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# Applying integrated Triassic biostratigraphy in Timor-Leste to unlock an under-sampled Gondwanan sector of the Tethys puzzle

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## ABSTRACT

The contribution to Tethyan and global Triassic studies from the Australian sector of southeastern Tethys is limited relative to that from the Himalayan sector. Whilst many of the Triassic successions from the Australian sector are located offshore, one succession is exposed on the island of Timor. This marine succession, dismembered during collision between the Australian continent and the volcanic Banda Arc, has been investigated for over 100 years but has also made limited modern contributions to Tethyan and global Triassic studies. To address this a new integrated Triassic biostratigraphic microfossil database (conodonts, palynomorphs and radiolarians) from Timor-Leste is presented here that compliments published foraminiferal data. This integrated data set 1) supports application in Timor of the endemic palynomorph zonal scheme from the North West Shelf of Australia whilst providing additional ties for this to the Geological Time Scale (GTS), 2) provides paleobiogeographic support for accumulation of the Timor-Leste Triassic succession within a southeast Tethyan Gondwanan basin and informs discussions about Tethyan paleobiogeography, 3) calibrates over 300 outcrops to the GTS enabling an improved reconstruction of the dismembered succession that will facilitate enhanced regional and local paleogeographic and tectonostratigraphic assessments, and 4) provides independent GTS calibration for published basinal foraminiferal assemblages which will assist understanding the biostratigraphic utility of these assemblages. This database identifies key outcrops, such as the first outcropping Permian-Triassic Boundary section from this sector of southeastern Tethys, that will facilitate targeted studies addressing a range of Tethyan and global Triassic issues unlocking insights from an under-sampled Gondwanan sector of Tethys.

## 1. Introduction

Triassic Gondwanan successions accumulated on the southeastern Tethyan margin and now exposed in the Himalayas have played a key

role in understanding the evolution of eastern Tethys and the global Triassic System (for some more recent examples see [Zhu et al., 2011](#); [Hermann et al., 2012](#); [Li et al., 2014](#); [Peng et al., 2018](#); [Li et al., 2019](#); [Li et al., 2020](#); [Liu et al., 2020a](#); [Liu et al., 2020b](#); [Chen et al., 2022](#); [Wu](#)

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et al., 2023). Key contributions from investigations of the Triassic successions preserved on the Australian continental sector of eastern Tethys have also been made (for some more recent examples see Nicoll, 2002; Thomas et al., 2004; Gortler et al., 2009; Riding et al., 2010; Metcalfe et al., 2013; Jitmahantakul and McClay, 2013; Lewis & Sircombe, 2013; Marshall and Lang, 2013; Haig et al., 2015; Gartrell et al., 2016; Morón et al., 2019; Gartrell et al., 2022). However, these contributions have not been as numerous, in large part, due to the offshore location of much of the succession which can only be studied through petroleum wells and seismic data. A more accessible and typically more marine Triassic succession from this sector of eastern Tethys is exposed on the island of Timor. This succession has been the subject of investigation for over 100 years (see summary in Charlton et al., 2009) and has provided some important insights into the Triassic evolution of southeastern Tethys and the global Triassic System. However, when compared to the Himalayan succession, this comprises relatively limited modern contributions (Bird and Cook, 1991; Sashida et al., 1996 and 1999; Martini et al., 2000; Charlton et al., 2009; Haig and McCartney, 2010 and 2012; Boger et al., 2017; Kwon et al., 2014; Peyrot et al., 2019; Zimmerman and Hall, 2016; Haig et al., 2021; Barros et al., 2022) applying the latest tools and knowledge to interrogate this succession.

The collision between the Australian continent and the volcanic Banda Arc (Audley-Charles, 2004; Harris, 2006; Keep and Haig, 2010; Hall, 2017) has dismembered the Triassic succession exposed in Timor-Leste into isolated and stratigraphically restricted outcrops. As is the case in places like the Himalayas (Li et al., 2020) stratigraphic reconstruction of the succession requires calibration of individual outcrops to the Geological Time Scale (GTS) through the application of chronostratigraphic and geochronometric tools. Existing calibration points are limited in Timor-Leste, the eastern half of Timor island (Fig. 1), with very few outcrops calibrated to the GTS, even when including recent additions (Haig and McCartney, 2010 and 2012; Haig et al., 2021; Kwon et al., 2014; Boger et al., 2017; Zimmermann and Hall, 2016; Peyrot et al., 2019; Haig et al., 2021; Barros et al., 2022). As a result, the various chronostratigraphic ranges proposed for the lithostratigraphic units in Timor (e.g. Harris et al., 1998; Charlton et al., 2009; Charlton and Gandara, 2014; Kwon et al., 2014; Duffy et al., 2017), have limited published chronostratigraphic constraints from Timor-Leste. This limits the resolution and accuracy of the reconstructed stratigraphic succession and the contribution it can make to global Triassic studies, and understanding the evolution of Timor and southeastern Tethys.

Whilst the marine Triassic succession in Timor-Leste includes macrofossils (see Summary in Charlton et al., 2009) these are rare to very rare in much of the succession, providing limited GTS calibration points. Many past documented macrofossils were collected from units that comprise a minor component of the Triassic succession and without stratigraphic context (see summary in Charlton et al., 2009). Detrital zircons are useful tools to assist with geochronometric calibration of the succession to the GTS for some stratigraphic levels (Kwon et al., 2014; Boger et al., 2017; Zimmerman and Hall, 2016) and the geochronology of igneous rocks, at some stratigraphic levels, may assist in the future. However, microfossil biostratigraphy represents the most widely applicable tool available for calibration of this Triassic succession.

Conodonts, palynomorphs, radiolarians, foraminifers and calcareous nannofossils represent the key microfossil groups that collectively provide calibration for the entire Triassic succession in Timor-Leste. Historically these have been applied sparingly in Timor-Leste (Nogami, 1968; Berry et al., 1984; da Costa Monteiro, 2003; Haig et al., 2007, 2010 and 2012; Benincasa et al., 2012; Peyrot et al., 2019; Barros et al., 2022) and in the western Indonesian half of the island, West Timor (Fig. 1; Bird and Cook, 1991; Barkham, 1993; Rose, 1994; Sashida et al., 1996 and 1999; Martini et al., 2000). Of these, Triassic conodonts, radiolarians and calcareous nannofossils are well studied groups within Tethys, and globally, and readily provide robust chronostratigraphic calibration. Shallow-water carbonate-cemented, involutinid and duostominid foraminifers also provide good calibration for the shallow-

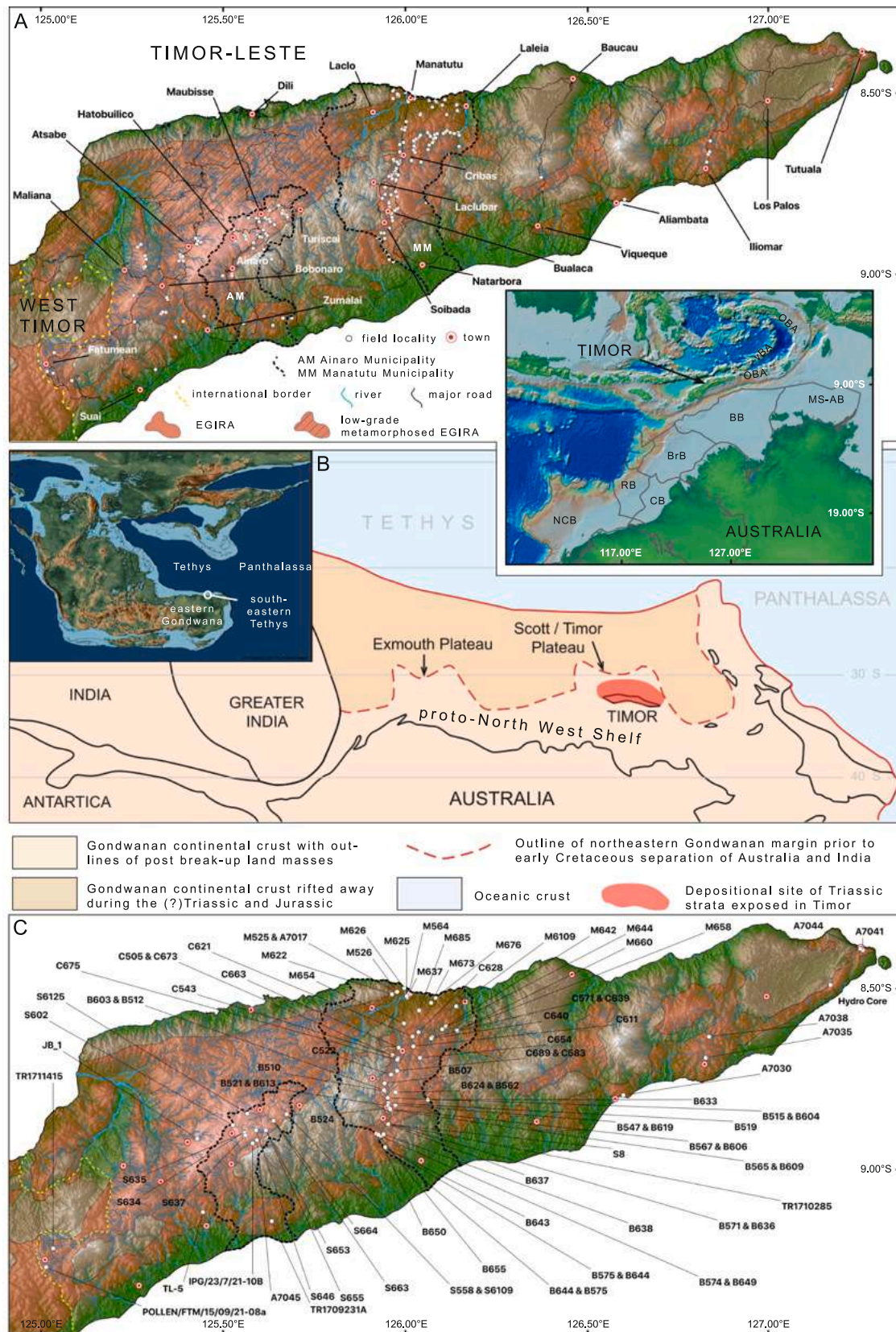
water Triassic carbonate unit in Timor-Leste (Haig et al., 2021). Foraminifers are also common within the basinal carbonate and siliciclastic-dominated units in Timor-Leste, but globally foraminifers typical of such depositional systems have received limited investigation (see Haig and McCartney, 2010) and the biostratigraphic utility of these requires further development. Finally, palynomorphs are present throughout all the basinal units exposed in Timor-Leste and some intervals of the shallow-water carbonate-dominated units. In the rare cases palynomorphs have been utilised in Timor-Leste (Haig et al., 2007; Benincasa et al., 2012; Peyrot et al., 2019), it has been assumed the criteria for the endemic palynomorph zonal scheme established for assemblages from the North West Shelf (NWS) of Australia are applicable and have the same chronostratigraphy. However, such assumptions are yet to be adequately tested and this endemic zonal scheme also has limited calibration to the GTS.

A new integrated microfossil biostratigraphic database recovered from Triassic strata exposed in Timor-Leste is presented here. This comprises conodonts, palynomorphs and radiolarians, and compliments previously published foraminiferal data (Haig and McCartney, 2010, 2012; Haig et al., 2021). This database comprises over 300 outcrops calibrated to the Triassic System and will be used to 1) provide insights into the applicability of the endemic NWS palynomorph zonal scheme to the Triassic succession in Timor-Leste and, through co-occurrences of conodonts, provide additional calibration of this scheme to the GTS, 2) assess the paleobiogeographic affinities of the documented faunas and discuss the implications for Tethyan paleobiogeography and paleogeography, and 3) re-evaluate the chronostratigraphic range of Triassic lithostratigraphic units in Timor-Leste. The database provides updated and integrated chronostratigraphic calibration of published basinal foraminifers from Timor-Leste (Haig and McCartney, 2010, 2012), which will facilitate an improved understanding of the biostratigraphic utility of these globally. The chronostratigraphically calibrated Triassic outcrop database will enable a greater Timor-Leste contribution, through future targeted studies, to Tethyan and global Triassic issues from a data poor Gondwanan sector of Tethys.

## 2. Geological setting

Following the Neoproterozoic amalgamation of Gondwana (Veevers, 2004), sedimentary successions accumulated in basins along north-eastern Gondwana (proto Tethyan Himalayas–Australian NWS sector; Fig. 1) that were formed and deformed through multiple phases of regional tensional stress (e.g. Yeates et al., 1987; Audley-Charles, 1988; Brookfield, 1993; Etheridge and O'Brien, 1994; Liu and Einsele, 1994; Garzanti et al., 1995; Robertson, 1998; Longley et al., 2002; Sciunnach and Garzanti, 2012; Marshall and Lang, 2013; Gartrell et al., 2022). Many of these phases led to continental blocks rifted away from northeastern Gondwana and were associated with the opening of successive Tethyan oceans (e.g. Audley-Charles, 1988; Görür and Sengor, 1992; Hall, 2017; Metcalfe, 2021). Triassic strata exposed in Timor were accumulated significant distances inboard of the coeval southern Tethyan oceanic-continental crust boundary (Fig. 1). Blocks rifted from this margin, in the Late Jurassic and possibly Late Triassic, carried Triassic Gondwanan successions that accumulated more proximal, relative to strata exposed in Timor, to the Triassic oceanic-continental crust boundary (Fig. 1).

Timor island is a subaerial expression of the orogenic Outer Banda Arc (Fig. 1) formed through the Neogene collision between the Australian continent and the volcanic Banda Arc (Audley-Charles, 2004; Harris, 2006; Keep and Haig, 2010; Hall, 2017). This collision significantly deformed the pre-collision rock-record exposed in Timor. Prior to collision, the volcanic Banda Arc may have included Gondwanan Triassic strata that were accreted to Sundaland in the Cretaceous as part of continental blocks rifted from Gondwana in the Late Jurassic (e.g. van Leeuwen et al., 2016; Hall, 2017). However, all Triassic strata exposed in Timor-Leste are currently interpreted to have come from the



(caption on next page)

**Fig. 1.** A: Triassic localities documented in this study and the distribution of Carboniferous–Jurassic strata of the East Gondwana Interior Rift Association (EGIRA). The latter is modified from Harris et al. (1998) and requires further ground truthing in many places. Map underlain by Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global data courtesy of the U.S. Geological Survey. Inset: Present-day setting of Timor and the basins of the NWS together with the Money Shoals and Arafura basins. Bathymetry and topography are from GEBCO Compilation Group (2020). vBA = volcanic Banda Arc, OBA = Outer Banda Arc, NCB = Northern Carnarvon Basin, RB = Roebuck Basin, CB = Canning Basin, BrB = Browse Basin, BB = Bonaparte Basin, and MS-AB = Money Shoals and Arafura basin. B: Schematic Triassic reconstruction of northeastern Gondwana and southeastern Tethys showing the continental crust rifted from this sector of Gondwana during the (?)Late Triassic and Late Jurassic. The depositional site of Triassic strata exposed in Timor was several 100's of kilometers inboard of the coeval continental-oceanic crust boundary. Inset: global paleogeography during Late Triassic (Scotese, 2021). C: Triassic localities mentioned in the text see 1A for legend and data. Localities starting with M are centered around Manatutu, those starting with C are centered around Cribas, those starting with B are centered around Bualaca, and those starting with S are centered around Maubisse.

Australian side of the collision and they are placed by Haig et al. (2019) within the East Gondwana Interior Rift Association (EGIRA).

Reflecting collision-related deformation and non-continuous exposure, thick and accessible coherent Triassic stratigraphic sections in Timor are relatively rare with most accessible sections in the order of 5–30 m thick. Formal and informal Triassic lithostratigraphic nomenclature have been erected for the Triassic succession (Fig. 2 and Table 1; Audley-Charles, 1968; Berry et al., 1984; Bird and Cook, 1991; Haig et al., 2021). The strata of these units indicate a complex array of depositional settings (see summary in Charlton et al., 2009), ranging from shallow-water carbonate-dominated settings (Haig et al., 2021) to basinal siliciclastic and carbonate-dominated settings deposited below storm wave base (e.g. Audley-Charles, 1968; Bird and Cook, 1991; Kwon et al., 2014). Deposition during active extensional deformation has often been proposed for this succession (e.g. Bird and Cook, 1991; Charlton et al., 2009). However, the very high levels of collision-related structural deformation in Timor largely precludes the observation of pre-collision structures to constrain such a model.

Published Triassic geochronological data from Timor is restricted to detrital zircon data (Zobell, 2007; Kwon et al., 2014; Zimmermann and Hall, 2016; Boger et al., 2017), which provide estimates on the maximum depositional age (MDA) for strata. However, without continuous igneous activity over the chronostratigraphic interval of interest, the depositional age of the host sedimentary strata can be significantly younger than the youngest zircon grain (e.g. Cawood et al., 2012). Whilst sandstones within the Triassic succession in Timor are rich in lithic igneous grains (Zimmermann and Hall, 2016; Peyrot et al., 2019), as yet no outcrops of igneous rocks have been correlated to the Triassic and a continuous record of igneous activity is yet to be proven. In such cases biostratigraphic data from the same outcrop section can provide additional constraints on depositional age. The MDA's from strata attributed to the Babulu Formation in Timor-Leste range from 238 to 227 Ma (Kwon et al., 2014; Zimmermann and Hall, 2016; Boger et al., 2017), which equates to the latest Ladinian to late Carnian (ICS, 2022). Younger MDA's from strata attributed to the Babulu Formation have been documented from West Timor (Zimmerman and Hall, 2016). None of the detrital zircon data sets are paired with biostratigraphic control, so questions remain around the true depositional age of the strata from which they come.

