The Paleocene - Eocene mangroves of South-eastern Australia: spatial and temporal occurrences across four geological basins.

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ABSTRACT:

The advent of the Paleocene-Eocene Thermal Maximum (PETM), a ~200 kyr period of global warming *ca.* 56 Ma, caused sea-levels to rise, transgressing near-coastal environments in South-eastern (SE) Australia over >55,000 km^2. During the PETM, warming tropical climates may have extended south to ≥60 °S paleolatitude. The PETM in SE Australia is corroborated primarily by stable carbon isotope chemostratigraphy and detailed palynology records in four geological basins. Previous work showed that, in addition to the globally recognized carbon isotope excursion, the PETM interval in coastal SE Australia can be identified using the dual occurrence of the tropical mangrove *Nypa* palm pollen (*Spinizonocolpites prominatus*) accompanied by thermophilic marine dinoflagellate cysts (mainly *Apectodinium hyperacanthum*). We here document a total of twenty-six Gippsland Basin wells that record this *Nypa-A.hyperacanthum* association in the earliest Eocene Kingfish Formation (Lower *Malvacipollis diversus* Zone). In the Bass Basin, eight wells record *Nypa-A.hyperacanthum* association within the Eastern View Group basal Koorkah Formation, or lower part of the Lower *M. diversus* Zone (earliest Eocene). In the Bass Basin a further thirteen wells with *Nypa* occurrences near the top of the Cormorant Formation are found, which might be associated with the longer-term warmth of the Early Eocene Climatic Optimum (EECO, ~53 – 49 Ma). Government bores and petroleum wells across the Otway Basin record the *Nypa-A. hyperacanthum* PETM association within the Pember Mudstone Lower *M. diversus* Zone in twenty-one bores. Nine horizons with *Nypa* occurrences occur within the Burrungule Member (EECO) at the top of the Dilwyn Formation. In western Tasmania, *Nypa* occurs in the Sorell Basin and Macquarie Harbour area within the Lower *M. diversus Zone*. Together, these observations show the remarkable extent of the mangrove-coasts that were established across the mid-high paleolatitudes in SE Australia during the warmest intervals of the Cenozoic, the PETM and EECO.

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1 INTRODUCTION

The Paleocene-Eocene boundary ca. 56 million years ago (Ma) is defined by the onset of a global 2 – 8‰ global negative carbon isotope excursion (CIE) (McInerney & Wing, 2011). The CIE marks the Paleocene-Eocene Thermal Maximum (PETM); a period of extremely warm climatic conditions (e.g., Frieling et al. 2017, Inglis et al. 2020) that is estimated to have lasted about 200,000 years (e.g., Murphy et al. 2010, Zeebe & Lourens, 2019). As a consequence of the massive carbon emissions during the PETM, deep sea sediments experienced strong carbonate dissolution and ocean acidification has been documented in surface and subsurface waters (e.g. Penman et al. 2014, Babila et al. 2016, Gutjahr et al. 2017), and global temperatures increased by ~5°C on average within a few thousand years (Frieling et al. 2017, Inglis et al. 2020). The carbon cycle and climate perturbations that occurred during the PETM and other similar hyperthermal events during the Early Eocene climatic optimum (EECO, *ca.* 53 – 49 Ma; Westerhold et al. 2018) are recognised as useful partial analogues to present day climate change and provide a glimpse into potential end-member greenhouse climates. One such effect may be large-scale poleward migrations of thermophilic flora and fauna (e.g. Pross et al., 2012; Willard et al., 2019; Huurdeman et al., 2021; Popescu et al., 2021; Suc et al. 2020).

In South-eastern Australia (SE), Frieling et al. (2018) identified the onset of the PETM using carbon isotope stratigraphy and palynology; documenting the first occurrence of the regional markers *Spinizonocolpites prominatus* (suggested Nearest Living Relative or NLR as the palm genus *Nypa* – Pocknall et al. 2023) along with the dinoflagellate species *Florentinia reichartii* and common *Apectodinium* species including *A. hyperacanthum* and *A. homomorphum*. *Apectodinium* is well-known for its global occurrence and acme at the PETM (e.g. Crouch et al. 2001, Sluijs et al. 2007, Denison, 2021) but the abundance of this genus around SE Australia was not limited to the PETM. Instead, the co-occurrence of three thermophilic taxa/groups (*S. prominatus, Apectodinium & F. reichartii*) during the PETM CIE was highlighted by Frieling et al. (2018), as it may serve to identify PETM-age sediments elsewhere in the same or adjacent basins.

To date, published PETM palynological records from SE Australia are restricted to the Otway Basin Latrobe-1 drill core and Point Margaret outcrop near Princeton, Victoria (Frieling et al. 2018; Huurdeman et al. 2021, Frieling et al. 2023), but even these records captured only a short sequence near the base of the PETM (Point Margaret) or were able to achieve only limited resolution through the event due to sparse core material (Latrobe-1) (Huurdeman et al. 2021,

Frieling et al. 2023). Other noteworthy reconstructions of climate and environmental conditions during the PETM and EECO in the wider region include those from Site 1172 on the East Tasman Plateau (Bijl et al. 2009, Sluijs et al. 2011, Contreras et al. 2013, Bijl et al. 2021) and the early Eocene at Site U1356 on the southern edge of the Australo-Antarctic Gulf (Pross et al. 2012, Bijl et al. 2013, Contreras et al. 2013). The purpose of this paper is to document other PETM occurrences within the Otway Basin, as well as within the Gippsland and Bass basins and possibly the Sorell Basin of SE Australia from freely available palynological records held within government databases (Table 1). Published reports were used where available, and we performed analysis of new samples from the Glenelg-1 bore in the western Otway Basin and Strahan-BH1 bore from the Strahan area, Sorell Basin. We also present stable carbon isotope value data of organic matter ($\delta^{13}C_{org}$) from seventeen Glenelg-1 drill core samples (Table 2).

2 BACKGROUND

2.1 The occurrence and relevance of specific microfossil taxa

Although with unknown significance at the time, the first Australian record of *Nypa* pollen or *Spinozonocolpites prominatus* was inadvertently described as the fossil acritarch *Baltisphaeridium taylori* in samples from the Pember Mudstone outcropping north of Dartmoor along the north-western margins of the Otway Basin (Cookson & Eisenack, 1965a). At Strahan in the Port Macquarie Formation Cookson & Eisenack (1967) acknowledged that "taylori" was actually McIntyre's *Monosulcites prominatus* (Fig. 1). The same fossil was also found in Pember Mudstone outcrops near Princetown at the eastern end of the Otway Basin (Cookson & Eisenack, 1965b). The erroneous attribution as *Baltisphaeridium taylori* was later corrected to *Spinozonocolpites prominatus* when the fossil taxon was identified as the fossil palm *Nypa* with the form taxon name now more or less universally accepted as *Spinizonocolpites prominatus* (Pocknall et al. 2023).

More recently, the significance of *Nypa* co-occurring with dinocyst taxa including thermophilic *Apectodinium* spp. and *Florentinia reichartii* (Frieling & Sluijs, 2018) near Princetown (eastern Otway Basin), in cores from Latrobe-1 bore and detailed outcrop sampling at Point Margaret, were considered indicators of tropical climates in the Otway Basin (Frieling et al. 2018, Huurdeman et al. 2021, Frieling et al. 2023). *Nypa* at the present day, grows in tropical tidal rivers with freshwater influence where roots are flushed regularly (Pocknall et al. 2023).

Nypa is considered to provide evidence of megathermal (Nix, 1991) conditions and frost-free winters with an average temperature of >18°C in the geological past (Reichgelt et al. 2018). In Australia, the southern end of the present-day range approximates to Hinchinbrook Island in North Queensland at latitude 18.4°S (BOM, 2024) (Fig. 1). Modern *Nypa* occurrences are exclusively in tropical biomes, with mean annual temperatures (MAT) ranging from 24–28°C (Reichgelt et al. 2018). The thermal affinities of extinct dinoflagellate taxa such as *Apectodinium* were established as thermophilic by Bujak & Brinkhuis (1998) and Crouch et al. (2001) and later refined using sea surface temperature estimates from the lipid-biomarker proxy TEX_{86} (Frieling et al. 2014, Frieling & Sluijs, 2018).

2.2 Previous studies in the region & existing biozonation schemes

During the main 1966 - 1983 period of petroleum exploration in Australia's SE basins (Gippsland, Bass and Otway basins – see Fig. 1), recognition of *Nypa* palm pollen as *Spinizonocolpites prominatus*, accompanied by the dinoflagellate *Apectodinium hyperacanthum* was instrumental in advancing the palynological zoning system. This concurrence identified by Partridge (1999, 2006) as the *Apectodinium hyperacanthum* Zone, was ultimately used to define the Paleocene-Eocene boundary (Fig. 2). The unusual flora in this zone was recognised as a warm to hot basin-wide transgression combining major flooding with widespread mangrove development (Partridge, 1976, 1999). Examination of hundreds of publicly available palynology records from petroleum exploration wells, bores and other government stratigraphic drilling throughout the SE Australian Gippsland, Bass and Otway basins found this interval to be a widespread but short-lived event immediately above the Paleocene-Eocene boundary (see Fig. 2).

Biostratigraphically, the Paleocene-Eocene boundary interval was usually placed immediately above the spore-pollen Upper *L. balmei* Zone-Lower *M. diversus* Zone palynological boundary of Partridge (2006) (Fig. 2). Occurrences of fern spores associated with *Nypa* also have included species of *Crassoretitriletes vanraadshoovenii* and *Polypodiaceoisporites varus* (Stacy & Partridge, 1978). *Nypa* also occurs with thermophilic marine dinocyst taxa including *Apectodinium* species and with the much rarer *Florentinia reichartii.*

In the Otway and Bass basins, *Nypa* may sometimes reappear later in some wells and bores in the late Lower Eocene, some 70m or more above the P-E boundary interval and falls within the broader Early Eocene Climatic Optimum (EECO, ca. 53 – 49 Ma) interval at the Upper *M.*

diversus-P. asperopolus palynological boundary (~50.5 Ma) (Fig. 2). In a few cases, the EECO correlates with rare appearances of calcareous planktonic foraminifera in the Burrungule Member at top of the Dilwyn Formation (Abele, 1994). After the Early Eocene, *Nypa* is not recorded again in any SE Australian sedimentary basins.

In the Gippsland and Bass basins, the recognition of the PETM evolved over time, and the mangrove taxa associated with the widespread transgression in SE Australia has subsequently been interpreted to represent the PETM. In the earliest drilled wells, the PETM was thought to lie within the Upper *L. balmei* Zone, but with further well results and more detailed side-wall-coring, the event was recognised to lie at the base of the Lower *M. divers*us Zone (Figs. 2, 3 & 4). In the Otway Basin, in addition to petroleum well reports, an extensive Victorian State stratigraphic and groundwater repository of core is available from the Government core repository. This "legacy" coring spanned a period from the early 1960s to the end of the 1980s. Most Victorian Otway Basin stratigraphic definitions and nomenclatures derives from these programmes (e.g. Bock & Glenie, 1965). During this time period, foraminiferal age dating was possible in the more fossiliferous younger carbonate formations summarised by Gallagher & Stanislaus (2019), but only rarely was palynological analysis routinely undertaken. In a large government funded Otway Basin gas exploration program, Charles et al. (2019) re-examined 748 samples (cores, side wall cores and drill cuttings) from 115 legacy drill hole bores, particularly from the Lower Eocene Dilwyn Formation and Pember Mudstone, and the Upper Cretaceous Sherbrook Group, and updated previous findings to reflect modern taxonomic nomenclature. In the process, they reported the occurrence of *Nypa* with *Apectodinium hyperacanthum* near the Paleocene-Eocene boundary zone, with some younger (post-PETM) *Nypa* occurrences as well. The presence of *Nypa*, however, relies on the relevant depth being sampled coincidentally from intermittent coring. In many wells and bores no core is available, and/or only cuttings exist over the possible interval that *Nypa* may occur. Nevertheless, the PETM event was recorded in 21 bores within the Pember Mudstone Lower *M. diversus* Zone (see Fig. 5). An additional nine *Nypa* occurrences are reported from the Burrungule Member Upper *M. diversus* Zone- *P. asperopolus*- Zone in the upper part of the Dilwyn Formation, which are considered to represent the EECO (Fig. 2). In four bores (Bootahpol-2, Cobboboonee-2, Codrington-1, Najaba-1A) both PETM and EECO were sampled. Table 1 lists the key Gippsland, Bass and Otway Basin bores containing *Nypa-A. hyperacanthum* and shows cores/side-wall core depths where these key fossil taxa occur, along with references to these observations.

