.55
MQ149	Carbonaceous siltstone	491	1.59	−25.44
H18	Carbonaceous siltstone	491.15	2.48	−25.97
H17	Carbonaceous siltstone	491.35	1.11	−25.50
H16	Carbonaceous mudstone	491.68	1.48	−25.18
MQ150	Mudstone	491.7	0.76	−25.35
MQ151	Mudstone	491.85	0.86	−24.60
H15	Mudstone	492	0.56	−25.25
H14	Carbonaceous mudstone	492.3	42.68	−26.40
H13	Carbonaceous mudstone	492.6	29.49	−26.27
MQ152	Carbonaceous mudstone	492.7	1.05	−25.01
H12	Mudstone	492.9	0.72	−25.23
H11	Carbonaceous mudstone	493.2	34.03	−25.41
H10	Carbonaceous mudstone	493.5	34.58	−26.01
H09	Carbonaceous mudstone	493.8	27.39	−25.79
H07	Carbonaceous mudstone	494	3.49	−23.31
H08	Mudstone	494.1	0.74	−24.76
MQ153	Carbonaceous mudstone	495.22	38.50	−24.31
H06	Carbonaceous mudstone	495.5	21.77	−24.86
H05	Carbonaceous mudstone	495.8	4.31	−23.44
MQ154	Carbonaceous mudstone	495.9	5.80	−24.03
H04	Carbonaceous mudstone	496.1	9.19	−24.80
H03	Carbonaceous mudstone	496.4	3.52	−23.74
H02	Carbonaceous mudstone	496.7	20.73	−24.51
MQ155	Carbonaceous mudstone	496.8	7.05	−24.21
H01	Carbonaceous mudstone	497	6.10	−23.31
MQ156	Carbonaceous mudstone	497.32	4.59	−23.82

palynozonation schemes (Pereira et al., 2019; Galasso et al., 2019b).

Palynofacies analysis was based on counts of 250 organic particles per sample, using transmitted- and fluorescence-light microscopy of non-oxidised organic residues. Organic components were grouped into opaque and non-opaque phytoclasts, palynomorphs (spores, pollen, and freshwater algae), structureless organic particles (SOP) and minor components (fungal remains, cuticles, resins). The SOP show no UV fluorescence and consists of highly degraded terrestrial plant material. We opted for this designation for organic particles that lack defined structures, rather than amorphous organic matter (AOM), because, in palynofacies analysis, the latter is often an indicator of ancient aquatic environments (anoxic, dysoxic) formed by microbial degradation of phytoplankton, which does not align with our interpretation of the original organic matter and the formation of SOP. Quantitative data are presented in Tables 2 and 3 and summarised in Fig. 7.

3.4. Bulk organic carbon content and stable isotope analysis

The TOC and $\delta^{13}\text{C}_{\text{org}}$ values were determined on decarbonated (by treatment with 10% v/v HCl solution) powdered samples by elemental analysis/isotope ratio mass spectrometry (EA/IRMS) at the Institute of Earth Surface Dynamics of the University of Lausanne (IDYST-UNIL), Switzerland. The EA/IRMS system consisted of a Carlo Erba 1108 (Fisons Instruments, Milan, Italy) elemental analyser connected to a Delta V Plus isotope-ratio mass spectrometer via a ConFlo III open-split interface (both from Thermo Fisher Scientific, Bremen, Germany). The carbon isotope compositions were reported in the delta (δ) notation as per mil (‰) variations of the molar ratio of the heavy to light isotope ($^{13}\text{C}/^{12}\text{C}$) relative to the international standard Vienna Pee Dee Belemnite limestone (VPDB). A four-point calibration using international reference materials (RMs) and UNIL laboratory standards was used to normalise the measured $\delta^{13}\text{C}$ values to the international scales (VPDB-LSPVEC lithium carbonate scale). The used standard materials include UNIL-Glycine ($\delta^{13}\text{C}_{\text{VPDB}} = -26.02 \pm 0.05\text{‰}$), UNIL-Urea-1 ($-43.69 \pm 0.08\text{‰}$), UNIL-Urea-2 ($-26.86 \pm 0.05\text{‰}$), UNIL-Urea-3 ($-10.09 \pm 0.05\text{‰}$), and USGS24 graphite ($-16.05 \pm 0.04\text{‰}$). The repeatability and intermediate precision of the $\delta^{13}\text{C}$ analyses were better than 0.05‰. The organic carbon concentration was determined from the peak areas of the major isotopes using $\delta^{13}\text{C}_{\text{org}}$ calibration and showed a repeatability better than 0.1 wt% for TOC. Details of the instrumental setup and the calibration and quality control standards can be found in Spangenberg et al. (2006) and Spangenberg and Zufferey (2019). TOC contents are reported as weight percent (wt%) (Table 1).

4. Lithological description of the borehole CIMENT-014 interval (500–462 m depth)

This section presents a detailed relogging and lithological description of the 500–462 m interval in borehole CIMENT-014 (Figs. 3 and 4).

4.1. 500–489 M: carbonaceous mudstones and siltstones (upper Matinde Formation)

From 500.0 m to approximately 489.0 m depth, the core consists mainly of carbonaceous mudstones and siltstones (Figs. 4, 5), interbedded with fine- to medium-grained sandstone beds less than 0.5 m thick. The sandstone beds are normally graded and, locally, display cross-lamination near their tops. The siltstones show planar parallel lamination and grade upward into carbonaceous mudstones containing thin to very thin coal layers. This interval corresponds to the upper part of the Matinde Formation and spans the latest Changhsingian to earliest Triassic (Galasso et al., 2019b; see Section 5.1). In this study, the palynologically defined PT boundary is placed at sample H24, at a depth of 489.39 m (see Section 5.1; Figs. 4, 5), 0.39 m below the base of the overlying conglomerate, and matches the PT boundary defined by Galasso et al. (2019b) at sample MQ148.

Table 2
Percentage of palynomorphs.

Samples	Depth (m)	Taeniate bisaccate pollen (%)	Non Taeniate bisaccate pollen (%)	Ferns (%)	Lycophytes (%)	Sphenophytes (%)	Algae (%)	Number of palynomorphs
H34	482,3	32,5	50	5	5	2,5	5	47
H31	484,3	27,3	21,2	24,8	1,8	18,2	6,7	168
H26	487,5	0	0	41,7	25	25	8,3	50
MQ147	489,0	28,2	28,2	22	2,5	5,8	13,3	255
H25	489,1	27,9	31,4	20	3	6	11,7	249
H24	489,4	25	26,7	25,4	3,9	6,3	12,7	254
MQ148	489,4	20,6	24,5	34	3,8	10,8	6,3	263
H22	490,0	36	36,9	12,4	2,7	2,7	9,3	263
H20	490,6	42,9	34,6	9,4	2	2,8	8,3	261
H16	491,7	39,5	41,5	7,9	2	2,8	6,3	258
H13	492,6	22	38,3	15,7	1,2	3,1	19,7	257
H07	494,0	46,5	27,3	10,9	1,2	5,1	9	261
MQ153	495,2	40,7	28,7	15,7	1,2	3,9	9,8	258
MQ154	495,9	42,7	24,4	17,4	1,9	4,7	8,9	259
H5	496,1	32	36,2	17,1	0	3,7	11	258
H04	496,1	45	26,2	16,5	1,5	4,6	6,2	257
H3	496,4	43,7	25,4	16,4	1,2	4,7	8,6	261
MQ155	496,8	43,5	26	16	1,2	3,8	9,5	257
H1	497,0	45,4	25,5	16,2	0,8	3,6	8,5	259
MQ156	496,7	46,6	27,9	11,3	1,3	2,9	10	261

4.2. 489–ca. 483 m: conglomeratic interval at the Matinde–Cádzi formations boundary

At ~489.0 m depth (Figs. 4, 5), there is a sharp lithological change marked by an abrupt, erosive contact between the underlying carbonaceous mudstones and an overlying conglomerate bed approximately 1.5 m thick. The conglomerate is dominated by angular to sub-angular clasts ranging from very coarse sand to pebble size. Pebble-sized clasts are clast-supported within a coarse-sand matrix, and the bed exhibits reverse to normal grading. Clasts are composed mainly of igneous and metamorphic quartz and metamorphic lithic fragments derived from the adjacent Mesoproterozoic Furuncungo Suite (Fig. 1A), with very rare intraformational clasts of Permian lithologies (coal, carbonaceous mudstone, and sandstone). There is no evidence of palaeosols or other features indicative of prolonged subaerial exposure at the top of the underlying carbonaceous mudstones.

Above the basal conglomerate, from ~489.0 m to ~483.0 m depth, the core comprises a ~ 5 m-thick succession of interbedded conglomerates, coarse- to medium-grained sandstones, and thin grey siltstone beds. The lowermost conglomerate in this package is ~1.0 m thick and has a clast composition and fabric similar to those of the basal conglomerate. The upper part of the package includes two matrix-supported conglomerate beds, each ~0.8 m thick, containing granule- to pebble-sized, angular to sub-angular clasts dominated by metamorphic lithic fragments from the Furuncungo Suite. These upper conglomerates lack clear grading. The increased matrix content and the absence of coal or carbonaceous mudstone clasts distinguish them from the underlying Matinde Formation. This conglomeratic interval coincides with the lithostratigraphic boundary between the Matinde and Cádzi formations, which is placed at the base of the first conglomerate bed at 489.0 m (Galasso et al., 2019b).

4.3. Ca. 483–463.3 m: fine-grained siltstones and mudstones with thin sandstones

From the top of the upper matrix-supported conglomerate at ~483.0 m to 463.3 m depth, the core is composed of a ~ 20 m-thick succession of interbedded grey siltstones, mudstones and a few thin beds of fine-grained sandstone with planar parallel lamination (Figs. 4, 6). Coal and carbonaceous laminae are absent. Palynomorphs recovered from a siltstone at 482.22 m depth (sample H34) indicate an Induan (Early Triassic) age for the base of this fine-grained interval (Galasso et al., 2019b; see Section 5.1).

4.4. <463.3 m: overlying conglomerate and fining-upward cycles

At ~463.3 m depth, a thick, base-erosive conglomerate truncates the fine-grained succession and marks the onset of a series of fining-upward cycles that characterise the overlying part of the Cádzi Formation in borehole CIMT-014 (Figs. 3 and 6). From a depth of 463.3 m to the top of the borehole, the Cádzi Formation consists of red-brown, coarse- to medium-grained arkosic sandstones interbedded with red-, green-, and buff-coloured siltstones and mudstones (Fig. 3). The sandstones exhibit normal grading and large-scale cross-bedding, indicating a channel-fill succession of braided rivers (Fernandes et al., 2024a, 2024b). In contrast, the siltstones and mudstones represent overbank deposits. Mudstones at a depth of ~330 m contain palynomorphs ascribed to the Olenekian age, while at ~140 m depth, Carnian-age (Upper Triassic) palynomorphs were identified (Galasso et al., 2019b).

The Lower Triassic sandstones (Induan to Olenekian) are divided into three braided belts (Fig. 3), which are multistory channel bodies, interpreted as major basinwide tectonic events that tilted the basin floor via extensional faulting. This process created steeper gradients across the basin and its watershed, resulting in faster flow, greater river discharge, and increased bedload transport (Fernandes et al., 2024a). The supplementary material includes core photographs of the first braided belt at depths of 463.7 m–432.3 m. The absence of the Middle Triassic strata in borehole CIMT-014 (Fig. 3) indicates a Middle Triassic hiatus associated with a rapid cooling and exhumation event between 240 and 230 Ma, described by Fernandes et al. (2015). However, these aspects of the NCC's geology are outside the scope of this work. In the present study, we focus on the underlying 500–462 m interval, which encompasses the PTB and the transition from coal-bearing floodplain deposits to conglomeratic and fine-grained Triassic strata.

