

# THE MIDDLE–LATE PLEISTOCENE BRIDGEWATER FORMATION ON CAPE BRIDGEWATER, SOUTH-WESTERN VICTORIA: CHRONOSTRATIGRAPHY AND PALAEOCLIMATIC SIGNIFICANCE

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**ABSTRACT:** The Pleistocene Bridgewater Formation is well exposed at Cape Bridgewater and surrounding areas in south-western Victoria, where field studies, mineralogical and isotopic analyses and OSL dating have shown that it can be divided into three members, here named (in stratigraphic order) the Descartes Bay, Bats Ridge and Duquesne members. Each member consists of aeolian calcarenite deposited as a coastal dune, that was karstified (with solution pipe development) and then overlain by a red or purple palaeosol. The aeolianites were deposited in three distinct phases corresponding to interglacials MIS 11, MIS 9 and MIS 7, respectively, when the shoreline was near present sea level. Karstification occurred as a result of the high effective precipitation characteristic of the transition between interglacial and glacial periods, followed by aeolian dust accretion and palaeosol formation during the drier, windier glacial climates. Comparison with the coeval Tamala Limestone in south-western Western Australia shows simultaneous changes in palaeoclimate: high effective precipitation during the transition from MIS 11 to MIS 10, and a relatively dry transition from MIS 9 to MIS 8. Abundant rainfall during MIS 5 caused extensive limestone dissolution (solution pipes in Victoria, pinnacles in Western Australia) and the resulting quartz sand residue was redeposited during MIS 2–4.

**Keywords:** sedimentology, aeolianite, Pleistocene, Bridgewater Formation, Victoria

The Bridgewater Formation is a predominantly Pleistocene aeolian calcarenite (aeolianite), outcropping along the south-eastern Australian coast, that was deposited in distinct phases correlated with climate and sea level fluctuations (Brown & Stephenson 1991; Oyston 1996; White 2000; Cupper et al. 2003). It is particularly well

exposed in south-western Victoria on the western part of Cape Bridgewater (Cape Duquesne), Cape Nelson and Bats Ridge (Figure 1), where the aeolianites contain abundant solution pipes (Lipar et al. 2015). This paper uses these outcrops to determine the chronostratigraphy and palaeoclimate history of the Bridgewater Formation.

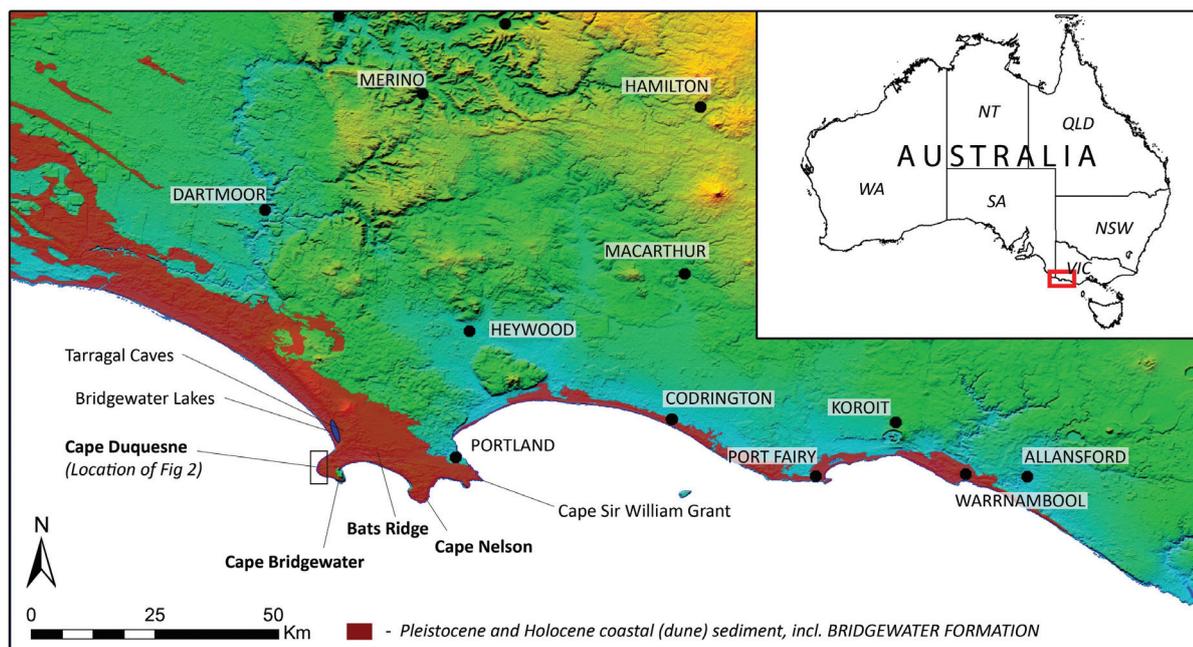


Figure 1: Locality map of south-western Victoria. The Bridgewater Formation distribution is based on Geoscience Australia 1:1,000,000 scale Surface Geology of Australia (digital dataset, 2008). DEM downloaded from Shuttle Radar Topographic Mission website.

## REGIONAL SETTING

Cape Bridgewater lies within the Otway Basin, an east-west trough spanning ~60,000 km<sup>2</sup> of south-eastern South Australia and south-western Victoria. The Otway Basin is one of a series of basins across the southern Australian continental margin formed during the Antarctic–Australian separation (Willcox & Stagg 1990; Duddy 2003). It is limited to the north (onshore) by outcropping Palaeozoic basement, and to the south (offshore) by the present continental slope. The basin is filled with a maximum of 7500 m (Kenley 1976) of mostly Cretaceous and Cainozoic sedimentary and volcanic rocks (Duddy 2003; Holdgate & Gallagher 2003).