Another known *Nypa* occurrence is on the southwest coast of Tasmania near Strahan within outcrops and in a bore core through the Port Macquarie Formation (Sorell Basin) where *Nypa* pollen, macrofossil palm fronds and fruits have been identified (Carpenter et al. 2012; Pole & Macphail, 1996) (Figs. 1 & 6). The exact age of the *Nypa* occurrences that outcrop around Strahan, whilst thought to be within the Lower Eocene, appear to lack the key age-defining dinoflagellate taxa to provide a closer timing to this event. Macphail (2011), however, recognises the presence of the Lower *M. diversus* Zone within the lower beds of the bore core.

3 METHODS:

3.1 *Nypa* and the *Apectodinium hyperacanthum* Zone in Previous Well Completion Reports

In order to identify strata associated with the geologically brief (~200 kyr) PETM event and their spatial distribution in the three main basins, publicly available well-completion palynology reports were examined including ~305 in the Gippsland Basin, 32 in the Bass Basin and 115 in the Otway Basin. The reports were searched for occurrence of *Spinizonocolpites prominatus* together with *Apectodinium hyperacanthum* (Table 1) which was taken to represent the PETM event, based on the findings of Frieling et al. (2018). The occurrence of the much rarer *Florentinia reichartii* as a regional marker is of less value outside the most recent works considering the species was not described until after many of the wells were completed (Sluijs & Brinkhuis, 2009). In most cases frequencies of the above species are unavailable from the well completion reports – presence/absence is only recorded. However in rare cases quantitative counts were carried out eg. Konkon-1 in the Bass Basin where counts per an average of 300 specimens of both terrestrial and aquatic palynomorphs were counted per sample – (Partridge in Blevin et al. 2003). In this well *Spinizonocolpites prominatus* amounted to ~2% of the spore-pollen counts and *Apectodinium hyperacanthum* amounted to ~30% of the dinoflagellate counts. This is in broad agreement to counts made on samples from Glenelg-1 and Strahan-BH1 bores, and also similar to results obtained at Point Margaret (Frieling et al. 2023).

3.2 Palynology

In the Otway Basin 17 mudstone samples from the lower Pember Mudstone were examined for occurrence of *Spinizonocolpites prominatus* together with *Apectodinium hyperacanthum* to support the carbon isotopes readings from the same 17 sample intervals. Similarly, for the Sorell Basin in Tasmania, 8 samples from outcrops at Regatta Point and 8 samples from Strahan-1 bore were prepared by Global Geolab Services (Medicine Hat, Canada) and their dinoflagellates identified (Figs. 7 & 8).

3.3 Carbon Isotope Analyses

Stable isotope value data of organic matter ($\delta^{13}C_{org}$) from seventeen Glenelg-1 drill core samples were analysed at the University of Hawaii School of Ocean Earth Science Laboratories. Carbon and nitrogen weight percentages and isotopic composition were analysed with a Costech ECS 4010 Elemental Combustion System/Zero Blank Autosampler/Thermo Scientific Config IV/Thermo Scientific Delta V Advantage. Quantification and isotopic corrections were calculated using standards prepared in the Hawaii lab and run along with the Glenelg-1 samples.

3.4 Lithostratigraphy

To show the lithostratigraphy for ~100m above and below the PETM, gamma logs were compiled from various sources including original well logs from the Gippsland Basin, summary logs from the Bass Basin compiled by Blevin et al. (2003) and summary well logs from the Otway Basin compiled by Charles et al. (2019) (Fig. 3 – 5). The gamma logs show sandstones to the left and shales-mudstones to the right. The coloured motifs applied to the logs are a result of interpretation of the gamma log between the two extremes. Normally gamma logs would show coals on the far left but we place coals on the far right for ease of pattern recognition. The palynology ages from cores/sidewall cores are located on the gamma logs as black arrows with the zones determined from the palynology reports. The zones are signified as Ah,Sp = *A. hyperacanthum* - *S. prominatus* (i.e. PETM); Lb = *L. balmei* Zone; Ulb = Upper *L. balmei* Zone; LLb = Lower *L. balmei* Zone; LMd = Lower *M. diversus* Zone; M = *M. diversus* Zone; P = *Proteacidites tuberculatus* Zone; UM = Upper *M. diversus* Zone.

4 RESULTS

4.1 Gippsland Basin

In the Gippsland Basin, cross sections of the gamma-well logs demonstrate that similar facies surround the *Apectodinium hyperacanthum* Zone for about 100m below and ~100m above the relevant strata (Fig. 3). Results indicate that wells across the basin show the *Apectodinium hyperacanthum* Zone occurred at the end of a significant shale fining-upwards (right shifting gamma) trend implying probable lacustrine-marine deposition prevailed during the later stages of the Upper *L. balmei* Zone.

Sedimentary facies during the PETM tend to show a transition between marine and terrestrial with some coal seam development. In most wells (e.g. Speke-1, Bream-4A, Luderick-1, Veilfin-1, Whiting-1, and Sweetlips-1) the PETM is often directly overlain by a prominent sandstone. It is likely this transition represents a change from marine shales to mixed fluvial and marine environments such as occurs at a delta edge. Sedimentary facies after the PETM vary between a short-lived continuance of mostly shale deposition (e.g. wells Sawbelly-1, Whiting-2, Snapper-5 and Turrum-3) to sandstones-shales and regionally correlatable coal seams suggesting more terrestrial depositional environments in the Lower *M. diversus* Zone replaced the lacustrine-marine shales of the *L. balmei* Zone, accompanied by common development of thicker coal seams.

4.2 Bass Basin

In the Bass Basin, PETM appears to cover some 10 to 15m of stratigraphic thickness (Fig. 4), similar to that in the Gippsland Basin (Fig. 3). Wells particularly in the western areas of the Bass Basin, *i.e.* Kon Kon-1 and Koorkah-1 show the PETM, in a similar manner to Gippsland, occurred at the end of a significant shale fining upwards trend.

In the Kon Kon-1 well a second zone of *Spinizonocolpites prominatus* occurrences between 1312.0 and 1285.0m is interpreted here to represent the EECO interval. The two *S. prominatus* zones are separated by ~40m of sediments in the Kon Kon-1 well (Fig. 4). The accumulation of sediment between the PETM and EECO is considerably reduced compared to other wells in the Bass Basin where the two intervals are separated by > 200m. This suggests that the Kon Kon-1 locality was on a depositional high, and that the Middle and Upper *M. diversu*s Zones are condensed or may contain some unconformities in the section.

4.3 Otway Basin

Within the Otway Basin the PETM is corroborated by carbon isotope and palynology results at each end for Glenelg-1 and Latrobe-1 bores (Fig. 5) and in general appears to cover some 10 to 15 m in stratigraphic thickness within the Pember Mudstone. At Glenelg-1, where the carbon isotope analysis have been conducted the CIE, with values below -30 ‰ spans ~28.0 m between 1086.0 and 1114.0 m depth (see Fig. 8 and Table 2). Between these depths, a strong CIE is present and $\delta^{13}C_{org}$ values below -30 ‰ are recorded over an interval of 28m. This interpretation is supported by palynology from the Glenelg-1 drill core where *Nypa* occurs alongside *A. hyperacanthum, A. homomorphum and F. reichartii*. The zone thickness of the PETM in the Otway Basin is slightly greater than that in the Gippsland and Bass Basins. Most of the PETM is associated with Pember Mudstone facies, but above the PETM there are localised sandstone facies, analogous to the Rivernook Member of the type section for Pember Mudstone at Princetown (Baker, 1950, 1953).

In the Portland Trough, the Pember Mudstone extends above the PETM for up to 100m, becoming progressively silty and sandy upwards grading into the lower sandstone beds of the Dilwyn Formation. In some wells east of the Portland Trough (e.g. Codrington-1), the PETM may interbed with the lower sands of the Dilwyn Formation.

In summary, *Nypa* occurrences are widespread throughout the onshore Victorian Otway Basin and can extend offshore as indicated by palynology reports for gas wells such as Minerva-1 (see Table 1). Onshore, *Nypa* extends to the northern limits of the Otway Basin such as at Dartmoor, and presumably occurs in the South Australian part of the basin as well. The *Nypa* 'zone of occurrence' within the lower part of the Pember Mudstone can be up to 28.0 m thick, as in Glenelg-1, but at the Point Margaret outcrop is only 2-3m thick because the top of the zone has been truncated and is overlain by Quaternary soils (Frieling et al. 2018).

4.4 Sorell Basin

Examination of eight outcrop samples at Regatta Point in Strahan from an 8m thick mudstone section showed the most numerous dinoflagellate taxon is *Homotryblium tasmaniense*. *Kenleyia lophopora* occurs in greater numbers in the middle of the outcrop. *Homotryblium tasmaniense* has a well-defined Eocene range in the Gippsland and Otway Basins and its presence gives an age constraint of ~53 to ~45.5 Ma according to Partridge (2006) and Gallagher & Stanislaus (2019).

Previous analysis of the Strahan-1 bore (Fig. 7) 2.5 km NW of Strahan township suggested there were several *Nypa* horizons present within the bore (Macphail, 2011). In this study we found that at 349.0 and 348.5m *Spinizonocolpites* is common and the dinoflagellate assemblages include up to a third *Apectodinium* species, including *A. homomorphum* and possibly *A. longispinosum*, but not *A. hyperacanthum*, within an identified Lower *M. diversus* Zone (Macphail, 2011). At 346.3m, *Nypa* occurs without *Apectodinium*, but other dinoflagellate taxa are frequent. Three samples from 343.0 to 330.9m did not contain dinoflagellates. This result does not preclude a ~2.7m thick PETM between 346.3 and 349.0m, but a more parsimonious interpretation is that the entire interval is slightly younger within the *A. homomorphum* Zone. Even so, this may be the most southerly location for *Nypa*, some 4 degrees paleogeographically further south than any other SE Australia and New Zealand occurrences (Pocknall et al. 2023; Frieling et al. 2023) (see Fig. 6).

5 DISCUSSION:

5.1 The maximum mangrove spread during the PETM and EECO.

Globally, the interval from the Paleocene-Eocene transition to the middle Eocene represents an acme in *Nypa* distribution (Lim et al., 2022; Pocknall et al., 2023). Although other mangrove taxa may have spread to the Arctic and Antarctic during the PETM (Willard et al., 2019; Suc et al., 2020), neither *Spinozonocolpites* pollen nor *Nypa* macrofossils have been reported from there. They have, however, been recorded in deposits as far north as Germany and England, with likely depositional paleolatitudes of up to 50°N (Collinson, 1993, 2000; Popescu et al., 2021; Lim et al., 2022). In the Southern Hemisphere, *Spinozonocolpites* records from South America and Zealandia (Archangelsky and Zamaloa, 1986; Crouch and Brinkhuis, 2005) show a *Nypa* distribution near or below 50°S during the Paleocene and Eocene (Lim et al., 2022). The southernmost occurrence known to date comprises *Nypa* fruits and *Spinozonocolpites* from Tasmania (Pole and Macphail, 1996; Carpenter et al., 2013; Pocknall et al., 2023; this paper) with a paleolatitude of at least 59°S (Strogen et al., 2022; Vaes et al., 2023) but potentially to >65°S (Fig.6, using the reconstruction of Seton et al. 2012). Very high sea level for the Paleocene and Eocene, and in particular the PETM and EECO, likely saw the widespread inundation of low elevation continental landmasses, as *Nypa* records are recorded in inland sequences from disparate locations such as the US Gulf Coast plane and what is now the Sahara Desert (Lim et al., 2022), consistent with our Australian results.