5. Results

5.1. Palynostratigraphy

Of the 75 rock samples collected across the PTB interval, 18 yielded palynomorph assemblages suitable for palynostratigraphic analysis; 7 samples contained scarce palynomorphs for reliable zonation, and the remaining samples were barren. The vertical distribution of palynomorph taxa was assessed both qualitatively (relative abundance, FO/LO of key taxa) and quantitatively. Two age-diagnostic assemblages were recognised (Fig. 4), corresponding to the Late Permian L3-*Osmundacidites senectus* and the Induan T1-*Densoisporites nejburgii*

Table 3

Percentage of palynofacies groups.

Samples	Depth (m)	Opaque phytoclasts (%)	Non-opaque phytoclasts (%)	SOP (%)	Pollen and Spores (%)	Freshwater algae (%)	Others (%)	Number of grains counted
H58	463,37	28,8	38,8	8	1,6	6,4	16,4	250
H59	463,42	80	12	8	0	0	0	250
MQ140	464,85	68,4	23,6	8	0	0	0	250
H57	465,32	73,6	17,6	7,2	0,8	0	0,8	250
MQ141	466,22	60	7,2	32,8	0	0	0	250
H56	466,32	62	8	30	0	0	0	250
H55	467,22	63,6	14	13,6	0,4	7,6	0,8	250
H54	467,92	70,8	11,6	17,2	0	0	0,4	250
H53	468,42	76	8	16	0	0	0	250
MQ142	468,6	64,8	13,6	10,8	0	10	0,8	250
H52	469,42	60	17,2	8	0,8	12	2	250
H51	469,72	64,8	22,8	12,4	0	0	0	250
H50	470,75	68	20	12	0	0	0	250
H49	471,25	63,6	22,8	12	0	0	1,6	250
MQ144	471,92	66	11,6	22,4	0	0	0	250
H48	472,15	65,2	10	24	0,8	0	0	250
MQ145	472,42	70,8	15,6	12	0	0	1,6	250
H46	473,85	64,8	10,4	24,8	0	0	0	250
MQ146	474	45,6	14	6	0,8	28,8	4,8	250
H45	474,85	73,2	8,8	18	0	0	0	250
H44	475,85	74,8	14,8	10,4	0	0	0	250
H43	476,6	69,2	9,2	20,8	0	0	0,8	250
H42	477,6	77,2	16	6	0	0	0,8	250
H41	478,1	68	18	12,8	0	0	1,2	250
H40	478,6	70	16	14	0	0	0	250
H39	479,1	68	18	14	0	0	0	250
H38	479,6	24	43,2	8	12,8	0	12	250
H37	480,1	44	24	30,8	0	0,4	0,8	250
H36	480,7	56,8	21,2	22	0	0	0	250
H35	481,67	53,2	17,6	29,2	0	0	0	250
H34	482,25	46,8	22,8	16	11,2	0	3,2	250
H33	482,75	9,2	2,8	88	0	0	0	250
H31	484,25	61,6	10,8	14	10,8	0	2,8	250
H30	484,4	55,2	15,2	29,6	0	0	0	250
H29	485,42	42,8	6,8	46,4	2,8	0	1,2	250
H28	485,8	46	16,8	37,2	0	0	0	250
H27	486,9	38	39,2	22,8	0	0	0	250
H26	487,5	41,2	47,2	9,2	0,4	0,8	1,2	250
MQ147	489	4	43,2	19,2	24,8	2	6,8	250
H25	489,09	8	45,2	20	22,4	0	4,4	250
H24	489,39	8,4	45,6	12	26	4	4	250
MQ148	489,42	19,2	58	10,8	8	0	4	250
H23	489,69	41,2	48,8	10	0	0	0	250
H22	489,99	29,2	38,8	30,8	0,4	0	0,8	250
H21	490,29	38	19,2	42,8	0	0	0	250
H20	490,59	11,2	40	47,2	0,8	0	0,8	250
H19	490,89	26	52,8	19,6	0,8	0	0,8	250
MQ149	491	4,8	61,6	26	4,8	0	2,8	250
H18	491,15	14,8	47,2	35,2	2	0	0,8	250
H17	491,35	19,2	54	23,6	1,2	0	2	250
H16	491,68	5,6	35,2	40	15,2	0	4	250
MQ150	491,7	24	60,4	8	1,6	0	6	250
MQ151	491,85	26	47,6	20,8	4,8	0	0,8	250
H15	492	18,8	55,2	15,6	4	1,6	4,8	250
H14	492,3	16	10,8	72,4	0	0,8	0	250
H13	492,6	8,4	28	52	6,8	2	2,8	250
MQ152	492,7	23,6	42,8	14,8	12,4	2,4	4	250
H12	492,9	18,8	42,8	24,4	2,8	3,2	8	250
H11	493,2	14,8	8,4	76,8	0	0	0	250
H10	493,5	6,4	22,4	71,2	0	0	0	250
H09	493,8	15,2	12,8	66,8	2,8	0	2,4	250
H07	494	10	18	18,8	42,4	0	10,8	250
H08	494,1	23,6	48,8	12	7,2	0,4	8	250
MQ153	495,22	15,2	8	69,2	6,4	0	1,2	250
H6	495,5	24	6	63,6	6,4	0	0	250
H5	495,8	6,8	22	16	40,8	0	14,4	250
MQ154	495,9	0	0	0	0	0	0	250
H04	496,1	10	35,2	22	29,2	0	3,6	250
H03	496,4	6	34	12	40,8	0	7,2	250
H02	496,7	4	12	76	8	0	0	250
MQ155	496,8	0	0	0	0	0	0	250
H01	497	6	24,8	7,6	54,4	1,6	5,6	250
MQ156	497,32	6	20	4	66	0	4	250



Fig. 5. Photographs of the core from 500 to 480.62 m depth. The position of the palynologically inferred PT boundary (sample H24) is indicated. Also indicated is the position of sample H30, marking the spike of the $\delta^{13}\text{C}_{\text{org}}$ negative excursion and the position of the chronostratigraphic Permian-Triassic Boundary (PTB). The length of the core boxes is 1 m.



Fig. 6. Photographs of the core section within 480.62 to 458 m depth. This core interval lies above the PTB and the negative $\delta^{13}\text{C}_{\text{org}}$ spike. The samples collected from this core interval have very low organic and palynological content. At ~463.7 m depth, the first braided belt (Bb) begins (see supplementary material), which characterises most of the Lower Triassic succession of the NCondézi Coalfield (Fig. 3). The length of the core boxes is 1 m.

assemblages of Galasso et al. (2019b).

5.1.1. Assemblage L3-*Osmundacidites senectus* (late Lopingian; samples MQ156 to H24)

Assemblage L3 extends from 497.32 m (sample MQ156) to 489.39 m (sample H24). It is defined by the first occurrences of *Osmundacidites senectus*, *Protohaploxylinus microcorpus* and rare *Klausipollenites schaubergeri*, and is assigned to the late Lopingian (Fig. 4). The assemblage is dominated by moderately to well-preserved spores, including *Apiculatisporis* spp., *Baculatisporites* spp., *Calamospora* spp., *Cyclogranisporites*

spp., *Horriditritiles* spp., *Leiotritiles* spp., *Microbaculispora* spp., *Microgranulatisporites* spp., *Verrucosporites* spp., and monolete taxa such as *Laevigatisporites* spp., *Thymospora pseudothiessenii* and *Polypodiisporites* spp., *Lophotritiles* spp., and *Kraeuselisporites* spp. also occur within this interval.

Pollen assemblages are characterised by common to abundant taeniate and non-taeniate bisaccate grains, notably *Protohaploxylinus* spp., *Striatopodocarpites* spp. (showing a gradual decline up-section), and *Alisporites* spp., together with rare to common *Guttulapollenites harmonicus*, *Corisaccites* spp. and *Lueckisporites virkkiae*. *Osmundacidites*

senectus and *Protohaploxylinus microcorpus* commonly co-occur throughout L3. The upper part of the assemblage is marked by the FO of the rare *Klausipollenites schaubergeri* and *Lunatisporites pellucidus*.

5.1.2. Assemblage T1-*Densosporites nejburgii* (Induan; samples H25 to H34)

Assemblage T1 is recorded from 489.09 m (H25) to 482.25 m (H34) and is assigned to the Induan (Early Triassic) (Fig. 4). It is characterised by an increased abundance of spores, particularly *Cyclogranisporites areosus*, *Granulatisporites* spp., *Horriditrites tereteangulatus*, *Leiotrites*, *Lophotrites novicus*, *Osmundacidites senectus*, *Thymospora pseudothiesseni* and *Verrucatisporites* spp. Diagnostic of this assemblage are the first occurrences of rare *Aratrisporites* spp., *Densosporites nejburgii*, *D. playfordii*, other *Densosporites* spp., *Lundbladispora* spp., *Playfordiaspora cancellosa* and additional *Verrucatisporites* spp.

Pollen grains persist but are generally less abundant than in L3. Non-taeniate and taeniate bisaccate pollen include *Alisporites* spp. and *Protohaploxylinus* spp. (with rare *P. microcorpus*), together with *Cycadopytes* spp., *Corisaccites* spp., *Gnetaceaepollenites sinuosus*, *Guttulapollenites hannonicus*, *Hamiapollenites* spp., *Lueckisporites virkkiae*, *Lunatisporites pellucidus*, *Lunatisporites* spp., *Klausipollenites schaubergeri* and *Weylandites lucifer*. *Striatopodocarpites* spp. decline markedly within this assemblage, and some are absent above the last coal beds below T1.

Both assemblages contain rare freshwater algae and other organic-

walled microfossils, including *Peltacystia venosa* and *Peltacystia* sp. (Zygnemataceae), *Cymatiosphaera gondwanensis*, *Mehlisphaeridium* and *Leiosphaeridia* (Prasinophyceae; Riboulleau et al., 2018; Spina et al., 2018), and the rare *Reduviasporonites chalastus* (Spina et al., 2015, 2018). Fungal hyphae and root hairs are also present but are never dominant.

5.2. Palynofacies

Of the 75 sediment samples analysed, 71 yielded sufficient organic residues for palynofacies analysis (Fig. 7; Table 3). Organic components were grouped into opaque and non-opaque phytoclasts (including cuticles), palynomorphs (spores, pollen and freshwater algae), structureless organic particles (SOP), and minor constituents (fungal remains, resins, and root hairs). Across the 500–462 m interval, assemblages are dominated by phytoclasts (mean 73%), followed by SOP (mean 20%) and palynomorphs (mean 7%). Variations in the relative proportions of these groups define two palynofacies types from base to top; here, we summarise the two main intervals encompassing the PTB.