### 3. Methodology and material

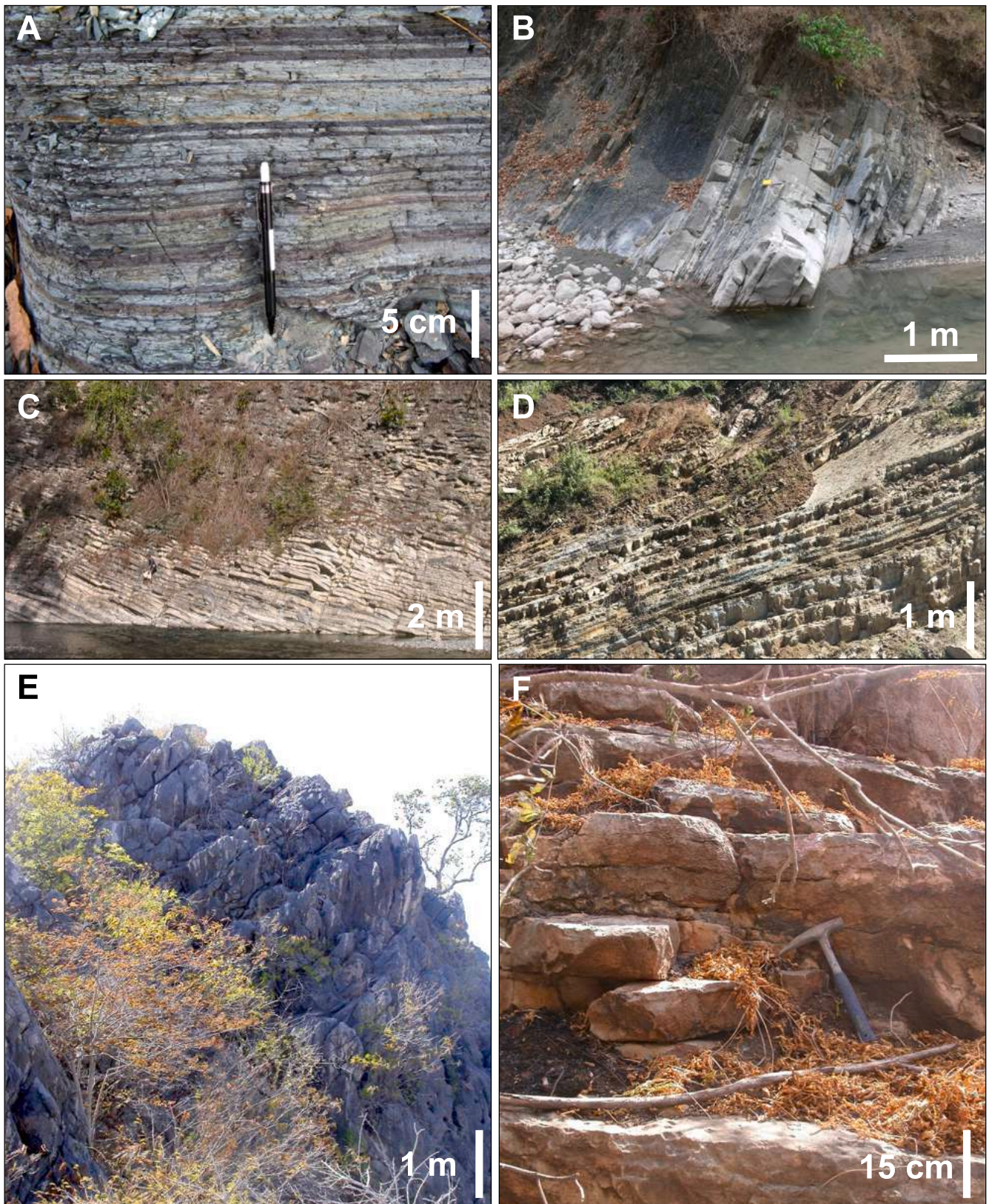
The new data presented here were collected as part of The University of Western Australia (UWA) geological investigations across Timor-Leste between 2004 and 2010 and more recently by the Instituto do Petróleo e Geologia (IPG) and Timor Resources Pty Ltd. The database includes over 300 outcrops and over 450 biostratigraphic samples (see Supplementary online material Table S1). All UWA samples are stored in the collections of the Earth Science Museum at the University of Western Australia whilst TR sample numbers are stored at MGPaleo in Perth, Australia. Only a handful of key Triassic sections in Timor-Leste were known prior to this work with much of the new data collected as part of reconnaissance fieldwork. Representative biostratigraphic and lithostratigraphic samples were collected together with stratigraphic and sedimentological observations. Bed-by-bed analysis was not undertaken.

#### 3.1. Lithostratigraphic challenges in Timor-Leste

Application of standard lithostratigraphic methodologies (e.g. North American Commission on Stratigraphic Nomenclature, 2021) in Timor-Leste is inherent with challenges due to the highly deformed succession, discontinuous exposures and the poorly understood stratigraphic complexity. With current knowledge, whilst mappable at a regional scale, the existing formal lithostratigraphic units do not meet all guidelines for formal lithostratigraphic units e.g. lower and upper contacts are largely undefined, and lateral stratigraphic variation is poorly understood. Whilst an improved understanding of these units is required to address these deficiencies the established formal units are used here. If internal variation is mappable at a regional scale, new formations may be justified. If not, this variation is best captured by formal lithostratigraphic sub-units, e.g. members, or left in informal nomenclature e.g. facies associations. The nature of the exposed Triassic succession in Timor-Leste also renders ascertaining stratigraphic relationships between outcrop sections in the field very difficult. Robust reconstruction therefore requires the application of additional tools (e.g. biostratigraphy) to place isolated outcrops in stratigraphic order, as is the case in other similarly deformed areas like the Himalayas (e.g. Li et al., 2020). This requirement in Timor-Leste has been previously demonstrated in the literature e.g. see Charlton and Gandara (2014) versus Peyrot et al., (2019).

Finally, the stratigraphic complexity and highly discontinuous nature of outcrops adds additional challenges to establishing the chronostratigraphic range of lithostratigraphic units and assigning isolated outcrop sections to these units. Guidelines stipulate a lithostratigraphic unit must be laterally and stratigraphically contiguous (e.g. North American Commission on Stratigraphic Nomenclature, 2021) or where not laterally continuous have similar chronostratigraphic range (Kumpulainen, 2016). How do we treat an isolated outcrop of strata typical of lithostratigraphic unit 'A' but surrounded by other isolated outcrops of lithostratigraphic unit 'B'? Is it 1) an example of a facies association typical of Unit 'A' occurring within Unit 'B'; 2) a lateral extension of Unit 'A' interfingering with Unit 'B'; or 3) a section of Unit 'A' structurally juxtaposed with sections of Unit 'B'? In some example's mapping, structural observations and or calibration to the GTS, highlighting different chronostratigraphy, may assist identify the scenario 3, but often exposures of structural contacts are not available. Without laterally continuous exposures it is also impossible to distinguish between scenarios 1 or 2. Selection of these different scenarios could lead to incorrect chronostratigraphic range of units e.g. if scenario 2 is incorrectly assumed then the outcrop will incorrectly contribute to the chronostratigraphic range of Unit 'A'. Incorrect choices will also clearly lead to incorrect assignment of outcrops to lithostratigraphic units. Additional uncertainty arises when the outcrop section in question is not typical of any established lithostratigraphic unit but instead shares characteristics of two or more.

Detailed mapping and structural analysis were not undertaken as part of this project. The local and regional distribution of units were observed and, together with obvious structural boundaries, used to assign sections to lithostratigraphic units. In this approach with the absence of obvious structural boundaries, lithologically anomalous or ambiguous outcrops, relative to surrounding exposures, are assigned to



**Fig. 2.** Outcrop photos showing typical characteristics of the key Triassic lithostratigraphic units in Timor-Leste. **A:** Laminated and variegated claystone typical of the Baharedu beds. Locality C505. **B:** Sandstone-dominated interval within mudstone-dominated section of the Babulu Formation. Locality B633. **C:** Mud-wackestone dominated Aitutu Formation with thin interbeds of siliciclastic mudstone. Locality B636. **D:** Interbedded, light-grey, bioturbated medium to thickly bedded marl and thinly bedded calcareous mudstone typical of the Wai Luli Formation. Locality C583. **E:** Massive, thickly bedded light-grey rudstone-dominated outcrop of the Bandeira Formation. Locality M526. **F:** Bedded ammonoid rich Hallstatt-like Lulu Facies Association. Locality M525.

**Table 1**  
Description of key Triassic lithostratigraphic units in Timor-Leste.

Unit & Chronostratigraphy	Description
<p><b>Baharedu beds</b></p> <p>Induan – middle Anisian</p>	<p>New informal unit established here for bedded clay-dominated mudstone (often variegated) rarely with laminae or thin beds of sandstone and limestone. Some horizons rich in bivalves (including <i>Claraia</i> spp.) and rare, poorly preserved ammonoids. Deposited below storm wave base.</p> <p><i>Suggested type section:</i> western bank of Summasse River near Cribas in the Manatutu Municipality (Locality C505 see Supplementary online material Table S2). The unit name is derived from the Baharedu village to the southwest.</p> <p><i>Boundaries:</i> lower and upper boundary yet to be identified in outcrop.</p> <p><i>Key fossil groups for chronostratigraphy:</i> palynomorphs, bivalves, (?) ammonoids, (?) foraminifers, and (?) conodonts.</p>
<p><b>Babulu Formation</b></p> <p>Middle Anisian – Carnian (locally lower Norian)</p>	<p>Erected by Bird &amp; Cook (1991). Here, in Timor-Leste, dominated by weakly-bedded silty mudstone. It may include thin to thick sandstone interbeds that often include abundant terrestrial phyto-detritus. Limestone-dominated facies associations present including Aitutu Formation-like sections of bedded mud-wackestone and grainstone as well as conglomeratic beds with clasts and grains typical of the Aitutu Formation, Bandeira Formation, and Babulu Formation. Whilst there is very rare evidence for deposition near storm wave base, deposition was primarily by density currents below this hydrodynamic boundary. Unit includes a range of different facies associations in Timor-Leste (see McCartney, 2014).</p> <p><i>Suggested Timor-Leste reference section:</i> eastern bank of Laçlo River just south of Dili-Manatutu bridge (location M501-M504 &amp; M624 &amp; M625 see Supplementary online material Table S2).</p> <p><i>Boundaries:</i> lower boundary yet to be identified in outcrop with further work required to constrain boundaries with the Aitutu Formation.</p> <p><i>Key fossil groups for chronostratigraphy:</i> palynomorphs, foraminifers, conodonts, and bivalves.</p>
<p><b>Aitutu Formation</b></p> <p>Carnian – lowermost Rhaetian</p>	<p>Erected by Audley-Charles (1968). Here, in Timor-Leste, typified by bedded dark grey mud-wackestone, with variable abundance of bioturbation, radiolarian and halobiid filaments. Mud-wackestone beds may be interbedded with siliciclastic mudstone, with variable bed thicknesses from very thin (&lt;1cm) to very thick (&gt;1 m), and vary in colour. Grainstone and conglomerates present with clasts and grains typical of the Aitutu and Bandeira formations. Unit includes a range of different facies associations not yet well documented in Timor-Leste.</p> <p><i>Type area:</i> Aitutu Anticline (Audley-Charles, 1968).</p> <p><i>Boundaries:</i> see Babulu Formation above for lower boundary. Further work required to constrain boundaries with the Wai Luli Formation.</p> <p><i>Key fossil groups for chronostratigraphy:</i> conodonts, palynomorphs, bivalves, radiolarian, foraminifers, and ammonoids.</p>
<p><b>Bandeira Formation</b></p> <p>Carnian – lowermost Rhaetian</p>	<p>Erected by Haig et al. (2021). Dominated by several facies associations representing shallow-water carbonate factories deposited on platforms above storm wave base. These include thickly bedded rudstone with less common grain-stone and rare boundstone, bedded wackestone and floatstone, and interbedded siliciclastic mudstone-sandstone. Also includes the Lulu facies association deposited when platforms, on which the shallow-water carbonate factories accumulated, were submerged (see Barros et al., 2022). This is equivalent of the Lulu beds (Berry et al., 1984), Cephalopod limestone facies (Charlton et al., 2009) and Lulu facies (Haig et al., 2021; Barros et al., 2022).</p> <p><i>Type area:</i> exposure on northern slopes of Bandeira River just upriver of Atsabe-Lete Foho road (see Haig et al., 2021)</p> <p><i>Boundaries:</i> lower boundary documented here at Locality M525. Upper boundary documented near Maliana in the western part of Timor-Leste where it passes into the Wai Luli Formation (see Barros et al., 2022).</p> <p><i>Key fossil groups for chronostratigraphy:</i> foraminifers, conodonts, and ammonoids.</p>
<p><b>Wai Luli Formation</b></p> <p>Rhaetian – Toarcian (Lower Jurassic)</p>	<p>Erected by Audley-Charles (1968). Here, in Timor-Leste, Triassic component typified by light grey marl to siliciclastic mudstone, reflecting variable calcium carbonate content, and pervasive bioturbation (including <i>Thalassonoides</i>, <i>Zoophycos</i> and <i>Chondrites</i>) with conspicuous dark grey burrow infills. May include subordinate light-coloured mud-wackestone beds rich in radiolaria.</p> <p><i>New suggested type area:</i> due to better and more easily accessible sections, a new type area is proposed to replace that in Audley-Charles (1968). This new area is along Cribas-Natarbora road in the Manatutu Municipality between locality C583 (see Supplementary online material Table S2) and junction to the south where road splits to Natarbora and Laclubar.</p> <p><i>Boundaries:</i> lower boundary with Bandeira Formation documented in Barros et al. (2022). Boundary with overlying units yet to be documented in outcrop.</p> <p><i>Key fossil groups for chronostratigraphy:</i> palynomorphs, calcareous nannofossils, ammonoids, and foraminifers.</p>

the lithostratigraphic unit which dominates the area. For reasons outlined above we acknowledge this will not always be correct. An example of this approach is the outcrop exposed at locality POLLEN/FTM/15/09/21-08a near the West Timor border (see Fig. 1c and Supplementary online material Table S1). This outcrop is dominated by alternating thin beds of red marl and mudstone rich in Halobiid bivalves which is not typical of any unit. This outcrop occurs in an area dominated by Babulu Formation strata and therefore is interpreted as a facies association of the Babulu Formation.

### 3.2. Key fossil groups

The chronostratigraphic utility of various fossil groups for the Triassic succession in Timor is outlined in (Table 1). Of the fossil groups, palynomorphs, conodonts and foraminifers have the most utility throughout the Triassic succession. Radiolarian provide additional control for some Middle to Upper Triassic strata, and together with conodonts and palynomorphs these make up the new data presented here that compliment published foraminifera data (Haig and McCartney, 2010, 2012; Haig et al., 2021). Other fossil groups important for specific lithostratigraphic units include calcareous nannofossils, bivalves and ammonoids. The following is a discussion on the utility and challenges of using these groups as biostratigraphic tools in Timor-Leste.

#### 3.2.1. Conodonts

Conodont samples were processed using a buffered 7 % acetic acid solution with recovered faunas listed in Supplementary online material Table S2. Owing to logistical constraints the sample sizes processed for conodonts as part of this study were extremely small (ca. 600 g). Due to their global distribution across a range of facies, relatively high evolutionary rates and resistance to diagenetic alteration conodonts are key microfossils for understanding Paleozoic to early Mesozoic successions. Some of the Triassic Global Boundary Stratotype Sections and Points (GSSP) of the GTS are chronostratigraphically defined by conodonts (see Ogg et al., 2020). A comprehensive Triassic conodont biozonation was introduced by Sweet et al. (1971) and updated summaries were given by Kozur (2003) and Orchard (2010a). More focussed studies include Orchard (2007a) for the Lower Triassic, Chen et al. (2015) for the Middle Triassic, and Rigo et al. (2018) and Karádi et al. (2020) for the Upper Triassic. Contrasting taxonomies developed around the Carnian–Norian boundary in Tethys (Mazza et al., 2012a) and in eastern Panthalassa (Orchard, 2014) offer two interpretations for many of the Timor-Leste conodont faunas. The Lower Triassic conodont record is not disputed. Within the Upper Triassic conodont faunas, differing taxonomic approaches have recently resulted in variable use of generic names (see Orchard, 2019). In this work, competing generic names are included to facilitate comparison with current literature, and differing species concepts are applied (Supplementary online material Table S2). Despite the nomenclatural disparities, the determined chronostratigraphy of > 95 % samples are consistent.

#### 3.2.2. Palynology

Palynomorph samples were processed following Wood et al. (1996) with a summary of recovered assemblages documented in Supplementary online material Table S3. Prior to this study, published records of Triassic palynofloras from Timor-Leste were limited (see Roniewicz et al., 2005; Haig et al., 2007; Benincasa et al., 2012; Peyrot et al., 2019) as it was in West Timor (see Cook, 1986; Bird, 1987; Martini et al., 2000). Palynomorphs are the key chronostratigraphic tool for Triassic successions along the NWS of Australia (Helby et al., 1987; Marshall and Lang, 2013), where an endemic zonal scheme (Fig. 3) has been developed over many years (Dolby and Balme, 1976; Helby et al., 1987; Backhouse and Balme, 2002; Dixon et al., 2012; MGPaleo, 2020; Mantle et al., 2020). Many of the NWS fossil spore and pollen are endemic or near-endemic, particularly many of the key marker taxa, leading to uncertainty for zonal and subzonal chronostratigraphy.

Limited chronostratigraphic constraint of this zonal scheme is provided by conodonts from petroleum wells (e.g. Nicoll and Foster, 1998); cosmopolitan dinocysts for the Upper Triassic (Riding et al., 2010); maximum depositional ages derived from detrital zircons (e.g. Lewis and Sircombe, 2013); and some cosmopolitan spore-pollen genera that have better chronostratigraphic constraints in Europe and East Asia (see Dolby and Balme, 1976; Hermann et al., 2012). The limited published palynological data from Timor-Leste has shown that, for studied intervals, the palynological assemblages include many of the species recorded from the NWS of Australia suggesting the NWS zonal scheme can be applied.

#### 3.2.3. Radiolarians

Radiolarians were not specifically targeted in this study, with recovered radiolarians coming from limestone residues processed for conodonts, but they do represent useful chronostratigraphic tools for the Triassic strata in Timor (Rose, 1994; Sashida et al., 1996, 1999; Martini et al., 2000). The preservation of the material recovered in this study varies from poorly preserved tests that have undergone calcite recrystallisation to very well preserved pyritized tests.

