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# The Sedimentology and Palaeoenvironments of the Late Cretaceous Sherbrook Group in the Otway Basin

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## ABSTRACT

The first marine incursions that flooded the Otway Basin, southern Australia, during the Late Cretaceous are preserved in the Sherbrook Group. The purpose of this preliminary study is to describe the depositional environments of the sediments of the Sherbrook Group.

Core was logged from the Waarre, Flaxman, Belfast Mudstone, Nullawarre Greensand, Paaratte and Timboon Sandstone units in the Port Campbell Embayment and the Southern Australian part of the Otway Basin. This was combined with ditch cutting, foraminiferal and wireline log data to arrive at the following palaeoenvironmental evolution of these units:

The shallow marine lower to upper-deltaic sediments of the Waarre and Flaxman formations represent the initial deposits of the Late Cretaceous transgression. From Coniacian to Santonian time, the Otway Basin was dominated by open marine conditions leading to the deposition of the inner to outer shelf Belfast Mudstone. Three distinct units (Lower, Middle and Upper) can be recognised in the Belfast Mudstone based on fauna and lithology. From Santonian to Maastrichtian times, regressive, shallow-marine, lower to upper-deltaic and interdistributary sediments of the Nullawarre Greensand, Paaratte Formation and the Timboon Sandstone prograded over the Belfast Mudstone.

## INTRODUCTION

The initial development of the Otway Basin began in response to Late Jurassic-Early Cretaceous continental extension between Australia and Antarctica around 158 million years ago (Cooper 1995). The second stage of rifting and sea floor spreading initiated around 97 million years ago (Veevers et al. 1991, Figure 1), a widespread hiatus marks this event in sediments along the southern margin of Australia. The break up of Australia from Antarctica at around 97 million years ago established marginal to open marine conditions in various basins along the southern margin of Australia. These basins accumulated thick sequences of Late Cretaceous marine siliciclastics and Tertiary carbonates that preserve faunal and sedimentological signals relating to the progressive opening of the Southern Ocean from this time. Marine conditions spread from southwestern to southeastern Australia by the Late Cretaceous (c. 70 million years ago). At this time, 70 million years ago, it is thought a land barrier prevented any oceanic circulation between the Tasman Rise and Antarctica (Exon et al. 1997). It was not until the latest Cretaceous that marine circulation breached the Tasman Rise (Exon et al. 1997), culminating with the establishment of the 'proto' Antarctic Circumpolar Current in the Southern Ocean during middle Tertiary times (around 35 million years ago; Gallagher & Holdgate 2000). Late Cretaceous strata along Australia's southern margin preserve the first shallow marine vestiges of the now vast Southern Ocean. An extensive database has been accumulated during petroleum exploration along the southern Australian basins. These data will form the basis for an integrated study of Late Cretaceous marine strata of Australia's southern margin, the preliminary results of which are presented here.

The first marine sediments are thought to have a Late Cenomanian age (c. 95 ma) and are preserved as the Waarre Formation in the Otway Basin (Figure 1), representing a marine inlet between Antarctica and Australia that progressively widened as rifting proceeded. From Turonian time, sequences in the Otway Basin became progressively more open marine in character as sea-level rose. The peak of marine sedimentation in the Late Cretaceous began in the Coniacian and is represented by the deposition of the deltaic Belfast Mudstone (Figure 1). Long term eustatic sea-level fall commencing sometime during the Coniacian led to the Sherbrook Group sediments becoming progressively less marine in character (Nullawarre Greensand, Paaratte Formation and Timboon Sandstone, Figure 1).

The stratigraphy of the Otway Basin was first described by Bock & Glenie (1965) and Glenie (1971). An attempt to reconcile some of the stratigraphic problems of the Otway Basin was made by Moreton et al. (1994). A more recent description of the Otway Basin stratigraphy is given by Morton & Drexel (1995), whilst Moore et al. (2000) give a revised summary version (Figure 1). Taylor (1964a, b; 1971) described the foraminifera and palaeoenvironmental evolution of the Late Cretaceous (Coniacian-Santonian) Belfast Mudstone in the onshore Otway Basin based on a study of over 20 wells. Using Taylor's initial study as a basis, further foraminiferal analyses, wireline log and sedimentological analyses can be used to chart the palaeoenvironment of the Belfast Mudstone. Since the early 1970's, numerous wells have been drilled both onshore and offshore in the Otway Basin and have intersected units of Late Cretaceous age. In the past ten years the most significant gas discoveries have been recovered from the Late Cretaceous Waarre Sandstone Formation. The discovery wells include La Bella-1 and Minerva-1 in 1993, and Thylacine-1, Geographe-1 and Croft-1 discovered earlier this year (PESA News 2001).

