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An Early Paleogene Palynological Assemblage from the Sabrina Coast, East Antarctica: New Species and Implications for Depositional History

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An Early Paleogene Palynological Assemblage from the Sabrina Coast, East Antarctica: New
Species and Implications for Depositional History

by

Catherine D. Smith

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
College of Marine Science
University of South Florida

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ABSTRACT

Palynological analyses of 13 samples from two sediment cores retrieved from the Sabrina Coast, East Antarctica, provide the first information regarding the paleovegetation within the Aurora Subglacial Basin. The assemblages, hereafter referred to as the Sabrina Flora, are dominated by angiosperms, with complexes of *Gambierina* (*G.*) *rudata* and *G. edwardsii* representing 38–66% of the assemblage and an abundant and diverse Proteaceae component. The Sabrina Flora also includes *Battenipollis sectilis*, *Forcipites* sp. and *Nothofagidites* spp. (mostly belonging to the *N. cf. rocaensis-flemingii* complex), along with a few fern spores, including *Laevigatosporites ovatus*, a moderate presence of conifers, and previously undescribed morphospecies, two of which are described herein. A majority of the assemblage is interpreted as deposited contemporaneously with sedimentation, including *Gambierina* spp., which is traditionally assigned a Cretaceous–earliest Eocene age range. However, our age diagnosis for the Sabrina Flora, based on key morphospecies, indicates that sediment was most likely deposited between the latest Paleocene to possibly early–middle Eocene, if *Gambierina rudata* and *G. edwardsii* extended longer than previously thought. Additionally, we observed abundant dinoflagellate cysts of Campanian age. The absence of typical Paleocene–middle Eocene dinoflagellate cysts suggests that strata recovered were fluvial-dominated or proximal marine, with a major contribution of reworking of Campanian marine sediment. This study adds to the available East Antarctic palynological data and provides information on regional differences along the East Antarctic margin, as well as with southern Australia. The pollen diversity and the large relative abundance of *Gambierina* spp., along with the rarity of *Nothofagidites* spp., (*fusca* group), and

the lack of megathermal elements (e.g., *Arecaceae*) separate the Sabrina Flora from those of other East Antarctic margin and southern Australian basin sites.

INTRODUCTION

The Sabrina Coast is located on the Wilkes Land continental margin (Figs. 1 and 2) between 115°–121°E and 67°S. The region is marked by the periphery of the East Antarctic Ice Sheet, along with floating ice tongues and ice shelves, most notably the Totten Glacier (TG) and Moscow University Ice Shelf (MUIS) (Young et al., 2011). Aerogeophysical surveys reveal that the TG/MUIS system is the main drainage for the Aurora Subglacial Basin (ASB) (Fretwell et al., 2013; Rignot et al., 2013; Greenbaum et al., 2015), a large intracratonic basin that contains sedimentary and crystalline rock (Ferraccioli et al., 2009; Aitken et al., 2016). As the ASB is the likely provenance for sediment deposited seaward of the Sabrina Coast, sediment cores collected on the continental shelf adjacent to the ASB drainage basin likely provide insight to the evolution of the regional sedimentary layers (Close et al., 2007). Consequently, one of the primary goals of the first geological survey of the Sabrina Coast, (United States Antarctic Program cruise NBP 14-02), was to understand the past and present glacial dynamics of the ASB, as well as the marine geology of the region. Previous work on this part of the Antarctic margin has focused farther offshore, across the continental rise and abyssal plain, where an abnormally thick sedimentary package has been imaged and is postulated to be post early–middle Eocene (Close et al., 2007). Such sediment accumulation is thought to represent deposition leading up to and immediately following the development of large ice sheets in East Antarctica (Close et al., 2007).

The first evidence of Cretaceous (Aptian) strata in East Antarctica came from offshore, via a 40-cm long piston core (DF79-38) collected off the George V-Adelie (GVAL) coast, which

provided the first Mesozoic palynological reconstruction of the Wilkes Land region (Domack et al., 1980; Fig 1). Subsequent palynological studies related to East Antarctica include, but are not limited to: Prydz Bay (e.g., Macphail and Truswell, 2004; Hannah, 2006; Truswell and Macphail, 2009), the Shackleton Ice Shelf region (Truswell, 1982, 2012), the Wilkes Land margin (Pross et al., 2012; Contreras et al., 2013), the McMurdo Erratics (e.g., Mildenhall, 1989; Askin, 2000), the Mertz-Ninnis Trough (Schrum, 2004), and the McMurdo Sound area (e.g., Hannah et al., 1998; Askin and Raine, 2000; Raine and Askin, 2001; Prebble et al., 2006; Warny et al., 2009; Feakins et al., 2012; Griener et al., 2013; Griener and Warny, 2015).

Our study of terrestrial palynomorphs from the Sabrina Coast is based upon two sediment cores recovered from the continental margin and provides a unique opportunity to study a nearshore Cenozoic section in a heretofore-unsampled area of East Antarctica (Fig. 1). Two jumbo piston cores (JPC; JPC-54 and JPC-55) retrieved during the NBP 14-02 expedition contain an abundant, diverse, and well-preserved terrestrial palynomorph assemblage, providing a rich, paleobotanical archive that adds to the available East Antarctic margin sections. Here we report the affinities and significance of the palynology recovered in these cores.

STRATIGRAPHIC CONTEXT

Core sites were chosen based on high resolution seismic data acquired during the United States Antarctic Program RV/IB *Nathaniel B. Palmer* cruise NBP 14-02, which identified sub-crops near the seafloor (Figs. 2 and 3). Two significant windows into the pre-glacial strata were revealed by the reflection data (Fig. 3). JPC-54 and JPC-55 were collected above and below a prograding clinoform, respectively (Fig. 3). The Jumbo Piston Coring (JPC) system of the ship includes a 5000-lb bomb and lengths of 3-m long by 10-cm diameter core pipe, which can be added to reach 27 m maximum length. Since our goal was to recover material from near-seafloor sub-cropping units revealed on the seismic reflection data (Fig. 3), we rigged the JPC system with a single 3-m barrel and piston release via a trigger core. JPC-54 (121 cm in length) and JPC-55 (170 cm in length) recovered ~22 cm and ~40 cm of late Pleistocene to Holocene glaciomarine sediment (Unit I) respectively, overlying a partially consolidated, organic-rich interval (Unit II). Unit II in both cores consists of black, organic and mica-rich silty sand separated by a clear disconformity, with a downcore decrease in water content and overall magnetic susceptibility, and an increase in density (Fig. 4). Unit II in JPC-54 contains intervals of gravelly sandy silts to sandy silts, while Unit II in JPC-55 contains sandy silt. Furthermore, JPC-54 recovered angular, crystalline and sedimentary clasts scattered throughout the core (denoted by high magnetic susceptibility). JPC-55 contained a large, spherical, calcareous concretion with a 1-cm long plant macrofossil as the nucleus.

METHODS

Palynology

To quantify absolute abundance of terrestrial palynomorphs and to assign an age to Unit II of JPC-54 and 55, nine samples from JPC-54 and eight samples from JPC-55 were split and processed for terrestrial palynomorphs at Global Geolab Limited (Alberta, Canada), and marine palynomorphs at the Laboratory of Paleobotany and Palynology (Utrecht, Netherlands). For each sample preparation, ~5 g of dried sediment was weighed out; the terrestrial palynomorph splits were spiked with a known quantity of *Lycopodium* spores to allow for the quantitative assessment of terrestrial palynomorph concentrations. Acid soluble minerals (carbonates and silicates) were digested in HCl and HF. For terrestrial palynomorphs, controlled oxidation followed by rinsing to neutrality was performed, while samples for marine palynology were treated separately, without the oxidation step. Residues were concentrated by filtration on a 10 µm mesh sieve. The 13 samples in Unit II from JPC-54 and JPC-55 allowed tabulation of at least 300 terrestrial palynomorphs per sample, counted using a snaking transect method. The four samples from Unit I samples yielded an insufficient number of terrestrial palynomorphs, and are excluded from this study. We prepared a database of all palynomorphs recovered and key species were documented photographically. Identification for terrestrial palynomorphs was done using a Zeiss Axio Vert.A1 inverted microscope using a 100x oil immersion lens. Qualitative dinoflagellate cyst analyses in which all of the dinoflagellate cysts encountered in 2 slides were identified using 400x magnification.

Taxonomy

Taxonomic evaluation of palynomorphs utilized established literature (e.g. Cookson, 1950; Cookson and Pike, 1954; Couper, 1960; Stover and Partridge, 1973; Jarzen and Dettmann, 1992; Macphail and Truswell, 2004; Hou et al., 2006; Truswell and Macphail, 2009; Raine et al., 2011; Pross et al., 2012; and Contreras et al., 2013) and collections curated at the Louisiana State University Center for Excellence in Palynology (CENEX). Fensome and Williams (2004) was used for taxonomical evaluation of dinoflagellate cysts.

