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

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SUPPLEMENTAL DATA

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Supplemental data

Character of the Port Campbell Limestone. A detailed description of the overall composition, carbonate components and minor components.

Data tables available at https://dx.doi.org/10.26186/146045

Character of the Port Campbell Limestone

Composition

Carbonate

The Port Campbell Limestone is dominated by carbonates, calcite with lesser dolomite and aragonite, which were identified through XRD analysis and corroborated though calcium carbonate content analysis. Total carbonate content ranges from 50 to 97%, with an average of 85%. (Figures 10 and 12).

There is an inverse relationship between $CaCO_3$ content (largely representing calcite) and MgO, which serves as a proxy for dolomite (as determined through XRD) in the Port Campbell Limestone. From the MgO signature, four discrete dolomitised zones can be seen within the Port Campbell Limestone, occurring at depths of 11–19 m (SPCL3 and SPCL4), 48–54 m (mainly SPCL10), 75–88 m (mainly SPCL17), located just above the top of the fault zone, and 100–113 m (mainly SPCL22 and SPCL23) (Figure 12). The dolomite zones are associated with zones of higher permeability observed in the core and appear to record a diagenetic response to post-depositional fluid flow through the sediment. Aragonite is generally absent or rare (<4%) throughout the sequence, but there is a higher abundance at 22 m, 28.6 m, 59.3 m, 63.3 m, peaking at 19% within a very compact interval directly above the upper fault zone (91 m) and exceeding 10% in the lower part of the basal transition zone (SPCL1). This presence of aragonite appears to be inversely related to the permeability of the immediate host sediment. This is consistent with the observation that aragonite content is positively correlated with Al_2O_3, i.e., detrital input, suggesting that aragonitic zones indicate minimal diagenesis.

Siliciclastic content

Petrographic evidence indicates that all quartz and minor feldspar in the Port Campbell Limestone sequence are detrital. The mineralogy chart (Figure 9b) clearly shows the fluctuating presence up sequence but remaining predominantly between 1–5% as silt to very-fine-grained sand grains. There are three discrete intervals with higher siliciclastic content than the majority of the carbonate-dominated Port Campbell Limestone. These include the transition zone at the base of the Port Campbell Limestone and top of the Gellibrand Marl; the clay-rich glauconite zones at ~23–24 and 28–29 m; and at the top of the fault zone, ~90 m depth. 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% to 1–2% (Figures 12 and 17). These cycles appear to closely (but not exactly) correspond to the identified SPCL subdivisions (Figure 17).

The SiO_2/Al_2O_3 ratio acts as a proxy for the maturity of the sediment, or clay content (higher Si/Al corresponds with more mature, quartz-rich sediment, while lower Si/Al corresponds with a higher clay/labile and less recycled content) (Roser & Korsch, 1986; Roser *et al.,* 1996; Scheffler *et al.*, 2003). This ratio is relatively steady at ~4 throughout much of the Port Campbell Limestone, although there are zones with broad deviations, such as at ~11–23 m and ~92–120 m depth, the latter of which includes the fault zone to the base of the unit (Figure 12). The “least mature” sediment is found within the glauconite zones (discussed below). Zr/Ti, a potential proxy for provenance (with higher values corresponding to more granitic/cratonic provenance) (Scheffler *et al.*, 2003), shows a pronounced increase to generally higher values above ~30 m. This may indicate progressively more proximal, if varying, source of sediments in the upper part of the Port Campbell Limestone. It is noted, however, that correlations of other elements with Zr/Ti are inconclusive or contradictory. For example, although there is a general increase in Si/Al with increasing Zr/Ti this is also accompanied by increases in Eu/Eu*, suggesting a change to a different and/or more complex provenance in the upper part of the Port Campbell Limestone.

Clay

Clay content in the sequence is very low, generally absent but with some zones up to 10%. Montmorillonite occurs in 2 narrow zones of the lower sequence, while kaolinite is present in 5 specific zones of the upper sequence, from SPCL13 upwards. Several methods were used to estimate clay content in the sequence. Gamma Vcl (volume of clay) estimation, XRD and geochemical signatures each have limitations so the non-carbonate content with the subtraction of siliciclastics is the best approximation of the amounts of clays in sequence. The derivation of these clays, detrital versus diagenetic, has not been determined.