5.2.1. Palynofacies 1 (MQ156–H24; upper Matinde Formation)

Palynofacies 1, extending from 497.32 m (MQ156) to 489.39 m (H24), is characterised by structured terrestrial phytoclasts (16–90%, mean 54%), subdominant SOP (4–77%, mean 33%), and subordinate

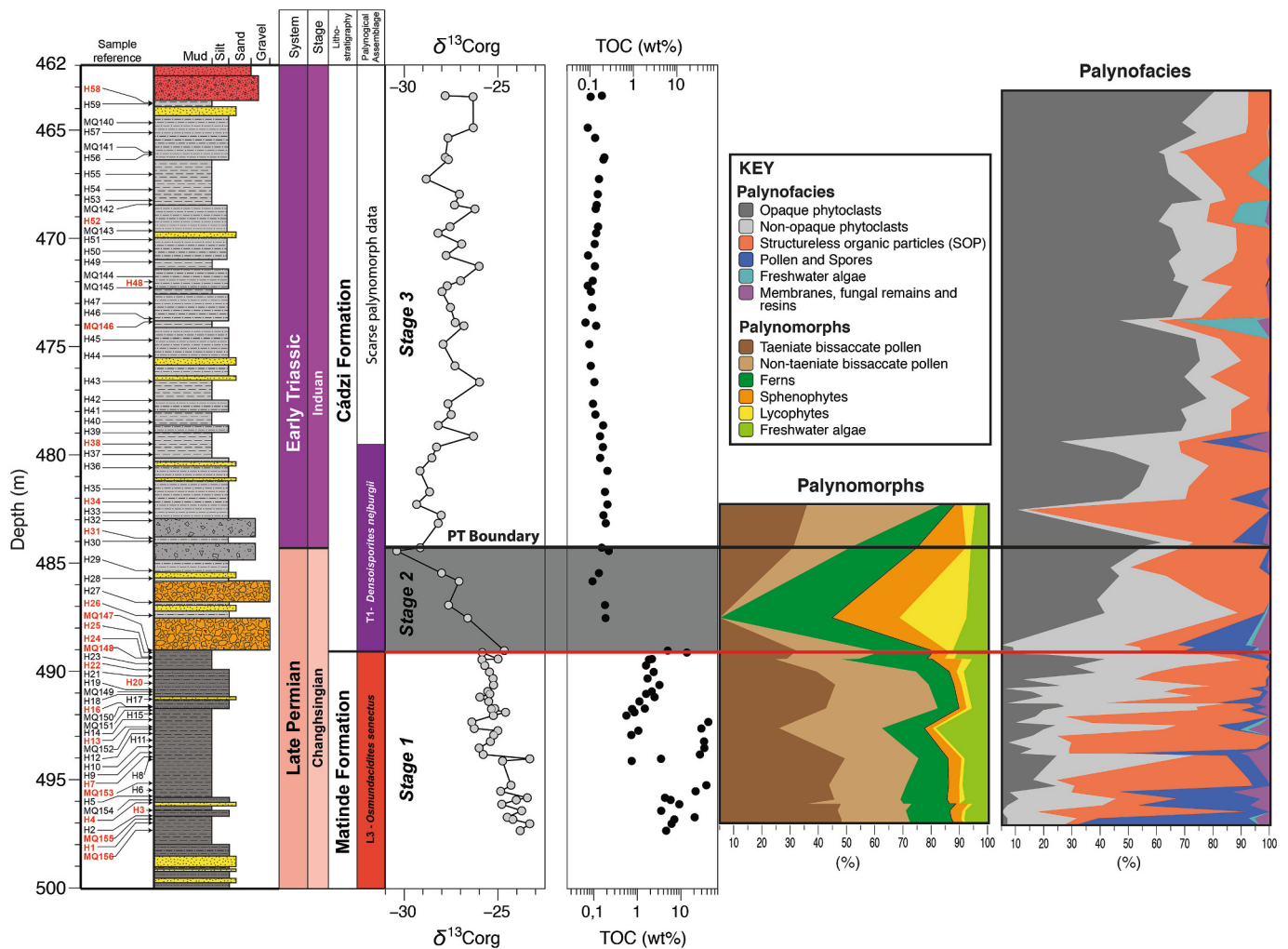


Fig. 7. Complete dataset of borehole CIMT-014 across the PTB section (carbon isotopes, TOC, palynomorphs and palynofacies). The sample references marked with red letters and numbers correspond to the palynological positive samples. The horizontal red line marks the position of the palynologically defined PTB. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

palynomorphs (0–66%, mean 13%) (Figs. 7 & 8). Within the phytoclast group, non-opaque fragments (mean 35%) and cuticles/membranes (mean 4%) are more abundant than opaque grains. Palynomorphs are mainly pollen grains (mean 15%), dominated by saccate forms (mean 12%), with fewer asaccate pollen (mean 3%) and spores (mean 3%). SOP is common, comprising angular to subangular particles that appear dark brown to black in transmitted light and show no fluorescence under UV light.

5.2.2. Palynofacies 2 (H25–H58; lowermost Cádzi Formation)

Palynofacies 2, from 489.09 m (H25) to 463.37 m (H58), is also phytoclast-dominated but differs markedly from Palynofacies 1. Structured terrestrial phytoclasts account for 12–93.2% (mean 77%), with SOP reduced to 6–88% (mean 20%) and palynomorphs to 0–29.6% (mean 4%) (Figs. 7 & 8). Opaque phytoclasts are the dominant component (mean 58%), whereas non-opaque grains remain common (mean 18%). Palynomorphs are rare to common (ca. 1–7%), including spores (mean 3%), asaccate pollen (mean 1%), saccate pollen (mean 5%) and freshwater algae (mean 1–2%). Compared with Palynofacies 1, the proportion of sharply bounded, subangular SOP particles decreases (mean 20%), and total palynomorph concentrations decline markedly above the PTB.

An important change in palynomorph abundance occurs at the base of Palynofacies 2, between samples H24 and H34 (Fig. 7). First, there is a sharp decrease in pollen, and no pollen was observed in sample H24 (Table 2), followed by a recovery of pollen-producing plants by sample H34. The palynomorph counts above sample H34 constitute less than 5% of all particulate organic matter and are unreliable for statistical analysis. However, their occurrence in this part of the core is shown in Fig. 4.

5.3. Organic carbon stable isotopes

The $\delta^{13}\text{C}_{\text{org}}$ record from CIMT-014 (Fig. 7; Table 1) was divided into three stages to facilitate comparison with lithostratigraphy and palynostratigraphy.

5.3.1. Stage 1 – Uppermost Permian (Matinde Formation; MQ156–H24)

Stage 1 comprises samples from 497.32 m (MQ156) to 489.39 m (H24) within the upper Matinde Formation. $\delta^{13}\text{C}_{\text{org}}$ values show a slight overall decrease with minor oscillations, from –23.8‰ at 497.32 m to –25.0‰ at 489.39 m, where the PTB is placed based on palynological and lithological criteria.

5.3.2. Stage 2 – Lowermost Triassic (Induan; H25–H30)

Stage 2 extends from the palynologically defined PTB at 489.39 m (H24) to 484.40 m (H30). The decreasing trend observed in Stage 1 continues and culminates in a pronounced negative excursion, with $\delta^{13}\text{C}_{\text{org}}$ values reaching a minimum of –30.4‰ at 484.40 m (H30), approximately 4.5 m above the palynologically defined PTB (Fig. 7). The Permian–Triassic boundary is placed at sample H30. Within Stage 2, the difference between maximum and minimum $\delta^{13}\text{C}_{\text{org}}$ values is 5.4‰.

5.3.3. Stage 3 – Lower Triassic (Induan; H30–H58)

Stage 3 includes samples from 484.40 m (H30) to 463.37 m (H58), all of Induan age. $\delta^{13}\text{C}_{\text{org}}$ values in this interval range from –30.0 to –26.0‰, with a mean of –27.61‰. No clear long-term trend is apparent; instead, values fluctuate within this generally low range throughout the interval.

5.4. Total organic carbon

TOC contents show a strong contrast between the organic-rich sediments of $\delta^{13}\text{C}_{\text{org}}$ Stage 1 and the organic-poor sediments of Stages 2 and 3 (Fig. 7; Table 1).

In Stage 1 (uppermost Permian; MQ156–H24), TOC values are highly

variable, ranging from 0.56 to 42.7 wt%. Most samples have TOC >1 wt%, with the highest values (>30 wt%) recorded in carbonaceous mudstones and coal-bearing intervals, indicating that the mudstones in this part of the borehole are generally rich in organic matter.

In contrast, Stages 2 and 3 (Induan; H25–H58) are characterised by a sharp, sustained decline in TOC. At the base of Stage 2, TOC values of 13.7 wt% (H25) and 5.0 wt% (MQ147) drop abruptly to 0.17 wt% at H26. Above this level, TOC remains consistently low throughout Stages 2 and 3, ranging from 0.07 to 0.21 wt%. This indicates a transition to organic-lean sediments in the lowermost Triassic succession.

In summary, across the 500–462 m interval of CIMT-014, the integrated datasets document a coordinated set of changes at the Permian–Triassic transition. The upper Matinde Formation (Stage 1) comprises organic-rich, coal-bearing mudstones and siltstones with glossopterid-dominated L3 palynofloras, phytoclast-rich palynofacies with abundant non-opaque plant debris and pollen, relatively high TOC values, and moderately negative $\delta^{13}\text{C}_{\text{org}}$ values (–23.8 to –25.0‰). At the palynologically defined PTB (H24) and immediately above, $\delta^{13}\text{C}_{\text{org}}$ values fall sharply to a minimum of –30.4‰ (Stage 2), coinciding with the disappearance of coal, the decline of taeniate bisaccate pollen (including *Striatopodocarpites* spp.), the rise of lycophyte-dominated T1 spore assemblages, a shift to phytoclast assemblages dominated by opaque particles, and an abrupt drop in TOC to <0.2 wt%. In the overlying Induan interval (Stage 3), palynomorphs become sparse to absent, palynofacies remain dominated by opaque phytoclasts, $\delta^{13}\text{C}_{\text{org}}$ values remain persistently low (–30 to –26‰), and TOC remains uniformly low, indicating suppressed organic accumulation throughout the earliest Triassic. This reflects a change in the depositional system from a low-energy mud-siltstone setting to a high-energy fluvial system, thereby diluting organic matter.

6. Discussion

6.1. Depositional evolution across the PTB

The uppermost Matinde Formation in CIMT-014 (500–489 m) comprises thinly interbedded, cross-laminated sandstones and organic-rich siltstones and mudstones, with thin coal seams (Fig. 5). Centimetre-scale, normally graded, cross-laminated sandstones record low-flow-regime traction currents, whereas laminated siltstones and mudstones were deposited by suspension fallout during waning floods. Together with coal and carbonaceous mudstones, these features are consistent with deposition on low-energy alluvial floodplains, where thin distal crevasse-splay sand bodies prograded into waterlogged, peat-bearing floodbasins and abandoned channels (e.g. Kedzior, 2016; Collinson et al., 2019). This interpretation aligns with previous work on the Matinde Formation elsewhere in the Moatize–Minjova Sub-Basin (Lopes et al., 2021b; Fernandes et al., 2024a) and corresponds to isotopic Stage 1, characterised by high TOC and Glossopterid-rich L3 palynofloras.

This latest Permian floodplain succession is abruptly truncated at 489.0 m by a 1.5 m-thick, erosive-based conglomerate composed of angular to sub-angular, pebble- to very coarse sand-sized clasts, predominantly basement-derived metamorphic lithologies and quartz, with rare intraformational coal and carbonaceous mudstone fragments. The conglomerate displays poorly sorted, clast-supported to matrix-supported fabrics and reverse-to-normal grading, indicating rapid deposition from high-density, viscous flows. Overlying this basal bed is a ~5 m-thick package of interbedded conglomerates, sandstones and thin siltstones, including matrix-supported conglomerates lacking clear grading. These characteristics are typical of debris-flow and cohesive debris-flow deposits in alluvial settings (Nemec and Steel, 1984; Jorgensen and Fielding, 1999) and suggest a short-lived episode of high-energy, gravity-driven sedimentation at the Matinde–Cádzi formations boundary.