Evaluation of Kerogen and Organic Particulates

A rock plug sample of the concretion found at 125 cm in JPC-55 was processed in the organic geochemistry laboratory at Weatherford International (Shenandoah, Texas). The goal was to evaluate the nature of the organic particulates and their thermal-alteration history, and therefore to distinguish different palynomorph sources if multiple thermal-alteration periods were represented. A portion of the rock plug was dissolved in acid to provide a separate sample for particulate mounting, polishing and petrography. Initially, spore and pollen color indices were observed under ultraviolet and white light and related to standard indices of thermal alteration of color (e.g., Chevron index; Jones & Edison, 1978). Thermal history was also evaluated by quantitative measurement of vitrinite and associated maceral reflectance according to ASTM D-7708 Standards.

Core Physical Properties

Measurements of magnetic susceptibility (multi-sensor track) and density were acquired after the cores were split at the Antarctic Marine Geology Research Facility at Florida State University (Tallahassee, FL) using standard protocols on a GEOTEK™ Multi Sensor Core Logger (MSCL).

Water content was determined by direct sampling (approximately every 5 cm in the upper 50 cm, and approximately every 10 cm below 50 cm), drying and weight determinations after water loss.

RESULTS

Organic Particulate and Thermal Histories

The detrital organic particulates are of marine (amorphous) and nearshore character with an admixture of spores, pollen, and structured humic macerals including vitrinite (both collotelinite and collodetrinite), semifusinite, and inertinite (Jones and Edison, 1978). The evaluation of all these particles for thermal alteration revealed a bimodal vitrinite reflectance distribution of organic particulates with one population clearly reworked from an older, more thermally altered source. Distribution histograms (Fig. 5) on the vitrinite and associated macerals show two populations, one with a mode centered at $\sim 0.59\%R_o$ (mean of $0.58\%R_o$ with negative skewness) and another more thermally altered population centered at around $0.70\%R_o$ (mean of $0.72\%R_o$ with a positive skewness). Of significance is the data gap between the two modal populations between $0.60\%R_o$ and $0.63\%R_o$, signifying that these are indeed two separate populations and not one large continuum. In addition, it is important to note that the lower vitrinite population clearly has an associated semifusinite population with a slightly higher reflectance, typically due to the oxidized nature of this maceral compared to its paired vitrinite. The more thermally altered vitrinite lacks a correlative population of semifusinite, suggesting the removal of this population during erosion from an older source. Color indices on spore coloration also indicate two maturation populations, one with a Thermal Alteration Index (TAI, Chevron scale) of 2.5–2.6 and another population with a TAI of 2.7–2.8, corresponding to maturity estimates of 0.5–0.6% VR/e & 0.7–0.8% VR/e respectively.

Palynological results from JPC-54 and 55

Terrestrial Palynology

The sediment matrix yielded abundant, diverse and well-preserved palynomorphs allowing for quantification of flora for the 13 samples processed from Unit II in JPC-54 and JPC-55. Palynomorph concentrations (Fig. 7) ranged from 3540 to 6560 grains per gram dry sediment (gdw^{-1}) for JPC-54 and from 4200 to 8570 gdw^{-1} for JPC-55 with a mean of 4330 gdw^{-1} and 6390 gdw^{-1} , respectively. These concentrations represent rich assemblages for Antarctic materials and therefore provide a thorough documentation of the diversity within previously undescribed floral assemblages. These assemblages provide the first glimpse into the terrestrial environment of the ASB before the onset of the EAIS.

Relative abundances of key (age diagnostic) morphospecies and complexes for JPC-54 and 55 are summarized in Fig. 7. JPC-54 and JPC-55 can be distinguished by differences in their respective palynological assemblages. The JPC-55 assemblage contains 16–23% *Battenipollis sabrinae* sp. nov., a previously undescribed angiosperm similar to *Battenipollis sectilis* (formally described below). Only one sample from JPC-54 (46–47 cm) contains *Battenipollis sabrinae* (2% of the total assemblage). Furthermore, JPC-54 contains a higher total abundance of *Nothofagidites* spp. (5–12%), when compared with JPC-55 (1–3%), and both *N. emarcidus* and *N. cranwelliae*, while JPC-55 does not.

There are similarities between the two assemblages. For both JPC-54 and 55, the palynological assemblages are dominated by *Gambierina rudata* and *G. edwardsii* and related complexes (38–66%). Proteaceae (7–17%) are diverse, consisting mostly of *Proteacidites tenuixinus*. This angiosperm-dominated assemblage also includes *Battenipollis sectilis*, *Forcipites* spp. and *Nothofagidites* spp. (mostly belonging to the *N. cf. rocaensis*-*cf. flemingii* complex). Conifer

pollen is present (3–10%), including *Phyllocladidites mawsonii*, *Microcachrydites antarcticus*, and *Microalaticites paleogenicus*, as are fern spores [e.g. *Laevigatosporites ovatus* (1–8%)]. Due to similarities between JPC-54 and JPC-55, we refer to these new palynological assemblages as the “Sabrina Flora” (SF), named after the Sabrina Coast.

Marine Palynology

Palynological assemblages of both cores contain, alongside the diverse Paleocene-Eocene terrestrial palynomorphs, an abundant and diverse marine palynological component. Marine palynological assemblages in the glaciomarine Unit I of both JPC-54 and JPC-55 contain protoperidinioid dinoflagellate cysts typical of recent Antarctic sediments (including the modern *Selenopemphix antarctica*, *Brigantedinium* spp. (e.g., Prebble et al. 2013)] and middle to late Eocene reworked dinoflagellate cysts, a common feature in the region (e.g., Truswell et al., 1982; Escutia et al., 2011).

Assemblages in Unit II are remarkably different from those in Unit I described above. Species of stratigraphic significance in this interval in JPC-55 include abundant *Palaeohystrichophora infusorioides*, *Odontochitina spinosa*, *Xenascus ceratoide*, *Dinogymnium* sp., *Raphidodinium furcatum*, *Vozzhennikovia spinulosa* and *Heterosphaeridium difficile*. In Unit II of JPC-54, stratigraphically significant species include abundant *Chatangiella victoriense*, *Isabellidinium pellucidum*, *Vozzhennikovia spinulosa*, *Epelidosphaeridium* sp., *Odontochitina spinosa*, *Tanyosphaeridium xanthiopyxides*, and *Senoniasphaera edenensis*.

SYSTEMATIC PALEONTOLOGY

Anteturma POLLENITES H. Potonié 1893

Turma POROSES Naumova 1937–39

Subturma TRICOLPORATES Iversen et Troels Smith, 1950

Genus *Battenipollis* Jarzen and Dettmann 1992

Type species. *Triporopollenites sectilis* Stover in Stover and Partridge 1973

Battenipollis sabrinae sp. nov.

Plate 1, figures 1–4

Holotype. Plate 1, figure 1.

Type locality. Offshore of the Sabrina Coast, East Antarctica (S66°20.998, E120°30.454)

Diagnosis. Pollen tricolporate, amb concavely triangular, apertures broadly rounded to truncate, apices smooth. Exine 2–3 μm thick, vaguely to moderately well differentiated, sexine thicker than nexine, with sexine smooth at apertures and irregularly roughened between apertures. Scabrate to granulate sculpturing. Colpi poorly discernible. Dimensions, equatorial 23 (28) 31 μm , 15 specimens measured.

Dimensions. Overall diameter of 15 specimens from JPC-55: 23 (28) 31 μm

The mean distal exospore thickness is 2.5 μm .

Remarks. *Battenipollis sabrinae* sp. nov. is distinguished from *Battenipollis sectilis* by a thicker (2–3 μm vs 2 μm), a highly irregular exine between apertures, and scabrate to granulate sculpturing. Specimens vary in oblateness and thickness of legs. *Battenipollis sabrinae* is slightly smaller in size than *Battenipollis sectilis* (mean diameter is 28 μm vs. 31 μm)

Derivation of name. *Battenipollis sabrinae* is named for the Sabrina Coast of East Antarctica where this morphospecies is first described.

Anteturma POLLENITES H. Potonié 1893

Turma POROSES Naumova 1937-39

Subturma TRICOLPORATES Iversen et Troels Smith 1950

Genus *Gambierina* Harris 1972 emend. Stover and Partridge 1973

Type species. *Gambierina rudata* Stover in Stover and Partridge 1973

Gambierina truswelliae sp. nov.

Plate 1, figures 5–8

Holotype. Plate 1, figure 5.

Type locality. Offshore of the Sabrina Coast, East Antarctica (S66°20.998, E120°30.454)

Diagnosis. Pollen tricolpate, amb triangular to concavely triangular, apertures rounded, apertures smooth. Exine 1–2.5 μm thick, vaguely differentiated, sexine thicker than nexine, with sexine smooth at apertures and slightly to drastically irregularly roughened between apertures. Scabrate

to granulate sculpturing. Colpi poorly discernible. Distinguishable nick point within the apertures. Dimensions, equatorial 23 (25) 30 μm , 15 specimens measured.