The onshore Otway Basin sediments are overlain by Pliocene-Holocene basalt lavas of the Newer Volcanic Province, which stretches through central Victoria to south-eastern South Australia. This province is an extensive intraplate basaltic lava field, produced by intermittent, dominantly tholeiitic to alkaline, low volume volcanism that initiated at ~4.5 Ma and continued to recent times (Price et al. 2003; Gillen et al. 2010; Matchan & Phillips 2011). Basalt lavas of the Newer Volcanics outcrop at Cape Bridgewater and on the east side of Cape Sir William Grant, where they were dated as 3.12 Ma and 2.76 Ma (Aziz-Ur-Rahman & McDougall 1972). Cape Bridgewater (including Cape Duquesne) is the western half of a volcanic cone; movement along the Bridgewater Fault caused the eastern part of the volcano to subside beneath the water of Bridgewater Bay (Boutakoff 1963; Nicholls & Sukhyar 1993).

During the Quaternary, a predominantly carbonate sequence was deposited over the basalt and tuff of the Newer Volcanics at Cape Bridgewater (Schwebel 1984):

- Nelson Bay Formation, a sequence of subhorizontal marine calcarenite, lagoonal sediments and palaeosols up to 30 m thick, probably deposited in the Early to Middle Pleistocene (Boutakoff 1963; Allnut 1975).
- Bridgewater Formation, dune calcarenites with various amount of quartz sand (aeolianites) deposited during sea level fluctuations in the Middle to Late Pleistocene (Boutakoff 1963; Huntley et al. 1993; Oyston 1996; White 2000; Cupper et al. 2003).
- Unconsolidated siliceous Malanganee and calcareous Discovery Bay and Bridgewater Bay sands of Late Pleistocene to Holocene age (Boutakoff 1963; Gibbons & Downes 1964; Kenley 1971, 1976; Cupper et al. 2003).

The soils on the carbonate sediments are sandy aeolian regosols (terra rossa and rendzina; Gibbons & Downes 1964).

The aeolianites at Cape Bridgewater lie within the Gambier Karst Province of south-eastern South Australia

and south-western Victoria (White 2005). They have undergone simultaneous lithification and the development of solutional karst features (White 1994, 2005; Lipar et al. 2015), i.e. syngenetic karst (Jennings 1968). Because the Bridgewater Formation aeolianite has not been deeply buried, the karst is also eogenetic (early diagenesis of relatively young, soft, porous carbonates; Choquette & Pray 1970).

In general, there is limited surface exposure at Cape Bridgewater because the poorly cemented aeolianites have weathered to an extensive cover of silicate/calcareous sand. Where the calcreted surface of the aeolianite is exposed, irregular pitting or small areas of rillenkarren are evident. Karst features, mainly caves and solution pipes, are well developed in some areas (Coulson 1940; White 1984, 1994, 2000, 2005; Grimes 1994; Grimes et al. 1999; Webb et al. 2003; Grimes & White 2004). Shallow dolines are frequently present, but are hard to distinguish from the dune-swale topography on Cape Bridgewater.

Surface drainage on Cape Bridgewater is generally absent. Small, mostly ephemeral, springs occur on the cliff edges, where water seeps out along the contact between the Newer Volcanics basalt and the overlying Nelson Bay calcarenite or Bridgewater Formation aeolianite.

The area has a Mediterranean climate (Csb in the Köppen classification) with warm, dry summers and cool, wet winters (Peel et al. 2007; Bureau of Meteorology 2014). The average annual rainfall ranges from 822 mm at Portland Airport to 693 mm on Cape Nelson, with a winter maximum. The mean annual temperature for Portland Airport is 13.4°C, and 14.5°C for Cape Nelson. There is a general eastwards movement of high and low pressure systems accompanied by strong westerly winds; at Portland the wind blows at more than 30 km/h for ~15% of the year (Bureau of Meteorology 2014; Department of Environment and Primary Industries 2013).

## METHODS

This study is based on detailed field mapping on Cape Bridgewater in the Discovery Bay National Park (Figure 2), with additional observations at Bats Ridge and Cape Nelson (Figure 1).

Rock and sand samples were examined in thin section for mineralogy and texture under a petrological microscope. Some aeolianite samples were examined using a JEOL JSM 840A Scanning Electron Microscope operated at 25kV and a beam current of approximately 2 x10<sup>-10</sup>A, fitted with an Oxford Instruments Aztec X-ray analytical system (X-Max 150 mm<sup>2</sup> Silicon Drift Detector with a take off angle of 40°). Samples were sputter coated with 2 nm platinum. X-ray counts were background subtracted and corrected for peak overlaps and displayed as elemental images (TruMap) at a