Grain size variability

The Port Campbell Limestone is a relatively uniform sequence of carbonate muddy sands and lesser sandy muds with minor quartz and clay. The general sand–mud content is shown in Figure 10. Repeated cyclicity from muddy sands up to cleaner sands is evident in the numerous thin 3rd order depositional events (Figure 6, column 3), based on the proportion of clean (lower gamma) carbonate over muddier and marly (higher gamma) carbonate. At the coarser 2nd order level, progressive changes in sand–mud proportions are not readily apparent except at the base of the formation (SPCL1, SPCL2) and above the fault zone from SPCL8 to SPCL12. Directly above this there are muddier composite units (SPCL13 to SPCL19, SPCL20 to SPCL21, and SPCL22 to SPCL24).

The variations in particle size within the sand fraction of the carbonates offer little information due to varying size of bioclasts and their subsequent comminution by bioturbation, as well as fragmentation, abrasion and micritisation prior to burial. There is no true gravel fraction in the Port Campbell Limestone at the site. The indicated sieved gravel fraction (Figure 10) is an artefact from the presence of cemented lumps, formed either as incomplete initial cementation of cleaner bioclastic sands, and/or from subsequent partial dissolution of cemented bands or patches. Many of these lumps have rough irregular surfaces and moldic porosity that indicate a dissolution overprint. Their presence is taken to indicate the sand.

Carbonate components

Bioclasts

In Brumbys 1, macrofossils such as scaphopod and bivalve fragments and echinoid plates are 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 18). Many carbonate particles (30–60%) are of indeterminate because 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). In the core of Brumbys 1 they have not been identified but may constitute some of the indeterminate bioclastic material. Echinoid spines and fragments are readily identifiable by their syntaxial cement overgrowths that create a random induration in the sediment.

Pellets

Pellets, of presumed faecal origin, are generally not common (<20%).

Minor components

Dolomite

Dolomite is notably present in four intervals (Figure 10) as an interparticle cement of discrete honey-coloured euhedral rhombs (<60 to 150 µ), with an overall abundance between 0 and 23% of the sediment. Dolomite-rich intervals are associated with high permeability zones.

The highest dolomite content is in SPCL16 with up to 23% (XRD quantified estimate is much higher at 36–46% for this interval). Dolomite is consistently present in the lower sequence, in SPCL3, immediately below and into the lower fault zone (SPCL4), and again above the upper fault zone in the uppermost SPCL8, throughout SPCL9, and into lower SPCL10. SPCL16 has the highest content of dolomite just below an indurated band, and within highly porous and friable unit at the junction of SPCL22 and SPCL23, which are directly above a less permeable clay rich band (SPCL20, SPCL21).

Dolomite rhombs of comparable size and post-dating earlier calcite cements elsewhere in the Port Campbell Limestone were studied by Nicolaides (1997), who reported high-Ca nonstoichiometric dolomite with high Fe and Mn content. Subsurface marine precipitation under reducing conditions was proposed. Despite no detailed chemistry of the dolomite in Brumbys 1, the general relationship of dolomite cements with aquifer zones suggests that the dolomite precipitated much later, presumably from migrating groundwater.

Glauconite

While glauconite is almost ubiquitous as trace amounts throughout the Port Campbell Limestone in Brumbys

1, two glauconite-rich zones (SPCL20 and SPCL21) were identified in core and through thin section petrography. Geochemistry (K_2O%) confirms its presence in SPCL1, SPCL2, SPCL7, SPCL8, SPCL13, SPCL14, SPCL15, SPCL20 and SPCL21 (Figure 12), but not its observed presence in SPCL4 and SPCL5, within and adjoining the lower fault zone where subsequent diagenetic alteration is probable.

The distinctive glauconite-rich bands within a thin central part of SPCL21, and in the upper part of SPCL20 collectively form the thickest mud-dominant interval, constituting the best aquitard in the upper PCL sequence. The key clay-rich, glauconitic horizon occurs at 28–29 m and a secondary, less distinct horizon is found at 23.5 m depth.