Dimensions. Overall diameter of 10 specimens from JPC-55: 23 (25) 30 μm

The mean distal exospore thickness is 1.5 μm .

Remarks. *Gambierina truswelliae* is distinguished from *Gambierina rudata* by its scabrate to granulate sculpturing and irregular exine between the apertures. *Gambierina truswelliae* differs from *Gambierina edwardsii* by having less concave sides, rounder apertures and smaller diameters. *Gambierina truswelliae* compares to *Gambierina* sp. A from Jarzen and Dettmann (1992) by having distinctive sculpturing, however *Gambierina* sp. A is rugulate and has a slightly thicker mean exine than *Gambierina truswelliae*.

Derivation of name. *Gambierina truswelliae* is named for Elizabeth Truswell, whose work in Prydz Bay and southern hemisphere palynology significantly influenced our modern view of Eocene climate in East Antarctica.

AGE INTERPRETATION AND SIGNIFICANCE

Reworking is characteristic of palynological assemblages (Traverse, 2007). But it is a particularly difficult issue to deal with when working in Antarctic sequences where normal maturation schemes cannot always be used, as extreme polar conditions have tempering and preserving effects on palynomorphs. For example, Warny et al. (2016) recovered a diverse assemblage from a Miocene outcrop on King George Island with reworked species ranging from Permian to Paleogene in age, showing minimal differences in thermal maturation. Thus, extreme caution must be taken when assigning ages to sedimentary sequences based on palynomorphs alone, especially in these mixed glacial and marine environments. JPC-54 and JPC-55 contain sediments representative of the ASB and its tributaries. Therefore, this assemblage represents flora that could be derived from the ASB, as these palynomorphs and sediments were funnelled to the Sabrina Coast shelf from nearly the entire catchment. The ASB likely served as a large interior seaway during later parts of the Mesozoic (similar to the Great Australian Basin; Fig. 1), into portions of the Paleogene (Young et al., 2011, Scherer et al., 2016). Therefore, we would expect to see a diversity of ages within any palynological preparation from these sediments.

We make the case that we have two age-diagnostic assemblages; one with reworked palynomorphs of Late Cretaceous age, which is a mixed marine and terrestrial assemblage, and an autochthonous, terrestrial assemblage of latest Paleocene to potentially as young as middle Eocene age. This argument is based on the spore and pollen identifications, key dinoflagellate-cyst identifications, and the thermal maturation character of the amorphous organic matter and palynomorphs, recognizing that this scheme is not straight forward for Antarctic sequences.

Based on the review of known ranges of all pollen and spore species recovered, an age assignment is provided. The age-diagnostic species are presented in the biostratigraphic chart (Fig. 8). Because studies from the East Antarctic margin are limited, we incorporate age constraints from southern Australian basins (e.g., Stover and Partridge, 1973; Jarzen and Dettmann, 1992; Partridge, 2006), the Antarctic Peninsula (e.g., Francis et al., 2008; Warny and Askin, 2011), and McMurdo Sound erratics (e.g., Askin, 2000; Francis, 2000; Levy and Harwood, 2000). Therefore, the ages assigned to certain morphospecies on the East Antarctic margin should be considered with caution. For instance, there are a number of new species in the SF assemblage (two of which we formally describe here), which present challenges when assigning an age to the assemblage. Also, many morphospecies vary slightly from the holotypes of previously described species, and many of them were thus assigned to complexes and are thus not useful for biostratigraphic purposes. While some may be new species, some might represent new stages in a morphological continuum. This is particularly true for the species of *Gambierina* and *Nothofagidites* recovered from the two cores studied. Therefore, we were conservative in assigning new species names and take an approach similar to that used in Prydz Bay (Truswell and Macphail, 2009).

Based on the biostratigraphic data common to both JPC-54 and JPC-55, such as the first appearance datum (FAD) of *Proteacidites tenuinexinus* in the upper *Lygistepollenites balmei* Zone (Stover and Partridge, 1973), and the most abundant genus (*Gambierina* spp.), the assemblages could fit within the latest Paleocene upper *L. balmei* Zone to early Eocene *Malvacipollis diversus* Zone. However, we caution that the assigned age zonations were established in southern Australia, and there is a lack of comparable data from the East Antarctic margin. Most of the pollen recovered are light in color and well-preserved, suggesting that these derive from penecontemporaneous

vegetation consistent with the population of thermally less mature organic macerals with a TAI of 2.5–2.6 and a vitrinite reflectance of 0.58% R_o.

Furthermore, the presence of *Proteacidites* spp. and small numbers of *Nothofagidites* spp. (*fusca*), in addition to age-diagnostic morphospecies, suggest a late Paleocene/early to middle Eocene age. Notably, many typical late Eocene flora are missing or rare, such as abundant *Podocarpidites* spp. and *Nothofagidites lachlaniae*. Also absent or rare are palm pollen (Arecaceae) and other paratropical vegetation elements recorded from an early Eocene assemblage from eastern Wilkes Land (IODP 318 Site U1356) only 600 km from the source of our cores (Pross et al., 2012; Contreras et al., 2013). Megathermal forest elements such as Arecaceae are typically underestimated in pollen assemblages due to low pollen production (Pross et al., 2012). Therefore, even the small relative abundance of Arecaceae at Site U1356 is significant and thus differentiates Site U1356 from our localities, suggesting either an age difference or major environmental gradient between the sites.

However, Site U1356 sediments were dated using dinoflagellate biostratigraphy. The dinoflagellate cysts examined in our sediments are narrowly defined as mid-Campanian (JPC-55) and Campanian–Maastrichtian (JPC-54) in age. No *in situ* dinoflagellate species of Paleocene–Eocene age were identified (Bijl et al., 2011; Bijl et al., 2013; Crouch et al., 2014). This suggests that the dinoflagellate cysts in our record are reworked into the Paleocene–Eocene deposits and that the Paleocene–Eocene sequence could represent a very restricted marine or fluvial-dominated deposit that would be unfavourable for dinoflagellate cysts. The dinoflagellate cyst assemblages are likely reworked from marine sediments within the ASB, as they correlate to the more thermally altered TIA values of 2.7–2.8 and vitrinite R_o of 0.7–0.8% VR/e. The reworked marine sediments at JPC-55 can be dated to the mid-Campanian, ranges of species encountered converge to an age

between around 85 and 81 million years (Williams et al., 2004). Because the spread of age ranges for the species encountered is limited, and all dinoflagellate cysts co-occur within the mid-Campanian, we suggest that an erosion of a specific mid-Cretaceous marine deposit contributed the dinoflagellate cysts in JPC-55. Interestingly, JPC-54 has a reworked component of slightly younger age close to the Campanian-Maastrichtian Boundary (Williams et al., 2004). Unit I of both cores contain middle Eocene dinoflagellate cysts, suggesting middle Eocene marine deposits occurred in the vicinity of the site.

INSIGHTS ON *GAMBIERINA* SPP.

Gambierina spp., the most abundant (38–66%) genus in JPC-54 and JPC-55, presents certain issues when determining our age assignment and paleoenvironmental interpretation. Most of the *Gambierina* spp. specimens in JPC-54 and JPC-55 are light in color and well preserved, suggesting that these *Gambierina* specimens were deposited *in situ*. Furthermore, there are clusters of both *G. rudata* and *G. edwardsii* species, with up to 40 specimens per cluster, in JPC-54 and JPC-55 (Fig. 6). These clusters indicate that these specimens were deposited close to the anther of the angiosperm parent plant, indicating most *Gambierina* specimens are not reworked (Fig. 6). Therefore, *Gambierina* spp. grains are contemporaneous with sedimentation, and constitute a major component of the assemblages.

Stover and Partridge (1973) classified *Gambierina rudata* as a new species, and renamed *Triorites edwardsii* (Cookson and Pike, 1954) *Gambierina edwardsii*. Stover and Partridge (1973) also classified *G. edwardsii* and *G. rudata* as Late Cretaceous–late Paleocene from Gippsland Basin sections. However, Partridge (1999) later noted that these species became extinct in the earliest early Eocene in the Gippsland Basin. Cookson and Pike (1954) originally assigned *Gambierina* spp. a Paleocene to early Eocene range, as do studies in New Zealand (e.g., Wanntorp et al., 2011). Finally, *Gambierina* spp. is found in Late Cretaceous sediments from Seymour Island (Askin 1990, Bowman et al., 2014) and Vega Island (Jarzen and Dettmann, 1992), but is absent from the McMurdo erratics of Eocene age (Askin, 1990).

