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Calcareous microplankton biostratigraphy of the Eocene Browns Creek Clay in the Aire District, Otway Basin of southeastern Australia: an update

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In updating the calcareous microplankton stratigraphic record of the lower part of the Browns Creek Clay (the *Turritella* clays and *Notostrea* greensand), Otway Basin of southeastern Australia, unexpected problems with significant consequences were encountered. Assemblages from the base of the formation include two key species, the nannofossil *Isthmolithus recurvus* (hitherto unknown from this level) and the foraminiferid *Acarinina collactea* (unknown from this formation until fairly recently)—in association with *Neococcolithes dubius*, *Chiasmolithus oamaruensis*, *Cyclicargolithus recticulatus*, *Discoaster saipanensis*, *Globigerinatheka index*, *Tenuitella aculeata*, *T. gemma* and *T. insolita*. The stratigraphic range of *I. recurvus* is disjunct (in this respect, *I. recurvus* resembles the two Eocene foraminiferids *T. aculeata* and *G. index* in southern Australia): in its lower range *I. recurvus* is rare, but it is common in its upper range—with a substantial gap in between, within which *N. dubius* disappears. Elsewhere, including other southern high-latitude sections, *A. collactea* is known to disappear well below the first appearance datum (FAD) of *I. recurvus*, and the split stratigraphic range of *I. recurvus* has not been explicitly reported. Reworking could be the cause of the overlap in the stratigraphic ranges of *I. recurvus* and *A. collactea* at Browns Creek, although a seemingly wide geographic distribution of the association of these two species and *N. dubius* in southern Australia has been indicated herein. Evidence (including the presence of rare *T. gemma*) has been discussed, favouring *I. recurvus* (in preference to *A. collactea*) as a prime evidence for dating the base of the Browns Creek Clay. This base has been correlated with the sequence boundary between the third order cycles 4.1 and 4.2, and dated late Eocene, at about 36.2 Ma. *Cyclicargolithus reticulatus* disappears near the *Turritella* clays/*Notostrea* greensand boundary—within the foraminiferid *Hantkenina alabamensis primitiva* interval, which has long been accepted as isochronous across southern Australia. The event of disappearance of *C. reticulatus* is thought to be at 34.9 Ma, in agreement with a previously given K-Ar age limits for the *Hantkenina* interval. The combined evidence of *I. recurvus* and *C. reticulatus* assigns the lower part of the Browns Creek Clay a late Eocene age, equivalent to low either Zone NP19/20 or Subzone CP15b. A correlation with the foraminiferal zonal interval high P15 to within P16 of the tropics is possible.

Introduction

The importance of the Browns Creek section of the Aire District in the Otway Basin, southeastern Australia, to the calcareous microplankton (nannofossil and foraminifera) biostratigraphy of southern Australia cannot be overstressed. Because of its accessible outcrops and richly fossiliferous open-marine facies, the Browns Creek section has been included in numerous palaeontological (e.g. Cookson 1965; Cookson & Eisenack 1965) and biostratigraphic studies (e.g. Carter 1958; McGowran 1973, 1978, 1989; Shafik 1981, 1983; McGowran & Beecroft 1986b; Waghorn 1989; Abele 1994), making it an important reference section in the marine Palaeogene record of southern Australia. Indeed, it "has been a standard for the Upper Eocene" in Australia since the discovery of the foraminiferid *Hantkenina* in it by Parr in 1947 (McGowran 1978, p. 89). The present study is an update of the calcareous microplankton biostratigraphy of the lower part of this important section: closely spaced samples made it possible to precisely determine the levels of several nannofossil biostratigraphic events. New foraminiferal data (e.g. in McGowran & Beecroft 1986b) have provided a good basis for this update; and an unpublished magnetostratigraphic record of the same part of the section made this update especially relevant.

A brief account of the sequence outcropping at Browns Creek (Fig. 1) has been presented by Shafik (1983), but a

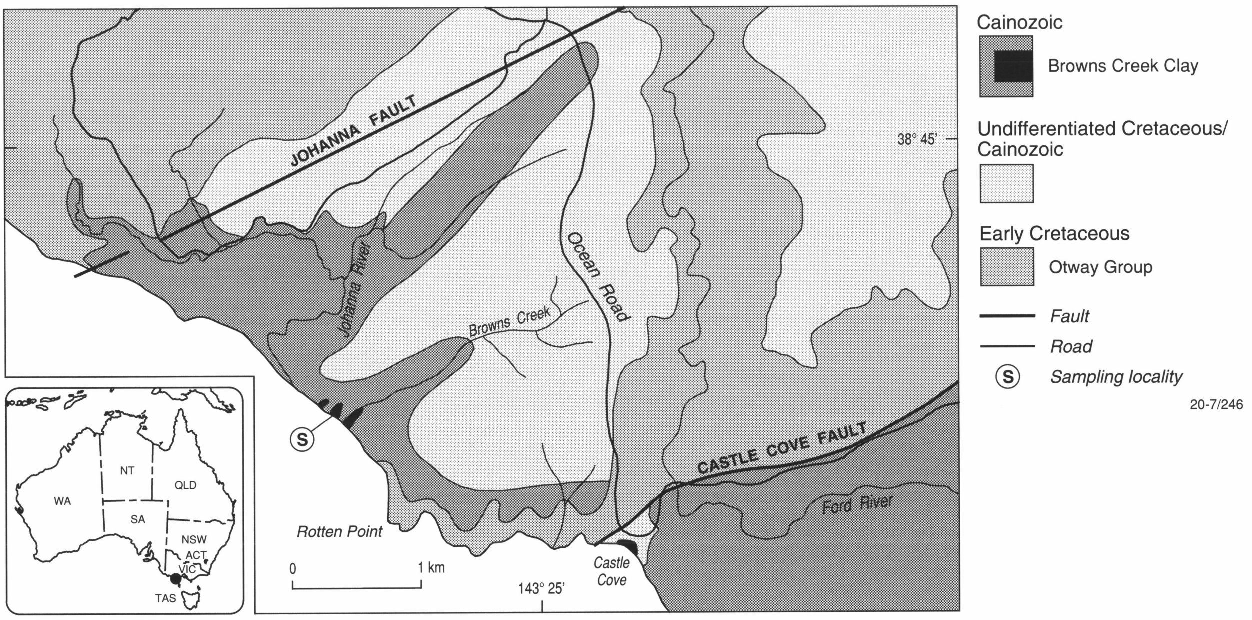

Figure 1. Geological sketch map of the Browns Creek area, Aire District, southeastern Australia. AGSO samples were collected at the gully at S.

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detailed description of the same sequence has been given by Abele et al. (1976) and recently has been discussed by Abele (1994). The transition between the Browns Creek Clay and the underlying Johanna River Sand is usually well exposed in a small gully immediately west of Browns Creek (known as the first gully section—see Tickell et al. 1992; Abele 1994). There, the base of the Browns Creek Clay approximates to a thin discontinuous calcarenite band (the lower in a twin calcarenite band, 60 cm thick—see Fig. 2). The Johanna River Sand is devoid of calcareous microfossil remains, and the base of the Browns Creek Clay coincides with the very first up-section appearance of calcareous microplanktic remains (nannofossils and foraminiferids). This base has been related to a major marine transgression in southern Australia: the later part of the Tortachilla Transgression or the early part of Tuketja Transgression of McGowran & Beecroft (1986b).

In the first gully section at Browns Creek, the lower 9 m of the Browns Creek Clay is predominantly dark grey clay, with common *Turritella* spp., *Spirocolpus aldingae* and the bivalve *Limopsis chapmani*—the so-called *Turritella* clays. A prominent, 1–2 m thick bed of glauconitic sand, the *Notostrea* greensand, separates the *Turritella* clays from an overlying succession of bryozoal marls (20 m thick) and light grey clays (10 m thick).