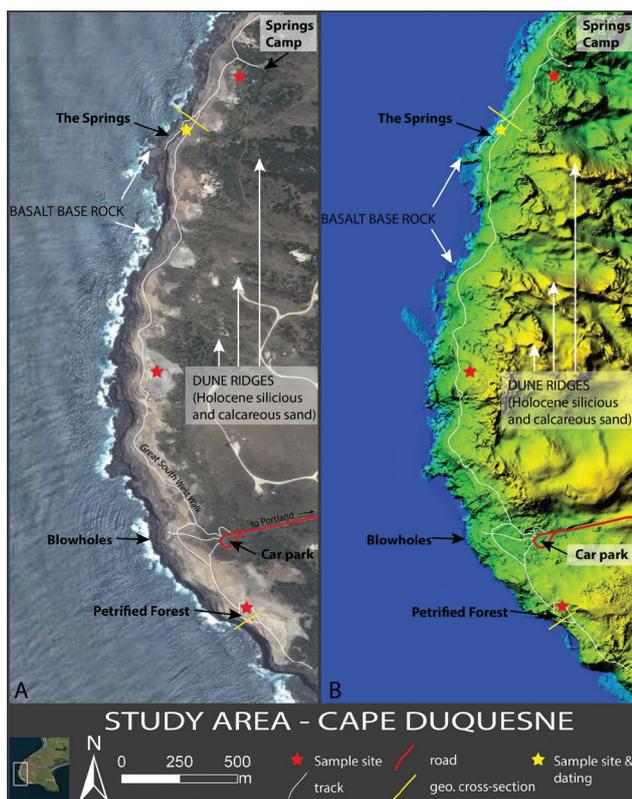


Figure 2: The research area on Cape Duquesne, the western side of Cape Bridgewater. The satellite map (A) is based on GoogleEarth imagery, and the digital elevation model map (B) is based on LiDAR sourced from the Vicmap Elevation – Coastal 1m DEM, Department of Sustainability and Environment, Victoria, Australia.

resolution of 512 x 512 pixels. Spectra were obtained from selected regions as maps or secondary electron images and quantified using the Aztec XPP software.

The qualitative and quantitative mineral composition of samples was determined by X-ray powder diffraction (XRD) analysis, using the La Trobe University Siemens D5000 equipped with a Cu K $\alpha$  source, operating at 40kV and 30mA in continual scan mode with a speed of 1 $^\circ$ /min from 4 $^\circ$  to 70 $^\circ$  2 $\theta$ . Eva software was used for both qualitative and quantitative mineralogical analysis; the quantitative analysis combined XRD data with the chemical composition (obtained by X-ray fluorescence (XRF), based on the reference-intensity-ratio (RIR) method (Bruker 2010).

To determine bulk chemistry, samples were analysed by XRF at La Trobe University on a Siemens SRS 303AS Sequential X-Ray Spectrometer.

Aeolianite samples were analysed for both  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  isotopes at the stable isotope laboratory at the University of Melbourne. Analyses were performed on  $\text{CO}_2$  produced by reaction of the sample with 100%  $\text{H}_3\text{PO}_4$  at 90 $^\circ$  using continuous-flow isotope ratio mass spectrometry (CF-IRMS), following the method previously described in Drysdale et al. (2009) and employing an AP2003

instrument. Results were reported using the standard  $\delta$  notation (per mil ‰) relative to the Vienna Peedee Belemnite (V-PDB) scale. Based on an internal working standard, the uncertainty was 0.04‰ for  $\delta^{13}\text{C}$  and 0.07‰ - 0.09‰ for  $\delta^{18}\text{O}$ .

Bridgewater Formation samples containing quartz sand were dated by the optically stimulated luminescence (OSL) method at the University of Melbourne. Full details of this analytical procedure are provided in Cupper (2006).

The ages of the boundaries of the marine isotope stages (MIS) reported in this paper are from Lisiecki & Raymo (2005).

## BRIDGEWATER FORMATION

The Bridgewater Formation is a series of Pleistocene calcareous coastal dune ridges generally aligned parallel to the present coastline, extending along the southern Australian coastline from Victoria to South Australia (Figure 1), and marking shoreline highstands during glacio-eustatic changes in sea level (Sprigg 1952; Boutakoff 1963; White 1984; Belperio 1995; Cupper et al. 2003). The source of the calcareous material for these dunes is the shells and skeletons of shallow marine organisms which have been subject to vigorous wave action, breaking them down into bioclastic sand (Boutakoff 1963; Kenley 1976). The dunes are separated by linear interdune swamps (Boutakoff 1963), which contain estuarine to lacustrine limestones, dolomites, marls and clays up to 13 m thick (Grimes et al. 1999). The Bridgewater Formation is mostly between 15 and 25 m thick, but locally up to 45 m (Cupper et al. 2003). The slow, continuous uplift of the eastern coastal part of South Australia through the Pleistocene has resulted in the preservation of the Bridgewater Formation there as a series of separate strandline dunes over an extensive area (Belperio 1995). In contrast, in Victoria the dune ridges are generally stacked on top of each other (Cupper et al. 2003), most probably because of the lack of uplift in this area during the Pleistocene.

In Victoria, the Bridgewater Formation was upgraded to group status by Orth (1988), but most authors still refer to it as a formation, and that usage is retained herein.

Three new members have been defined within the Bridgewater Formation on Cape Bridgewater as a result of mapping carried out during the present study. In stratigraphic order (oldest to youngest), these are the Descartes Bay (MIS 11-10), Bats Ridge (MIS 9-8), and Duquesne members (MIS 7-6) (Figures 3 and 4). These newly defined units have been reserved by the Australian Stratigraphy Commission – Geoscience Australia.

Each member consists of aeolianite and an overlying distinctive red or purple palaeosol. Solution pipes, tubular vertical karst voids formed by focused vertical solution,

