Marked Depositional and Organic Facies Change across the Paleocene-Eocene in the Gippsland Basin, Australia.

Greg Smith
Curtin University
Earth & Planetary Sciences
Kent Street, Bentley, WA
gregory.c.smith@curtin.edu.au

Simon Lang
University of Western Australia
School of Earth Sciences
35 Stirling Highway, Perth, WA
simon.lang@uwa.edu.au

Adam Charles
MGPalaeo
Palynologist
5 Arvida St, Malaga, WA
adam.charles@mgpalaeo.com.au

Chris Watts
MGPalaeo
Geologist, Data Scientist
5 Arvida St, Malaga, WA
chris.watts@mgpalaeo.com.au

Simon Horan
CarbonNet, Resources Branch
Dept. Jobs, Precinct & Regions
1 Spring St, Melbourne, Victoria
simon.horan@ecodev.vic.gov.au

Nick Hoffman
CarbonNet, Resources Branch
Dept. Jobs, Precinct & Regions
1 Spring St, Melbourne, Victoria
nick.hoffman@ecodev.vic.gov.au

SUMMARY

Significant organic facies change occurred in the Latrobe Group during the Eocene to Oligocene transition (EOT) in the Gippsland Basin, controlled by climate, basin tectonics and sedimentary facies. The transition from more subdued progradational-transgressive tracts in the Paleocene-Early Eocene, to markedly westward backstepping transgressive systems tracts in Middle-Late Eocene, is documented by integrated sedimentary, palynology and organic petrology studies of recent extensive coring tied to seismic. The present-day nearshore area was dominated in the Palaeocene and Early Eocene by alluvial plain/upper delta plain facies, behind a barrier system located 50-70km further east near Nannygai-Luderick. Rapid transgression by the middle Eocene transformed the area into coastal plain/marginal marine facies behind a barrier system which had moved to near the Barracouta gas field, with the barrier system backstepping further west into the onshore area by the Oligocene.

The organic-rich facies in Paleocene-Early Eocene upper delta plain facies mainly developed in abandoned channels or between channel belts in back-levee swamps and are thin, discontinuous and prone to splitting due to channel switching and splay avulsion. The coals are mainly durains with high telovitrinite:detrovitrinite, a gelified detrovitrinite groundmass, high inertinite from seasonal wet-dry conditions, clays and low pyrite.

The middle-late Eocene organic facies include thick ombrogenous peats developed in lower coastal plains during the late transgressive/aggradational phases. They comprise upward drying clarain lithotypes with moderate telovitrinite:detrovitrinite and upwards increasing perhydrous liptinite, developed in extensive peat swamps adjacent to but isolated from the main distributary channel belts. More distal back-barrier marshes form thinner clarain and cannel peats with perhydrous high detrovitrinite:telovitrinite and liptinite (14-26%) and together with back barrier lagoon mudstones are very good source rocks.

The abrupt change from inertinite rich to poor coals over the EOT results from the interaction of rapid and pronounced changes in climate, flora and depositional facies.

Key words: Paleocene-Eocene, organic facies, source rocks.

INTRODUCTION

The sedimentary record in the Gippsland Basin, Australia (Figure 1), records the marked changes in depositional environments and their contained organic matter over the Paleocene to Oligocene (Figure 2). This includes the Late Paleocene to Early Eocene thermal maximum (PETM) and the rapid global cooling over the Eocene to Oligocene transition (EOT). The global climate changed over this period from hot and wet greenhouse conditions with a nadir in the PETM, to much colder and drier icehouse conditions by the Oligocene (Zachos *et al.*, 2001; Barnet *et al.*, 2019). Various theories are proposed for the PETM while the cooling is ascribed to the onset of Southern Ocean circulation about 36Ma (Scher *et al*., 2015). The effects of plate tectonics on the Gippsland Basin also were changing significantly with cessation of Tasman Sea spreading ending widespread normal growth faulting and convergence of the Australian and Pacific plates transitioning the basin to a compressional regime (Yang & Smith, 2022).

A major transgressive phase occurred in the Gippsland Basin from the Paleocene into the Oligocene and a large number of papers have documented the resulting considerable sedimentation changes (Brown, 1985; Johnstone *et al.*, 2001; Holdgate & Gallagher, 2003; Mahon & Wallace, 2021; Yang & Smith, 2022). Various theories or causes have been proposed for this transgressive phase including changes in subsidence, sedimentation, uplift, sea level or accommodation space. Recently a numerical basin-wide study has shown that it results from the interplay of many of these factors including climate and the influence of each changed with time (Yang *et al.*, 2022).

In the Gippsland Basin the literature focuses on the sedimentation and structural changes that are involved in this basinwide evolution and for the PETM the literature focuses on the marine records for an understanding of the temperature and CO_2 changes. Very little has been published on the remarkable changes in the organic matter components (the organic macerals) within the coaly sediments, which is just as substantial and less understood.

The palynology and evolution of the flora are well documented (Helby *et al.*, 1987; Hill, 1994; Sluiter *et al.*, 1995; Partridge, 1999; Greenwood *et al.*, 2000b; Martin, 2006; Korasidis *et al.*, 2017; Korasidis *et al.*, 2019) especially with regard to the palynological changes from the Middle Eocene to Miocene in the onshore thick brown coals. However, the pollen and spores from the Paleogene are not confidently related to plant species and many are now extinct. The macro-flora have also been studied and they provide a good local floral reconstruction without a regional wind-borne signal, though they mainly rely on outcrops of the onshore Eocene to Miocene coals and coaly sediments (Christophel & Greenwood, 1989; Hill, 1994: Greenwood *et al.*, 2000a; Greenwood *et al.*, 2000b; Reichgelt *et al.*, 2022). Nevertheless, it is clear the floral communities should have reacted to these global climate changes.

The corresponding organic petrology has been documented by Smith (1981; 1982) who recognised a major change in the maceral composition in both the Bass and Gippsland basins but did not speculate on its origin. The relationship of the maceral composition to the organic geochemistry was studied in detail by Kim (1987, unpublished). The organic geochemistry of the source rocks has been extensively researched for the Latrobe Group in general (Burns *et al.*, 1987) but very little has been related to the organic maceral composition or to the palynological changes (Abbassi *et al.*, 2016). The organic petrological changes are even more remarkable given they did not appear to be affected significantly by the global extinction event at the end of the Cretaceous and start of the Paleocene (the K-P event) but were affected more by the PETM. Why was this so?

This paper considers these changes given the results of the detailed core, organic petrological and palynological study of the organic matter over the Paleocene to Oligocene phase in the Gippsland Basin based mostly on extensive coring in the Gular-1 well drilled offshore Gippsland in late 2019. The results are integrated with the depositional facies interpreted from the logs and core in Gular-1 (Hoffman *et al.*, 2021) and with data from many other wells and seismic obtained in the basin, most of which are now on open file from the Australian and Victorian government geoscience sites (National Offshore Petroleum Titles, n.d.; Victoria State Government, n.d.).

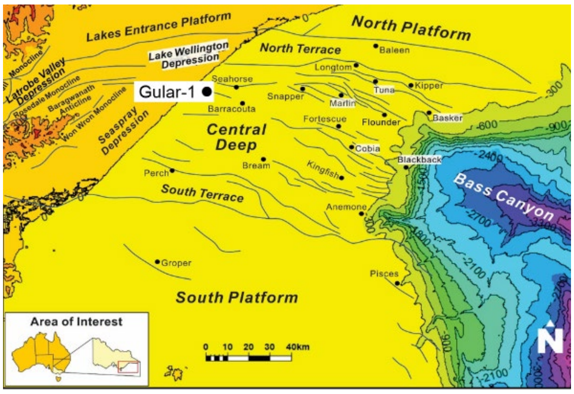

Figure 1. Location Map for Gular-1.