Material studied. Four sets of samples from the *Turritella* clays and the *Notostrea* greensand in the first gully section were examined: an AGSO set of closely spaced samples (prefixed by either BCN or M, Fig. 2) collected by M. Idnurm and myself in 1987 for a combined nannofossil/palaeomagnetic study; a UA set, also closely spaced samples (prefixed by BC82, Fig. 3), collected for palaeontological studies in 1982 by a group of geologists from the University of Adelaide; a GSV set of samples (prefixed by the letter A, Fig. 4) collected by C. Abele of the Geological Survey of Victoria in 1977 and 1994; and a combined SADME/ESSO set of samples—collected during 1970 and 1971 (prefixed by either V70 or BC71, Fig. 5)—which was partly studied by Shafik (1981). In Figures 2–5 the same thicknesses were adopted for the *Turritella* clays and the *Notostrea* greensand despite differences among the four sets of samples in measurements of these two units. Also sample levels were not always measured relative to the same datum (which has been either the base or the top of the *Notostrea* greensand, or the lower calcarenite band at the base of the *Turritella* clays), but in Figures 2–5 a uniform practice is adopted: the base of the *Notostrea* greensand is taken as the datum for those samples obtained from this unit or from near its boundaries, and the lower calcarenite band is taken as the datum for all other samples. Abele (1994) has shown that the published estimates for the thickness of the *Notostrea* greensand vary between 2.7 m (Raggatt & Crespin 1955) or 2.6 m (Tickell et al. 1992), and 1.2 m (as measured by Hocking et al. 1963 in Cookson & Eisenack 1965 fig. 1); Abele's (1994) own estimate is 0.6 m.

Documentation and significance of the nannofloras

The distribution of calcareous nannofossils in the four sets of samples is given in Figures 2–5. The relative abundance of each species in the AGSO set of samples, given in Figure 2, was determined by counting all specimens in at least 200 fields of view, using a magnification of 1250. The nannofossils in the other sets of samples were not counted. However, these sets were studied to check the distribution pattern of certain key species and to establish a direct link with the foraminiferal results.

Composition of the nannofloras. Species diversity is generally high in both the *Turritella* clays and the *Notostrea* greensand, but the majority of species in a given assemblage occur in low numbers (Fig. 2). And it is the composition of the rare species which determines the main differences between the assemblages. The few species which are common in most assemblages are *Coccolithus eopelagicus, C. pelagicus, Cyclicargolithus floridanus, C. reticulatus, Lanternithus minutus, Reticulofenestra hampdenensis, R. umbilicus*, *Sphenolithus moriformis* and *Zygrhablithus bijugatus*. Most specimens of *Coccolithus pelagicus* have a central plug.

The range of the biostratigraphically important *Isthmolithus recurvus* appears to be disjunct: this species is rare, but undeniably consistently present in the basal 1.65 m of the *Turritella* clays, virtually absent in the overlying 5 m, and reappears in large numbers higher up. A similar disjunct range for *I. recurvus* has not been explicitly reported from any other section anywhere, and, therefore, is worthy of further discussion (see below).

The occurrence of *Neococcolithes dubius* and *Isthmolithus recurvus* together in the basal 1.65 m of the *Turritella* clays requires special attention (see below) because, almost everywhere, a stratigraphic gap has consistently been recorded between the highest occurrence of the former and the lowest occurrence of the latter. A few other cases where the two species occur together are known from southern Australia and New Zealand, however (Shafik 1983; Waghorn 1985; this study). These occurrences conceivably give some physical evidence to the notion commonly held that *I. recurvus* has evolved from *N. dubius* (e.g. Edwards 1971)—but no forms transitional between the two species were recorded there.

Palaeoenvironmental significance of the nannofloras. The palaeontological evidence suggests that the *Turritella* clays were deposited in a neritic environment, on the continental shelf. The nannofossils include several pentaliths and other hemipelagic species such as *Braarudosphaera bigelowii, Holodiscolithus macroporus, Lanternithus minutus, Micrantholithus inaequalis, Orthozygus aureus, Pemma basquense, Pontosphaera multipora* and *Zygrhablithus bijugatus*. Ascidian spicules, common at some levels, support the conclusion of shallow-water deposition. Lithologically the *Turritella* clays and the *Notostrea* greensand are consistent with deposition on the shelf by an advancing sea. Because of the relatively high abundance of mesotrophic species, such as *Cyclicargolithus reticulatus*, and the relatively low abundance of discoasters, it is suggested that levels of nutrients were high during the deposition of the *Turritella* clays (see also Aubry 1992b).

Surface water temperatures were mild as suggested by low abundances of species of both genera *Discoaster* and *Chiasmolithus*. However, there is some evidence of intermittent, warm surface-water currents brought south by the Proto-Leeuwin Current (Shafik 1990) in the Browns Creek area during the late Eocene. This includes the sporadic occurrence of rare *Sphenolithus predistentus* and other warm-water species (see Fig. 2). Notable among these species are *Discoaster barbadiensis* and *Helicosphaera reticulata*, which were found in low abundance in one sample, about 50 cm above the base of the *Turritella* clays.

Biostratigraphic events. Assemblages from the base of the Browns Creek Clay include several biostratigraphically important species: *Isthmolithus recurvus, Neococcolithes dubius, Cyclicargolithus reticulatus*, and *Discoaster saipanensis*. Four significant nannofossil biostratigraphic events are discernible within the *Turritella* clays (Fig. 2):

- *Isthmolithus recurvus* disappears about 1.65 m above the base of the formation. This event (first disappearance of *I. recurvus*) is stratigraphically well below the disappearance levels of the Eocene *Neococcolithes dubius, Cyclicargolithus reticulatus* and *Discoaster saipanensis* in the Browns Creek section. It is yet to be identified in other sections.
- *Neococcolithes dubius* disappears 5.0 m above the base of the formation. The species has been recorded from neritic and oceanic sediments at a wide range of latitudes,