5.2 Facies trends and the PETM:

The shale fining-upwards trends in the Late Paleocene (Upper *L. balmei* Zone) prior to the appearance of *Spinizonocolpites* together with *Apectodinium hyperacanthum* is common to all three main basins, but particularly in the Gippsland and Bass Basins (Figs. 3 & 4). This could suggest facies trends here are associated with causative effects leading up to the PETM. The shale fining-upward trends suggests an increasing deepening trend (accompanied by more offshore dinoflagellate taxa - Frieling et al. 2023) prior to the PETM was caused by latest Paleocene warming and thermal expansion of seawater affecting the lacustrine-marine shale basins. Sluijs et al. (2007) suggest a 5°C increase in global ocean temperatures could cause 3 – 5 m eustatic sea-level rise that would impact low-lying flatlands and coastal basins like Gippsland, Bass and Otway basins. Although this seems a relatively modest rise in sea level, transgressive phases and sea level high-stands are widely reported from the PETM (Sluijs et al. 2008). The facies change between apparent prodelta shales (*L. balmei* Zone) and top-set terrestrial delta front facies (*M. diversus* Zone) results in an organic facies change and distinction in the coal petrology (Smith, 1982; Smith & Cook, 1980; Smith et al, 2023). The coal seams and carbonaceous clays before the PETM are thinner, discontinuous, prone to splitting, and are clayey with low pyrite content. Above the PETM, the organic facies include thick ombrogenous peats developed in lower coastal plains during the late transgressive/aggradational phases. The extensive peat swamps were likely located adjacent to, but isolated from, the main distributary channel belts.

The PETM in the Gippsland and Bass basins is characterized by a transition between marine and terrestrial facies with some coal seam development. The PETM strata are often directly overlain by a prominent sandstone (e.g. Speke-1, Luderick-1 and Snapper-5 in Gippsland; and Koorkah-1, Tilana-1 and Pelican-5 in Bass) (Figs. 3 & 4). It is likely that this transition represents a change from lacustrine-marine shales to mixed fluvial, barrier sands and marine environments such as occurs at a delta edge. Facies following the PETM include a short-lived continuance of mostly shale deposition in the Gippsland Basin and most of the Bass Basin suggesting continuance of lacustrine-marine depositional environments in the Lower *M. diversus* Zone similar to the marine shales of the *L. balmei* Zone. The common development of thicker coal seams in the Lower *M. diversus* Zone, however, is also apparent (Figs. 3 & 4).

Partridge (2002) proposed that the Gippsland and Bass Basins were largely closed basins during the Late Cretaceous to Eocene, comprising large palaeolakes, coastal lagoons and

marine bay's (Figs. 9A & 9B). Marine incursions into these basins were minor and mainly restricted to the PETM. From occurrences in the northwest corner of the Bass Basin of *Nypa* with marine *Apectodinium* microplankton in trace numbers, Partridge (2002) concluded marine ingressions occurred in the northwest into a dominantly freshwater lacustrine sequence referred to as Palaeolake Koorkah (Fig.9B). The palaeolake was considered to cover the north-western half of the Bass Basin. Based on our comprehensive analyses, base levels across the whole basin deepened accompanying progressive transgression through the Late Paleocene (Upper *L. balmei* Zone). The palaeogeographic reconstruction (Figs. 6 & 9B) implies any transgression caused by Southern Ocean sea-level rise would most likely bridge across the gap between the King Island High-King Island uplifted area and the Tasmania mainland. Later marine incursions occur in the middle Eocene, interspersed with the thickest and most extensive coal seams in the basin record (Smith, 1982; Partridge, 1999; Blevin et al. 2003). Terrestrial deposition terminated in the latest Middle Eocene by widespread marine Boonah Sand Formation and subsequent finer grained Anglesea Formation. The latter formations include evidence of abundant marine dinoflagellates (Partridge, 2002; Blevin et al., 2003).

In the Otway Basin, the Late Paleocene of the Pember Mudstone comprises siltstones and mudstones with some sandstones of varying thickness (see below). The Rivernook Member within the Pember Mudstone is a marine sandstone facies and occurs stratigraphically shortly above the PETM. This member contains the upper part of the marine calcareous foraminiferal Zone P5 (McGowran, 1965) (see Fig. 2) representing a localised change from marine shales to marine sandstones. It is possible that the Rivernook Member represents an offshore submarine channel within the overall prodelta marine Pember Mudstone facies suggested by Holdgate (1981) and Keating (1993). All the above facies are considered deposits within a fully marine environment immediately overlying the Middle to Late Paleocene marine Pebble Point Formation, itself a marine formation that includes several stratigraphically significant interbeds of shaley fine sandstones containing lower P5 Zone calcareous foraminifera and shelly macrofossils. (McGowran, 1965; Keating, 1993; Frieling et al. 2018, Huurdeman et al., 2021, Frieling et al., 2023) (see Fig. 2). In the Portland Trough area consecutive *Nypa* occurrences in Glenelg-1 and Cobboboonee-2 appear locally to exceed 60m. Wells particularly in the central-western Portland Trough such as Cobboboonee-2 and Heywood-13 show the PETM occurs in the upper part of the Pember Mudstone which overlies >200 m of Late Paleocene - Upper *L. balmei* Zone Pember Mudstone (Fig. 5). In turn, these mudstones overlie the sandy Middle-Late Paleocene Pebble Point Formation (Keating, 1993). Wells located towards the eastern

basin limits tend to have an overall reduced thickness of the Late Paleocene Pember Mudstone, such as at Latrobe-1 and the Point Margaret cliff section, where Frieling et al. (2018) record ~2m of truncated PETM-aged Pember Mudstone above 28m of Late Paleocene Pember Mudstone and ~20m of sand-, silt- and mudstones of the Late Paleocene Pebble Point Formation. Therefore, the Upper *L. balmei* Zone experienced a significantly increased depositional rate in the Portland Trough that continued into the Early Eocene *M. diversus* Zone where post-PETM Pember Mudstone can be >100m thick (e.g. Wanwin-3) (Fig. 5).

Faulting that only affects up to the Middle-Late Paleocene (Upper *L. balmei* Zone) Pebble Point Formation in Dilwyn Bay outcrops lends support to the suggestion by Denison (2021) that localised diastems are common in and around the PETM in many parts of the world. Such is the case in Glenelg-1 (Fig. 5) where the *Apectodinium hyperacanthum* Zone directly overlies chamositic-glauconitic facies of the Pebble Point Formation which is typical in this westerly area of the basin (Holdgate, 1977). In detailed coring at Lindon-1 near Dartmoor (Fig. 1), Tabassi & Davey (1986) record this pisolitic and oolitic facies to be over 30m thick. Using X-ray diffraction and scanning electron microscopy they recognised chamositic, chloritic and glauconitic clay minerals pervasive through the upper beds of the Pebble Point Formation that occluded original grain porosity, suggesting widespread lateritic weathering. This reflects a subaerial exposure surface and a significant hiatus on the top of the Pebble Point Formation and below the Pember Mudstone. Tabassi & Davey (1986) further suggested this lateritic surface resulting from tropical weathering was the cause of high-amplitude seismic lines in this area as a result of cemented layering at the top of the Pebble Point. This explanation was considered more plausible than previously held beliefs that the high-amplitude events were caused by an unconformity between base Pebble Point and top (Upper Cretaceous) Sherbrook Group below (e.g. Leslie, 1966; Glenie, 1971; Ellenor, 1976).

In the Bass Basin several wells record a high-amplitude event on seismic lines considered to occur at around the PETM interval (Blevin et al. 2003). We also recognize these in the Koorkah-1 and Nangkero-1 wells near the upper part of the PETM (Fig. 4). The exact nature of the amplitude event is not stated but could be a similar cemented horizon similar to the western Otway Basin.

5.3 Unconformities and the *Apectodinium hyperacanthum* Zone.

In the offshore Gippsland and Bass basins, the existence of an angular unconformity at the end of the *L. balmei* Zone was suggested by Partridge (1976). This unconformity is overlain by a transgressive marine influx of *M. diversus* Zone *Nypa*-bearing facies (Fig. 9A) accompanied by reworking of older spore-pollen assemblages into the *Apectodinium hyperacanthum* Zone, and by dolomitic cementation. Although an unconformity may exist in the western part of the Otway Basin (see above) it is difficult to corroborate this unconformity with our data from the Gippsland and Bass basins, despite our more widespread well correlations. In the Gippsland and Bass basins the unconformity may have been interpreted in local, more detailed field drilling (e.g. in the Marlin Field) but on a regional basis, the angular unconformity is not evident (e.g. Figs. 3 & 4).

Partridge's (1976) proposed angular unconformity at the end of the *L. balmei* Zone overlain by a transgressive marine influx of *M. diversus* zone *Nypa*-bearing facies is partly corroborated by the outcrop at Point Margaret (Frieling et al. 2018). In Dilwyn Bay outcrops 1700m southeast of Point Margaret, ENE striking normal faulting in the Pebble Point Formation produces anomalous thinning, an absence of the constituent upper Cobble Cove and part-Buckleys Member beds of the Pebble Point Formation, and an unconformity over uplifted blocks between Pebble Point Formation and Pember Mudstone (see Fig.10A). Beds in the overlying Pember Mudstone do not show the same fault-offsets, and distinctive beds of the Pember Mudstone can be correlated along all the 2km of outcrop. The pronounced thinning of Pebble Point over the uplifted block is interpreted as erosional loss to its upper beds, implying a hiatus followed after normal fault block movements. After some depositional hiatus during "marine" planation, deposition of marine beds of the Pember Mudstone resumed, and this is reminiscent of the concept proposed by Partridge (1976). Other ENE striking normal faults where upper Pebble Point beds are removed occur near Buckleys Point (500m east of Point Margaret) and Moonlight Head (1300m east of Dilwyn Bay). The fault movements can be timed to the late Paleocene because at Point Margaret 48m of late Paleocene mudstones were deposited between the top of the Pebble Point Formation and the base of the PETM (Fig. 10B). Similar style faulting probably occurs in the Portland Trough, producing the large thicknesses of Pember Mudstone below the *Apectodinium hyperacanthum* Zone beds and above the Pebble Point Formation. The faulting probably represents early break-up faults during rifting of Australia-Antarctica (Arditto, 1995) that, in the Paleogene, only affects up to the Middle-Late Paleocene (Upper *L. balmei* zone) Pebble Point Formation. In Dilwyn Bay, however, there appears to have been later renewed fault reversal of movement sometime in the Miocene (K.

Hill pers comm. February 2024). The widespread occurrence of Middle-Late Paleocene faulting has been noted on seismic lines offshore to the Princetown section (Arditto, 1995).

5.4 Terrestrial and marine consilience in the PETM

In all basins flanking the Tasman Sea and Southern Ocean, regional palynological studies (Partridge 2002c; Sluiter and Macphail 1984) suggest terrestrial vegetation within the Late Paleocene was rainforest dominated by Podocarpaceae, Araucariaceae including common *Dilwynites* along with abundant ferns and lycopods. A shift to increasing angiosperms occurs in the Early Eocene dominated by *Malvacipollis diversus* (*Austrobuxus-Dissiliaria-Petalostigma*), *Nothofagidites* (*Nothofagus* subgenus *Brassospora*) and *Proteacidites* (Proteaceae). This vegetation across the Paleocene-Early Eocene is consistent with the Austral Polar Forest Biome of Macphail et al. (2022) and a meta-analysis from New Zealand (Prebble et al. 2021). Towards the end of the Paleocene Epoch paratropical forests replaced the temperate forests, ferns increased and angiosperms increased at the expense of the gymnosperms (Partridge, 1999; Macphail, 2007). The appearance in the Early Eocene strata of the sporomorph *Spinizonocolpites prominatus* represents a peak 'hothouse' condition in the swampy and estuarine margins of the Early Eocene. The modern mangrove palm *Nypa* is a megathermic indicator, found in MATs of 24-28°C (Reichgelt et al., 2018).

