Geology, geochemistry and depositional history of the Port Campbell Limestone on the eastern flank of the Otway Basin, southeastern Australia

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ABSTRACT
A fully cored sequence of Hesse Clay, Port Campbell Limestone and uppermost Gellibrand Marl in the onshore Otway Basin, southeastern Australia, offers new insight into the evolution of the middle Miocene Port Campbell Limestone. The Port Campbell Limestone comprises grey unconsolidated to semi-consolidated and rarely lithified bioclastic muddy carbonate sands in a stack of thin repetitive cycles within cycles of predominantly shoaling-upward character. A glauconitic band with a distinctive mollusc–echinoderm–bryozoan fauna provides a distinctive marker interval in the sequence. In mineralogy, the Port Campbell Limestone is predominantly calcite with traces of remnant aragonite in muddier low-permeability sands, and with dolomitic zones in permeable intervals. The small non-carbonate component of the Port Campbell Limestone is between 3 and 15 wt% and comprises quartz silt with minor clay, feldspar and mica. Dissolution overprints are prominent throughout the carbonate sequence. Three distinct geochemical signatures of provenance are evident in the Port Campbell Limestone, including possible volcanogenic contributions with felsic sources. Foraminifera are common and generally well preserved. Foraminiferal data suggest a depositional transition from outer shelf conditions in the Gellibrand Marl at ca. 15 Ma to middle shelf environments in the lower part of the Port Campbell Limestone during the Middle Miocene Climatic Optimum (MMCO) at ca. 14.24 Ma. Shallowing after 14 Ma indicates variable paleodepths of <70 m during and following the end of the Middle Miocene Climatic Transition (MMCT) at ca. 13.2 Ma when the sequence was emergent for a brief but undetermined period, corresponding with sharp changes in geochemical ratios. Observed cyclicity in these mid-shelf, cold-water carbonates is strongly correlated with orbital forcings—eccentricity and obliquity. Sedimentation rates determined from cyclostratigraphic analysis indicate 4–6 cm/kyr at the end of the MMCO, diminishing to 1.5–3 cm/kyr during the MMCT and the subsequent accumulation of the Port Campbell Limestone.

KEY POINTS
1. The Port Campbell Limestone is a stack of thin repetitive depositional cycles within cycles. The cyclicity is strongly correlated with orbital forcings—eccentricity and obliquity—and this is reflected in the geochemistry.
2. Foraminiferal data suggest a depositional transition from outer shelf conditions in the Gellibrand Marl at ca. 15 Ma to middle shelf environments in the lower part of the Port Campbell Limestone during the Middle Miocene Climatic Optimum (MMCO) at ca. 14.24 Ma.
3. The sequence was emergent for a brief but undetermined period at ca. 13.2 Ma, corresponding with sharp changes in geochemical ratios.
4. Three distinct geochemical signatures of provenance are evident in the Port Campbell Limestone sequence, including possible volcanogenic contributions with felsic sources.

Introduction
The middle to upper Miocene Port Campbell Limestone is perhaps best known internationally as the host sequence that forms the Twelve Apostles, the iconic tourist attraction on the southern coastline of Victoria. Groundwater from the Port Campbell Limestone supports regional agriculture.

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industry and town water supplies, and the aquifer has been the subject of extensive monitoring and hydrogeological studies (e.g. Bush, 2009). Despite the abundance of coastal outcrop and substantial subsurface investigation of these middle to upper Miocene units in the region, cores are rare for the Port Campbell Limestone.

Two fully cored shallow drillholes were completed in 2019 on the eastern flank of the Port Campbell Embayment at the CO2CRC Otway International Test Centre (Figure 1). This facility hosts a carbon capture and storage demonstration project that has, to date, injected over 80,000 tonnes of CO2 into two separate deep reservoirs (Jenkins et al., 2012; Pevzner et al., 2017). While the geology of these deeper reservoirs is well understood through seismic and other investigations, relatively little was known about the near-surface geology, particularly within the Port Campbell Limestone (Bailey et al., 2017).

CO2CRC is undertaking a feasibility study for a planned controlled release and monitoring experiment at a shallow geological fault on this site (Feitz et al., 2017, 2021; Feitz, Tertyshnikov, et al., 2018). Drilling was undertaken to characterise the near-surface geology and to provide a basis for understanding the influence of faulting on CO2 migration behaviour. The main objectives of the drilling of Brumbys 1 and 2 bores, as well as two sets of co-located dual piezometers, were to: obtain a cored section of the Port Campbell Limestone, confirm the position and vertical displacement on the fault; investigate the character of the fault zone; establish the geotechnical and hydrogeological properties of the sequence; install fibre optics and geophones for later monitoring; and to complete the holes as piezometers and groundwater monitoring wells. Sonic drilling was employed to ensure excellent recovery of the mostly friable carbonate and to minimise fluid contamination of the sequence.

This paper describes the lithostratigraphy, mineralogy, diagenesis, geochemistry and micropaleontology of the stratigraphy intersected by the Brumbys 1 drillhole, and interprets age, environments and influences on deposition of the Port Campbell Limestone. Some comparisons are made with coastline outcrops and with the Nullawarre 3 well.

Regional geology

The coastal Otway Basin in southeastern Australia has an area of ~150,000 km² onshore and offshore and is characterised by a thick succession of Mesozoic to Cenozoic terrestrial to marine strata that were deposited as Australia rifted away from Antarctica and drifted northward (Laing et al., 1989; McLoughlin, 2001). Its Paleogene to Neogene history is characterised by increasingly fully marine carbonate sequences that were deposited in neritic to upper slope conditions (Gallagher & Holdgate, 2000; Holdgate & Gallagher, 2003). The Oligocene to Miocene Heytesbury Group forms a significant portion of the Cenozoic Otway Basin succession (Figure 2) representing the final
megacycle of sediment accumulation in the Otway Basin. The region was covered by extensive alluvial outwash deposits of the Hanson Plain Sand during the Pliocene and aerial exposure led to the development of the Timboon Surface with karstic topography on Port Campbell Limestone (Edwards, Tickell et al., 1996). Large outpourings of basalt covered the northern margin of the basin, and younger, explosive volcanism (Newer Volcanics) produced numerous scoria cones and maar craters (Edwards, Leonard, et al., 1996). A derivative of this volcanism appears to be the thin Hesse Clay that caps the Timboon Surface across the region.

Site stratigraphy and geomorphology

The CO2CRC Otway International Test Centre is located at South Nirranda, Victoria, on a private farming property ~35 km southeast of Warrnambool (Figure 1). The stratigraphy of interest is the sequence intersected by the Brumbys 1 drillhole, namely the uppermost Gellibrand Marl, Port Campbell Limestone and Hesse Clay. Within the Port Campbell Embayment, the Port Campbell Limestone reaches a thickness of 297 m in Mepunga-25 (Tickell et al., 1992), whereas at the CO2CRC site (Brumbys 1), it is only 120 m thick. In a north-to-south section line of this part of the embayment (Figure 3), the regional cyclic character of the Port Campbell Limestone is indicated in resistivity logs. This character is attributed to cycles at various scales, of upward diminishment of clays and fine-grained siliclastics, with corresponding increased porosity and permeability. In Brumbys 1, only a continuous gamma log is available, and this larger-scale cyclicity is not readily evident. However, the entire formation comprises thin carbonate cycles (third order), each with a predominant upward decrease in total silicate content.

The CO2CRC site lies within flat black soil terrain with Brumbys 1 at 43.90 m AHD (Australian Height Datum) and Brumbys 2 at 43.95 m AHD. Subtle swale features align northeast in the direction of local drainage (Figure 4). There is a gentle rise in elevation southwards to a dune crest at 50 m AHD. This broad dune complex of southeast alignment adjoins immediately to the south of the study area. The feature was mapped as coastal dune deposits of mixed quartz and calcareous sand, and ascribed a
Figure 3. (a) Isopach map of the Port Campbell Limestone in the Port Campbell Embayment (Bush, 2009). (b) Character of the Port Campbell Limestone is defined by SP (LHS) and Resistivity (RHS) logs in all wells except Brumbys 1 (Vcl gamma only). Shoaling-upward cyclicity (Resistivity) appears to be characteristic. Resistivity cycles suggest both decreasing salinity of porewaters and/or increased porosity in cleaner carbonates upcycle. The thick black line indicates the boundary between the Port Campbell Limestone (PCL) and Gellibrand Marl (GBM) based on resistivity/gamma signal and well logs. In Brumbys 1, the boundary between the Hesse Clay and Port Campbell Limestone is also shown.
Quaternary age (Edwards, Tickell et al., 1996). The substrate to this feature may be much older, predating the development of the Timboon Surface as inferred from atypically deeper oxidation of the Port Campbell Limestone sequence adjoining this complex. To the south of the dune, subtle undulating karst topography suggests erosional loss of the Hesse Clay (Figure 4).