#### 3.2.4. Foraminifers

Foraminifers have been recovered from all Triassic lithostratigraphic units in Timor-Leste providing good constraints for paleoenvironmental interpretations and in some cases chronostratigraphy (e.g. Haig and McCartney, 2010, 2012; Haig et al., 2021). Free specimens have been recovered from friable mudstone through disaggregation in water and subsequent sieving, and from conodont processing residues. Foraminifers within indurated lithologies have been studied by making acetate peels (following Wilson and Palmer, 1989) and examining these using transmitted light microscopy. Non-calcareous agglutinated foraminifer groups are largely resistant to diagenetic processes providing important information for thermally mature strata. Although foraminifers are critical markers to correlate shallow-water facies of the Bandeira Formation to the GTS (Haig et al., 2021), foraminiferal assemblages extracted from basal Triassic units in Timor-Leste have been only partially documented (Haig and McCartney, 2010, 2012) and their stratigraphic ranges are less well known globally. The co-occurrence of conodont faunas and palynomorph assemblages provide an opportunity to improve the biostratigraphic utility of these foraminifers.

#### 3.2.5. Other fossil groups

Several other fossil groups not described in this work offer chronostratigraphic control in Timor. Ammonoids represent widely used biostratigraphic indices for Triassic chronostratigraphy (see Ogg et al., 2020) and are well known from Timor (see summary in Charlton et al., 2009). However, the majority of these Timor occurrences are from the ammonoid-rich Hallstatt-like strata and were collected from scree or without stratigraphic context. These strata are here referred to the Lilu facies association of the Bandeira Formation (see Section 5.2 for further discussion) which, although important, represents a minor component of the Triassic succession in Timor. Ammonoids from other lithostratigraphic units have been recorded as part of this study but they are rare. Calcareous nannofossils also have great potential in the Upper Triassic to Jurassic succession in Timor. These have been documented from West Timor (Barkham, 1993) and have been documented during the current study but are not included in the present compilation. Bivalves and brachiopods occur throughout the Triassic succession with 'flat clam' bivalves the most conspicuous (see summary in Charlton et al., 2009). These flat clam bivalves represent key chronostratigraphic tools globally (McRoberts, 2010) but it is often difficult to find well preserved complete specimens needed for robust taxonomy.

## 4. Results

Following are the biostratigraphic results from this study divided by

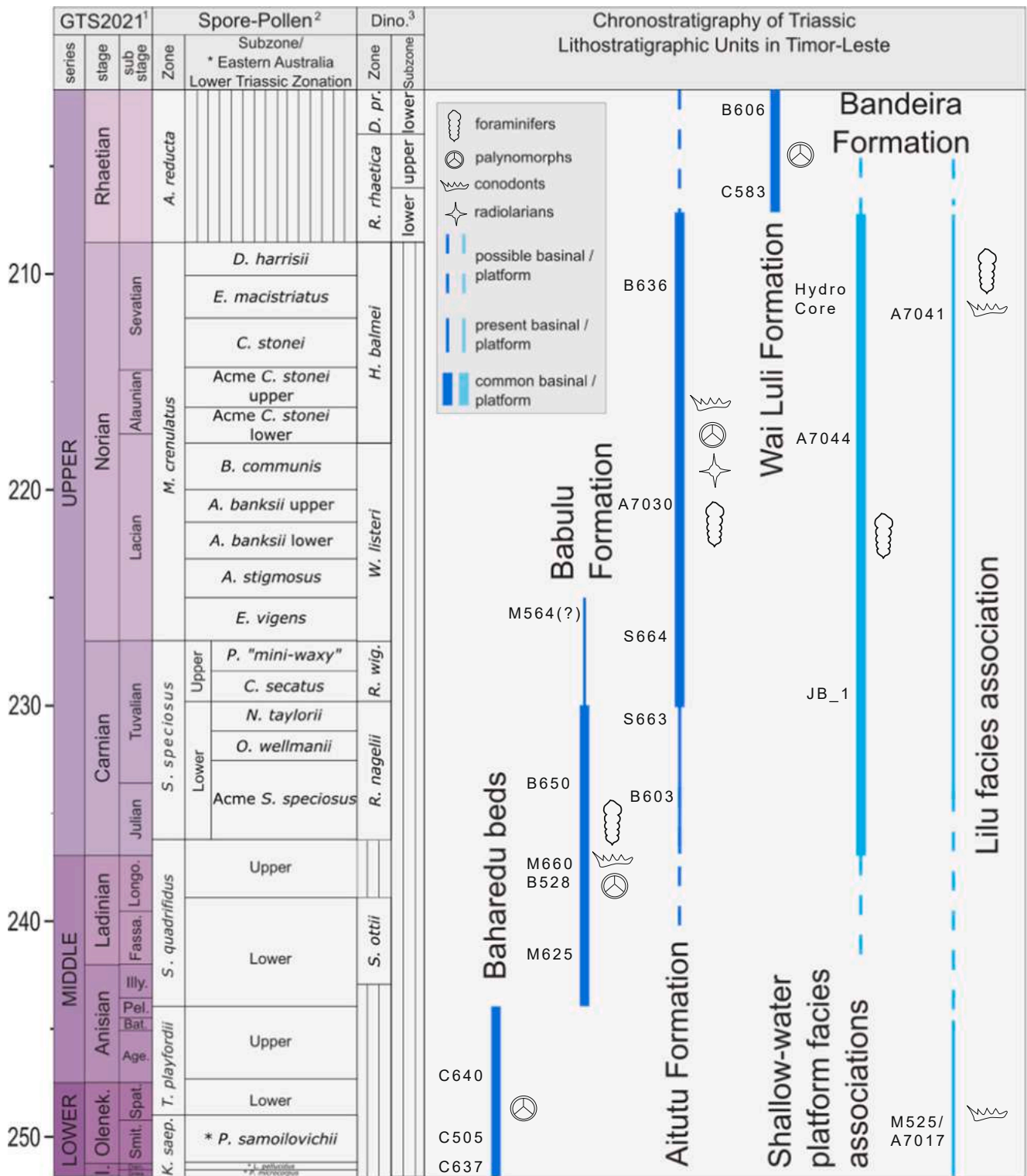


Fig. 3. Chronostratigraphic chart showing palynomorph zonations utilised in this study and data-supported chronostratigraphy of the key lithostratigraphic units exposed in Timor-Leste. The Liliu facies association is not a stratigraphically continuous unit but comprises condensed isolated sections with different chronostratigraphic ranges. Key localities for each unit are given (e.g. S664) as are key fossil groups. The Induan (I.) comprises the Griesbachian and Dienerian and the eastern Australian *P. microcorpus* and *L. pellucidus* spore-pollen Zones. <sup>1</sup> Timescale taken from ICS (2022). <sup>2</sup> Spore-pollen Zonation from Helby et al. (1987), Backhouse and Balme (2002), Dixon et al. (2012), MGPalaeo (2020), Mantle et al. (2020), and Helby (1974) for eastern Australian Lower Triassic zonation. <sup>3</sup> Dinocyst Zonation from Helby et al. (1987) and Mantle et al. (2020). For conodont zones referred to in text and Supplementary online material Table S2 please refer to Ogg et al. (2020) and specific references provided in the text where the zones are discussed.



Triassic stages and the key fossil groups. A summary of conodont faunas is presented in Supplementary online material Table S2 and palynomorph assemblages in Supplementary online material Table S3. All localities mentioned in the text and figure captions can be found in Fig. 1c and Supplementary online material Table S4.

#### 4.1. Induan biostratigraphy

##### 4.1.1. Conodonts

Ten conodont faunas from locality M525/A7017 are the first Induan conodonts documented from Timor and identify the first Induan strata in Timor-Leste. Key species are included in Figs. 4 and 5. The oldest fauna (samples A7017k and M525p) contains *Hindeodus typicalis* and *Isarcicella* aff. *staeschei* but are otherwise dominated by neogondolellins including *Clarkina carinata*, *C. kazi*, *C. krystyni*, *C. meishanensis*, *C. nassishucki*, *C. nevadensis*, *C. planata*, *C. taylorae*, *C. tulongensis* and *Neoclarkina discreta*. These collectively imply an uppermost Griesbachian age based on correlation with faunas described from Tibet (Orchard et al., 1994), Spiti (Orchard and Krystyn, 1998) and Kashmir (Brosse et al., 2017). The occurrence of *Sweetospathodus kummeli* implies a probable lower Dienerian age (Orchard, 2007a), although it occurs in the upper Griesbachian Strigatus ammonoid Zone in the Arctic (Orchard, 2008), so an age close to the substage boundary seems probable.

From the same section multiple lower to upper Dienerian conodont faunas have been documented. Some of the neogondolellins of samples A7017k and M525p continue to dominate the lowermost Dienerian fauna (sample A7017e) that contains the first *Neospathodus* species in *Ns. dieneri* (Fig. 5) and its probable synonym *Ns. svalbardensis*. In addition to this cosmopolitan species, *Scythogondolella?* n. sp. A (Fig. 4) of Orchard (2008) and *Borinella?* *megacuspa* (Fig. 4), suggest correlation with the lower Dienerian *Candidus* ammonoid Zone of the Canadian Arctic (Orchard, 2008).

*Neospathodus* species, including *Ns. cristagalli*, *Ns. dieneri*, *Ns. novae-hollandiae*, *Ns. pakistanensis*, and *Novispathodus posterolongatus* dominate the latest Dienerian and earliest Smithian fauna. The presence of common *Borinella nepalensis* (e.g. sample A7017i) mirrors occurrences around the, as yet undefined, Induan–Olenekian boundary in Spiti, northern India (Orchard and Krystyn, 2007) and the Waili cave section in Guangxi, southern China (Goumand, 2014). Additional conodont elements documented as part of Induan faunas include *Ns. robustus*, *Ns. tongi*, *Borinella* sp., and elements similar to *Discretella* sp.

##### 4.1.2. Palynomorphs

Sample C673b is assigned to the Induan–Olenekian *Kraeuselisporites saeptatus* Spore-Pollen Zone (Fig. 3) with the absence of *Aratrisporites* suggesting a correlation with the lower part (i.e. Induan) of this zone. Other possible Induan samples include two questionable *K. saeptatus* Zone assemblages (C611b and S602b) and several likely Lower Triassic assemblages (e.g. C654a and TR1711415), most of which are dominated by the spinose acritarchs, *Micrhystridium* and *Veryhachium*.

#### 4.2. Olenekian biostratigraphy

##### 4.2.1. Conodonts

Conodont faunas have been previously attributed to the Olenekian in Timor-Leste (Nogami, 1968; Berry et al., 1984) and from West Timor (Barkham in Charlton et al., 2009). Eleven conodont faunas are here attributed to the Olenekian from locality M525/A7017. *Novispathodus waageni* (Fig. 5), *Nv. posterolongatus* (Fig. 5), and *Discretella* spp. are typical of the lower Olenekian, and these are variously accompanied by Dienerian holdovers *Ns. dieneri*, *Ns. cristagalli*, and *Ns. pakistanensis* placing these faunas within the lower Smithian (samples M525c, M525e, M525q, A7017j and M622c). Spathian strata are identified based on the presence of *Nv. abruptus*, *Spathicuspathi* (Fig. 5), *Tr. homeri*, and *Tr. brochus* (sample M525k). Other Olenekian conodonts include *Columbitella jubata* (Fig. 5) and *Tr. symmetricus* (Fig. 5) but these come from an

admixed fauna (sample M525l) including Middle Triassic conodonts. The genesis of these admixed faunas remains uncertain.

##### 4.2.2. Palynomorphs

Five palynological samples containing rare *Aratrisporites* spp. are attributed to the upper part of the *K. saeptatus* Zone and more tentatively to the eastern Australian *Protohaploxylinus samoilovichii* Spore-Pollen Zone of Helby (1974). The first appearance of these monolet lycophyte spores (*Aratrisporites*) is a moderately consistent marker across the NWS approximating the base Olenekian. In contrast, the stratigraphic ranges of various key miospores of the *P. samoilovichii* Zone are not very well constrained in western Australia or Timor. All five samples contain diagnostic *K. saeptatus* Zone assemblages dominated by spiny acritarchs (with variable proportions of *Veryhachium* and *Micrhystridium*) and/or trilete lycopoid spores, particularly *Kraeuselisporites saeptatus* (Fig. 6), *Densoisporites playfordii* (Fig. 6), and *Lundbladispota* types. These upper *K. saeptatus* Zone assemblages, together with the possible Induan assemblages, represent the first records of Lower Triassic palynofloras from Timor. In Western Australia, the lower/upper *K. saeptatus* subzonal boundary, equivalent to the base of the *P. samoilovichii* Zone in eastern Australia, is placed at or close to the Induan–Olenekian boundary (Fig. 3; Nicoll et al., 2010; MGPalaeo, 2020), although a Dienerian or even Griesbachian age cannot be discarded (see discussion in Helby et al., 1987). Some tentative *P. samoilovichii* Zone palynofloras in this study come from thin outcrop sections, such as locality C505 (Fig. 1c), where *Claraia* bivalves, tentatively identified as ?*Claraia stachei* and ? *C. griesbachi* suggesting a Griesbachian assignment (e.g. Nakazawa, 1977; Wignall et al., 1988), are also present. Three further samples tentatively attributed to the *Triplexisporites playfordii* Spore-Pollen Zone, which is in part Olenekian, are discussed in the Anisian section.

#### 4.3. Anisian biostratigraphy

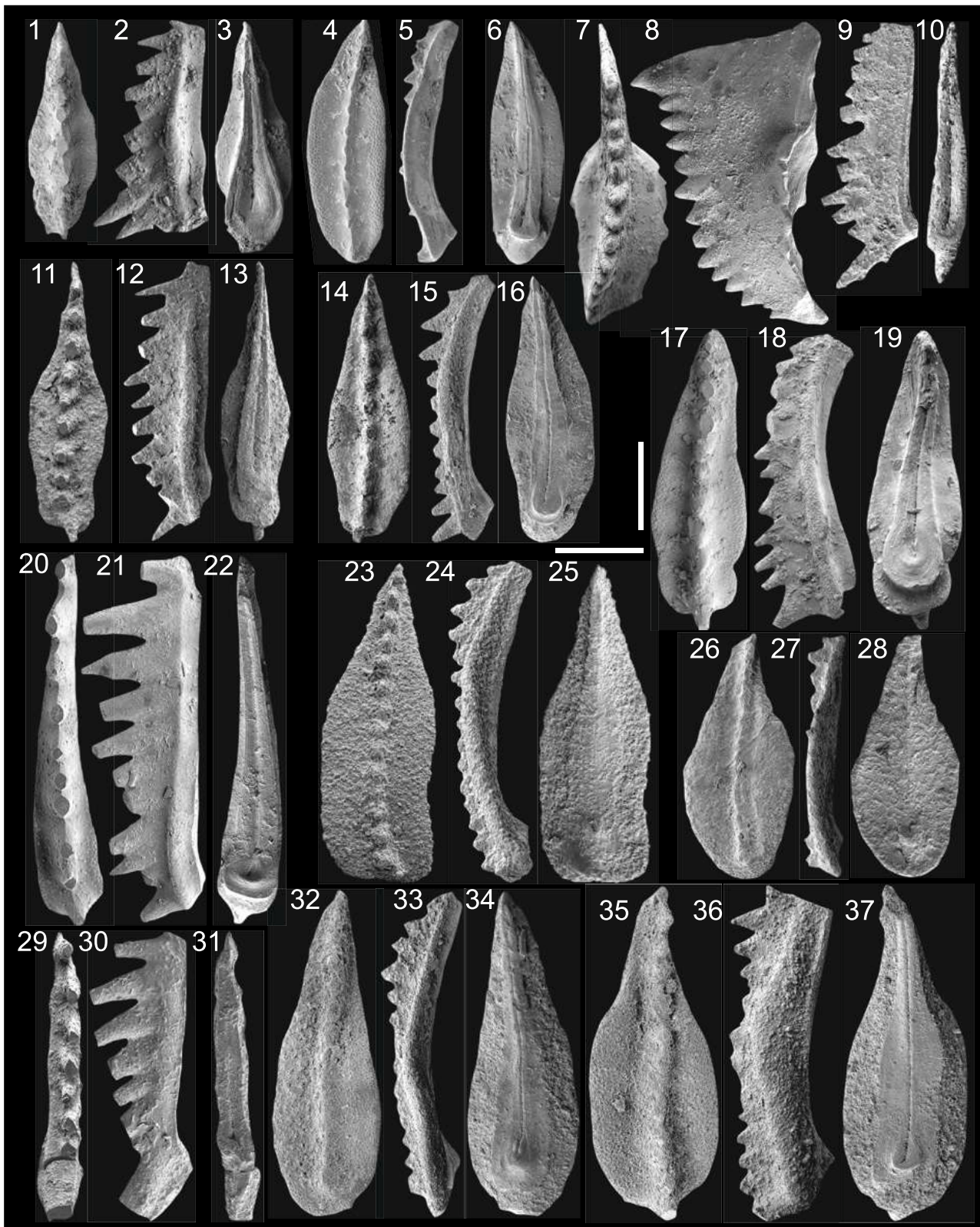
##### 4.3.1. Conodonts

Anisian conodont faunas have been recognised by Orchard (1994) in West Timor, and Nogami (1968) from Mount Lulu in Timor-Leste. Just three faunas with an Anisian, or part Anisian, stratigraphic range are documented in this study. Neogondolellin species include *Neogondolella bifurcata* (Fig. 4) typical of the Pelsonian Substage (Kovacs, 2003). Sample C621a contains *Paragondolella* ex gr. *excelsa* and *Gladigondolella tethydis* (Fig. 4) which together indicate an upper Anisian–mid Ladinian range (Krystyn, 1983). A similar range is suggested by *Ng. cf. bakalovi* (Fig. 4) and *Ng. tenera* (Fig. 4; sample M626b). *Neogondolella tenera* was recently described from the middle and upper Anisian of western Canada (Golding and Orchard, 2016), whereas *Ng. bakalovi* occurs in the lower Ladinian *Curionii* ammonoid Zone in Hungary (Kovács, 1994).