The widespread appearance of *Nypa* supports MAT estimates from Point Margaret and Latrobe-1 (Frieling et al., 2018, Huurdeman et al., 2021, Frieling et al., 2023). *Apectodinium* is an indicator of very warm conditions recorded throughout the world and the spread of this genus and a few other taxa (e.g. *Florentinia reichartii*) has been proposed to result from reduced latitudinal temperature gradients (Sluijs et al., 2007, Frieling & Sluijs, 2018). In the Gippsland Basin, species of *Apectodinium* were also found as far south as Site 1172 east of Tasmania together with other warm-water species, *Florentinia reichartii* (Frieling et al., 2018, Huurdeman et al., 2021, Frieling et al., 2023).

A depositional environment that would meet our reconstruction of such a tropical terrestrial-marine regime occurs in the present day tropical deltaic environments of southeast Asia and in particular the Mahakam Delta in coastal Borneo (Fig. 9C & D). Moore (2015) presents field descriptions of this delta and the aerial view of the delta shows it comprises high sinuosity delta front tributaries opening seaward into the tropical marine waters of the Celebes Sea (Fig.10C). Lining the tributaries are prolific *Nypa* palms (Fig.10D). Between the distributaries are raised

peat bogs accumulating terrestrial plant materials and pollen-spores within some of the thickest peat deposits in the world (Moore, 2015). Any influx of marine waters into the distributary bar mouths would mix the terrestrial-marine species within a muddy substrate. Around SE Australia, rapid transgressions as a result of a few meters of eustatic (thermosteric) sea level rise (e.g. Sluijs et al. 2008), at the advent of the PETM would have flooded these delta front environments, burying the peat lands under prodelta muds, transgressing inland over low coastal environments across areas of greater than the ~55,000 km^2 proposed for the inundation across the four SE Australian basins studied here.

The PETM preceded the longer-lasting warmth of the Early Eocene climatic optimum (EECO) that peaked at 52–50 Ma. At sea-level in the Sorell Basin's Macquarie Harbour Formation, outcrops of mudstones contain megathermal plant fossils that provide a MAT estimate of 24 °C at ≥60°S paleolatitude (Carpenter et al. 2012, Macphail & Jordan 2015), although a later analysis reconstructed a MAT of 19.2 – 20.7 °C for Regatta Point (Reichgelt et al., 2022). It should be noted that the Sorell Basin flora cannot be accurately dated to the PETM. The post-PETM occurrences of *Nypa* around SE Australia likely date mostly to the EECO and support the view that the EECO greenhouse climate was not much cooler than that during the PETM (e.g. Bijl et al. 2021, Frieling et al. 2023) and marked by a similar vegetation distribution. Paleoclimate and environmental reconstructions indicate that temperatures remained well above freezing even during several months of winter near- or total darkness in the southern high latitudes (Bijl et al. 2009; Pross et al. 2012; Contreras et al. 2013; Pocknall et al. 2023; Reichgelt et al. 2022; Frieling et al. 2023; McGowran 2023).

6 CONCLUSIONS:

During the PETM in SE Australia, sea-levels rose by approximately 5 m. Despite the modest sea level rise low-lying near-coastal environments were inundated and likely an area >55,000km^2 was flooded. Megathermal biota are found at localities down to ≥60°S paleolatitude. Building on previously proposed regional stratigraphic marker taxa, the PETM is identified from palynological records across four coastal depositional basins, along with supporting evidence from carbon isotope analyses. The PETM-aged strata in the four studied (Gippsland, Bass, Otway and Sorell) SE Australian basins diagnostically include tropical mangrove *Nypa* palm pollen (*Spinizonocolpites prominatus*) accompanied by the thermophilic marine dinoflagellate *Apectodinium hyperacanthum*. In the Gippsland Basin, 26 wells record

this *Nypa-A. hyperacanthum* concurrence over most of the offshore basin during the earliest Eocene part of the Kingfish Formation (Lower *M. diversus* Zone). In the Bass Basin eight wells record *Nypa-A. hyperacanthum* concurrence, within the Eastern View Group as well as the lowest part of the Koorkah Formation (Lower *M. diversus* Zone - earliest Eocene). Thirteen wells also record *Nypa* occurrences near the top of the Cormorant Formation that probably represent the EECO event – a long period of warmth *ca.* 53 - 49 Ma. In the Otway Basin, 21 wells record the *Nypa-A. hyperacanthum* concurrence within the Pember Mudstone Lower *M. diversus* Zone. *Nypa* occurrences also occur within the Burrungule Member (EECO) at the top of the Dilwyn Formation.

In western Tasmania, fossil *Nypa* together with thermophilic dinoflagellates occur in an offshore well in the Sorell Basin and outcrops and a bore in the Macquarie Harbour area, in sediments that are mostly considered to be slightly younger than the PETM, but offshore could include the PETM.

Some structural events accompanied by diagenetic changes, particularly in the Otway Basin, probably precede the PETM transgression and suggest early break up events on the Australia-Antarctica Gulf and even subaerial exposure before the main PETM transgression. Although evidence for these events is less obvious in Gippsland and Bass Basins, it is possible there were condensing of sections around this time, corroborated by seismic data.

Altogether, the data from industry wells allows us to reconstruct the area affected by the marine transgression during the PETM, likely the warmest period of the Cenozoic. Further, our compiled well data illustrates the extent of the PETM mangrove coasts that characterized SE Australia. The mangrove coasts cover a large area (>55,000 km^2), a feat even more remarkable considering the high paleolatitudes of the study area (60 – 65^o S). Our comprehensive reconstruction of SE Australian mangrove distribution during the PETM and also EECO confirms earlier studies that these regions were characterized by ecosystems that are confined to the tropics at present.

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Data for the Otway Basin largely comes from a report reviewing and revising palynology data in government legacy cores and petroleum exploration (Charles et al. 2019) supplemented in this paper by extra palynology in the Glenelg-1 bore. In the offshore Sorell Basin publicly available well data was available for Cape Sorell-1, and for the onshore Strahan-1 core bore palynology available from Macphail (2018) supplemented by extra palynology for this paper. The authors gratefully acknowledge all the publicly available palynology data, in particular scans and compilations by Federal Geological Survey of Australia and the State Victorian Geological Survey of petroleum well completion biostratigraphic reports.

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Table-1. Lists of publicly available well completion palynology reports containing occurrence of Nypa (*S. prominatus*) mostly with *Apectodinium hyperacanthum* (ie. PETM) and Nypa (*S. prominatus*) without *Apectodinium hyperacanthum* (ie. EECO & MECO). ns: key species mentioned in reports but depth not specified. Total zone thicknesses queried in some reports by a "?" on the "from" or "to" depth because of lack of, or incomplete sampling. The zones are signified as Ah = *A. hyperacanthum*; Ah,Sp = *A. hyperacanthum*/*S. prominatus* (ie. PETM); A.homo = *A. homomorphum.* Lb = *L. balmei* Zone; LLb = Lower *L. balmei* Zone; LMd = Lower *M. diversus* Zone; Lwr. *N. asp.*= Lower *N. asperus* Zone; M. N.asp. = Middle *N. asperus* Zone; M = *M. diversus* Zone; *P. asp. = P. asperopollis* Zone; P = *P. tuberculatus* Zone; Sp = *S. prominatus*; Ulb = Upper *L. balmei* Zone; UMd = Upper *M. diversus* Zone. Age/event

abbreviations: Middle Eocene Climate Optimum (MECO, ca. 40 Ma), Early Eocene Climate Optimum (EECO, ca. 53 – 49 Ma), Paleocene-Eocene Thermal Maximum (PETM, ca. 56 Ma)

TABLE 1

GIPPSLAND BASIN

WELL	Author	From	To	Palynology Zone	Interpreted age / event
Albatross-1	Stacy 1979c	679.6	713.2	Lwr. *N. asp;* Sp.	EECO?
Bonita-1	Stover & Partridge 1971, Partridge 1975b, Harris 1983a	2444.9	2482.7	Ah; LMd	PETM
Bream-4A	Stacy 1982	2234.0	?	Ah; LMd	PETM
Bullseye-1	Stover 1974b, Harris 1983c	2355.9	?	Ah; LMd	PETM
Chimaera-1	van Niel 1984	1996.8	2001.6	LMd; Sp.	PETM?
Cobia-2	Partridge 1977b	2393.4	2394.1	Ah,Sp; LMd.	PETM
Cod-1	Stover 1970, 1973c	2390..4	2396.2	Ah; LMd	PETM
Conger-1	No author cited	2215.0	?	Ah; LMd?	PETM
Drummer-1	Macphail 1986	2487.8	?	Ah; LMd?	PETM
Edina-1	Harris 1983b	2514.5	?	Ah; LMd	PETM
Fortescue-1	Stacy & Partridge 1978	2666.0	2672.0	Ah,Sp; LMd.	PETM
Fortescue-2	Stacy 1979a	2520.5	2556.5	Ah; LMd	PETM
Fortescue-3	Stacy & Partridge 1979b	2589.0	2605.0	Ah,Sp; LMd.	PETM
Fortescue-4	Stacy 1979b	2498.8	2501.0	Ah; LMd	PETM
Gannet-1	Stacy 1979d	698.0	?	Lwr. *N. asp.*	MECO?
Gummy-1	Macphail 1990	2098.0	?	Ah; LMd	PETM
Gurnard-1	No author cited	2383.5	?	Ah; LMd?	PETM
Kahawai-1	Macphail 1982	1572.2	?	Ah,Sp; LMd.	PETM
Kipper-1	Marshall & Partridge 1986	1478.0	1493.0	Ah,Sp; LMd.	PETM
Kipper-2	Hannah 1987	1577.0	1585.5	LMd; Sp.	PETM?
Luderick-1	Macphail 1983c	2270.0	?	LMd; Sp.	PETM?
Manta-1	van Niel 1986	2006.0	2040.0?	LMd; Sp.	PETM?
Marlin-4	Stover 1973e	1859.0	1892.1?	Md; Sp.	PETM?
Marlin-A24	Davies 1996	2597.0	2615.0	LMd; Sp.	PETM?
Morwong-1	Partridge 1973	1751.2	?	Md; Sp.	PETM?
Rockling-1	Stacy & Partridge 1979c	2582	2584.0	Ah,Sp; LMd.	PETM
Sawbelly-1	Partridge 1990a	2438.0	?	Ah,Sp; LMd.	PETM
Snapper-4	Macphail 1983a	1765.5	1780.3	LMd; Sp..	PETM?
Snapper-5	Partridge 1986	1834.5	?	Ah,Sp; LMd.	PETM
Speke-1	Martin 1984	2304.0	?	Ah,Sp; LMd.	PETM
Sweetlips-1	Partridge 1990b	1559.0	?	Ah,Sp; LMd.	PETM
Swordfish-1	Partridge 1977a	2426.3	2431.6	Ah,Sp; LMd.	PETM
Turrum-3	Marshall 1985	1736.9	1750.5	Ah,Sp; LMd.	PETM
Veilfin-1	Hannah & Macphail 1985	2399.0	2430.0	Ah,Sp; LMd.	PETM
Whaleshark-1	Partridge 1993	2760.0	2765.0	LMd; Sp..	PETM?