**Methods**

**Brumbys 1 drillhole and reference depth measurements**

Brumbys 1 was drilled in February 2019 as part of near-surface characterisation drilling campaign at the CO2CRC Otway research site. Two inclined groundwater observation wells (Brumby 1 at 80° to 126.6 m and Brumby 2 at 45° to 36 m) were successfully drilled through Brumbys Fault. Core material was collected for geochemical and geomechanical testing (Feitz et al., 2020). Depths cited are downhole core depth unless otherwise stated; because of the 80° inclination of Brumbys 1, true depths are 0.985 of core depth. The two fully cored boreholes intercept Brumbys Fault at two different depths within the Port Campbell Limestone. Brumbys 2 was designed for a shallow intercept of the fault, just below the Hesse Clay, intercepting the fault at ~4.7 m downhole. Brumbys 1 intercepted the fault deeper at 91 m depth (Figure 5). The bores were cored/drilled using a Sonic Boart Longyear LS600 coring rig. Two pairs of groundwater piezometers (one of each pair in the upper clay layer 2–3 m, the other 24 m into the Port Campbell Limestone) were also installed (Figure 4).

In addition to the core, a full suite of logging runs were acquired in Brumbys 1 well, and consequently this well is the focus of the present paper. The 95% core recovery from the Port Campbell Limestone at this site is a valuable addition to the few incomplete cores available for study even though 2 m of section is absent in the Brumbys 1 sequence through fault displacement. In all sonic drillholes at the CO2CRC site, the sequence of Port Campbell Limestone...
Limestone is undisturbed except within the fault zone, although the sequence is affected by diagenetic modification.

**Wireline logs**

During the drilling of Brumby’s 1, loss of circulation in thin aquifers and upper fault zone necessitated steel casing of the hole below 40 m. Casing was extended to 96 m, but the deepest interval remained uncased from 96 to 126.6 m. Two runs of the full suite of wireline logs (i.e. sets of geophysical tools lowered into the drillhole) were conducted. An early run of all logs was made in the uppermost uncased 40 m. The second run was from surface to total depth. The wireline suite included caliper, density, gamma, spontaneous potential, short and long normal resistivity, neutron porosity, and sonic imaging. Analysis and interpretation of logs and their derivatives are presented in Wang et al. (2020).

**Sediment/rock analyses**

Detailed description of sampling strategy and procedure, sample preparation, analytical procedures and data are presented in appendices of Radke et al. (2020). These appendices address: thin-sectioning and petrography, X-ray diffraction, geochemistry, mercury injection capillary pressure (MICP), porosity and permeability, rock properties, surface area analysis, bulk density, carbonate content, grain-size analysis and geochemistry of major and trace elements. Further interpretation of MICP, porosity and permeability are covered by Wang et al. (2020).

**Lithostratigraphic subdivision of the Port Campbell Limestone using geophysical logs**

With the uniform appearance of the core of the Port Campbell Limestone, it was necessary to use the geophysical logs for lithostratigraphic subdivision. The gamma log is a splice of several runs down open and cased intervals of the hole. The reduced resolution of the gamma log in the cased middle part of the sequence negated a consistent delineation of third-order units. Delineation at higher resolution of the third-order unit is based on the proportion of clean (lower gamma) carbonate over mudier and more marine carbonate (Radke et al., 2020).

Mineralogical, geochemical and permeability data indicated a need for a lower-resolution subdivision of the formation. Neural network modelling (Aliouaine et al., 2013) using a multilayer perceptron (MLP) classifier enabled an objective identification of second-order units through the integration of gamma logs, effective porosity and permeability logs (Wang et al., 2020). This second subdivision was also integrated with seismic data for subsequent static and dynamic modelling (Wang et al., 2020).

**Biostratigraphy**

Qualitative benthic and planktic foraminiferal analyses were carried out on 47 samples from Brumby’s 1 well. Samples were processed for foraminifera by standard microfossil techniques. Each sample was water-washed and wet-sieved (>63 μm) to disaggregate the samples. The dried residue was spread on a picking tray, and foraminifera were documented for biostratigraphic and paleoenvironmental analyses.

The preservation state of the assemblages was qualitatively estimated and ranged from excellent to good to poor (where the foraminiferal tests were either broken or fully replaced by diagenetic minerals). Qualitative benthic assemblage (C = common, X = present) and presence/absence biostratigraphic data were compiled from the >63 μm fraction (Table 1). Randomised transects of parts of the residue were counted for planktic vs benthic foraminifera. For this study, >100 tests were counted to determine the %planktics.

Benthic (and planktic) foraminiferal taxonomy followed that of Gallagher et al. (1999, 2001), Gourley and Gallagher (2004), Gallagher and Gourley (2007) and Li and McGowran (1994). The Cenozoic planktic foraminiferal taxonomy followed Bolli et al. (1985) and Wade et al. (2018). The Cenozoic foraminiferal biostratigraphy was calibrated to the Gradstein et al. (2020) biochronology tables (Table 1). This was used to recalculate the Taylor Zonation (Taylor, 1971a, 1971b), and extra range datums listed in Bolli et al. (1985) and the Globorotalia lineage of Cifelli and Scott (1986), Scott et al. (1990) and Wade et al. (2011, 2018).

The paleoenvironmental interpretation of the foraminiferal assemblages was based on regional modern analogues (Smith et al., 2001; Smith & Gallagher, 2003), where inner shelf = 0–50 m depth, middle shelf = 50–100 m and outer shelf = 100–200 m (Table 1), and comparative Otway, Murray, Port Phillip and Gippsland basin regional Miocene microfossil studies (Gallagher et al., 1999, 2001; Gourley & Gallagher, 2004; Gallagher & Gourley, 2007; Li & McGowran, 1994). The total percentage planktic foraminifera in marine strata is related to the proximity of the shoreline (oceanicity) and paleodepth (van der Zwaan et al., 1990, 1999). Approximate paleodepths may be calculated from the %planktic (%P) using the equation of van der Zwaan et al. (1990) as follows:

\[
\text{Depth (m)} = e^{3.58718 + (0.03534\%P)}
\]  