Importantly, there is no evidence of prolonged subaerial exposure immediately beneath the conglomerate (e.g., palaeosols, deep

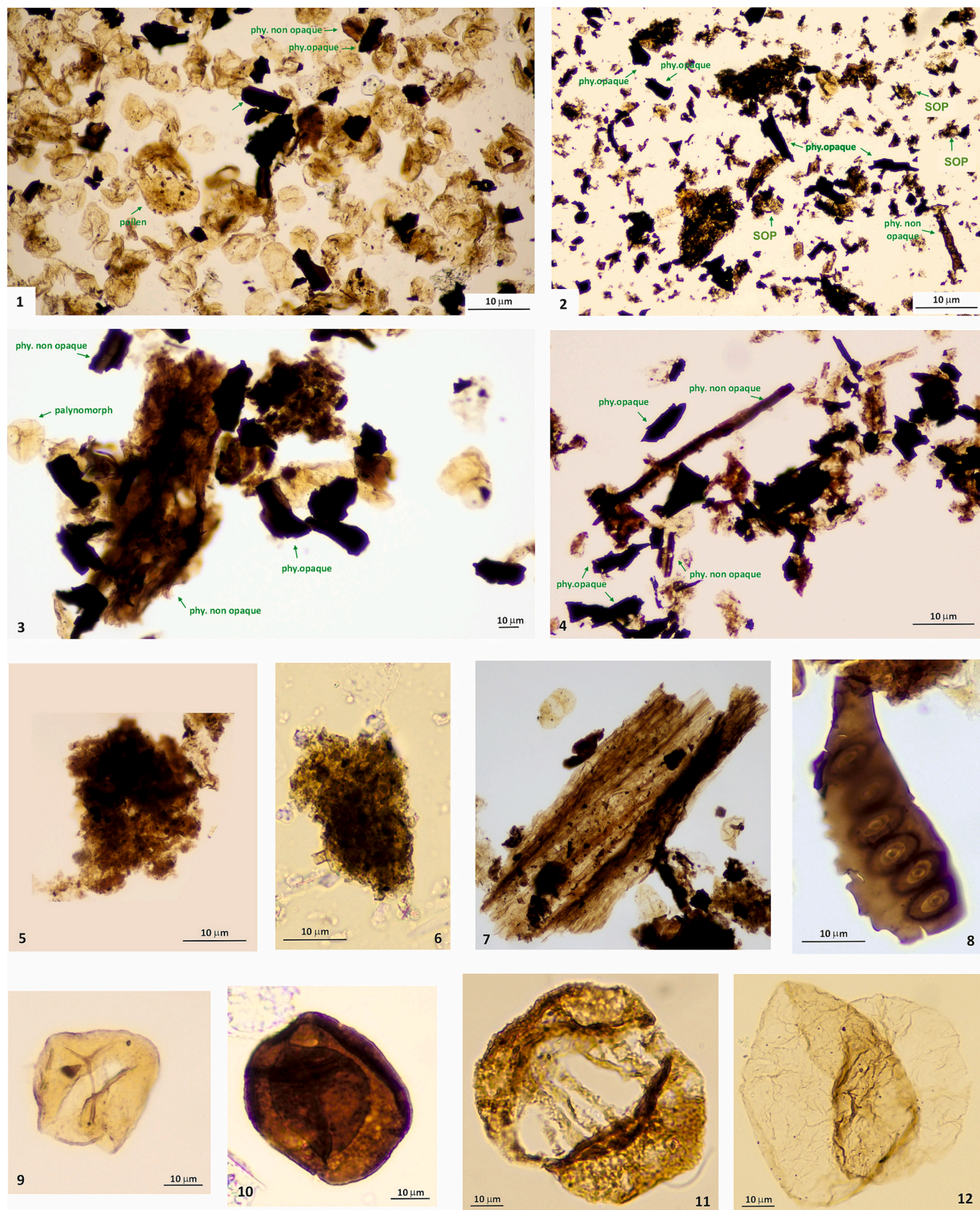


Fig. 8. Illustration of the palynofacies groups documented in this study 1–4. Palynofacies general view: 1. Palynofacies 1, sample MQ156; 2. Palynofacies 2, sample H25; 3. sample MQ147; 4. sample H19; 5–6. Structureless organic particles (SOP): 5. sample H25; 6. sample MQ142; 7–8. Non-opaque phytoclasts: 7. sample H25; 8. sample MQ147; 9–12. Palynomorph group: 9. Spore: sample H24; 10. Spore: sample H38; 11. Saccate pollen grain, sample H38; 12. Algae: sample MQ146.

weathering profiles, or thick intraclast lags), and the underlying carbonaceous mudstones retain their fine lamination. Although the conglomerate's erosive base necessarily implies some time condensation and sediment removal, the absence of clear pedogenic or angular unconformities suggests that any hiatus was short relative to the temporal resolution of the palynostratigraphic record. We therefore interpret the PTB interval in CIMENT-014 as largely continuous, with the conglomerates recording an abrupt but not necessarily long-lived perturbation of the fluvial system.

Above the conglomeratic interval, from ~483 to 463.3 m depth, the succession comprises a ~20 m-thick package of grey siltstones and mudstones interbedded with thin, parallel-laminated fine sandstones. Coal and carbonaceous laminae are absent; TOC is uniformly low, and palynofacies are dominated by opaque phytoclasts, with sparse Induan microfloras at the base (H34, MQ141). These features are consistent with quiet, relatively deep-water deposition in a lacustrine or floodplain-pond setting, and/or strong oxidation of organic matter at or near the sediment–water interface.

At ~463.3 m, this fine-grained interval is sharply truncated by a thick conglomerate marking the onset of stacked fining-upward cycles dominated by conglomerate and coarse sandstone, with only subordinate mudrocks. The overlying Cádzi Formation succession has been interpreted as having been deposited by high-energy, bedload-dominated braided river systems, with its cyclicity linked to rift-related tectonic activity (Fernandes et al., 2025). Although tectonism likely influenced accommodation and sediment supply during the Early Triassic, the specific transition recorded across the PTB in CIMENT-014, from peat-bearing meandering-style floodplains to debris-flow conglomerates, lacustrine fines, and ultimately braided fluvial systems, is best explained by the combined effects of climatic change and vegetation collapse. In particular, the loss of dense trees and shrubs cover and associated soil pedogenic structures, and horizonation would have increased runoff, sediment yield, and hydrological variability, preconditioning the system for debris-flow generation and favouring sandy, laterally unstable channels under increasingly arid, seasonally variable climatic conditions (Retallack, 2021).

Shifts from meandering, coal-bearing fluvial systems to high-energy, sand-dominated braided systems across the PTB, accompanied by the end of peat formation and increased sediment flux, have been documented in a range of continental basins, including the Sydney and Bowen basins of eastern Australia, the Karoo Basin of South Africa, and PTB successions in China and Antarctica (Ward et al., 2005; Fielding et al., 2019, 2021; Zhu et al., 2019; Cornamusini et al., 2023; Zhang et al., 2023). These changes are widely interpreted as responses to rapid global environmental perturbations linked to Siberian Traps volcanism, which drove climate warming, intensified hydrological extremes, and caused vegetation loss and soil erosion. The CIMENT-014 record thus provides important corroborating evidence from the KZBM that rift-margin terrestrial depositional systems in southeastern Gondwana were highly sensitive to the end-Permian global crisis.

6.2. Potential controls on $\delta^{13}\text{C}_{\text{org}}$ values

Bulk $\delta^{13}\text{C}_{\text{org}}$ values of sedimentary rocks can be influenced by both primary controls (e.g., isotopic composition of the dissolved inorganic carbon pool, vegetation types, and productivity) and secondary processes, including selective preservation, diagenesis, and thermal maturation (Tissot and Welte, 1984; Hayes, 1993; Pancost and Sinninghe Damsté, 2014; Peters et al., 2018). During burial heating, preferential release of isotopically light carbon (^{12}C) as CO_2 , CH_4 , and hydrocarbons can enrich the residual organic matter in ^{13}C and shift $\delta^{13}\text{C}_{\text{org}}$ towards less negative values. Variations in kerogen type and the relative contributions of terrestrial versus marine sources can also affect $\delta^{13}\text{C}_{\text{org}}$.

In CIMENT-014, vitrinite reflectance data indicate thermal maturities ranging from the late oil window (1.5% Ro) towards the base, where the PTB interval is located (Galasso et al., 2019b). Within the ~40 m

interval encompassing the PTB, however, VR values show no variation, and palynofacies analysis indicates that the organic matter is overwhelmingly terrestrial, dominated by structured phytoclasts, degraded terrestrial SOP and sporomorphs, consistent with type III–IV kerogens. Experimental studies demonstrate that the $\delta^{13}\text{C}$ of type III kerogen is relatively insensitive to increased thermal maturation across the oil-to-early gas window (Bjørøy et al., 1992), and no systematic correlation is observed between $\delta^{13}\text{C}_{\text{org}}$ and either TOC or VR in our dataset.

These observations suggest that neither differences in thermal maturity nor preferential loss of ^{12}C -rich components during diagenesis can account for the ~5.4‰ negative excursion observed across the PTB in CIMENT-014. Although some contribution from changes in organic-matter source and preservation (e.g. varying proportions of woody vs herbaceous or algal material) cannot be ruled out, the magnitude and stratigraphic coherence of the $\delta^{13}\text{C}_{\text{org}}$ shift imply that it primarily records changes in the isotopic composition of primary organic matter, driven by perturbations to the coupled atmosphere–ocean carbon cycle during the Permian–Triassic transition (Payne et al., 2004; Korte and Kozur, 2010; Schobben et al., 2016).

6.3. Latest Permian (Stage 1): humid coal swamps under progressive carbon-cycle perturbation

The latest Permian L3 - *Osmundacidites senectus* assemblages in CIMENT-014 document a diverse, well-structured terrestrial ecosystem dominated by glossopterid and other gymnospermous trees, with abundant taeniate bisaccate pollen (*Protohaploxylinus*, *Striatopodocarpites*), non-glossopterid forms (e.g. *Lunatisporites*, *Guttulapollenites*, *Lueckisporites*, *P. microcorpus*), and a background of fern and sphenophyte spores. Together with coal seams, carbonaceous mudstones, and a palynofacies rich in non-opaque phytoclasts and pollen, this assemblage reflects extensive peat-forming vegetation in waterlogged floodplain environments under warm, humid climatic conditions (Fig. 9).

During isotopic Stage 1, $\delta^{13}\text{C}_{\text{org}}$ values show a weak but consistent decrease from -23.8‰ at the base of the studied interval to -25.0‰ at the palynologically defined PTB (H24). Palynofacies composition changes little across this interval, and TOC remains generally high, indicating that the trend is not primarily driven by a shift in OM source or preservation. We interpret this progressive ^{13}C depletion as the local expression of an initial, pre-PTB perturbation of the global carbon cycle, consistent with the onset of Siberian Traps magmatic activity and associated thermogenic degassing documented in high-precision geochronological and modelling studies (Burgess et al., 2017; Ganino and Arndt, 2009; Ogden and Sleep, 2012; Shen et al., 2023; Wu et al., 2023a, 2023b). The gradual addition of ^{12}C -rich CO_2 and CH_4 to the atmosphere–ocean system prior to the main extinction pulse would have driven a slow decline in the $\delta^{13}\text{C}$ of the global carbon reservoirs, recorded in both marine carbonates and terrestrial organic matter (Korte and Kozur, 2010; Dal Corso et al., 2022).