W Halibut-1	Stacy & Partridge 1979a	2510.5	2522.0	Ah,Sp; LMd.	PETM
Whiting-1	Macphail 1983b	1859.1	?	LMd; Sp..	PETM?
Whiting-2	Macphail 1985	1874.9	?	Ah,Sp; LMd.	PETM

BASS BASIN

WELL	Author	From	To	Palynology Zone	Interpreted age / event
Cormorant-1	Morgan 1985a	1682.5	2036.1	P.asp. Sp	MECO-
	Partridge 2003	2033.0		UMd, Sp	EECO
Dondu-1	Stover 1973b	2156.3	?	M-LMd, Sp	PETM
Flinders-1	Partridge & Morgan 1993	2365.5?	2417.0	LMd, Sp, Ah	PETM
Kon Kon-1	Stover 1973a; Partridge 2002a	1359.3	1365.4	LMd, Sp	PETM
Koorkah-1	Morgan 1986b	1897.0	1972.5	P.asp. Sp	EECO
Nangkero-1	Harris 1974	?	2514.0	LMd. Common dinos.	PETM?
Narimbah-1	Stover 1974a	2539.7	2680.5	UMd. – P.asp. Sp	EECO
Pelican-1	Partridge & Stover 1971	2362.6	22426.6	UMd, Sp	EECO
Pelican-2	Stover & Thompson 1970	2483.9	?	LMd. Sp	PETM
Pelican-5	Morgan 1986a	2557.0	?	MMd, Sp	EECO?
Pipipa-1	Stacy et al 1982	1521.2	?	M.N.asp-L.N.asp. Sp	MECO?
Poonboon-1	Partridge 1972b,	2362.0	2651.4	M-UMd, Sp	MECO
	Partridge 2002b	2651.8	?	LMd, Ah, Sp	PETM
Seal-1	Morgan 1986c	1350.0	1365.0	UMd. Sp	EECO
Squid-1	Evans 1984; Martin 1985	2095.0	2125.0	P.asp.-UMd. Sp	EECO
Tarook-1	Partridge 1972c	2535.8	2604.0	LMd, Sp	PETM
Tilana-1	Morgan 1985c	2356.0	2464.0	P.asp-U.Md, Sp	EECO
		2745.0	2754.0	LMd, Sp, Ah	PETM
Toolka-1	Stover 1974c	1933.2	?	UMd, Sp	EECO
Yolla-1	Morgan 1985b	2138.0	2354.0	P.asp-U.Md. Sp	EECO
Yurongi-1	Stover 1973d	1709.8	1775.0	P.asp-U.Md. Sp	EECO

OTWAY BASIN

Bore-Well	Author	From	To	Palynology Zone	Interpreted age / event
Belfast-11	Charles et al 2019	845.0	847.0	LMd. Sp	PETM
Bootahpol-2	Charles et al 2019	524.0		UMd. Sp	EECO
		752.8		LMD. Ah	PETM
Cobbo-onee-2	Charles et al 2019	886.8	?	UMd. Sp	EECO
		1587.0	?	LMd. Sp	PETM
Codrington-1	Charles et al 2019	469.0	481.0	P.asp-UMd. Sp	EECO
		670.0		M-LMd, Sp	PETM
Coriejong-1	Charles et al 2019	366.0	372.0	LMd, Sp Ap	PETM
Dartmoor-25	Charles et al 2019	426.0	428.0	LMd, Sp	PETM
Glenelg-1	this paper	1086.0	1114.0	LMd, Sp, Ap	PETM
Glenaulin-2	Charles et al 2019	666.6	671.2	LMd, Sp	PETM
Gorae-4	Charles et al 2019	931.3	?	UMd. Sp	EECO

Heywood-13	Charles et al 2019	997.9	?	LMd. Sp.	PETM
Latrobe-1	Frieling et al 2018	295.0	308.0	LMd, Sp, Ah	PETM
Lavers-1	Charles et al 2019	1002.0	1005.0	LMd, Sp	PETM
Malanganee-4	Charles et al 2019	661.0	665.0	LMd. Sp .Ah	PETM
		780.0	784.0	LMd. Sp. Ah	PETM
Minerva-1	Morgan & Hooker (1993)	617.0	?	LMd. 6% dinos A.homo	PETM
Mepunga-7	Charles et al 2019	854.0	860.0	LMd. Sp, Ah	PETM
Mumbannar-4	Charles et al 2019	560.0	608.6	LMd, Sp, Ah	PETM
Mumbannar-6	Charles et al 2019	628.6	629.6	LMd, Sp, Ah	PETM
Najaba-1A	Charles et al 2019	320.0	?	P.asp-U.Md, Sp	EECO
		1311.0	1382.0	LMd, Sp,	PETM
Narrawong-15	Charles et al 2019	1449.0	1454.0	M.Md, Sp.	EECO?
Narrawong-15	Charles et al 2019	1674.0	1676.0	L.Md, Sp, Ap	PETM
		1834.0	1840.0	LMd, Sp, Ap	PETM
Nullawaare-3	Charles et al 2019	738.5	795.0	P.asp.-UMd. Sp	EECO
Squatter-1	Charles et al 2019	790.0	?	U.Md. Sp	EECO
Wanwin-3	Charles et al 2019	1089.4	?	L.Md. Sp,	PETM
Werrikoo-1	Charles et al 2019	376.0	396.0	L.Md. Ap	PETM
Yambuk-2	Charles et al 2019	506.9	566.0	P.asp. Sp	EECO
Yangery-1	Charles et al 2019	604.0	609.0	L.Md. Sp, Ap	PETM

SORELL BASIN

WELL	Author	From	To	Palynology Zone	Interpreted age / event
Cape Sorell-1	Hughes et al 1983; Micro-Strat 1986, Macphail 2007	841.0	1234.0	*Wetzeliella-1-3-9*, Sp U.Lb.	PETM?
Strahan-BH1	Macphail 2011	346.5	349.0	L.Md	EECO
	This paper	348.5	349.0	L.Md	ECCO-PETM?

TABLE 2: CARBON ISOTOPE ANALYSIS – GLENELG-1 BORE

Sample depth	$\delta^{13}C$ ($^0/_{00}$ vs. VPDB)	Interpreted age / event
3390ft, 1033.2m	-27.5	
3566ft, 1086m	-30.2	PETM
3612ft, 1100.9m	-30.4	PETM
3617ft, 1102.5m	-30.7	PETM
3618ft, 1102.8m	-30.6	PETM

3625ft, 1104.8m	-30.7	PETM
3626ft, 1105.2m	-30.7	PETM
3630ft, 1106.4m	-30.7	PETM
3633ft, 1107.3m	-30.7	PETM
3634ft, 1107.6m	-30.7	PETM
3635ft, 1107.9m	-30.5	PETM
3636ft, 1108.2m	-30.5	PETM
3647ft, 1111.6m	-30.6	PETM
3650ft, 1112.5m	-30.9	PETM
3655ft, 1114.0m	-30.9	PETM
3690ft, 1124.6m	-16.5	
3690ft, 1124.6m	-16.4	
3712ft, 1131.3m	-18.4	

FIGURES

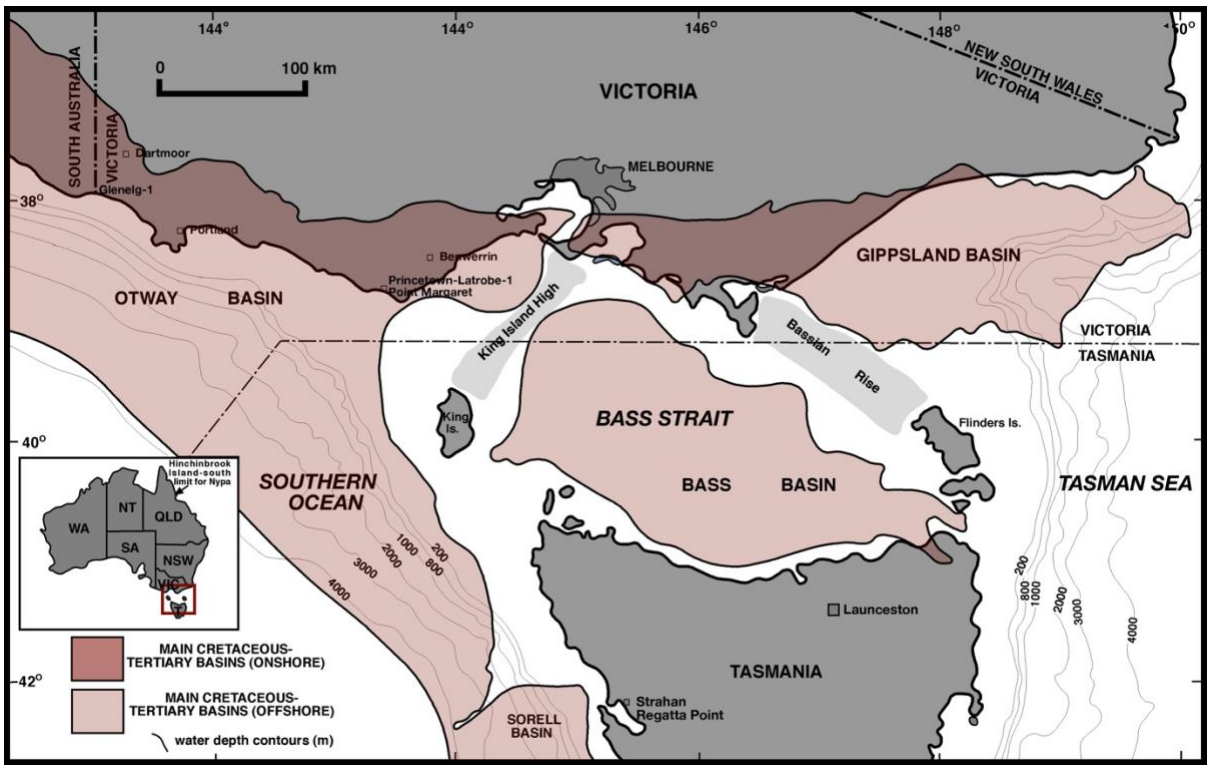


Figure 1. Locality map for SE Australian basins showing localities noted in the text.

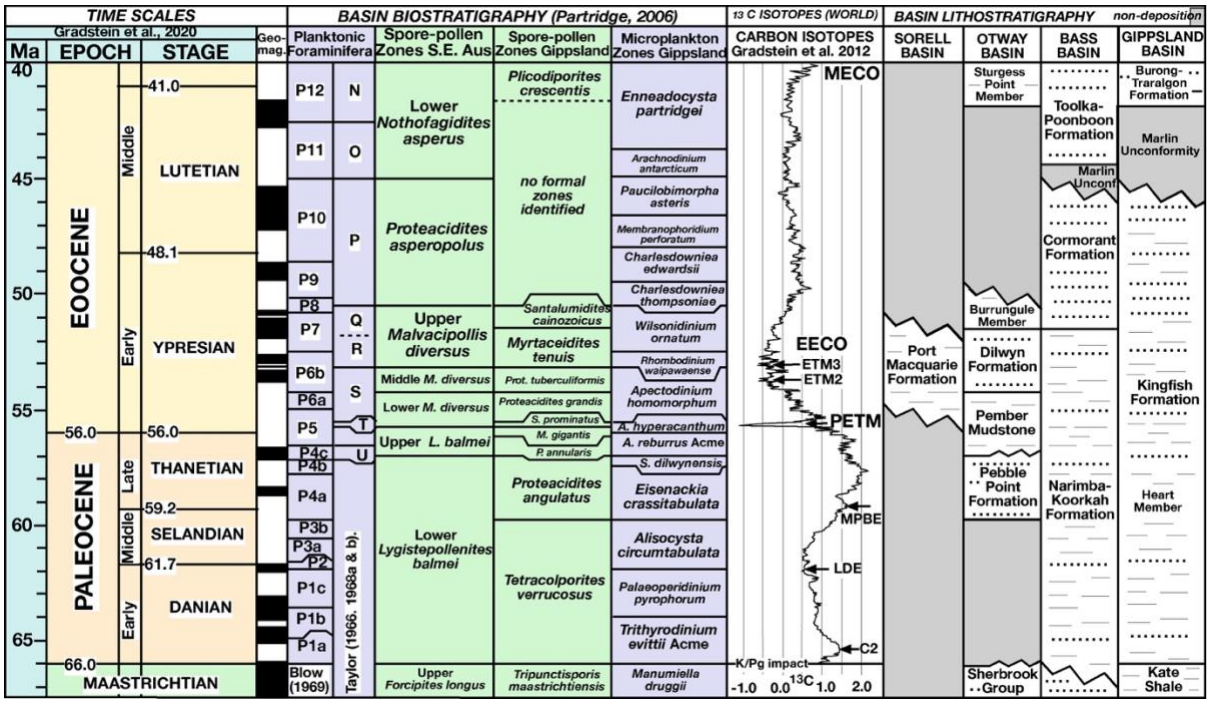


Figure 2. Biostratigraphy for SE Australian basins in conjunction with the composite carbon isotope data for benthic foraminifera (Gradstein et al. 2012). For explanation of biostratigraphy and time scales see Partridge (2006) and Gradstein et al. (2020). Generalised lithostratigraphic schemes for the four SE Australian basins shown in the four right hand columns.

