The Morphology and Evolution of Rock Coasts Over Eustatic Cycles in Temperate, Wave Dominated Environments

Submitted in total fulfilment of the requirements
of the degree of Doctor of Philosophy
February 2019

UNIVERSITY OF MELBOURNE
FACULTY OF SCIENCE
SCHOOL OF GEOGRAPHY

Rhiannon Bezore
School of Geography
Faculty of Science
rbezore@student.unimelb.edu.au

ORCID: 0000-0002-1792-9444
Abstract

Rock coasts comprise 80% of the world’s shorelines and about 50% of the Victorian coast. Their morphology and evolution over time is the result of marine and subaerial erosional processes that carve features such as sea cliffs, shore platforms, and sea stacks out of the landscape. Rock coasts, therefore, evolve over multiple sea level cycles and create dynamic landscapes on an interglacial timescale. Sea level has risen and fallen over geologic time, with coastal features being formed during sea level high stands. While most coastal landforms found along the modern coast were formed over the past 6,000 years, older coastal features have also been preserved over multiple eustatic cycles, both above and beneath modern sea level. As coastal landforms are formed at or very near sea level, preserved paleo-shoreline features can be used as proxies to reconstruct past sea levels on a regional scale, which had not previously been done for the coast of Victoria, Australia.

In this study, an integrated aerial LiDAR and bathymetric multibeam dataset from +20 to -80 m water depth was used to precisely map and quantify the morphology of the rock coast features along the coast of Victoria from Port Fairy in the west to Wilsons Promontory in the east and to analyze the relation between the features’ elevations and the sea levels at which they first formed. This was completed for both the modern coastline as well as paleo-shoreline landforms found 50-60 m below modern sea level, where the offshore geology reflected the onshore geologic units, allowing for an analogous study. These preserved features are believed to have formed during the MIS 3 high stand, during which time sea level most closely matched their average present depths. The culminating results provide not only the first study of the precise morphology of these submerged features in Victoria but also have wider applications for modelling sea level and rocky coast evolution in other temperate, wave dominated environments.
DECLARATION

This is to certify that:

i. the thesis comprises only my original work towards the PhD,

ii. due acknowledgement has been made in the text to all other material used,

iii. the thesis is less than 100,000 words in length, exclusive of tables, maps, bibliographies and appendices.

Rhiannon Bezore
February 2019
Acknowledgements

This research was made possible through funding by the Australian Research Council (LP130100204), the University of Melbourne International Research Scholarship, and Deakin University. The work done in this thesis was a true collaboration between the University of Melbourne’s School of Geography, Deakin University’s Marine Mapping team, and Parks Victoria.

I would like to sincerely thank my co-supervisors, Dr. David Kennedy from University of Melbourne and Dr. Daniel Ierodiaconou from Deakin University. It was only through your tireless guidance that this thesis was completed, and for that I am eternally grateful. I thank you both for being generous with your time and advice and always being a joy to work with. I could not ask for a better pair of supervisors.

I would also like to thank my fellow graduate students in the School of Geography. Alissa Flatley, you always were there to bounce ideas and complaints off of and made the coastal lab so much more enjoyable. Hanna Kowalczyk, thank you for being such a great friend and support system. Teresa Konlechner, you were always available to give advice on coastal matters as well as career matters. Sarah McSweeney and Justin Stout, you both were the first graduate students from the department that I met and were always there to make the department more fun and entertaining. Tom Savige, thank you for always being a good mate and excellent field trip leader. Runjie Yuan, I will always remember trying (and failing) to dig out an estuary opening with you. Alex Sims, thank you for providing excellent New Zealand stories and being all-around entertaining. Abdullah Baky, the New Zealand conference would not have been as great without your company. Nuo Sha Zhang, thank you for helping me when I needed it and being a great Coastal Lab buddy. Jonathan Garber, thank you for helping with coding and for being a fellow Yankie in the Land Down Under. Finally, thank you to Joanne Patton and Tina Soundias for always helping everything run smoothly and being there to answer any question I could ever have.

I would lastly, but most wholeheartedly, like to thank my family for their unwavering support and kindness throughout my academic career, which I am sure they looked forward to the end of many times. Thank you Peter for always being there to celebrate the good moments and listen to me lament the not-so-great moments, and thank you for all your cartography and photo-editing skills. Thank you to my mom for being my number one supporter in every way and for everything you have done and continue to do for me. Thank you to my dad, my gramma, and my brother for listening to my science babble and for your support of me following my passions. You are all the reason I have made it this far, and I love you all.
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CHAPTER 1

Introduction
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1.1 Introduction

Rocky coasts are predominately erosional landforms that comprise 80% of the world’s shorelines (Emery and Kuhn, 1982) and about 40% of those in Australia (Short and Woodroffe, 2009). They tend to form on coastlines where marine processes dominate, though their form is the result of both between marine and subaerial processes (Kennedy, et al., 2014). Rocky coasts, therefore, evolve over multiple sea level cycles and create dynamic landscapes on an interglacial timescale (Trenhaile, 1987; Trenhaile, 2010).

Rocky coasts are commonly associated with tectonically-active margins, with plate collision or convergence resulting in tectonic uplift acting as the main forces for active margins (Inman and Nordstrom, 1971; Griggs and Trenhaile, 1994). On passive margins, such as Australia, rocky coasts also occur where factors such as the structural bedding having a high angle to the coast, or a sediment deficit, preference erosional to depositional landforms (Griggs and Trenhaile, 1994). Here, wave attack is the primary driver for eroding the coast line, rather than tectonic activity. As sea level fluctuates over geologic time, coast landforms are either exposed above or submerged below sea level until sea level reaches a stillstand at the elevation the landforms were originally formed at once again.

Preserved coastal landscapes, both above and beneath modern sea level, can be used as proxies to reconstruct past sea level (Li, et al., 2001; Belperio, et al., 2002; Boreen and James, 1993). In passive settings such as Victoria, Australia, the presence of rocky coast features formed at previous sea level positions which are now submerged makes for an in-situ laboratory to test hypotheses about how these features formed over time. As regional sea level in Victoria is considered to closely follow global sea level trends (Pirazzoli, 1991; Lambeck, et al., 2014), it is an ideal area for studying past global sea level fluctuations and how they shaped the rocky coast.

While submerged features can be considered analogous to examples seen at or above current sea level, little is quantitatively known about how their geomorphology actually relate to the modern onshore features and environments onshore. This is often because multiple sea level cycles have repeatedly exposed and submerged these paleo-shorelines, likely causing significant modification to their form since their initial formation. This leads to the focus of this research; analyzing the geomorphology of submerged features and modelling their evolution over geologic time.

1.2 Geomorphological features found on- and offshore of rocky coasts

Some of the most common features found along rocky coasts include sea cliffs, natural bridges, sea stacks, shore platforms, incised river mouths, and coastal estuaries. The presence of cliffs can either be
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the result of tectonic uplift or due to the structural grain and stratigraphy of the bedrock, and the evolution of cliffed coastlines is influenced by erosive processes (Griggs and Trenhaile, 1994). Headlands and sea stacks along a rocky coast indicate that erosion is focused on joints, faults, and bedding plains in an otherwise uniform lithology (Bird, 2000). Estuaries are fluvial coastal environments where fresh river water and saline ocean water mix at least intermittently, and along rocky coasts are flooded river valleys incised into bedrock or otherwise geomorphically low areas (Kjerfve, 1994). Relict coastal features formed during Quaternary sea level stillstands can be found on- and offshore of many coastlines, such as along the coast of Victoria, Australia (Woodroffe, et al., 1995; Beaman, et al., 2008; Shaw, et al., 2009; Nichol, et al., 2011; Brooke, et al., 2017).