6.4. Earliest Triassic (Stage 2): negative $\delta^{13}\text{C}_{\text{org}}$ excursion

The earliest Triassic T1 - *Densioisporites neburgii* assemblages (H25–H34) mark a profound restructuring of the terrestrial flora. Taeniate bisaccate pollen, including *Striatopodocarpites* and non-glossopterid gymnosperms, declines sharply and eventually disappears, coinciding with the last coal beds and indicating a sharp reduction of *Glossopteris*-dominated peat-forming ecosystems. In their place, spores of opportunistic lycopphytes and ferns (e.g. *Densioisporites*, *Lundbladispora*, *Cyclogranisporites*, *Horriditrites*) become relatively more abundant. This spore-rich, gymnosperm-poor assemblage reflects a stressed, low-diversity “survival” flora, similar to those documented in other Gondwanan PTB sections (Hermann et al., 2011) (Fig. 9). However, the spore spike, corresponding to sample H26, was short-lived, as shown by a recovery of palynomorph percentages similar to those of isotope Stage 1, with pollen more abundant than lycopphytes and ferns

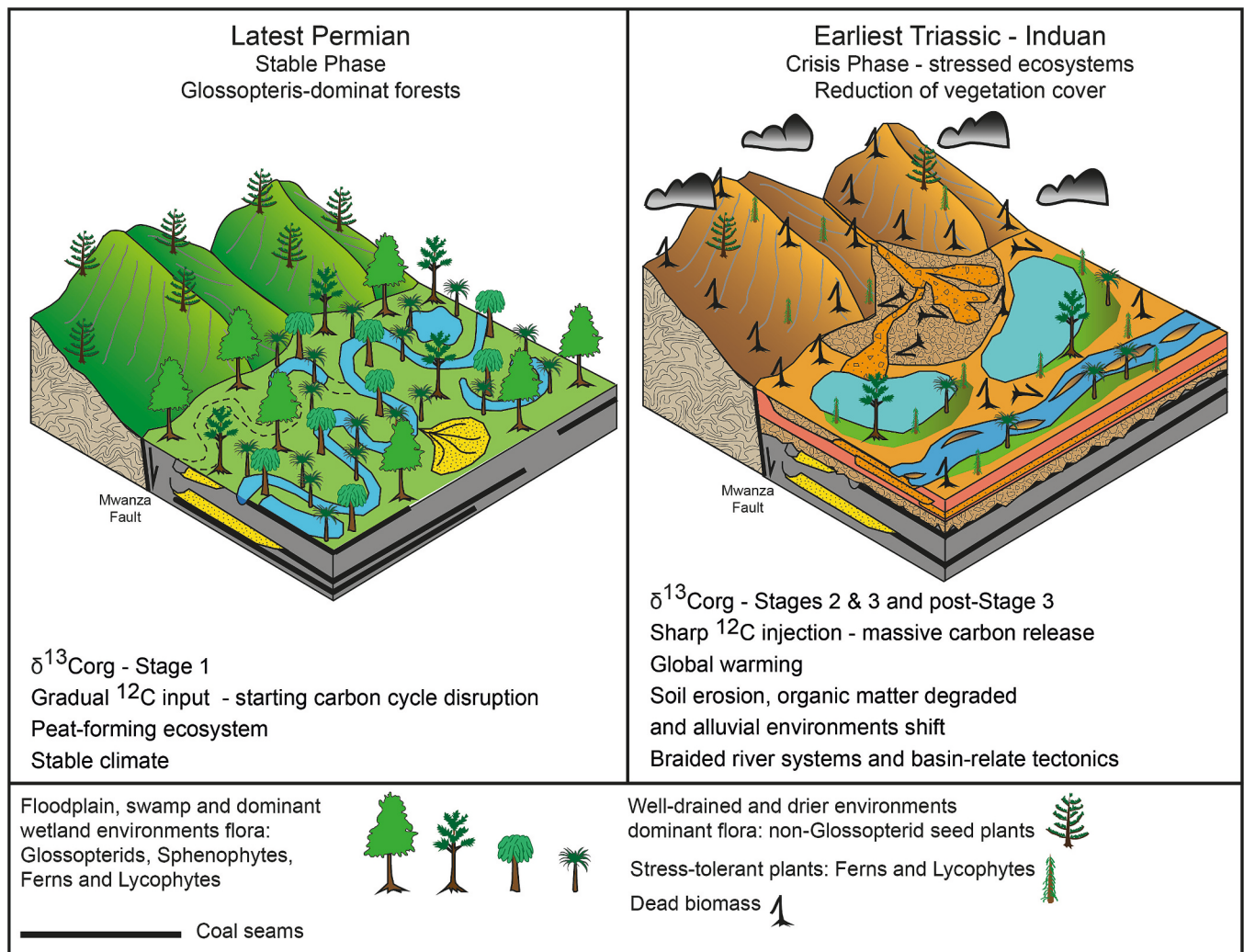


Fig. 9. The main features of the Permian-Triassic transition in the N'Condédzi Coalfield.

(Fig. 7).

The weakly decreasing $\delta^{13}\text{C}_{\text{org}}$ trend initiated in Stage 1 continues into Stage 2 and culminates in a pronounced negative excursion, with values dropping to -30.4‰ at H30. This represents a 5.4‰ shift relative to the most ^{13}C -enriched latest Permian values and falls within the range of negative $\delta^{13}\text{C}_{\text{org}}$ excursions reported from other continental Gondwana successions (e.g., Sarkar et al., 2003; Saitoh and Isozaki, 2021). The main excursion coincides with a drastic reduction in TOC (to $<0.2\text{ wt\%}$ above H26), the disappearance of coal, a shift to palynofacies dominated by opaque phytoclasts, and a floral turnover from glossopterid-dominated to lycophyte-dominated assemblages, indicating a tight coupling between perturbations of the carbon cycle and the terrestrial ecosystem.

Given the lack of evidence for significant diagenetic overprint and the magnitude of the shift, we interpret the Stage 2 excursion as indicating a major input of ^{12}C -enriched carbon into the exogenic carbon cycle, most plausibly from a combination of magmatic CO_2 and thermogenic $\text{CH}_4\text{-CO}_2$ released during intrusive heating of organic-rich sediments associated with Siberian Traps emplacement (Svensen et al., 2009; Black et al., 2018; Wu et al., 2023a, 2023b). Secondary feedbacks, such as destabilisation of sedimentary methane reservoirs, may have further amplified warming and isotopic depletion (Krull and Retallack, 2000; Krull et al., 2000).

The negative carbon-isotope excursion across the PTB is one of the most distinctive chemostratigraphic markers in the Phanerozoic (Korte

and Kozur, 2010). Found in marine and terrestrial records worldwide, it reflects a major disturbance in the global carbon cycle linked to the end-Permian extinction (Shen et al., 2011a, 2011b; Payne and Clapham, 2012). Its widespread occurrence in both marine and continental strata, together with its close timing with biotic and environmental changes, makes it a key datum for PTB correlation (Korte and Kozur, 2010; Cui et al., 2017; Wu et al., 2023a, 2023b). Although the intensity and exact position vary due to local factors, its consistent presence across various environments provides a vital chronostratigraphic framework, especially where biostratigraphic markers are limited, as in our study, which relies solely on palynology and has low recovery of Triassic-aged rocks. Therefore, we draw the chronostratigraphic Permian-Triassic boundary in the core sequence at the location of sample H30, where the curve shows the most negative values. We use this negative shift to approximate the PTB in our section, in comparison with the carbon isotope minimum that precedes the PTB at the GSSP in Meishan (Yin et al., 2001).

The minimum $\delta^{13}\text{C}_{\text{org}}$ value is stratigraphically offset from the palynologically defined PTB, occurring several meters above the boundary. This may reflect a combination of factors, including: (i) the offset between floral perturbation and peak carbon-cycle perturbation may indicate diachrony between local terrestrial floral turnover and the marine GSSP-defined Permian-Triassic boundary; and (ii) local stratigraphic complexity associated with debris-flow conglomerates and erosion, leading to slight condensation of the isotope record.

Nonetheless, sedimentological evidence for largely conformable contacts, together with the absence of thick palaeosols or major lacunae, suggests that this offset is modest and that the PTB interval in CIMT-014 preserves the main structure of the global carbon-isotope signal.

6.5. Induan (Stage 3): Early Triassic Environmental Crisis

Isotopic Stage 3 (H30–H58) corresponds to an ~20 m-thick interval of organic-poor, fine-grained Induan sediments within the lower Cádzi Formation. With the exception of samples H31 and H34 at the base of this isotope stage, whose palynological assemblages are dominated by taeniate and non-taeniate bisaccate pollen, the palynology of the other samples is extremely sparse or barren; when present, they are dominated by rare lycophte spores (*Densosporites*, *Lundbladispora*) and rare gymnosperm pollen (Fig. 4). This pattern is consistent with a severely stressed, low-diversity ecosystem in the immediate aftermath of the extinction, and spore spikes documented in other PTB successions (Stemmerik et al., 2001; Hochuli et al., 2010; Looy et al., 2001; Vajda et al., 2020; Mays and McLoughlin, 2022) (Fig. 9).

Above the Stage 2 minimum, $\delta^{13}\text{C}_{\text{org}}$ values remain persistently low throughout Stage 3, fluctuating between -30 and -26‰ (mean -27.6‰) with no clear recovery trend. TOC remains uniformly low (0.1 – 0.2 wt%), and palynofacies are dominated by opaque phytoclasts, which may include a substantial charcoal component. Elevated wildfire activity across the PTB has been documented in a range of basins (Shen et al., 2011a, 2011b; Song et al., 2022; Cai et al., 2021; Vajda et al., 2020), and the abundance of opaque phytoclasts in CIMT-014 is consistent with enhanced combustion of terrestrial biomass. Experimental work indicates that charring of C_3 plant material leads to at most a small additional ^{13}C depletion ($\leq 1.3\text{‰}$; Turney et al., 2006), insufficient to explain the full magnitude and persistence of the observed $\delta^{13}\text{C}_{\text{org}}$ values. Therefore, even if all opaque phytoclasts were charcoal-like woody material resulting from intense wildfires, they alone could not cause the isotopic depletion.

Extremely negative $\delta^{13}\text{C}_{\text{org}}$ values in earliest Triassic palaeosols from Antarctica (down to -42‰) have been interpreted as evidence of extensive methanotrophy under high atmospheric CH_4 levels (Krull and Retallack, 2000). By analogy, the persistently low $\delta^{13}\text{C}_{\text{org}}$ values in CIMT-014 likely indicate sustained elevated atmospheric concentrations of ^{12}C -rich greenhouse gases, including CO_2 and CH_4 , during the early Induan. These gases may have derived from protracted volcanic degassing, ongoing thermogenic decomposition of organic-rich strata (including underlying coals of the Moatize and Matinde formations), and biogenic recycling of organic carbon in stressed terrestrial ecosystems.

The combination of sustained $\delta^{13}\text{C}_{\text{org}}$ depletion, the collapse of coal-forming vegetation, and lacustrine-to-braided-fluvial depositional systems with low organic accumulation indicates that terrestrial environments in the NCC remained highly perturbed well into the Early Triassic. Persistently elevated greenhouse gas concentrations would have led to extreme climatic conditions, including high temperatures, increased hydrological variability, and potential soil acidification (Sephton et al., 2015), thereby inhibiting ecosystem recovery. The absence of a clear upward trend towards less negative $\delta^{13}\text{C}_{\text{org}}$ values and the appearance of more well preserved palynofloras in the overlying Olenekian succession (~150 m above the palynological PTB defined in Galasso et al., 2019b) support the view of a protracted recovery interval on land, consistent with patterns recognised in other Gondwanan and global records (Hochuli et al., 2010; Viglietti et al., 2021; Dal Corso et al., 2022; Smith et al., 2022).

Overall, the integrated sedimentological, palynological, palynofacies, and geochemical data from the CIMT-014 borehole constitute a rare PTB record of the rift-basins north of the Main Karoo Basin of South Africa. The PTB is marked by the negative excursion of the $\delta^{13}\text{C}_{\text{org}}$ curve, which is accompanied by environmental changes, namely the end of low-energy mud-siltstone fluvial systems where coal accumulated, to

the onset of high-energy fluvial systems that cause degradation of plant material prior to its deposition. Although local tectonics and basin configuration controlled the depositional style in the Permian in the Karoo basins of Mozambique (Fernandes et al., 2024a, 2024b), the negative excursion in the $\delta^{13}\text{C}_{\text{org}}$ curve links the changes to the end-Permian global crisis.

7. Conclusions

This study presents a high-resolution, multidisciplinary record of the Permian-Triassic transition from borehole CIMT-014 in the NCC, Mozambique, a terrestrial PTB succession from the Gondwana Karoo rift basins. The integration of sedimentology, palynostratigraphy, palynofacies, TOC, and $\delta^{13}\text{C}_{\text{org}}$ data allows a detailed reconstruction of environmental, ecological, and carbon-cycle changes across the PTB. The results demonstrate a transition from organic-rich, coal-bearing floodplain environments of the upper Matinde Formation to organic-poor conglomeratic, lacustrine, and braided-fluvial deposits of the lower Cádzi Formation.

The palynological record shows the decline of Glossopteris-dominated ecosystems and of gymnosperm pollen, followed by a brief rise in lycophte and fern. These shifts coincide with the loss of peat-forming environments, reduced organic matter, and major changes in fluvial systems. Palynofacies data reveal a move from plant debris to opaque phytoclasts and fewer palynomorphs.