The error range on this estimation is \(\pm 20\) m using regional southeast Australian modern analogues (Gallagher et al., 2013; Smith et al., 2001; Smith & Gallagher, 2003). A combination of benthic assemblage distribution with %planktics was used to determine relative paleodepths. As the benthic assemblages were established qualitatively, interpretations are deemed approximate.
| Miocene/Pliocene boundary | GTS2020 Age (Ma) | Trop/ subtrop Zone/ Subzone (base) | Planktic zones (Blow, 1969) | Taylor (1971a, 1971b) SE Australia | Datums of key zonal taxa in southeast Australia |
|---------------------------|------------------|-----------------------------------|-----------------------------|-----------------------------------|-----------------------------------------------|
| Miocene/Pliocene boundary | 5.33             |                                   |                             |                                   | T Globoquadrina dehiscens                     |
| T Globorotalia dehiscens  | 5.92             | M14                               | N17b                        | B1                                |                                               |
| B Neogloboquadrina dehiscens | 6.08           | M14                               | N17b                        | B1                                |                                               |
| B Globorotalia (Hirsutella) margaritae | 7.89        | M13b                              | N17a                        | B1                                |                                               |
| T Neogloboquadrina dehiscens | 8.83            | M13b                              | N17a                        | B1                                |                                               |
| T Paragloborotalia mayeri (sub)tropical | 10.46       | M11                               | N14                         | B2                                |                                               |
| T Neogloboquadrina acostaensis (temperate) | 10.63       | M11                               | N14                         | B2                                |                                               |
| T Neogloboquadrina acostaensis | 11.79           | M9b                               | N12                         | D1                                |                                               |
| B Neogloboquadrina (Fohsella) fohsi s.l. (inc. lobata) robusta | 13.13            | M9b                               | N12                         | D1                                |                                               |
| B Globorotalia (Fohsella) fohsi s.l. | 13.41           | M9a                               | N12                         | D1                                |                                               |
| T Globorotalia praescitula | 13.73            | M8                                | N11                         |                                   |                                               |
| T Globorotalia (Fohsella) peripheroronda | 13.80         | M7                                | N10                         | D2                                | T Globorotalia (Fohsella) peripheroronda      |
| B Globorotalia (Fohsella) peripherocuta | 14.24           | M7                                | N10                         | D2                                | B Paragloborotalia mayeri sensu stricto       |
| T Globorotalia praescitula | 14.38            | M6                                | N9                          | E1                                |                                               |
| T Praeorbulina sicana | 14.53             | M6                                | N9                          | E1                                |                                               |
| T Praeorbulina glomerosa sensu stricto | 14.78           | M6                                | N9                          | E1                                |                                               |
| T Praeorbulina circularis | 14.89            | M6                                | N9                          | E1                                |                                               |
| B Orbulina sutureal | 15.10             | M6                                | N9                          | E1                                | B Orbulina sutureal                           |
| B Praeorbulina circularis | 15.96            | M5b                               | N8                          | E2                                |                                               |
| B Praeorbulina glomerosa sensu stricto | 16.27           | M5b                               | N8                          | E2                                | B Praeorbulina glomerosa sensu stricto       |
| B Praeorbulina curva | 16.28             | M5a                               | N8                          | F                                 |                                               |
| T Globorotalia incognita | 16.39            | M4b                               | N7                          | F                                 |                                               |
| B Fohsella birnagae | 16.69             | M4b                               | N7                          | F                                 |                                               |
| B Globorotalia miozea | 16.70             | M4a                               | N7                          | F                                 |                                               |
| B Globorotalia zealandica | 17.26            | M4a                               | N7                          | F                                 |                                               |
| T Globorotalia semivara | 17.26            | M4a                               | N7                          | F                                 |                                               |
| T Catapsydrax dissimilis | 17.54            | M3                                | N6-N5                       | F                                 | B Praeorbulina sicana (biophaericus)          |
| B Globigerinatellina insueta | 17.59           | M3                                | N6-N5                       | G                                 |                                               |
| B Globorotalia praescitula | 18.26            | M3                                | N6-N5                       | G                                 |                                               |
| B Globigerinatellina sp. | 19.30             | M3                                | N6-N5                       | G                                 | FCO Globigerinoides trilobus                  |
| B Globigerinoides altiaperturus | 20.03         | M2                                | N6-N5                       | H1                                |                                               |
| T Tenuitella munda | 20.78             | M2                                | N6-N5                       | H1                                |                                               |
| B Globorotalia incognita | 20.93            | M2                                | N6-N5                       | H1                                |                                               |
| B Globigerinatellina angulissuturalis | 20.94        | M2                                | N6-N5                       | H2                                |                                               |
| T Paragloborotalia’ kugleri | 21.12            | M1b                               | N4b                         | H2                                | T Paragloborotalia’ kugleri                  |
| T Paragloborotalia’ pseudokugleri | 21.31          | M1b                               | N4b                         | H2                                |                                               |
| B Globoquadrina dehiscens | 22.44            | M1b                               | N4b                         | H2                                | B Globoquadrina dehiscens                    |
| T Globigerinoides trilobus | 22.90            | M1a                               | N4a                         | H2                                |                                               |
| B Globigerinoides trilobus | 22.96            | M1a                               | N4a                         | H2                                | B Globigerinoides trilobus                    |
| B Paragloborotalia kugleri | 22.96            | M1a                               | N4a                         | H2                                |                                               |

**Oligocene/Miocene boundary** 23.03

B, base; BC, base common; T, top; TC, top common; X, change in coiling direction.

*Regional age only.

Foraminiferal zonations: the Tropical Zones (Berggren et al., 1995; Wade et al., 2011), the Planktic Zones (Blow, 1969), the Planktic Taylor SE Australia Zonation (Taylor, 1971a, 1971b) tied to Gradstein et al. (2020) Timescale (GTS2020).
Cyclostratigraphy

All spectral analyses of the gamma log in this study were carried out using the multitaper method (MTM) with three $2\pi$-tapers (Thomson, 1982) and LOWSPEC background estimation (Meyers, 2012), as implemented in the R-package ‘astrochron’ (Meyers, 2014). The confidence levels were calculated applying the LOWESS-based (Cleveland, 1979) procedure of Ruckstuhl et al. (2001). Depth-to-time conversion and bandpass filtering was carried out using functions ‘tune’ and ‘bandpass’ from the same R-package.

Results

Brumbys Fault

The Brumbys Fault has characteristics of a shallow strike slip fault of Neogene age (Feitz, Tertyshnikov, et al., 2018) that is not coupled to deeper faulting in the underlying Nirranda Group (Feitz et al., 2017). In the Brumbys 1 drillhole, the fault is identified as two zones of thixotropic muddy breccia: an upper zone 1.2 m thick from 91.3 to 92.5 m; and a thicker 6 m zone from 101.8 to 108.0 m (Figure 5), in which some thin individual carbonate bands are brecciated (Figure 7). Between the upper and lower fault zones, there is an intermediate 9 m interval of relatively undisturbed sequence. Despite a loss to sequence through a 2 m fault displacement, Brumbys 1 is the most completely cored sequence available to date for the Port Campbell Limestone.

Cores from shallow holes, completed as piezometers at a distance of at least 100 m from the fault zone (Figure 4), indicate that the Port Campbell Limestone is undisturbed except within the fault zone. However, late diagenetic effects may be attributed to increased permeability along the fault zone.

Refraction seismic modelling (Feitz, Radke, et al., 2018) suggests that the fault follows a pervasive joint fabric, with intervening jogs of $30^\circ$ departure (Figure 8). Across the CO2CRC site, several paralleling dislocations were detected, showing the pervasive effects of stress and weathering on the sequence. The dip of Brumbys Fault plane flattens slightly downwards from near vertical at the base of the Hesse Clay, to $80^\circ$ at the top of the Gellibrand Marl (122.5 m), and merges into the bedding orientation at greater depth, presumably within the Clifton Formation (Feitz et al., 2017).

Stratigraphy

The cored sequence in Brumbys 1 consists of a thin 1.8 m cap of Hesse Clay overlying 121 m of Port Campbell Limestone, which gradationally transitions into the uppermost part of the underlying Gellibrand Marl (Figure 6). The thickness of this transition zone (SPCL1) is ~3.2 m.

Gellibrand Marl

The Gellibrand Marl is a compact fossiliferous dark greenish grey marl, with well-preserved bryozoans, scaphopods, bivalves, foraminifera, ostracods and echinoids. Porosity is generally extremely low but variable and higher in burrow-infill sediments with up to 20% interparticle porosity. The non-carbonate content in the Gellibrand Marl is high: quartz silt 12–24 wt%, muscovite 0–22.6 wt%, kaolinite 2.9–5 wt%, and anatase 0–2.3 wt% (Figure 9a). The carbonate content ranges from 35 to 70 wt% CaCO$_3$ compared with 50–97 wt% in the overlying Port Campbell Limestone. However, cement infill of grainstones is present in the heavily bioturbated parts of the Gellibrand Marl with CaCO$_3$ content up to 79 wt%. Aragonite abundance can be as high as 17 wt% but steadily decreases upwards from the Gellibrand Marl through the transitional zone of the Port Campbell Limestone to only trace amounts. Such high aragonite content in the Gellibrand Marl indicates the minimal diagenetic alteration of skeletal carbonate, presumably because of reduced permeability in the more compact sediment.

Port Campbell Limestone

Near the Brumbys Fault, the Port Campbell Limestone is primarily a permeable sequence of grey unconsolidated to semi-consolidated and ‘lumpy’ bioclastic muddy carbonate sands and limey marls. The carbonates are predominantly bioclastic, yet most bioclasts are largely of indeterminate origin, likely the result of high bioturbation, comminution and micritisation.

The formation is predominantly carbonate with minor siliciclastics. Minor aragonite is present in muddier units with lower permeability. Dolomite is present as a component of cements in four intervals associated with permeable intervals (SPCL3, SPCL4, mainly SPCL10 and SPCL17, and SPCL22–SPCL33) (Figure 9a). The non-carbonate component is between 3 and 10 wt%, comprising quartz silt with minor clay, feldspar and mica. At the Brumbys Fault, the Port Campbell Limestone is uniform in general appearance and colour making it difficult to subdivide visually, but it has variable and incomplete induration. The most distinctive zones within the Port Campbell Limestone sequence include: the basal transition zone up from the underlying Gellibrand Marl, the fault zone, a subtle discontinuity, a glauconitic mud interval and an upper weathered zone (Figure 10).