1.2a Sea Cliffs

The rate of erosion for coastal cliffs depends primarily on geology, with most igneous and metamorphic cliffs being more resistant to erosion than sedimentary and unconsolidated rock types (Griggs and Trenhaile, 1994; Lim, et al., 2010). Joints, faults, and other structural weaknesses also determine how a cliff will erode, such as the size and geometry of block failures (Griggs and Trenhaile, 1994; Young, et al., 2011). Some cliffs are more resistant at their base due to lithified well-consolidated material then being topped by younger less compacted soils and alluvial sediments, while other cliffs are most resistant to erosion at the uppermost layers due to a cemented sand or lava cap (Emery and Kuhn, 1982). Depending on the cliff’s lithology and dominant erosional processes, it will fit a given profile (Figure 1).

For example, cliffs found along marine process dominant coasts typically have near-vertical faces, while cliffs in subaerial dominant systems will have more rounded, gently sloping profiles (Emery and Kuhn, 1982; Ruggerio, et al., 2001; Young, et al., 2009; Kennedy, 2007). Cliffs are also classified as being either active, where the bedrock is exposed by the retreat of cliff due to marine and subaerial erosion; inactive, where the cliffs are fronted by a cover of talus with slopes up to 30°; or former, where subaerial processes round the cliff crests and act as the dominant erosion type (Emery and Kuhn, 1982).

Weather patterns such as ENSO (El Niño Southern Oscillation) as well as long-term climate change can significantly impact the erosion and evolution of sea cliffs. Large storm events can increase wave erosion at the base of cliffs, leading to notching and weakening of the cliff base, and heavy precipitation can increase the erosion of cliffs, usually by way of mass wasting events, such as landslides and rockfalls (Emery and Kuhn, 1982; Griggs and Trenhaile, 1994; Trenhaile, 2011; Ruggiero, 2012). Eustatic sea level changes have varying impacts on cliffed coastlines, mostly depending on the tectonic setting of the region. On coasts where there is tectonic uplift that matches or exceeds the rate of sea level rise, cliffs will continue to rise above sea level and can ultimately form marine terrace profiles as sea level continues to oscillate over time (Griggs and Trenhaile, 1994). Rising sea levels can lead to an increase in erosion rates,
which can then lead to the formation of wide shore platforms and marine terraces (Bradley, 1958; Trenhaile, 2002). In regions of rapid uplift or where uplift outpaces sea level rise, these platforms may obtain steeply sloping seaward profiles. For steep platforms on both tectonically active and passive shorelines, more erosion occurs during periods of rising sea levels than falling, but erosion increases with increasing change in sea level either way (Trenhaile, 2002). Tectonically passive coasts or those with active subsidence will be eroded at increasing rates and can become submerged under rising sea levels as the shoreline progrades landward (Emery and Kuhn, 1982). These submerged cliffs may have different profiles than those found onshore nearby due to prolonged erosion as well as varying processes that may have acted on them over multiple eustatic cycles.

1.2b Sea Stacks

Sea stacks are remnants of promontories stranded in the sea after the sea cliffs have retreated landward and are closely related to mean sea level, as they form through the erosive action of waves. Rapid erosion of sea stacks globally suggests that they are ephemeral features, and their preservation across eustatic
cycles requires a change of the processes acting upon them. Sea stacks are formed as areas of weaker lithology or structure along a coast are preferentially eroded, leading to the formation of headlands (Limber and Murray, 2015). As the erosion continues, the headlands are dissected, creating caves and then arches. Further undercutting of the rock by hydraulic action eventually leads to collapse of the arch, leaving a free-standing sea stack (Figure 1.2) (Bird, 2000). Sea stacks will form only under certain boundary conditions. The rock must be soft enough to be eroded by waves but still have enough compressive strength to maintain the stacks’ overlying weight. For example, granite coastlines are generally too resistant to erode into stacks (Kennedy et al., 2014a), and cliffs made of clay or other soft strata do not have the compressive strength to support the weight of a tall stack (Trenhaile and Schwartz, 2006).

Figure 1.2 Schematic showing the erosion of a cliff leading to the formation of a headland, caves, arches, and ultimately sea stacks (adapted from Bird, 2000).

1.2c Shore Platforms

Shore platforms form in erosional environments where the hydraulic action forces of the ocean are greater than the resistive forces of the rock (Sunamura, 1991). Ocean waves are a primary formative agent, with the majority of the erosion occurring at the surf-rock interface in the surf break. The important wave erosion variables include wave height and period, tidal range, breaker height and depth, breaker type, surf zone width and bottom roughness, submarine gradient, rock resistance, and elevational frequency of wave action within the intertidal zone (Trenhaile, 2001; 2005; 2010; 2011). Wave erosion processes are concentrated between mean high and mean low water for microtidal environments (Carr and Graff, 1982). As a result they are important proxies for determining past sea levels (Trenhaile, 1987). Downwearing also plays a significant role in the evolution of platforms, especially in the intertidal, due to
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repeated tide induced wetting and drying cycles, exposure to sea water, and salt weathering (Stephenson, et al., 2013; Trenhaile, 2005; 2007). There are two types of shore platforms: those that slope seaward as a uniform ramp (Type A) and those that have a distinct seaward edge marked by a cliff or scarp (Type B) (Sunamura, 1991; Kennedy, 2015). For both types, the landward edge is generally identified by either a cliff or is buried below the beach or hillslope talus, in which case it can be delineated as the slope becoming greater than 12 - 15˚, (Kennedy, 2015). Defining the seaward edge of shore platforms, however, is not necessarily a straight forward task, and there are five commonly used criteria for defining the seaward edge of a shore platform: 1) tidal elevation, 2) morphology, 3) sedimentology, 4) biology, and 5) wave processes (Kennedy, 2015).

For tidal elevation, the seaward edge of Type A platforms is defined as being at Mean Sea Level (MSL) (Sunamura, 1992), while Mean Lower Water Springs (MLWS) is typically used in mathematic modelling of the seaward edge. Both of these methods pose a problem for studying submerged platforms that are no longer in the modern tidal zone. The morphological approach is generally used for Type B platforms, where the edge is easier to define. In this approach, the edge is defined as the point on the platform where there is an abrupt change in slope, such as a cliff or scarp. The third approach uses a sedimentological approach that defines the edge as being wherever the environment is no longer erosional. The biological approach to designating the seaward edge is based on the fact that the edge of platforms is often inhabited by benthic flora and fauna, especially in low intertidal zones. Using this method, the seaward edge is then defined as the position where the benthic biology completely protects the platform and the bedrock is no longer eroding. The final approach is the process based approach, which focuses on shore platforms being dynamic features. Wave erosion is highest during low tides, where the slope of the subtidal zone is greater than the slope of the intertidal platform (Kennedy, 2015).