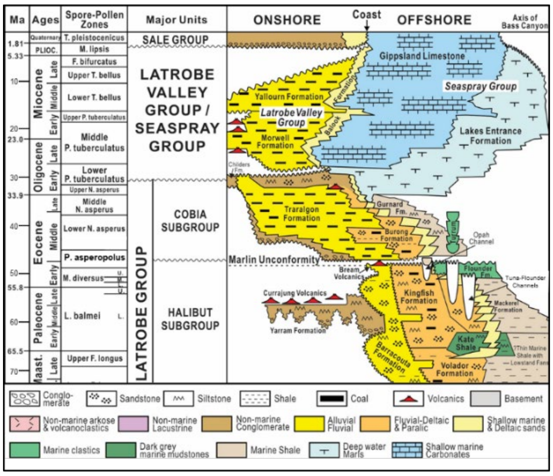

Figure 2 Gippsland Basin Cainozoic stratigraphy (based on Yang & Smith, 2022).

METHODS

The stratigraphy, lithofacies and depositional environments in Gular-1 discussed below are based on interpretation of the wireline logs, cores and cuttings samples logged and analysed by the authors. High quality 3D seismic data and numerous offset wells are also available to place the Gular-1 well data in regional context. The cores were logged in detail including the coals to assess the depositional environments and guide the sampling. The palynology samples included 12 from the conventional core augmented by 8 cuttings samples. MGPalaeo processed and analysed the samples quantitatively, with the first 100 specimens in each sample counted (where possible) and subsequent species recorded as present. Palaeoenvironment assessments are based on proportions of marine microplankton (saline algae) to non-marine spores, pollen and freshwater algae, and marine microplankton diversity. Age assignments follow Paleocene-Eocene palynological zonation schemes for Gippsland and Otway Basins (Partridge, 2006).

The coal samples used in this study were all from the Gular-1 conventional cores. They were prepared as duplicate resin mounted blocks polished using diamond lapping machines down to half micron for the optical microscopy and less for SEM blocks. The organic maceral analysis followed the ICCP 1994 systems and the ASA (1986, 1996); and for reflectance analysis according to ISO/ICCP standard methods (ISO 7404-5:2009). The organic petrology used a Leitz Orthoplan research microscope equipped with a Hilgers Fossil Diskus digital PC reflectance recording system. The samples were assessed under incident white light (filtered to 546nm) and fluorescent blue light excitation, using oil immersion lens with total magnification x500 up to x1250.

Mineral, organic and porosity analyses on the coal samples were performed using the TESCAN Integrated Mineral Analyzer (TIMA) in the John de Laeter Centre (JdLC) at Curtin University. This is an FESEM-based automated analysis of elements that are automatically classified into the main mineral species based on four EDS, SE and BSE detectors, with the analyses run to obtain 1000 counts at a resolution of 1-2µ.

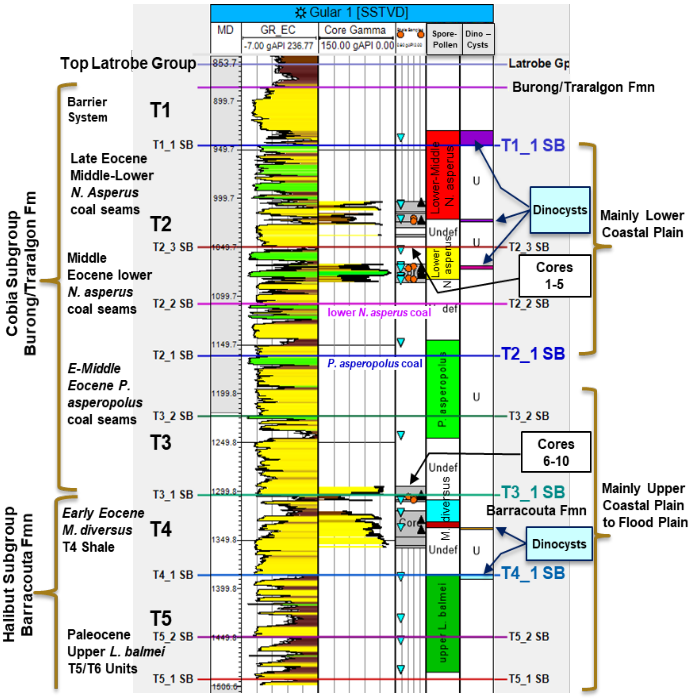

Figure 3 Gular-1 Well log section with the main lithologies (gamma ray, core gamma, cored intervals, palynological , micropalaeontological zones). The T units follow nomenclature of Wallace *et al*., 2018). Only main parasequence sets shown. Coals coloured green.

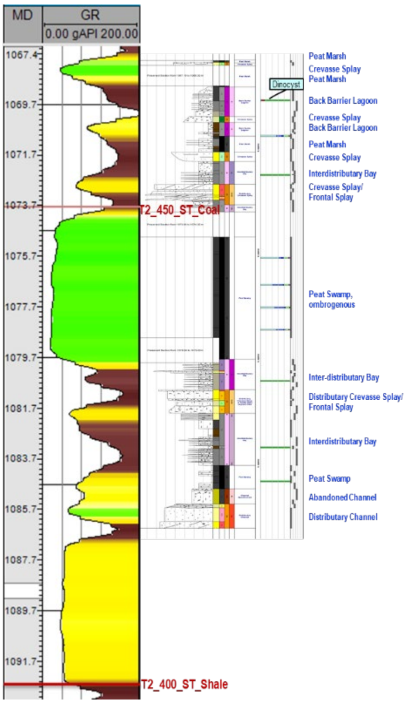

Figure 4. Gular-1 cored section in T2 unit showing basal distributary sandstone upward fining through interdistributary bay mudstones into thick T2 coal seam. Single parasequence between shale/coal tops T2_400 and T2_450.

DEPOSITIONAL FACIES

Stratigraphically, Gular-1 drilled through an upper marine section and into the Latrobe Group where the section is probably Late Eocene (middle-lower *Nothofagidites asperus* palynozone*)* down to Late Paleocene (upper *Lygistepollenites balmei* palynozone) (Figure 3). The upper units in Gular-1 (T1 to T3 equivalents of Holdgate & Sluiter, 2021) are referable to the Cobia Subroup sediments known onshore and inshore as the Traralgon Formation and further offshore as the Burong Formation (Bernecker & Partridge, 2001). The lower units (informally referred to here as T6-T4) belong to the Halibut Subgroup and upper Barracouta Formation (Bernecker & Partridge, 2001). The Cobia and Halibut Subgroups are commonly separated by a disconformity/unconformity in offshore wells (the Marlin unconformity) and in some onshore wells below the T2 Seam (Holdgate & Smith, 2018), which was accompanied by waning of extensional faulting and a significant downward shift of sedimentation characterized by non-deposition and erosion of upper *M. diversus* and or *P. asperopolus* aged strata (Bernecker a& Partridge, 2001; Johnson *et al*., 2001). There is a noticeable change in the coal type across this boundary (Smith, 1982). In Gular-1 this may be represented by the T3_1 SB sequence boundary (Figure 3).