Although south Australian and New Zealand reports (referenced above) define the age range of *Gambierina* spp. to Late Cretaceous–late Paleocene/earliest early Eocene, Truswell and Macphail (2009) suggested that *Gambierina* spp. likely extended through the late Eocene in Prydz Bay. Pross et al. (2012) also suggested that the parent plant for *Gambierina edwardsii* survived during the early and middle Eocene along the Wilkes Land coast at Site U1356. Pross et al. (2012) used a climate argument, stating that longevity of *Gambierina* spp. could be due to perennially cool-cold climates in East Antarctica persisting through the late Paleocene to early-middle Eocene, while a rapidly warming climate in southern Australia during the Paleocene–Eocene Thermal Maximum could have eliminated *Gambierina* spp. parent plants (Macphail et al., 1994; Truswell and Macphail, 2009). Because *Gambierina* spp. was likely deposited penecontemporaneously in JPC-54 and 55, and because we find at least one morphospecies in our assemblage with a FAD in the early Eocene (*Nothofagidites emarcidus*) only in JPC-54, we suggest that *Gambierina edwardsii* and *G. rudata* could extend into the early Eocene (based on our data), possibly to the middle–late Eocene if Truswell and Macphail (2009) and Pross et al. (2012) are correct. We are thus extending our potential range to the middle Eocene to take these two studies in consideration (Fig. 8).

Additional morphospecies with of unknown paleobotanical affinity include *Battenipollis sectilis* [renamed by Jarzen and Dettmann (1992) from *Triporopollenites sectilis* in Stover and Partridge (1973)] and *Forcipites* spp. *Gambierina* spp., *Battenipollis sectilis* and *Forcipites* spp. have all been found in the Otway Basin within upper Cretaceous sequences, where the authors compared them to pollen produced by Northern Hemisphere Normapolles (Jarzen and Dettmann, 1992). Although there are similar morphological characteristics with the Normapolles, which are brevixial, transcolpate and have a triangular amb (Batten, 1981; Batten and Christopher 1981), closer analyses revealed that these genera evolved separately, and thus any paleobotanical affinity

is speculative. These three genera (*Gambierina*, *Battenipollis* and *Forcipites*) likely grew within forest communities adjacent to, or fringing, an estuary (Dettmann and Jarzen, 1988); however, their parent plants and affinities are still unknown. Although specimens of *Battenipollis sectilis*, as well as *Battenipollis sabrinae* sp. nov. might be *in situ*, the lack of additional *in situ* evidence, such as clusters like those of *Gambierina* spp., prevents a similar age extension for *Battenipollis* spp. And it is possible that these species are indeed strictly restricted to the Cretaceous. Additional study of this region is needed to define whether *Battenipollis sabrinae* sp. nov. has a range that extends to the Eocene. Furthermore, *Forcipites longus* specimens are dark in color and often broken, and therefore we believe this species to be reworked from Cretaceous or early Paleocene sources.

SABRINA COAST FLORA: A COMPARISON

As the Sabrina Flora is a new, unique floristic assemblage, it is important to compare its elements to proximal and distal Southern Hemisphere locations. First, there are both similarities and differences when compared with the two previously documented Eocene sedimentary sections from the East Antarctic margin: Wilkes Land (Site U1356) and Prydz Bay (Site 1166). At Site U1356, the early Eocene assemblage is dominated by pteridophyte spores (40%) compared to a much smaller percentage of spores (<10%) at the Sabrina Coast. Furthermore, at Site U1356, angiosperms only represent 25% of the total assemblage, with *Nothofagidites* spp. (mostly *fusca* group) dominating the angiosperm assemblage, and tropical elements, such as *Arecaceae*, present, thereby greatly differing from the Sabrina Flora. At Wilkes Land, the middle Eocene assemblage is dominated by *Nothofagidites* spp. (50%), *Proteacidites* spp. and *Malvacipollis* spp., and gymnosperms (30%), mostly represented by *Dilwynites granulatus* and *Araucariacites* spp., indicating a cool temperate forest environment, while the Sabrina Flora have very few of these elements.

Although Prydz Bay sediments are late Eocene in age, the Sabrina Coast and Prydz Bay assemblages share a number of similar morphotaxa. For example, the spore (e.g., *Laevigatosporites ovatus*) and gymnosperm assemblages at Prydz Bay (e.g., *Dilwynites granulatus*, *Cupressacites*, and *Phyllocladidites mawsonii*) are very similar to those of the Sabrina Coast, except that the podocarp abundances (e.g., *Podocarpidites* spp.) are much higher at Prydz Bay (14–22%), which is consistent with late Eocene sediments on the Antarctic Peninsula (Warny and Askin, 2011; Feakins et al., 2014). The angiosperm assemblage differs, however, between the

Sabrina Coast and Prydz Bay. For example, *Proteacidites* spp. are much less abundant at Prydz Bay (<5%) compared to the Sabrina Coast (7–17%), although both assemblages contain diverse Proteaceae morphospecies. The *Nothofagidites* spp. abundance, especially of the *N. fusca* group, is much higher at Prydz Bay (52–60%), again consistent with late Eocene sections from the Antarctic Peninsula, and discussed further below.

Other East Antarctic sites include the McMurdo erratics (middle–late Eocene; Askin, 2000), dredges from the Mertz Glacier region (Early Cretaceous and Paleogene; Schrum et al., 2004), and sedimentary sections from the Shackleton Ice Shelf region (Late Cretaceous–Eocene; Truswell 1982, 2012) and from George V Land (Cretaceous; Domack et al., 1980). The dredges collected offshore of the Shackleton Ice Shelf contain a qualitatively similar assemblage to the Sabrina Coast sedimentary sections. Similar morphotaxa include *Gambierina edwardsii* and *G. rudata*, *Proteacidites* spp. and *Nothofagidites* spp. (*N. fusca* and *N. brassii* types), however percentages and species are not specified, and therefore caution is taken when comparing this site to the Sabrina Flora (Truswell, 1982). The McMurdo erratics share more similarities with Prydz Bay samples (Truswell and Macphail, 2009), such as a dominance of *Nothofagidites fusca* due to the middle-late Eocene age, yet they do not contain *Gambierina* spp. (Askin, 1990). The Mertz dredges consist of trilete spores, *Nothofagidites flemingii-rocaensis* complex specimens and diverse Proteaceae, however these dredges were not quantitatively analysed (Schrum et al., 2004). The George V Land palynomorphs contained mostly spores and saccate pollen, with no morphospecies overlap with the SF palynomorphs, attributed to the Early Cretaceous (Aptian) (Domack et al., 1980).

West Antarctica and Antarctic Peninsula palynomorphs have been studied, mostly addressing the Cretaceous–Paleocene (Askin, 1990; Bowman et al., 2014) and the late Eocene (e.g., Batten, 1981; Warny and Askin, 2011), some of which is summarized in Francis et al. (2008). These sites

differ more from the SF than the more proximal East Antarctic margin sites described above. These differences are attributed to the distance from the Sabrina Coast, and age, as these sections either preceded the age attributed to the Sabrina Coast sediments, or succeeded them in the late Eocene, directly prior to the expansion of Antarctic ice sheets (e.g., Zachos et al., 2001, 2008).

PALEOBOTANICAL GRADIENT

Differences between assemblages from the Sabrina Coast and the Antarctic margin, and also with the south Australian margin, provide insights into diverse paleoenvironments in this Southern Hemisphere sector. One example, *Nothofagidites* spp. is more abundant in southeastern Australia and at Site U1356 in Wilkes Land, suggesting a paleobotanical gradient. The relatively low abundances of *Nothofagidites* spp. in JPC-54 and 55, especially in both the *N. fusca* and *N. menziesii* (*N. asperus*) groups, are comparable to early Eocene eastern Eucla Basin sediments (6% in early Eocene, 16–42% in middle Eocene) (Hou et al., 2006). In Wilkes Land sediments, *Nothofagidites* spp. (mostly *fusca* group) dominates both assemblages (5–35% in early Eocene, 25–60% in middle Eocene). Stover and Partridge (1982) note that the absence of the *N. menziesii* group in the western Australian basins (e.g., Bremer sub-basin, Eucla Basin) compared to the Victoria basins (e.g., Gippsland, Bass and Otway basins), is paleobotanically significant. The *Nothofagidites* spp. relative abundance is high at Prydz Bay (52–60%), but this is in a late Eocene section and therefore we would expect a higher concentration of *Nothofagidites* spp. than we see at the Sabrina Coast. When comparing early–middle Eocene sections along the East Antarctic margin and with their respective conjugate margin sections, the palynological differences suggest more similarities between north–south relations between Australia and Antarctica than east–west along the East Antarctic margin. The palynological assemblages from the Sabrina Coast and Eucla Basin sediments share more similarities than the Sabrina Coast and Site U1356 palynological assemblages. This could be attributed to a complex current system in the proto-Leeuwin Gulf at this time, such as gyres allowing for north–south circulation compared to east–west, for example.