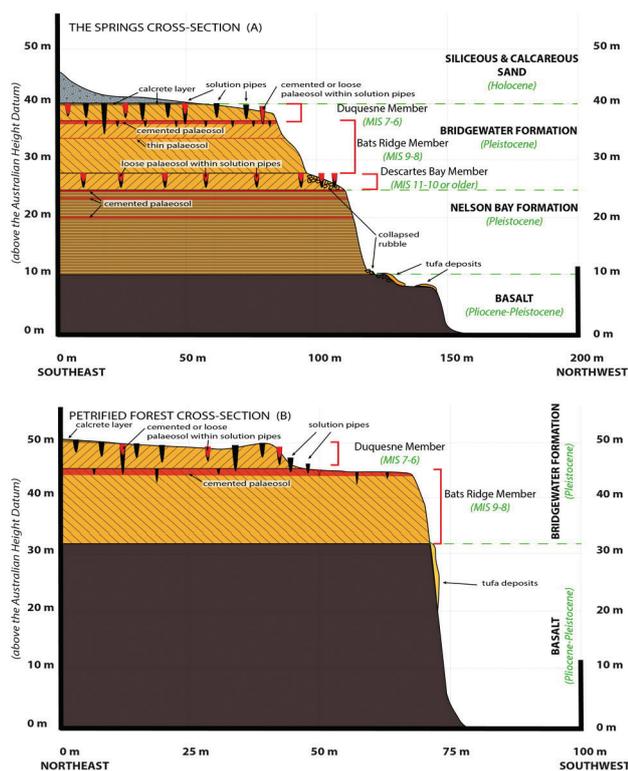


Figure 3: Cross-sections of The Springs area (A) and Petrified Forest area (B) on Cape Duquesne. See Figure 2 for location. Thicknesses of Pleistocene-Holocene units based on the altitude of surface occurrences. Vertical exaggeration = 2.5 (A) and 1.25 (B).

have developed to varying extents within each of these members (Lipar et al. 2015). The carbonate component of all aeolianites comprises detrital biogenic carbonate grains (including some reworked Tertiary carbonate clasts) and carbonate cement (Figure 5). The bioclasts were originally aragonitic (molluscs) or high-Mg-calcite (foraminifera, bryozoans, echinoderms, red algae and some molluscs) in composition. These two minerals are stable only in the marine environment; under subaerial conditions, they alter to low-Mg calcite (Bathurst 1971; Gardner 1983). A general reduction in aragonite and high-Mg calcite content with increasing age was noted in the aeolianites of the Bridgewater Formation (Figure 6B), also reported by Reeckmann & Gill (1981), but this change in mineralogy is not sufficiently distinctive to be used to differentiate the members of the Bridgewater Formation on Cape Bridgewater.

The grains are predominantly cemented by drusy calcite that rims grains; meniscus sparry calcite is also present (Figure 5). The presence of these cements indicates vadose (subaerial) freshwater cementation (Scholle 1978; Flügel 2010).

The input of low-Mg calcite during meteoric diagenesis of the aeolianites, replacing bioclasts and precipitating as cement, is accompanied by a progressive depletion in

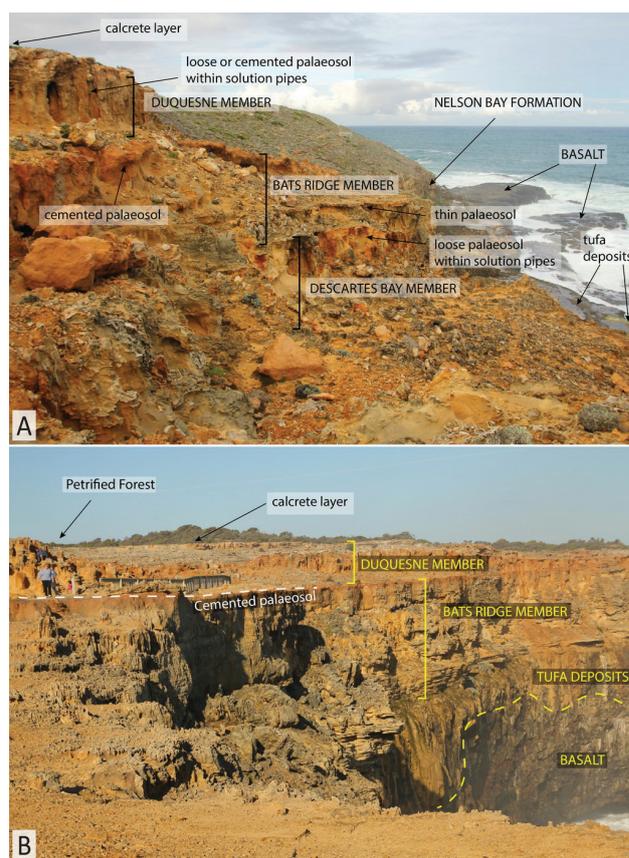


Figure 4: The stratigraphy at The Springs area (A) and Petrified Forest area (B). See Figure 3 for illustrated geological cross-sections.

the whole rock stable isotope compositions (Figure 6C). The oldest aeolianites have undergone the most extensive diagenesis and therefore have the most depleted stable isotope signatures.

The lighter carbon isotope composition of the altered aeolianites is due to the strong input of very light carbon derived from  $\text{CO}_2$  released by degradation of terrestrial plants in the soil (e.g. Gardner 1983; Beier 1987). The  $\delta^{13}\text{C}$  signature of this  $\text{CO}_2$  is dependent on the ratio of  $\text{C}_4$  plants (warm season grasses, sedges and a few halophytic shrubs; average  $\delta^{13}\text{C} \sim -13\text{‰}$ ) to  $\text{C}_3$  plants (trees, most shrubs and herbs, and cool-season grasses; average  $\delta^{13}\text{C} \sim -27\text{‰}$ ) (Deines 1980; Cerling & Quade 1993);  $\text{C}_3$  plants predominate in the flora of southwest Victoria (Hattersley 1983). The average  $\delta^{13}\text{C}$  of calcite precipitated from  $\text{CO}_2$  derived from the decomposition of  $\text{C}_3$  plants is  $\sim -11.4\text{‰}$  at the present-day average temperature of  $14.5^\circ\text{C}$  (due to fractionation, includes diffusional model; Deines 1980; Cerling 1984). The addition of this depleted carbon accounts for the decrease in  $\delta^{13}\text{C}$  values from  $-0.59\text{‰}$  for young, relatively unaltered unconsolidated sand to  $-5.42\text{‰}$  for the oldest, most diagenetically altered aeolianites (Figure 6C).