Basal transition zone

The transitional zone (SPCL1 in Figure 6) is a dark greenish grey, heavily bioturbated, calcareous muddy clay with fine sand bioclastic-pelletal grainstone infill of burrows. This marl is compact with wavy laminae and variably bioturbated. The sediment becomes increasingly compact and higher in siliciclastic content down into the Gellibrand Marl.
Figure 6. Port Campbell Limestone lithofacies: column 1, core log depth; column 2, second-order SPCL units; column 3, gamma log (GRI) and graphic of inferred lithology (mud(brown)-sand (yellow)); column 4, high-resolution (GR) and smoothed gamma (GRS) logs with SP log; column 5, visually interpreted third-order depositional events. The second-order cycles were determined from integration of gamma logs, effective porosity and permeability logs with correlation to seismic data. Core log depths and SPCL units (column 2) are used for all discussion in this paper.
Fault zone

The fault zone has an upper and lower component at the level it was intersected (Figures 5 and 6). Between the upper thin zone (SPCL7) and a thicker lower zone (SPCL4) lies an intervening undisturbed sequence (SPCL5, SPCL6). The fault zones are recognised by bands of a soft mud matrix containing brecciated and rotated clasts of limestone.

Disconformity

A subtle disconformity at 65.5 m depth (at the top of SPCL12) is indicated by an underlying lighter colour, slight U enrichment, and rough corrugate dissolution surfaces on thin indurated carbonate bands with vuggy macroporosity exceeding 40%. There is a distinct change in geochemistry across this disconformity (Figure 11).

Glaucenitic clay marker

Distinctive intervals of glauconitic carbonate mud, occur in units SPCL20 and SPCL21 (Figures 5 and 6) with greenish grey-coloured gritty bioclastic sands (Figure 10) containing scaphopod molluscs, echinoderms and bryozoans. The distinctive character of these glauconitic zones, evident in geochemical profiles in both Brumbys 1 and Brumbys 2, was used to establish a 2 m faulted downthrow to the east within the upper sequence of the Port Campbell Limestone (Figure 5).

Figure 7. Limestone clasts of variably rotated orientation within a dense muddy matrix exhibiting flow laminae. Lower fault zone, NPCL4, Brumbys 1. Horizontal field of view is 23 mm; blue denotes porosity.

Figure 8. Brumbys Fault and intercepting boreholes Brumbys 1 and 2 within part of the CO2CRC Otway site. Variable depth and degree of weathering in the upper Port Campbell Limestone is influenced by regional jointing as indicated by refraction seismic tomography using seismic P velocities. Alignment of lower velocity zones (<1900 m/s) caused by higher porosity carbonates along apparent joint sets. The trace of the Brumbys Fault at the top of the Port Campbell Limestone shows strike slip character, both paralleling jointing and with jogs up to 30°. Note that regional seismic suggests that Brumbys Fault is ~1.2 km long and only the portion imaged using high-resolution seismic (top of Port Campbell Limestone) is shown here.
Figure 9. (a, b) Whole-rock mineralogy determined through XRD analysis. Only the mud fraction is presented. Grainsize was determined through dry sieving into Wentworth scale fractions (wt%), with mud/silt/clay (<63 μm), sand (63–2000 μm) and gravel (>16 mm) proportions for each sample. Laser diffraction analysis was used for very fine-grained samples and the results are included in the ‘mud’ size fraction (converted to wt%).
Weathered zone

The uppermost surface of the Port Campbell Limestone is a 6 cm thick yellowish brown pisolith ferricrete crust atop a 2.7 m interval of thick light olive brown oxidised ferruginous carbonate sand (SPCL25 in Figures 6 and 10). This unit has minor quartz, kaolin and aragonite. Uranium content, although lower in this uppermost oxidised unit, shows a progressive increase upwards from 15 m depth through SPCL23, and SPCL24 towards this weathering zone, with a corresponding increased gamma response (Figure 11). This weathering zone and lateritic crust probably correspond to the development of the Pliocene Timboon Surface (Edwards, Leonard, et al., 1996; Gill, 1965; Wallace et al., 2005).

Hesse Clay

The thin surface interval of a dense clayey mud 1.8 m thick is assigned to the Hesse Clay. This assignation was made by comparison with the stratigraphic relationships defined at Sturgess Point, Port Campbell by Bailey et al. (2017). The Hesse Clay is made up of quartz silt (33–47 wt%), kaolinite (35–47 wt%), sub to euhedral microcline feldspar silt (10–13 wt%), and anatase (3.1–3.3 wt%) (Figure 9). The unit
Figure 11. (a, b) Geochemical signatures and ratios from XRF and ICP-MS analysis (note, CaCO3 analysis was completed separately). (c) Plots of Ce, Eu/Eu*, (La/Nb)N, Th and Zr/TiO2 vs depth (m). Green circles = Hesse Clay; blue squares and yellow circles = Port Campbell Limestone (high- and low-U, respectively see Figure 20); and orange diamonds = Gellibrand Marl. Values for Ce and Th for Hesse Clay are significantly higher (Ce 169–217 ppm, Th 24.6–30 ppm), than in the other units (and plot off the figures). Note the broad increase up hole (decreasing depth) in Ce, Th and ratios Eu/Eu*, (La/Nb)N, and corresponding decrease in Sr. The Zr/TiO2 ratio also shows a broad increase up hole with a pronounced increase in range above 30 m, suggesting input of a more siliceous source. Also of note are the samples from the lower part of the Port Campbell Limestone (below 115 m), which show a transition for many elements with the underlying Gellibrand Marl (most evident in Ce and Eu/Eu*). Eu/Eu* = (2*Eu/0.058)/(Sm/0.153 + Gd/0.2055), is a measure of the degree of enrichment (>1) or depletion (<1) in Eu relative to the other rare earth elements. (La/Nb)N [La/Nb ratio normalised to primitive mantle] = (La/0.687)/(Nb/0.713), and is a measure of the relative depletion of Nb relative to La.
has an overall very low calcium carbonate content of <1 wt%, with traces of aragonite (0–4.2 wt%) and dolomite (1.3–2.5 wt%). Within the lowermost part of this unit, there is a minor presence of coarse ferruginous-stained quartz sand. Thorium has a significant influence in the gamma response of the Hesse Clay (Figure 11), as indicated by lowered U/Th ratios.

The mineralogical characteristics of this unit suggest derivation from a volcanogenic source. Hesse Clay mineralogy includes a significant proportion of both microcline and kaolinite, in addition to quartz, suggesting some igneous input, most probably airborne. The presence of euhedral microcline feldspar supports a direct volcanic source, possibly from original xenocrysts. Joyce (1975) noted alkali feldspar xenocrysts in scoria cones in the western plains of Victoria. Another possible source is from more differentiated alkaline volcanism. Wellman (1974) reported alkali feldspar in trachytic volcanics to the northwest of Melbourne. The southern extent of the Western Plain Subprovince of the Pliocene–Holocene Newer Volcanics (Lesti et al., 2008) lies 12 km to the north of the CO2CRC site. Without dating, the Hesse Clay is considered possibly coeval with or younger than the Newer Volcanics and postdates the Pliocene Timboon/Hanson Plain surface rather than precede it as suggested by Williams et al. (2013).

Based on regional mapping, the Hanson Plain Sand is indicated to overlie the Port Campbell Limestone at this site (Edwards, Tickell et al., 1996; Edwards, Leonard, et al., 1996) but is absent in all cores near the Brumby’s Fault. Only the minor presence of ferruginised quartz sand in the lowermost part of the Hesse Clay suggests a possible contribution from Hanson Plain Sand. The uppermost ferruginised weathered zone of the underlying Port Campbell Limestone lacks any quartz sand.
Cyclicity within the Port Campbell Limestone

Large period cycles in the Port Campbell Limestone, in the order of tens of metres, are seen in the coastal cliffs (Figure 12) and in adjoining wells (Figure 3), especially Nullawarre 3 (Figure 13). Such decametre-scale cycles appear to culminate in cleaner limestones with corresponding higher resistivities. However, comparable large period cycles are not evident in the sequence in Brumbys 1. Casing used during drilling has resulted in incomplete self-potential and resistivity logs (Wang et al., 2020) and precludes any direct comparison with adjoining wells (Figure 3). Only one shoaling-upward cycle (from SPCL20 up to SPCL23) of comparable scale is evident in the sequence at the CO2CRC Otway site (Figure 6). It is possible that because of the proximity to the fault, larger cyclic signals have been diminished by diagenetic alteration, especially carbonate dissolution.