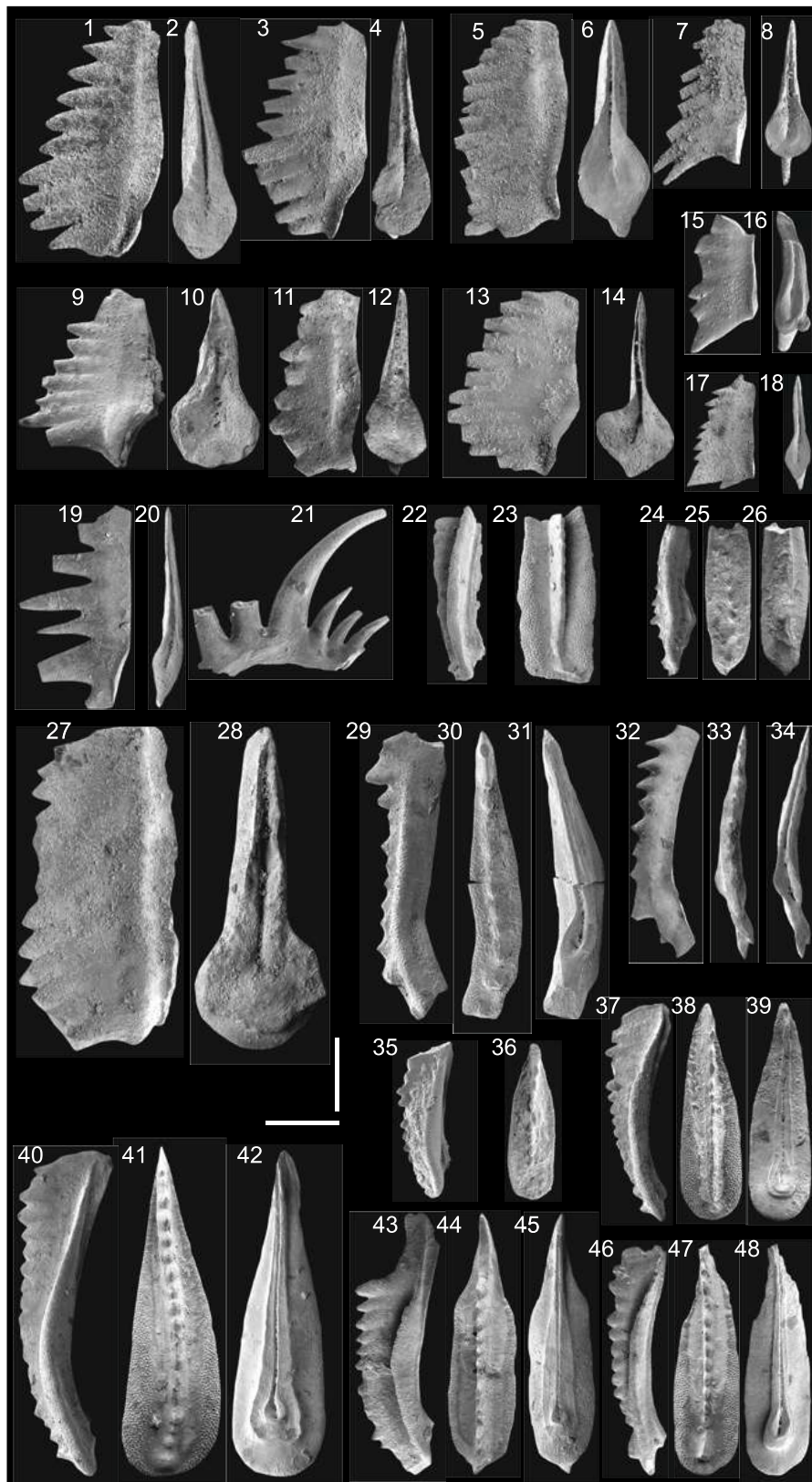
Three admixed faunas (A7017n, M525i and M525l) include Anisian conodonts. Both *Chiosella* sp. and *G. tethydis* (Fig. 4) occur at, or near, the base of the Anisian in the boundary sections in Romania (Orchard et al., 2007a) and south China (Orchard et al., 2007b; Chen et al., 2020). *Paragondolella* ex gr. *excelsa* (Fig. 4) is common in the upper Anisian (Mosher, 1968). *Nicoraella kockeli* (Fig. 4), *Pg.* ex gr. *excelsa*, and ‘*Pg.*’ *trammeri* (Fig. 4) represent successive zones of the Pelsonian and Illyrian substages (Budurov, 1976). ‘*Paragondolella*’ *trammeri* is typical of the *Reitzi* ammonoid Zone in Tethys (Kozur et al., 1994).

##### 4.3.2. Palynomorphs

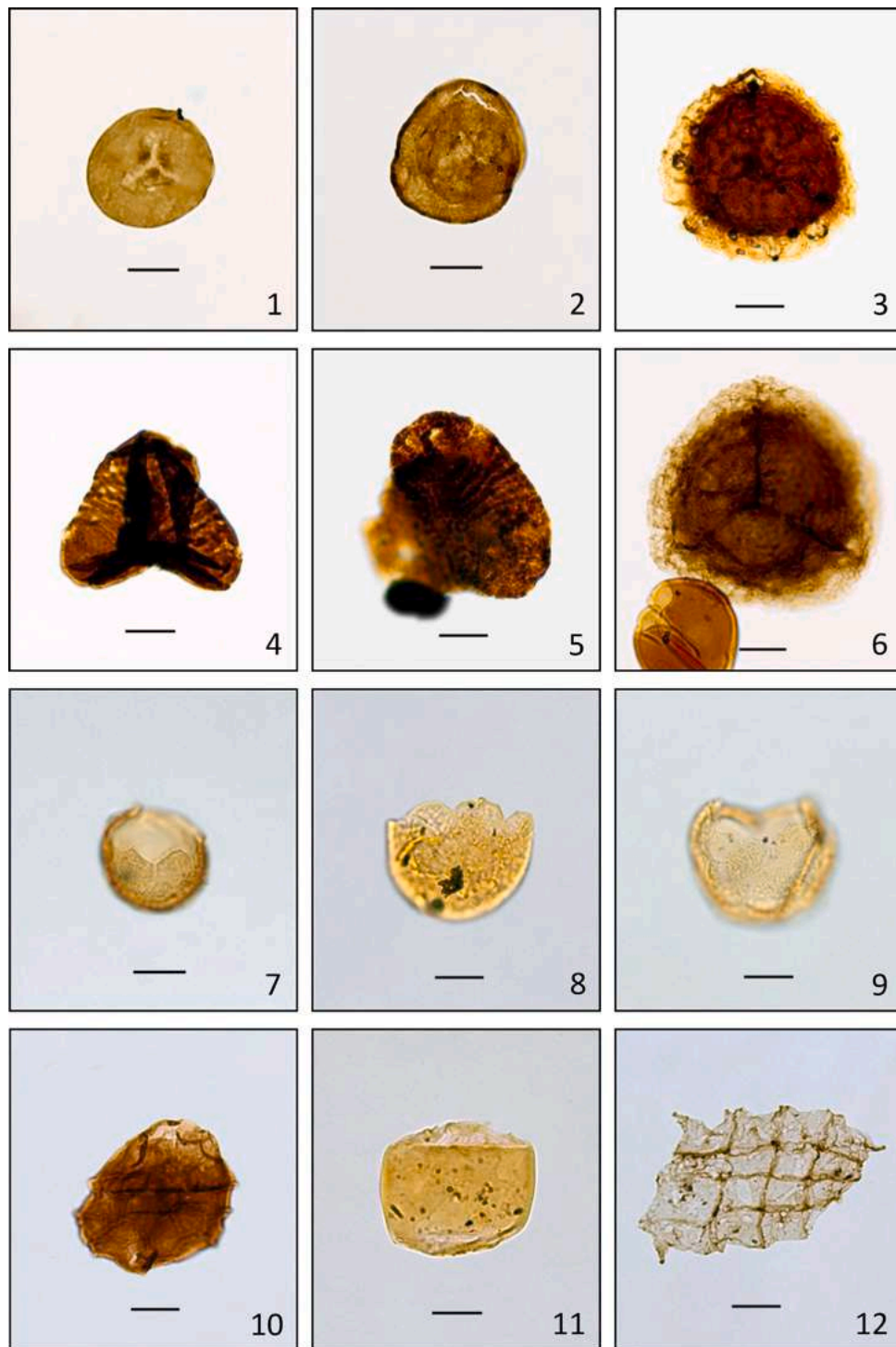
Three assemblages, characterized by rare *Triplexisporites playfordii* (C675a), frequent *Aratrisporites parvispinosus* (C640a), and lacking palynomorphs indicating an older age are tentatively assigned to the *T. playfordii* Zone. Two further samples (B507a and C522) are assigned to the *T. playfordii* Zone or younger based on the presence of low numbers of *Staurosaccites quadrifidus* (Fig. 7) or the unpublished spore *Cingulisporites ‘caperoradiatus’* which has a stratigraphic range restricted to the *T. playfordii* Zone in the Roebuck Basin on the NWS. The *T. playfordii* Zone is considered to range from the Olenekian (Dolby and



**Fig. 4.** Key Lower Triassic conodonts documented in this study. Scale bars 200 µm; 1–3, 17–19: *Scythogondolella* n. sp. A, sample A7017e. 4–6: *Clarkina nassichuki*, sample A7017k/M525p. 7–8: *Hindeodus typicalis*, sample A7017k/M525p. 9–10: *Sweetospathodus kummeli*, sample A7017k/M525p. 11–13: *Neoclarkina discreta*, sample A7017k/M525p. 14–16: *Clarkina krystyni*, sample A7017k/M525p. 17–19: *Scythogondolella* n. sp. A, sample A7017e. 20–22: *Borinella nepalensis*, sample M525q. 23–25: *Clarkina tulongensis*, sample A7017k/M525p. 26–28: *Clarkina planata*, sample A7017k/M525p. 29–31: *Borinella? megacuspa*, sample M525r. 32–34: *Clarkina taylora*, sample A7017k/M525p. 35–36: *Clarkina kazi*, sample A7017k/M525p.



**Fig. 5.** Key Lower and Middle Triassic conodonts documented in this study. Scale bars 200  $\mu\text{m}$ ; 1–2: *Neospathodus cristagalli*, sample A7017i. 3–4: *Novispathodus posterolongatus*, sample M525q. 5–6: *Triassospathodus symmetricus*, sample M525l. 7–8: *Neospathodus dieneri*, sample A7017e. 9–10: *Neospathodus robustus*, sample M525o. 11–12: *Neospathodus pakistanensis*, sample A7017i. 13–14: *Neospathodus waageni*, sample A7017m. 15–16: *Spathicuspus spathi*, sample M525k. 17–18: *Nicoraella kockeli*, sample M525l. 19–20: *Discretella discreta*, sample A7017j. 21: *Gladigondolella tethydis*, sample C621a. 22–23: *Paragondolella* cf. *bifurcata*, sample C628a. 24–26: *Neogondolella bakalovi*, sample M626b. 27–28: *Neospathodus novaehollandiae*, sample A7017i. 29–31, 32–34: *Gladigondolella tethydis*, sample A7017n. 35–36: *Neogondolella tenera*, sample M626b. 37–39: *Paragondolella* ex gr. *excelsa*, sample M525l. 40–42: *Paragondolella* ex gr. *excelsa*, sample A7017n. 43–45: *Columbitella jubata*, sample M525l. 46–49: *Paragondolella trammeri*, sample M525l.

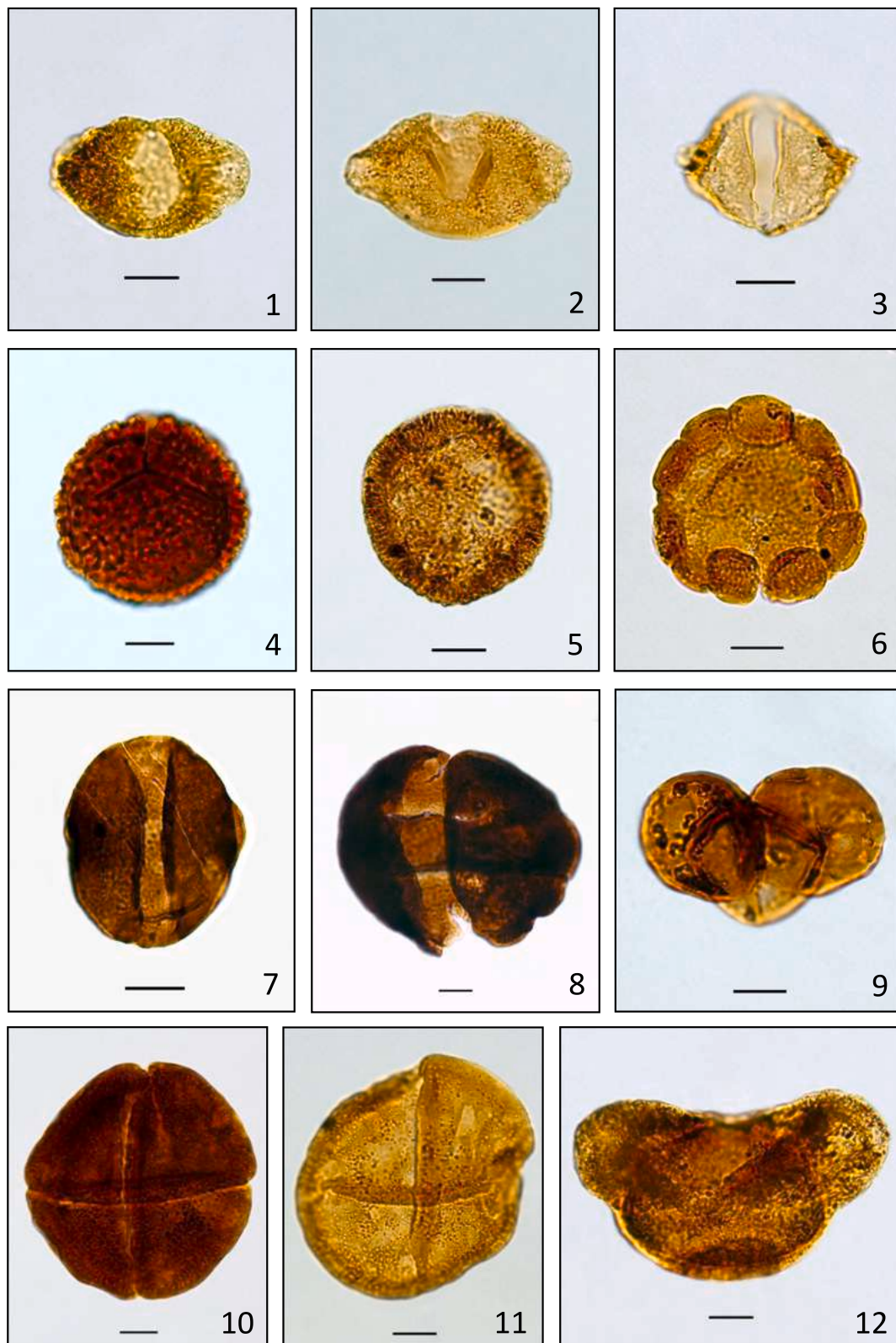


**Fig. 6.** 1–6: Key Triassic spore-pollen marker taxa documented in this study. 1–2: *Densoisporites playfordii* (Balme) Dettmann 1963, sample TR1709231A. 3 & 6: *Kraeuselisporites saeptatus* Balme, 1963, sample TR1709231A. 4–5: *Triplesporites playfordii* (de Jersey & Hamilton) Foster 1979, sample IPG/23/7/21-10B. 7–12: Key Triassic dinocyst and algal marker taxa documented in this study. 7–9: *Suessia? scabrata* Mantle, Riding & Hannaford, 2020, 7 & 9: sample B637h, 8: sample B637d. 10: *Dapcodinium priscum* Evitt 1961, sample B567. 11: *Bartenia communis* Helby 1987, sample B637d. 12: *Plaesiodyctyon mosellanum* spp. *variabile* Brenner & Foster 1994, sample C571. All scale bars = 10  $\mu$ m. Slide location of imaged taxa are included in Supplementary online material Table S6.

Balme, 1976 following McTavish, 1973) to the middle Anisian (Fig. 3).

Eight of the palynological samples attributed to the *Staurosaccites quadrifidus* Spore-Pollen Zone are assigned to the Lower *S. quadrifidus* Subzone, considered to range from middle Anisian to middle Ladinian (Fig. 3; Dolby and Balme, 1976; Helby et al., 1987). These samples all

contain rare to frequent *S. quadrifidus*, low numbers of *Camerosporites secatus* compared to younger samples, and they all lack the Upper *S. quadrifidus* Subzone markers *Enzonalsporites vigens* and *Samaropollenites speciosus*. A further three samples are attributed to the broader *S. quadrifidus* Zone that is in part Anisian.



**Fig. 7.** Key Triassic spore-pollen marker taxa documented in this study. 1–2: *Minutosaccus crenulatus* Dolby in Dolby & Balme, 1976, 1: sample B643c, 2: sample B637d. 3: *Minutosaccus* “timorensis” sensu MGPalaeo (informal industry name), sample B637f. 4: *Leschikisporis* sp. B Backhouse & Balme, 2002, sample B567d. 5: *Enzonalasporites vigens* Leschik 1955, sample B650c. 6: *Camerosporites pseudoverrucatus* Leschik 1956, sample B650c. 7: *Ashmoripollis reducta* Helby 1987, sample C583c. 8: *Infernopollenites claustratus* Dolby & Balme, 1976, sample C571. 9: *Platysaccus* “mini-waxy” sensu MGPalaeo (informal industry name), sample S653a. 10–11: *Staurosaccites quadrifidus* Dolby in Dolby & Balme, 1976, 10: sample M659a, 11: sample B637d. 12: *Samaropollenites speciosus* Goubin 1965, sample B643c. All scale bars = 10  $\mu$ m. Slide location of imaged taxa are included in Supplementary online material [Table S6](#).