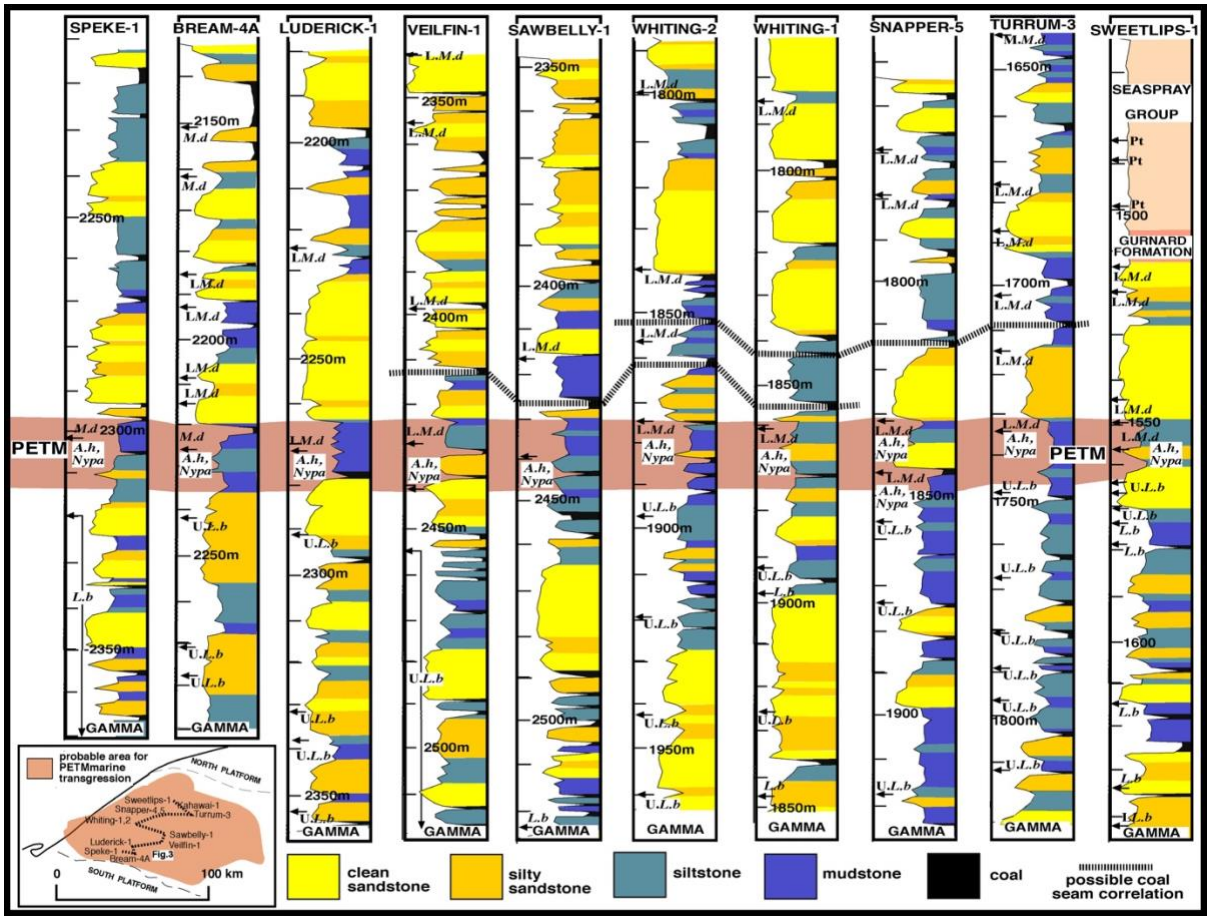


Figure 3: SW to NE gamma well log cross-section across the Gippsland Basin showing the main facies around the PETM for about 100m below and ~100m above the PETM-aged strata. The PETM is shown by the horizontal

pink band which provides an approximate base line. Depths are in well depth (meters) below Kelly bushing (mmd). The palynology ages from sidewall cores (mostly) are located by the thick red arrows with the palynology zones as determined by the well completion palynology reports (see Table 1). The zones are signified as Ah,Sp = *A. hyperacanthum*/*S. prominatus* (ie. PETM); Lb = *L. balmei* Zone; LLb = Lower *L. balmei* Zone; Ulb = Upper *L. balmei* Zone; LMd = Lower *M. diversus* Zone; M = *M. diversus* Zone; P = *P. tuberculatus* Zone; UM = Upper *M. diversus* Zone. For location of section, see Figure 6.

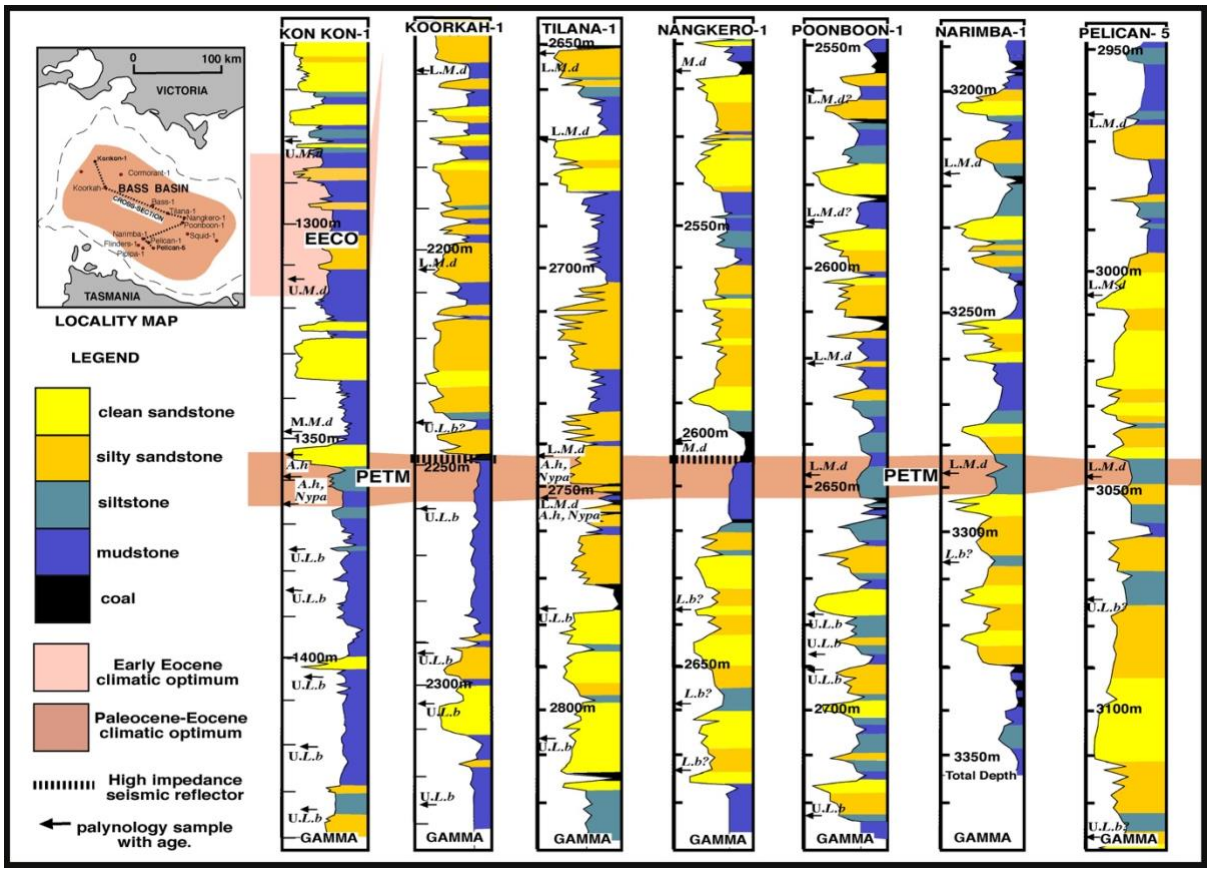


Figure 4: NW to SE gamma well log cross-section across the Bass Basin showing the main facies around the PETM for about 100m below and ~100m above the PETM-aged strata. The PETM is shown by the horizontal pink band (the PETM zone) which provides an approximate base line. Depths are in well depth (meters) below Kelly bushing (mmd). Location of high amplitude zones in wells shown by striped black line. Palynology ages shown by thick black arrows as determined from the palynology reports (see Table 1). Zones signified as for Figure 3. For location of section see Figure 6. Mean annual temperature (MAT) shown for Kon Kon-1 well derived from quantified palynology counts of Partridge (2002a).