A number of large scale retrogradational sequences below and especially above this sequence boundary are recognizable on the logs and in the core. Together they comprise a series of stacked parasequence sets, each showing lateral lithofacies change within from more proximal to more distal depositional environments. The coals and coaly mudstones, which are the focus of this paper, occur mainly in the coastal plain or deltaic depositional environments, where typical parasequence sets or parasequences comprise a vertical upward fining sequence, schematically illustrated in Figure 4 and summarised below (here between two transgressive parasequence tops marked ST):

a) basal channel belt sandstone, fluvial or distributary, single or multi-storey, fining upwards, with channel abandonment or interfluve overbank mudstone fill, may be overlain by local thin (topogenous) peats,
b) overlain by mudstones, commonly heterolithic (thin beds of claystone, silt, very fine sand) interbedded with thin splay sandstones, can include marginal marine interdistributary bay and intertidal deposits,
c) overlain by a carbonaceous mudstone or thick coal at the top (mostly topogenous or ombrogenous in long lived peats) the top of which may represent an emergence surface (used to define parasequence tops ST).

This apparently fining up sequence is typical of a coastal plain coal measure parasequence in a retrograde setting, where the coastal plain sediments aggrade to fill the accommodation space behind a barrier system and shoreface facies, which in contrast exhibit the characteristic coarsening up marine facies profile, with starved marine mudstones basinward. These parasequences are commonly combined into parasequence sets by addition of multi-storey sandstones and backstepping distributary systems with overlying mudstones and thin coals. These then pass upwards into additional marginal marine sediments, with overlying thicker coals that can regressively build out over the muds and show the thickest development behind stable coastal barriers, as can be seen in Gular-1 (Figure 3). The stacked retrogradational parasequence sets in the Eocene seen in Gular-1 and other nearby wells result from the interplay between waning precipitation, hinterland uplift, sediment supply and subsidence relative to episodically falling and rising sea levels, which is consistent with the Eocene basin history in Gippsland Basin (Yang *et al*., 2022; Yang & Smith, 2022).

Paleocene – Early Eocene (Halibut Subgroup)

Paleocene

An open marine strandline had been established in east Gippsland during the Campanian behind which alluvial, fluvial and deltaic sediments accumulated (Yang & Smith, 2022). In the Paleocene this had developed into a well-established complex coastal plain system behind a barrier system orientated NE-SW from the Basker-1 region to near the Kingfish field and Helios-1 area (Johnstone *et al*., 2001; Yang & Smith, 2022). The Paleocene to Early Eocene section (*L. balmei* to lower *M. diversus* palynozones) contains four main depositional sequences, recognizable on seismic and in well logs (Figure 3, lowest T6 sequence not penetrated). They comprise a set of regressive-transgressive sequences each back-stepping a few km behind a newly formed barrier system (Mahon & Wallace, 2021).

Gular-1 is located some 70km inland from the barrier system. Here, the Paleocene (upper *L. balmei)* parasequences comprise a channel belt of stacked thin fining-upwards sandstones at the base, that pass into overlying mudstones and thin coals near or at the top, which are immediately overlain by either very thin mudstones or the next basal sandstone (Figure 3, T5 sequence penetrated). These fluvial channel belt sands and overbank sediments were deposited in an upper coastal plain, with sinuous channels that were undergoing autocyclic channel switching on a fluvial floodplain. The thin coals represent transitory interfluve or floodplain lake peats, developed between or adjacent to the channels. Palynological samples in the mudstones record non-marine assemblages. The deepest sample contained rare *Botryococcus spp*., which is a freshwater to brackish water algae, probably in a floodplain lake with episodic marginal marine influence. The mudstone at the top of the upper *L. balmei* parasequence had traces of two dinoflagellates and a foraminiferal test lining, suggesting flooding by an interdistributary bay or back barrier lagoon.

Early Eocene

The overlying Early Eocene lower to middle *M. diversus* subzones sequence truncates the T5 sequence below at the T4_1 SB (Figure 3). It contains two main parasequence sets, each comprising thick multi-storey stacked channel belt sandstones that fine and thin upwards towards the top into mudstones and coals. The lower set includes channel belt point bar sandstones, with very thin levee or abandoned channel sediments, deposited in a floodplain to upper coastal plain (Figure 5, left). They are erosionally overlain by fining up distributary channel belts, which represent autocyclic channel switching, as the distributary bayhead delta back-steps over the more fluvial channel belt sandstones.

The upper T4 parasequences contain several thin channel–levee cycles at the base comprising stacked distributary channel belts, that fine upwards into levees and overbank with some levee bank slumping, reworking of channel tops and rare indications of micro-tidal influence (Figure 5, middle). The heterolithic mudstones in the reworked top contained abundant spore-pollen but with traces of acritarchs (undifferentiated leiospheres and algae) and a dinocyst (*Cerodinium obliquipes*, inferred to tolerate a wide salinity range). These beds are overlain by fluvial channel belt sand, thick non-marine bioturbated mudstones, a seat earth and a thin durain coal at the top (Figure 5, right). Palynological samples in the uppermost mudstones contained a non-marine spore-pollen assemblage with rare *Botryococcus* spp.

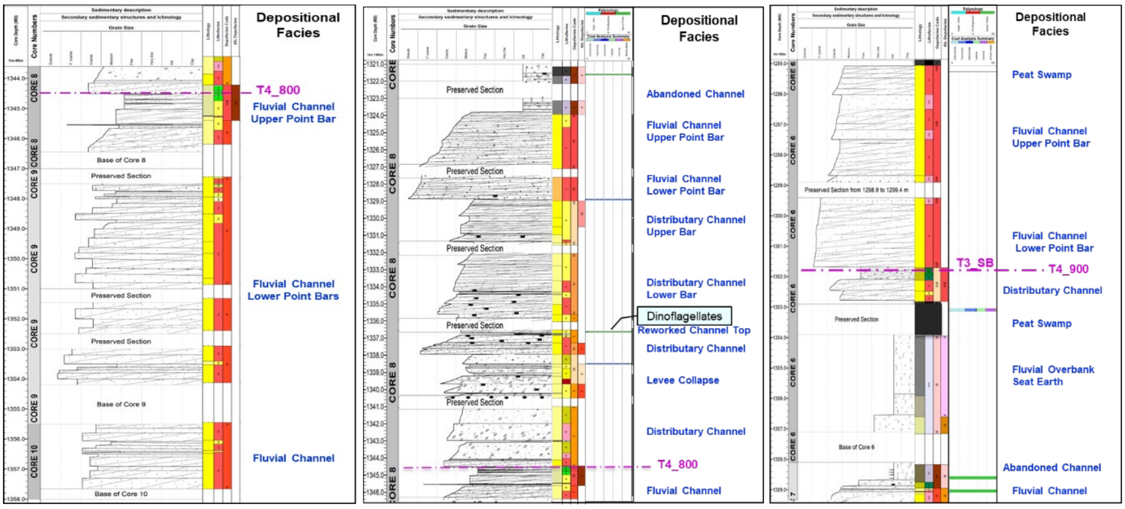

Figure 5. Summary log showing fluvial channel point bars in Cores 8, 9, 10 (left). Transition into distributary channels and fluvial channels in Core 8 (middle). Transition back from distributary channel/overbank and durain coal in upper part of T4 squence at T3_1 SB sequence boundary into overlying Fluvial channels in lower part of T3 sequence Core 6 (right). Note logs not to same vertical scale.

Early-Middle Eocene (*P. asperopolus* zone)

The overlying mainly *P. asperopolus* T3 sequences intersected in Gular-1 comprise two regressive-transgressive sequences that are mostly aggradational (Figure 3). The basal units, which were cored, erosionally overlie the older sequences (T3_1 SB; Figure 5 right). The T3_1 SB may represent the widespread base level drop or disconformity/unconformity recognised further to the east in the offshore basin (eg. Johnstone *et al.*, 2001) or substantial switching of the main channel belts after the last retrograde transgression to the west. The T3 sections comprise multi-storey channel belt sandstones which have prograded out over the more distal facies below, but change upwards to aggradational stacking patterns, and pass into mudstones and coals at the top which thicken upwards (Figure 3). The thick coals are laterally extensive and able to be correlated over a wide area (the 10.5m thick coal at ~ 1165mMD is probably the *P. asperopolus* coal recognised in the Barracouta Field (Roder & Sloan, 1986). Palynological samples analysed from the thick interbedded mudstones yielded diverse spore-pollen assemblages, including rare *Botryococcus* spp., consistent with non-marine overbank or floodplain lake lithofacies.