Based on all five methods, an all-inclusive definition has been created to delineate the seaward edge of shore platforms:

“The seaward edge of a shore platform is defined as: the point where active erosion of the bedrock ceases at or landward of wave base. This is characterized in the field by erosional features such as notches, block-plucking scars, or the deposition of sediment of such a thickness that the underlying bedrock is not exposed during decadal-scale storm events” (Kennedy, 2015. p.8).
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The gradient of a shore platform can provide insight into the boundary conditions acting upon it. In studying shore platform development, Trenhaile’s model suggests that both platform gradient and width increase with increasing tidal range, but that the width actually decreases with fast downwearing (Trenhaile, 1981; 2005). This study also found that platform gradient decreases and width increases with increasing wave energy and with decreasing rock resistance and decreasing platform roughness (Trenhaile, 2005). In Victoria’s high wave-energy microtidal coastal environment, these results imply that platforms should be relatively narrow with low gradients. In reality, they are actually relatively wide, averaging about 50 m in width due to high wave energy and are near horizontal (Kennedy and Milkins, 2015). These gently sloping, near horizontal platforms are common in microtidal environments and often have no clear seaward scarp, which makes them generally classified as either Type A or Type B platforms (Kennedy and Dickson, 2006; Stephenson, et al., 2013). Their width is measured from cliff toe to the seaward edge (Stephenson, et al., 2013), which for submerged platforms would mean measuring from the edge of the backing submerged cliff to the seaward scarp. Increased beach sediment was found to lead to narrower and steeper platforms (Trenhaile, 2005). Platform gradient also increased and platform width decreased with increased cliff height and with decreased cliff debris mobility (Trenhaile, 2005). Therefore platforms backed by high cliffs, such as near the 12 Apostles in Port Campbell, Victoria, where there are often large scale mass erosion events, would be narrow with a higher gradient than platforms in other non-cliffed areas of Victoria.

In studying the Quaternary evolution of platforms, it was found that shore platforms trend toward a static equilibrium. Platforms tend to be narrower and steeper during glacial cycles when sea level is falling and the coastline is retreating seaward, and they tend to be wider with a gentler slope during interglacial cycles when sea level is rising and the coast is transgressing landward (Trenhaile, 2001; Dickson, et al., 2013). It was also found that a reduction in slope gradients seaward on the slope will gradually affect the higher elevations on the erosional profile and that many platforms are at least partially inherited from past interglacial cycles when sea level was close to present level, with multiple erosional and depositional cycles constructing the platforms’ present morphology (Trenhaile, 2001; Thom, et al., 2010). Finally, in regards to future changes in sea level, Trenhaile found that rising sea level will lead to faster rates of cliff recession and that the current width of intertidal platforms may give a rough estimate of what cliff recession rates for that area may be over the next century (ie. a narrow platform may either mean that the rock type is very resistant to erosion or that there is rapid submarine erosion occurring) (Trenhaile, 2011).
1.2d Estuaries

There are many definitions of estuaries based on their form and boundary conditions. An inclusive and complete definition is: the seaward portion of a transitional zone “which receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave and fluvial processes; the estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth” (Dalrymple, et al., 1992, p1131). Most coastal lagoons formed during the Holocene when sea levels rose and sand spits and barriers were created at the mouths of coastal river outlets (Woodroffe, 2002; Duck and Silva, 2012). Coastal lagoons tend to form where marine influences dominate, as compared to environments where river processes dominate, forming delta systems (Duck, 2012). Another feature differentiating coastal lagoons from delta systems is the net landward movement of sediment over time compared to the net seaward transport of sediment seen in deltas (Dalrymple, et al., 1992). These lagoons occur generally on gently sloping substrates and are considered ephemeral, as they infill with sediment over time (Adlam, 2014). The accommodation space, or total subaqueous volume of a coastal lagoon basin available for sediment deposition, can be altered however. For instance, relative sea level rise can create more accommodation space in a basin, and reduced sediment supply can reduce the rate that the accommodation space is consumed (Adlam, 2014).

Estuaries can be classed in one of the three following groups: drowned river valleys, barrier estuaries, or saline coastal lakes (Roy, et al., 1980; Roy, 1984). Drowned river valley estuaries are fluvial-dominated systems that have tidal deltas at their entrances and a full tidal range throughout the entire estuary (Roy, 1984; Roy, et al., 2001). Barrier estuaries form either as transgressive features as sea level moves landward or as a result of littoral drift during sea level standstills if sediment supply is adequate and are wave-dominated systems (Orford, 2004; Roy, et al., 2001).

The longevity of estuaries is determined primarily by the infill rate of sediment filling the basin and by changes in sea level (Kennedy, 2011). Coastal estuaries have a finite amount of accommodation space, and as such, unless there is very high seaward discharge they will infill with inflowing sediment over time, which may take several eustatic cycles (Kennedy, 2011). For instance, the geomorphology of many modern coastal estuaries is strongly inherited from earlier Quaternary highstands (Heap and Nichol, 1997; Abrahim, et al., 2008). As estuaries infill with sediment and evolve over geologic time, former estuarine environments can transform into terrestrial flood plains, levees, and backswamps (Roy, et al., 2001). As for sea level rise, some estuarine systems, such as those on soft sandy coasts or those fronted by beach barrier systems, may shift landward and therefore possibly shift the balance of landward versus seaward net transport of sediment for that system (Kennedy, 2011). Other estuary systems will change much more
Chapter 1. Introduction

with increased sea levels, especially those with large intertidal zones that will be pushed inland while the lower intertidal environment will be inundated (Freidrichs, et al., 1990; Kennedy, 2011).

1.3 Quaternary sea level

Sea level is not static, but rather it rises and falls over eustatic cycles as the Earth’s climate switches between glacial and interglacial periods (Figure 4). During glacial maxima, sea level is lower as more water is removed from the oceans and locked away as ice. When the climate begins to switch back to an interglacial, or warmer, period, the land ice and ice shelves begin to melt and flows back into the ocean, which couples with increasing ocean temperatures, leading to thermal expansion of the water, thus raising sea level (Rahmstorf, 2007). While global sea level follows the pattern of interglacial highstands and glacial lowstands (Figure 1.3), local or relative sea level often varies from the global trends. This can be due to local temperature anomalies, tectonic uplift and subsidence, ocean circulation, or glacial rebound (Nicholls, et al., 1999). For instance, relative sea level may actually appear to be dropping below the global average rate of rise due to ongoing tectonic uplift in California and glacial rebound as well as uplift in Alaska, whereas in low-lying island nations and areas with significant subsidence such as the Gulf Coast of America relative sea level may be rising much faster than the global rate (Hampton and Griggs, 2004).

Australia is located in the middle of the Indo-Australian tectonic plate, making it a passive margin setting (Pirazzoli, 1991). During the Last Glacial Maximum, there was very little continental ice on the land mass, which combined with the passive tectonic setting, means that Australia’s regional sea level signal very closely matches the eustatic signal (Murray-Wallace and Belperio, 1991; Pirazzoli, 1991; Murray-Wallace, 2007; Grant, et al., 2014; Kennedy, 2014). During the Last Glacial Maximum, sea level in Australia was 130-150 m below present level (Chappell, 1987).
Figure 1.3 Graph showing sea level oscillation over the past 250 ka shown in black, based on data collected by Grant, et al. (2014) with a smoothed sea level curve shown in red. The top figure is the time period shown in the blue box in the bottom graph, highlighting sea level during MIS 3.