Glauconite was confirmed in petrography (Figure 18) but not detected XRD analysis due to its non-crystalline manifestation. Glauconitic horizons (particularly at 28–29 m) are however, marked by sharp deviations in several geochemical signatures, especially Fe/P (Figure 12). These include an overall reduction in $CaCO_3$ content, which is reflected by decreased calcite, although, interestingly, sharply increased aragonite content in these zones (as determined through XRD). Decreased SiO_2/Al_2O_3 and an increased abundance of kaolinite suggests a higher proportion of clay in these zones, and is accompanied by increases in K_2O, U, Th. Increased V/Cr (Jones & Manning, 1994) and Fe/Al (Algeo & Liu, 2020) suggest more reducing bottom water conditions at this time. The decreased U/Th over the same zone, which would ordinarily suggest more oxidising conditions (Jones & Manning, 1994), relates to elevated Th and reduced U at this point. The elevated Th is accompanied by elevated REE and HFSE and along with the higher detrital content (total silicates) suggests a specific sediment input. Notably, similar features (elevated Th, Th/U, REE, HFSE) are evident in the Hesse Clay in the top few meters of Brumbys-1. Other notable geochemical peaks that coincide with the glauconite zones are in elevated Fe/P, Zr/Ti, Th/Y, and reduced SO_3 content.

Reducing depositional conditions of these units is additionally inferred from the presence of glauconite in the mostly mud-dominated units. Forbes *et al.* (2020) reported elevated Fe and P concentrations throughout the Otway Basin sequence, attributing these to the presence of berthierine or glauconite pellets, both coexisting in the Nullawarre Greensand (Boyd *et al.*, 2004). It is speculated that the higher P in the glauconitic zones indicates a presence of phosphatic skeletal fragments in the fossiliferous bands (Figure 18).

Kaolinite

Kaolinite is relatively rare in the sequence. In the basal transition zone (SPCL1), 4.7% kaolinite content is comparable to the proportion within the underlying Gellibrand Marl. In the lower sequence, from SPCL2 up to SPCL13, no kaolinite was detected. Within SPCL13 and SPCL14 intervals of ~10% Kaolinite corresponds with detected higher aragonite (Figure 10). Kaolinite is present at levels of 6 to 10% in SPCL20 and a little in SPCL21 and may reflect the presence of berthierite. In the uppermost weathered zone (SPCL25) kaolinite is present (4.4%), directly beneath the Hesse Clay, which contains 43 to 45% kaolinite, so the presence in the top of the weathered zone is likely related to eluviation from the overlying Hesse Clay.

Montmorillonite–smectites

These swelling clays have the most limited detected occurrence within the Port Campbell Limestone. The basal transition zone within SPCL1, directly above the Gellibrand Marl, has 9.4 to 7% montmorillonite but it is absent above this unit. The only other presence of montmorillonite is variably between 12.5 and 0% in SPCL8, the unit directly above the upper fault zone (Figure 10).

Pyrite

Pyrite, detectable by XRD, occurs only in the lower units of the Port Campbell Limestone. There is a transition up from the Gellibrand Marl (no pyrite detected by XRD) to 1.4% pyrite in SPCL 1, then a trace (<1%) at the top of this unit and in SPCL2. Trace amounts of pyrite (<1%) occur in the unit SPCL6, between fault zones, in the upper fault zone (SPCL7) and in the overlying units, SPCL8 and SPCL9 (Figure 10).

At the top of SPCL12 and in the base of SPCL13, there is a substantial presence of pyrite as observed in core, but only an isolated detected by XRD analysis.

Geochemical and petrographic evidence indicate the presence of pyrite in the glauconitic zones of SPCL20 and SPCL21. Petrographic observations suggest an even more ubiquitous presence, usually as small framboids within and partially or totally infilling chambers of foraminifera and zooecia of bryozoans. Such framboids may be neither stoichiometric nor crystalline and hence be undetectable with XRD.

Microcline

Microcline is present within the Port Campbell Limestone in small amounts, 0.2 to 2.1% within only one unit, SPCL20 (Figure 10). It is present both in the lower glauconitic zone and directly below in the mud-dominated carbonate facies of this unit. Entrainment of minor microcline in the carbonate of SPCL20 is attributed to derivation as detritus from an alkaline to trachytic volcanogenic source, either onshore or offshore (Niyazi *et al.*, 2021).