Middle Eocene (lower *N. asperus* zone)

Thick fluvial channel sandstones directly overlie the *P. asperopolus* coal seam and this T2_1 SB sequence boundary is also recognizable in the Golden Beach and Barracouta fields indicating it is of wide extent (Figure 3). It appears to mark the final downward or lateral shift of the main channel belt in the area and the turning point to the dominance of the subsequent transgressive sequences. The basal multi-storey channel belt sandstones have aggradational stacking patterns, the overlying mudstones have the last non-marine palynological assemblages, and thick, extensive coal seams are developed at their top. The parasequence sets can be recognized in the adjacent Golden Beach-1A well and into the nearby Barracouta field (the coal at ~ 1115mMD is probably the lower *N. asperus* coal of Roder & Sloan, 1986) and is probably equivalent to the lower *N. asperus* onshore Traralgon 3 seam (Holdgate & Sluiter, 2021).

The overlying sequences (T2_2) record the change from upper to lower coastal plain, with the basal units representing fluvial channel belt sandstones becoming distributary channel sandstones, with interdistributary bay mudstones, splay sandstones and thick coal seams. In the upper sequences thin tidal flats and back barrier lagoonal sediments occur while micro-tidal features and bioturbation become more common. The basal units contain non-marine palynological assemblages but the upper mudstones and claystones in interdistributary bays and back barrier lagoons increasingly have characteristic syneresis cracks, low diversity dinocyst assemblages and *Botryococcus* spp. indicating saline marginal marine conditions (Figure 3).

The thick coal seams include a 6m seam (cored from ~1073.8-1080.0mMD) that is a clean clarain- vitrain coal (Figure 4) and is probably equivalent to the T2B seam (Holdgate & Sluiter, 2021). Three palynological samples from the mudstones below all had non-marine spore-pollen assemblages. The thick peat swamp is overlain by several cycles of interdistributary bay mudstones, which also yielded non-marine spore-pollen assemblages, into which intermittent crevasse splays were deposited, re-colonized by thin peats. These pass upwards into mudstones and claystones in back barrier lagoon/interdistributary bays that had syneresis cracks, a low diversity dinocyst assemblage (~9%) and *Botryococcus* spp., probably representing the maximum flood of the transgressive phase for this parasequence. The logs show that subsequently the peats re-established over the interdistributary bay muds with development of an upper 9m thick seam (Figure 3). This coal seam has a much higher retained moisture content than the lower coal seam and is overlain by thin mudstones which have a non-marine spore-pollen assemblage, together suggesting the upper coal seam represents a regressive phase with significant elapsed time between the two. That is, the two seams represent the lower transgressive and upper regressive splits of one seam that should form one thick T2 seam updip (Diessel, 1992).

Late Eocene (middle *N. asperus* zone)

The overlying upper T2 sequences (above T2_3 SB) repeat this upward retrogradational stacking pattern. The basal sands represent fluvial channel belts becoming distributary channels at the top and the succeeding sandstones are dominated by distributary channels, frontal splay and splays into the bays which were cored (Figure 3). These represent bayhead deltas comprising heterolithic fine sandstones and mudstones with multiple thin cyclic or rhythmic ripple cross-laminated bedsets and mud-drapes, which are highly bioturbated (*Palaeophycus, Thalassinoides, Planolites*, muddy *Arenicolites*). Each parasequence fines up through mudstones, mainly interdistributary bay facies with spore-pollen assemblages towards the base, that include dinocysts higher in the section where thin lagoonal mudstones occur at some levels. The coals seams become more prevalent and thicker as the barrier systems move closer to the Gular-1 area. The thick coal seams are probably clean clarain-vitrains representing ombrogenous swamp peats. A petrographic core sample of the thin coals had high detrital liptinite and mineral matter contents including pyrite which is more typical of swamp marsh peats adjacent to the back barrier lagoons. The uppermost T2 parasequence is capped by a thick coal seam developed over bay mudstones (Figure 3). This coal deteriorates upwards and sulphur increases, while the porosity/free moisture decreases. Together this indicates this seam is affected by the overlying transgressive sediments either syndepositionally or post-depositionally and probably both.

The T1 parasequence (above the T1_1 SB) is more marginal marine and represents a transgressive system backstepping over the underlying coal seam. A palynological sample at 930-935mMD contains dinocysts, algal cysts and *Botryococcus* spp. with a low diversity spore-pollen assemblage mainly *Nothofagidites spp*. (wind and river borne from some distance away). The section comprises basal thin interbedded interdistributary bay and back barrier lagoonal mudstones and sandstones which thin upwards, most likely distributary frontal splays in front of the bayhead deltas. A 2m inferior coal at the top may represent a true back barrier marsh peat, which is truncated by the transgressive barrier system above (Figure 3).

ORGANIC FACIES

The extensive conventional core has allowed detailed description, sampling and analysis of the coal lithotypes and palynology of the fine-grained sediments. A summary of the maceral analyses is plotted in Figure 6. The coal samples can be separated into distinct coal types according to age, thickness, composition and facies associations. The Paleocene-Early Eocene coals in the Halibut Subgroup (*M. diversus* palynozone, at 1302.85mMD) and deeper, are vitrinite-inertinite durain coals with a very characteristic diverse inertinite population. They are very different to the younger coals sampled from the Traralgon Formation in the Cobia Subgroup (*N. asperus* palynozone coals between 1003.34mMD to 1077.68mMD) which are vitrinite-liptinite coals. These Traralgon seams also show a distinct change between the thin coals (eg. samples from 1003.34 – 1021.77mMD) and the thick coal seams (eg. samples between 1074.83-1077.68mMD). The latter are also different to the very thick Oligocene-Miocene age ombrogenous coals in the Latrobe Valley (Smith, 1982), that are almost entirely vitrains, with minor thin clarain bands, and essentially no inertinite except for rare fungal remains.

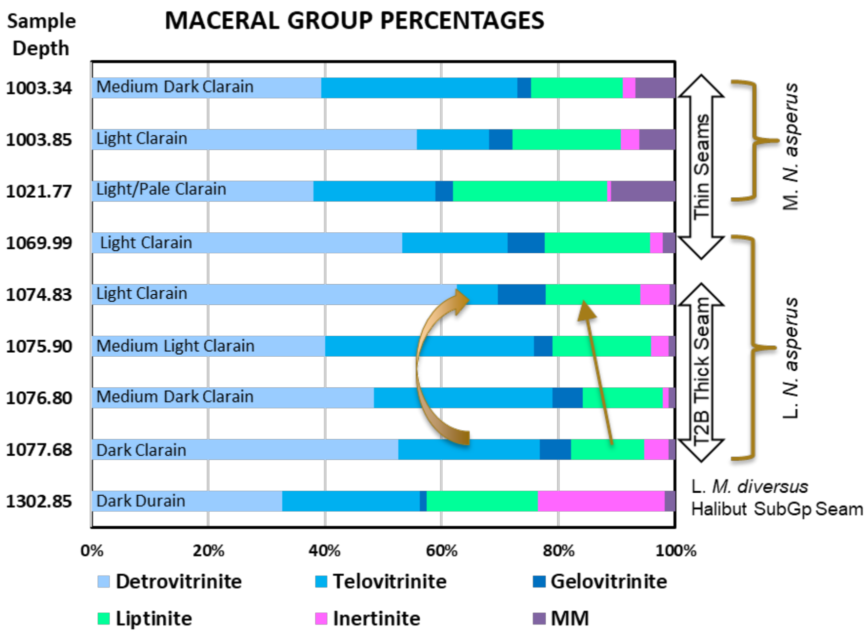

Figure 6. Percentage occurrence for the main maceral groups/subgroups in the coal samples. Note the upward change in Detrovitrinite:Telovitrinite ratio and Liptinite content between lithotypes in the thick coal seam.