1.4 Research Aims

The overarching questions that this thesis aims to answer are:

“How are interstadial shorelines preserved over multiple eustatic cycles?” and

“How accurate a sea level proxy are erosional rocky landforms?”

In order to answer this broad question, two sub-questions have been identified:

(i) What boundary conditions determine the geomorphology of the modern coastline during sea level stillstands with regard to the sea cliffs, shore platforms, sea stacks, incised river channels, and estuaries?

(ii) How do rocky coast landforms form and evolve over multiple sea level changes?

To answer these questions, the modern coast of Victoria was mapped to identify the above rocky coast features and then analyzed to quantify their morphological characteristics. The same process was then
applied to any paleo-shoreline landforms found offshore of the modern coast to better understand the processes involved in creating and preserving such landforms over geologic time. Combining the onshore and offshore shoreline data and analysis, a rocky coast evolutionary conceptual model was created that will be applicable to temperate, high energy coasts globally.

1.5 Geology of the Victoria’s rocky coast

There are three dominant lithologies along the coast of Victoria: basalt, limestone, and non-carbonaceous sandstone (Birch, 2003) (Figure 1.4). The basalts are comprised of the Miocene- Holocene Newer Volcanic Group and the Eocene – Oligocene Older Volcanic Group. The Newer Volcanic Group is predominantly in Western Victoria and tends to be better preserved and less eroded due to its younger age. These basalts include cinder cones, scoria, ash, and lava flows. The maximum thickness for the Newer Volcanic is 200 m (Geoscience Australia, 2013). The Tertiary Older Volcanic Group is more dominant in the Otway Coast region and is comprised of a sequence of basaltic lava with a maximum thickness of 400 m and overlies the Werribee Formation, which is comprised of Tertiary non-marine sands, clays, and coal (Birch, 2003). In many places, it has buried Late Oligocene to Middle Miocene aged marine sediments (Clark, 1988). The Mornington Peninsula Volcanic Group (formerly called the Flinders Volcanic Province), which stretches from Cape Schanck east across the Port Phillip Bay, is a subset of the Older Volcanic Group. This group is Eocene in age and has a slight southeasterly dip to the basaltic pahoehoe sheet lavas and debris flows that are found in the region (Simmons, et al., 2014).
In western coastal Victoria, the Quaternary Bridgewater Formation is the most common type of sandstone. It is a steeply cross-bedded and carbonate-cemented aeolian sandstone that formed as dune sequences running parallel to the shore during the middle to late Pleistocene (Birch, 2003). The Bridgewater Formation is poorly cemented and highly weathered with various karst features present near Cape Bridgewater, such as caves and solution pipes (Grimes and White, 2004). The calcareous material found in the formation is comprised of the shells and bioskeletons of shallow marine organisms from Pleistocene sea level highstands. Lack of tectonic uplift during the Pleistocene in coastal Victoria has led to the dune ridges that formed in a stacked formation with linear interdune swamp deposits between such as limestones, dolomites, and clays (Grimes, et al., 1999). The Bridgewater Formation is typically between 15-25 m thick but has a maximum thickness of 45 m (Cupper, et al., 2003).

The predominant types of sandstone in Port Philip Bay are the Red Bluff Sandstone and the Black Rock Sandstone that make up the Brighton Group. The Red Bluff Sandstone is Late Miocene to Pliocene in age and was formed by the deposition of coarse fluvial sediments in shallow water during a sea level regression. The Black Rock Sandstone (sometimes called Beaumaris Sandstone) underlies the Red Bluff Sandstone and is Late Miocene in age. It is comprised of sand, sandstone, conglomerate, some minor sandy limestone, and local ironstone. It is well-sorted and variably cemented with some shelly fossils and burrows (Birch, 2003). The Black Rock formation formed about 12 million years ago when sea level fell and tectonic uplift of the coast continued. The coarser sediments from inland flowed down to sea level and were deposited in the shallow sea, cementing and forming sandstone. This formation contains mainly quartz sand and is significantly richer in iron compounds than the Red Bluff Sandstone (Bird, 1990).
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East of Port Philip Bay, the Otways Formation (also referred to as the Wonthaggi Formation and the Eumeralla Formation) is the prevalent type of sandstone, being a lithic volcaniclastic sandstone that has a maximum thickness of 2500 m and is Cretaceous in age (Bryan, et al., 1997). The Otways sediments were deposited by several sheetflood to braided river channel systems, up to 200 m thick and separated by overbank sequences 5-100 m thick (Bryan, et al., 1997). The uniform grain size of the formation is also indicative of being formed in a fluvial system with high volume and energy discharge events (Bryan, et al., 1997). The mineral composition of the Otways Formation is primarily volcanic lithic grains of andesite, dacite, and rhyolite, with detrital minerals including lesser quartz, hornblende, pyroxene, apatite, titanate, and zircon (Bryan, et al., 1997). The volcanic materials found in the formation are thought to have originated to the east of the Gippsland Basin (Bryan, et al., 1997).

Of the limestone formations in coastal Victoria, one of the better known is the Port Campbell Limestone, of which the 12 Apostles are composed. Port Campbell Limestone is found in the Otway Basin, which starting forming in the Mesozoic era with the rifting of Australia and Antarctica (Geological Survey of Victoria, 1995). The Port Campbell Limestone was deposited in a mid-shelf environment during a sea level highstand about 5 million years ago, and in some outcrop sections three sea level regressions and two transgressions can be identified. The upper sections of the Port Campbell Limestone show a continuous drop in relative sea level throughout the end of the Miocene (Phillips, et al., 2003). Since the Late Miocene, the Port Campbell Limestone has been exposed to subaerial processes but has seen no major dissolution or moldic porosity (the dissolution of shells which leaves behind empty pore spaces), which is thought to be due to the fine grained nature and low permeability of the limestone and the aforementioned Bridgewater formation (Nicolaides, 1997).

As cool water carbonaceous sediments have been deposited on the continental margin of southeastern Australia since the Eocene, it provides the opportunity to compare analogous offshore sediments and onshore Tertiary rocks (James and Bone, 1991; Boreen and James, 1995). Shallowly buried dolomites have been found in the Gambier Embayment of the Otway Basin, as well as limestones formed in cool water during the Oligocene and Miocene (James, et al., 1993). The limestones of the Torquay and Port Campbell Embayments were formed on the middle to inner part of the shelf and are similar to the bioclastic limestones currently accumulating on the continental shelf (Boreen and James, 1995). While sediments deposited during sea level highstands in this region are progradational, wedge-shaped, and upward shoaling, lowstand events can be either erosional or depositional and result in complex sequences (Boreen and James, 1995).

It is also important to note that there is granite found in coastal Victoria, primarily on Wilson’s Promontory and on the south-eastern tip of Philip Island. The granite on Philip Island is Woolamai
Chapter 1. Introduction

Granite, which is late Devonian in age (Higgins, 2011) and has a high biotite content that is prone to microfracturing (Hill, 1995). Wilson’s Promontory is comprised of Wilson’s Promontory Granite, Vereker Granite, Mount Norgate Granite, Sealers Cove Granite, Mount Singapore Granite, and Lilly Pilly Granite (Higgins, 2011). These granites have eroded at a decimetre scale over the past million years (Bierman and Caffee, 2013) and thus evolve slowly over multiple eustatic cycles (Trenhaile, 1987). The granite outcrops of Wilson’s Promontory descend into the sea at angles up to 70° (Kennedy, et al., 2014a) and are intruded into tightly folded Ordovician shales and sandstones (Hill and Joyce, 1995). Shore platforms are absent in this region except between South East and Waterloo Points and on Wattle Island, where there is a high density of joints that allow for bedrock erosion (Kennedy, et al., 2014a).