Although the Port Campbell Limestone is a visually uniform sequence, thin depositional cycles of predominantly shoaling-upward character are interpreted from the gamma log. Depositional cycles are seen to be third-order units in the order of 1.7 m thickness in the lower part of the formation below the fault zone and diminishing to an average of 1.14 m thickness in the upper 35 m of the formation.

Wang et al. (2020) used a MLP classifier to differentiate 25 SPCLunits as a framework (Figure 8, column 2) to better describe the variations within the Port Campbell Limestone based on mineralogy (Figure 9), geochemistry (Figure 11) and porosity/permeability (Figure 14). The SPCLunits were also correlated to seismic horizons. Further cyclicity is observed in the variation of total silicates with depth. Repeated cycles of silicate-rich (5–6%) to silicate poor (1–2%) variations, with length-scales of ~10 to <5 m, are evident. These cycles appear to correspond closely (but not exactly) to the identified SPCL subdivisions (Figure 15). An additional approach to understand the cyclicity is through the application of quantitative cyclostratigraphic methods (Sinnesael et al., 2019). Here we use the gamma-log curve integrated with biostratigraphic foraminifera datums (refer to the Cyclostratigraphy section).

Character of the Port Campbell Limestone

The generally unconsolidated fine-grained carbonate sediment has uniform mid-grey appearance but is ‘lumpy’ and texturally variable (Figure 16) from bioturbation, as well as from subsequent cementation and later dissolution effects. Grainstone and packstone textures predominate. The matrix of variably indurated lumpy limestones is packstone. Wackestone and mudstone textures are rare.

In Brumbys 1, macrofossils such as scaphopod and bivalve fragments and echinoid plates are also rare. In thin-section, echinoid fragments and foraminifera are the most ubiquitous identifiable bioclasts. Identifiable fragments of molluscs, bryozoans, brachiopods and bivalves, as well as disarticulated ostracod valves, are not as common (Figure 17). Many carbonate particles (30–60%) are of indeterminate origin as a result of fragmentation, abrasion and some micritisation, but they are interpreted to have a bioclastic origin.

Serpulid worm tubes and calcareous red algal fragments have been recorded in the Port Campbell Limestone elsewhere (Nicolaides, 1995) but have not been identified in Brumbys 1 core. Echinoid spines and fragments are readily identifiable by their syntaxial cement overgrowths that create a random induration in the sediment. Pellets, of presumed faecal origin, are generally not common (<20%).

The Port Campbell Limestone is dominated by carbonates, calcite with lesser dolomite and aragonite, which were identified through XRD analysis and corroborated by calcium carbonate content analysis. Total carbonate content ranges from 50 to 97 wt%, with an average of 85 wt% (Figures 9 and 11).

Quartz and minor feldspar in the Port Campbell Limestone sequence are detrital. The mineralogy (Figures 9a and 15) clearly shows the fluctuating presence up sequence but remaining predominantly between 1% and 5% as silt to very-fine-grained sand grains. Despite the low detrital content, a consistent cyclic zonation is evident within the Port Campbell Limestone comprising cycles of decreasing detrital content, from 5–10 wt% to 1–2 wt% (Figures 11 and 15).

The clay content in the sequence is very low, generally absent but with some zones up to 10 wt% (Figure 9a). Montmorillonite occurs in two narrow zones of the lower sequence, while kaolinite is present in five specific zones of the upper sequence, from SPCL13 upwards. Mineralogical and grain-size variations in a stratigraphic context are presented in Figure 9. A detailed description of these characteristics is presented in the Supplemental data.

Diagenesis

The lumpiness of carbonates in the sequence appears to be predominantly the result of patchy localised cementation. Stratiform horizons with concretions, continuous over kilometres, occur in outcrop along coastal cliffs (Tickell et al., 1992). Once such cemented patches develop as concretions, they may subsequently be subjected to dissolution on their outer margins, with a residue of less soluble particles and fines accumulating in the surrounding matrix (Figure 17d).

Where calcite cements are present, they are predominantly syntaxial overgrowths on clean echinoid fragments that may develop into localised poikilotopic cement patches that envelop other bioclasts. Scalenohedral and blocky druse cements fringe internal cavities of larger bioclasts. If particles other than echinoids are encrusted by cement, it is as thin inconspicuous fringe cements. Where moldic porosity has developed with dissolution of shell material, these fine cement fringes may remain intact and retain the outline of the bioclast, preserving the original texture but with porosity greatly enhanced.
Hardbands, indurated by carbonate cements, are generally 1–10 cm thick and typically have a grainstone texture; porosity is generally moldic. The surface of hardbands is commonly rough to rugose to cuspate, indicative of surface dissolution. Loss of carbonate in the sequence can be at varying scales and to different degrees, and accordingly has been difficult to quantify. The contrast between well-cemented low-porosity grainstones and high moldic porosity in

| MD (m) | 2nd order units | GRI | GR | Average porosity by zone | Average permeability by zone |
|--------|-----------------|-----|----|--------------------------|-----------------------------|
| 10     | SpCL25          |     |    |                          |                             |
| 20     | SpCL24          |     |    |                          |                             |
| 30     | SpCL23          |     |    |                          |                             |
| 40     | SpCL22          |     |    |                          |                             |
| 50     | SpCL21          |     |    |                          |                             |
| 60     | SpCL20          |     |    |                          |                             |
| 70     | SpCL19          |     |    |                          |                             |
| 80     | SpCL18          |     |    |                          |                             |
| 90     | SpCL17          |     |    |                          |                             |
| 100    | SpCL16          |     |    |                          |                             |
| 110    | SpCL15          |     |    |                          |                             |
| 120    | SpCL14          |     |    |                          |                             |

Figure 14. Averaged porosity and permeability for SpCL units of the sequence: column 1, core depth; column 2, lithostratigraphic SpCL units; column 3, gamma log (GRI) and graphic of inferred lithology (mud (brown)-sand (yellow)); column 4, high-resolution gamma (GR) and smoothed gamma (GRS) log; column 5, porosity; column 6, permeability (mD).
similar grainstones is most clearly illustrated in a comparison of intervals affected by only phreatic cementation, and those with subsequent vadose diagenesis in Nullawarre 3 (Figure 18). Vadose diagenesis is apparent in the upper weathered interval of the Port Campbell Limestone (core 1, Figure 13). Where continuous hardbands exist in the sequence in Brumbys 1, they may form a roof to narrow stratiform cavities that are in the order of centimetres in height. Such cavities generally coincide with circulation loss during drilling, indicating lateral continuity of cavity and very high permeabilities as seen in SPCL23 and an upper interval in SPCL16.

In the sequence of Brumbys 1, the remnant presence of aragonite is thought to indicate extremely low permeabilities, preventing mineralogical inversion or leaching through contact with groundwater.
Porosity and permeability

The semi-consolidated and unconsolidated sequence of the Port Campbell Limestone has high porosity (Figure 14). Only in the rare thin hardbands is cementation so pervasive as to significantly reduce porosity and permeability.

A generalisation could be made from this data that the Port Campbell Limestone adjoining Brumbys Fault has an averaged effective porosity exceeding 25% in all lithostratigraphic units, with no apparent trend with depth. One anomalous zone reaches 58.5% in a shallow aquifer (SPCL23), which has permeabilities in the order of 2 darcy. Permeability for much of the remaining sequence ranges between 100 and 400 mD, with aquitard zones as low as 20 mD (SPCL20, SPCL21).

When permeability is modelled in 3D with seismic control beyond Brumbys 1, lateral variations of permeability become apparent. There are near-surface stratiform zones of higher permeability related to deep weathering as indicated by low seismic velocities (Figure 8).