Paleocene-Early Eocene

A core sample was taken from the thin coal at the top of the Early Eocene sequences in the Barracouta Formation (Figure 5, right, 1302.85mMD). It is typical of Halibut Subgroup coals and similar coals are found of that age in the Bass Basin (Smith, 1982). This coal is low rank with R_{vmax} 0.38%, poorly compacted, relatively soft with high porosity. Macroscopically it is dull, dark brown-black comprising thin gelified bands of clarain, durain and vitrain. Microscopically it contains bands of highly gelified Detrovitrinite (Densinite), containing liptodetrinite, sporinite and inertodetrinite, interbedded with almost equal amounts of thinly bedded Telovitrinite, commonly associated with suberinite (mainly cork tissue) and cutinite (Figure 6). The bands and elongate clasts of Inertinite comprising a diverse assemblage of mainly degrado-inertinite sub-macerals including semi-fusinite, macrinite, micrinite, fusinite, with rare funginite and pyrofusinite (Figure 7). They contain laminae with high mineral matter contents, including syndepositional clays, common early diagenetic pyrite, high organic sulphur levels, and rare fine quartz silt. They are mostly topogenous peats that were not able to sustain prolonged development of thick ombrogenous peats.

The flora remained Mesophytic (as per the Mesozoic) in the Paleocene with warm temperate rainforests dominated by gymnosperms (eg. cycads, conifers) with pteridophytes (ferns) and minor but diverse angiosperms including proteas. The Araucariaceae and Podocarpaceae pines were especially dominant (many species persisting to the present day whereas they died out in the northern hemisphere after K-P). The macrofossils record seasonal growth rings, is expected given the high latitudes, with the peat swamps being deposited on floodplains and coastal plains that were subject to wet and dry seasonal fluctuations in the water table. Many of the larger emerging angiosperms such as *Nothofagus* (southern beech) occurred outside the peat swamps in drier highland areas (Martin, 2006).

The Early Eocene had hotter conditions producing sub-tropical rainforests and high seasonal rainfall (MacPhail *et al.*, 1994; Greenwood *et al.*, 2000a; Reichgelt *et al.*, 2022). The flora included Araucariaceae, less Podocarpaceae, and increased numbers of angiosperms more typical of present day north Queensland and New Guinean flora, including Euphorbiaceae (herbs, shrubs, small trees), Sapindaceae (soapberry family), Casuarinaceae, ferns and mangroves.

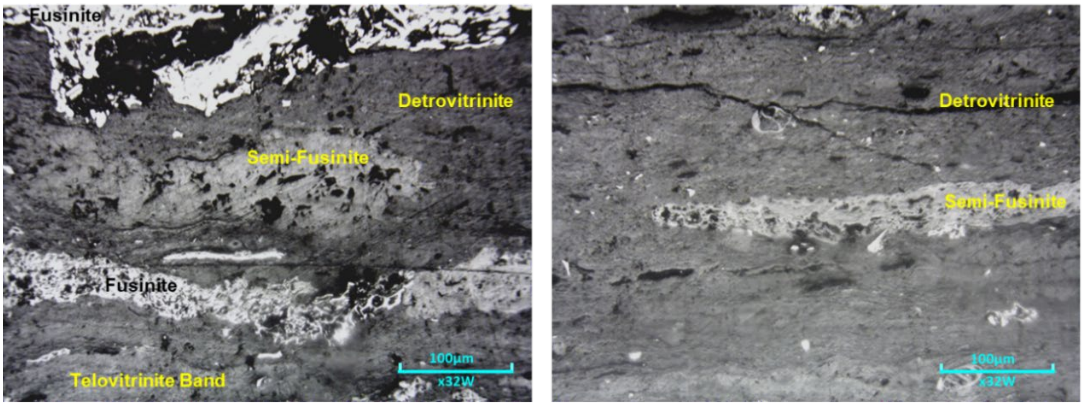

Figure 7. Photomicrograph of coal at 1302.85mMD: Detrovitrinite (Densinite) groundmass with inertodetrinite and liptodetrinite. Inertinite bands varying from Semi-fusinite to Fusinite. Incident white light x32 objective.

Middle Eocene

Four core samples were taken from the lower of two thick coals within the lower *N. asperus* zone (equivalent to the T2B seam) within the Cobia Subgroup (Figure 4). This coal is a low rank with R_{vmax} 0.41% at the base to 0.38% near the top, poorly compacted, relatively soft with high porosity. The petrography is consistent with the Traralgon Seam T2 coals in the Latrobe Valley mainly containing vitrinite, but with moderately high amounts of liptinite, and negligible mineral matter mostly pyrite and organic sulphur.

The coal seam overall comprises clarain lithotypes that show a typical drying-up sequence from Medium-dark lithotypes at the base to Light lithotypes at the top. Microscopically they are dominated by vitrinite, mainly a groundmass of gelified Detrovitrinite (densinite and corpogelinite, from broken-down and degraded plant tissue), containing moderate amounts of liptinite and rare funginite, interbedded with thin bands of Telovitrinite. The proportion of detrovitrinite:telovitrinite decreases upwards as plant tissue is preserved, but reverses in the uppermost Light lithotype at the seam top, from exposure above the water table causing increased tissue degradation (Figure 6). Gelification is more pronounced near the base where the telovitrinite is mainly eu-ulminite, becoming less gelified towards the top where it includes some texto-ulminite (compare Figure 8 left and right). However, the uppermost light lithotype is degraded with both gelified densinite and porigelinite. The liptinite is mainly liptodetrinite dispersed in the groundmass together with microspores/pollen grains and they increase upwards, whereas resinite/fluorinite, cutinite (leaf cuticles) and suberinite (cork tissue) are more common in the lower lithotypes. Inertinite is rare, mainly Funginite (Figure 9). The lowest darker lithotype sample contains well preserved plant tissue varying from texto-ulminite to minor amounts of fusinite.

This thick coal seam was most likely deposited in an ombrogenous peat swamp (representing around 20m of peat) between fluvial/distributary channels in a coastal plain setting. The lithotype and maceral variations are consistent with a drying up profile, produced by development of a raised bog with low nutrients and acid conditions, promoting preservation of the plant tissue and restricting the influx of sediment from stream flooding.

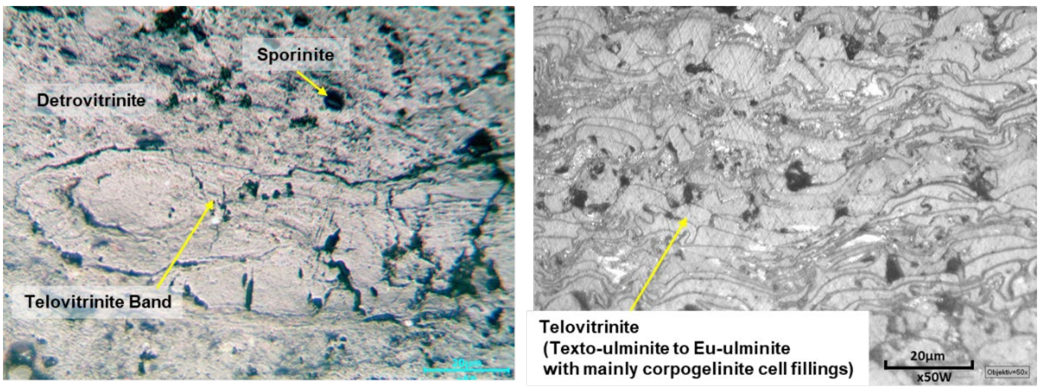

Figure 8. Photomicrograph (left) coal at 1076.8mMD: Gelified Telovitrinite (Eu-ulminite) (shrinkage cleat from sample prep) and gelified Detrovitrinite. Photomicrograph (right) coal at 1075.9mMD: Telovitrinite showing preserved tissue cell walls and gelified cell fill (Corpogelinite). Incident white light x50 objective.