## METHODS

Three sections were logged and sampled from the Sherbrook Group for this study: core from Nirranda-6 and Port Campbell-2 wells from the Victorian Otway Basin and Mt Salt-1 from South Australia (Figure 2). Wiltshire Geological Services supplied the wireline (log) data. The facies analyses used to construct the logs in Figures 3 to 6 were carried out principally by visually logging the core and description of ditch cutting (DC) samples using a stereobinocular microscope.

Twelve core and twenty ditch cutting (DC) samples were processed for foraminifera in the Nirranda-6 well. The foraminiferal assemblages derived in this study for Nirranda-6 are illustrated in Figures 5 & 6. The taxonomy used in this study follows that outlined in Taylor (1964a). Foraminiferal data from Taylor (1964a) for Port Campbell-2 and from Ludbrook (1971) for Mt Salt-1 are illustrated on Figures 3 & 4. The palynological zonal data was obtained from Partridge (1996) for Port Campbell-2 and from Evans (1966) for Mt Salt-1 with supplementary data derived from Morton & Drexel (1995, Figure 1).

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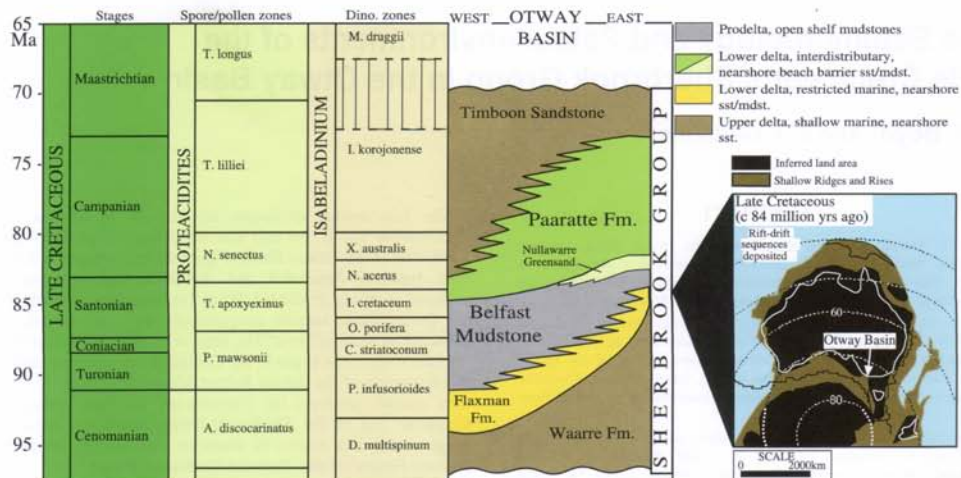


FIG 1 - Late Cretaceous stratigraphy and palaeogeography of the Otway Basin (adapted from Veevers et al. 1991 and Moreton et al. 1994). The palynozones are adapted from Morton & Drexel (1995).

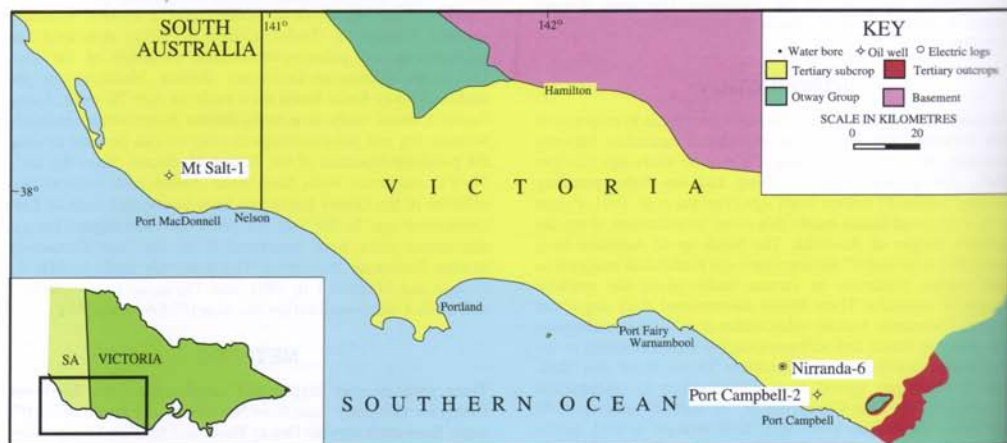


FIG 2 - Otway Basin bore and well location map.

## RESULTS

The results will be given in three sections, Waarre and Flaxman formations, the Belfast Mudstone and the Paaratte Formation including the Nullawarre Greensand and Timboon Sandstone. To characterise the palaeoenvironment of each unit in the Sherbrook Group, it was necessary to incorporate wireline log data, lithologies, as well as original contributions by previous authors to interpret the foraminiferal distributions. The palaeoenvironmental interpretations are based on comparisons with extant forms with reference to Murray (1991). In addition, the deltaic biofacies of Nagy (1992) and Van Den Akker et al. (2000) were used for comparative purposes to interpret agglutinated foraminiferal assemblages.