	Blackites spp.	*Braarudosphaera bigelowii*	*Calcidiscus protoannulus*	*Chiasmolithus altus*	*Chiasmolithus oamaruensis*	*Clausicoccus cribellum*	*Coccolithus eopelagicus*	*Coccolithus formosus*	*Coccolithus pelagicus*	*Corannulus germanicus*	*Cyclicargolithus floridanus*	*Cyclicargolithus luminis*	*Cyclicargolithus reticulatus*	*Daktylethra punctulata*	*Discoaster barbadiensis*	*Discoaster distinctus*	*Discoaster saipanensis*	*Discoaster tanii*	*Discoaster tanii nodifer*	*Helicosphaera lophota*	*Helicosphaera reticulata*	*Helicosphaera* aff. *seminulum*	*Holodiscolithus macroporus*	*Isthmolithus recurvus*	*Lanternithus minutus*	*Lithostromation operosum*	*Lithostromation simplex*	*Markalius inversus*	*Micrantholithus inaequalis*	*Neococcolithes dubius*	*Orthozygus aureus*	*Pedinocyclus larvalis*	*Pemma basquense*	*Pontosphaera multipora*	*Reticulofenestra hampdenensis*	*Reticulofenestra* cf. *oamaruensis*	*Reticulofenestra scissura*	*Reticulofenestra scrippsae*	*Reticulofenestra umbilicus*	*Sphenolithus moriformis*	*Sphenolithus predistentus*	*Syracosphaera labrosa*	*Transversopontis* spp.	*Zygrhablithus bijugatus*
M63	C	F	F			F	F		F		C						C							F	C			R	R					C	C		F	F	C	F			C	C
M61	C	F	F	F	R		C	R	C		C		cf				F			F				F	C	F		R	R			R		C	C	R	F		C	F		F	C	C
BCN16	C	F	F			F		F	C	F	F	R					C	F	F				R	C	C			R							C	R	C	F	C	F			C	C
M39	C		F		R	R	F	R	C				cf					F						C	C	F		R						F	F		C		C	F	R	R	C	C
M100	C		R	R									R											C	C			R						R	F	R	C	R	C	C		R	F	C
M49	C	R		R		R	F		C	R	C		F						R					F	A			R						R	F	R	F	F	C	C		R	F	C
M41	C		F		R		C		C		C		C											C	C		R								C		F	F	C	C			C	C
M103	C		F	R		R	F		C		C		C				F	R	R					C	A		R							R	C	?	R	F	F	C			F	C
M43	C		F	R	R				C		C		A				F							A	A									R	C		F	F	C	C		F	C	C
M47	A	F	F		F	F		R	C		C		A			R	R		R						A	R			R					R	C		F	F	C	C		F	C	F
M71	C		R		R	F			F		F		C						R					R	C										C		F	F	F	C			C	C
M45	C	F	F		R	F			C		F		C				R		F						C	R			F						C		F	F	F	C			C	C
BCN14	C		F		F	F	R		F	R	F		C				R		F						C			R					R		C		C	C	C	C		R	C	C
M57	C		F			R	F		F		F		C				R								C					R					C		F	F	C	C	R		C	F
M60	F	F	F		R	R	F	R	C	R	C		C						R						C			R		R			R		F		F	F	C	C	R		C	F
BCN12	F	F	F	F	R	R	F	R	C		C		C				F		C						C				F				R		F		F	F	C	C		R	C	F
M13	F	F	F	F	R		F		C	R	F		C				F						R		C		R			R			R		F		F	F	C	C		R	C	C
BCN11	C	F		F		F	F		F		F		C				C		F						C				R				R	F	F		F	F	C	C			C	C
M21	C	F			F	F	F	R	F	F	F		F				C								C	R		R		R				F	F		C	F	C	C		R	C	C
BCN10	C				F	F	C		C		F		F	R			F								C		R	R		R				F	C		F	F	C	F			C	C
BCN9	C	F	F		F	F	C		C		F		C			F	F		F				R		C		R	R		R			F	F	C		F	F	C	C		R	C	C
M86	C	F			F		C		C		F		C				F		F					R	C	R				R					C		F	F	C	C			C	C
BCN8	C	F			F	F	C		C		F		C				F		F					R	C	R			F	R					F		F	F	C	C			C	C
BCN7	C	F	F		F	F	C	R	C	R	C		C						F				R	R	C			R	F	R	R			F	F		C	C	C	C			C	C
BCN5	C	R	R	?	F		F	R	C	R	F		C	R				R	F	R			R	R	C	R		R	F	F			F	F	F		C	F	C	C			C	C
M33	C	F			R		F	R	C		F		C						F		R	R		R	C			R					F	F	F		C	F	C	C			A	F
BCN4	C	F			F		F	R	C		C		C	R	R		R		F		R	R		R	C				F	R			F	F	F		C	F	C	C		R	C	C
BCN3	A		F		F	R	F		C	R	C		C	R									R	?	C			R						C	C		C	C	C	C			A	C
BCN2																																												
BCN1																																												

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Based on counts in >200 fields of view at 1250X:

A (abundant) = >10 specimens/field of view; C (common) = 1-10 specimens/field of view;

F (few) = one specimen in <10 fields of view; R (rare) = one specimen in >10 fields of view.

In the columnar section, samples BCN1 up to M41 are tied to the lower calcarenite bed, higher samples are tied to the base of the greensand; distance between samples M41 and M49 is exaggerated for consistency with Figs 3 - 5. *Sequence boundary of Haq et al. (1988).

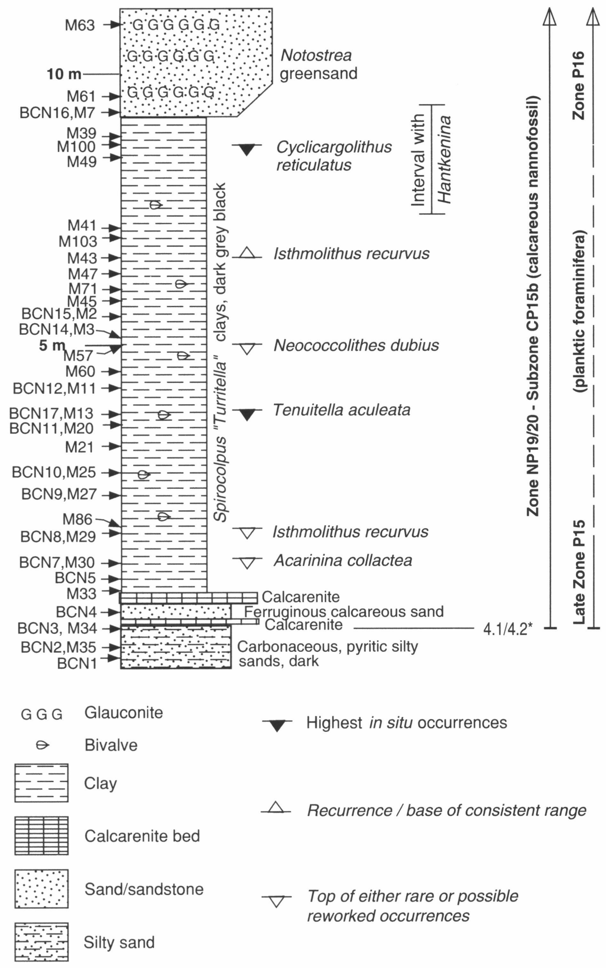
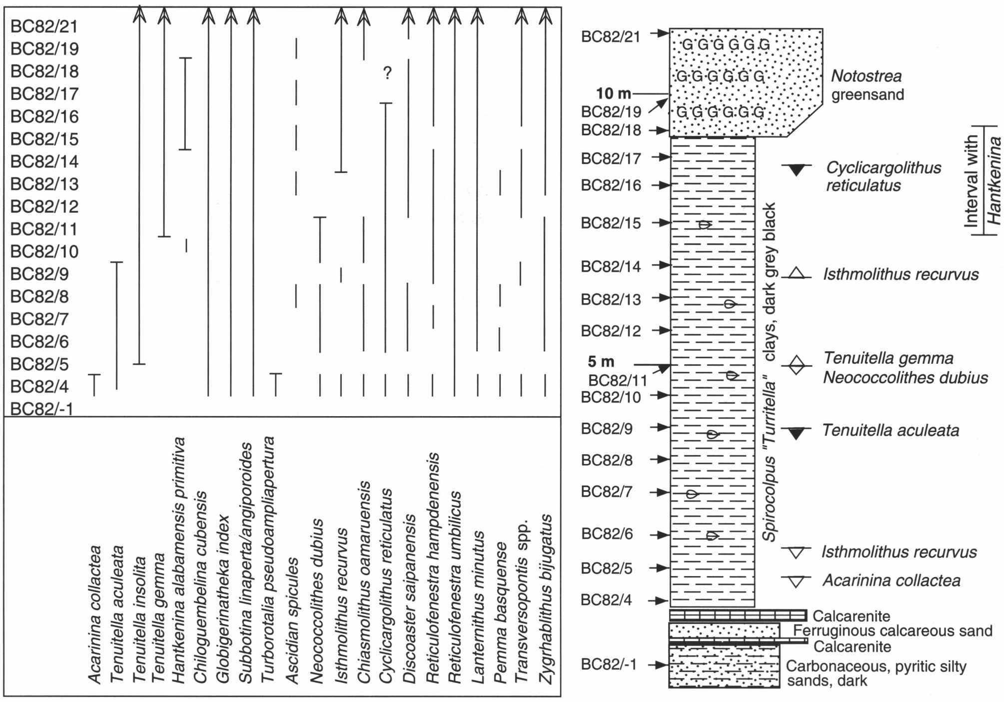


Figure 2. Distribution of selected calcareous nannofossil species in the AGSO set of samples from the lower part of the Browns Creek Clay (first gully, Browns Creek).



In the columnar section, samples BC82/1 up to BC82/15 are tied to the lower calcarenite bed, higher samples are tied to the base of the greensand; distance between samples BC82/15 and BC82/17 is exaggerated for consistency with Figure 4.

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Figure 3. Distribution of selected key calcareous planktic species in the UA set of samples from the lower part of the Browns Creek Clay (first gully at Browns Creek); foraminiferal distributions are from McGowran & Beecroft (1986) and McGowran (1989). Explanation of symbols as in Figure 2.

and its extinction datum could be useful for biostratigraphic correlation over long distances. However, possible reworking in the lower part of the *Turritella* clays, evidenced by the presence of *Daktylethra punctulata* (Figs 2, 4, 5), throws some doubt about the usefulness of this event in correlation of the Browns Creek section.