Another group that can be compared among East Antarctic sites and south Australian sites is Arecaceae, or palm pollen, and other megathermal elements such as Bombacoideae. As previously mentioned, even small relative abundances of these morphotaxa indicate paratropical paleoflora (Pross et al., 2012, Contreras et al., 2013). Although *Arecipites* spp. is found in Prydz Bay samples, Truswell and Macphail (2009) note that these morphospecies most likely do not represent palms, as this is a megathermal element and not expected to be found in a *Nothofagus* shrub-dominated forest. However, megathermal elements are absent from the SF. Therefore, assuming a latest Paleocene–middle Eocene age for the SF assemblage, the lack of megathermal elements and a low percentage of *Nothofagidites* spp., especially the *N. fusca* group, differentiates the SF from the Wilkes Land early and middle Eocene assemblages. This suggests a paleoenvironmental gradient between these sites, as there must have been environmental factors allowing for the predominance of the *Gambierina* spp. parent plant at the Sabrina Coast, and the predominance of *Nothofagidites* spp. and megathermal elements at Wilkes Land during the early–middle Eocene.

The absence of palm pollen and low numbers of *Nothofagidites* spp. in JPC-54 and JPC-55 compared to recently documented sites from this same margin would suggest either a significant paleoenvironmental difference from east to west along the East Antarctic margin and/or restriction to a middle Eocene age for the assemblage we describe herein. A early–middle Eocene age diagnosis would be consistent with the interpretation that the crystalline clasts scattered throughout JPC-54 are ice-rafted, and corroborate suggestions of small to moderate ice sheets in East Antarctica, commencing possibly as early as the Maastrichtian (Miller et al., 1999) or the middle Eocene (Villa et al., 2014).

CONCLUSIONS

The terrestrial palynomorphs preserved in JPC-54 and JPC-55 collected offshore of the Sabrina Coast are well-preserved and diverse, and are suggested to be deposited contemporaneously with sedimentation (likely Paleocene/Eocene), but include a minor reworked component of Cretaceous age. The marine palynomorphs in JPC-55 and JPC-54 are strictly reworked from the Late Campanian and Campanian–Maastrichtian, respectively. The palynomorphs recovered appear to have been deposited with sediments funnelled from the ASB through the Sabrina Coast and into the collecting basin. The reworked palynomorph component of Cretaceous age agrees with two different thermally altered populations illustrated via vitrinite reflectance analysis. The diverse and abundant terrestrial palynomorph assemblages, paired with a lack of *in situ* dinoflagellate cysts could be explained by a fluvial-dominated or proximal marine setting that could be uninhabitable by dinoflagellates.

Although the palynomorph assemblage is representative of the larger region of the ASB, they provide valuable insight on the paleoflora of this region of East Antarctica not studied previously. Furthermore, these palynomorphs provide a comparison to the few East Antarctic palynological studies of Paleocene to Eocene age. The terrestrial assemblage is angiosperm-dominated, and about half of the assemblage is composed of *Gambierina* spp., a tricolporate angiosperm of unknown paleobotanical affinity. The large percentage of diverse Proteaceae, rarity of *Nothofagidites* spp. and lack of megathermal elements differentiates this assemblage from proximal Wilkes Land and Prydz Bay assemblages. These new palynomorph assemblages is herein referred to as the Sabrina Flora.

The terrestrial palynological samples from JPC-54 and 55 allowed us to provide an age for the organic-rich sub-cropping Unit II in both cores. We suggest a latest Paleocene–middle Eocene as the age range for both cores. Although the palynological assemblages bear many similarities, there are subtle differences between JPC-54 and JPC-55 that allow for an age distinction between the two cores. *Nothofagidites emarcidus*, with an FAD in the early Eocene, is only present in JPC-54, therefore suggesting a likely early–middle Eocene for JPC-54. Clearly stratigraphic principle dictates that JPC-55 is older, and the two cores are separated by 150 m of strata, including a clinof orm. Overall, the assemblage fits in the late Paleocene–early Eocene biostratigraphic range zones from southern Australia (Stover and Partridge, 1973; Partridge, 2006). However, we are cautious in limiting our age diagnosis exclusively to these zones, in corroboration with the limited studies from proximal East Antarctic margin sites, and in consideration of the disparity in diversity between Antarctic and Australian palynological assemblages from this time.

Regional contrasts, such as the differences in *Gambierina* spp., *Nothofagidites* spp., and Arecaceae (palm pollen) suggest a potential paleobotanical gradient that existed in the Australo-Antarctic region during the latest Paleocene to middle Eocene. We suggest that this illustrates complexity in the proto-Leeuwin system, such as local north–south gyres allowing for more similar palynological assemblages between the Sabrina Coast and the Eucla Basin than with proximal East Antarctic margin sites. Lastly, the SF could differ from proximal East Antarctic margin sites if it was the first region with ice present at sea-level, evidenced by ice-rafted debris in JPC-54, which we have assigned an early-middle Eocene age range. Therefore, the SF and its palynomorphs provide valuable insight to the paleoenvironment during the latest Paleocene-middle Eocene at the Sabrina Coast, and elucidate regional climatic details along the East Antarctic margin.

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FIGURES

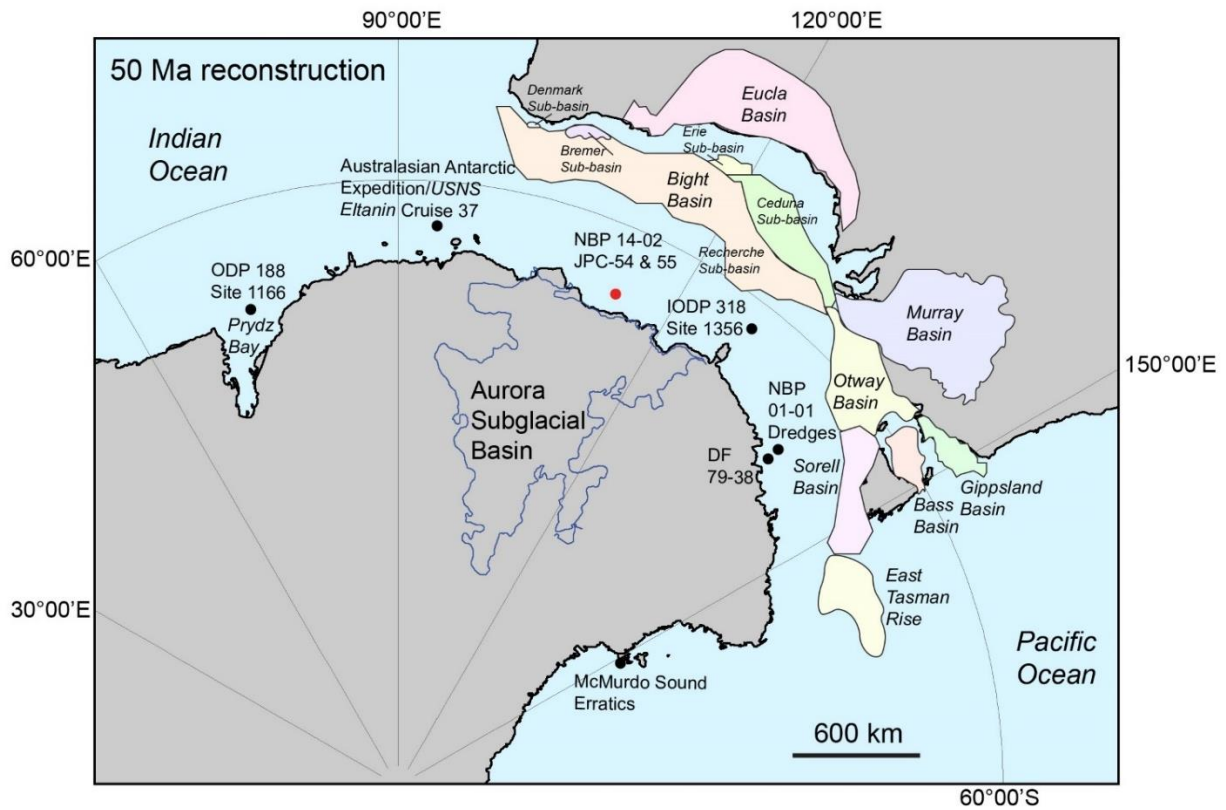


Figure 1. Paleogeographic reconstruction for the Australian-Antarctic margins at 50 ma including sedimentary basins. Paleogeographic charts obtained from the Ocean Drilling Stratigraphic Network (ODSN).