Note on stratigraphy: The Flaxman Formation was originally referred to as 'Flaxmans Beds' by Bain & McQueen (1964) but was later re-named the Flaxman Formation by Bock & Glenie (1965). Similarly, the Belfast Mudstone was first nominated as a member of the Paaratte Formation by Bock & Glenie (1965); however, Reynolds (1971) reinstated formation status. In this work, the Belfast Formation is identified in Mt Salt-1 where Reynolds et al. (1966) had previously defined the Mt Salt Formation. Based on the lithological similarity between logged sections of the Belfast Mudstone in Victoria with that of the Mt Salt Formation' in Mt Salt-1 in South Australia we follow the Belfast Mudstone stratigraphy of Ludbrook (1971) for this well. Morton & Drexel (1995, in Appendix 8.1) place the interval we identify in Mt Salt-1 as the Belfast Mudstone and the Nullawarre

Greensand into the Paaratte Formation, having studied the sections we have been able to subdivide this unit further. The Nullawarre Greensand was first established as a member of the Paaratte Formation by Bock & Glenie (1965), more recently Moreton et al. (1994) refer to it as a formation. The Timboon Sandstone is regarded as a formation in South Australia but an upper member of the Paaratte Formation in Victoria (Morton & Drexel 1995). The Timboon Sandstone will be regarded in this paper as a member in Port Campbell-2 and Nirranda-6, and as a formation in Mt Salt-1. The Flaxman, Belfast, and Nullawarre Greensand units will be referred to by their most recently assigned rank as given above.

### Waarre and Flaxman Formations

The Waarre Formation in Port Campbell-2 (Core 9, Figure 3) is characterised by heavily burrowed carbonaceous coarse-grained sandstone. Other than occasional bioturbation, the Waarre Formation of Port Campbell-2 yields no shells or foraminifera (Taylor 1964a). However, this unit yields common microplankton (Partridge 1996).

The Flaxman Formation consists of fine-grained grey-brown sandstone with occasional coarse sandstone interbeds. This unit coarsens upward from medium-grained sandstone to coarse-grained sandstone with rare bioturbated horizons (Core 6 and 7, Figure 3). The upper part of the Flaxman Formation fines upward from grey, fine-grained bioturbated sandstone with possible limonite oolites to interbedded fine-grained sandstone and grey mudstone. Foraminifera such as *Dorothia filiformis* and *Ammobaculites goodlandensis* and rare calcareous forms such as *Hoeglundina subcretacea* and *Lenticulina* sp. are rare in the Flaxman Formation (Figure 3).

### Palaeoenvironment and age

The presence of microplankton in the Waarre Formation together with the inherent bioturbation suggests a marine environment for this interval in Port Campbell-2. A high-energy shelfal environment is suggested for this part of the unit, possibly representing a beach barrier facies equivalent to Waarre Formation Units B or C of Buffin (1989). The finer-grained facies and coarsening up nature of the Flaxman Formation probably heralds the onset of lower delta progradation in a shallow marine environment (the oolites, bioturbation and microplankton present suggests shallow marine facies). The lack of macrofauna (this study) and foraminifera (Taylor 1964a) in this part of the unit is probably due to a combination of high sedimentation rates and the high-energy nature of the environment. The upper part of the Flaxman Formation in Port Campbell-2 preserves the transgressive phase to the lower energy shelfal facies of the Belfast Mudstone. The limited calcareous foraminiferal fauna in this part of the unit typify middle to outer shelf palaeoenvironments. The Waarre Formation in Port Campbell-2 lies within the Turonian *P. infusorioides* dinocyst Zone/*P. mawsonii* spore pollen Zone (Partridge 1996). The foraminiferal fauna in the Flaxman Formation is typical of the lower part of the B zone (Turonian) of Taylor (1964a). This unit lies within the Turonian *P. infusorioides* dinocyst Zone (Figure 1).

### Belfast Mudstone

Based on wireline log interpretation, core description and foraminiferal data, the Belfast Mudstone Formation can be divided into three distinct sedimentary units, the Lower Belfast Mudstone, the Middle Belfast Mudstone and the Upper Belfast Mudstone.

### 1. The Lower Belfast Mudstone

The Lower Belfast Mudstone consists of dark grey-brown mudstone with minor fine-grained sandstone interbeds, common shell fragments and siderite concretions in Port Campbell-2 (Figure 3). In Mt Salt-1, this unit is a bioturbated dark grey silty mudstone with glauconite, rare shelly material and thin interbeds of light grey fine-grained sandstone (Figure 4). Based on foraminiferal data (see below) we consider that this basal unit was not intersected in Nirranda-6. The SP values for this unit are high (80-240) in Mt Salt-1 with values decreasing upward. Calcareous foraminifera such as *Gyroidinoides nitida*, *Lenticulina* and *Hoeglundina elegans* are relatively common in this unit in Port Campbell-2. They are associated with a diverse agglutinated assemblage similar to the underlying Flaxman Formation with the addition of *Haplophragmoides* sp. A and B (Taylor 1964a, Figure 3). In Mt Salt-1, the assemblage is less diverse comprising minor agglutinated forms including the calcareous taxa *Gavellinella* and *Lenticulina* (Ludbrook 1971, Figure 4).