- *Isthmolithus recurvus* reappears 6.6 m above the base of the formation: in its higher range, *I. recurvus* is common and consistent. Shafik (1993) argued for equating this event of reappearance with the first appearance datum (FAD) of *I. recurvus* elsewhere. However, it can also be argued (see below) that the basal assemblages with rare *I. recurvus* in the Browns Creek section are above the species FAD elsewhere.
- *Cyclicargolithus reticulatus* disappears about 0.5 m below the base of the *Notostrea* greensand. This confirms Shafik's (1981) record of this event within the interval with the foraminiferid *Hantkenina alabamensis primitiva* at Browns Creek (see below). It is worth noting here that the event of disappearance of *Calcidiscus protoannulus* shortly below the last appearance datum (LAD) of *C. reticulatus* at the South Atlantic ODP Site 522 (Backman 1987) could not be identified at a relatively similar level in southern Australia. At Browns Creek, *C. protoannulus* ranges well above the LAD of *C. reticulatus* (see Fig. 2), in agreement with the nannostratigraphy of the (Eocene/Oligocene boundary stratotype) Massignano section in Italy (Premoli Silva & Jenkins 1994). In the Gambier Embayment (western Otway Basin), *C. protoannulus* and *C. reticulatus*, together with *Discoaster saipanensis*, disappear at the same level—at a disconformity at the top of the Eocene (Shafik 1983).

It is difficult to judge whether the gap in the stratigraphic range of *Isthmolithus recurvus* (i.e. between the species disappearance and reappearance levels) in the *Turritella* clays at Browns Creek is due to some local conditions, unlikely to be repeated elsewhere, or could be found somewhere else. In the case of the Browns Creek section, the presence of (rare) *I. recurvus* in the basal 1.65 m (the species lower range) could only be detected by detailed sampling and very careful examination of the assemblages: the species lower disappearance level and, therefore, the gap in its stratigraphic range had not been detected in previous investigations (Shafik 1981, 1983; Waghorn 1989). For a possible documentation of such a stratigraphic distribution of *I. recurvus* in other sections, detailed sampling and thorough examination of the assemblages of the interval between the FAD of *Chiasmolithus oamaruensis* and the LAD of *Neococcolithes dubius*, particularly in facies similar to the Browns Creek Clay (shelfal as opposed to oceanic deposits), are highly recommended. The basal Browns Creek Clay was formed immediately after an environmental change from a non-marine or marginal marine regime to open marine.

Zonal assignment and age. The combination of the age-diagnostic nannofossil species *Chiasmolithus oamaruensis, Cyclicargolithus reticulatus, Discoaster saipanensis* and *Isthmolithus recurvus*, recorded in the base of the *Turritella* clays, suggests a late Eocene age. Strict application of the widely used biostratigraphic zones of Martini (1971) or of Okada & Bukry (1980) indicates an assignment to the late Eocene combined Zones NP19/20 or their equivalent, Subzone CP15b. This assignment is based on the co-occurrence of *I. recurvus* and *D. saipanensis*: FAD of *I. recurvus* defines the base of either NP19/20 or CP15b, and the extinction of *D. saipanensis* defines the tops of these biostratigraphic units. *Discoaster saipanensis* ranges well above the *Notostrea* greensand in the first gully section at Browns Creek (Shafik 1983; Waghorn 1989); most authors consider the extinction datum of *D. saipanensis* as a good approximation of the Eocene/Oligocene boundary (e.g. Perch-Niesen 1985). *Cyclicargolithus reticulatus*, which consistently ranges in the *Turritella* clays to about 0.5 m below the base of the *Notostrea* greensand, is known to disappear well below the extinction

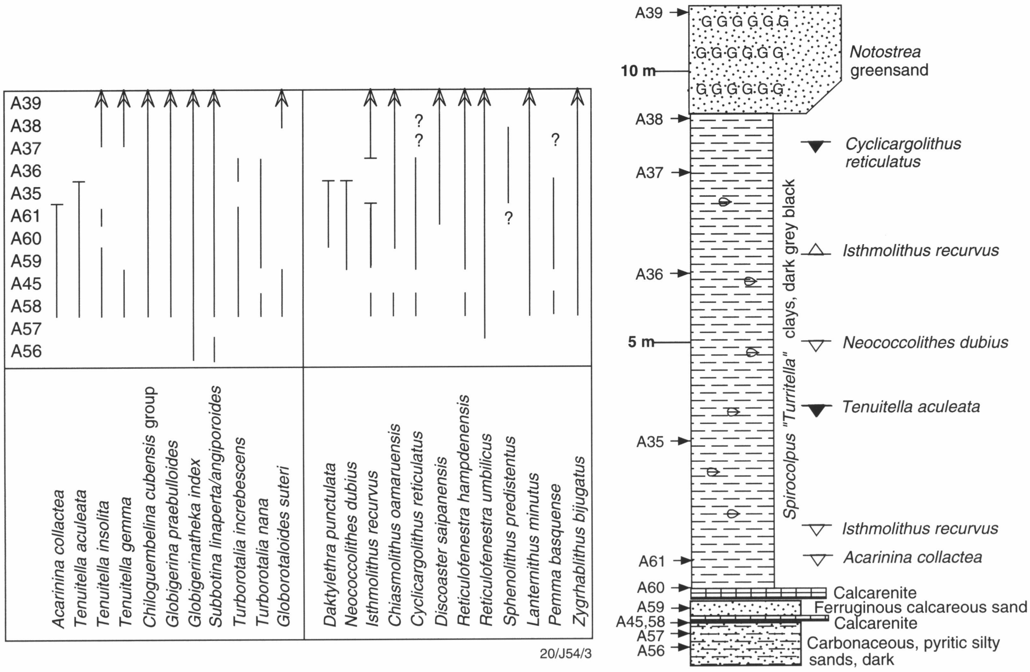

Figure 4. Distribution of selected key calcareous planktic species in the GSV set of samples from the lower part of the Browns Creek Clay (first gully at Browns Creek). Foraminiferal distribution, columnar section and sample levels are from Abele (1994). Explanation of symbols as in Figure 2.

of *D. saipanensis* in mid and low-latitude sections (e.g. Gartner 1971; Shafik 1981; Aubry 1992b). This evidence substantially narrows the biostratigraphic assignment of the *Turritella* clays to the lower part of either the NP19/20 or CP15b zonal interval, which is equivalent to the foraminiferal zonal interval high P15 to within P16, as indicated in the AGSO charts (Chaproniere et al. in press).

The interval of deposition of the *Turritella* clays is substantially less than the duration of either the NP19/20 or CP15b zonal interval.

Sedimentation rate. Published estimates of the duration of the NP19/20 and CP15b zonal intervals vary greatly because they use different time scales. For example, it is 3 m.y. (41–38 Ma; Okada & Bukry 1980), 2 m.y. (38.5–36.5 Ma; Haq et al. 1988) (36.2–34.2 Ma; Wei & Peleo-Alampay 1993), or 1 m.y. (37.8–36.8 Ma; Berggren et al. 1992). Among the numerical age brackets published for either zonal interval, that of Wei & Peleo-Alampay (1993), 36.2–34.2 Ma, is favoured in this study. This is partly because it accommodates the older of the K-Ar age limits of 35.9(±0.5)–32.9(±0.5) Ma estimated for the interval with *Hantkenina alabamensis primitiva* in the St Vincent Basin by Lindsay & Webb (1979). The *H. alabamensis primitiva* interval, thought to be isochronous across southern Australia, is within the zonal interval NP19/20 or its equivalent CP15b at Browns Creek (see below).

I suggest that the deposition of the *Turritella* clays may have occurred in less than two million years (i.e. less than the duration of the NP19/20 and CP15b, as calculated by Wei & Peleo-Alampay, 1993)—probably 1.3 m.y, 36.2–34.9 Ma. This estimate is not in disagreement with the numeric age difference of 1.77 m.y. between the FAD of *Isthmolithus recurvus* and the LAD of *Cyclicargolithus reticulatus* as given by Hazel (1989).