1.6 Existing knowledge and research gaps

There are several key gaps in previous research and knowledge regarding the rocky coast of Victoria in particular. Most studies are highly limited on a spatial scale, whereas this study will include the rocky coast from Wilson’s Promontory west to the border between Victoria and South Australia as a case study for creating a global rocky coast model. Most of the offshore geologic work that has been done in Victoria has focused on either benthic habitats (Ierodiaconou, et al., 2007; Rattray, et al., 2009), oil drilling (Currie and Isaacs, 2005; Edwards, et al., 1999), or structural geology and tectonic movement (Etheridge, et al., 1987; Cande and Mutter, 1982), while the bathymetry and geomorphic features have not been analysed. This study will not only identify different offshore bathymetric features, but it will also provide an explanation for how and when they formed. There is also a significant gap in the research field pertaining to relative sea level in Victoria in relation to Milankovich-scale cycles. While there are numerous studies that have been completed using relative sea level in East Australia (Woodroffe, et al., 1995; Murray-Wallace and Belperio, 1991; Siddall, et al., 2007; Lewis, et al., 2013), there is virtually no work specific to the Victorian coast. By identifying offshore features and the sea level insterstadials during which they formed, this study will help verify whether historic global sea level trends are indeed acceptable to use for Victoria. This study also has access to the latest bathymetrical and terrestrial LiDAR data sets as well as high resolution bathymetric data, providing detailed coverage of the coast of Victoria to 60 m depth, for identification and analysis of onshore and offshore geomorphic features.

These aims were achieved through the use of multibeam and aerial LiDAR survey data of the Victoria coast. The final raster grid of the data has a 5 m horizontal resolution providing full coverage capturing the coastal bathymetry to depths of 60 m. The morphological features identified in the LiDAR data were then measured and analyzed in ArcGIS V.10.1. Offshore geomorphic features were identified and mapped.
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around the coast of Victoria, including drowned cliffs, rivers, estuaries, shore platforms, and sea stacks. For drowned sea stacks, height, area, perimeter, and distance from a drowned cliff were measured and recorded. For drowned river channels and estuaries, length, width, and depth were noted. The definition described by Kennedy (2015) was then used to delineate the leading seaward edge of each platform that has been identified. Based on the results of these tests, the depth of the seaward edge of each platform was recorded.

For creating a global rocky coast model, existing models such as those by Emery and Kuhn (1982), Limber (2011), and Trenhaile (2011) were tested using the rocky coast of Victoria as a case study. A working hypothesis was proposed that stated: 1.) lithology and erosive processes would be the main driving forces in the morphology of onshore and offshore landforms, 2.) offshore submerged landforms would have formed in a similar manner to the landforms found on the modern coast, and 3.) the submerged landforms would have a differential erosion history compared to the modern coast due to multiple changes in sea level since their formation. Each of the sets of features identified onshore were tested against the existing models to see if the above hypotheses matched the actual morphology of the coastal landforms. In cases where the study site measurements did not match the anticipated results of the given models, a new model of evolution was offered. Then using the existing models and new it-situ observations as a guide, a global rocky coast theoretical model was created, synthesizing the onshore and offshore evolution over multiple sea level cycles.

1.7 Dissertation overview

The research for this dissertation can be divided into four primary areas of study that all focus on the geomorphological history of rocky coast landforms in Victoria, Australia over multiple eustatic cycles.

1. **Chapter 1** is an introduction to rocky coasts and the features found along them, as well as an introduction to the importance of studying their morphological characteristics to infer past and present erosion processes acting upon them. This chapter also provides a thorough literature review of rocky coast landforms, their formation, and their morphology on a global scale.

2. **Chapter 2** is a case study focusing on sea stacks and a comparison between morphology and formation during past and present sea levels. This chapter has been published in the Journal of Coastal Research (Bezore, et al., 2016).

3. **Chapter 3** is a study of the morphology of sea cliffs along the modern coast of Victoria as well as sea cliffs offshore that are submerged 50 m below sea level. This chapter is currently being reviewed for publication in the Journal of Continental Shelf Research (2019).
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4. Chapter 4 is a study focusing on shore platforms found along the coast of Victoria and offshore at 50 m depth, comparing the morphology and evolution of both. This chapter is currently being prepared for submission to Geomorphology (2019).

5. Chapter 5 is a comprehensive synthesis of all the rocky coast landforms found offshore of Victoria at 50 m depth that comprise an extensive Marine Isotope Stage 3 paleo-shoreline. This chapter is currently being prepared for submission to the Australian Journal of Earth Sciences (2019).

6. Chapter 6 is a conclusion section offering a closing dialogue about modern and paleo-landforms and how their morphology and evolution relates to past sea levels.

1.8 References


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CHAPTER 2

The Drowned Apostles: The Longevity of Sea Stacks Over Eustatic Cycles
Preface

The following chapter was carried out in collaboration with my supervisors, David M. Kennedy and Daniel Ierodiaconou and was published in the Journal of Coastal Research on January 5th, 2015 in Volume 75 of the journal. I was the main author on this publication with a contribution percentage of 70%.

2.1 The Drowned Apostles: The Longevity of Sea Stacks Over Eustatic Cycles

Rhiannon Bezore‡, David M. Kennedy†, and Daniel Ierodiaconou‡
† School of Geography, The University of Melbourne, Parkville VIC 3010, Australia
‡ Deakin University, School of Life and Environmental Sciences, Centre for Integrative Ecology, Warrnambool VIC 3280, Australia

ABSTRACT

Cliffed rocky coasts are erosional environments, the remnants of which can be preserved as sea stacks as the shoreline retreats. These sea stacks form spectacular landscapes, such as the iconic Twelve Apostles in Victoria, Australia. However, they are ephemeral features formed on a centennial scale, continually eroding and collapsing, meaning that coasts characterised by sea stacks often have fewer features than when first described. The question arises then as to the longevity of such features and whether they can be preserved over eustatic cycles.

The modern Twelve Apostles, of which 8 are still standing, are comprised of the Miocene Port Campbell Limestone and reach 45 m above sea level. Recent multibeam sonar data show five features around 6 km offshore, in 40-50 m water depth that appear to be relict sea stacks. Based on the morphology and geology of both the modern and drowned Apostles, it is inferred that the drowned and modern stacks evolved in a similar manner. While the modern sea stacks have an average height of 45 m, the drowned stacks have an average height of 4 m, suggesting a much greater age and also the possibility of multiple exposures to subaerial processes. The drowned stacks lay 655 m seaward of a drowned cliff averaging 14 m high which likely represents a former interstadial shoreline. This is much greater than the 91 m average distance between stack and cliff for the Modern Apostles, which may imply a more prolonged period of erosion along the drowned coastline.