### Palaeoenvironment and age

The foraminiferal and facies data suggest a low-energy outer-shelf prodelta setting for the lower part of the Belfast Mudstone in Port Campbell-2. This interval in Mt Salt-1 was probably deposited in a slightly shallower inner to middle shelf prodelta setting and, biostratigraphically, lies within Taylor's Turonian to Santonian Zonule B. The lowest part of the Lower Belfast Formation is no older than the Turonian *P. infusorioides* dinocyst Zone/*P. mawsonii* spore pollen Zone in Mt Salt-1 and lies within the Turonian to Coniacian *C. striatoconum* dinocyst Zone in Port Campbell-2 (Figure 1). The upper part of this unit is Early Santonian in age (*O. porifera* dinocyst Zone, Figure 1).

### 2. The Middle Belfast Mudstone

Lithologically, the Middle Belfast Mudstone in Port Campbell-2 is similar to the Lower and Upper Belfast Mudstone since it consists of glauconitic mudstone. However, it can be distinguished from these units by its lack of shelly material (Bain & McQueen 1964). In Port Campbell-2 a distinctly lower diversity foraminiferal assemblage is preserved compared to the Upper and Lower Belfast Mudstone which contains common agglutinated foraminifera and rare calcareous foraminifera (Taylor 1964a). In Mt Salt-1, the equivalent interval consists of medium to coarse-grained light green homogeneous sandstone interbedded with dark grey mudstone and siltstone with no macrofauna and minor agglutinated forms (Figure 4). The wireline log signatures for the Middle Belfast Mudstone in Mt Salt-1 show a distinctly coarsening upward profile (Figure 4). Subsequently it fines upward to the Upper Belfast Mudstone.

### Palaeoenvironment and age

The prevalence of agglutinated forms in this interval in Port Campbell-2 have been interpreted by Taylor (1964a) to indicate a time of more restricted marine circulation in the Port Campbell Embayment. Reduced oxygen levels on the sea floor led to acidic conditions promoting dissolution of the majority of calcareous forms (cf. Van Den Akker et al. 2000). These dysaerobic conditions could presumably be related to high surface productivity conditions where abundant infauna would be expected. However, the prevalence of epifaunal agglutinated taxa such as *Haplophragmoides* sp. B and *Dorothia filiformis* (the morphotype characterisations follow Nagy 1992) and epifaunal calcareous taxa in all three units in the Belfast Mudstone suggests oxygenated benthic conditions during the deposition of the Belfast Mudstone. The agglutinated morphotypes present are