Sedimentation rates in the lower 10 m of the Browns Creek Clay were very slow relative to those for the remainder of the formation in the first gully section (Shafik 1983)—probably about 0.7 cm/k.y. (assuming 1.3 m.y. for the deposition of the *Turritella* clays); this rate is significantly faster, however, than that estimated for the deposition of the coeval part in the (Eocene/Oligocene boundary stratotype) Massignano section in Italy (estimated herein as about 0.3 cm/k.y. for the 4 m thick interval, between the FAD of *I. recurvus* and the LAD of *Cyclicargolithus reticulatus*, in Premoli Silva & Jenkins 1994). The 5 m section at Browns Creek, between the disappearance and reappearance of *I. recurvus*, represents a relatively long time interval—the few isolated occurrences of extremely rare *I. recurvus* noted in this section notwithstanding (Figs 2, 3).

Biostratigraphic significance and age of the foraminiferal assemblages

Foraminiferal results based on examination of the UA set of samples (Fig. 3) have been presented by McGowran & Beecroft (1986b) and McGowran (1989), and those based on the GSV set of samples (Fig. 4) have recently been given by Abele (1994).

Biostratigraphic events. Several key planktic foraminiferal species are present in the base of the Browns Creek Clay in the first gully section. These include common *Acarinina collactea, Chiloguembelina cubensis*, *Globigerinathika index, Subbotina linaperta*, *S. angiporoides* and *Tenuitella aculeata,* in addition to very rare *Tenuitella gemma* and *T. insolita*. The levels of several significant events in the lower 10 m of the Browns Creek Clay, pointed out below, are from McGowran & Beecroft (1986b), Abele (1994) and McGowran (personal communication, Dec. 1993):

- *Acarinina collactea*, common at the base, disappears about 1.1 m above the base of the formation, largely on the basis of the GSV set of samples (Fig. 4). The species occurs, however, in small numbers in a few samples in the uppermost part of the Browns Creek Clay at Castle Cove as well as in the second gully section at Browns Creek; but these high occurrences are probably a result of some reworking (Abele 1994).
- The lowest occurrence of consistent *Tenuitella insolita* is at 1.2 m, based on the UA set of samples (Fig. 3).
- *Tenuitella aculeata* disappears about 3.8 m above the base of the formation, based mainly on the UA set of samples (Fig. 3). The species reappears higher up in the formation

and its second disappearance is also biostratigraphically useful (e.g. McGowran & Beecroft 1986b; Abele 1994).

- The lowest occurrence of consistent *T. gemma* is at about 5.0 m above the base of the formation, based on the UA set of samples (Fig. 3); a few specimens of this species have been recorded from the base of the formation.
- The interval with *Hantkenina alabamensis primitiva* is 7.6–9.3 m, extending from the uppermost part of the *Turritella* clays to within the basal *Notostrea* greensand, based on the UA set of samples (Fig. 3). An isolated occurrence of *H. alabamensis primitiva* at 4.4 m apparently was significant in identifying the Tuketja Transgression at this level at Browns Creek (McGowran 1989).

The stratigraphic order of events indicated above is essentially the same as that summarised by Lindsay (1985) in the intracratonic St Vincent Basin, with two significant exceptions. The lowest consistent occurrence of *Tenuitella gemma* in the St Vincent Basin is at a much lower level, being below the first disappearance level of *Tenuitella aculeata* (this tends to indicate a special importance for the rare *T. gemma* in the base of the *Turritella* clays—Fig. 4). *Acarinina collactea* ranges higher than the interval with *Hantkenina alabamensis primitiva* in the St Vincent Basin (Lindsay 1969). In New Zealand, *A. collactea* ranges to within the interval with *H. alabamensis primitiva* (Jenkins 1985).

Correlation with P zones. Successive attempts at correlating the top of *Acarinina collactea*, and the interval with *Hantkenina alabamensis primitiva* in southern Australia, with the P zonation of the tropics (e.g. McGowran 1978, 1989; McGowran & Beecroft 1986; McGowran et al. 1992) have not differed significantly. Collectively, these correlations suggest the placement of the lower 10 m of the Browns Creek Clay within Zone P15 of middle–late Eocene age—the top of *A. collactea* being within the lower Zone P15, close to the middle/late Eocene boundary, and the top of the interval with *H. alabamensis primitiva* near the top of Zone P15.

Accordingly, the lower 10 m of the Browns Creek Clay was probably deposited over more than 2 m.y., suggesting a significantly slower rate of deposition than indicated above; any possible gaps in this section are deemed to be beyond the current biostratigraphic resolution and, therefore, will not be considered here. The present study suggests a younger correlation with the P zones (see above; Fig. 2).

Discussion

The nannofossil evidence and foraminiferal evidence apparently conflict in dating the base of the Browns Creek Clay (as it coincides with the base of the calcareous microplanktic section at Browns Creek). Thus, this base is late middle Eocene according to the foraminiferal evidence of *Acarinina collactea*, but late Eocene based on the nannofossil evidence of *Isthmolithus recurvus*. This is understandable, especially in terms of data from outside the southern Australian region: the top of the range of *A. collactea* has been used, among other criteria, for approximating the middle/late Eocene boundary at low latitude sites (e.g. Berggren et al. 1985), while the base of the range of *I. recurvus* has been used widely as a good datum well within the late Eocene (e.g. Martini 1971; Hornibrook & Edwards 1971; Perch-Nielsen 1985). The overlap in the stratigraphic ranges of *A. collactea* and *I. recurvus* has not been recorded outside the Australian region. It will be shown below that the record of both *I. recurvus* and *A. collactea* in the base of the Browns Creek Clay is not a result of errors in sampling or sample preparation.

The *Isthmolithus recurvus* record. The occurrence of rare *I. recurvus* at the very base of the Browns Creek Clay, and within the basal 1.65 m, has not been reported in previous studies of the formation (Shafik 1981, 1983; Waghorn 1989). Because these occurrences are in association with *Neococcolithes dubius* (Fig. 2), and because the stratigraphic ranges of these two species are not usually known to overlap, either *I. recurvus* may not be *in situ* (owing to sampling errors or contamination during sampling or sample preparation etc.), or *N. dubius* may have been displaced as a result of reworking from older sediments in the west or south. The possibility of reworking can not be ruled out, especially with the presence of *Daktylethra punctulata* in the lower part of the Browns Creek Clay; *D. punctulata* is thought to disappear below the top of the middle Eocene in the Otway Basin (Shafik 1983). However, because several co-occurrences of *I. recurvus* and *N. dubius* are known from other parts of the Otway Basin and beyond, in New Zealand, and because the stratigraphic range of *D. punctulata* is not well established, the record of both *I. recurvus* and *N. dubius* at Browns Creek is likely to be real. This study records the two species occurring together in a core sample from the western Otway Basin; see also Shafik (1983) for another such a co-occurrence from the western Otway Basin. The two species share a short stratigraphic range in the rapidly deposited Kaiata Creek section in New Zealand (Waghorn 1985).

Based on the UA set of samples, McGowran & Beecroft (1986b) were the first to record the foraminiferid *Acarinina collactea* in the basal part of the Browns Creek Clay—almost two decades after the first record of this species in the Eocene of southern Australia by Ludbrook & Lindsay (1969). Subsequently, this species was identified from the basal 1 m in the AGSO set of samples (A. Beecroft, written communication, Dec. 1993). More recently, Abele (1994) recorded common *A. collactea* in the GSV set of samples, from the basal 1.1 m of the formation (Fig. 4). These records of *A. collactea* indicate that the basal part of the formation in all three sets of samples studied is similarly represented and, therefore, the possibility of a sampling error can be eliminated. The same conclusion is reached from examination of the nannofossil assemblages: a similar distribution of *I. recurvus* can be shown in the three sets of samples, i.e. this species first appears at the base of the formation, and disappears at about 1.65 m to reappear higher up (Figs 2, 3, 4).