This study describes a well-defined negative $\delta^{13}\text{C}_{\text{org}}$ excursion of approximately 5.4‰ . The magnitude, stratigraphic coherence, and close association with floral turnover and sedimentological change indicate that the isotopic signal primarily records a global perturbation of the carbon cycle rather than local diagenetic effects. The negative excursion is consistent with widespread carbon-cycle disruption linked to Siberian Traps magmatism and associated greenhouse-gas emissions, providing a robust chemostratigraphic marker for correlation with other Gondwanan and global PTB records.

The combined sedimentological and geochemical evidence indicates that terrestrial environments in the NCC were profoundly affected by the end-Permian crisis. The reduction increased erosion and sediment flux, the cessation of coal formation, and the establishment of high-energy fluvial systems reflect the interplay between climatic deterioration and regional tectonic processes. Although local tectonics influenced basin evolution, the synchrony between environmental changes and the carbon-isotope excursion demonstrates that the observed transformations were fundamentally linked to the global end-Permian environmental crisis.

CRediT authorship contribution statement

P. Fernandes: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Z. Pereira:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **J.E. Spangenberg:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation. **M. Mendes:** Writing – review & editing, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **G. Lopes:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis. **R.C.G.S. Jorge:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis. **L. Albardeiro:** Writing – review & editing, Visualization, Validation, Software, Investigation. **E. Font:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **T. Adatte:** Writing – review & editing, Validation, Investigation, Formal analysis. **T. Vennemann:** Writing – review & editing, Visualization, Validation, Resources, Methodology, Investigation. **J. Marques:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources,

Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this study.

Acknowledgements

This work was fully supported by the project PALEOCLIMOZ (PTDC/CTA-GEO/30082/ 2017), funded by Fundação para a Ciência e Tecnologia (FCT), Portugal. The authors would like to acknowledge the funding provided by the FCT to the projects LA/P/0069/2020, awarded to the Associate Laboratory ARNET, UIDP/00350/2020, awarded to the CIMA of the University of the Algarve. R. Jorge acknowledges FCT, I.P./MCTES funding through national funds (PIDDAC): LA/P/0068/2020 (<https://doi.org/10.54499/LA/P/0068/2020>), UID/50019/2025 (<https://doi.org/10.54499/UID/50019/2025>), UID/PRR2/50019/2025 (<https://doi.org/10.54499/UID/PRR2/50019/2025>.) The authors would like to thank Coal India Africana, Limitada, and Gondwana Empreendimentos e Consultorias, Limitada for borehole access and complementary information. LNEG technician Irene Sousa is acknowledged for their laboratory support and sample preparation. P. Fernandes would like to especially thank the Gondwana staff from the Tete office, namely Alfredo Tembo, Tomé Eneia, Jorge Bettencourt and Humberto Lobo, for their help over the last few years. Lastly, we would like to acknowledge the comments and suggestions made on our manuscript by Dr. Elke Schneebeil and an anonymous reviewer, which greatly improved our work.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.palaeo.2026.114049>.

Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

References

- Achimo, M., Vasconcelos, L., Marques, J., Ferrara, M., 2014. Sedimentologia dos depósitos tilíticos do vale do Rio Murrongódzi, Bacia Carbonífera de Moatize – Minjova, Tete, Moçambique, 2^o Congresso Nacional de Geologia e 12^o Congresso de Geoquímica dos Países de Língua Portuguesa, Maputo, Moçambique, pp. 57–61.
- Afonso, R.S., 1984. Ambiente geológico dos carvões gondwanaicos de Moçambique — uma síntese. In: Lemos de Sousa, M.J. (Ed.), Symposium on Gondwana Coals, Lisbon, 1983. Proceedings and Papers. Comunicações dos Serviços Geológicos de Portugal, 70, pp. 205–214.
- Aftabuzzaman, M., Kaiho, K., Biswas, R.K., Liu, Y., Saito, R., Tian, L., Bhat, G.M., Chen, Z.-Q., 2021. End-Permian terrestrial disturbance followed by the complete plant devastation, and the vegetation proto-recovery in the earliest-Triassic recorded in coastal sea sediments. *Glob. Planet. Chang.* 205, 103621.
- Beerling, D.J., Harfoot, M., Lomax, B., Pyle, J.A., 2007. The stability of the stratospheric ozone layer during the end-Permian eruption of the Siberian Traps. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* 365, 1843–1866.
- Benton, M.J., Newell, A.J., 2014. Impacts of global warming on Permo-Triassic terrestrial ecosystems. *Gondwana Res.* 25, 1308–1337.
- Bhattacharya, S., Ankit, Y., Murthy, S., Kushwaha, V., 2021. Biotic response to environmental shift during the Permian-Triassic transition: assessment from organic geochemical proxies and palynomorphs in terrestrial sediments from Raniganj Sub-basin, India. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 576.
- Bjorøy, M., Hall, P.B., Hustad, E., Williams, J.A., 1992. Variation in stable carbon isotope ratios of individual hydrocarbons as a function of artificial maturity. *Org. Geochem.* 19, 89–105.
- Black, B.A., Neely, R.R., Lamarque, J.-F., Elkins-Tanton, L., Kiehl, J.T., Shields, C.A., Mills, M., Bardeen, C., 2018. Systemic swings in end-Permian climate from Siberian Traps carbon and sulfur outgassing - link to CESM model output, Supplement to: Black, BA et al. (2018): systemic swings in end-Permian climate from Siberian Traps carbon and sulfur outgassing. *Nat. Geosci.* 11 (12), 949–954. <https://doi.org/10.1038/s41561-018-0261-y>. PANGAEA.
- Bond, D.P.G., Wignall, P.B., 2014. Large igneous provinces and mass extinctions: an update. In: Keller, G., Kerr, A.C. (Eds.), *Volcanism, Impacts, and Mass Extinctions: Causes and Effects*. Geological Society of America (p. 0).
- Botha, J., Huttenlocker, A.K., Smith, R.M.H., Prevec, R., Viglietti, P., Modesto, S.P., 2020. New geochemical and palaeontological data from the Permian-Triassic boundary in the South African Karoo Basin test the synchronicity of terrestrial and marine extinctions. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 540, 109467.
- Burgess, S.D., Muirhead, J.D., Bowring, S.A., 2017. Initial pulse of Siberian Traps sills as the trigger of the end-Permian mass extinction. *Nat. Commun.* 8, 164.
- Cai, Y.-f., Zhang, H., Cao, C.-q., Zheng, Q.-f., Jin, C.-f., Shen, S.-z., 2021. Wildfires and deforestation during the Permian-Triassic transition in the southern Junggar Basin, Northwest China. *Earth-Sci. Rev.* 218, 103670.
- Carvalho, L.H.B., 1977. Formações vulcânicas de Carinde, Tete, Moçambique. Tese de doutoramento. Instituto Superior Técnico, Lisboa, Portugal. , 213 pp.
- Collinson, J.D., Mountney, N., Thompson, D.B., 2019. *Sedimentary Structures*, 4th edition. Dunedin Academic Press, London, p. 204.
- Cornamusi, G., Zurl, L., Liberato, G.P., Corti, V., Gulbranson, E.L., Perotti, M., Sandroni, S., 2023. A lithostratigraphic reappraisal of a Permian-Triassic fluvial succession at Allan Hills (Antarctica) and implications for the terrestrial end-Permian extinction event. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 627, 111741.
- Cui, Y., Bercovici, A., Yu, J., Kump, L.R., Freeman, K.H., Su, S., Vajda, V., 2017. Carbon cycle perturbation expressed in terrestrial Permian-Triassic boundary sections in South China. *Glob. Planet. Chang.* 148, 272–285.
- Dal Corso, J., Song, H., Callegaro, S., Chu, D., Sun, Y., Hilton, J., Grasby, S.E., Joachimski, M.M., Wignall, P.B., 2022. Environmental crises at the Permian-Triassic mass extinction. *Nat. Rev. Earth Environ.* 3, 197–214.
- Erwin, D.H., 1994. The Permo-Triassic extinction. *Nature* 367, 231–236.
- Fernandes, P., Cogné, N., Chew, D.M., Rodrigues, B., Jorge, R.C.G.S., Marques, J., Jamal, D., Vasconcelos, L., 2015. The thermal history of the Karoo Moatize-Minjova Basin, Tete Province, Mozambique: an integrated vitrinite reflectance and apatite fission track thermochronology study. *J. Afr. Earth Sci.* 112, 55–72.
- Fernandes, P., Hancox, P.J., Mendes, M., Pereira, Z., Lopes, G., Marques, J., Jorge, R.C.G.S., Albardeiro, L., 2024a. The age and depositional environments of the lower Karoo Moatize Coalfield of Mozambique: insights into the postglacial history of Central Gondwana. *Palaeoworld* 33, 979–996.
- Fernandes, P., Jorge, R.C.G.S., Albardeiro, L., Chew, D., Drakou, F., Pereira, Z., Marques, J., 2024b. Detrital zircon U-Pb geochronology of the Moatize and N'Condédzi coalfields, Zambezi Karoo Basin of Mozambique: implications for provenance, sediment dispersal and basin evolution. *J. Afr. Earth Sci.* 220, 105458.
- Fielding, C.R., Frank, T.D., McLoughlin, S., Vajda, V., Mays, C., Tevyaw, A.P., Winguth, A., Winguth, C., Nicoll, R.S., Bocking, M., Crowley, J.L., 2019. Age and pattern of the southern high-latitude continental end-Permian extinction constrained by multiproxy analysis. *Nat. Commun.* 10.
- Fielding, C.R., Frank, T.D., Tevyaw, A.P., Savatic, K., Vajda, V., McLoughlin, S., Mays, C., Nicoll, R.S., Bocking, M., Crowley, J.L., 2021. Sedimentology of the continental end-Permian extinction event in the Sydney Basin, eastern Australia. *Sedimentology* 68, 30–62.
- Galasso, F., Fernandes, P., Montesi, G., Marques, J., Spina, A., Pereira, Z., 2019a. Thermal history and basin evolution of the Moatize - Minjova Coal Basin (N'Condédzi sub-basin, Mozambique) constrained by organic maturation levels. *J. Afr. Earth Sci.* 153, 219–238.
- Galasso, F., Pereira, Z., Fernandes, P., Spina, A., Marques, J., 2019b. First record of Permo-Triassic palynomorphs of the N'condedzi sub-basin, Moatize-Minjova coal basin, Karoo supergroup, Mozambique. *R. Micropaleontol.* 64.
- Ganino, C., Arndt, N., 2009. Climate changes cause by degassing of sediments during the emplacement of large igneous provinces. *Geology* 37, 323–326.
- Gastaldo, R.A., Bamford, M.K., 2023. The influence of taphonomy and time on the paleobotanical record of the Permian-Triassic transition of the Karoo basin (and elsewhere). *J. Afr. Earth Sci.* 204, 104960.
- Gastaldo, R.A., Adendorff, R., Bamford, M., Labandeira, C.C., Neveling, J., Sims, H., 2005. Taphonomic Trends of Macrofloral Assemblages Across the Permian-Triassic Boundary, Karoo Basin, South Africa. *PALAIOS* 20, 479–497.
- Gastaldo, R.A., Kamo, S.L., Neveling, J., Geissman, J.W., Bamford, M., Looy, C.V., 2015. Is the vertebrate-defined Permian-Triassic boundary in the Karoo Basin, South Africa, the terrestrial expression of the end-Permian marine event? *Geology* 43, 939–942.
- Gastaldo, R.A., Kamo, S.L., Neveling, J., Geissman, J.W., Looy, C.V., Martini, A.M., 2020. The base of the *Lystrosaurus* Assemblage Zone, Karoo Basin, predates the end-Permian marine extinction. *Nat. Commun.* 11, 1428.
- Gastaldo, R.A., Neveling, J., Kamo, S.L., Akatapo, S.O., Geissman, J.W., Rochín-Bañaga, H., Tabor, N., 2026. Conundrums of Wapadsberg Pass and other locales in the Karoo Basin, South Africa: the death knell of the end-Permian vertebrate-extinction model. *Geol. Soc. Am. Bull.* <https://doi.org/10.1130/B38563.1>.
- Götz, A.E., Hancox, P.J., Lloyd, A., 2017. Permian climate change recorded in palynomorph assemblages of Mozambique (Moatize Basin, eastern Tete Province). *Acta Palaeobot.* 57, 3–11.
- Graham, G., Macey, P., Ingram, B., Roberts, M., Armstrong, R., Hokada, T., Shiraiishi, K., Jackson, C., Bisnath, A., Manhica, V., 2008. Terrane correlation between Antarctica, Mozambique and Sri Lanka; comparison of geochronology, lithology, structure and metamorphism and possible implications for the geology of southern Africa and Antarctica. *Geol. Soc. Lond. Spec. Publ.* 308, 91–119.
- GTK-Consortium, 2006. Map Explanation, Sheets 1630–1634, 1732–1734, 1832–1834 and 1932–1934. Geology of Degree Sheets, Mecumbura, Chioco, Tete, Tambara, Guro, Chemba, Manica, Catandica, Gorongosa, Rotanda, Chimoio and Beira,