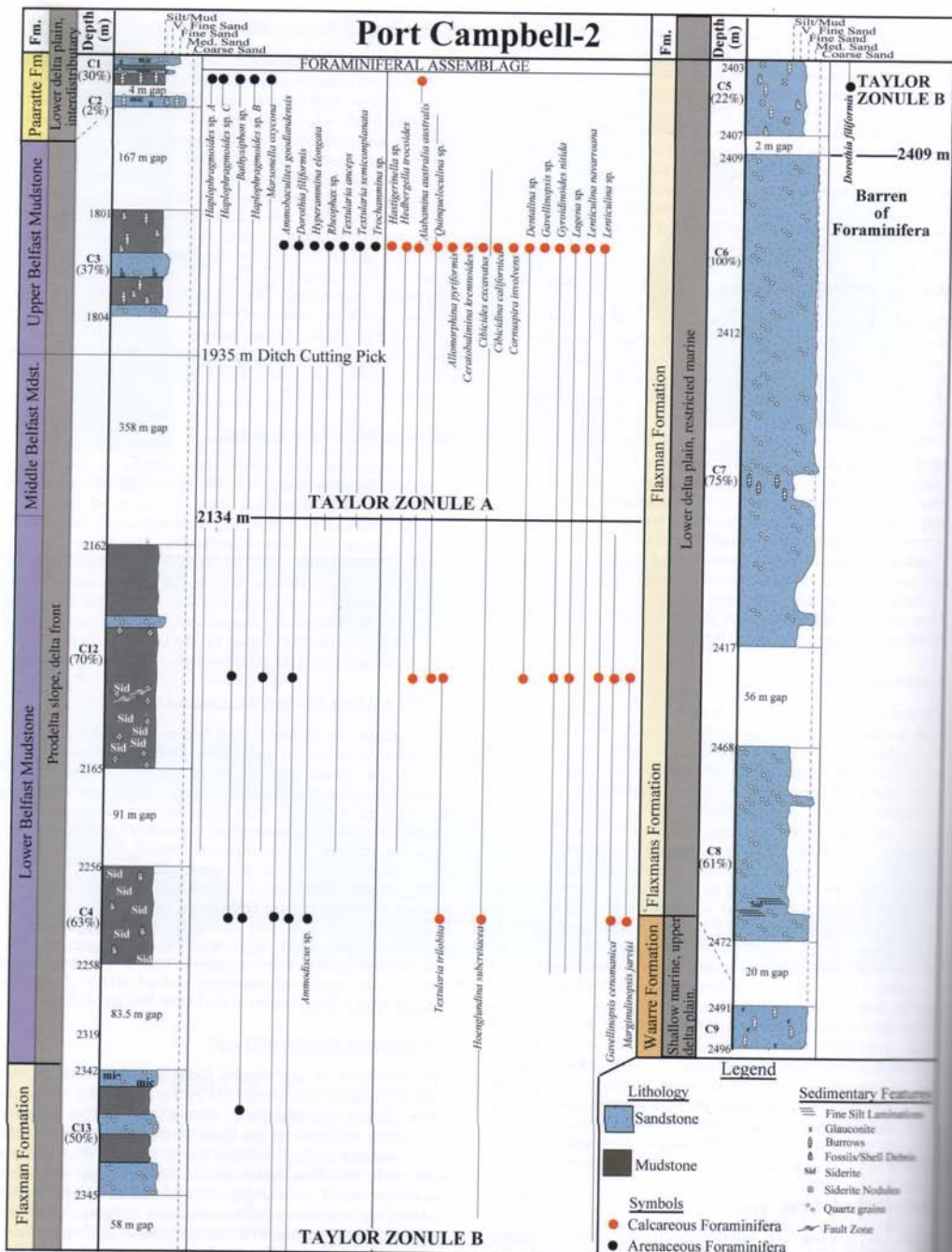


FIG 3 - The facies and foraminiferal distribution in the lower part of the Sherbrook Group in Port Campbell-2. The foraminiferal data is derived from Taylor (1964a). The interpreted palaeoenvironments of the units are to the left of each log. The percentage of core recovered for each depth interval is given in the depth column below the core number. Note that the vertical scale is not to scale.