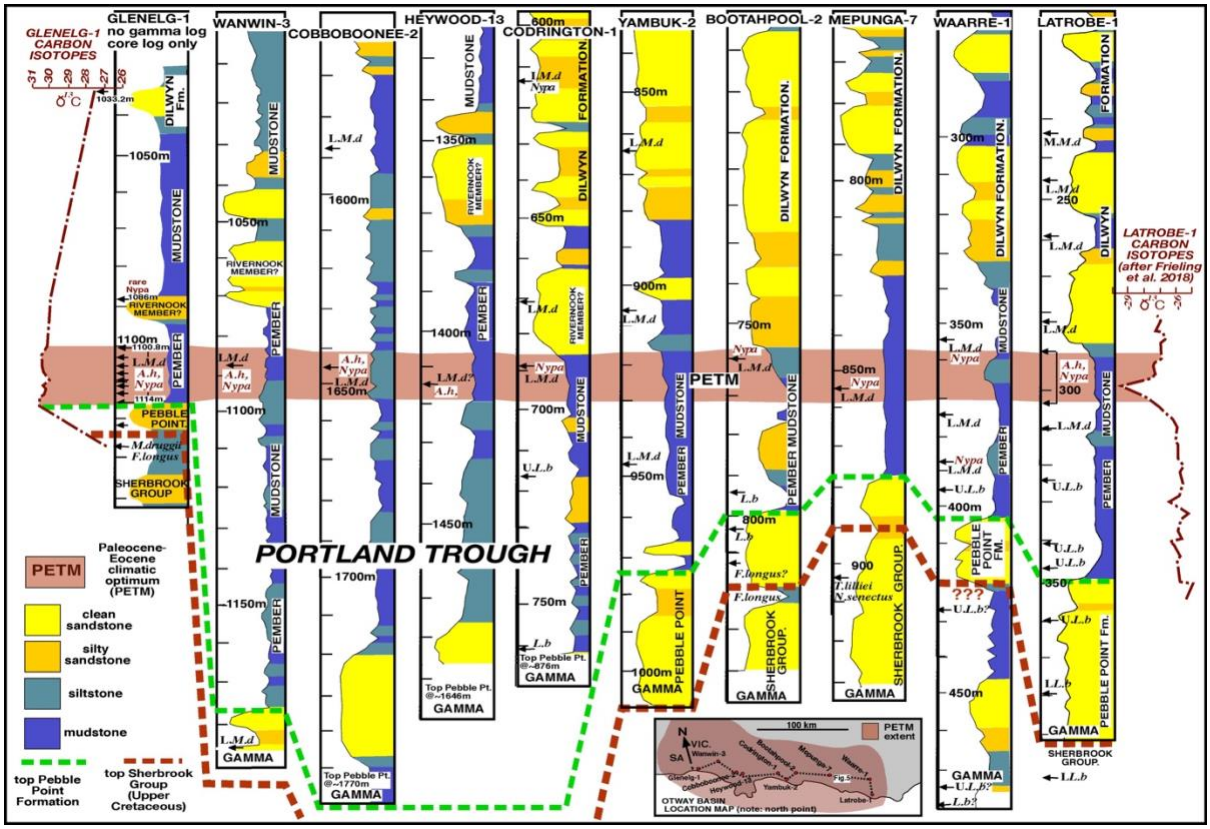


Figure 5: West to east gamma log cross section across the Otway Basin showing palynology dates and main facies around the PETM for about 100m below and ~100m above the PETM-aged strata. The PETM, aligned with a combination of carbon isotope data (Glenelg-1 and Latrobe-1) and biostratigraphy, is shown by the horizontal pink band which provides an approximate base line. Depths are in well depth (meters) below Kelly bushing (mmd). The palynology ages from cores (mostly) are located by the thick black arrows with the palynology ages determined by Charles et al. 2019. CIE results shown for Glenelg-1 (this paper) and Latrobe-1 (from Frieling et al 2018), see Figure 8 for details in Glenelg-1. Top Pebble Point Formation boundary shown by thick dotted green lines; Thick dotted red lines show where top Sherbrook Group (Upper Cretaceous) where known. For location of section see Figure 6.

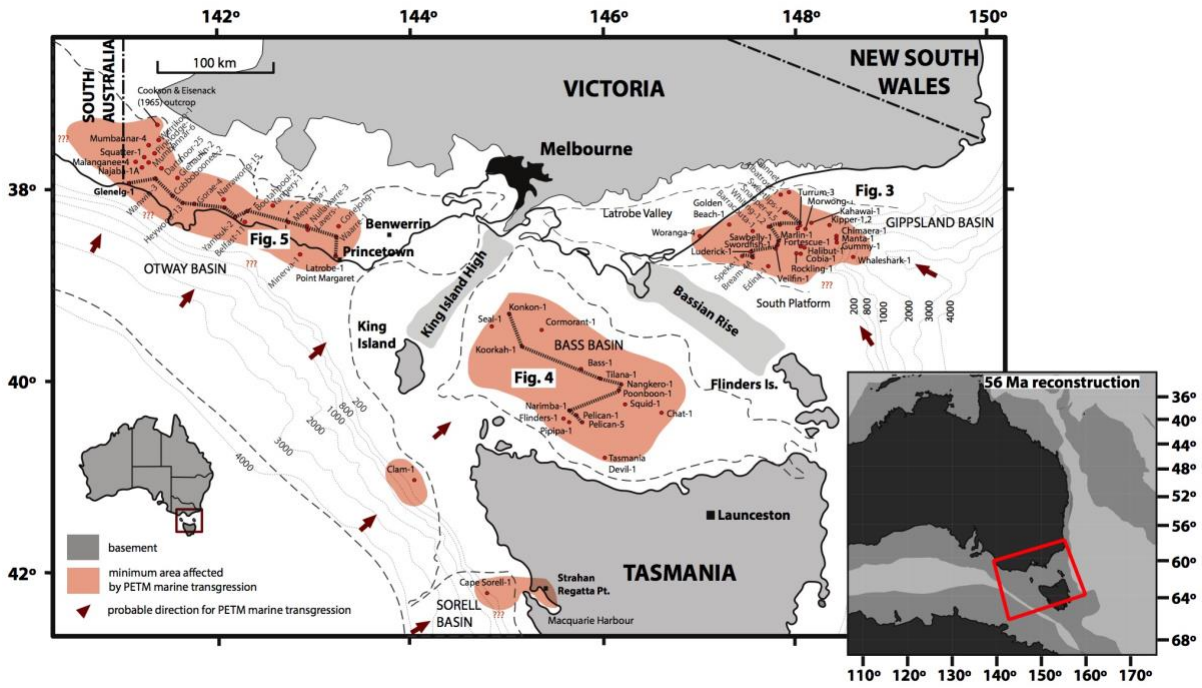


Figure 6. Summary location map for figures 3, 4 & 5 cross-sections covering the main SE Australian basins. The extent of occurrences of *Nypa* with the dinoflagellate *Apectodinium hyperacanthum* is shown by the pink/orange areas, and is taken to indicate the extent of the *Apectodinium hyperacanthum* Zone-PETM transgression. Their occurences in western Tasmania are generalised as here the extent is limited to only a few wells and bores. Suffice this represents the furthest south extent for the Australian mainland. The lines of cross-sections for each basin are shown by the dotted lines. Inset shows the reconstruction for the paleogeographic position for the Australian-Antarctica area at 56 Ma made with GPlates using the reconstruction of Seton et al. (2012). The area for the main diagram is shown by the red box.

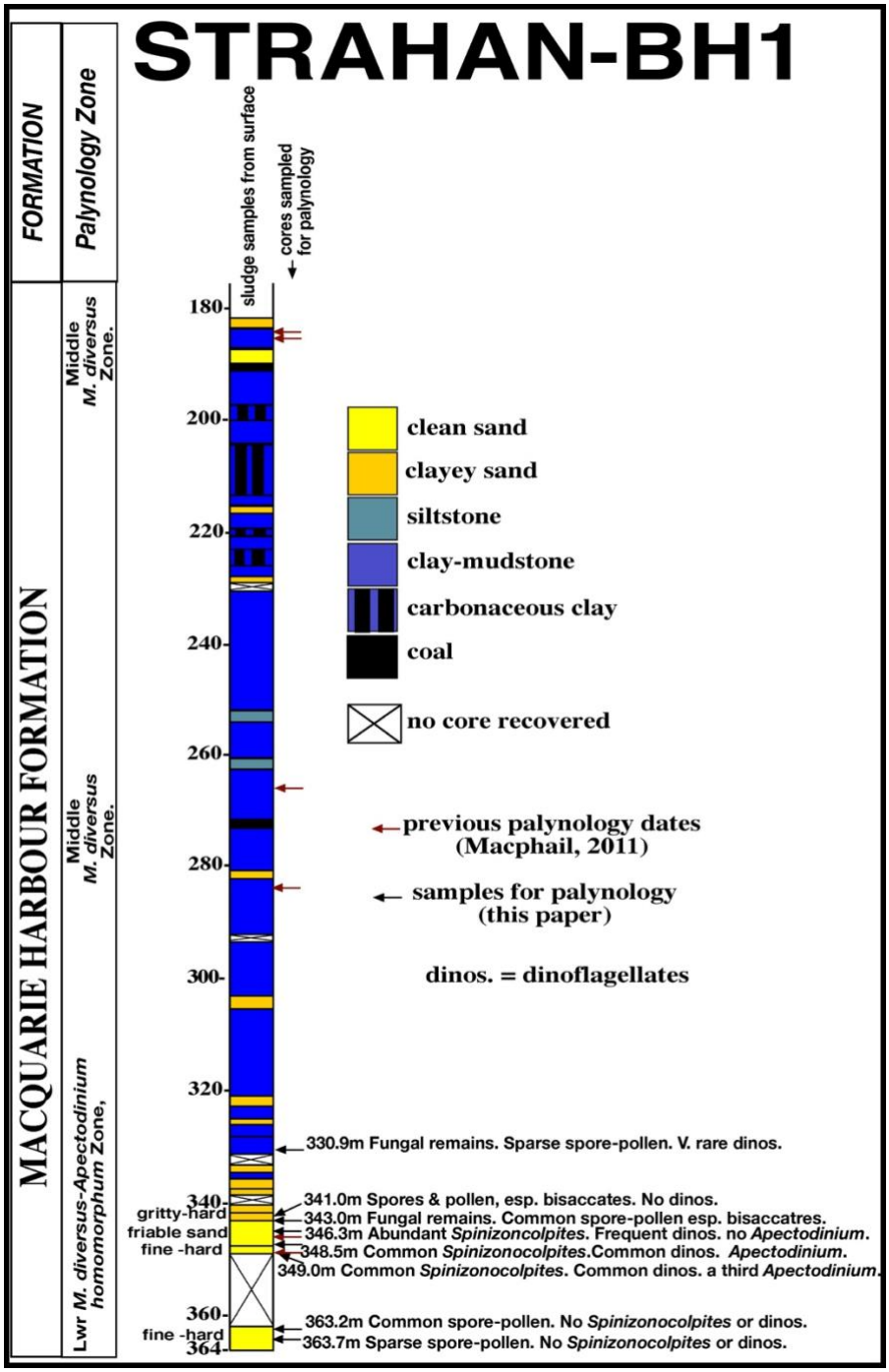


Figure 7. Palynology results from samples from Strahan-BH1 drilled near the known outcrops of the Port Macquarie Formation at Strahan in SW Tasmania. In these outcrops macrofossils and microfossils of *S. prominatus* have been recovered (Pole & Macphail, 1996; Carpenter et al. 2012; Macphail, 2011).