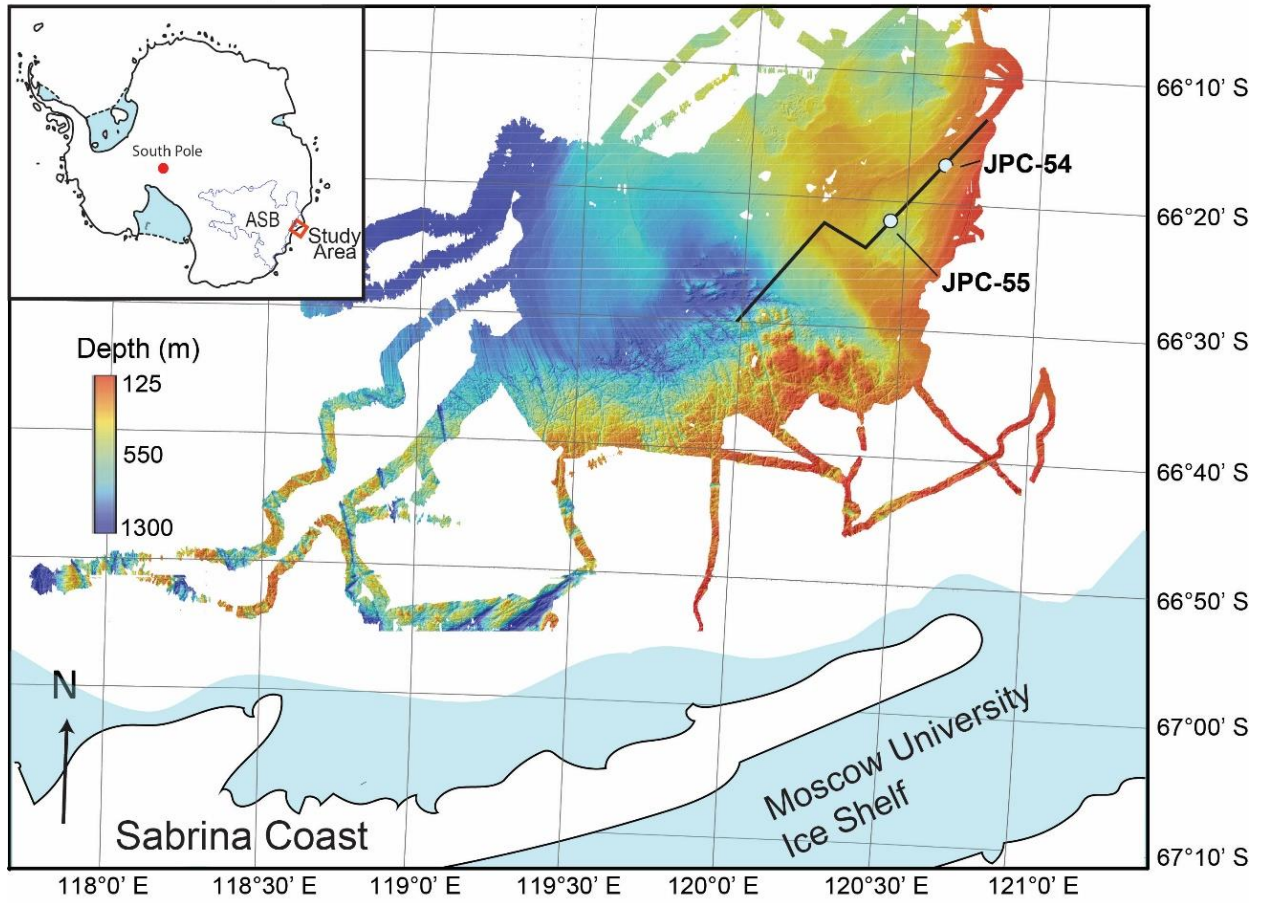


Figure 2. Locations of cores JPC-54 and 55 are denoted by blue circles. Bathymetry data was collected on NBP 14-02 using a Kongsberg EM 120 multibeam system. The ASB catchment area is modified from Pierce et al. (2011). Black line represents seismic line 17 collected on NBP 14-02.

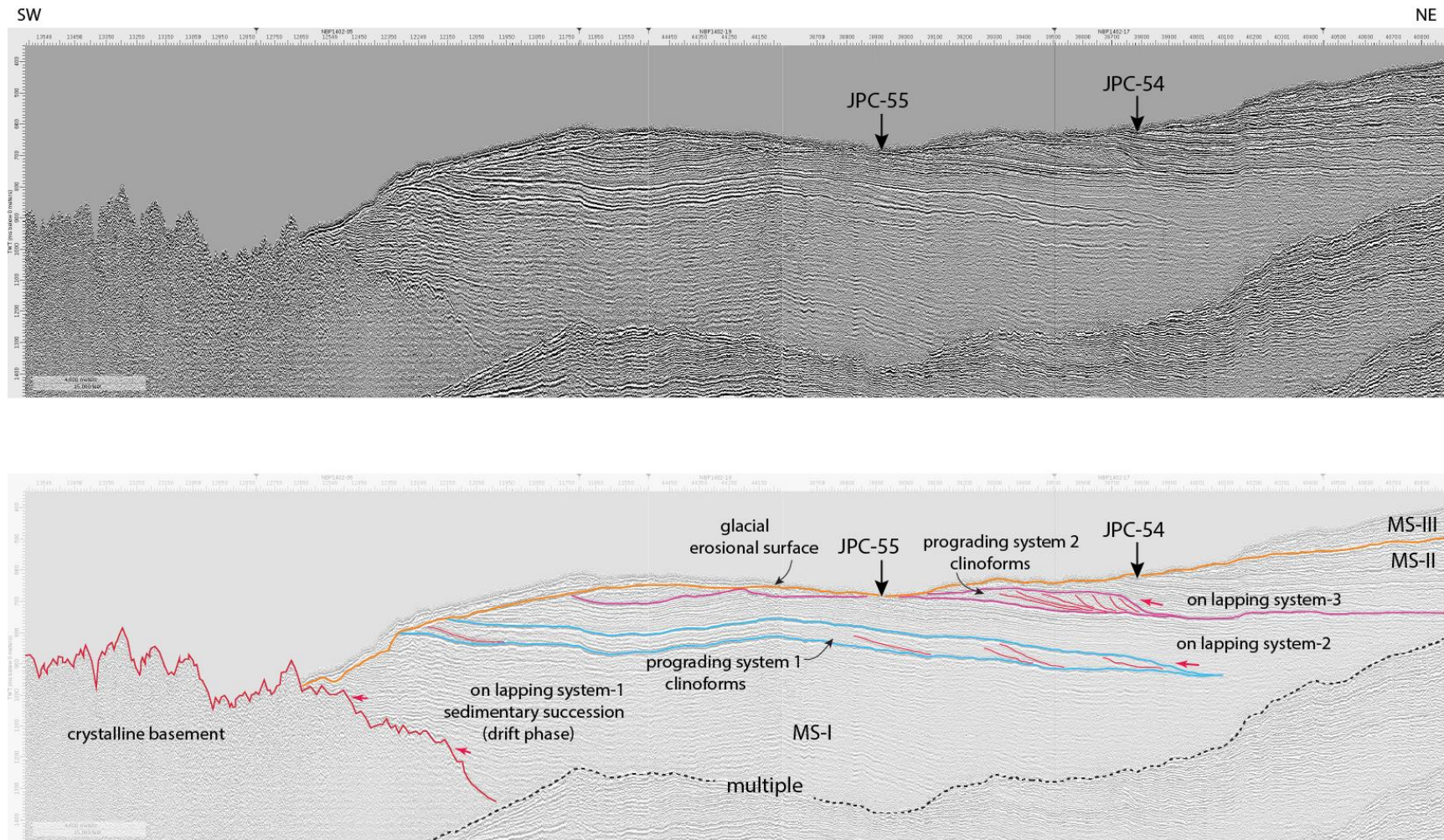


Figure 3. Seismic image collected on NBP 14-02 utilized to target JPC-54 and 55 sites. The composite seismic line illustrates erosional and onlapping surfaces, which denote clinofolds. JPC-54 and JPC-55 are above and below these clinofolds, respectively. Modified after Gulick et al. (*in prep*).