The similarity in the distribution of both *A. collactea* and *I. recurvus* in all three sets of samples is good evidence that the overlap in the ranges of these species within the basal 1 m of the Browns Creek Clay is real, in the sense that it is not the result of contamination during either sampling or sample preparation. The possibility that the presence of *A. collactea* may have been in the first instance a result of recycling of (slightly) older sediments during the early phases of deposition of the Browns Creek Clay can not be ruled out completely, despite a wide geographical spread of occurrences of that species in association with *I. recurvus* (and *Tenuitella gemma*—see below) being apparent in southern Australia.

The presence of the foraminiferid *Tenuitella gemma* at the base of the Browns Creek Clay (Fig. 4) supports dating this base as late Eocene age (as indicated by the co-occurrence of *Isthmolithus recurvus* and *Cyclicargolithus reticulatus*) and, consequently, strengthens the case for *I. recurvus* being *in situ*. Interestingly, Li Qianyu (1987) showed the stratigraphic range of *Praetenuitella praegemma/Tenuitella gemma* in the United States Gulf Coast, beginning at the base Zone P16 of the late Eocene.

The stratigraphic range of *Isthmolithus recurvus* in the Browns Creek Clay appears disjunct or split, and a similar disjunct range for this species has not been explicitly reported previously in the formation nor in any other section. However, the records of the species by both Shafik (1981) and Waghorn (1989) are largely consistent with the results of the present study. Shafik (1981) recorded the lowest occurrence of *I. recurvus* at 5.5 m above the base, and in a subsequent publication (Shafik 1983) revised this level to 7.0 m above the base. Older levels, studied by Shafik (1981) are where the species is likely to be extremely rare (at 0.9 m) or absent (2.4 & 4 m) according to the data in Figure 2. Similarly, Waghorn (1989) did not report *I. recurvus* from his lower three samples, below the 4 m level, and identified this species unreliably in sample A36, but confidently in sample A37 (see Fig. 4 herein for levels of these samples). Re-examination of Shafik's (1981) material showed that *I. recurvus* at the 5.5 m level (sample BC71/5 in Fig. 5) must be extremely rare, for it could not be identified again. The species occurs in the next sample up, BC71/6 at the 7.0 m level above the base of the *Turritella* clays—consistent with Shafik's (1983) results (see Fig. 5). Shafik's (1981) record of *I. recurvus* at 5.5 m level is regarded as an isolated occurrence of the species, similar to that at 3.8 m (sample BC82/9 in Fig. 3) or that at the 6.0 m level (M71 in Fig. 2). The reappearance of consistent *I. recurvus* at 6.6 m (in sample M43 in Fig. 2) is also supported by the distribution of the species in other sets of closely spaced samples (UA set, Fig. 3 and GSV set, Fig. 4).

Two key Eocene foraminiferids, *Tenuitella aculeata* and *Globigerinatheka index,* have disjunct stratigraphic ranges in the neritic facies of southern Australia (e.g. McGowran & Beecroft 1986a).

At the South Atlantic DSDP Site 523, the stratigraphic range of *Isthmolithus recurvus* is disjunct, but the lower occurrences of the species are bracketed up and down with occurrences of *Chiasmolithus grandis* and are regarded, therefore, as a result of downhole contamination (Backman 1987).

The *Acarinina collactea* record. The occurrence of *A. collactea* in the basal part of the Browns Creek Clay presents a problem because of the associated *Isthmolithus recurvus*. An overlap in the stratigraphic ranges of these two species has not been reported outside the southern Australian region. For example, evidence from oceanic southern high-latitude sections, in the South Atlantic, Antarctica and Kerguelen Plateau (compare Pujol 1983 and Backman 1987 for DSDP Site 523; Wei & Wise 1990 and Stott & Kennett 1990 for ODP Site 689; Huber 1991 and Wei & Thierstein 1991 for ODP Site 738; Aubry 1992a and Berggren 1992 for ODP Site 748) shows a gap between their stratigraphic ranges. Indeed, at ODP Site 689 the top of the range of *A. collactea* is shown to be slightly below the middle/late Eocene boundary (Stott & Kennett 1990), whereas the base of the range of *I. recurvus* has been used at the same site as a good late Eocene datum (Wei & Wise 1990).

The overlap in the stratigraphic ranges of *Acarinina collactea* and *Isthmolithus recurvus* in the lower part of the Browns Creek Clay in the Aire District (this study) seems to be real, as it is repeated in widely spaced areas in southern Australia: (a) *I. recurvus* has been reported in the lower Blanche Point Formation (the Transitional Marl or the Tuketja member), in the St Vincent Basin (Shafik in Jenkins 1974; Shafik 1981), and higher up in the same formation (Waghorn 1989), seemingly within the stratigraphic range of *A. collactea* as shown by Lindsay (1985, 1969); (b) *I. recurvus* has been reported occurring with *A. collactea* in dredge and core samples from the offshore western Otway Basin (Shafik 1992; Abele

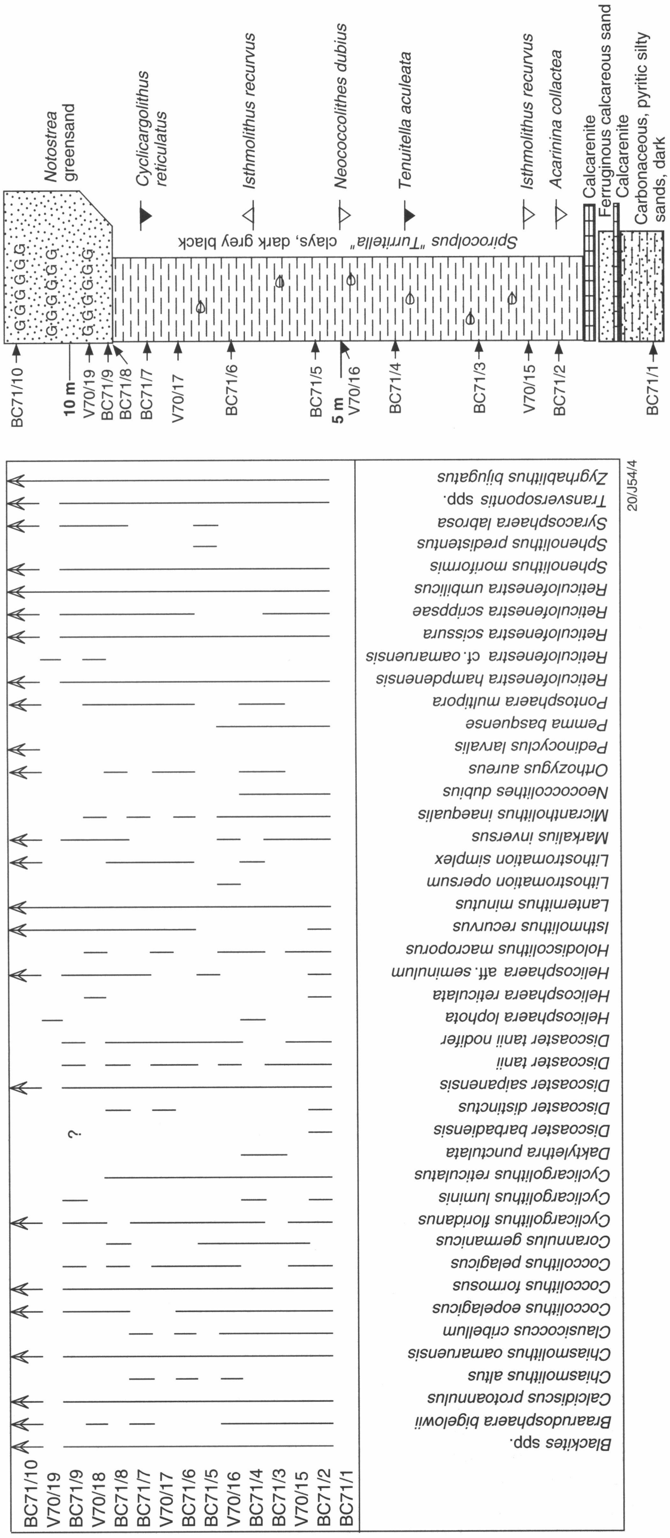

Figure 5. Distribution of selected calcareous nannofossil species in the SADME/ESSO set of samples from the lower part of the Browns Creek Clay (first gully at Browns Creek) revised from Shafik (1981). Explanation of symbols as in Figure 2.