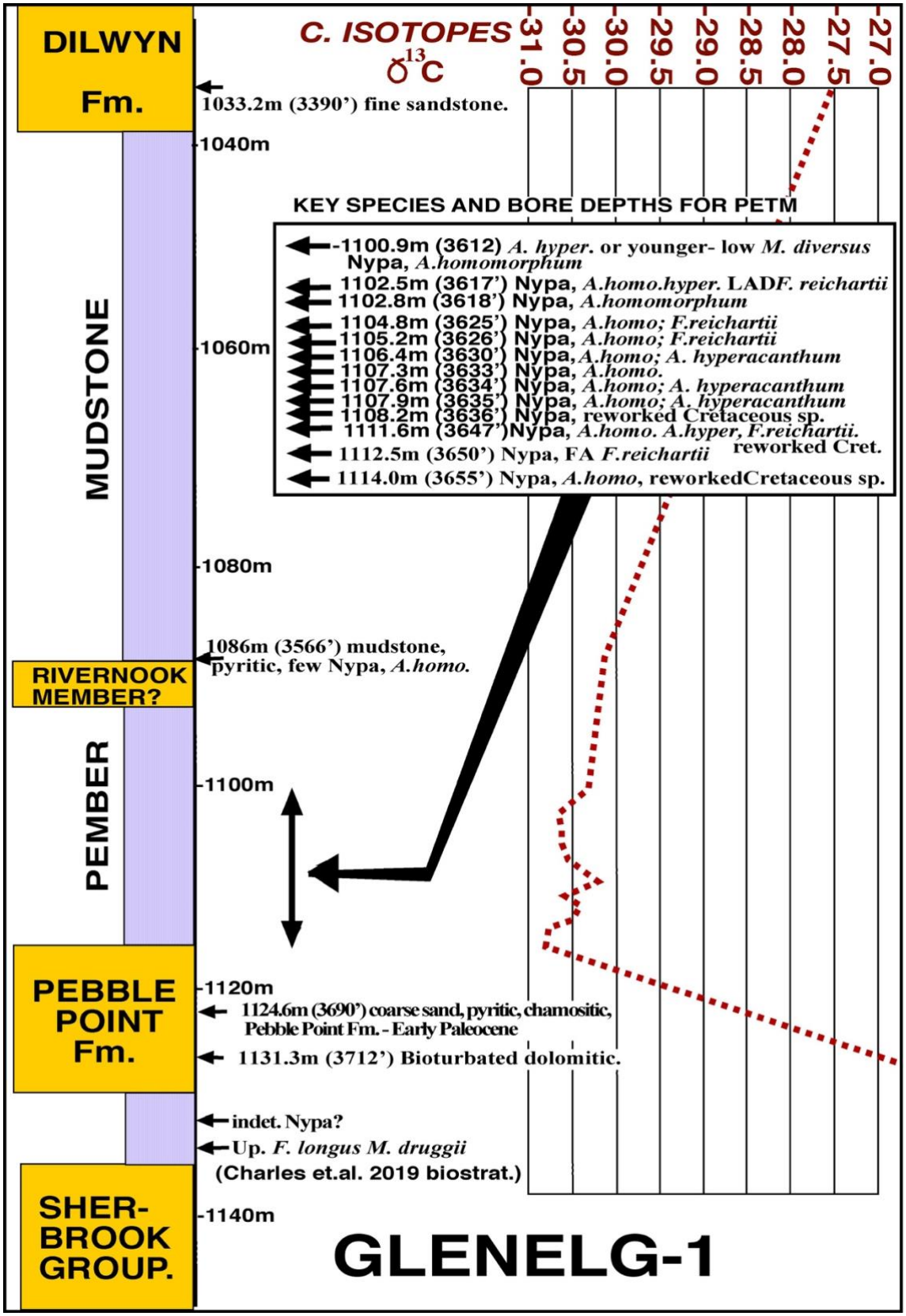


Figure 8. *Apectodinium hyperacanthum* and Nypa occurrences in samples from Glenelg-1 together with results of carbon isotope analysis (dotted red line). Abbreviations include: *A. hyper* = *A. hyperacanthum; hyper* = *hyperacanthum; A. homo* = *A. homomorphum;* FA = first appearance; FMT.N = formation; LAD = last appearance datum; sp = species.

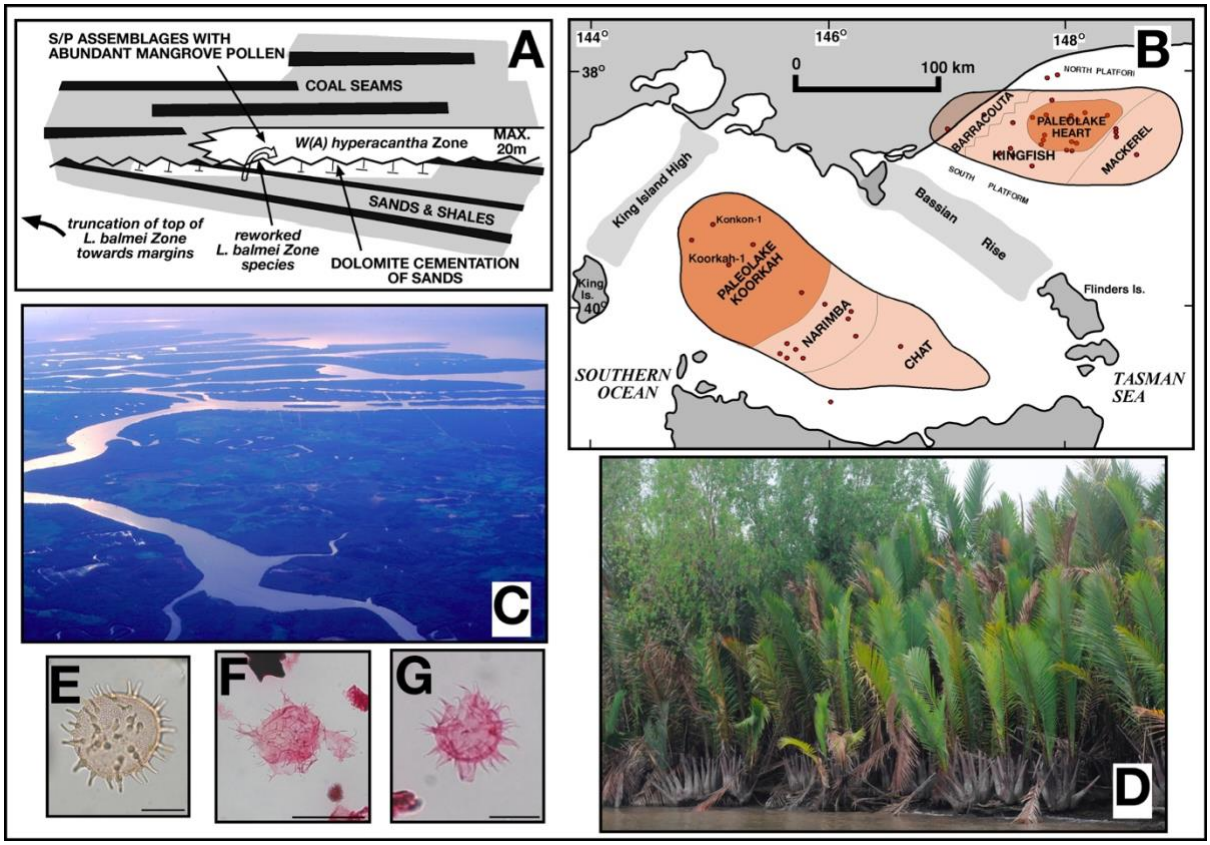


Figure 9. Paleoenvironment models for the PETM in SE Australian basins. 9A; Partridge (1976) model for an angular unconformity prior to deposition of transgressive *W (A). hyperacanthum* Zone. Note cementation and reworking of top *L. balmei* Zone beds. 9B; Conceptual palaeogeographic map of the Bass and Gippsland Basins for the Late Paleocene (after Partridge, 2002c). The PETM transgression is pictured flooding these basins from the SE for the Gippsland Basin (into 'Palaeolake Heart') and from the West into the Bass Basin (into 'Palaeolake Koorkah), (for paleogeographic reconstruction see fig. 6 inset). 9C; An oblique aerial view of a modern analogue for the PETM in SE Australia - the Mahakam Delta looking northward (after Moore 2015). 9D; Mangrove *Nypa* palms along the banks of the Mahakam River (after Moore, 2015). 9E; *Spinizonocolpites prominatus* (Strahan-1, 348.5m, scale bar 20 um). 9F; *Apectodinium hyperacanthum* (Glenelg-1, 1106.4m, 3630'. Scale bar 50 µm). 9G; *Florentinia reichartii* (Glenelg-1 (1104.8m, 3625'. Scale bar 20 µm).

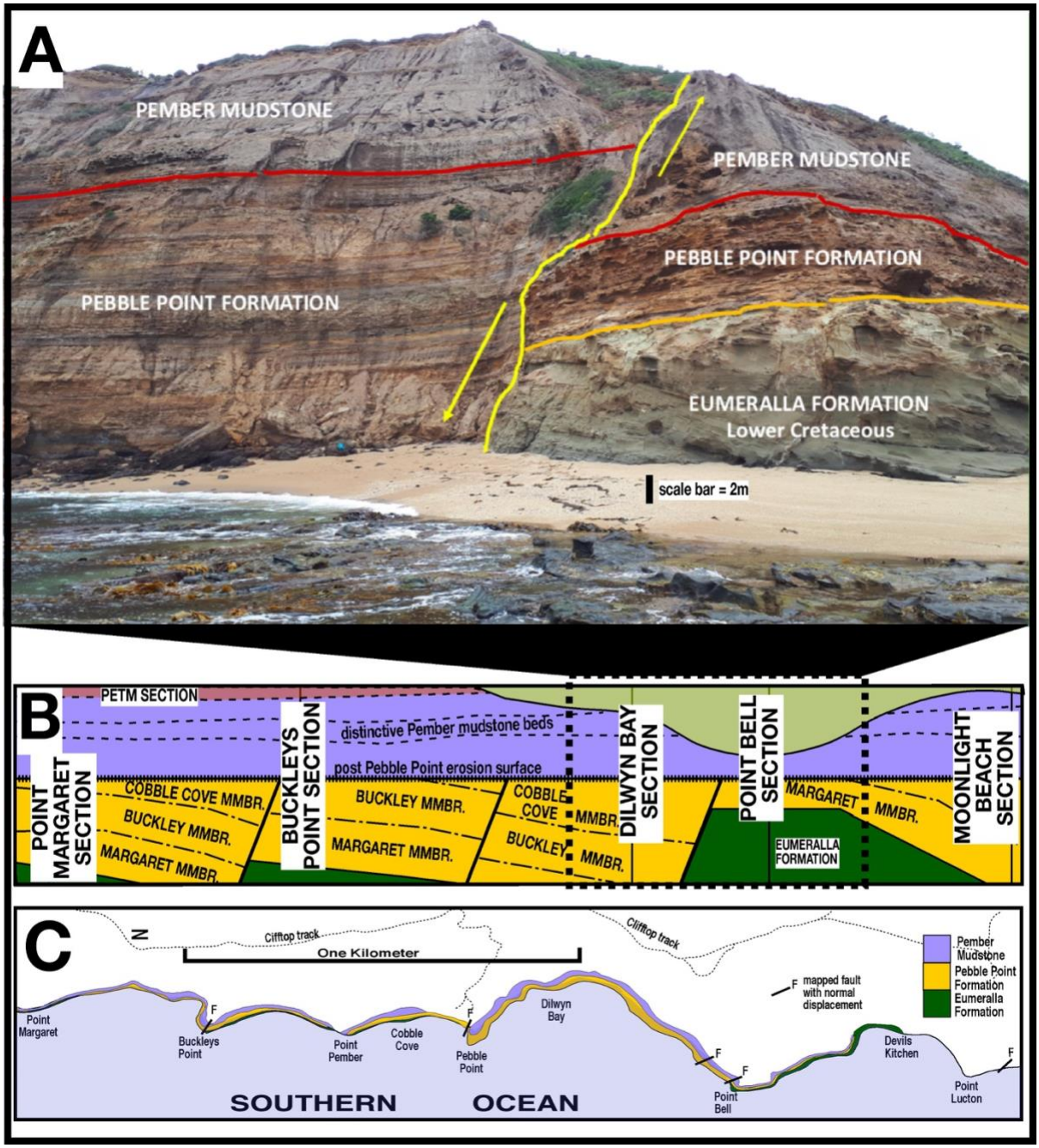


Figure 10. Faults in the Dilwyn Bay section east of Princetown, suggesting erosion along the top of Pebble Point Formation prior to Pember Mudstone deposition. 10A; Photo of Dilwyn Bay outcrops taken from offshore. The interpreted sequence of events is i) deposition of Pebble Point beds; ii) hiatus in sedimentation and normal faulting to Pebble Point beds; iii) marine planation removes youngest beds of Pebble Point across uplifted blocks; iv) unfaulted Pember Mudstone smoothes over the faulting; v) reverse movements on faults during Miocene inversion. 10B; Measured sections along the Princetown cliff sections between Point Margaret and Moonlight Beach adapted from Baker (1950, 1953) and Keating (1993) showing disposition of beds before Miocene inversion faulting. The top of Pebble Point Formation is used as a base line which illustrates the variable erosion to the upper beds (Cobble Cove and Buckley Members) of the Middle Paleocene (Middle-Late *L. balmei* Zone) Pebble Point Formation. Note that outcropping PETM beds at Point Margaret can be extrapolated east to Cobble Cove. Further east in Dilwyn Bay the Pember sections do not extend up to the PETM level due to young cover and recent erosion. 10C; Locality map between Point Margaret and Point Lucton showing outcrops of Otway Group, Pebble Point Formation and Pember Mudstone. Location of various ENE striking normal faults that effect Pebble Point thicknesses also shown as adapted from Baker (1950, 1953) and Keating (1993).