ADDITIONAL INDEX WORDS: Rocky coasts, coastal geomorphology, coastal processes, sea level, sea stacks.

INTRODUCTION

Rocky coasts are predominately erosional landforms that comprise 80% of the world’s shorelines (Emery and Kuhn, 1982), from which sea stacks can be created. These limestone stacks form spectacular landforms along coastlines worldwide such as California, US and Victoria, Australia. They are not static features, though, as evidenced by collapses like that of a 50 m high Twelve Apostle stack in 2005.

The question arises, then, as to whether sea stacks can persist over eustatic cycles. This study focuses on the limestone sea stacks known as the 12 Apostles in Victoria, Australia and compares their morphology and formation with a drowned shoreline found nearly 6 km offshore from the modern stacks. By comparing the modern and submerged shoreline, inferences on the temporal stability of limestone sea stacks can be made.

Background

The modern Apostles are found within the Otway Basin between Peterborough and Princetown on the southwest coast of Victoria, Australia (Figure 2.1). The Otway Basin is a north-northwest trending feature that covers an area of about 150,000 km² and contains over 10,000 m² of Late Jurassic to Tertiary sediments. The basin was formed during the late Jurassic rifting of Australia and Antarctica. Initial infill during the mid-Cretaceous was characterized by volcaniclastic and fluvial deposits with later Tertiary coastal and shallow marine clastic deposits (Nicolaides, 1995).

The onshore surface geology of the 12 Apostles (Figure 2.2) is Port Campbell Limestone overlaying the Gellibrand Marl. They tend to form on coastlines where marine processes dominate, and their form is the result of the relative balance between marine and subaerial processes (Kennedy et al., 2014b).

Sea stacks are formed as areas of weaker lithology or structure along a coast are preferentially eroded, leading to the formation of headlands. As the erosion continues, the headlands are dissected, creating caves and then arches. Further undercutting of the rock by hydraulic action eventually leads to collapse of the arch, leaving a free-standing sea stack (Bird, 2000).

Sea stacks will form only under certain boundary conditions. The rock must be soft enough to be eroded by waves but still have enough compressive strength to maintain the stacks’ overlying weight. For example, granite coastlines are generally too resistant to erode into stacks (Kennedy et al., 2014a), and cliffs made of clay or other soft strata do not have the compressive strength to support the weight of a tall stack (Trenhaile and Schwartz, 2006). With a compressive strength between 60 -170 MPa, limestones are an ideal rock type in

DOI: 10.2112/SI75-119.1 received 15 October 2015; accepted in revision 15 January 2015
*Corresponding author:
rbezore@student.unimelb.edu.au ©Coastal Education and Research Foundation, Inc. 2016
The cliffs backing the Modern Apostles, as well as the 12 Apostles themselves, are comprised of alternating bands of hard and soft Port Campbell Limestone (Birch, 2003). The offshore geology in this region replicates the onshore geology, consisting of calcarenite, limestone, sandstone, and marl (LCC, 1993).

The Port Campbell area is exposed to swells from the southwest from the Southern Ocean. SWAN (Simulating WAves Nearshore) models show average wave heights ranging between 2 - 3 m (Flocard et al., 2015), and wave periods in the region are typically 8 - 12 sec (LCC, 1993). The average spring tidal range is 0.6 m (Bureau of Meteorology, 2015). Port Campbell has a mean annual rainfall of 923 mm (Bureau of Meteorology, 2015).

This study uses bathymetric and terrestrial LiDAR data collected in 2007 using a LADS Mk II system with a GEC-Marconi FIN3110 inertial motion sensing system and a dual frequency kinematic geographic positioning system (kGPS). This dataset includes seamless terrestrial -marine mosaics from elevations of +10 m to depths of -25 m (Quadros and Rigby, 2010). Multibeam data were acquired as part of the ongoing Victorian Marine Habitat Mapping Project (Ierodiaconou et al., 2007). This data was combined with Multibeam sonar data using a Reson Seabat 101 multibeam echosounder operating at a frequency of 240 kHz and 150 degree angular sector coverage. Positioning was accomplished using a real-time differential GPS integrated with a positioning and orientation system for marine vessels (POS MV) for dynamic heave, pitch, roll and yaw corrections (± 0.1° accuracy). The final raster grid of the data has a 5 m horizontal resolution providing full coverage capturing the coastal to depths of 60 m. The data was analyzed using the geographic information system software ArcGIS V.10.1. All data used in this study was projected in the World Geodetic System (WGS) 1984 in Universal Transverse Mercator (UTM) Zone 54s. The morphological features identified in the LiDAR data were then measured and analyzed in ArcGIS. Cliff erosion was analyzed for the modern shoreline, using a combination of aerial and satellite images and the Digital Shoreline Analysis System (DSAS) (Thieler et al., 2009). Aerial photographs from 1947 and 1994 and Google Earth Ikonos satellite images from 2004 and 2014 were used to measure change in cliff position over time and were all georeferenced in ArcMap using a minimum of 30 ground control points. A single road was identified in all three images that ran parallel to the shore, and a polylines was created to represent it as a baseline for cliff erosion measurements. DSAS was then run for the years 1947-1994, 1947-2004, and 2004-2014.

RESULTS

Five sea stacks were identified off the coast of Peterborough, sitting seaward of a drowned cliffline about 50 m below modern sea level (Figure 3). For both the modern and drowned cases, there is a cliffline fronted seaward by sea stacks that are the remnants of the cliff likely eroded by wave activity. The paleo-stacks are generally shorter and wider than the current stacks and are located farther seaward from the cliffs than the modern Apostles (Figure 4). The height of the stacks was measured from base to top and showed the modern stacks to be nearly ten times taller on average than the drowned stacks. The length was measured across the longest portion of each stack, perpendicular to the shoreline, and showed the drowned stacks to be almost an average of 20 m longer than the current stacks. For the width of the stacks, measured parallel to the shoreline at the longest point, the drowned sea stacks were nearly twice as wide on average as the modern stacks.

METHODS

This study uses bathymetric and terrestrial LiDAR data collected in 2007 using a LADS Mk II system with a GEC-Marconi FIN3110 inertial motion sensing system and a dual frequency kinematic geographic positioning system (kGPS). This dataset includes seamless terrestrial -marine mosaics from elevations of +10 m to depths of -25 m (Quadros and Rigby, 2010). Multibeam data were acquired as part of the ongoing Victorian Marine Habitat Mapping Project (Ierodiaconou et al., 2007). This data was combined with Multibeam sonar data using a Reson Seabat 101 multibeam echosounder operating at a frequency of 240 kHz and 150 degree angular sector coverage. Positioning was accomplished using a real-time differential GPS integrated with a positioning and orientation system for marine vessels (POS MV) for dynamic heave, pitch, roll and yaw corrections (± 0.1° accuracy). The final raster grid of the data has a 5 m horizontal resolution providing full coverage capturing the coastal to depths of 60 m. The data was analyzed using the geographic information system software ArcGIS V.10.1. All data used in this study was projected in the World Geodetic System (WGS) 1984 in Universal Transverse Mercator (UTM) Zone 54s. The morphological features identified in the LiDAR data were then measured and analyzed in ArcGIS. Cliff erosion was analyzed for the modern shoreline, using a combination of aerial and satellite images and the Digital Shoreline Analysis System (DSAS) (Thieler et al., 2009). Aerial photographs from 1947 and 1994 and Google Earth Ikonos satellite images from 2004 and 2014 were used to measure change in cliff position over time and were all georeferenced in ArcMap using a minimum of 30 ground control points. A single road was identified in all three images that ran parallel to the shore, and a polylines was created to represent it as a baseline for cliff erosion measurements. DSAS was then run for the years 1947-1994, 1947-2004, and 2004-2014.