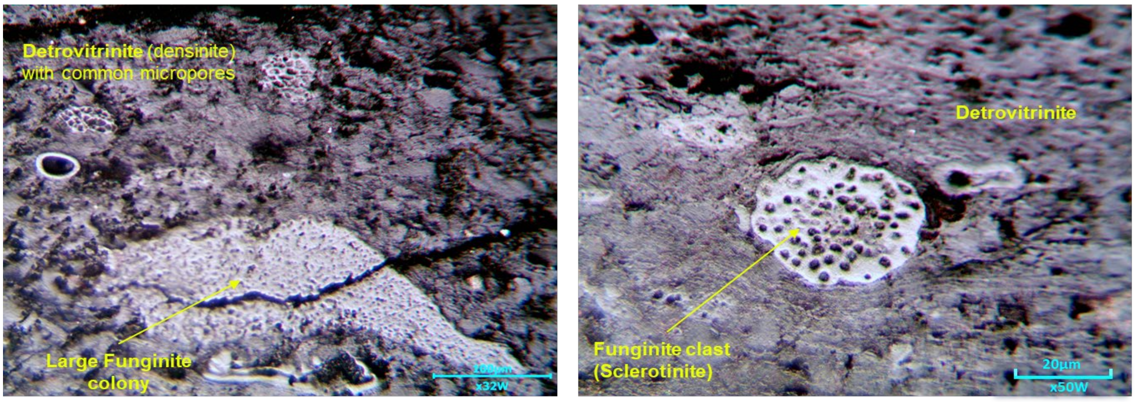

Figure 9. Photomicrograph coal at 1074.83mMD: Detrovitrinite microporous groundmass with Liptinite and large Funginite colony and sclerotia. Detrovitrinite on right shows ~3:1 differential compaction around Sclerotinite. Incident white light x32 objective left, x50 objective right.

The Lower *N. asperus* thin coal some 3m above the thick seam (at 1069.99mMD core) is a poorly bedded clarain in which the macerals are mostly disorientated. The vitrinites are highly gelified with higher reflectance, detrovitrinite dominates, the telovitrinite occurs as large fragments rather than bands, there is a high proportion of liptinite especially spores/pollen and detrital resinite. It contains dispersed clays, rare large quartz grains and disseminated post-depositional pyrite grains. This peat has colonised the underlying splay sand and is overlain by a back barrier lagoon, with dinoflagellate marginal marine indicators. Hence, the coal is part of the transgressive tract and represents a peat marsh developed on the margins of an interdistributary bay with some brackish influence.

The climate was cooling in the Middle Eocene and began to produce a warm-temperate rainforest flora, with angiosperms now dominant. The palynological record is swamped by the emergence of angiosperms *Nothfagidites emarcidus-heterus* and Casuarinaeceae especially *Haloragacidites harrisii* (primarily from *Gymnostoma*), in addition to Lauraceae and Proteaceae, though gymnosperms are still common, and importantly the first sclerophyllous taxa first appear (Martin, 2006). The assemblage is indicative of the rapid climate change, with *Nothofagus* spp. now forming the dominant canopy on the floodplains adjacent to the coal swamps.

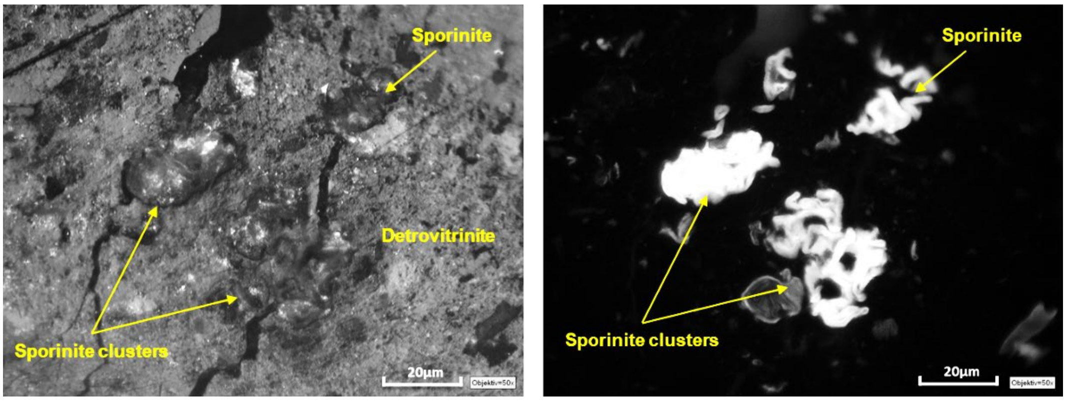

Figure 10. Photomicrograph coal at 1069.99mMD: Detrovitrinite microporous groundmass with Liptinite (liptodetrinite, resinite and sporinite) and large sporinite clusters (sporangia?). Incident white light left, fluorescent right, x50 objective.

Middle - Late Eocene

The coal samples within the Cobia Subgroup from the younger middle-lower *N. asperus* zones (age equivalent to the onshore upper T2 coals and possibly lower T1 coal seam) (Figure 6) are all from thin coals typically 0.5-1m thick. Compositionally they are clarain (Light) lithotypes, mainly comprising Vitrinite but with high amounts of Liptinite and mineral matter (Figure 6). The Vitrinite is highly gelified and mainly Detrovitrinite containing unusually high amounts of Liptinite (eg. 15-25%) as shown in Figure 11. The Telovitrinite occurs as thin bands or rootlets growing through the Detrovitrinite. Liptinite is mainly detrital with sporinite, resinite (including fluorinite) and liptodetrinite. Inertinite overall and funginite are rare. The mineral matter is interlaminated with the coal macerals, with some clays in the cell lumens or as clay laminae indicating periodic fresh water flooding (Figure 11). There are rare scattered pyrite grains but high organic sulphur resulting from episodic saline influence. They represent ephemeral peats deposited in swamp marshes, developed over interdistributary bays or over sand splays into the bays, and adjacent to back barrier lagoons. They are not salt marsh coals developed over extensive tidal flats. However, some thick coals occur in the overlying section that was not cored which are expected to be similar to the thick coal seam around 1075mMD.

The Late Eocene to Oligocene records the major change to cool temperate wetlands and rainforests, with flora dominated by angiosperms but with decreased diversity, mainly *Nothofagus* spp. and some Casuarinaceae, with increased proportions of gymnosperms such as Podacarpaceae (conifers). The Eocene coals mostly are not exposed in outcrop hence no macrofossil assemblage has been described. However the Oligocene-Miocene Morwell coal seams and interseams contain a diverse flora typical of modern temperate to subtropical rainforest including gymnosperms such as Agathis (kauri), and angiosperms including Diospyros (eg ebony) and casuarinas such as *Gymnostoma*. Dacrycarpus and Proteaceae dominate the palynomorph flora with myrtaceae.