Provenance interpretation

The geochemical signatures (Figure 11; online data file) in the Port Campbell Limestone sequence are indicative of mixed provenance, particularly in the upper part of the Port Campbell Limestone. Despite local perturbations such as locally increased siliciclastic input (Figure 15), there is a clear overall progressive change in certain elements up hole, e.g. increasing Th, LREE, Zr/TiO$_2$, La/Nb, decreasing Sr, that together suggest a switch in provenance to more felsic compositions (Figure 11c). The range and variation in chemistry also increase up hole, indicating an increasingly complex or mixed provenance. For example, the increase in the Eu/Eu$^+$ ratio and concentration of Eu and the LREEs up hole suggests a change to more enriched basaltic rocks and/or their fractionates. Wide variations in La/Nb for given Zr/TiO$_2$ ratios indicate the presence of a more typical continental provenance component, such as the outcropping Paleozoic sediments and granites in the hinterland to this region.

Various ratios (e.g. Zr/TiO$_2$, La/Nb, Eu/Eu$^+$) suggest that the overlying Hesse Clay has a very similar provenance signature to the upper Port Campbell Limestone (Figure 11c). Equally, despite a higher siliciclastic content, ratios such as La/Nb, Zr/TiO$_2$ in the Gellibrand Marl suggest a similar provenance to the lower Port Campbell Limestone. Variations in Nb/Y (Figure 11) suggest the Gellibrand Marl may include both alkaline and non-alkaline volcanic components (e.g. Forbes et al., 2020; Winchester & Floyd, 1977). This alkaline component appears to be greatly diminished in the overlying lower Port Campbell Limestone.

From the signatures of U, K and Th, it is clear that the gamma response within the Port Campbell Limestone is largely derived from K content, with increased U in weathered zones (Figure 11). Except for Ca and Mg, and also U, major elements and most trace elements are enriched in zones that have a greater abundance of clay and silicate minerals. This is supported by the reasonable to good correlation between most elements and Al$_2$O$_3$ content (Figure 19).

Uranium

As noted above U content is not solely controlled by detrital contribution. This is best demonstrated by the variable behaviour vs indicators of detrital content, such as Al$_2$O$_3$. Figure 19 shows that a subset of Port Campbell Limestone rocks show a good positive correlation with Al$_2$O$_3$ suggestive of control by detrital phases. This is also supported by the good positive correlation between U and Th, and U and K$_2$O, for these samples. The majority of these are characterised by low U (<1.5 ppm) and come from the lower 40 m of the Port Campbell Limestone (Figure 11c). The remainder of the samples show no correlation with Al$_2$O$_3$ and notably have elevated U contents (1.3–6 ppm) (Figures 19 and 20a) suggesting a major source of U that is not detrital in origin. Importantly, it is also evident that this anomalous U contributes significantly to the median of the gamma-ray signature through the sequence (over 80% of the gamma-ray response is due to U in the most U-enriched samples). The origin of this anomalous U
Figure 17. Overview of carbonates in the Port Campbell Limestone and Gellibrand Marl examined in thin-section.
is uncertain. As noted earlier possible weathering affects may be responsible for changes in U content in the upper 15 m, and it is feasible that some redistribution of U has occurred elsewhere in the Port Campbell Limestone, e.g. elevated U below the subtle disconformity at 65 m (Figure 11). There is no observable relationship between U contents and zones of enhanced permeability, i.e. dolomitic intervals. For example, highest U contents are in zones with very low dolomite contents. In contrast, zones with minimal diagenetic alteration and elevated aragonite (>5 wt%), interpreted to indicate low permeability, have low U contents (1–1.5 ppm), consistent with a primary detrital origin for the U in these zones.

**Biostratigraphy**

As observed in previous studies (Gallagher et al., 1999; Gallagher & Holdgate, 2000, Gallagher & Stanislaus, 2019), the Gellibrand Marl and Port Campbell Limestone of the Heytesbury Group yielded common to abundant foraminifera. We found microfauna offers an excellent control on age as well as depositional conditions and paleodepths. All
foraminiferal data from Brumbys 1 used to interpret the age and environmental evolution of the sequence are provided as online data files.

**Environment and age of the Gellibrand Marl in Brumbys 1**

Foraminifera are abundant and preservation is poor to good. The percentage of planktics is variable, ranging from 18–70% reflecting an outer shelf environment (≥100 m paleodepth). Inner shelf taxa are absent, instead the benthic assemblage is dominated by middle to outer shelf taxa (and *Discorbinella berthelotii*, *Cibicidoides perforatus* and *Cibicides* spp.) and outer shelf species such as *Cassidulinoides* spp., *Cassidulina* spp. and *Sphaeroidina bulboides*. The marly (wackestone) facies in this unit reflects low energy below wave base deposition in outer shelf or even upper slope environments (Gallagher et al., 1999).

The top of the Gellibrand Marl (122.3–126.1 m; Figure 21) is above the *Praeorbulina glomerosa* sensu stricto but lies in the middle Miocene M6/N9/E1 zones (Table 1; <15.1 Ma). This is similar to other onshore Otway wells: Brucknell 2, Mepunga 25, Nirranda 6, Nullawarre 3 and Terang 1 (Gallagher & Stanislaus, 2019). The Top of *Praeorbulina glomerosa* sensu stricto is at 112.3 m suggesting a minimum age of 14.78 Ma. Other taxa present include typical Miocene species such as *Globorotalia miozea*, *Topoarbulina peripheroronda* (>13.8 Ma), *Globoquadryina dehiscens*, *Globigerinoides trilobus* and *Globoturborotalia woodi*.

**Environment and age of the Port Campbell Limestone in Brumbys 1**

The Port Campbell Limestone microfauna is not as well preserved as those in the Gellibrand Marl with relatively lower %planktics (average ∼16% with a range of 6–55%). This is similar to previous data from cores of the Port Campbell Limestone in the Otway Basin (Gallagher & Stanislaus, 2019), but unlike Brumbys 1, none of the sections analysed by Gallagher and Stanislaus (2019) were continuously cored. Microfaunal analysis reveals significantly more variability in preservation quality and %planktics than previous known from discontinuously sampled cored sections.

There are several intervals in Brumbys 1 with poorly preserved faunas (121–108.2 m, 87.3–65.15 m, 41.3–39.3 m and 14.1–11.3 m), that alternate with horizons of good to
excellent preservation. Maxima of %planktics (55 to >24%), suggestive of paleodepths of >100 m, decrease up section above ~90 m alternating with planktic minima from 6% to 17% (<100 m paleodepths; Figure 21). Planktic maxima, which correspond to several horizons with 80% or less carbonate (Figure 21), are likely to be marly sediments, alternating with limestones (>80% carbonate, Port Campbell Limestone packstone to grainstones). The relatively planktic-rich lower-energy marly limestones were deposited below wavebase in middle to outer shelf environments, whereas many of the planktic-poor limestone intervals (especially above 70 m) were deposited above wavebase at inner to middle shelf paleodepths (Gallagher et al., 1999).

The interval from 121 to 96 m downhole lacks common inner to middle species (Figure 21) yet yields low %planktics. Instead, the outer shelf taxa, Cassidulinoides spp., Cassidulina spp. and Astrononion spp., dominate with abundant cibicidids (middle to outer shelf species). This suggests that despite the minor %planktics in this interval, which might indicate inner shelf depths using the formula of van der Zwaan et al. (1990), the 20 m section of limestones immediately above the top of the Gellibrand Marl was likely deposited in middle to outer shelf environments. The %planktic-rich unit at 90 m also lacks middle and inner shelf taxa and is interpreted to represent outer shelf paleodepths. Above drillhole log level 90 m, shallower inner to middle shelf taxa such as Rosalina spp., Patellina spp., Discorbis spp., Elphidium spp. and Glabratellina spp. dominate carbonate-rich intervals with lower %planktics indicating paleodepths generally less than 70 m. This shallow-water facies is punctuated with occasional slightly deeper marly horizons that are richer in planktics.