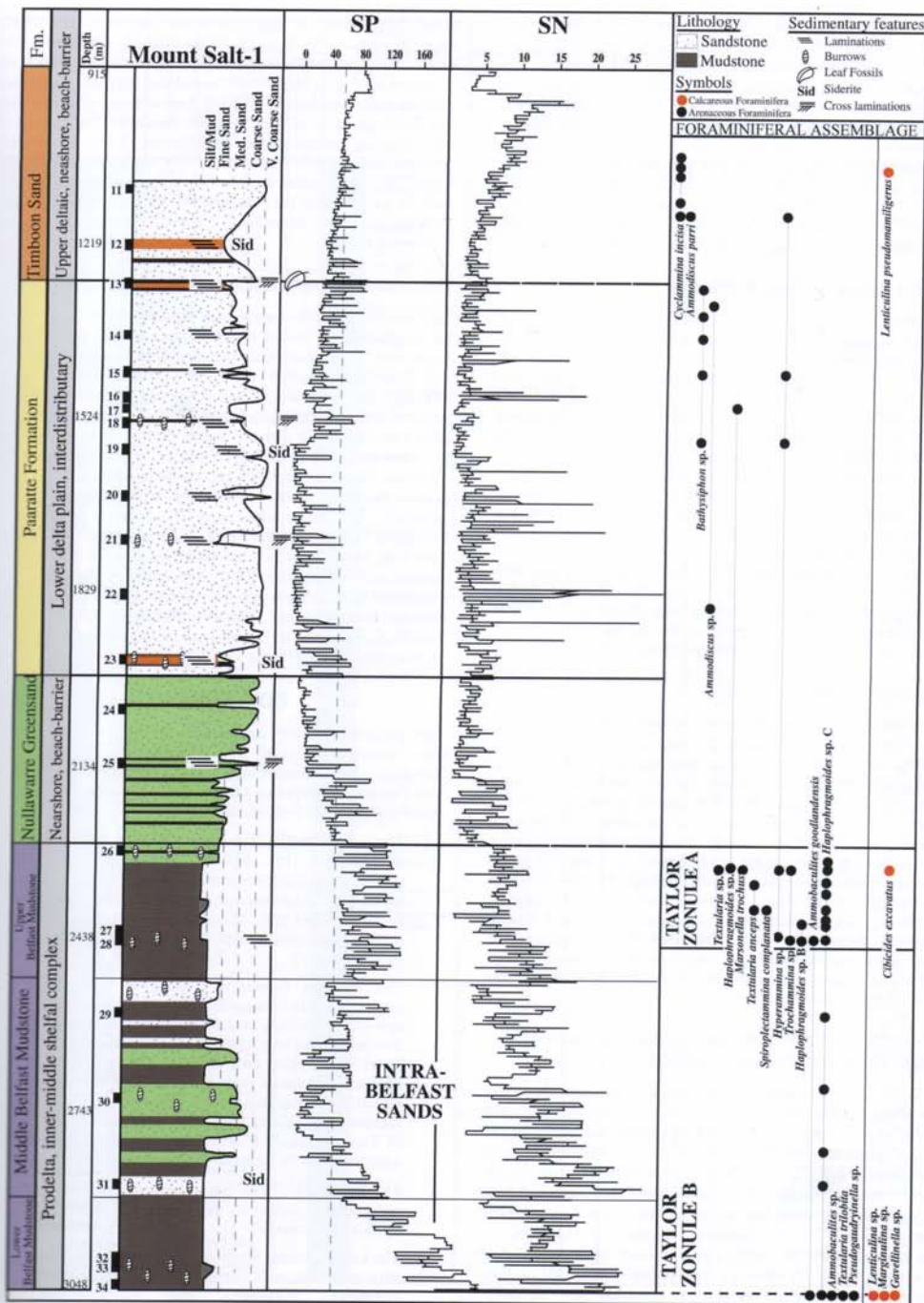


FIG 4 - The facies and foraminiferal distribution in the Sherbrook Group of Mt Salt-1. The foraminiferal data is derived from Ludbrook (1971). The stratigraphic positions of the cores logged are shown as black boxes.

characteristic of prodelta settings (Nagy 1992). The limited calcareous forms present in the Middle Belfast Mudstone typify middle to outer shelf palaeoenvironments. The relatively low abundance of calcareous forms in this interval probably relates to high sedimentation rates in this middle to outer shelf prodelta setting. The coarsening upward nature of the Mt Salt-1 facies probably represents progradation of delta front facies. The facies and faunal data suggest shallower possible inner shelf upper deltaic conditions during deposition of this unit at Mt Salt-1. The Middle Belfast Mudstone in Port Campbell-2 lies in the lower part of Taylor's Santonian Zonule A. This unit in Mount Salt-1 lies between clearly defined Zonule B and Zonule A strata.

### 3. The Upper Belfast Mudstone

Bioturbated shelly dark grey glauconitic mudstones and siltstones characterise this upper unit of the Belfast Mudstone. Shelly material was not observed in the core of this unit in Mt Salt-1 (Figure 4). Siderite is more rare in this upper unit compared to the lower unit. Interbeds of homogeneous, very fine-grained sandstone with flame structures occur. The typical SP of this unit is high and relatively homogeneous. The gamma signature of this interval in Nirranda-6 shows several 10 m-scale coarsening upward sedimentary units where each 'cycle' coarsens from mudstone at the base to a thin muddy sandstone or fine-grained sandstone at the top (Figure 5). Agglutinated and calcareous foraminifera (with some planktonic forms) and molluscs are most common in this unit in Port Campbell-2 (Figure 3) and in core from Nirranda-6 (Figure 6). The ditch cuttings of Nirranda-6 yield typically Upper Belfast foraminiferal assemblages that have been diluted by down hole caving. Agglutinated forms dominate this interval in Mt Salt with minor calcareous forms in the absence of molluscs (Figure 4).

#### Palaeoenvironment and age

The relatively common calcareous and agglutinated foraminifera and shelly glauconitic facies in this interval in Port Campbell-2 and Nirranda-6 are typical of an open marine middle to outer shelf prodelta palaeoenvironment. The coarsening upward units in this part of the Belfast Mudstone are interpreted to represent minor sand units prograding in a prodelta setting. The presence of flame structure at the base of the fine sandstones preserve evidence of rapid deposition quite possibly as gravity flows or possibly turbidites in this prodelta setting. The foraminiferal assemblage in Mt Salt-1 is interpreted to reflect slightly shallower inner to middle shelf deposition in an open marine prodelta setting. The lower diversity and abundance of foraminifera in this unit in Mt Salt-1 probably relates to high sedimentation rates. The upper part of the Belfast Mudstone lies within Taylor's Santonian Zonule A.