The lighter oxygen isotope compositions of the altered aeolianites are due to the input of diagenetic calcite

with a depleted  $\delta^{18}\text{O}$  signature. The oxygen isotope composition of calcite is determined by the oxygen isotope composition of the water from which it precipitated and the temperature (Cerling 1984; Hays & Grossman 1991; Cerling & Quade 1993). The weighted average present  $\delta^{18}\text{O}$  rainfall composition in western Victoria is  $-4.02\text{‰}$  (calculated from the data Global Network of Isotopes in Precipitation and isotope Hydrology Information System (GNIP) for Adelaide), and is generally very similar to the groundwater  $\delta^{18}\text{O}$  composition (e.g. Bennetts et al. 2006). At a temperature of  $14.5^\circ\text{C}$  (average temperature at Cape Nelson), this groundwater will precipitate calcite with a  $\delta^{18}\text{O}$  of  $-3.1\text{‰}$  (using the Tremaine et al. (2011) equation), and the addition of this will account for the decrease in  $\delta^{18}\text{O}$  values from  $-0.93\text{‰}$  for unconsolidated sand to  $-1.71\text{‰}$  for the oldest aeolianites (Figure 6C).

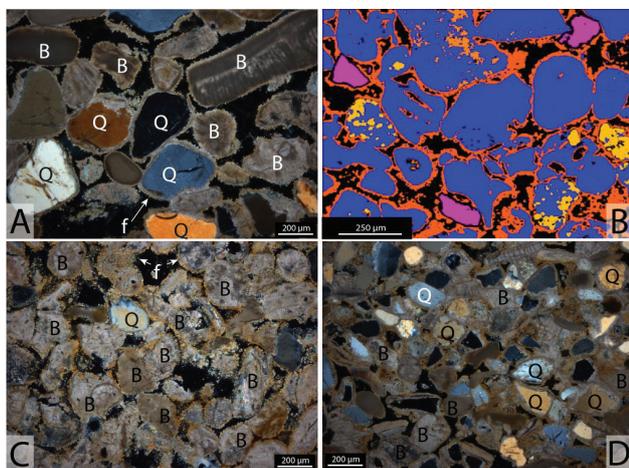


Figure 5: Microphotographs (all in cross polarised light) and electron micrograph of aeolianites of the Duquesne Member (A, B), Bats Ridge Member (C) and Descartes Bay Member (D). Microphotographs showing quartz grains (Q), bioclasts (B) and fringe cement (f). Electron micrograph and elementary X-ray analysis of the aeolianite (B) shows low-Mg calcite and aragonite bioclasts (blue), high-Mg calcite bioclasts / patches of bioclasts (yellow), quartz grains (pink), and low-Mg calcite cement (orange). The carbonate phases are differentiated based on their densities (i.e. count rates for carbon and oxygen) and the amount of magnesium.

#### *Descartes Bay Member (new name)*

Outcrops of the Descartes Bay Member on Cape Bridgewater are limited and mostly occur at The Springs area, about 25 to 30 m above sea level (type locality;  $38^\circ21'50.78''\text{S}$ ;  $141^\circ22'04.10''\text{E}$ ). Where present, the member's thickness ranges from barely noticeable to  $\sim 3$  m. It overlies the Nelson Bay Formation and is overlain by the Bats Ridge Member. Some cross-bedding can be seen within the aeolianite, but details are obscured by extensive erosion and karstification. Outcrops of the Descartes Bay Member, contain large (0.5–1 m wide) solution pipes with almost no original host aeolianite preserved (Lipar

et al. 2015). Loose dark orange to red palaeosol with no carbonate content infills these solution pipes; the tops of the solution pipes abut the overlying Bats Ridge Member, so the thickness of this palaeosol cannot be determined. A cemented (calcreted) and generally 10–20 cm thick pale-red palaeosol occurs beneath the Descartes Bay Member, formed on the uppermost Nelson Bay Formation calcarenite.

The aeolianite of the Descartes Bay Member is pale yellow, moderately to well cemented, mostly fine grained ( $\sim 100$ – $200\ \mu\text{m}$ ) and composed of variable amounts of carbonate (36–37%), quartz ( $\sim 61\%$ ; predominantly angular to subrounded  $100$ – $300\ \mu\text{m}$  grains with occasional subrounded to rounded up to  $1000\ \mu\text{m}$  grains), and feldspar (both microcline and orthoclase; up to 3%) (Figure 6A). Carbonate comprises low-Mg calcite ( $\sim 71\%$ ), aragonite ( $\sim 14\%$ ) and high-Mg calcite ( $\sim 15\%$ ) (Figure 6B). The average whole rock  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopic values obtained from the aeolianite are  $-1.71\text{‰}$  and  $-5.42\text{‰}$ , respectively (Figure 6C).

The Descartes Bay Member was not dated directly. Following the general pattern of Pleistocene aeolianite deposition in southern Australia (i.e. during sea level highstands; Huntley et al. 1993; Murray-Wallace 1995; Lipar & Webb 2014) and its stratigraphical position beneath the younger, dated, Bats Ridge Member aeolianite (MIS 9; see below), it was probably deposited during the interglacial MIS 11 (374 – 424 ka). In this case, it would be contemporaneous with the Baker Dune of the Bridgewater Formation in South Australia, dated using thermoluminescence (TL) as  $456 \pm 37$  ka (Huntley et al. 1993).

#### *Bats Ridge Member (new name)*

The Bats Ridge Member outcrops along the entire coastline of Cape Duquesne at about 20 to 40 m above sea level. The type locality of the Bats Ridge Member is the same as for the Descartes Bay Member ( $38^\circ21'50.78''\text{S}$ ;  $141^\circ22'04.10''\text{E}$ ), with the name derived from the nearby Bats Ridge area, where this member outcrops extensively and was first dated (White 2000).