- Mozambique. Direção Nacional de Geologia, Ministério dos Recursos Minerais, Maputo, Moçambique, p. 411.
- Hayes, J.M., 1993. Factors controlling ^{13}C contents of sedimentary organic compounds: principles and evidence. *Mar. Geol.* 113 (1–2), 111–125.
- Hermann, E., Hochuli, P.A., Bucher, H., Brühwiler, T., Hautmann, M., Ware, D., Roohi, G., 2011. Terrestrial ecosystems on North Gondwana following the end-Permian mass extinction. *Gondwana Res.* 20, 630–637.
- Hiller, N., Stavrakis, N., 1984. Permo-Triassic fluvial systems in the southeastern Karoo Basin, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 45, 1–21.
- Hochuli, P.A., Hermann, E., Vigran, J.O., Bucher, H., Weissert, H., 2010. Rapid demise and recovery of plant ecosystems across the end-Permian extinction event. *Glob. Planet. Chang.* 74, 144–155.
- Hochuli, P.A., Sanson-Barrera, A., Schneebeil-Hermann, E., Bucher, H., 2016. Severe crisis overlooked—Worst disruption of terrestrial environments postdates the Permian–Triassic mass extinction. *Sci. Rep.* 6 (1), 28372. <https://doi.org/10.1038/srep28372>.
- Jamal, D.L., 2005. Crustal Studies Across Selected Geotranssects in NE Mozambique: Differentiating Between Mozambican (~ Kibaran) and Pan-African Events, With Implications for Gondwana Studies. University of Cape Town, pp. 1–730.
- Jha, N., Aggarwal, N., Mishra, S., 2018. A review of the palynostratigraphy of Gondwana sediments from the Godavari Graben, India: global comparison and correlation of the Permian–Triassic palynoflora. *J. Asian Earth Sci.* 163.
- Jorgensen, P.J., Fielding, C.R., 1999. Debris-flow deposits in an alluvial-plain succession; the Upper Triassic Callide Coal measures of Queensland, Australia. *J. Sediment. Res.* 69, 1027–1040.
- Kedzier, A., 2016. Reconstruction of an early Pennsylvanian fluvial system based on geometry of sandstone bodies and coal seams: the Zabrze Beds of the Upper Silesia Coal Basin, Poland. *Ann. Soc. Geol. Pol.* 84, 437–472.
- Korte, C., Kozur, H.W., 2010. Carbon-isotope stratigraphy across the Permian–Triassic boundary: a review. *J. Asian Earth Sci.* 39, 215–235.
- Krull, E., Retallack, G., 2000. delta C-13 depth profiles from paleosols across the Permian–Triassic boundary: evidence for methane release. *Geol. Soc. Am. Bull.* 112, 1459–1472.
- Krull, E.S., Retallack, G.J., Campbell, H.J., Lyon, G.L., 2000. 613Corg chemostratigraphy of the Permian–Triassic boundary in the Maitai Group, New Zealand: evidence for high-latitude methane release. *N. Z. J. Geol. Geophys.* 43, 21–32.
- Lindström, S., McLoughlin, S., 2007. Synchronous palynofloristic extinction and recovery after the end-Permian event in the Prince Charles Mountains, Antarctica: implications for palynofloristic turnover across Gondwana. *Rev. Palaeobot. Palynol.* 145, 89–122.
- Liu, F., Peng, H., Bomfleur, B., Kerp, H., Zhu, H., Shen, S., 2020. Palynology and vegetation dynamics across the Permian–Triassic boundary in southern Tibet. *Earth Sci. Rev.* 209.
- Liu, F., Peng, H., Marshall, J.E.A., Lomax, B.H., Bomfleur, B., Kent, M.S., Fraser, W.T., Jardine, P.E., 2023. Dying in the sun: direct evidence for elevated UV-B radiation at the end-Permian mass extinction. *Sci. Adv.* 9, eabo6102.
- Looy, C.V., Twitchett, R.J., Dilcher, D.L., Van Konijnenburg-Van Cittert, J.H.A., Visscher, H., 2001. Life in the end-Permian dead zone. *Proc. Natl. Acad. Sci. USA* 98, 7879–7883.
- Lopes, G., Pereira, Z., Fernandes, P., Marques, J., Mendes, M., Gotz, A.E., 2021a. Permian stratigraphy and palynology of the Lower Karoo Group in Mozambique - a 2020 perspective. *Newsl. Stratigr.* 54, 335–362.
- Lopes, G., Pereira, Z., Fernandes, P., Mendes, M., Marques, J., Jorge, R.C.G.S., 2021b. Late Permian palaeoenvironmental evolution of the Matinde Formation in the Muaradz Sub-basin, Moatize-Minjoia Basin, Mozambique. *J. Afr. Earth Sci.* 176, 104138.
- Lu, J., Wang, Y., Yang, M., Zhang, P., Bond, D.P.G., Shao, L., Hilton, J., 2022. Diachronous end-Permian terrestrial ecosystem collapse with its origin in wildfires. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 594, 110960.
- Lucas, S.G., 2009. Timing and magnitude of tetrapod extinctions across the Permian–Triassic boundary. *J. Asian Earth Sci.* 36, 491–502.
- Lucas, S.G., 2017. Permian tetrapod extinction events. *Earth Sci. Rev.* 170, 31–60.
- Mays, C., McLoughlin, S., 2022. End-Permian burnout: the role of Permian–Triassic wildfires in extinction, carbon cycling, and environmental change in eastern Gondwana. *Palaios* 37, 292–317.
- McLoughlin, S., Lindström, S., Drinnan, A.N., 1997. Gondwanan floristic and sedimentological trends during the Permian–Triassic transition: new evidence from the Amery Group, northern Prince Charles Mountains, East Antarctica. *Antarct. Sci.* 9, 281–298.
- Mishra, S., Jha, N., Stebbins, A., Brookfield, M., Hannigan, R., 2019. Palaeoenvironments, flora, and organic carbon and nitrogen isotope changes across the non-marine Permian–Triassic boundary at Wybung Head, Australia. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 534, 109292.
- Nemec, W., Steel, R.J., 1984. Alluvial and coastal conglomerates: their significant features and some comments on gravely mass-flow deposits. In: Steel, R.J.K. (Ed.), *Sedimentology of Gravels and Conglomerates*. Canadian Society of Petroleum Geologists, pp. 1–31.
- Norconsult Consortium, 2007. Sheet Explanation, Report No. B6.f: Sheets 1039 Muidine, 1040 Palma, 1134 Ponta Messuli, 1135 Lupilichi, 1136 Milepa, 1137 Macalange, 1138 Negomano, 1139 Mueda, 1140 Mocimboa da Praia, 1234 Metangula, 1235 Macalange-Chiconono, 1236 Mavago, 1237 Mecula, 1238 Xixano, 1239 Meluco, 1240 Quissanga-Pemba, 1334 Meponda, 1335 Lichinga, 1336 Majune, 1337 Marrupa, 1338 Namuno, 1339 Montepuez, 1340 Mecúfi, 1435 Mandimba, 1436 Cuamba, 1437 Malema, 1438 Riba' u'e-Mecubúri, 1535 Isaca, 1536 Gurú'e, 1635 Milange, 1636 Lugela-Mocuba, Geological Mapping – Lot 1. National Directorate of Geology, Ministry of Mineral Resources and Energy, Maputo, Mozambique, p. 778.
- Nowak, H., Schneebeil-Hermann, E., Kustatscher, E., 2019. No mass extinction for land plants at the Permian–Triassic transition. *Nat. Commun.* 10, 384.
- Nowak, H., Vêrad, C., Kustatscher, E., 2020. Palaeophytogeographical patterns across the Permian–Triassic boundary. *Front. Earth Sci.* 8–2020.
- Ogden, D.E., Sleep, N.H., 2012. Explosive eruption of coal and basalt and the end-Permian mass extinction. *Proc. Natl. Acad. Sci.* 109, 59–62.
- Pancost, R.D., Sinninghe Damsté, J.S., 2014. Carbon isotopic compositions of sedimentary biomarkers as indicators of environmental change. In: Holland, H.D., Turekian, K.K. (Eds.), *Treatise on Geochemistry*, 2nd ed. vol. 12. Elsevier, pp. 373–406.
- Payne, J.L., Clapham, M.E., 2012. End-Permian mass extinction in the oceans: an ancient analog for the twenty-first century? *Annu. Rev. Earth Planet. Sci.* 40, 89–111.
- Payne, J.L., Lehmann, D.J., Wei, J., Orchard, M.J., Schrag, D.P., Knoll, A.H., 2004. Large perturbations of the carbon cycle during recovery from the end-Permian extinction. *Science* 305, 506–509.
- Pendkar, N., Rubino, J.-L., Jean-Baptiste Baby, G., Sia, S.S.L., Prasetyotomo, W.S., 2014. Lower Karoo Sedimentation in Moatize Basin, Mozambique: Analogue for Understanding the Deep Rift Sequence in Offshore Rovuma Basin, International Petroleum Technology Conference.
- Pereira, Z., Fernandes, P., Lopes, G., Marques, J., Vasconcelos, L., 2016. The Permian–Triassic transition in the Moatize-Minjoia Basin, Karoo Supergroup, Mozambique: a palynological perspective. *Rev. Palaeobot. Palynol.* 226, 1–19.
- Pereira, Z., Fernandes, P., Lopes, G., Marques, J., Vaz, M., Costa, M., Correia, J., Castro, L., Galasso, F., 2019. Palynology of the Muaradz sub-basin, Moatize-Minjoia Coal Basin, Karoo Supergroup, Mozambique. *Rev. Palaeobot. Palynol.* 269, 78–93.
- Peters, K.E., Walters, C.C., Moldowan, J.M., 2018. *The Biomarker Guide: Biomarkers and Isotopes in Petroleum Systems and Earth History*, 3rd ed. Cambridge University Press, Cambridge.
- Pinna, P., Jourde, G., Calvez, J.Y., Mroz, J.M., Marques, J.M., 1993. The Mozambique Belt in northern Mozambique: neoproterozoic (1100–850 Ma) crustal growth and tectogenesis, and superimposed Pan-African (800–550 Ma) tectonism. *Precambrian Res.* 62, 1–59.
- Raup, D.M., Sepkoski, J.J., 1984. Periodicity of extinctions in the geologic past. *Proc. Natl. Acad. Sci.* 81, 801–805.
- Raup, D.M., Sepkoski Jr., J.J., 1982. Mass extinctions in the marine fossil record. *Science* 215, 1501–1503.
- Retallack, G.J., Smith, R.M.H., Ward, P.D., 2003. Vertebrate extinction across Permian–Triassic boundary in Karoo Basin, South Africa. *GSA Bull.* 115, 1133–1152.
- Retallack, G.J., 2021. Multiple Permian–Triassic life crises on land and at sea. *Glob. Planet. Chang.* 198, 103415. <https://doi.org/10.1016/j.gloplacha.2020.103415>.
- Retallack, G.J., Jahren, A.H., Sheldon, N.D., Chakrabarti, R., Metzger, C.A., Smith, R.M. H., 2005. The Permian–Triassic boundary in Antarctica. *Antarct. Sci.* 17, 241–258.
- Riboulleau, A., Spina, A., Vecoli, M., Riquier, L., Quijada, M., Tribouillard, N., Averbuch, O., 2018. Organic matter deposition in the Ghadames Basin (Libya) during the Late Devonian—A multidisciplinary approach. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 497, 37–51. <https://doi.org/10.1016/j.palaeo.2018.02.004>.
- Sahney, S., Benton, M.J., 2008. Recovery from the most profound mass extinction of all time. *Proc. R. Soc. B Biol. Sci.* 275, 759–765.
- Saitoh, M., Isozaki, Y., 2021. Carbon isotope chemostratigraphy across the permian-triassic boundary at chaotian, China: implications for the global methane cycle in the aftermath of the extinction. *Front. Earth Sci.* 8, 596178. <https://doi.org/10.3389/feart.2020.596178>.
- Sarkar, A., Yoshioka, H., Ebihara, M., Naraoka, H., 2003. Geochemical and organic carbon isotope studies across the continental Permo–Triassic boundary of Raniganj Basin, eastern India. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 191, 1–14.
- Saxena, A., Cleal, C.J., Singh, K.J., 2025. The Permian–Triassic boundary in Peninsular India and the extinction of the Glossopteridales. *Gondwana Res.* 137, 318–330.
- Schneebeil-Hermann, E., Galasso, F., 2025. Resilient gymnosperms: reassessing floral dynamics at the Permian–Triassic extinction in Meishan. *Rev. Palaeobot. Palynol.* 341, 105373.
- Schneebeil-Hermann, E., Kürschner, W.M., Kerp, H., Bomfleur, B., Hochuli, P.A., Bucher, H., Ware, D., Roohi, G., 2015. Vegetation history across the Permian–Triassic boundary in Pakistan (Amb section, Salt Range). *Gondwana Res.* 27, 911–924.
- Schneebeil-Hermann, E., Hochuli, P.A., Bucher, H., 2017. Palynofloral associations before and after the Permian–Triassic mass extinction, Kap Stosch, East Greenland. *Glob. Planet. Chang.* 155, 178–195.
- Schobben, M., Ullmann, C.V., Leda, L., Korn, D., Struck, U., Reimold, W.U., Ghaderi, A., Algeo, T.J., Korte, C., 2016. Discerning primary versus diagenetic signals in carbonate carbon and oxygen isotope records: an example from the Permian–Triassic boundary of Iran. *Chem. Geol.* 422, 94–107.
- Sephton, M.A., Jiao, D., Engel, M.H., Looy, C.V., Visscher, H., 2015. Terrestrial acidification during the end-Permian biosphere crisis? *Geology* 43, 159–162.
- Shen, S.Z., Crowley, J.L., Wang, Y., Bowring, S.A., Erwin, D.H., Sadler, P.M., Cao, C.Q., Rothman, D.H., Henderson, C.M., Ramezani, J., Zhang, H., Shen, Y., Wang, X.D., Wang, W., Mu, L., Li, W.Z., Tang, Y.G., Liu, X.L., Liu, L.J., Zeng, Y., Jiang, Y.F., Jin, Y.G., 2011a. Calibrating the end-Permian mass extinction. *Science* 334, 1367–1372.
- Shen, W., Sun, Y., Lin, Y., Liu, D., Chai, P., 2011b. Evidence for wildfire in the Meishan section and implications for Permian–Triassic events. *Geochim. Cosmochim. Acta* 75, 1992–2006.
- Shen, J., Zhang, Y.G., Yang, H., Xie, S., Pearson, A., 2022. Early and late phases of the Permian–Triassic mass extinction marked by different atmospheric CO₂ regimes. *Nat. Geosci.* 15, 839–844.