#### Paaratte Formation, including the Nullawarre Greensand and Timboon Sandstone

In Nirranda-6, the gamma values decrease markedly above the top of the Belfast Mudstone, representing a coarsening upward profile of fine- to very coarse-grained glauconitic sandstones of the Nullawarre Greensand (Figure 5). The initial coarsening upward interval of the Nullawarre Greensand is well preserved in Mt Salt-1, where interbedded fine-grained green sandstones and dark grey mudstone coarsen upward to laminated and cross-bedded coarse grained green sandstone (Figure 4). Medium to fine-grained sandstone with rare molluscs with bioturbated mudstones typify the base of the Paaratte Formation in Port Campbell-2 (Figures 3 & 6). A relatively low diversity agglutinated foraminiferal assemblage with rare calcareous forms occurs in this interval. A typical logged section of the upper Paaratte Formation and Timboon Sandstone from Mt Salt-1 is

shown on Figure 4. Grey to white laminated and ripple cross-laminated fine to very coarse-grained sandstones with minor mudstone interbeds are typical of this unit. Within the Timboon Sandstone intermittent bioturbated horizons with minor agglutinated foraminifera such as *Ammodiscus*, *Hyperammina* and *Bathysiphon* occur. The Timboon Sandstone also consists of fine to very coarse-grained sandstones, lacks bioturbated horizons and contains leaf fossils. Only the upper beds of this unit contain agglutinated foraminifera (although these forms may well be caved since the taxa present are more typical of the Palaeocene units immediately above the logged section (Ludbrook 1971)).

#### Palaeoenvironment and age

The wireline and lithological data provide strong evidence for the progradation of marine lower to upper deltaic, and nearshore facies over the Belfast Mudstone during Nullawarre Greensand and Paaratte Formation times. The foraminiferal fauna is relatively poor and not particularly depth diagnostic, although some of the epifaunal forms, typical of the Belfast Mudstone, persist into the upper part of Paaratte Formation suggesting that the environment was still open marine and oxygenated. The Timboon Sandstone probably represents deposition in an upper deltaic to near shore environment with marginal marine influence. The foraminifera near the base of the Paaratte Formation in Port Campbell-2 lie in the upper part of Taylor's Santonian zonule A, which has been placed in the Santonian *T. apoxyxinus* spore/pollen Zone. The fauna in the Nullawarre Greensand in Nirranda-6 also lies within Taylor's zonule A. The Paaratte Formation and Timboon Sandstone lie within the Santonian to Campanian *I. cretaceum*, *N. aceris* and *X. australis* dinoflagellate Zones (Figure 1).

## CONCLUSIONS

This preliminary study integrates core logs, well completion data, wireline log data, and foraminiferal assemblages to investigate the sedimentology and palaeoenvironments of the Late Cretaceous Sherbrook Group in the Otway Basin. From this initial study we can conclude the following:

1. The Cenomanian-Turonian Waarre Formation is characterised by heavily burrowed coarse-grained sandstones and carbonaceous material. The unit contains no shells or foraminifera, however, the presence of microplankton and abundant bioturbation indicate a shallow marine, upper delta plain depositional environment.
2. The Flaxman Formation consists of fine grey brown sandstones with occasional coarse sandstone interbeds. The upwards coarsening and finer grained facies suggest that this part of the unit represents the onset of deposition in a lower delta plain environment. The upper part of the Flaxman Formation fines upwards from fine-grained grey bioturbated sandstone into fine-grained inter-bedded sandstone. It contains a foraminiferal assemblage indicative of Taylor's zonule B and lies within the *C. striatocornutum* dinocyst Zone of Turonian to Coniacian in age.
3. The Belfast Mudstone can be separated into three distinct sedimentary packages, the Upper, Middle, and Lower Belfast Mudstone.

The Lower Belfast Mudstone is characterised by dark grey silty mudstone with minor fine sandstone interbeds, shell fragments, glauconite, and siderite concretions. Foraminiferal and microplankton suggest deposition from Coniacian to Santonian time in a middle to outer shelf open marine prodelta environment.