1992); and (c) re-examination of the Lacepede Formation core F84/70 from SADME Observation Bore #2 (Shafik 1983, table 5) in the Gambier Embayment (western Otway Basin) which contains rare *A. collactea* (McGowran 1973), confirmed the presence of rare *I. recurvus*, incidentally with rare *N. dubius*. [It is worth noting that the Lacepede Formation core F84/70, at 135.0 m in SADME Observation Bore #2 is immediately above the top of *A. collactea*, which is at 135.3 m according to McGowran (1973) and Lindsay (1985); the few specimens of *A. collactea* in this core (McGowran, 1973) notwithstanding. Indeed, it is McGowran's (1989, p. 52) opinion that the occurrences of *A. collactea* in the Blanche Point Formation (Stuart 1969; Lindsay 1981, with references) and in the younger Port Willunga Formation (as high as the basal Oligocene) are sporadic and "do not seriously affect the top of the species' range" being below the first disappearance level of *Tenuitella aculeata* (as shown, e.g., in Fig. 3).]

Dating the base of the *Turritella* clays

The question here is which of the two biostratigraphic criteria should be used—the top of *Acarinina collactea* or the base of *Isthmolithus recurvus*? In the first instance, the traditionally accepted concept 'that the first appearance of a species is usually more reliable that its extinction because of possible problems with reworking' would suggest greater confidence in using the base of *I. recurvus* than the top of *A. collactea*. This is particularly so considering that 'reworked' *A. collactea* has been recorded in the upper parts of the Browns Creek Clay (Abele 1994) and, especially, because using the top of *A. collactea* suggests an older age than the base of *I. recurvus*. The older age based on the *A. collactea* evidence is negated by other nannofossil events (see below) and, to a lesser degree, by foraminiferal evidence (as indicated above).

The use of the top of *Acarinina collactea* would suggest placement of the base of the *Turritella* clays very close to the middle/late Eocene boundary (e.g. McGowran 1989). Nannofossil evidence for identifying this boundary in the Otway Basin (in particular the Gambier Embayment) has already been found to match that used elsewhere, and this supports a late Eocene age for the base of the *Turritella* clays. The FAD of *Chiasmolithus oamaruensis* (= base of Zone NP18 of Martini 1971; base of Subzone CP15a of Okada & Bukry 1980) has been used widely to indicate the base of Priabonian (e.g. Berggren et al. 1985; Haq et al. 1988) and, similarly, the extinction of *Chiasmolithus grandis* has been used, particularly in low-latitude sections, to indicate the top of the middle Eocene (e.g. Bukry 1973). Very rarely do *C. oamaruensis* and *C. grandis* occur together, and only for a short time. This overlap has been recorded in one core sample in the Gambier Embayment of the Otway Basin (Shafik 1983). *Chiasmolithus grandis* has not been found in the *Turritella* clays. Instead, *Chiasmolithus oamaruensis* was found at the base of this unit (Shafik 1981, 1983; Waghorn 1989) in association with *Isthmolithus recurvus* (this study): the base of the *Turritella* clays is *well* above the FAD of *C. oamaruensis*, and the middle/late Eocene boundary. This conclusion is supported by the presence of the foraminiferid *Tenuitella gemma*, also in the base of the *Turritella* clays, suggesting a late Eocene age.

Relative to other biostratigraphic events, the top of *Acarinina collactea* may not be a reliable event in southern Australia (Shafik 1983). For example, common *A. collactea* and *Tenuitella gemma* have been recorded together in the offshore Otway Basin (Abele 1992) with *Isthmolithus recurvus* (Shafik 1992), whereas data from the onshore part of the basin suggest that consistent *T. gemma* first appears well above the top of *A. collactea* (McGowran 1978, 1986); this offshore Otway Basin record fits with the stratigraphic ranges of these species in the St Vincent Basin as shown by Lindsay (1985). The stratigraphic range of *A. collactea* overlaps with that of *Hantkenina alabamensis primitiva* in St Vincent Basin (e.g. in SADME South Parklands Bore, Adelaide City area—Lindsay 1985), whereas in the Otway Basin a stratigraphic gap exists between the top of *A. collactea* and first *H. alabamensis primitiva* (McGowran 1978, 1986, 1989). That the top of *A. collactea* is inconsistent, relative to other biostratigraphic events, is also shown in other southern mid to high-latitude locations. For example, the relative order of disappearance of *A. collactea* and *Subbotina linaperta* on the Kerguelen Plateau (several ODP sites: see Huber 1991; Berggren 1992) is the reverse to that at the Antarctic Site 690 (Stott & Kennett 1990)—as already noted by Berggren (1992). *Acarinina collactea* ranges well above the base of *Chiasmolithus oamaruensis* on the Kerguelen Plateau (ODP Sites 738, 748 & 749: Huber 1991 and Wei & Thierstein 1991 for Site 738; Aubry 1992a and Berggren 1992 for Sites 748 & 749), and in New Zealand (Waghorn 1985). However, the reverse is true at several DSDP/ODP sites in the South Atlantic and near Antarctica (e.g. Pujol 1983 and Wei & Wise 1989 for DSDP Site 516; Stott & Kennett 1990 and Wei & Wise 1990 for ODP Site 689), where *A. collactea* disappears well below the base of *C. oamaruensis*.

Isthmolithus recurvus is rare or absent at low latitudes, but common in mid and high latitude areas, and "... can be considered a consistent marker fossil only at latitudes higher than 30° north or south" (Bukry 1975, p. 682). The present latitude of Browns Creek is higher than 30°, at about 38° 50′S (Fig. 1), and according to the pole deduced in a parallel study (Idnurm 1994), the first gully section was at about 58°S during the late Eocene. Nevertheless conditions probably were not optimum during the deposition of the *Turritella* clays, as evidenced by the species' poor record in the lower part of these clays.

In view of the above, *Isthmolithus recurvus* seems a more serious contender for dating the *Turritella* clays than *Acarinina collactea*. However, the split range of *I. recurvus* in these clays poses a difficult question—particularly in view of the fact that the species, being rare in its lower range, can be easily missed (as was the case with Shafik 1981 and Waghorn 1989). The question is: which of the species' two appearance levels is correlatable with the species FAD elsewhere at mid and high latitudes? In an abstract, I favoured the species' reappearance level at Browns Creek, on the basis of the presence of *Neococcolithes dubius* and *A. collactea*, and the rarity of *I. recurvus* in the lower occurrences (Shafik 1993). Since then, I have found, as indicated above, *A. collactea*, *N. dubius* and *I. recurvus* occurring together in material in southern Australia other than the Browns Creek Clay (admittedly from sections with apparently very slow rates of deposition). This evidence, in addition to the presence of *Tenuitella gemma* (at the base of the formation, Fig. 4) indicating a late Eocene age for the base of the *Turritella* clays, favours considering the lower occurrence of *I. recurvus* at Browns Creek as being above the species FAD elsewhere.

Acarinina collactea may have survived longer in some higher latitude neritic environments than at low-latitudes, as probably was the case in the St Vincent and Otway Basins (southern Australia) and Chatham Islands (New Zealand). This species has been found in one basal Runangan (upper Eocene) sample from the Chatham Islands of New Zealand (Hornibrook et al. 1989). It is worth mentioning that the base of the range of *I. recurvus* in New Zealand has been indicated to be well below the Runangan, within the Kaiatan (Hornibrook & Edwards 1971), but *A. collactea* and *I. recurvus* have yet to be found together in New Zealand.