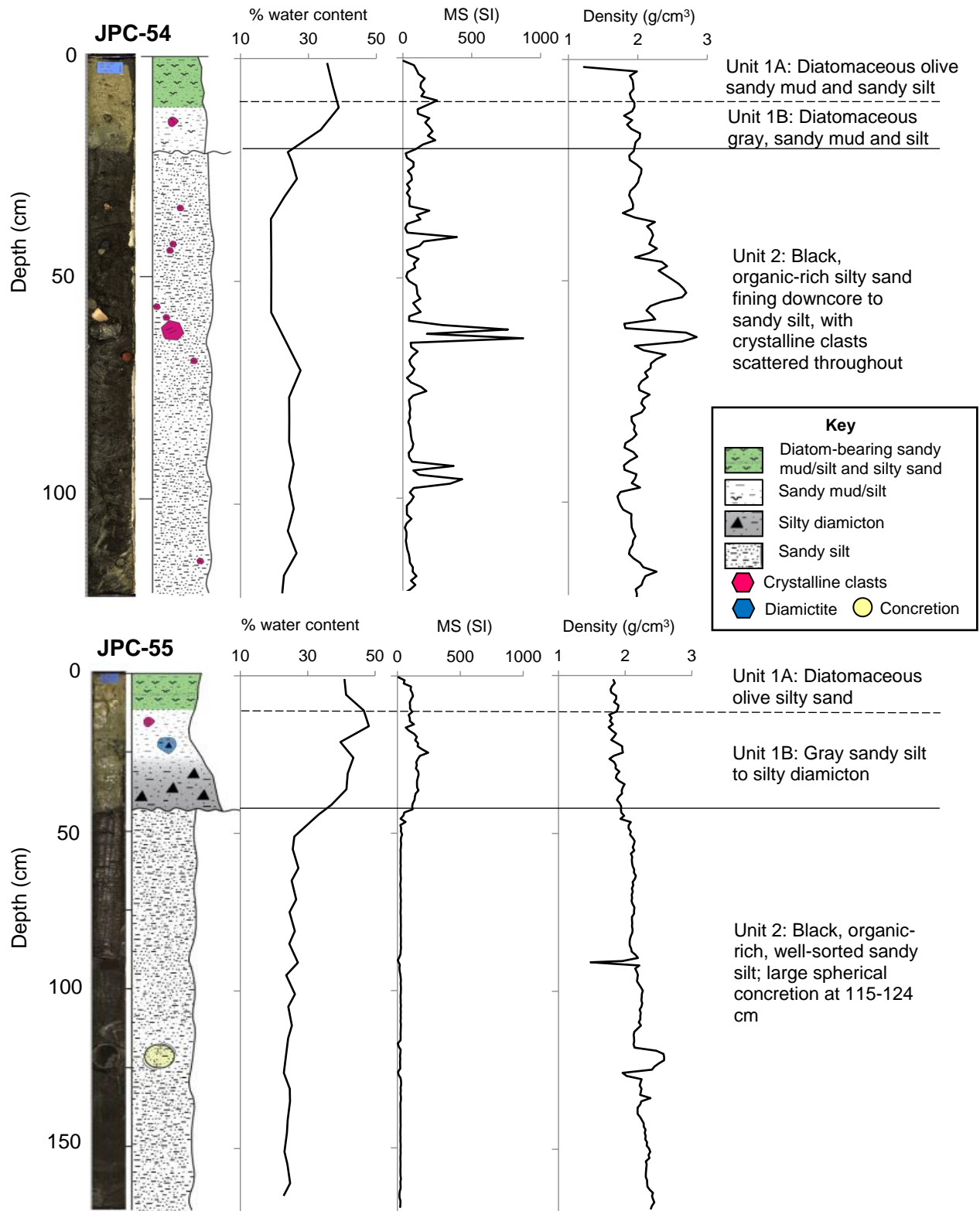


Figure 4. Physical properties of JPC-54 and 55. Lithology log, water content, and magnetic susceptibility shown. Dotted line separates Unit IA and Unit IB, solid line separates Unit I from Unit II.

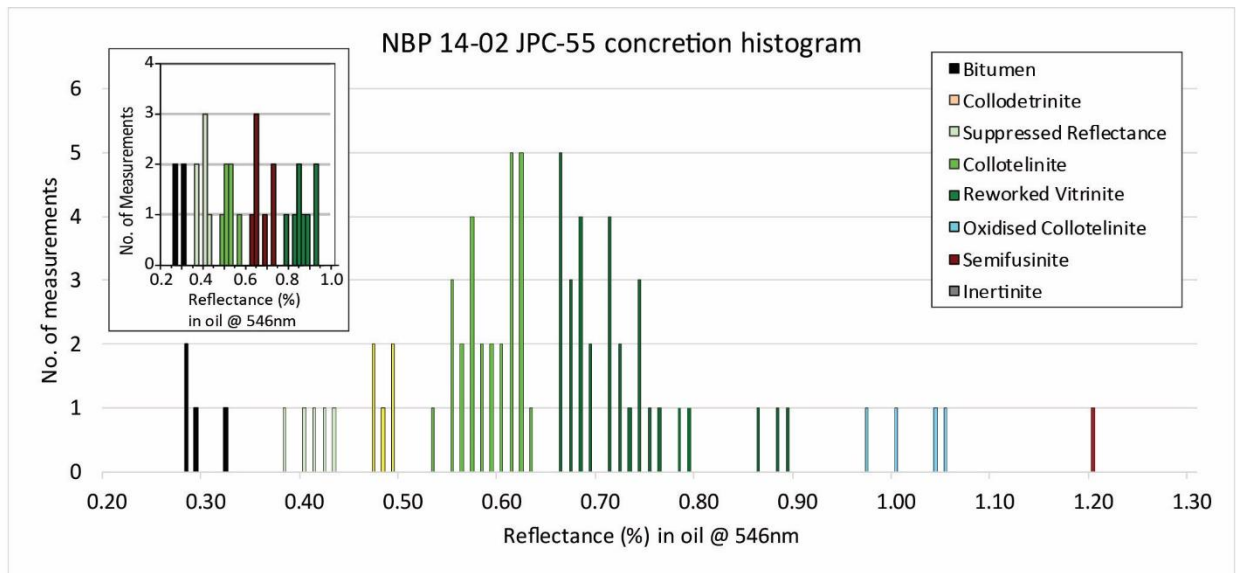


Figure 5. Histograms showing vitrinite reflectance and thermal maturity history. The original analysis is displayed as an inset. The collotelinite group represents the less thermally altered source and correlates to the autochthonous palynomorph population, and the reworked vitrinite represents the more thermally altered source, correlating to the reworked/allochthonous palynomorphs population.

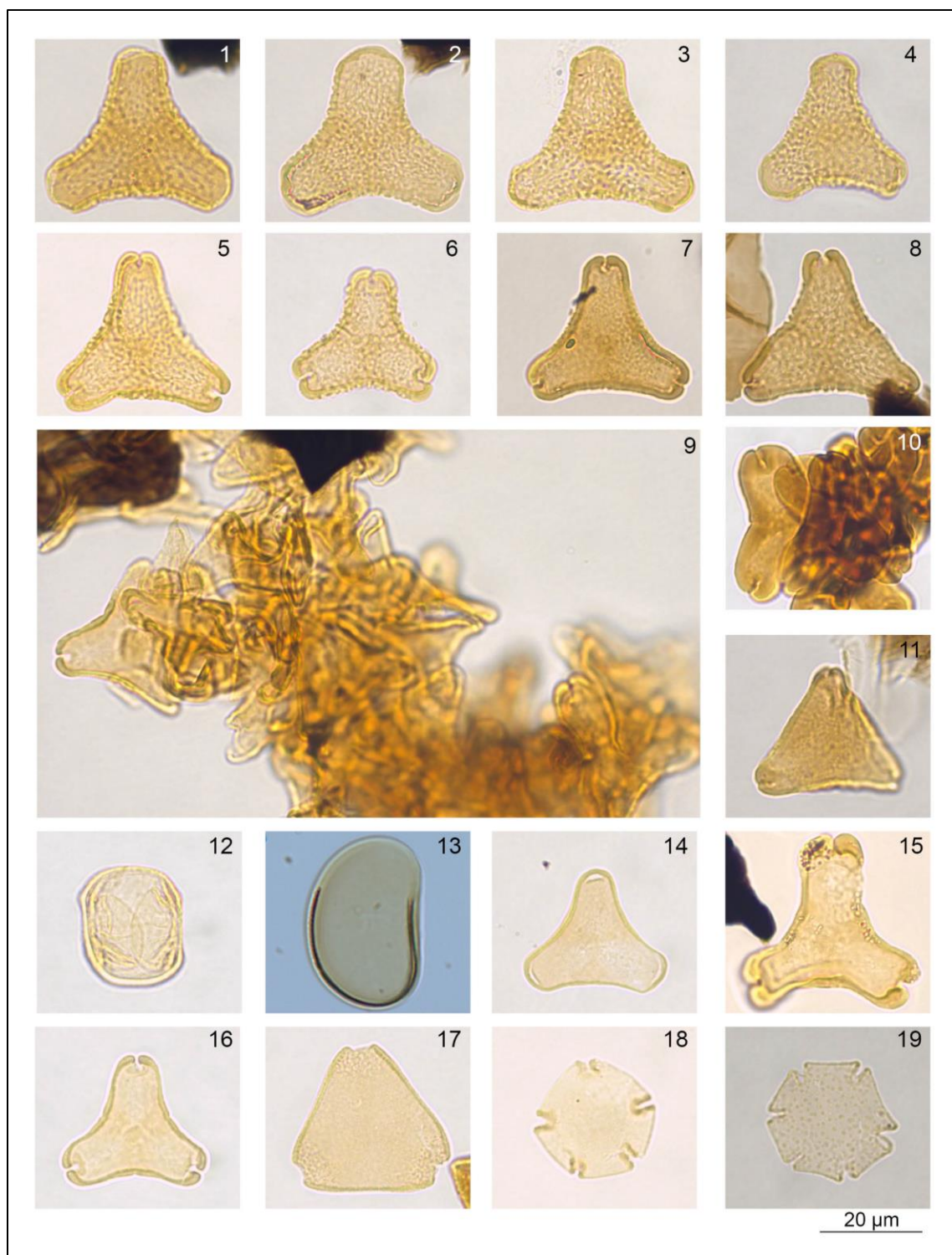


Figure 6. Plate 1. Pollen morphospecies of age significance for JPC-54 and 55. 1-4) *Battenipollis sabrinae* sp. nov. 5-8) *Gambierina truswelliae* sp. nov. 9-10) *Gambierina* spp. clusters 11) *Forcipites longus* 12) *Phyllocladidites mawsonii* 13) *Laevigatosporites ovatus* 14) *Battenipollis sectilis* 15) *Gambierina edwardsii* 16) *Gambierina rudata* 17) *Proteacidites tenuixinus* 18) *Nothofagidites flemingii-rocaensis* complex 19) *Nothofagidites emarcidus*