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Modern Apostles

Of the original 12 Apostles, there are currently eight standing along the contemporary coast. The Modern Apostles range in height from 12.98 - 67.45 m with an average height of 45.31 m, while the average length was 52.38 m with a range of 25.82 - 95.68 m (Figure 2.5). The modern stacks range in width from 31.99 - 70.14 m (average 46.58 m) and have an average area of 2,678.45 m² (714.42 m² - 7,900.24 m²) (Table 2.1). The current stacks sit at an average distance of 118.65 m offshore (Table 2.1), with the modern cliffs behind them averaging at 48.92 m in height. There is a sea stack height to cliff height ratio of 0.93. The modern cliffs have a more angular toe and head and have a mean cliff face slope of 75°.

Drowned Apostles

There are five drowned stacks that range in height from 3.32 - 6.47 m with an average height of 4.37 m. The average length of the drowned stacks was 71.76 m (range 25.17 - 116.33 m), and the average width of the drowned stacks was 86.11 m (range 38.27 - 207.94 m). The average area was 8,183.97 m² (range 207.94 - 7,900.24 m²) (Figure 2.4). The drowned stacks have a mean cliff face slope of 75°.

Drowned Apostles span from 58.11 - 62.12 m depth with an average depth of 59.72 m (Table 2.1). The presence of sea stacks along both the modern and drowned coastlines is evidence of long term erosion. It was found that the mean long term rates of erosion both from 1947-1994 (Figure 2.7) and from 1947-2014 were 0.22 m/yr and that the short term rate of erosion from 2004-2014 was 0.36 m/yr (Figure 2.8). In addition to these erosion rates, there are also known accounts of cliff failure and slumping as well as documented cases of sea stack and arch collapses along this section of modern coastline. In 1990, part of the London Bridge sea arch collapsed with two tourists left in need of rescue, and in 2009 one of the 12 Apostles collapsed near Loch Ard Gorge. Such collapses indicate that cliff retreat is episodic.

Table 2.1. Dimensions of each drowned and modern sea stack.

<table>
<thead>
<tr>
<th>Heights (m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Area (m²)</th>
<th>Perimeter (m)</th>
<th>Dist. from cliff (m)</th>
<th>Depth stack base (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drowned Apostle</td>
<td>1</td>
<td>3.32</td>
<td>70.45</td>
<td>57.55</td>
<td>4,346.00</td>
<td>274.35</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6.47</td>
<td>98.78</td>
<td>117.24</td>
<td>1,103.48</td>
<td>423.18</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3.95</td>
<td>25.17</td>
<td>38.27</td>
<td>902.88</td>
<td>127.07</td>
</tr>
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DISCUSSION

The 12 Apostles provide a contemporary analogue for the formation of the drowned Apostles. The Port Campbell Limestone along this section of coast has a maximum burial depth of close to 300 m (Nicolaidis, 1997), so it is assumed that the drowned stacks are also made of limestone since they found at only about 60 m depth. There is also no evidence that the submarine features are volcanic necks or pipes, as there is no igneous geology in the surrounding region (Higgins, 2011).

Since both set of stacks are comprised of the same lithology of their adjacent cliffs, it can be assumed that they evolved in a similar manner as the modern Apostles and may have had similar rates of erosion when they sat above sea level.
Chapter 2. The Drowned Apostles: The Longevity of Sea Stacks over Eustatic Cycles

During MIS 3, sea level was 60-90 m below present sea level, which correlates to the average depth of the drowned Apostles at 59.72 m. MIS 3 does not fit the typical profile of a 100 ka interstatal period that has characterized the last million years, since there were significant temperature and ice-volume fluctuations across the period (Meerbeeck, et al., 2009). There was an initial rise in sea level to roughly 60 m below present levels that lasted the first half of MIS 3, followed by a drop to -80 m (Siddall et al., 2008). It is likely, then, that the Drowned Apostles initially formed during the first half of MIS 3, when sea level was at -60 m.

Sea stacks are closely related to mean sea level, as they form through the erosive action of waves. The base of the modern stacks is within 10 m of the current mean sea level, while the average depth of the base of the drowned stacks is 59.72 m. This means that sea level must have been roughly 60 ± 10 m below present when the drowned stacks were formed. Prior to the Holocene, the previous sea level interstadial and interglacial highstands occur at c. 60 ka, 85 ka, 110 ka, and 135 ka (Grant et al., 2014). Except for the highstand at 60 ka, all of the other highstands saw sea levels much higher than the -60 ± 10 m expected to have formed the drowned stacks. Due to the high contemporary erosion rates of Port Campbell Limestone and the appearance of the last interglacial landforms, it is unlikely that the drowned stacks would correlate to the older sea level highstands.

Figure 2.9. Reconstructed sea level curve (Grant et al., 2014) for the past 250 thousand years with the best fit for the age of formation of the drowned sea stacks based on the depth of water in which they sit currently.

While it is inferred from the morphology of the current cliffs that hydraulic erosion is the dominant form of erosion for the current coastline, the drowned cliffs show a more slumped and low angle toe morphology that might point to a slightly different erosion process (Emery and Kuhn, 1982). The dominant process was still most likely marine erosion while the sea level was highest during MIS 3, but it is likely that the zone of erosion moved vertically at a different rate than is seen along the current coastline. There may have also been large scale slumping or cliff failure that could account for the diminished slope of the drowned cliff face (Emery and Kuhn, 1982). During the second half of MIS 3, when the stacks would have been roughly 20 m above sea level at that time, the main processes of erosion would have been subaerial rather than hydraulic (Siddall et al., 2008).

Rapid erosion of sea stacks globally suggests that they are ephemeral features, and their preservation across eustatic cycles requires a change of the processes acting upon them. With a combination of high cliff erosion rates, low sea level, and a fairly wet climate based on the fact that MIS 3 was a warm stand (Siddall et al., 2007), the paleo-shoreline would have kept eroding and periodically failing due to terrestrial processes, while the stacks would hold their stationary location but also continue to be eroded. During the first 3,000 years of MIS 3, sea level rise was its peak with a rate of nearly 6 mm per year, compared to the current rate of 3.2 mm per year (Siddall et al., 2007). As sea level rose, beaches would have been removed as
they could not migrate inland past the cliffs, and perhaps this loss of abrasive material from the lack of sand could have also slowed the erosion rates enough to preserve the stacks (Limber and Murray, 2011). The rates of sea level rise during the postglacial marine transgression were significantly higher in Eastern Australia (Lewis et al., 2013) and it appears to have been too rapid to completely erode the drowned stacks as the shoreline migrated from -120 m to present levels (+/- 1 m) (Lewis et al., 2013). A prolonged exposure to subaerial erosion may also explain the much shorter and wider shape of the submerged stacks, as opposed to the modern stacks that have been formed solely at present sea level.