#### 4.4. Ladinian biostratigraphy

##### 4.4.1. Conodonts

No exclusively Ladinian conodonts have been documented from Timor prior to or as part of this study. Two faunas (M626b and C621a), discussed within the previous section, have an in part Ladinian range, as do the mixed faunas from locality M525/A7017 (M525l and A7017n).

##### 4.4.2. Palynomorphs

Forty-three assemblages are attributed to the Upper *S. quadrifidus* Subzone which is considered upper Ladinian (Fig. 3), though with limited direct chronostratigraphic tie-points. The Upper *S. quadrifidus* Subzone samples are identified by the rare to common occurrences of *S. quadrifidus* along with rare to frequent *Rimaesporites aquilonalis*, very rare *Infernopollenites claustratus* (Fig. 7), and rare to common *E. vigens* (Fig. 7) and *S. speciosus* (Fig. 7). The high abundances of *Falcisporites australis* is another key feature of the *S. quadrifidus* Zone that distinguishes it from the lower subzones of the *Samaropollenites speciosus* Spore-Pollen Zone as observed by DM in the Northern Carnarvon and Bonaparte basins. Five further samples with elevated abundances of *E. vigens* are considered to belong to the upper part of the Upper Subzone and thought to be latest Ladinian–early Carnian (discussed further under the Carnian section).

#### 4.5. Carnian biostratigraphy

##### 4.5.1. Conodonts

Carnian conodonts have previously been documented from Timor (Harris et al., 2000 reported in Charlton et al., 2009; Barkham in Charlton et al., 2009). Here 20 conodont faunas correlated to the Carnian can be split into those typical of the Julian and Tuvalian substages, and key species are imaged in Figs. 8 and 9. The Julian faunas are dominated by paragondolellids including common *Pg.* (= *Quadralella*) *polygnathiformis* and *Pg. tadpole* along with *Pg. inclinata* and elements closely related to *Pg. foliata* and *Pg. auriformis*. *Paragondolella tadpole* is common in the Tethyan Julian (Mietto et al., 2012; Rigo et al., 2007, 2018), and defines a North American conodont zone ranging from the *Desatoyense* through *Nanseni* ammonoid zones (Orchard, 2007b). In addition, the co-occurrences of the upper Ladinian to Julian *Pg. inclinata* and *Pg.* (= *Q.*) *polygnathiformis*, which spans the Carnian (e.g. sample M676a), support a Julian correlation. No elements of *Budurovignathus*, which often occurs in the Julian, were found, possibly due to unfavourable facies.

Tuvalian strata are identified by a rich association of species including *Carnepigondolella* (= *Q.*) *angulata*, *Pg.* (= *Q.*) *carpathica*, *Pg.* (= *Q.*) *oertlii*, *Cg.* (= *Q.*) *tuvatica* and *Cg. zoeae*. These species are typical of the lower Tuvalian in Tethys (Mazza et al., 2012b; Rigo et al., 2018) and of the *samueli* conodont Zone in North America (Orchard, 2014). Both *Neocavitella cavitata* and *Norigondolella trinacriae* are Tethyan species that are not known to occur in North America. *Norigondolella trinacriae* occurs earlier in the Carnian in Timor than known elsewhere in Tethys (Rigo et al., 2018). Lower Tuvalian species recorded here and previously identified only in Panthalassa include *Cg. anitae*, *Kraussodontus ludingtonensis*, *Kr. vancouverense*, *Q. mcrobertsi* and *Q. postlobata*.

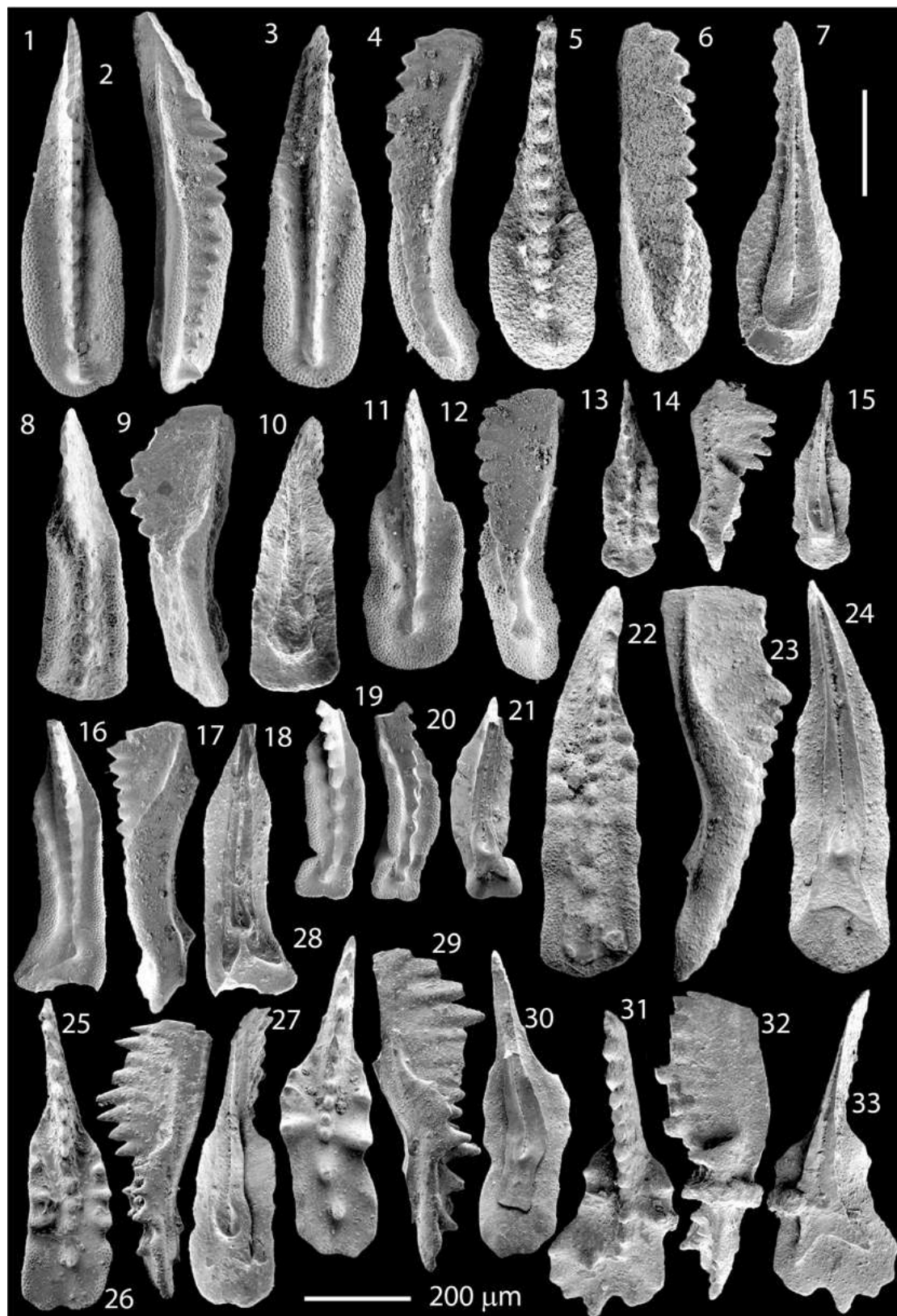
Five uppermost Tuvalian conodont faunas documented here are chronostratigraphic equivalents to the Tethyan *N. cavitata*, *Cg.* (= *Primatella*) *orchardi*, “*Epigondolella*” *vialovi*, *Metapolygnathus communis* and *Mg. parvus* conodont zones (Rigo et al., 2018; Mazza et al., 2011, 2012a, 2012b, 2018) and to the lower part of the North American *Primatella primitia* conodont Zone (Orchard, 2014, =faunas 4–7 of Orchard, 2010b). These conodont zones correspond to the uppermost Tethyan *Tropites subullatus* and *Anatropites spinosus* ammonoid zones (Rigo et al., 2018) and the North American *Klamathites macrolobatus* ammonoid Zone (Orchard, 2014, 2019), respectively. This interval is characterized by species of *Metapolygnathus*, *Carnepigondolella*, *Quadralella*, *Kraussodontus* and associated with increasing numbers of the

ornate genus *Primatella* and rare *Mg. parvus*. The latter species is restricted to the uppermost Tuvalian *Mg. parvus* Zone in both Tethys and North America (Nicora et al., 2007; Orchard, 2007c, 2014, 2019; Mazza et al., 2011, 2012a, 2012b, 2018; Rigo et al., 2018). Similarly, two other species described from North America, *Pr. asymmetrica* (= *Mg. mazzai* part) and *Pr. bifida* (= *Mg. linguiformis sensu Mazza et al., 2012b*) may provide correlative biomarkers for the Carnian–Norian boundary interval worldwide (Orchard, 2019). *Mg.* (= *Q.*) *praecommunisti* is known from the upper Tuvalian of both Sicily and British Columbia, but the Tethyan concept appears to embrace several taxa subsequently differentiated in North America, including *Kraussodontus peteri*, *K. urbanae*, *K. roberti*, *K. vancouverense*, *Q. kathleenae*, and *Q. mcrobertsi* (Orchard, 2019). In Tethys, the upper Tuvalian contains the oldest elements identified as *Ancyrogondolella* species that provide the basis for the *vialovi* conodont Zone (Rigo et al., 2018). Comparable specimens have been referred to *Carnepigondolella* or *Primatella* in North America, where the first *Ancyrogondolella* occurs within the Norian (Orchard, 2019).

##### 4.5.2. Palynomorphs

The chronostratigraphic range of five samples assigned to the uppermost Upper *S. quadrifidus* Zone likely extend into the lowermost Carnian. These samples are characterized by the co-occurrences of *S. quadrifidus* with common *E. vigens* and *S. speciosus*, and often accompanied by rare *I. claustratus*, rare *Cadargasporites* spp., and common to abundant *F. australis*. A total of 25 assemblages are assigned to the overlying *S. speciosus* Zone which spans the remainder of the Carnian. It is likely that strata spanning all five subzones of the *S. speciosus* Zone (Fig. 3) are present in Timor, although the *Osmundacidites wellmanii* and *Neorastrickia taylorii* subzones are mostly recorded as ranged intervals i. e. *O. wellmanii*–*N. taylorii* subzones. Many of the key Carnian biostratigraphic events recognised for the NWS are also recorded in the Timor material. For example, the last appearance datum of *Platysaccus* “*mini-waxy*” (informal industry taxon; Fig. 7) and the last persistent occurrences of *C. secatus* are both placed at the top of the *S. speciosus* Zone on the NWS and are correlated with the Carnian–Norian boundary. The latter event is particularly important as it correlates well with similar increases at the Carnian–Norian boundary in Europe (Cirilli, 2010). Thus, the rare to occasionally frequent occurrences of *C. secatus* and *P. “mini-waxy”* when recorded from the *P. “mini-waxy”* Subzone (uppermost subdivision of the *S. speciosus* Zone) in Timor are considered likely to represent the late Carnian. The common occurrences of *Camerosporites pseudoverrucatus* (Fig. 7) are also notable, as this taxon is typically most prominent in the Lower *S. speciosus* Zone on the NWS, particularly in the Acme *S. speciosus* and *O. wellmanii* subzones.

The oldest dinoflagellate cysts recorded in this study are small *Rhaetogonyaulax* types, including *Rhaetogonyaulax nagelii* and further undescribed forms, that occur as rare components in very low diversity marine suites. A single sample (B575a) is confidently assigned to the lower–mid Carnian *R. nagelii* Dinocyst Zone and three further samples (B643c, B637f, B637h) are assigned to questionable or ranged *R. nagelii*–*R. wigginsii* zones. Samples with frequent to common occurrences of *Rhaetogonyaulax* cf. *wigginsii* (Fig. 10), rare *Suessia* spp. and *Dapcodinium tabulodiniopsis* (Fig. 10 and 8.5), very rare ?*Dapcodinium brenneri* and ?*Heibergella* sp., and other indeterminate dinoflagellate cysts are assigned to the overlying mid–upper Carnian *R. wigginsii* Dinocyst Zone. These records correlate well with the oldest dinoflagellate cyst records in the Norwegian Arctic (Vigran et al., 2014; Paterson and Mangerud, 2015) and from Alaska and Arctic Canada (Wiggins, 1973; Felix and Burbridge, 1978) where small *Rhaetogonyaulax* types also first occur in the Carnian. Samples with frequent to common occurrences of *Bartenia communis* (Fig. 6), a likely algal cyst, are here recorded from the *P. “mini-waxy”* Subzone of the *S. speciosus* Zone. This correlates well with the oldest common occurrences of this taxon from the Bonaparte Basin and across the NWS.

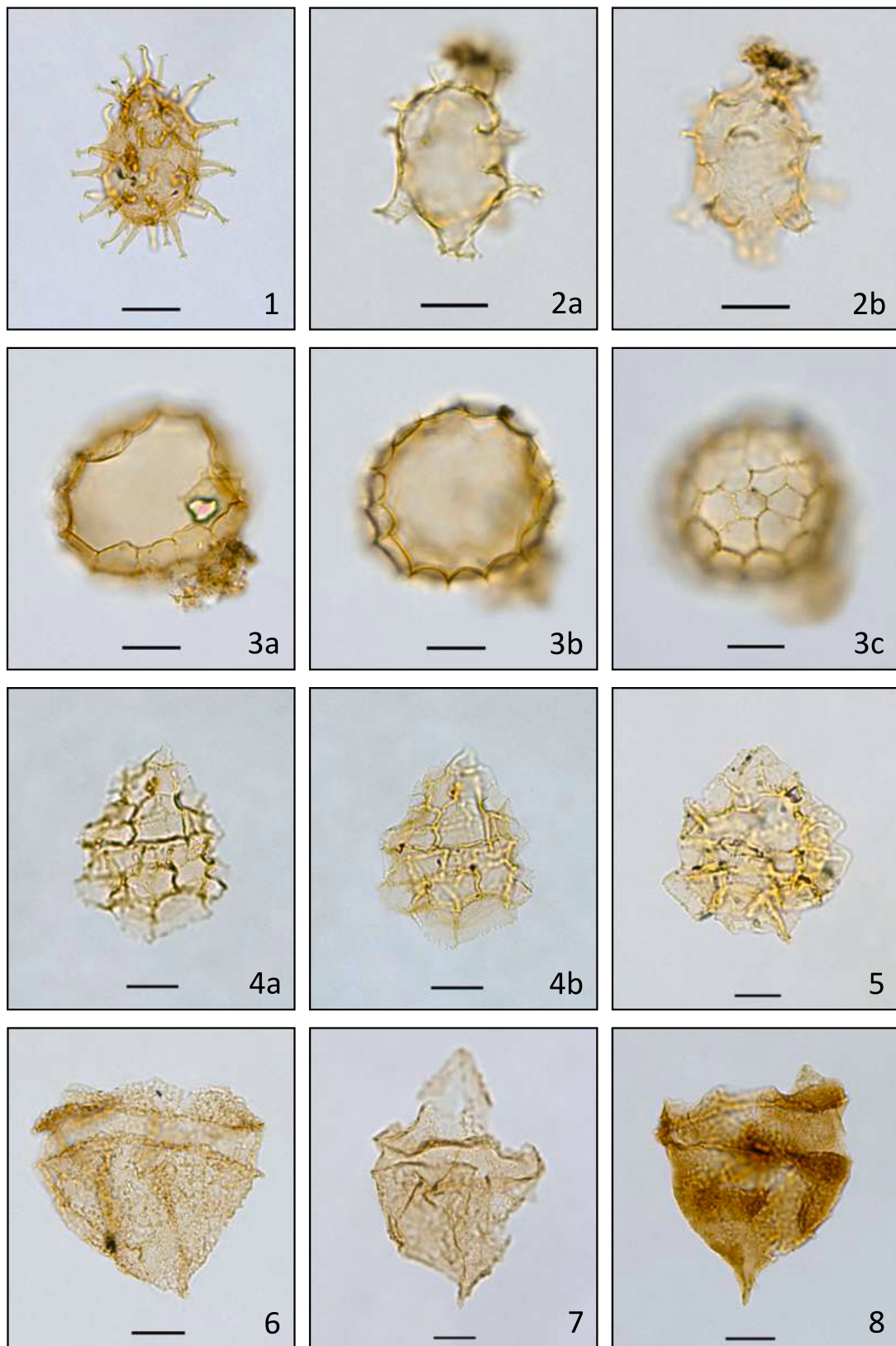


**Fig. 8.** Key Upper Triassic conodonts documented in this study. Scale bars 200  $\mu\text{m}$ ; 1–2: *Paragondolella/Quadralella polygnathiformis*, sample M673a. 3–4: *Paragondolella inclinata*, sample M676a. 5–7: *Paragondolella tadpole*, sample M622b. 8–10: *Paragondolella/Quadralella carpathica*, sample B609a. 11–12: *Carnepigondolella/Quadralella tuvalica*, sample B643a. 13–15: *Carnepigondolella zoeae*, sample M685a. 16–18: *Carnepigondolella/Quadralella angulata*, sample M644a. 19–21: *Paragondolella/Quadralella lindae*, sample M644a. 22–24: *Metapolygnathus/Quadralella praecommunisti*, sample B638a. 25–27: *Carnepigondolella/Primatella orchardi*, sample S664a. 28–30: *Carnepigondolella/Primatella permica*, sample A7038a. 31–33: *Ancryrogondolella aff. vialovi*, sample B613b.



**Fig. 9.** Key Upper Triassic conodonts documented in this study. Scale bars 200  $\mu\text{m}$ ; 1–3: *Metapolygnathus/Primatella mersinensis*, sample S634a. 4–6: *Norigondolella trinacriae*, sample B643a. 7–9: *Ancyrogondolella quadrata*, sample B613b. 10–12: *Neocavitella cavitata*, sample B643a. 13–16: *Metapolygnathus parvus*, sample S646c. 17–19: *Ancyrogondolella uniformis*, sample S655a. 20–22: *Ancyrogondolella* aff. *spatulata*, sample B637h. 23–25: *Mockina* aff. *postera*, sample A7035d. 26–28: *Bajadontus* aff. *unicornis*, sample A7041f. 29–31: *Mockina elongata*, sample B604c. 32–34: *Mockina carinata*, sample A7035d. 35–36: *Norigondolella steinbergensis*, sample B604c. 37–38: *Misikella kolarae*, sample B636c. 39–40: *Parvigondolella prorhaetica*, sample A7041c.