The base of the unit overlying the Gellibrand Marl lies above the Praeorbulina glomerosa sensu stricto datum at 112.3 m suggesting a maximum age in this section of

Figure 20. U (ppm) versus Al₂O₃ (wt%) and Th (ppm). Note the two distinct trends, with detrital U (correlated with both Al₂O₃ and Th) versus U from a secondary source (decoupled from both Al₂O₃ and Th; see Figure 19f).
14.78 Ma (Table 1; Figure 21). The next most significant datum is *Globorotalia conica*, which first appears at 94 m in the upper part of the middle Miocene M6/N9/E1 zone (Cifelli & Scott, 1986; Scott *et al*., 1990), this is followed up section by the base of *Globorotalia mayeri* at 87.3 m denoting the base of the middle Miocene M7 to M10/N10 to N13/D1 to D2 zones at 14.24 Ma (Table 1; Figure 21). The next key datums are at 33.2 m and 29.1 m where bases of *Neogloboquadrina* spp., *Globoturborotalia nepenthes* (11.63 Ma) and *Globoturborotalia decoraperta* (11.49 Ma) define the base of M11/N14/B2-C zones, respectively. *Globorotalia miotumida* (conoidea) also appears at this level. This species first appears near the base of N14 (Cifelli & Scott, 1986) supported by the top *Globorotalia conica*, which is also within the N14 Zone. The last appearance of *Globorotalia mayeri* at log level 5.2 m suggests that the youngest strata in the Port Campbell Limestone are still within the M11/N14/B2-C zone with a minimum age of 10.46 Ma (Table 1; Figure 21). The absence of late Miocene planktic indicators such as *Globorotalia pleisiotumida*, *Globorotalia miotumida* (conoidea) and the presence of many middle Miocene taxa strongly suggests that the Port Campbell Limestone is no older than the middle Miocene in most sections in the Otway Basin (Gallagher & Stanislaus, 2019).

**Cyclostratigraphy**

The four significant biostratigraphic datums determined from the above biostratigraphy allow for a first-order depth-to-time conversion in Brumbys 1 (Figure 22a). This conversion is made by means of linear interpolation between the biostratigraphic tie points. The resulting gamma-log time series is then subjected to multitaper
method (MTM) spectral analysis, which yields a statistically significant spectral peak at the expected frequency of short (~100 kyr eccentricity (purple band in Figure 22b). Two even stronger spectral peaks occur at frequencies around ~20 cycles/Myr (51 kyr periodicity), which cannot be readily associated with an astronomical parameter. The latter three periods, with wavelengths between 51 and 100 kyr in the time domain, chiefly correspond to the third-order m-scale (1.14–1.7 m) shoaling-upward cycles in the depth-domain (see Stratigraphy).

At higher frequencies, a statistically significant (>95% confidence level) spectral peak occurs within the expected frequency range of precession (21 kyr periodicity). However, given the smoothed character and temporal resolution of the gamma-ray dataset, we cannot interpret these with any confidence.

Figure 22. Cyclostratigraphic analysis of Brumbys 1 gamma-ray series. (a) Gamma log in the depth-domain and along a simple biostratigraphic age model. (b) Multitaper method (MTM) power spectrum of the gamma-ray signal, along its biostratigraphic age–depth model. (c) Bandpass-filtered signal (75–130 kyr bandwidth) extracting gamma-ray signal components that could be related to ca 100 kyr short eccentricity. (d) The bandpass filter after tuning to the La2004 eccentricity target curve (Laskar et al., 2004). (e) Cyclostratigraphically refined gamma-ray time series compared with the benthic δ¹⁸O megasplice of De Vleeschouwer et al. (2017). (f) MTM power spectrum of the gamma-ray signal, along its cyclostratigraphic age–depth model. (g) Evolution of sedimentation rates in the cyclostratigraphic age–depth model throughout the studied interval.
In a next step, the 100-kyr variability in the gamma-ray log is isolated through bandpass filtering, extracting 75–130 kyr periodicities that are embedded in the signal (red curve in Figure 22c). This filtered signal forms the basis of our astrochronological tuning. Indeed, tuning of Brumbys 1 starts from the assumption that this filtered signal represents the imprint of Earth’s orbital eccentricity. A second tuning assumption pertains to the phase relationship between the gamma signal and eccentricity. Here, we assume that warmer intervals, generally corresponding to high-eccentricity configurations (De Vleeschouwer et al., 2017), are characterised by a wetter southern Australian climate, an increased detrital sediment flux and hence a higher gamma-ray signal. On the basis of these assumptions, we establish a correlation between the gamma-ray 100-kyr filter and the La2004 eccentricity solution (Laskar et al., 2004; Figure 22d) while also striving for a good match between the Brumbys 1 gamma-ray signal (black) and the δ18O benthic megasplice (De Vleeschouwer et al., 2017; Figure 22e). This astronomical tuning step refines the biostratigraphic age model by shifting, squeezing and stretching the biostratigraphic gamma-ray time series. The greatest disparity between the purely biostratigraphic age–depth model and the cyclostratigraphic age model amounts to 115 kyr and occurs around 14.0 Ma.

In tuning and correlation of cyclicity in the gamma signal of the Port Campbell Limestone in Brumbys 1 with the δ18O benthic megasplice, the median of an averaged curve of the high-resolution gamma trace of the Port Campbell Limestone sequence shows significant departures in the upper sequence from a trace anticipated to generally follow the δ18O trace (Figure 22e). These zones of increased median of the gamma signal in the Port Campbell Limestone correspond to an increased U content in SPCL24–SPCL22 and SPCL12–SPCL10 (Figure 11). Slight enrichment in U in these units is attributed to authigenic adsorption through groundwater processes during emergence and resultant weathering, a phenomenon not seen in deep ocean sequences on which the megasplice has been established.

The power spectrum of the tuned gamma-ray time series is juxtaposed to the power spectrum of the δ18O megasplice in Figure 22f. By comparing the cyclostratigraphic spectrum to the purely biostratigraphic spectrum (Figure 22b), it becomes clear that the tuning approach shifted power from the 51-kyr band towards the ca 100-kyr band associated with short eccentricity and the ca 41-kyr band associated with obliquity. The power in the precension band completely collapsed, reinforcing our evaluation that precension is not a significant component of the analysed gamma signal.

On the basis of interpolated thickness of third-order cycles against time, a sedimentation rate can be calculated throughout the Port Campbell Limestone (Figure 22g). However, these rates are determined on the assumption that the cored sequence has had no subsequent post-depositional alteration.

Discussion

Dissolution and proximity to fault

The sequence in Brumbys 1 is largely unconsolidated carbonate with gradations through lumpy unconsolidated carbonate to relatively few hardbands. The commonly rough to rugose surface of indurated lumps, and the difference between grainstone textures within lumps and packstone texture in surrounding unconsolidated matrix, is best explained through carbonate dissolution processes. These are inferred to extend laterally in the near-surface weathering that has been influenced by jointing (Figure 8), as well as further down sequence in closer proximity to the Brumbys Fault. Anomalous lower seismic velocities near surface and near fault were defined in the geological model of Feitz, Radke, et al. (2018). This would suggest that the fault and comparative fractures have been influential in locally channelling groundwater along structures, enhancing dissolution as well as dolomitisation. Our observations are consistent with previous suggestions that fractures and joints within the Port Campbell Limestone may have been widened by carbonate dissolution and form a secondary porosity to complement the primary intergranular porosity (Bush, 2009).

Cyclicity

Long-period cyclicity is not readily evident in the Port Campbell Limestone in Brumbys 1, in contrast to adjoining wells and coastline outcrop (Figures 3, 12 and 13). However, shorter-period cyclicity, driven by orbital forcing, especially eccentricity and to a lesser degree obliquity, has been demonstrated in modelling using the gamma log (Figure 22) on the basis of the repeated changes in detrital content in each such cycle. Sedimentation rates (Figure 22g) are indicated to decrease up sequence and corroborate with the diminishment in thickness of delineated third-order units (Figure 8) from the lowermost to uppermost part of the Port Campbell Limestone. The possible condensation of the upper sequence by dissolution processes could also be a contributing factor. Anomalous lower seismic velocities in the shallow sequence (Feitz, Radke, et al., 2018; Figure 8) suggest an irregular interval of lower density and/or reduced induration (Figures 17a and 18). Accordingly, the degree of influence of late dissolution effects vs changing sedimentation rates remains unresolved.

Disconformities and weathering

Two horizons of emergence and weathering are evident within the Port Campbell Limestone.
The disconformity below the Hesse Clay has a distinctive 3 m upper zone of oxidised limonitic stained unconsolidated carbonate sand above light coloured green-grey semi-consolidated carbonate down to 17 m, below which the sequence is predominantly dark green-grey. Uranium increases upwards in this weathered zone from 2 ppm in SPCL22–6 ppm in SPCL24 before sudden diminishment to 1 ppm in SPCL25, the highly oxidised upper zone where leaching by oxidised groundwater appears to have occurred. This disconformity is attributed to the regional development of the Timboon Surface post uplift and emergence of this sequence in the Port Campbell Embayment.