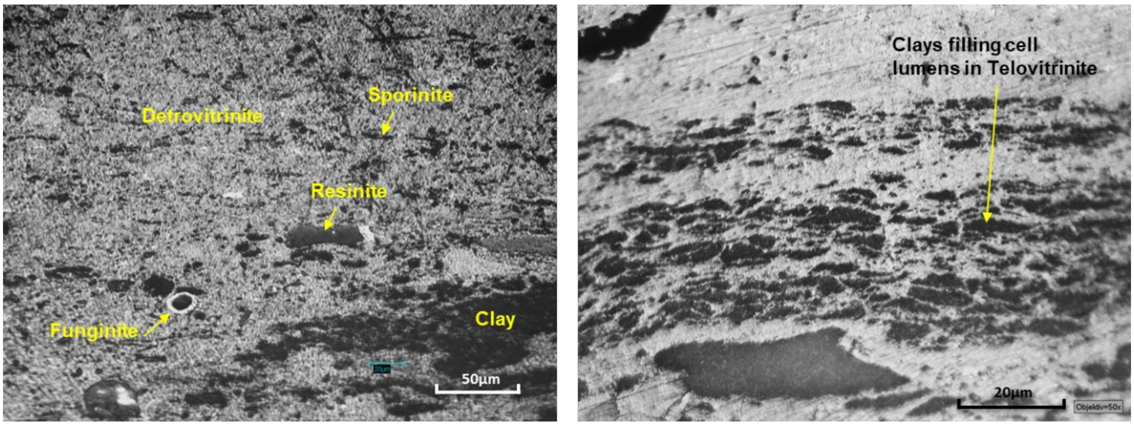

Figure 11. Photomicrographs of thin coals at 1003.33mMD: Detrovitrinite groundmass containing Liptinite (Sporinite, Resinite and Liptodetrinite) and clays (left, x32 objective). Telovitrinite bands with clays in cell lumens (right, x50 objective). Incident white light, oil immersion.

DISCUSSION & CONCLUSIONS

In the Gippsland Basin the most pronounced changes in the coal maceral composition and the floral assemblages occurred during the rapid Eocene-Oligocene transition (EOT) from hot greenhouse conditions to cold icehouse conditions, whereas most of the dominant floral elements were not obviously affected by the K-P events and neither it seems were the coals. The EOT also coincides with the marked changes in the depositional history when most of the offshore basin was drowned, pushing back the marine strandline from around the present shelf edge to near the present coastline, with maximum transgression into the onshore area during the mid-Oligocene, and only minor subsequent regression back to the present coastline.

The question remains what caused the loss of a diverse inertinite maceral assemblage from vitrinite-inertinite-liptinite coal to produce coals with vitrinite-liptinite maceral composition with essentially no inertinite other than rare fungal remains? The three most likely controls include: the change in climate, the changes in the floral components, and the changes in depositional environments.

The origin of such a diverse inertinite assemblage containing all the main inertinite submacerals (macrinite, micrinite, semi-fusinite, fusinite, inerto-detrinite and funginite) is well understood (Diessel, 1992). Most of the inertinite is due to syndepositional processes that include: dessication, dehydration and oxidation of plant tissue in the peat stopping the normal humification process; decomposition resulting from attack by organisms such as fungae, bacteria and insects; dessication of cell lumen colloids post gelification; and reworking of humified peat clasts. Only 10-20% of the inertinite is redeposited plant matter affected by fire (high reflectance pyrofusinite). However, this is much more prevalent than in the younger coals in which inertinite is rare and pyrofusinite is virtually non-existent (<0.1%). This is also the case for the very thick mined coals in the Latrobe Valley, in which pyrofusinite is restricted to litter on rare lithotype partings.

The reflectance of the inertinite rich coals in Gular-1 is not appreciably higher than the inertinite poor coals so rank effects are not an issue, though it is well known that inertinite undergoes further coalification with burial (Smith & Cook, 1980). Also, varying burial depths across the Gippsland Basin mean that some younger *N.asperus* age coals are buried deeper than the older *M. diversus* coals and they do not show increased inertinite occurrence.

The changes in depositional facies associated with the two sets of coals is different but probably not sufficient. The inertinite rich coals were deposited on floodplains in the Gular-1 area but also occur behind barrier systems that formed further east in the Kingfish-Halibut-Nannygai areas during the Paleocene-Early Eocene. In all areas and depositional environments the older coals are inertinite rich. However, these depositional environments were not maintained for very long periods, rather the barrier systems kept moving and the channel belt autocycling stopped the peats from stable long-term development of thick seams and the high inorganic content indicates they are mostly topogenous coals. In contrast, the thicker inertinite poor and largely mineral matter free coals are mostly ombrogenous peats, though the thin inertinite poor coals are also high in mineral matter and topogenous.

The changes in floral assemblages went from the old Mesophytic flora, with dominant gymnosperms and pteridophyts and low angiosperms (which were more affected by the K-P events), to a Cenophytic flora where the angiosperms were now dominant over the remaining gymnosperms. The gymnosperms and pteridophyts are much more shallow rooted and intolerant to rapid fluctuations in water tables that would have been prevalent during the the changing depositional environments making thick seam development less likely. The gymnosperms, especially the large trees, have considerably more resins and lignins that allow them to lie on the forest floor for long periods rather than decay quickly. In contrast, the angiosperms, are more cellulose rich without resin ducts allowing them to break down quickly into detrovitrinite, allowing development of raised acidic bogs with the peats accumulating in the more stable conditions behind the Late Eocene – Miocene barrier systems.

Interestingly, although south-eastern Australia was at high paleolatitudes moving from about 65-45°S during this period, in the Early-Middle Eocene it was still green with high net precipitation, net primary vegetation productivity and annual carbon exchange from high CO_2 levels of 1500-2000 ppm (Reichgelt *et al.*, 2022). So although conditions were favourable for plant growth overall in both periods, it seems the angiosperms were better able to adapt to the changing conditions in depositional facies and the significantly colder temperatures and they thrived in the more stable conditions behind the Oligocene barriers. A key factor is the more seasonal Paleocene-Early Eocene climate. This would have led to seasonal changes in the water table, with exposure of the peats to dessication and dehydration which is the critical control on development of a diverse inertinite population in coals.

The conclusion is that all three changes played a part in producing the dramatic change in coal compositons: climate, floral evolution and the style of deposition. The interactions between these three factors together produced a rapid and clear-cut change in the coals that each on their own may not have been sufficient. This is a classic case whereby the interactions produce an effect greater than expected from each of the individual factors working on their own.

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REFERENCES

Abbassi, S., Edwards, D. S., George, S. C., Volk, H., Mahlstedt, N., di Primio, R., & Horsfield, B. (2016). Petroleum potential and kinetic models for hydrocarbon generation from the Upper Cretaceous to Paleogene Latrobe Group coals and shales in the Gippsland Basin, Australia. *Organic Geochemistry, 91*, 54-67.

Barnet, J. S., Littler, K., Westerhold, T., Kroon, D., Leng, M. J., Bailey, I., . . . Zachos, J. (2019). A High-Fidelity Benthic Stable Isotope Record of Late Cretaceous–Early Eocene Climate Change and Carbon-Cycling. *Paleoceanography and Paleoclimatology, 34*, 672–691. doi:10.1029/2019PA003556

Burns, B., Bostwick, T., & Emmett, J. (1987). Gippsland terrestrial oils—recognition of compositional variations due to maturity and biodegradation effects. *Australian Petroleum Exploration Association Journal, 27*, 73-84.