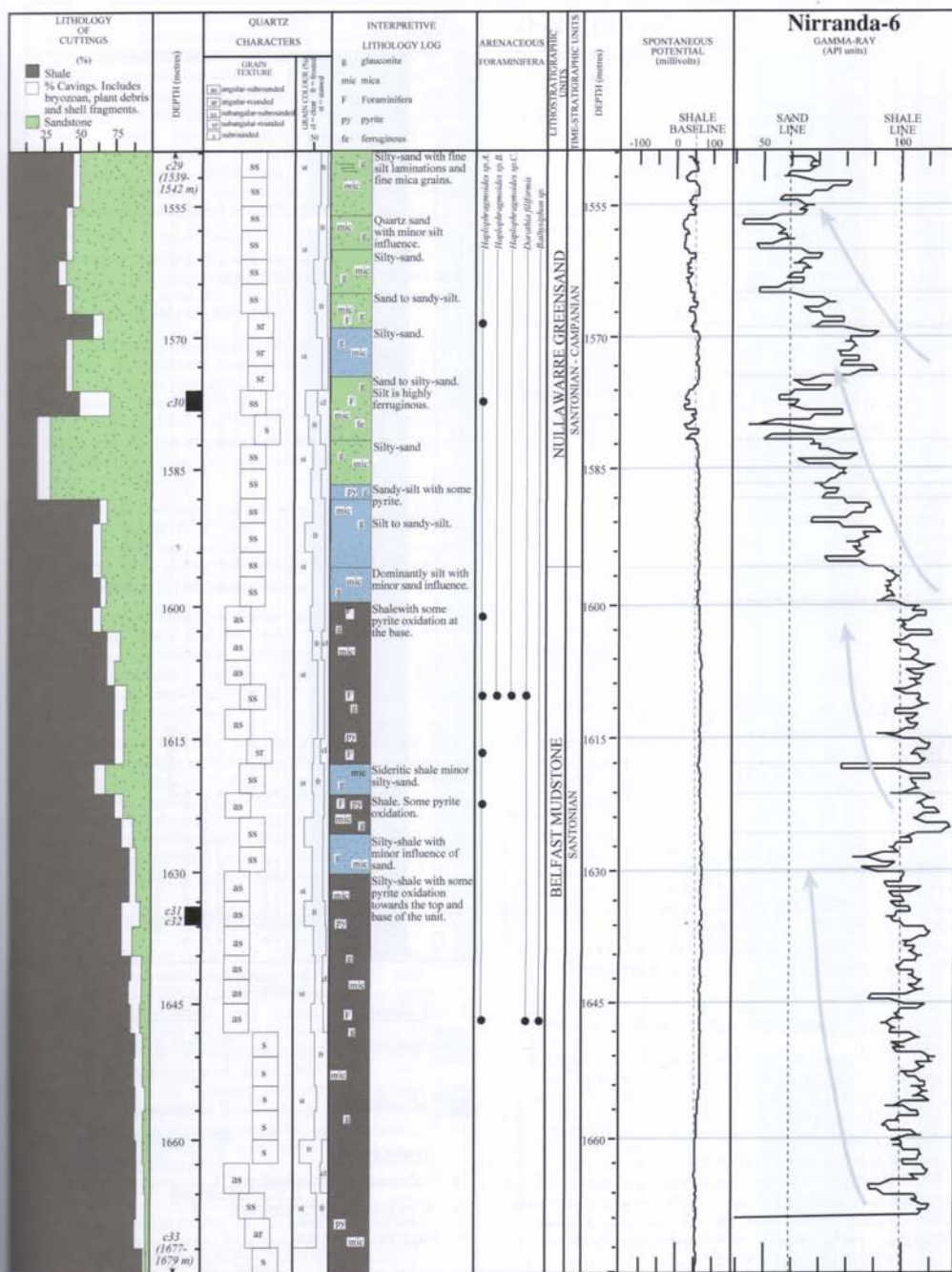


Fig. 5 - Composite well log of the facies and foraminiferal distribution in the lower part of the Sherbrook Group in Nirranda-6. The stratigraphic positions of the cores from Figure 6 are indicated as black boxes. The deltaic progradational 'cycles' are shown as grey arrows.



The Middle Belfast Mudstone comprises glauconitic silty mudstone in the southeastern Otway Basin, the Southern Australian equivalent of this interval is predominantly sandstone interbedded with dark grey silty mudstone. The agglutinated foraminifera present in the Middle Belfast Mudstone are indicative of an oxygenated open marine prodelta setting. The lateral lithological variation in this interval suggests an outer shelf depositional environment in southeastern Otway Basin and a progradational inner shelfal environment in South Australia. The Middle Belfast Mudstone is Coniacian to Santonian in age.

The Upper Belfast Mudstone consists of dark grey bioturbated shelly glauconitic silty mudstone. The calcareous and agglutinated foraminiferal biofacies was deposited in an open marine middle to outer shelf prodelta environment during the Santonian.

- The Nullawarre Greensand, deposited as part of the lower Paaratte Formation, is characterized by interbedded fine green sandstone and dark grey silty mudstone at base, coarsening up into coarse grained laminated and cross-bedded green sandstone. The Nullawarre Greensand represents the first progradation of marine upper deltaic, nearshore, beach-barrier facies over the Belfast Mudstone during the Santonian.
- The Paaratte Formation consists of medium to fine grained sandstone interbedded with bioturbated siltstone and mudstone with rare molluscs. This unit was dominantly deposited in a marine lower-upper deltaic environment from Santonian to Campanian times.
- The Timboon Sandstone is the upper most unit in the Sherbrook Group and represents the onset of fluvial terrestrial interdistributary deposition in the Otway Basin from Maastrichtian time. The unit is characterised by fine to very coarse sandstones with siltstone/mudstone interbeds with occasional leaf fossils.

The evidence suggests that the majority of the Late Cretaceous sediments in the Sherbrook Group studied so far were deposited in a shelfal open marine oxic deltaic setting. The results presented in this study provide a platform from which further integrated studies can correlate and interpret the Sherbrook Group stratigraphy. This study will also contribute towards better constraining the hydrocarbon bearing strata in the Otway Basin.

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