A subtle disconformity is indicated at the top of SPCL12 at 65.5 m depth. Rough corrugate dissolution surfaces are evident on thin indurated carbonate bands with vuggy macroporosity exceeding 40%. The uppermost 3 m of sequence below this disconformity is light green-grey and darkens gradually downwards for ~15 m back to dark green-grey. This lighter coloured zone contrasts with the dark green-grey of the overlying SPCL13. This weathering zone, although subtle in colour change, has an enhanced U content of ~3 ppm, in contrast to 1 ppm below this zone (Figure 11a). Foraminiferal paleodepth estimations (Figure 21) are the lowest above and below this horizon. Above the disconformity, with inferred increasing water depth, mud and quartz input increases, pyrite spikes, and there are sudden shifts in Fe/Al, Fe/P and V/Cr and Cr/Nb (Figure 11b). Importantly, there are increasing trends in both Cr and V in the 7 m of sediment below the disconformity (such elevated V and Cr also occur in the weathering zone in the top 10 m). This disconformity corresponds to the most pronounced lowstand of sea-level during the Mid Miocene Transition at ca 13.2 Ma (Figures 21 and 22) where δ18O CIB VPDB is highest, inferring the greatest volume of global ice sheets and corresponding lowest sea-level.

Mineralogy and geochemistry

Application of paleoredox proxies, such as U/Th, V/Cr, Fe/Al (e.g. Algeo & Liu, 2020; Jones & Manning, 1994; Tribovillard et al., 2006), suggests that the depositional environment for the Port Campbell Limestone ranged from oxic–suboxic (e.g. U/Th <1, V/Cr <5, Fe/Al <0.5–0.6) to euxinic/anoxic. These indicators are not always consistent (with respect to each other) and are, at least partly, responding to other factors. For example, many of these paleoredox elements are positively correlated with Al2O3, suggesting control by detrital material and not redox. Moreover, many of these proxies have been developed and applied to mudstones and shales, rather than carbonate dominated sequences (Jones & Manning, 1994). Of these, the V/Cr and Fe/Al appear to have the best correspondence in this study, and Fe/P closely resembles the Fe/Al signature. An increase in Fe content towards the top of the Port Campbell Limestone is a result of weathering at the top of the formation, which was also observed in core as an orange-coloured zone in an otherwise almost uniformly grey limestone. Further investigation is required to determine which proxies are most useful to determine depositional and post-depositional conditions for the Port Campbell Limestone. For U, both detrital and authigenic sources have been effectively differentiated (Figure 20).

Evolution of Miocene paleoenvironments and paleoclimate

Preliminary microfossil analysis using planktic foraminiferal biostratigraphic data reveals that the Gellibrand Marl and Port Campbell Limestone in Brumbys 1 were deposited from 15 to 10.5 Ma (Figure 21) during a major global climate transition from the warm Mid-Miocene Climate Optimum (MMCO) to the cooler Mid-Miocene Climatic Transition (MMCT) (De Vleeschouwer et al., 2017; Foster et al., 2012). Because of the northward migration of the Australian continent over time, accumulation of the Port Campbell Limestone during the Miocene was at higher latitudes, in the range 50 to ~48°S (Veevers, 2001, figure 44). Foraminiferal assemblage data indicates relatively deep paleodepths (>200 m) below log level 80 m in Brumbys 1 from ca 15 to 14 Ma (the Gellibrand Marl) correlating to a period of globally depleted δ18O values (De Vleeschouwer et al., 2017; Holbourn et al., 2013, 2014). Paleodepths shallower by around 100 m in the overlying basal Port Campbell Limestone and fluctuate up to ~200 m at around 14.24 Ma associated with relatively high sedimentation rates (Figure 22) during the MMCO. The MMCT (Figure 21) is marked by a shift to shallower paleodepths (<70 m) and lower sedimentation rates after 14 Ma, corresponding to a time of enriched δ18O values due to Antarctic Icesheet expansion and lower sea-levels. Future investigation with higher resolution microfossil assemblage analysis and benthic stable O/C isotope analyses of the Cibicidoides spp. (a relatively common taxon in the succession) in Brumbys 1 would enhance our preliminary correlation between this regional neritic archive and the global isotope datasets (Figure 21) and improve our understanding of the glacioeustatic consequences of Miocene cryosphere expansion.

Miocene cyclostratigraphy and astronomical climate forcing

The gamma-ray signal contains a mixed signal of obliquity and eccentricity and is thus generally congruent with the astronomical imprint observed in contemporaneous deep-sea benthic δ18O records (Holbourn et al., 2013, 2014). However, contrary to the δ18O records, the Brumbys 1 gamma signal does not show a major shift in absolute values or astronomical signature around 13.8 Ma, i.e. a period of extensive ice growth on Antarctica. The rate of sedimentation, however, did decrease significantly around 14.1 Ma. This could be related to the 6–7°C cooling of sea surface temperatures around Antarctica (14.2–13.8 Ma) in the run-
up to the major glaciation (Shevenell et al., 2004). However, further research is required to disentangle the precise cause-and-effect chains between both evolutions.

Conclusions

The Port Campbell Limestone at the CO2CRC site is a stack of thin repetitive depositional cycles within cycles. The third-order cycles of shoaling-upward character resulted predominantly from orbital forcings by obliquity and eccentricity. The carbonates are grey unconsolidated to semi-consolidated and rarely lithified bioclastic muddy carbonate sands. Most bioclasts are of indeterminate origin due to comminution and micritisation. The Port Campbell Limestone is predominantly calcite with traces of remnant aragonite in muddier low-permeability sands, and dolomitic zones in permeable intervals. The small non-carbonate component, between 3% and 15% in the sequence, comprises quartz silt with minor clay, feldspar and mica. An intraformational glauconitic mudstone with a distinctive molluscs–echinoderm–bryozoan fauna provides one distinctive marker interval in the sequence.

Dissolution overprints are prominent throughout the carbonate sequence, as moldic porosity that can exceed 60% in remnant indurated bands, and the degradation of such bands to irregular cemented lumps within an unconsolidated muddier matrix. The overall high porosity and permeability of the sequence may be attributed to proximity to the Brumbys Fault. Additional increased dissolution and disaggregation up sequence towards the top of the formation is evidenced by anomalous upward-diminishing seismic velocities and are attributed to weathering during development of the Timboon Surface. Despite weathering and small fault displacements, the shallow sequence remains correlatable across a distance of at least 300 m.

Provenance signatures of the non-carbonate component of the sediment indicate a predominant volcanogenic contribution in the upper Gellibrand Marl and lower Port Campbell Limestone. This transitions to a more complex provenance mix in the upper half of the Port Campbell Limestone. There is a clear temporal trend to a more felsic provenance component in the upper part of the sequence, accompanied by much greater geochemical variability that requires consideration of multiple provenances. This may reflect a switch to a more evolved volcanogenic component as well as contributions from older continental material.

Foraminiferal data show that the upper part of the Gellibrand Marl and Port Campbell Limestone were deposited from 15 to 10.5 Ma. Accumulation of the Port Campbell Limestone was at higher latitudes in the range 50 to −48°S. There was a depositional transition from outer shelf conditions (~200 m water depth) in the Gellibrand Marl at around 15 Ma to middle shelf (50–100 m water depth) environments in the lower part of the Port Campbell Limestone during the MMCO at ca 14.24 Ma. Shallowing after 14 Ma indicates variable yet shallower paleodepths (<70 m) during and following the end of the MMCT ca 13.2 Ma when the sequence was emergent for an undetermined brief period at the nadir of global sea-level. Following accumulation of the uppermost Gellibrand Marl at ~8 cm/kyr, depositional rates decreased to 4–6 cm/kyr up to ca 14.24 Ma and remained low at between 1.5 and 3 cm/kyr throughout the subsequent deposition of the Port Campbell Limestone.

Any future higher-resolution microfossil assemblage analysis in conjunction with stable isotope analyses would contribute to an improved cyclostratigraphic analysis on this sequence in Brumbys 1. This should substantiate correlation to global curves based on deep ocean datasets, and possibly elucidate climatic and eustatic consequences of Miocene cryospheric evolution.

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Data availability statement

The data that support the findings of this study are openly available at Geoscience Australia at https://dx.doi.org/10.26186/146045

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