Sequence stratigraphy of the *Turritella* clays and the *Notostrea* greensand

Loutit (1992 and personal communication 1994) and McGowran et al. (1992) identified correlatives in the Browns Creek section with sequence boundaries of Haq et al. (1988). Loutit correlated the base of the *Turritella* clays with the sequence boundary between the second-order cycles TA3 and TA4, and the base of the *Notostrea* greensand with the sequence boundary between the third-order cycles 4.1 and 4.2. McGowran et al. correlated a level within the basal 2 m of the *Turritella* clays with the sequence boundary between the third-order cycles 4.1 and 4.2. Critical to these correlations were the then known biostratigraphic events in the lower Browns Creek Clay (the *Turritella* clays and *Notostrea* greensand) and their numeric ages. Loutit's correlations are based on biostratigraphic events which could not make use of the presence of either *A. collactea* or *Isthmolithus recurvus* at the base of the formation, and those by McGowran et al. considered the presence of *A. collactea* (at the base of the formation, without the association of *I. recurvus*) as well as the presence of a perceived unconformity in the lower part of the *Turritella* clays (at the level of sample BC82/5 in Fig. 3).

The present study suggests correlation of the base of the *Turritella* clays with the sequence boundary between the third-order cycles 4.1 and 4.2 (see Fig. 2), making use of the presence of *I. recurvus* and *Tenuitella gemma*. Rates of deposition varied between the different subunits of the first gully section at Browns Creek (the *Turritella* clays, *Notostrea* greensand and the overlying marl/clay package), being relatively slow during the deposition of the *Turritella* clays and *Notostrea* greensand, and accelerating thereafter. The *Turritella* clays and *Notostrea* greensand are good candidates for being a condensed section.

Tickell et al. (1992) regarded the base of the *Turritella* clays as representing a change from a lowstand cycle to a transgressive cycle, and the *Notostrea* greensand as a condensed interval, and identified a sequence boundary within the Browns Creek Clay in the second gully section.

Summary and conclusions

The presence of *Isthmolithus recurvus*, *Acarinina collactea* and *Neococcolithes dubius* in the basal 1 m of the *Turritella* clays is not the product of error in sampling or sample preparation. A seemingly wide geographic distribution of the association of these three species in southern Australia suggests the possibility that *A. collactea* and *N. dubius* have survived longer at Browns Creek than at low-latitudes, but, based on the presence of *Daktylethra punctulata* in the lower part of the *Turritella* clays, it is difficult to rule out the possibility that these two species are the product of recycling of older sediments.

The evidence of *Acarinina collactea*, in indicating an age for the base of the *Turritella* clays close to the middle/late Eocene boundary, is weakened considerably by the association of both (albeit rare) *Tenuetella gemma* and *Isthmolithus recurvus*. The top of the stratigraphic range of *A. collactea* at several southern mid to high-latitude locations (St Vincent Basin of southern Australia, New Zealand, Kerguelen Plateau, South Atlantic) is inconsistent relative to the ranges of other calcareous microplankton key species (e.g. *Chiasmolithus oamaruensis* or *Subbotina linaperta*).

Isthmolithus recurvus has a seemingly disjunct range in the *Turritella* clays. The chances of finding a similar record elsewhere are largely dependent on a willingness to search diligently for the species (in the later part of the range of *Neococcolithes dubius*) in closely spaced samples, particularly, of similar (neritic) facies at comparable latitudes. The reward is great—two additional biostratigraphic events and finer resolution.

With *Isthmolithus recurvus* being present, the ranges of *Cyclicargolithus reticulatus* (disappearing about 0.5 m below the base of the *Notostrea* greensand—within the *Hantkenina alabamensis primitiva* interval), and *Discoaster saipanensis* (disappearing well above the *Notostrea* greensand) restrict the *Turritella* clays to the lower part of either the NP19/20 or CP15b zonal interval, and suggest a possible correlation within the foraminiferal zonal interval high P15 to within P16. The age is late Eocene, 36.2–34.9 Ma.

The contact Johanna River Sand/Browns Creek Clays at Brown Creek, Aire District of Victoria is correlated with the sequence boundary between the third-order cycles 4.1 and 4.2 of Haq et al. (1988).

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Appendix: Calcareous nannofossils referred to in this paper

Blackites spp. including
  Blackites perlongus (Deflandre) Shafik, 1981
  Blackites spinulus (Levin) Roth, 1970
  Blackites tenuis (Bramlette and Sullivan) Sherwood, 1974
Braarudosphaera bigelowii (Gran and Braarud) Deflandre, 1947
Calcidiscus protoannulus (Gartner) Loeblich and Tappan, 1978
Chiasmolithus altus Bukry and Percival, 1971
Chiasmolithus grandis (Bramlette and Riedel) Radomski, 1968
Chiasmolithus oamaruensis (Deflandre) Hay, Mohler and Wade, 1966
Clausicoccus cribellum (Bramlette and Sullivan) Prins, 1979
Clathrolitus ellipticus Deflandre *in* Deflandre and Fert, 1954
Coccolithus eopelagicus (Bramlette and Riedel) Bramlette and Sullivan, 1961
Coccolithus formosus (Kamptner) Wise, 1973
Coccolithus pelagicus (Wallich) Schiller, 1930
Corannulus germanicus Stradner, 1962
Cyclicargolithus floridanus (Roth and Hay) Bukry, 1971
Cyclicargolithus luminis (Sullivan) Bukry, 1971
Cyclicargolithus reticulatus (Gartner and Smith) Bukry, 1971
Daktylethra punctulata Gartner *in* Gartner and Bukry, 1969
Discoaster barbadiensis Tan Sin Hok, 1929
Discoaster distinctus Martini, 1958
Discoaster saipanensis Bramlette and Riedel, 1954
Discoaster tanii Bramlette and Riedel, 1954
Discoaster tanii nodifer Bramlette and Riedel, 1954
Helicosphaera lophota Bramlette and Sullivan, 1961
Helicosphaera reticulata Bramlette and Wilcoxon, 1967
Helicosphaera seminulum Bramlette and Sullivan, 1961
Holodiscolithus macroporus (Deflandre) Roth, 1970
Isthmolithus recurvus Deflandre *in* Deflandre and Fert, 1954
Lanternithus minutus Stradner, 1962

Lithostromation opersum (Deflandre) Bybell, 1975
Lithostromation simplex (Klumpp) Bybell, 1975
Markalius astroporus (Stradner) Mohler and Hay *in* Hay and others, 1967
Markalius inversus (Deflandre) Bramlette and Martini, 1964
Micrantholithus inaequalis Martini, 1961
Neococcolithes dubius (Deflandre) Black, 1967
Orthozygus aureus (Stradner) Bramlette and Wilcoxon, 1967
Pedinocyclus larvalis (Bukry and Bramlette) Loeblich and Tappan, 1973
Pemma basquense (Martini) Bouché, 1962
Pontosphaera multipora (Kamptner) Roth, 1970
Reticulofenestra hampdenensis Edwards, 1973
Reticulofenestra oamaruensis (Deflandre) Stradner and Edwards, 1968
Reticulofenestra scissura Hay, Mohler and Wade, 1966
Reticulofenestra scrippsae (Bukry and Percival) Shafik, 1981
Reticulofenestra umbilicus (Levin) Martini and Ritzkowski, 1968
Sphenolithus moriformis (Brönnimann and Stradner) Bramlette and Wilcoxon, 1967
Sphenolithus predistentus Bramlette and Wilcoxon, 1967
Syracosphaera labrosa Bukry and Bramlette, 1969
Transversopontis spp. including
    Transversopontis obliquipons (Deflandre) Hay, Mohler and Wade, 1966
    Transversopontis pulcher (Deflandre) Perch-Nielsen, 1967
    Transversopontis zigzag Roth and Hay *in* Hay and others, 1967
Zygrhablithus bijugatus bijugatus (Deflandre) Deflandre, 1959

Foraminifera referred to in this paper

Acarinina collactea (Finlay, 1939)
Chiloguembelina cubensis (Palmer, 1934)
Globigerinathika index (Finlay, 1939)
Hantkenina alabamensis primitiva Cushman & Jarvis, 1929
Praetenuitella praegemma Li Qianyu, 1987
Subbotina linaperta (Finlay, 1939)
Subbotina angiporoides (Hornibrook, 1965)
Tenuitella aculeata (Jenkins, 1966)
Tenuitella gemma (Jenkins, 1966)
Tenuitella insolita (Jenkins, 1966)

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