Its thickness ranges from 1 m to more than 15 m. It overlies the Descartes Bay Member or Nelson Bay Formation (where the Descartes Bay Member is absent). A dark-purple palaeosol, generally 30 cm to 60 cm thick, occurs at the top of the Bats Ridge Member, separating it from the Duquesne Member. This is cemented by fine-grained sparry or micritic and ferruginous calcite, occurring as menisci, pore-fills, but mostly as uniform concentric coatings around grains. A thin ( $\sim 10$  cm) dark-yellow to orange cemented palaeosol marks a break in deposition within the build-up of the Bats Ridge Member. Solution

pipes are less common and generally smaller than in the other two members of the Bridgewater Formation at Cape Bridgewater (Lipar et al. 2015).

The aeolianite of the Bats Ridge Member is dark to pale yellow, moderately to well cemented, predominantly fine to medium grained (~100–350  $\mu\text{m}$ ), and composed of variable amounts of carbonate (26–96%), quartz (5–73%; predominantly angular to subrounded 100–300  $\mu\text{m}$  grains with occasional subrounded to rounded up to 1000  $\mu\text{m}$  grains), and feldspar (both microcline and orthoclase; up to 1%) (Figure 6A). Carbonate comprises low-Mg calcite (~87%) with minor amounts of aragonite (~8%) and high-Mg calcite (~5%) (Figure 6B). The average  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  isotopic values obtained from the aeolianite are -1.40 ‰ and -3.66 ‰ respectively (Figure 6C).

Aeolian cross-bedding with a general east to south-east dip direction and inclination of up to 20° is present; the cross-bed laminae are tabular with mean thickness of ~1 cm. Horizontal laminae also occur.

Three consolidated aeolianite samples of the Bats Ridge Member at Cape Bridgewater were OSL dated during this study as 299 ± 34 ka (5 m below the surface of the member), 319 ± 43 ka (4 m below the surface of the member) and 344 ± 39 ka (1 m below the surface of the member) (Table 1); a TL age of 290 ± 34 ka was previously obtained from

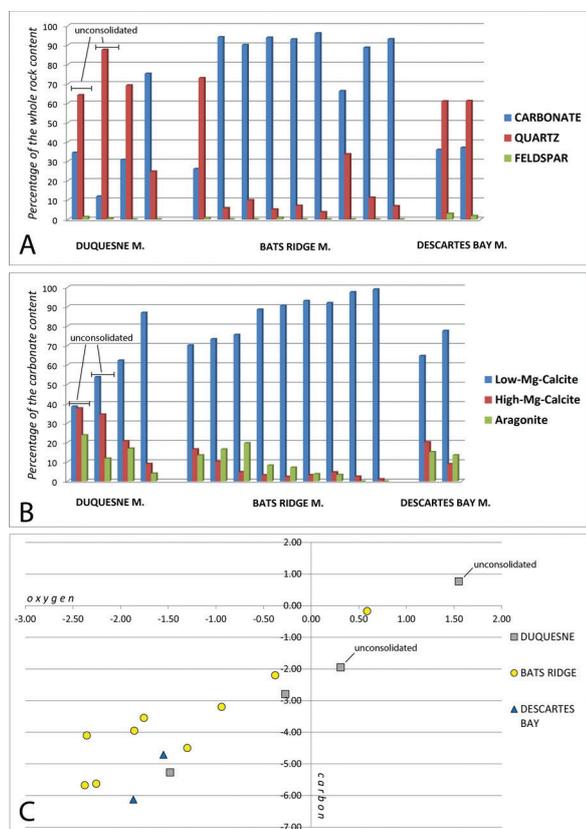


Figure 6: Mineralogical (A), carbonate (B), and isotopic (C) composition of the aeolianites within the members of the Bridgewater Formation.

the Bats Ridge area by White (2000). These ages correlate well with ages from a Bridgewater Formation dune in the Warrnambool area (342 ± 45 ka – Hopkins River; Oyston 1996) and the West Avenue Dune in South Australia (342 ± 32 ka; Huntley et al. 1993). Aeolianite deposition most probably occurred during the interglacial MIS 9 (300 – 337 ka).

#### *Duquesne Member (new name)*

The Duquesne Member outcrops along the whole coastline of Cape Duquesne at about 30 to 50 m above present sea level, and has the same type locality as the previous two members. Its thickness ranges from a few centimetres to over 12 m. It overlies the Bats Ridge Member and is overlain by unconsolidated Holocene quartzose and carbonate sand.

The Duquesne Member is grey to yellow coloured aeolianite, uncemented to well cemented, and mostly medium to coarse grained (~200 – 550  $\mu\text{m}$ ), i.e. coarser than the other members of the Bridgewater Formation. It has distinctive cross-bedding, with general eastward to south-eastward dip direction and inclination up to 30° (Figure 7). The cross-bed laminae are tabular with mean thickness of 0.5–2 cm. They are often deformed by vertical or horizontal (~5 mm thick) cracks, which were later filled by carbonate cement. The bedding is less visible or absent in places with abundant solution pipes.

The aeolianite contains variable amounts of carbonate (12–75%), quartz (25–88%; predominantly angular to subrounded 100–300  $\mu\text{m}$  grains with occasional subrounded to rounded up to 1000  $\mu\text{m}$  grains), and feldspar (both microcline and orthoclase; up to 1%) (Figure 6A). Unconsolidated sand of the Duquesne Member shows less diagenetic alteration than the cemented sand, as bioclasts in the unconsolidated sand contain ~18% and ~36% of the unstable carbonate minerals aragonite and high-Mg calcite respectively, compared with ~10% and ~15% of the same



Figure 7: Exposure of Duquesne Member at Cape Duquesne (note exposed cross-beds).