Christophel, D. C., & Greenwood, D. R. (1989). Changes in climate and vegetation in Australia during the tertiary. *Review of Palaeobotany and Palynology, 58*, 95-109. doi:10.1016/0034-6667(89)90079-1

Cohen, K.M.; Finney, S.C.; Gibbard, P.L.; Fan, J.-X. (2013 updated). *The ICS International Chronostratigraphic Chart. Episodes 36.* Retrieved from http://www.stratigraphy.org/ICSchart/ChronostratChart2020-01.pdf

Diessel, C. F. (1992). *Coal-bearing Depositional Systems.* Springer-Verlag, Berlin, 356pp. doi:doi.org/10.1007/978-3-642-75668-9

Greenwood, D. R., Vadala, A. J., & Banks, M. A. (2000a). Climate change and vegetation responses during the Paleocene and Eocene in southeastern Australia. *GFF, 112*(1), 65-66. doi:10.1080/11035890001221065

Greenwood, D. R., Vadala, A. J., & Douglas, J. G. (2000b). Victorian Paleogene and Neogene macrofloras: a conspectus. *Proceedings of the Royal Society of Victoria, 112*(1), 65-92.

Harvey, M., Brassell, S., Belcher, M., & Montanari, A. (2008). Combustion of fossil organic matter at the Cretaceous-Paleogene (K-P) boundary. *Geology, 36*, 355-358. doi:10.1130/G24646A.1

Helby, R., Morgan, R., & Partridge, A. (1987). *A palynological zonation of the Australian Mesozoic* (Vol. Memoir 4). (P. A. Jell, Ed.) Association Australasian Palaeontologists.

Hill, R. B. (1994). History of the Australian Vegetation. In R. Hill (Ed.). The University of Adelaide. doi:dx.doi.org/10.20851/australian-vegetation

Holdgate, G. R., & Gallagher, S. J. (2003). Tertiary, Gippsland Basin. In W. D. Birch (Ed.), *Geology of Victoria* (pp. 324-335). Geological Society of Australia Special Publication No. 23.

Holdgate, G. R., & Sluiter, I. R. (2021). The T0 coal seam in the Latrobe Valley: a revised age and implications to Traralgon Formation stratigraphy. *Australian Journal of Earth Sciences*. doi:10.1080/08120099.2021.1876762

Holdgate, G. R., & Smith, G. C. (2018). Basin-wide coal variation in the Gippsland Basin, SE Australia. In S. D. Tang (Ed.), *TSOP Thirty-Fifth Annual Meeting* (pp. 55-57). Beijing, China: The Society of Organic Petrologists.

Houben, A., van Mourik, C., Montanari, A., Coccioni, R., & Brinkhuis, H. (2012). The Eocene-Oligocene transition: Changes in sea level, temperature or both? *Palaeogeography, Palaeoclimatology, Palaeoecology, 335-336*, 75-83. doi:10.1016/j.palaeo.2011.04.008

Johnstone, E. M., Jenkins, C. C., & Moore, M. A. (2001). An integrated structural and palaeogeographic investigation of Eocene erosional events and related hydrocarbon potential in the Gippsland Basin. *Eastern Australasian Basins Symposium*, 403-412.

Kim, H. (1987). *A comparative study of the hydrocarbon generation potential of Korean and Australian tertiary/cretaceous sedimentary basins.* University of Wollongong, PhD Thesis. Retrieved from https://ro.uow.edu.au/theses/1391/

Korasidis, V. A., Wallace, M. W., Wagstaff, B. E., & Holdgate, G. R. (2017). Oligo-Miocene peatland ecosystems of the Gippsland Basin and modern analogues. *Global and Planetary Change, 149*, 91-104. doi:10.1016/j.gloplacha.2017.01.003

Korasidis, V., Wallace, M., Wagstaff, B., & Hill, R. (2019). Terrestrial cooling record through the Eocene-Oligocene transition of Australia. *Global and Planetary Change, 173*, 61-72.

MacPhail, M. K., Alley, N. F., Truswell, E. M., & Sluiter, R. K. (1994). Early Tertiary vegetation: evidence from spores and pollen. In R. S. Hill (Ed.), *History of the Australian Vegetation: Cretaceous to Recent* (pp. 104-142). The University of Adelaide. doi:dx.doi.org/10.20851/australian-vegetation

Mahon, E., & Wallace, M. (2021). Shoreline evolution from the Late Cretaceous to the Miocene: a record of eustasy, tectonics and palaeoceanography in the Gippsland Basin. *Basin Research*. doi:10.1111/bre.12620

Martin, H. (2006). Cenozoic climatic change and the development of the arid vegetation in Australia. *Journal of Arid Environments*, 533-563. doi:10.1016/j.jaridenv.2006.01.009

National Offshore Petroleum Titles. (n.d.). *Data Access*. (Geoscience Australia, Editor) Retrieved from NOPIMS: https://www.ga.gov.au/nopims

Partridge, A. (1999). *Late Cretaceous to Tertiary geological evolution of the Gippsland Basin, Victoria.* PhD Thesis, La Trobe University, Bundoora, Victoria.

Partridge, A. (2006). Jurassic – Early Cretaceous spore-pollen and dinocyst zonations for Australia. In E. Monteil (Ed.), *Australian Mesozoic and Cenozoic Palynology Zonations – updated to the 2004 Geologic Time Scale.* Geoscience Australia Record 2006/23.

Reichgelt, T., Greenwood, D. R., Steinig, S., Conran, J. G., Hutchinson, D. K., Lunt, D. J., . . . Zhu, J. (2022). Plant proxy evidence for high rainfall and productivity in the Eocene of Australia. *Paleoceanography and Paleoclimatology, 37*. doi:10.1029/2022PA004418

Roder, G., & Sloan, M. (1986). Barracouta: History of exploration and development, and geology of the field. In R. C. Glenie (Ed.), *Second South-Eastem Australia Oil Exploration Symposium* (pp. 75-87). Melbourne: Petroleum Exploration Society of Australia.

Scher, H. D., Whittaker, J. M., Williams, S. E., Latimer, J. C., Kordesch, W. E., & Delaney, M. L. (2015). Onset of Antarctic Circumpolar Current 30 million years ago as Tasmanian Gateway aligned with westerlies. *Nature, 523*(7562), 580-583. doi:10.1038/nature14598

Sluiter, I., Kershaw, A., Holdgate, G., & Bulman, D. (1995). Biogeographic, ecological and stratigraphic relationships of the Miocene brown coal floras, Latrobe Valley, Victoria, Australia. *International Journal of Coal Geology*, 277-302. doi:10.1016/0166-5162(95)00021-6

Smith, G. C. (1982). A review of the Tertiary-Cretaceous tectonic history of the Gippsland Basin and its control on coal measure sedimentation. *Australian Coal Geology, 4, 1-38, 4*, 1-38.

Smith, G. C., & Cook, A. C. (1980). Coalification paths of exinite, vitrinite and inertinite. *Fuel, 59*, 641-646.

Victoria State Government. (n.d.). *Earth Resources: Maps, reports and data*. (Victorian Geological Survery, Editor) Retrieved from https://earthresources.vic.gov.au/geology-exploration/maps-reports-data

Yang, X., & Smith, G. C. (2022). A review of the Gippsland Basin history based on comparison of 3D structural, stratigraphic and forward sedimentation models: recognition of source, reservoir, traps and canyons . *Australian Journal of Earth Sciences*. doi:10.1080/08120099.2023.2136241

Yang, X., Smith, G., & Gupta, R. (2022). Basin analysis palaeo-landscape modelling: Testing the critical controls using experimental design constrained by a real 3D geological model, Gippsland Basin, Australia. *Basin Research*, 1-30. doi:10.1111/bre.12710

Zachos, J., Pagani, M., Sloan, L., Thomas, E., & Billups, K. (2001). Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science Magazine, 293*, 686–693. doi:10.1126/science.1059412