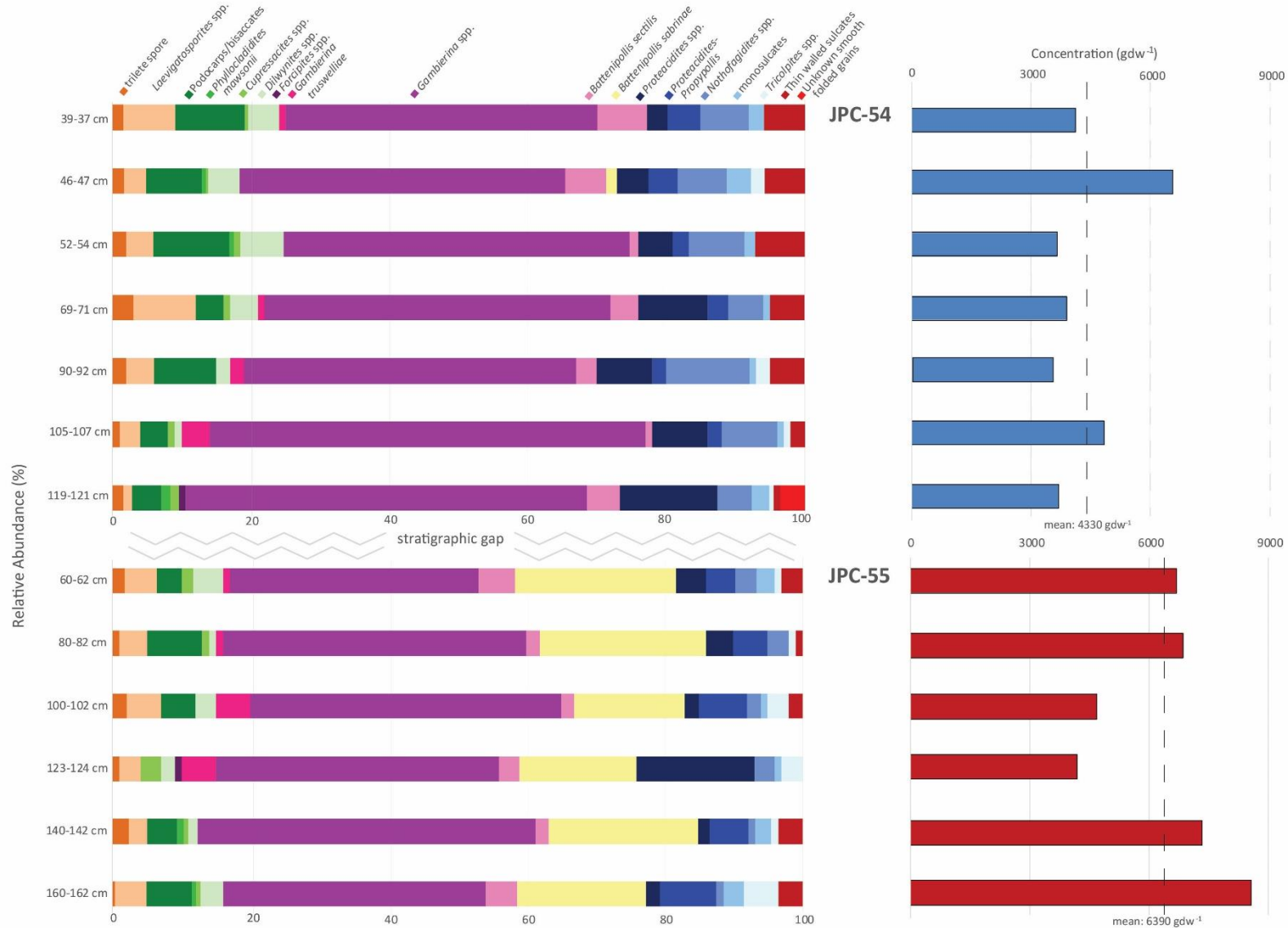


Figure 7. Palynological diagram summarizing relative abundances and concentrations for select intervals in JPC-54 and 55, organized by botanical affinity. Palynomorph concentrations were measured in concentration per gram of dried sediment (gdw⁻¹).

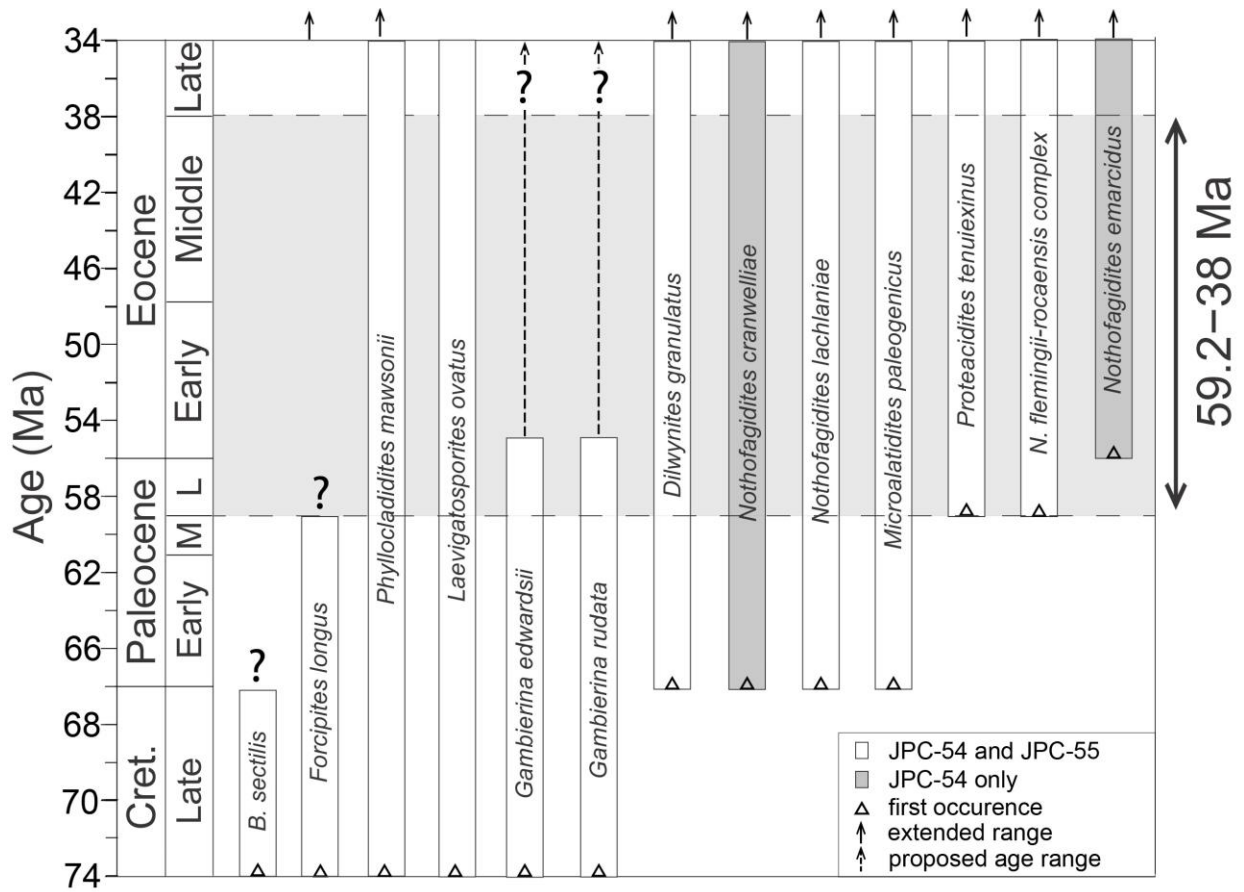


Figure 8. Biostratigraphic range chart including age diagnostic morphospecies.