Ca-heulandite

This zeolite occurs in trace amounts within the lower Port Campbell Limestone sequence (SPCL1 up to SPCL9), in SPCL15, and at the boundary from SPCL21 to SPCL22. The only measurable heulandite is at SPCL2 (1.4%) and ~1% in the unit (SPCL6) between the upper and lower fault zones (Figure 10).

Differentiation between heulandite and clinoptilolite has been shown to be difficult with XRD (Bish & Boak, 2001) and clinoptilolite, the most common natural zeolite, often has close association with heulandite. These minerals are known to be far more common in Cenozoic rocks that originally contained silicic vitric material (Sheppard, 1971) than in cavities within mafic igneous rocks. These trace amounts of detected heulandite indicate probable derivation from palagonised rocks in the onshore Older Volcanics, or from concurrent marine volcanism (Langford *et al.*,1995; Niyazi *et al.*, 2021).

References

Bish, D. L., & Boak, J. (2001). Clinoptilolite–Heulandite nomenclature. *Reviews in Mineralogy and Geochemistry*. https://doi.org/10.2138/rmg.2001.45.5

Boyd, G. A., Wallace, M. W., Holdgate, G. R., & Gallagher, S. J. (2004). Marine clays and porosity evolution in the Nullawarre Greensand, Otway Basin, southeastern Australia. In P. J. Boult, D. R. Johns & S. C. Land (Eds.), *Eastern Australasian Basins Symposium II, Adelaide 20–22 September 2004* (pp. 537–552).

Forbes, A., Munday, S., & Revie, D. (2020). *An elemental chemostratigraphic study, Onshore Otway Basin, Victoria.* Victorian Gas Program Technical Report 12. Geological Survey of Victoria. Department of Jobs, Precincts and Regions. Melbourne, Victoria, 346 pp.

Jones, B., & Manning, D. A. C. (1994). Comparison between geochemical indices used for the interpretation of palaeoredox conditions in ancient mudstones. *Chemical Geology, 111*, 111–129. https://doi.org/10.1016/0009-2541(94)90085-X

Langford, R. P., Wilford, G. E., Truswell, E. M., & Isern, A. R. (1995). *Palaeogeographic atlas of Australia, Volume 10 Cainozoic*. Australian Geological Survey Organisation, 38 p.

Nicolaides, S. (1997). Marine-derived dolomite in the shallowly buried temperate Port Campbell Limestone (Miocene), Otway Basin, Australia. *Sedimentology, 44*, 143–157. https://doi.org/10.1111/j.1365-3091.1997.tb00429.x

Niyazi, Y., Eruteya, O. E., Warne, M., & Ierodiaconou, D. (2021). Discovery of large-scale buried volcanoes within the Cenozoic succession of the Prawn Platform, offshore Otway Basin, southeastern Australia. *Marine and Petroleum Geology, 123*, 104747. https://doi.org/10.1016/j.marpetgeo.2020.104747

Roser, B. P., Cooper, R. A., Nathan, S., & Tulloch, A. J. (1996). Reconnaissance sandstone geochemistry, provenance, and tectonic setting of the lower Paleozoic terranes of the West Coast and Nelson, New Zealand. *New Zealand Journal of Geology and Geophysics, 39*, 1–16. https://doi.org/10.1080/00288306.1996.9514690

Roser, B. P., & Korsch, R. J. (1986). Determination of tectonic setting of sandstone-mudstone suites using SiO_2 content and K_2O/Na_2O ratio. *Journal of Geology, 94*, 635–650. https://doi.org/10.1086/629071

Scheffler, K., Hoernes, S., & Schward, L. (2003). Global changes during Carboniferous–Permian glaciation of Gondwana: linking polar and equatorial climate evolution by geochemical proxies. *Geology, 31*, 605–608. https://doi.org/10.1130/0091-7613(2003)031<0605:GCDCGO>2.0.CO;2

Sheppard, R. A. (1971). *Clinoptilolite of possible economic value in sedimentary deposits of the conterminous United States.* Geological Survey Bulletin 1332-B, United States Department of Interior, 15 p.