- Shen, J., Chen, J., Yu, J., Algeo, T.J., Smith, R.M.H., Botha, J., Frank, T.D., Fielding, C.R., Ward, P.D., Mather, T.A., 2023. Mercury evidence from southern Pangea terrestrial sections for end-Permian global volcanic effects. *Nat. Commun.* 14, 6.
- Smith, R.M.H., 1995. Changing fluvial environments across the Permian-Triassic boundary in the Karoo Basin, South Africa and possible causes of tetrapod extinctions. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 117, 81–104.
- Smith, R.M.H., Botha-Brink, J., 2014. Anatomy of a mass extinction: sedimentological and taphonomic evidence for drought-induced die-offs at the Permo-Triassic boundary in the main Karoo Basin, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 396, 99–118.
- Smith, R.M.H., Botha, J., Viglietti, P.A., 2022. Taphonomy of drought afflicted tetrapods in the Early Triassic Karoo Basin, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 604, 111207.
- Song, H., Wignall, P.B., Tong, J., Yin, H., 2013. Two pulses of extinction during the Permian–Triassic crisis. *Nat. Geosci.* 6, 52–56.
- Song, Y., Tian, Y., Yu, J., Algeo, T.J., Luo, G., Chu, D., Xie, S., 2022. Wildfire response to rapid climate change during the Permian-Triassic biotic crisis. *Glob. Planet. Chang.* 215, 103872.
- Spangenberg, J.E., Zufferey, V., 2019. Carbon isotope compositions of whole wine, wine solid residue, and wine ethanol, determined by EA/IRMS and GC/C/IRMS, can record the vine water status -a comparative reappraisal. *Anal. Bioanal. Chem.* 41, 2031–2043.
- Spangenberg, J.E., Jacomet, S., Schibler, J., 2006. Chemical analyses of organic residues in archaeological pottery from Arbon Bleiche 3, Switzerland - evidence for dairying in the late Neolithic. *J. Archaeol. Sci.* 33, 1–13.
- Spina, A., Cirilli, S., Utting, J., Jansonius, J., 2015. Palynology of the Permian and Triassic of the Tesero and Bulla sections (Western Dolomites, Italy) and consideration about the enigmatic species *Reduviasporonites chalastus*. *Rev. Palaeobot. Palynol.* 218. <https://doi.org/10.1016/j.revpalbo.2014.10.003>.
- Spina, A., Stephenson, M.H., Cirilli, S., Ariana-Sab, M., Rettori, R., 2018. Palynostratigraphy of the permian faraghan formation in the zagros basin, Southern Iran. *Riv. Ital. Paleontol. Stratigr.* 124, 573–595.
- Stanley, S.M., 2016. Estimates of the magnitudes of major marine mass extinctions in earth history. *Proc. Natl. Acad. Sci. USA* 113, E6325–e6334.
- Stemmerik, L., Bendix-Almgreen, S.E., Piasecki, S., 2001. The Permian-Triassic boundary in central East Greenland: past and present views. *Bull. Geol. Soc. Den.* 48, 159–167.
- Svensen, H., Planke, S., Polozov, A.G., Schmidbauer, N., Corfu, F., Podladchikov, Y.Y., Jamtveit, B., 2009. Siberian gas venting and the end-Permian environmental crisis. *Earth Planet. Sci. Lett.* 277, 490–500.
- Tabor, N.J., Sidor, C.A., Smith, R.M.H., Nesbitt, S.J., Angielczyk, K.D., 2017. Paleosols of the Permian-Triassic: proxies for rainfall, climate change and major changes in terrestrial tetrapod diversity. *J. Vertebr. Paleontol.* 37, 240–253.
- Tissot, B.P., Welte, D.H., 1984. *Petroleum Formation and Occurrence*, 2nd ed. Springer-Verlag, Berlin. <https://doi.org/10.1007/978-3-642-87813-8>.
- Turney, C.S.M., Wheeler, D., Chivas, A.R., 2006. Carbon isotope fractionation in wood during carbonization. *Geochim. Cosmochim. Acta* 70, 960–964.
- Vajda, V., McLoughlin, S., Mays, C., Frank, T.D., Fielding, C.R., Tevyaw, A., Lehsten, V., Bocking, M., Nicoll, R.S., 2020. End-Permian (252 Mya) deforestation, wildfires and flooding—an ancient biotic crisis with lessons for the present. *Earth Planet. Sci. Lett.* 529.
- Viglietti, P.A., Benson, R.B.J., Smith, R.M.H., Botha, J., Kammerer, C.F., Skosan, Z., Butler, E., Crean, A., Eloff, B., Kaal, S., Mohoi, J., Molehe, W., Mtalana, N., Mtungata, S., Ntheri, N., Ntsala, T., Nyaphuli, J., October, P., Skinner, G., Strong, M., Stummer, H., Wolvaardt, F.P., Angielczyk, K.D., 2021. Evidence from South Africa for a protracted end-Permian extinction on land. *Proc. Natl. Acad. Sci.* 118, e2017045118.
- Viola, G., Henderson, I.H.C., Bingen, B., Thomas, R.J., Smethurst, M.A., de Azavedo, S., 2008. Growth and collapse of a deeply eroded orogen: insights from structural, geophysical, and geochronological constraints on the Pan-African evolution of NE Mozambique. *Tectonics* 27.
- Ward, P., Botha, J., Buick, R., de Kock, M., Erwin, D., Garrison, G., Kirschvink, J., Smith, R., 2005. Abrupt and gradual extinction among late Permian land vertebrates in the Karoo Basin, South Africa. *Science (New York, N.Y.)* 307, 709–714.
- Wheeler, A., Van de Wetering, N., Esterle, J.S., Götze, A.E., 2020. Palaeoenvironmental changes recorded in the palynology and palynofacies of a Late Permian Marker Mudstone (Galilee Basin, Australia). *Palaeoworld* 29, 439–452.
- Wignall, P.B., 2001. Large igneous provinces and mass extinctions. *Earth Sci. Rev.* 53, 1–33.
- Wu, J., Chu, D., Luo, G., Wignall, P.B., Algeo, T.J., Xie, S., 2023a. Stepwise deforestation during the Permian-Triassic boundary crisis linked to rising temperatures. *Earth Planet. Sci. Lett.* 620, 118350.
- Wu, Y., Cui, Y., Chu, D., Song, H., Tong, J., Dal Corso, J., Ridgwell, A., 2023b. Volcanic CO₂ degassing postdates thermogenic carbon emission during the end-Permian mass extinction. *Sci. Adv.* 9, eabq4082.
- Xiong, C., Wang, J., Huang, P., Cascales-Miñana, B., Cleal, C.J., Benton, M.J., Xue, J., 2021. Plant resilience and extinctions through the Permian to Middle Triassic on the North China Block: a multilevel diversity analysis of macrofossil records. *Earth Sci. Rev.* 223, 103846.
- Yin, H., Zhang, K., Tong, J., Yang, Z., Wu, S., 2001. The global stratotype section and point (GSSP) of the Permian-Triassic boundary. *Int. Union Geol. Sci.* 24, 102–114.
- Zhang, P., Yang, M., Jing, L., Bond, D., Zhou, K., Xu, X., Ye, W., He, Z., Bian, X., Shao, L., Hilton, J., 2023. End-Permian terrestrial ecosystem collapse in North China: evidence from palynology and geochemistry. *Glob. Planet. Chang.* 222, 104070.
- Zhu, Z., Liu, Y., Kuang, H., Benton, M.J., Newell, A.J., Xu, H., An, W., Ji, S.A., Xu, S., Peng, N., Zhai, Q., 2019. Altered fluvial patterns in North China indicate rapid climate change linked to the Permian-Triassic mass extinction. *Sci. Rep.* 9, 16818.