**Fig. 10.** Key Triassic dinocyst and algal marker taxa documented in this study. 1: *Beaumontella langii* (Wall) Below 1987, sample B567. 2a, b: *Goodwynia dendroidea* Mantle, Riding & Hannaford, 2020, median and high focus respectively, sample B636a. 3a–c: *Wanneria cf. listeri* (Stover & Helby) Below 1987, high, median, and low focus respectively, sample B636a. 4–5: *Dapcodinium tabulodiniopsis* Mantle, Riding & Hannaford, 2020, 4a–b high and low focus respectively, 4: sample C543c, 5: sample B637d. 6: *Rhaetogonyaulax cf. wigginsii* (Stover & Helby) Lentin & Williams 1989, sample B636b. 7: *Rhaetogonyaulax cf. rhaetica* (Sarjeant) Loeblich & Loeblich 1968, high and low focus respectively, sample B636b. 8: *Rhaetogonyaulax rhaetica* (Sarjeant) Loeblich & Loeblich 1968, sample B567. All scale bars = 10  $\mu$ m. Slide location of imaged taxa are included in Supplementary online material Table S6.

#### 4.5.3. Radiolarians

Previous studies have documented Carnian radiolarians from West Timor (Rose, 1994; Sashida et al., 1996). One sample (M654a) yielded poorly preserved *Capnucho-sphaera* sp. which indicates a lower Carnian–middle Norian range. The co-occurrence of a Tuvallian conodont fauna from this same sample (Supplementary online material Tables S1 and S2) constrains the range to the Carnian.

### 4.6. Norian biostratigraphy

#### 4.6.1. Conodonts

Limited Norian conodont faunas have been previously reported from West Timor (Bird, 1987; Barkham, 1993; Martini et al., 2000) and Timor-Leste (Nogami, 1968; Hunter, 1993). In this study 19 conodont faunas represent the Norian stage. The recently selected biomarker for the base of the Norian is the bivalve *Halobia austriaca* (Hounslow et al., 2021), the first appearance of which in North America approximates the base of the *asymmetrica*–*Norigondolella* Subzone of the *primitia* conodont Zone (Orchard, 2014). In Tethys, a comparable datum is recognized close to the base of the “*Carnepigondolella*” *gulloae* conodont Zone (Rigo et al., 2018; Mazza et al., 2018). In both regions, this datum correlates with the top of an underlying *Metapolygnathus parvus* conodont (Sub-) Zone (Orchard, 2019). In North America, conodonts above this level in the earliest Norian, are characterized by the absence of common Carnian genera (*Carnepigondolella*, *Quadrallella*, *Kraussodontus*, and *Metapolygnathus*) and by the presence of *Primatella*, and *Norigondolella* dominated faunas. Succeeding the *Primatella* faunas in North America, near the top of the lower Norian *Kerri* ammonoid Zone, are faunas dominated by *Ancyrogondolella* (formerly *Epigondolella*) species (Orchard, 2014, 2019). These successive faunas are assigned to the *asymmetrica*–*Norigondolella* Subzone of the *primitia* conodont Zone, and the succeeding *quadrata* conodont Zone (Orchard, 2019). In Tethys, the disappearance of the Carnian forms are succeeded by similar conodont associations assigned to the *gulloae* and *rigoi*–*quadrata* conodont Zones (Rigo et al., 2018; Orchard, 2019).

Seven diverse lower Lacian *Ancyrogondolella* and *Primatella* faunas are recognized. Collectively, these include *Ancyrogondolella quadrata*, *An. aff. vialovi* sensu Orchard (2014), *An. uniformis* (Fig. 9) and several species first described from North America such as *Pr. asymmetrica*, *Pr. bifida*, *Pr. conservativa*, *Pr. orchardi*, *Pr. ovale*, *Pr. mersinensis*, *Pr. permica*, *Pr. rotunda*, *Pr. stanleyi* and *Pr. subquadrata*, which appear first in the uppermost Carnian, but no exclusively Carnian genera occur in these Timor collections. The younger suite of eight samples are assigned to the mid–upper Lacian North American *quadrata* conodont Zone (Orchard, 2014, 2019) or Tethyan *rigoi*–*quadrata* conodont zones (Rigo et al., 2018). These are characterized by *Ancyrogondolella* species, especially *An. quadrata*, *An. aff. uniformis*, and *An. aff. vialovi* sensu Orchard (2014), and in one sample, *Norigondolella*. Although regarded as exclusively Norian in North America, several of these *Ancyrogondolella* species have been recorded in Tethys first in the uppermost Tuvallian (Mazza et al., 2010, 2012b; Rigo et al., 2018), so these collections, and others discussed under Tuvallian, are presently differentiated in Timor as a “transitional fauna” encompassing the entire interval.

The middle Norian (Alaunian) is represented by *Mockina postera*, *Mo. elongata* and *Mo. carinata* (Fig. 9) which are sometimes associated with *Nr. imperfecta* and *Nr. steinbergensis* (Fig. 9). These latter two species range from the Alaunian to Rhaetian (Orchard et al., 2007c; Rigo et al., 2018; Golding and Orchard, 2021). The youngest three faunas are Sevatian based on *Parvigondolella prorhaetica* (Fig. 9) and *Mo. bidentata* (Rigo et al., 2018; Karádi et al., 2020; Golding and Orchard, 2021).

#### 4.6.2. Palynomorphs

Only two assemblages are confidently assigned to the Norian *Minutaccus crenulatus* Spore-Pollen Zone (Fig. 3) along with a few further

ranged zonal samples. These assemblages from Timor are similar to those in the Bonaparte Basin where key Norian subzonal markers (e.g. *Cycadopites stoneii* and *Ephedripites macstriatus*) are typically rare or absent. This renders the application of the ten *M. crenulatus* spore-pollen subzones developed in the Northern Carnarvon Basin challenging in both regions. However, dinoflagellate cysts are increasingly important and diverse stratigraphic markers in the Norian (Mangerud et al., 2019; Mantle et al., 2020) and key Australasian marker taxa, *Hebecysta balmei*, *Suessia swabiana* and *Wanneria cf. listeri* (Fig. 10) are recorded from the Norian samples in Timor. *Hebecysta balmei* is restricted to the mid–upper Norian *H. balmei* Dinocyst Zone and the common to abundant occurrences of this taxon noted from two samples (B562 and TR1710285) may correlate with the regional TR26.5 MFS flooding event (Marshall and Lang, 2013) of the Northern Carnarvon Basin. The frequent occurrences of *Goodwynia dendroidea* (Fig. 10) in one sample (B636a) represent an important record, as this widely dispersed but cryptic taxon has only rarely been recorded (Morbey, 1975; Mantle et al., 2020). It is most frequently recorded from the Norian of the NWS, though it ranges into the Rhaetian.

#### 4.6.3. Radiolarians

Norian radiolarian assemblages have been previously reported from Timor (Rose, 1994; Martini et al., 2000). Several samples from locality S8 yielded very rich and very well-preserved pyritized radiolarian assemblages (Fig. 11) all referable to the lower Norian (Lacian) following the species range given by Tekin (1999). Spumellarians are very common, mainly represented by three genera, *Capnodoce*, *Capnucho-sphaera* and *Sarla*, whereas Nassellarians are diverse, but less abundant. The Lacian marker species include *Dicapnucho-sphaera elegans* Tekin, 1999, *Kahlerosphaera? aspinosa* Kozur and Mock, 1981, *K. kemerensis adentatus* Tekin, 1999, *Orbiculiformella octogonalis* (Tekin, 1999), *Triassocrucella triassica* (Kozur and Mostler, 1978), *Xiphoteccaella longa* (Kozur and Mock, 1981) and *X. rugosa* (Bragin, 1991) together with *Caphtorocrytium paenuloides* Bragin, 2007, *Capnodoce anapetes* De Wever, 1979, *C. longibrachium* Tekin, 1999, *Icrioma* sp. A sensu Tekin, 1999, *Kahlerosphaera* sp. cf. *K. norica* Kozur & Mock, 1981, *Palaeososaturnalis triassicus* (Kozur & Mostler, 1972), *Renzium* sp. B sensu Tekin, 1999, *Senelella* sp. cf. *S. triassica* Tekin, 1999, *Xiphoteccaella* sp. and Nassellaria gen. et sp. indet. (Fig. 11). Assemblages from samples S8/2 and S8/6 lack key stratigraphic markers and may range from the upper Carnian to lower Norian.

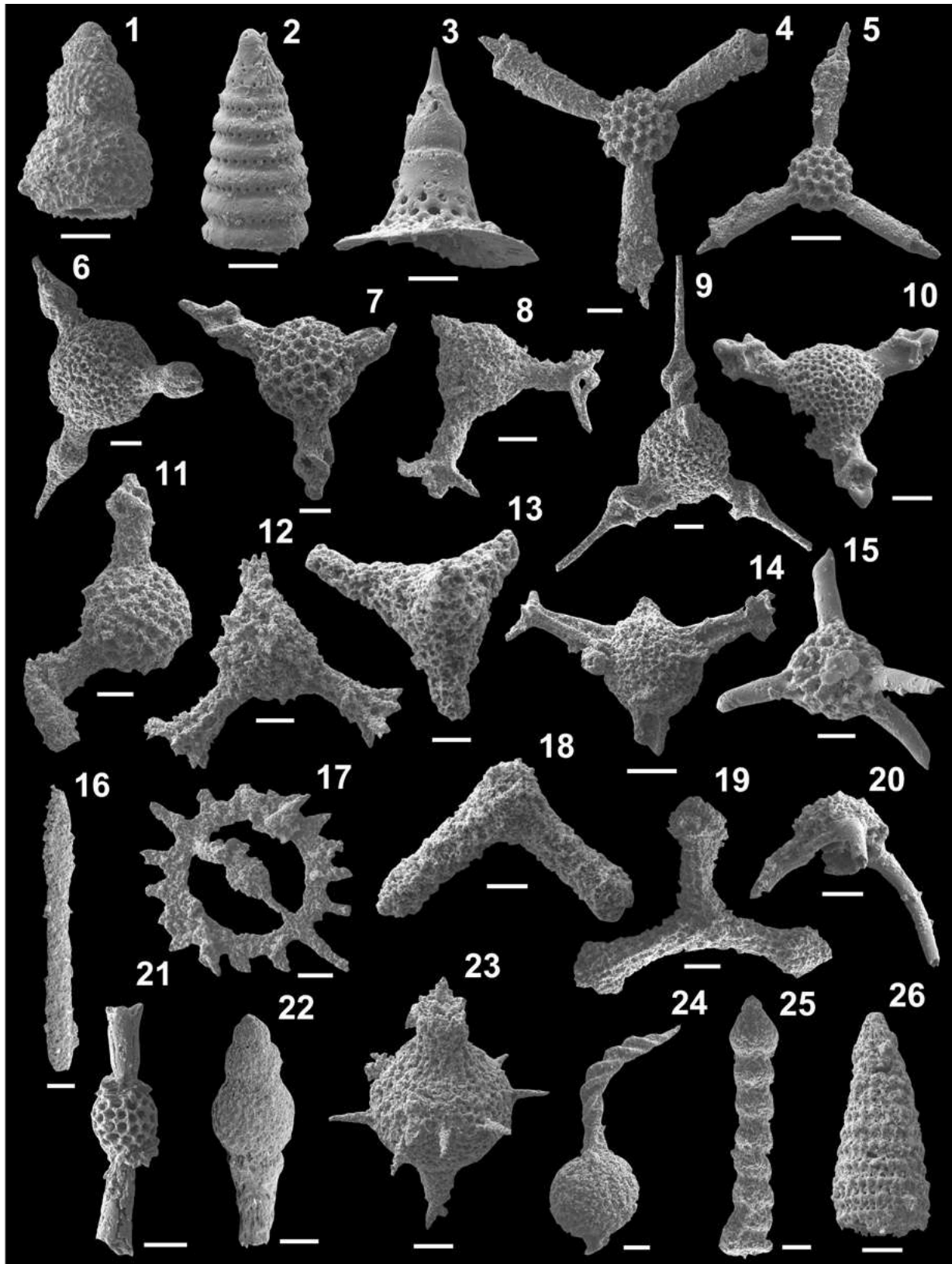
### 4.7. Rhaetian biostratigraphy

#### 4.7.1. Conodonts

Rhaetian conodont assemblages from West Timor have been previously documented (Nicoll, 2002; Barkham, 1993; Bird in Charlton et al., 2009). In Timor-Leste, the presence of *Misikella hernsteini*, transitional forms of *Mi. hernsteini/posthernsteini*, and *Mi. kolarae* (Fig. 9) correlate one fauna (sample B636c) to the Rhaetian (Karádi et al., 2020).

#### 4.7.2. Palynomorphs

Five assemblages in this study are assigned to the *Ashmoripollis reducta* Spore-Pollen Zone based on rare *A. reducta* (Fig. 7), very rare *Zebraspores* spp., rare to common *Leschiksporites* spp., abundant *F. australis*, and the lack of distinctive Carnian or Norian marker taxa. Four of these samples are also assigned to Rhaetian dinoflagellate cyst zones based on the occurrences of *Dapcodinium priscum* (Fig. 6), *Beaumontella langii* (Fig. 10), *Suessia swabiana* (Lower *D. priscum* Dinocyst Zone) and rare to frequent *Rhaetogonyaulax rhaetica* (*R. rhaetica* Dinocyst Zone; Fig. 10). *Rhaetogonyaulax rhaetica* is a global Upper Triassic marker taxon that is most prominent in Rhaetian assemblages (Mangerud et al., 2019; Mantle et al., 2020).



(caption on next page)

Fig. 11. Key Upper Triassic radiolarians documented in this study. Scale bar represents 50  $\mu\text{m}$ . 1: *Canesium lentum* Blome, 1984, sample S8/8. 2: *Canoptum macoyense* Blome, 1984, sample S8/8. 3: *Caphtorocyrtium paenuloides* Bragin, 2007, sample S8/8. 4: *Capnodoce anapetes* De Wever, 1979, sample TL010 05LP1. 5: *Capnodoce longibrachium* Tekin, 1999, sample TL010 05LP1. 6: *Capnuhosphaera crassa* Yeh, 1990, sample TL010 05LP1. 7: *Capnuhosphaera deweveri* Kozur & Mostler, 1979, sample TL010 05LP1. 8: *Capnuhosphaera tricornis* De Wever, 1979, sample TL010 05LP1. 9: *Capnuhosphaera* sp. cf. *C. borbala* Kozur, Moix & Ozsvárt, 2009, sample TL010 05LP1. 10: *Capnuhosphaera* sp. aff. *C. texensis* Yeh, 1989, sample S8/8. 11: *Capnuhosphaera* sp., sample TL010 05LP1. 12: *Icrioma* sp. A sensu Tekin, 1999, sample TL010 05LP1. 13: *Icrioma* sp., sample S8/2. 14: *Kahlerosphaera* sp. cf. *K. norica* Kozur and Mock, 1981, sample TL010 05LP1. 15: *Loffa mulleri* Pessagno 1979, sample S8/8. 16: *Mostlericyrtium sitepesiformis* Tekin, 1999, sample M685a. 17: *Palaeososarturnalis triassicus* (Kozur & Mostler, 1972), sample TL010 05LP2. 18: *Paratriassostrum?* sp., sample S8/6. 19: *Paronaella norica* Kozur & Mock, 1981, sample TL010 05LP2. 20: *Poulpus piabyx* De Wever, 1979, sample S8/8. 21: *Renzium* sp. B sensu Tekin, 1999, sample S8/8. 22: *Senelella* sp. cf. *S. triassica* Tekin, 1999, sample B613b. 23: *Spinoscapsa* sp. aff. *S. turriformis* (Tekin, 1999), sample TL010 05LP1. 24: *Spongotorilispinus carnicus* (Kozur & Mostler, 1979), sample TL010 05LP2. 25: *Xiphoteacella* sp., sample TL010 05LP2. 26: Nassellaria gen. et sp. indet., sample S8/8.

## 5. Discussion

### 5.1. Applying North West Shelf palynomorph zones in Timor-Leste

Data presented in Section 4 demonstrates the strong similarities in Triassic palynological assemblages between the NWS and Timor, suggesting the criteria defining the NWS zonal scheme may be applied to Timor-Leste assemblages. However, the veracity and synchronicity, between the NWS and Timor, of key zonal criteria is yet to be tested. Much of the NWS zonal scheme is based on criteria devised for stratigraphically ordered sample sets e.g. First or Last Appearance Datums and stratigraphic variations in abundances of marker species. The stratigraphically limited coherent outcrop in Timor-Leste and reconnaissance nature of this study restricted the collection of such samples sets. However, conodonts, and one occurrence of bivalves, co-occurring with palynomorph assemblages allow for independent calibration of these assemblages to the GTS and evaluation of these untested concerns. Co-occurrences from the same sample provide strong calibration points. Co-occurrences within the same outcrop but from different samples are useful, but it is possible chronostratigraphic and or biostratigraphic boundaries exists between the two sample points. Supplementary online material Table S2 summarise the conodont faunas and Supplementary online material Table S3 summarises the palynofloras of the samples discussed below. Due to the reconnaissance nature of this study stratigraphic logs of the key sections have not been included but sample positions are annotated on outcrop photos (Fig. 12).

The co-occurrence of Lower Triassic *Claraia* bivalves with *K. saeptatus* Zone palynological assemblages (see Section 4.1) suggests this zone extends down to the lowest Triassic in Timor-Leste as it does on the NWS. Further work is required to better understand the conflict suggested by the co-occurrence of possible upper *K. saeptatus* Zone (= *P. samoilovichii* Zone in eastern Australia), which is thought to be restricted to the Olenekian on the NWS, and possible Griesbachian *Claraia* spp. (see Section 4.1).