Table 1: Luminescence age data.

Sample name	Lithology / member	Coordinates	Depth (m)	Water <sup>a</sup> (%)	Radionuclide concentrations <sup>b</sup>						Cosmic-ray radiation <sup>f</sup> (Gy ka <sup>-1</sup> )	Total dose rate (Gy ka <sup>-1</sup> )	Equivalent dose <sup>e</sup> (Gy)	Optical age (ka)
					K (%)	Th (ppm)	U (ppm)	<i>a</i> radiation <sup>c</sup> (Gy ka <sup>-1</sup> )	<i>b</i> radiation <sup>d</sup> (Gy ka <sup>-1</sup> )	<i>g</i> radiation <sup>e</sup> (Gy ka <sup>-1</sup> )				
MCLB01A	unconsolidated sand / Duquesne M.	38°22'23"S; 141°21'57"E	0.7	5 ± 2	0.25 ± 0.02	1.1 ± 0.1	0.7 ± 0.1	0.03 ± 0.01	0.27 ± 0.02	0.18 ± 0.04	0.19 ± 0.02	0.67 ± 0.06	139 ± 8	206 ± 20
MCLB02A	aeolianite / Duquesne M.	38°21'56"S; 141°22'01"E	2	5 ± 2	0.17 ± 0.02	0.8 ± 0.1	0.9 ± 0.1	0.03 ± 0.01	0.24 ± 0.02	0.17 ± 0.03	0.15 ± 0.02	0.59 ± 0.05	153 ± 13	260 ± 32
MCLB7A	aeolianite / Bats Ridge M.	38°21'51"S; 141°22'04"E	3	5 ± 2	0.23 ± 0.02	1.3 ± 0.1	0.6 ± 0.1	0.03 ± 0.01	0.25 ± 0.02	0.17 ± 0.03	0.12 ± 0.02	0.57 ± 0.06	197 ± 12	344 ± 39
MCLB08A	aeolianite / Bats Ridge M.	38°21'51"S; 141°22'04"E	4	5 ± 2	0.09 ± 0.02	0.7 ± 0.1	1.0 ± 0.1	0.03 ± 0.01	0.19 ± 0.02	0.16 ± 0.03	0.11 ± 0.02	0.49 ± 0.05	156 ± 13	319 ± 43
MCLB09A	aeolianite / Bats Ridge M.	38°21'51"S; 141°22'04"E	5	5 ± 2	0.32 ± 0.02	1.3 ± 0.1	0.6 ± 0.1	0.03 ± 0.01	0.31 ± 0.02	0.20 ± 0.04	0.09 ± 0.02	0.62 ± 0.06	186 ± 11	299 ± 34

<sup>a</sup> estimated time-averaged moisture content, based on measured field water value (% dry weight)

<sup>b</sup> obtained by INAA (Becquerel Laboratories, Mississauga, ON, Canada)

<sup>c</sup> assumed internal alpha dose rate

<sup>d</sup> derived from INAA radionuclide concentration measurements using the conversion factors of Adameic and Aitken (1998), corrected for attenuation by water and beta attenuation

<sup>e</sup> derived from INAA radionuclide concentration measurements using the conversion factors of Adameic and Aitken (1998), corrected for attenuation by water

<sup>f</sup> calculated using the equation of Prescott and Hutton (1994), based on sediment density, time-averaged depth and site latitude and altitude

<sup>g</sup> central age model (Galbraith *et al.* 1999), including a ± 2% systematic uncertainty associated with calibration of the laboratory beta-source.

minerals in the cemented sand (Figure 6B). Similarly, the relatively unaltered unconsolidated sand of the Duquesne Member has heavier stable isotope values (0.93‰  $\delta^{18}\text{O}$ , -0.59‰  $\delta^{13}\text{C}$ ) than the consolidated Duquesne Member aeolianite (-0.88‰  $\delta^{18}\text{O}$ , -4.03‰  $\delta^{13}\text{C}$ ), due to alteration of the bioclasts and input of calcite cement (as discussed previously).

A laminar and laminated calcrete generally 5–20 cm thick commonly overlies the aeolianite, and is more strongly cemented than the aeolianite beneath due to additional micritic cement containing microbial alveolar-septal structures. Consequently, the calcrete has a high carbonate content (up to 95%). This horizontal or slightly undulating calcrete layer is underlain by numerous solution pipes, filled with a cemented or loose light-red palaeosol (Lipar *et al.* 2015).

Two samples of the Duquesne Member were dated using the OSL method as 206 ± 20 ka (unconsolidated sand; 2 m below the surface of the member) and 260 ± 32 ka (consolidated aeolianite; 3 m below the surface of the member) (Table 1). Similar TL ages have been obtained from the Bridgewater Formation near Codrington (244 ± 74 ka and 238 ± 45 ka; White 2000), Warrnambool (185 ± 19 ka - Ryot St. Quarry, 190 ± 16 ka and 263 ± 30 ka - Point Ritchie; Oyston 1996), and from the Woakwine II and Reedy Creek dunes in South Australia (230 ± 11 ka, 258 ± 25 ka, respectively; Huntley *et al.* 1993, 1994). These results indicate that the main period of deposition of the Duquesne Member aeolianite was during MIS 7 (191 – 243 ka), possibly beginning in late MIS 8 (~260 ka).