Several data points suggest the *S. quadrifidus* Zone extends up into the lowermost Carnian in Timor-Leste as has been proposed on the NWS (Fig. 3). These include co-occurrences of one conodont fauna and one Upper *S. quadrifidus* Zone palynoflora from different samples in each of the sections at localities S6109, M637 and M673 (Fig. 12). Whilst most samples are stratigraphically close to one another (Fig. 12) with no major lithological boundaries present, additional samples are required to confirm that *S. quadrifidus* Zone palynofloras are present both above and below the Carnian conodont faunas and that a palynological zonal boundary does not exist between the two data points in each outcrop. A Carnian upper stratigraphic range is also supported by questionable *S. quadrifidus* Zone palynoflora co-occurring in sample C663b with lower Carnian (Julian) conodonts, although this palynoflora has not been studied in detail as part of recent efforts.

Co-occurring conodonts and palynofloras also support a Carnian chronostratigraphic range for the *S. speciosus* Zone in Timor-Leste as proposed for the NWS. This calibration includes sample M642a where a palynoflora assigned to the Acme *S. speciosus*-*O. wellmanii* Subzones occurs with lower Carnian (Julian) conodonts. An Acme *S. speciosus* Subzone palynoflora in sample B609a occurring in the same sample with

Tuvalian conodonts, together with sample M642a, suggests that the Acme *S. speciosus* Subzone spans the Julian-Tuvalian boundary. Carnian conodont faunas from the same outcrop, but different samples, as palynofloras also assigned to the *S. speciosus* Zone are documented from localities B638, B643, B650 and B655 (Fig. 12). Further work is required to ascertain if the *S. speciosus* Zone palynofloras are present both above and below the Carnian conodont faunas. In contrast to Nicoll and Foster (1998) and Marshall and Lang (2013) no data to date from Timor-Leste indicate a Norian upper range for the *S. speciosus* Zone.

Whilst many more data points are required the database presented in this study provides support for the application of the NWS palynomorph zonal scheme in Timor-Leste for the *K. saeptatus*, *S. quadrifidus* and *S. speciosus* zones. Available co-occurrences of, primarily, conodonts with palynofloras support a similar chronostratigraphy for these zones in Timor and on the NWS. This in turn suggests the zonal criteria is workable even without stratigraphically ordered sample sets. The available data points also suggest subzonal criteria are applicable for the Upper *S. quadrifidus* and Lower *S. speciosus* zones. Further work is required to strengthen this, expand it to other zones and subzones, and resolve potential inconsistencies at the subzonal level for the *K. saeptatus* Zone. Lastly, these co-occurrences provide much needed additional calibration points of the NWS zonal scheme to the GTS and highlight the role Timor can play in improving this further.

### 5.2. Chronostratigraphic range of Triassic lithostratigraphic units

Here chronostratigraphic ranges for the lithostratigraphic units exposed in Timor-Leste (Fig. 3 and Table 1) are constrained by the large biostratigraphic database presented and supplemented by published biostratigraphic and geochronological data. These will improve regional correlations fostering an enhanced paleogeographic and tectonostratigraphic understanding of Timor and southeastern Tethys. It is likely these ranges will change as more data are collected. The current data set is biased to the Manatutu and Ainaro municipalities (Fig. 1a) and, whilst included data points outside these areas support the conclusions, a more extensive database across Timor-Leste is required.

#### 5.2.1. Baharedu beds

Lower Triassic to middle Anisian palynomorph assemblages documented in this study are exclusively from clay-rich mudstone-dominated strata in Timor-Leste that is often, but not always, variegated in colour (Table 1; Figs. 2 and 12). Minor laminae to thin sandstone beds are present in some outcrops e.g. locality S6125. These strata in Timor-Leste have been referred to the Niof Group (McCartain, 2014; Haig et al., 2019, 2021). However, for reasons outlined below the informal Baharedu beds is proposed here. Outcrop exposures of the contact between the Baharedu beds with underlying and overlying lithostratigraphic units have not been documented.

Lithologically similar Lower Triassic strata are documented across Triassic basins of the NWS (e.g. Thomas et al., 2004; Gorter et al., 2009; Haig et al., 2015) and these together with the Himalayan succession (e.g. Garzanti, 1999; Brookfield et al., 2003; Hermann et al., 2012) record a significant Lower Triassic transgression along the margin of south-eastern Tethys. In Timor-Leste these strata are distinct from the



**Fig. 12.** Outcrop photos of key sections from which both conodont faunas and palynomorph assemblages were recovered. **A:** Section of likely Aitutu Formation, but maybe Aitutu-like facies association in the Babulu Formation, at locality B655 comprising bedded mud-wackestone and grain-packstone interbedded with siliciclastic mudstone. **B:** Section of Aitutu Formation at locality B609 comprising interbedded siliciclastic mud-wackestone, marl and siliciclastic mudstone. Person in left of photo for scale. **C:** Section of likely Aitutu Formation, but maybe Aitutu-like facies association in the Babulu Formation, at locality B638 comprising interbedded siliciclastic mud-wackestone, marl and siliciclastic mudstone. **D:** Section of Aitutu Formation at locality B643 comprising interbedded siliciclastic mud-wackestone, rare grain-packstone, marl and siliciclastic mudstone. **E:** Deformed section of Babulu Formation at locality C663 dominated by silt-rich mudstone with rare sandstone beds up to 15 cm thick. **F:** Section of Babulu Formation at locality M637 dominated by silt-rich mudstone with rare mud-wackestone beds up to 15 cm thick. **G:** Proposed type section for the Baharedu beds at locality C505 dominated by laminated to thinly bedded variegated clay-dominated mudstone. **H:** Section of Babulu Formation at locality B650 comprising interbedded sandstone and mudstone with rare medium bedded mud-wackestone. Person in top right-hand corner for scale. **I:** Highly deformed section of Babulu Formation at locality M642 comprising silt-rich mudstone. **J:** Section of Babulu Formation at locality S6109/S558 comprising interbedded sandstone, mud-wackestone and siliciclastic mudstone. **K:** Section of Babulu Formation at locality M673 dominated by silt-rich mudstone with rare mud-wackestone beds up to 30 cm thick.

predominantly grey, but occasional mauve and blue-grey, silty mudstone-dominated strata that have a middle Anisian to Carnian chronostratigraphic range which here are placed in the Babulu Formation (discussed in following section). Lithologically similar strata to those attributed to the Baharedu beds have also been documented from West Timor and referred to as the upper Niplelo Member (Bird and Cook, 1991) of the Niof Formation. However, these strata were given a tentative Ladinian chronostratigraphic range. Until the relationship with this unit in West Timor is clarified, the new informal name of Baharedu beds is proposed here for the strata in Timor-Leste to avoid confusion and potential mis-correlation.

### 5.2.2. Babulu Formation

The Babulu Formation in Timor-Leste is dominated by grey, but occasional mauve to blue-grey, silty mudstone that shows limited signs of lamination or bedding in outcrop and is at times interbedded with thin to very thick sandstone beds (Table 1; Figs. 2 and 12). This is distinctly different to the well-bedded, laminated and variegated claystone typical of the Baharedu beds. Palynomorph and conodont assemblages documented in this study from the Babulu Formation indicate a predominant middle Anisian to upper Carnian (lower Tuvanian) chronostratigraphic range with two sections (M564 and AB088) indicating that locally the unit extends into the lower Norian (Lacian). This is consistent with the limited detrital zircon data from Timor-Leste which suggest a maximum depositional age near the Carnian–Norian boundary (see Section 2), whilst such data from West Timor suggests a younger age (Zimmerman and Hall, 2016). The Numfuamolo and lower Niplelo members of the Niof Formation in West Timor (Bird and Cook, 1991) have similar chronostratigraphic ranges and share some lithological characteristics with strata assigned here to the Babulu Formation.

Babulu Formation strata were predominantly deposited by density currents below storm wave-base (Giani, 1971; Bird and Cook, 1991; Roniewicz et al., 2005; Kwon et al., 2014). Channelised conglomeratic facies (see McCartney, 2014) suggest deposition by ignited gravity flows (sensu Parker, 1982) and significant bathymetric slopes whilst foraminifers suggest water depths < 200 m (Haig and McCartney, 2010). Considering deposition occurred well inboard of the coeval oceanic-continental crust boundary (Fig. 1b), observed sedimentary structures, and the foraminiferal evidence, deposition probably occurred in water depths ca. 100–500 m.

In this study over 80 % of all documented Babulu Formation exposures are mudstone-dominated (Column B Supplementary online material Table S5) suggesting the formation represents mudstone-dominated deep-water depositional systems. If the number of palynomorph zonal assignments are indicative of thicknesses or distribution, then the Babulu Formation is thickest or most widely distributed during the upper Ladinian–lowermost Carnian Upper *S. quadrifidus* Zone (70 % of all Babulu Formation outcrops with palynological data are assigned to this subzone). Whilst the highest proportion of sandstone-rich sections are attributed to the upper Ladinian–lowermost Carnian Upper *S. quadrifidus* Zone, some are attributed to the upper Anisian–upper Ladinian Lower *S. quadrifidus* Zone and the lower–Upper Carnian Lower *S. speciosus* Zone. Sand-rich deep-water depositional complexes within mud-dominated deep-water depositional systems are naturally laterally and vertically discontinuous. This, together with the long composite chronostratigraphic range of such sections in Timor-Leste, suggests these unlikely constitute a continuous succession. In addition, such sandstone-rich successions are unlikely to be mappable on a regional scale. In this light the sandstone-dominated units would not meet the requirements for a separate formal lithostratigraphic unit (e.g. North American Commission on Stratigraphic Nomenclature, 2021). Therefore, in Timor-Leste we suggest these are best left in informal nomenclature within the Babulu Formation, together with the silt-rich mudstone-dominated strata within which they sit.

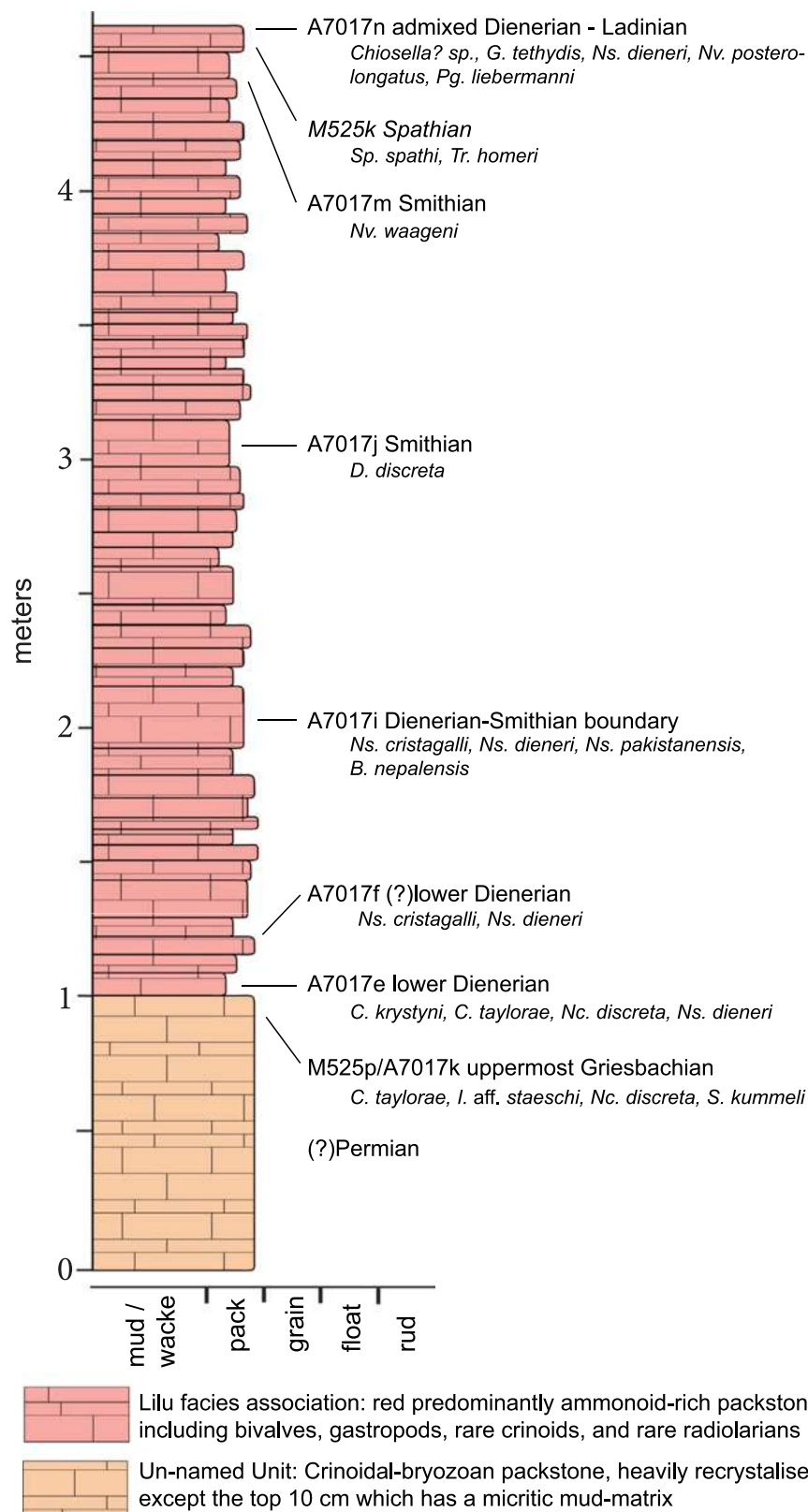
### 5.2.3. Aitutu Formation

The *peri*-platform Aitutu Formation is typified by well bedded mud–wackestone (Table 1; Figs. 2 and 12) but in Timor-Leste includes a range of poorly documented facies association. Conodonts, palynomorphs and radiolarians documented as part of this study indicate a predominant upper Carnian (Tuvanian)–Norian chronostratigraphic range but with extension, at least locally, down into the lower Carnian (Fig. 3). In the presented data set, definitive support for Ladinian or older sections of the Aitutu Formation is lacking, although several areas may yield such data with further work (e.g. around B507 and B519). Charlton et al. (2009) proposed a Ladinian lower chronostratigraphic range in Timor-Leste for this unit. One data point cited comes from blocks in scree (Nakazawa and Bando, 1968) in an area with no known Aitutu Formation, which questions the lithological attribution. Another data point, from Audley-Charles (1968), reports Ladinian *Daonella* bivalves from the Cribas Anticline near Cribas town (Fig. 1a) but no stratigraphic context is provided. The final data point from Wanner (1956) includes Ladinian *Daonella* bivalves, collected near localities B519 and B524, and these sections were attributed to the Aitutu Formation by Charlton et al. (2009). This area contains sections of strata typical of both the Aitutu and Babulu formations and isolated outcrops of facies associations rich in halobiids, such as that at B519, that are not typical of either unit. These are potentially equivalent to those recorded by Wanner (1956), but their lithostratigraphic affinity remains unclear. A lower chronostratigraphic range in the Ladinian has also been proposed in West Timor for the Aitutu Formation (Barkham, 1993).

In Timor-Leste the present data set suggests the majority of the Babulu Formation spans the Middle Triassic–upper Carnian (lower Tuvanian) with Carnian (Julian–lower Tuvanian) to Lower Norian (Lacian) overlap with the Aitutu Formation (Fig. 3). Several sections have been documented that transition from the Babulu to Aitutu formations with data suggesting, at least locally, this occurs around the upper Julian–Tuvanian (e.g. B574/B649 and B603). However, lower Norian (Lacian) occurrences of the Babulu Formation suggests this transition is diachronous in Timor-Leste. Current data from Timor-Leste does not support the Babulu Formation sitting stratigraphically above the Aitutu Formation (Kwon et al., 2014), nor extending into the Rhaetian (Charlton and Gandara, 2014; Duffy et al., 2017). Three data points (B547/B619, B624c, and B636c) indicate that, at least locally, the Aitutu Formation extends into the Rhaetian in Timor-Leste. Ongoing work to document chronostratigraphic control on key outcrops passing from the Aitutu to Wai Luli formations (e.g. A7045) will determine if a Rhaetian or younger upper range, as has been proposed in West Timor (see summary in Charlton et al., 2009), is more common in Timor-Leste than the current data suggests. Significant internal lithostratigraphic variation within the Aitutu Formation, reflecting the range of *peri*-platform depositional settings (Flügel, 2004), remains poorly understood.

### 5.2.4. Bandeira Formation

The Bandeira Formation (Table 1; Figs. 2 and 13) comprises facies associations, accumulated on shallow-water carbonate platforms (Haig et al., 2021), and the Lulu facies association, accumulated on the same platforms but during very different phases of the relative sea level curve (Barros et al., 2022). Foraminifers indicate a Carnian–Norian, possibly earliest Rhaetian, chronostratigraphic range for the shallow-water facies associations of the Bandeira Formation (Haig et al., 2021) and no new data is presented here for these. This range is similar to that of the Aitutu Formation, with much of the calcareous sediment of the Aitutu Formation likely derived from the shallow-water carbonate factories of the Bandeira Formation. The lower chronostratigraphic range for these shallow-water facies associations coincides with the first global Triassic reef optimum (Flügel, 2002). Whilst the Middle Triassic succession exposed in Timor accumulated in paleolatitudes conducive to warm-water reefs (Jones et al., 2022), globally Middle Triassic reefs have not been documented south of 2°S (Flügel, 2002). Only indirect evidence of Middle Triassic reefs (sensu Flügel, 2002) has been documented



**Fig. 13.** Stratigraphic log of the Permian-Triassic Boundary (PTB) section at locality M525/A7017 in the Manatutu Municipality (Fig. 1c), showing biostratigraphically important conodont taxa for key samples. Here the ammonoid-rich Lilu facies association overlies crinoidal-bryozoan packstone typical of the Permian. Further work is required to clarify the completeness of the PTB interval and where the PTB is located with current data suggesting it may be within the uppermost crinoidal-bryozoan packstone facies and not at the lithological boundary. M525q was collected laterally from the main section.

in Timor-Leste, including reworked corals, and potential oncoids, in a sandstone bed of the Babulu Formation at locality B510. Mudstone interbedded with this sandstone yielded a palynoflora attributed to the Lower *S. quadrifidus* Subzone, inferring an upper Anisian to upper Ladinian chronostratigraphic range. In addition, siliciclastic mudstone (locality M6109) of the Babulu Formation includes ooids, transported into a basinal setting, and has yielded an Upper *S. quadrifidus* palynoflora, which has a Ladinian to lowermost Carnian chronostratigraphic range.

The Lilu facies association is equivalent to, in part, the Lilu Beds (Berry et al., 1984), the Cephalopod limestone facies (Charlton et al., 2009), and the Lilu facies (Haig et al., 2021; Barros et al., 2022). This new name is proposed as the unit comprises numerous different facies and the Lilu Beds, as defined in Berry et al. (1984), comprise a range of lithostratigraphic units that are today assigned to different units. This unit is not stratigraphically continuous, with isolated examples throughout the Triassic succession across Timor-Leste and West Timor (see Charlton et al., 2009). As such it does not conform to the requirements for a formal lithostratigraphic unit (e.g. North American Commission on Stratigraphic Nomenclature, 2021). For now, we have placed the unit within the Bandeira Formation as, although lithologically distinct, they were accumulated on the same bathymetric highs as best evidenced by the section documented in Barros et al. (2022). As more data is collected it may be possible to establish formal nomenclature for each stratigraphically isolated example of the Lilu facies association. In addition to records summarised in Charlton et al. (2009) new outcrops of the Lower Triassic Lilu facies association are documented here at localities M525 and M622. Upper Norian-(?)lowermost Rhaetian conodont faunas were recovered as part of this study from an example of the Lilu facies association at locality A7041 in the Piti Leti area of Tutuala. Bando and Kobayashi, (1981) and Audley-Charles (1968) documented Carnian fossil assemblages from this locality suggesting a Carnian-(?)lowermost Rhaetian range.

The geographic distribution of the Bandeira Formation across Timor-Leste suggests laterally discontinuous platforms. Further work is required to understand the morphology of the shallow-water carbonate platform factories e.g. isolated platforms versus rimmed or un-rimmed shelves versus ramps. Whilst the siliciclastic sandstone-mudstone facies association at the Bandeira River section (Haig et al., 2021) may suggest land-attached systems (ramps, shelves or rimmed shelves), in an active tectonic regime, this sediment may also have been supplied from uplifted fault-blocks on an isolated platform.

The lower contact of the Bandeira Formation is present near Mount Lilu where the Lilu facies association stratigraphically overlies likely Permian limestone (discussed further in Section 5.5). Shallow-water strata of the Bandeira Formation crop out above these occurrences of the Lilu facies association, but as yet only structural contacts between the two units have been documented. Shallow-water facies associations are interpreted for strata cropping out in the Aitutu Anticline (locality S635 and S637) that are tentatively assigned to the Bandeira Formation. As yet stratigraphic sections comprising contacts with the Aitutu Formation have not been documented. The upper contact of the Bandeira Formation has been documented in one section where the Lilu facies association transitions into Rhaetian Wai Luli Formation (Barros et al., 2022).

#### 5.2.5. Wai Luli Formation

The Wai Luli Formation is here restricted to sections dominated by light-grey marl with conspicuous trace fossil assemblages comprising burrows filled with dark-grey to black calcareous mudstone (Table 1; Figs. 2 and 12). These marls may be interbedded with calcareous mud-wackestone often rich in radiolarians but typically much lighter in colour than those that dominate the Aitutu Formation. Palynofloras documented here (e.g. C583c) indicate that the lower chronostratigraphic range of the Wai Luli Formation is Rhaetian and the upper range is in the Lower Jurassic (Haig et al., 2019). Ongoing work is

investigating if the transition from the Aitutu to Wai Luli formations is diachronous across Timor-Leste as suggested in West Timor (Barkham, 1993).

### 5.3. Paleobiogeographic affinities of micro-biota

Paleobiogeography of Triassic biota has been used to assess the Triassic paleogeographic location of tectonic blocks rifted from northern Gondwana and now forming part of Asia (e.g. Peng et al., 2018; Wu et al., 2023). Accumulation of the Triassic succession exposed in Timor-Leste further north and in more marine environments than many successions preserved along the NWS of Australia, renders Timor a key location on the Australian continental sector of southeastern Tethys to test this.

#### 5.3.1. Conodont paleobiogeography

Lower Triassic conodont faunas from Timor-Leste are typical of those known from Pakistan (Sweet, 1970; Han et al., 2022), Tibet (Orchard et al., 1994), Spiti (Orchard and Krystyn, 1998, 2007), and Kashmir (Brosse et al., 2017; Lyu et al., 2021). These neogondolellin-rich faunas are typical of the cool-water realm along the southeastern margin of Tethys as well as northern Boreal regions (Orchard, 2008) during this time. These faunas contrast with more tropical faunas, such as those from China, which have few neogondolellins, have common *Isarcicella* spp. and lack *Borinella* spp. (Orchard, 2007a). By the Middle Triassic, Timor conodonts show distinct Tethyan character, exemplified by *Gladigondolella*, *Ng. bakalovi*, and 'Pg.' *trammeri*, none of which occur in the North American autochthon. The diverse Upper Triassic conodont faunas also have distinctive Tethyan elements, like *Nr. trinacriae*, *N. cavitata*, and *Bajadontus* sp. Many Upper Triassic conodonts identified from Timor-Leste are species differentiated in North America by Orchard (2007c, 2014). These faunas, though not widely recognized in Europe, indicate they are broadly distributed far beyond eastern Panthalassa. Timor-Leste provides a bridge to better integrate the Triassic provinces.

#### 5.3.2. Palynomorph paleobiogeography

The Lower Triassic palynofloras documented here, are dominated by lycopsid spores and/or spinose acritarchs that are of limited biogeographic value. Similar low diversity palynofloras and prodigious abundance of spinose acritarchs are recorded across much of the Tethyan realm and north into Laurasia during the Induan–Olenekian (Balme, 1963; Dolby and Balme, 1976; Helby et al., 1987; Ouyang and Utting, 1990; Grauvogel-Stamm and Ash, 2005; Lindström and McLoughlin, 2007; Kürschner and Hergreen, 2010; Looy et al., 2001; Liu et al., 2020b) as harsh global conditions followed the End Permian Extinction (Algeo and Twitchett, 2010; Retallack et al., 2011, Sun et al., 2012). These settings favoured opportunistic spore-producers such as herbaceous lycopsids and ferns. The initial recovery and replacement of these cosmopolitan floras in the late Olenekian–Anisian is so far poorly represented in the Timor successions, with very few palynofloras documented from this interval. However, the succeeding *S. quadrifidus* Zone interval is very well represented. The high spore-pollen species richness of this zone demonstrates that diverse floral communities were largely re-established, including arborescent gymnosperms and shrubby lycophytes. As distinct floral communities continued to develop across Gondwana and Laurasia, increasing provincialism is widely recorded by the Middle to Upper Triassic (Dolby and Balme, 1976; Zavattieri and Batten, 1996; Buratti and Cirilli, 2007; Césari and Colombi, 2013).

This provincialism is particularly well studied in Gondwana and around the Tethyan margin where Dolby and Balme (1976) first described the Onslow Microflora from the Northern Carnarvon Basin. This microflora differs from the more southerly Ipswich Microflora by the higher diversity of gymnosperms and the inclusion of various distinctive Eurasian taxa, such as *Aulisporites astigosus*, *C. secatus*, *Enzonalsporites* spp., *E. macstriatus*, *Minutosaccus*, *Ovalipollis* spp.,



*Rimaesporites aquilonalis* and *S. speciosus*. The Onslow Microflora has since been recognised across the NWS (Helby et al., 1987; Mantle et al., 2020) and on to India, Tibet, easternmost Antarctica, northern Madagascar and east Africa, and northwestern Argentina (Césari and Colombi, 2013; Kustatscher et al., 2018; Peng et al., 2018). Elements of this microflora are also recorded across much of the western Tethys (Buratti and Cirilli, 2007) and it is considered to represent temperate to warm, humid conditions with some monsoonal influences and periodic wet and dry intervals (Dickens, 1985; Bradshaw et al., 1994; Ratcliffe et al., 2010).

Overall, the Triassic palynofloras from Timor show a very close affinity to those from the adjacent Bonaparte Basin, and both these locations exhibit minor but consistent differences to the more intensely studied Northern Carnarvon Basin palynofloras. Despite all three localities lying at similar latitudes along the southern margin of the Tethys Ocean and with broadly similar palaeogeographies, the Timor and Bonaparte Basin assemblages have a stronger northern Onslow Microflora signature, often including higher abundances of *Camerosporites*, *Enzonasporites*, *Infernopolenites*, *Rimaesporites*, *Staurosaccites*, and *Triadispora*. As noted earlier, some of the key Northern Carnarvon Basin marker taxa, such as *C. stonei* and *E. macistriatus* are also notably rarer in Timor and the Bonaparte Basin. These minor palynofloral discrepancies may be partly due to differences in depositional facies (limited marine influence in the Bonaparte Basin and strong marine influence in Timor) or may be driven by varying local climate or rainfall regimes in the hinterlands of both areas. Floral provincialism is less well studied in the Late Triassic, as increased endemism and distinctly regional floras developed. It is much harder to correlate the northern Australian palynofloras with northern hemisphere spore-pollen associations and even to western Tethyan assemblages at this time. Note that very few *M. crenulatus* and associated dinocyst zone samples are included in this study due to the carbonate-dominated nature of the Norian succession in Timor-Leste. Processing of organic-rich limestone samples has delivered palynomorph assemblages and suggest more can be done in this time interval in Timor-Leste.

### 5.3.3. Radiolarian paleobiogeography

The radiolarian assemblages documented here share close affinities with those from western Tethys (De Wever et al., 1979; Tekin, 1999, 2002; Bragin, 2007; Dumitrica and Hungerbühler, 2007; Kozur et al., 2007a, 2007b, 2007c; Nicora et al., 2007; Dumitrica et al., 2010) with very common spumellarians, mainly represented by three very abundant genera, *Capnodoce*, *Capnuhosphaera* and *Sarla*, less abundant nassellarians, with *Mostlericyrtium*, *Spinoscapsa* and *Xiphoteccaella*, and rare entactinarians, with *Carinaheliosoma*. There are substantially fewer overlapping taxa with assemblages documented in Japan (Sugiyama, 1997) and even less overlap with assemblages from other Panthalassan locations such as the Philippines (Yeh, 1990, 1992), Baja California (Pessagno et al., 1979), Oregon (Blome, 1984; Yeh, 1989) and British Columbia (Carter, 1993; Carter and Orchard, 2000, 2013).

### 5.3.4. Paleobiogeographic implications for Tethys

Temperate-water Lower Triassic conodont faunas and Middle–Upper Triassic palynomorph assemblages typical of the Onslow Microflora support accumulation of the Triassic succession exposed in Timor-Leste within a Gondwanan basin of southeastern Tethys (e.g. Audley-Charles, 1968; Harris et al., 1998; Haig et al., 2021). Characteristics of the Timor-Leste Upper Triassic palynomorph assemblages share strong similarities to those from the Bonaparte Basin and key differences with those in the Northern Carnarvon Basin. Further work is required to understand if this has additional paleobiogeographic implications or if it is facies-driven. Palynoflora with typical Onslow Microflora characteristics were documented from the Lhasa block by Peng et al. (2018). Differences, compared to the NWS and Timor palynoflora, in composition (e.g. limited numbers of *S. speciosus* and *E. macistriatus*) and stratigraphic

ranges of key taxa (e.g. *Striatella* not ranging older than the Norian and *Triplexisporites* ranging up to the Norian–Rhaetian boundary) requires a comparative microscope-based study to better understand and investigate if these too have any paleobiogeographic implications.

Wu et al. (2023) suggested high diversity Norian conodont fauna and the presence of *Nr. steinbergensis* palaeobiogeographically distinguished tectonic blocks located in northern Tethys in the Triassic from those located in southern Tethys. The documentation of both *Nr. steinbergensis*, first documented from Timor by Barkham (1993), and high diversity Norian conodont faunas from the Timor-Leste succession indicates such criteria are problematic and that conodont faunas may not be useful Upper Triassic paleobiogeographic tools within eastern Tethys. Differences observed by Wu et al. (2023) may instead, at least in the case of the successions along the NWS of Australia, reflect facies controls and limited data sets highlighting the key role Timor can play in better understanding Tethyan paleobiogeography and paleogeography. Radiolarians do not allow paleobiogeographic differentiation between northern-southern Tethys and despite accumulation in a Tethyan location close to the Panthalassan Ocean, the radiolarian fauna documented here display very few similarities with Panthalassan fauna.

### 5.4. Independent calibration of basinal foraminifers to the GTS

As discussed in Section 3.2 the biostratigraphic utility of many Triassic foraminifer species from basinal mud-rich settings is poorly constrained globally. Timor provides an opportunity to improve the biostratigraphic understanding of these foraminifers through recovery of free foraminiferal tests from siliciclastic mudstone and the co-occurrence with other fossil groups. The dataset here provides updated calibration for 70 basinal organic-cemented siliceous agglutinated and Ophthalmitidid foraminiferal assemblages published in Haig and McCartney (2010, 2012). A detailed assessment of the implications of this calibration is beyond the scope of this paper.

### 5.5. A new Permian–Triassic boundary section

To highlight the value of this study to global Triassic studies the first Permian–Triassic Boundary (PTB) section documented in Timor-Leste is briefly discussed here. The section, found at Locality M525/A7017, is the first PTB in outcrop from the Australian sector of southeastern Tethys. The section passes from (?)Permian crinoidal and bryozoan-rich limestones into a 4 m thick interval of condensed red ammonoid-rich Lulu facies association of the Bandeira Formation (Fig. 13). The crinoidal–bryozoan limestone forms one thick bed with the top ca.10 cm of the bed comprising an original mud matrix with that below pervasively recrystallised. An uppermost Griesbachian conodont fauna (samples M525p and A7017k) from the upper 10 cm of this bed suggests the PTB may not be located at the lithological change. Refined sampling is underway to better constrain the chronostratigraphy across this key interval. To date unequivocal Griesbachian strata have not been documented from the Australian continental sector of southeastern Tethys (see Metcalfe et al., 2013). Below this uppermost Griesbachian conodont fauna no fossils that provide chronostratigraphic constraints have been documented in outcrop. Upper Permian *Colaniella* foraminifers have been documented from nearby scree blocks of similar facies but these are yet to be found in outcrop. These belong to *C. parva* indicative of the Changhsingian (Vachard, 2015). The overlying Lulu facies association comprises a conformable lowest Dienerian to Smithian section as indicated by conodont faunas (see Fig. 13 and Supplementary online material Table S2). A Spathian conodont fauna has been documented from an exposure ca. 10 m lateral to the main section, but not at the main section itself, suggesting laterally discontinuous beds not uncommon in Hallstatt-like depositional settings.

## 6. Conclusions

This study utilises a new integrated biostratigraphic database to unlock the contribution of the Triassic succession exposed in Timor-Leste to Tethyan and global Triassic studies. Available integrated conodont and palynomorph biostratigraphic data suggests a significant proportion of the endemic palynomorph zonal scheme established for the NWS of Australia is applicable to palynomorph assemblages recovered from the succession exposed in Timor-Leste but, further data points are required. This integrated database has also provided additional calibration points of this scheme to the GTS. These assemblages are recoverable from much of the Triassic succession and this study highlights the important role they can play in better understanding the Triassic succession exposed in Timor-Leste. In addition, the integrated database provides updated independent calibration of basinal foraminiferal assemblages to the GTS that will assist assess the biostratigraphic utility of these understudied assemblages.

Paleobiogeographic affinities of palynomorph assemblages and conodont faunas support accumulation of the Triassic succession exposed in Timor-Leste in a basin located on the northern Gondwanan margin of southeastern Tethys. Diverse Norian conodont fauna and the presence of *Nr. steinbergensis* in Timor suggests facies may control previously proposed northern versus southern Tethyan paleobiogeographic differentiation and not temperature gradients. Despite accumulating in a location close to the Panthalassan Ocean, Upper Triassic radiolarian faunas documented from Timor-Leste show a strong Tethyan characteristic with minimal similarities to faunas from the Panthalassan Ocean. The Upper Triassic conodont faunas also show strong Tethyan characteristics but display similarities with Panthalassan faunas. Any paleobiogeographic implications for reported differences between Upper Triassic Onslow Microflora assemblages from succession accumulated along southeastern Tethys, including those from Timor-Leste, remains uncertain.

The database presented provides a robust chronostratigraphic assessment of the Triassic succession in Timor-Leste which will facilitate improved understanding of Timor geology, regional correlations, and more nuanced paleogeographic and tectonostratigraphic understanding of southeastern Tethys. The 300 plus chronostratigraphic calibrated Triassic outcrops will enable targeted Triassic studies in Timor-Leste unlocking enhanced contributions to global and Tethyan Triassic studies from an under-sampled Gondwanan sector of Tethys. A prime example of this is the PTB section identified in Timor-Leste which represents the first exposed section from the Australian sector of southeastern Tethys.

## CRediT authorship contribution statement

**Eujay McCartney:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Michael.J. Orchard:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Daniel Mantle:** Data curation, Investigation, Writing – review & editing. **David W. Haig:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Angela Bertinelli:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Marco Chiari:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Florentino S. Ferreira:** Data curation, Investigation. **Zelia dos Santos:** Data curation, Investigation. **John Backhouse:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Barry A. Taylor:** Formal analysis, Investigation, Writing – review & editing. **Isaias S. Barros:** Data curation, Investigation. **Bernado N. de Araujo:** Data curation, Investigation. **Antonio de Araujo:** Data curation, Investigation. **Nazario Boavida:** Data curation, Investigation. **Daniel Peyrot:** Data curation, Investigation, Writing –

review & editing. **Manuel Rigo:** Data curation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

All data provided in [supplementary material](#)

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jseae.2024.106052>.

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