## PALAEOCLIMATIC SIGNIFICANCE

The deposition of the aeolianite/palaeosol cycles represented by the three Bridgewater Formation members reflects the alternating glacial/interglacial climates accompanied by changing sea level over the past 500 ka years (e.g. Wyrwoll 1979, 1993; Zheng *et al.* 2002; Tapsell *et al.* 2003). The results of this study show that aeolian carbonate sand deposition on Cape Bridgewater occurred during three interglacial periods (sea level highstands when the shoreline was near its present location): MIS 7 (243 – 191 ka), 9 (337 – 300 ka) and 11 (424 – 374 ka). This is in accordance with the suggested predominantly highstand deposition of aeolianites (Hearty & O'Leary 2008; Bateman *et al.* 2011; Lipar & Webb 2014).

The depositional history of the Bridgewater Formation at Cape Bridgewater strongly resembles that of the Tamala Limestone in south-western Western Australia (Lipar & Webb 2014), indicating that similar changes in palaeoenvironment were synchronous across the coastal areas of southern Australia. Carbonate sand in both areas was predominantly deposited as strandline dunes and sand sheets during interglacial periods (sea level highstands). The aeolianites of the Descartes Bay, Bats Ridge and Duquesne members (deposited during MIS 11, 9 and 7 respectively) in Victoria are correlated with the aeolianites of the Nambung, Stockyard Gully and Pinnacles Desert members respectively in Western Australia (Lipar & Webb 2014). The greater thickness of the Tamala Limestone (up to at least 250 m along the Zuytdorp Cliffs and more

than 150 m in the Perth Basin; Playford et al. 1976, 2013) compared with the Bridgewater Formation in Victoria (max 45 m; Cupper et al. 2003) may be a result of the stronger winds and/or greater amount of source carbonate material in Western Australia during the Pleistocene.

In both Victoria and Western Australia, the aeolianite within each member is generally karstified as a result of the high effective precipitation characteristic of the transition between interglacial and glacial periods; the karst surface is in turn overlain by calcrete (if present) and a palaeosol, containing silt and clay blown in by winds characteristic of the drier glacial climates (Turney et al. 2006; Lipar & Webb 2014). In Victoria, the Descartes Bay Member was strongly karstified during MIS 11-10, with the formation of numerous large solution pipes containing loose palaeosol, reflecting a time of high effective precipitation also seen in Western Australia, where the correlative Nambung Member also shows evidence of extensive karstification but of a different type, with massive microbialites deposited in widespread karst cavities and incipient pinnacle formation. The Bats Ridge and Stockyard Gully members from Victoria and Western Australia respectively are characterised by little or no karstification, indicating that the transition from MIS 9 to MIS 8 was drier than MIS 11-10. The strongly karstified surface of the Duquesne Member in Victoria (with abundant solution pipes) correlates with extensive pinnacle development in the Pinnacles Desert Member in Western Australia, indicating a relatively wet period after deposition of the calcareous sand in MIS 7, most likely during MIS 5. Aeolianite deposition during interglacial MIS 5 (130 – 71 ka) is absent in both areas and across southern Australia (Gardner et al., 2006), probably because the relatively high rainfall resulted in abundant vegetation growth and stabilised the dunes, confirming other evidence that the interglacial period MIS 5e was wetter than other interglacial periods (e.g. Murray-Wallace et al. 2010).

Limestone dissolution during the period of strong karstification in MIS 5 released abundant quartz sand residue, which was redeposited during the last glacial period in the Late Pleistocene (MIS 4-2) as the Malanganee Sand in Victoria and the Cooloongup Sand in Western Australia. Both areas are now experiencing additional deposition of aeolianite in MIS 1, following the pattern of interglacial aeolianite deposition.

## CONCLUSIONS

Field studies, mineralogical and isotopic analyses and OSL dating of the Bridgewater Formation on Cape Bridgewater in south-west coastal Victoria have revealed three intervals of Pleistocene aeolian carbonate deposition, each overlain by distinctive red or purple palaeosols. These units are here named, in stratigraphic order, the Descartes Bay, Bats Ridge and Duquesne Members. Aeolianite deposition took place during interglacial periods (MIS 11, MIS 9 and MIS 7 respectively) when the shoreline was near its present location. The aeolianites were subsequently karstified (with solution pipe development) as a result of the high effective precipitation characteristic of the transition between interglacial and glacial periods, followed by palaeosol formation and aeolian dust accession during the drier, windier glacial climates.

Comparison of the Bridgewater Formation in Victoria with the coeval Tamala Limestone on the south-western coast of Western Australia shows that similar changes in palaeoclimate occurred simultaneously across the coastal areas of southern Australia. Following aeolianite deposition during interglacial MIS 11, there was extensive karstification due to high effective precipitation during the transition from MIS 11 to MIS 10. This contrasts with little or no karstification during the relatively dry transition from MIS 9 to MIS 8. Aeolianite deposition occurred during interglacial MIS 7 but not MIS 5, probably because of relatively high rainfall during MIS 5 that resulted in abundant vegetation growth, stabilising the dunes. This period of high rainfall also karstified the MIS 7 aeolianite, forming extensive solution pipes in Victoria and pinnacles in Western Australia. The quartz sand residue formed by limestone dissolution was redeposited as a sand sheet during the last glacial period (MIS 4-2). Southern Australia is now experiencing additional deposition of aeolianite in MIS 1, following the pattern of interglacial aeolianite deposition.

## Acknowledgements

We wish to thank Roger Hocking and an anonymous peer reviewer for improving the manuscript. We also wish to thank Matthew Linden Cupper for performing the OSL analyses, and the Gunditj Mirring Traditional Owners Aboriginal Corporation for their approval to gather research materials from Cape Bridgewater. A permit to conduct research in Discovery Bay National Park was obtained from the Department of Sustainability and Environment, Victoria.

The research was carried out while the senior author was supported by a La Trobe University Postgraduate Research Scholarship.

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