CONCLUSIONS

The 12 Apostles are world renowned for their iconic pillar shapes standing tall against the waves, but the drowned Apostles provide insight into what their future might hold. Both the drowned and the modern sea stacks are indicative of a classic erosional rocky coast environment with high wave activity being the main cause of cliff erosion. As the drowned Apostles are found in the same geologic setting as the current 12 Apostles, it is reasonable to assume that they were formed under the same geomorphic processes, some 60,000 years apart. The drowned sea stacks would have been eroded from a rocky coast by waves, wind, and rain at a sea level lower than today.

The preservation of these stacks is due in part to the rapid rise of sea level in the first half of MIS 3 and the post glacial marine transgression, carving the features out of the cliffs and then submerging them as sea level continued to rise. Were it not for the relatively quick submergence of the stacks, they likely would have continued to erode at a similar rate as seen with the modern sea stacks until they collapsed.

LITERATURE CITED


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CHAPTER 3

The Evolution of Sea Cliffs Over Multiple Eustatic Cycles in High Energy, Temperate Environments
3.1 Introduction

Sea cliffs are steep coast features with slopes greater than 20° that are formed in bedrock or clay by erosive forces at the land-water interface, especially in areas of high relief (Inman and Nordstrom, 1971; Emery and Kuhn, 1982; Hampton and Griggs, 2004). The cross-sectional morphology of cliffs is commonly subdivided into a steep scarp that has talus and other debris deposited at the base (Hooke, 1999; Lim, 2014). The shape and rate of erosion of sea cliffs is primarily determined by the geology in which they are formed (Trenhaile, 1987; Lim, 2014; Naylor and Stephenson, 2010). In general, the more resistant the lithology, the lower the rates of erosion and the greater the potential elevation of the cliff (Griggs and Trenhaile, 1994). For example, in southern Italy, an inverse relationship was found to occur between coastal cliff erosion and compressive strength (Budetta, et al., 2000). However, erosion is not always a steady, continuous process but rather can result from episodic failures (Lee, et al., 2001). This poses a difficulty in the study of sea cliffs in that there is often a mismatch in the temporal scale of observed events and that of landform evolution (Kennedy, et al., 2017).

Marine and terrestrial climates are an important determinate of the erosive forces acting on the coast (Griggs and Trenhaile, 1994; Trenhaile, 2001). All contemporary cliffs are to some degree influenced by subaerial weathering processes, such as wind and rain (Lee and Clark, 2002; Hutchinson, 1973), water runoff (Morgan, 1986), bioerosion (Naylor and Viles, 2002), chemical weathering, and groundwater seepage (Griggs and Savoy, 1985). Any section of a cliff that sits close to sea level is also impacted by marine processes through tidally-modulated wave action. Marine processes both remove fallen debris as well as directly erode the cliff edifice (Hills, 1971). In addition, direct wave impact also transfers energy from the waves to the cliff, which can weaken the rock face through microseisms (Lollino, et al., 2008; Norman, et al., 2013; Young, et al., 2013, Kennedy, et al., 2018). As a result, sea cliffs are generally classified as either being dominated by subaerial or marine erosional processes (Emery and Khun, 1982; Kennedy and Dickson 2007).

As the evolution of sea cliffs is closely linked to sea level (Pluet and Pirazzoli, 1991; Woodroffe and Murray-Wallace, 2012), their base is often used to reconstruct past eustatic cycles. The accuracy of such reconstructions is dependent on the proxy used, but can reach decimeter scale, especially when using features such as notches (Pirazzoli, 1986; Kershaw and Guo, 2001; Sisma-Ventura, et al., 2017; Trenhaile, 2015). While this is not as accurate or precise as scleractinian coral proxies found in tropical settings (Siddal, et al., 2003; Woodroffe and Wallace, 2012; Woodroffe and Webster, 2014), sea cliff evolution can span multiple eustatic cycles and can occur in temperate erosive environments which may not favour depositional proxies. Thus, they are often used for identifying lower sea levels from bathymetric data (Kennedy, et al., 2002; Sivkov, et al., 2011; Westley, et al., 2011; Niedzielski, et al., 2013; Cawthra, et al., 2016; Brooke, et al., 2017).

Investigations of the precise morphology of sea cliffs found at lower sea levels are, however, lacking. While the link between coastal geomorphology and sea-level variations has been well known for decades, the reliability of sea cliffs as sea level proxies has not been quantifiably tested. This study, therefore, sets out to test the utility of sea cliffs as sea level proxies both at present and past lower elevations by quantifying the morphology of sea cliffs formed along the coast of Victoria, Australia from modern sea level to over 50 m depth.
3.2 Regional Setting

Victoria is located in south-eastern Australia between 38º - 39ºS and 141º - 147ºE (Figure 3.1). The coast is classified as a Mediterranean climate, having wet winters with average minimum temperatures between 12 - 15º C and dry summers with average maximum temperatures between 24 - 27º C (Bureau of Meteorology, 2017). Waves with a mean average height of 2 - 3 m impact the southern margins (Flocard, et al., 2016), while the eastern section of coast has an average height of 2 m. Winter swells reaching 8 m at Wilsons Promontory have been measured (Hemer, et al., 2007). Spring tidal range varies from 0.9 - 1.6 m (Bureau of Meteorology, 2017).

The coast is divided into five lithological regions, the first being Peterborough to Wattle Hill (Port Campbell region), where the primary units are mid-Miocene Port Campbell Limestone and overlying Pleistocene Bridgewater Formation (Birch, 2003). From Wattle Hill to Geelong (Otway region), siltstones of the mid-Eocene Demon’s Bluff Formation are found, as well as Oligocene marine carbonates of the Torquay Group between Airey’s Inlet and Torquay (Birch, 2003). From Cape Schanck to Phillip Island (Phillip Island region), Eocene Mornington Peninsula Volcanic Group, Devonian Woolamai Granite, and early Cretaceous Wonthaggi sandstone formation are dominant (Higgins, 2011). Wonthaggi to Inverloch (Cape Paterson region) is dominated by early Cretaceous Wonthaggi and Eumeralla Formations. From Sandy Point to Port Welshpool (Wisons Promontory region), granite is the predominant bedrock type, intruded into tightly folded Ordovician shales and sandstones (Hill and Joyce, 1995) (Figure 3.1).

The Victorian coast is considered to be broadly tectonically stable for reconstruction of sea level during the late Pleistocene and Holocene (Bryant, 1992). Recent evidence suggests that intraplate stress during the Neogene to present has led to localised deformation around some faults on the order 0.01 - 0.04 mm/a in central eastern Victoria such as at Cape Liptrap (Gardner, et al., 2009). Such movements appear confined to the immediate vicinity of the particular fault and therefore are assumed not to impact regional geomorphology of 100-km scales for this study.

Figure 3.1 The coast of Victoria in southeast Australia, showing the study extent from Warrnambool to Wilsons Promontory.
Chapter 3. The Evolution of Sea Cliffs Over Multiple Eustatic Cycles in High Energy Temperate Environments

3.3 Methods

Bathymetric and terrestrial LiDAR data were collected using a LADS Mk II system with a GEC-Marconi FIN3110 intertidal motion sensing system and a dual frequency kinematic geographic positioning system (kGPS). The resulting dataset includes seamless terrestrial-marine mosaics from elevations of +10 m to depths of -25 m (Quadros and Rigby, 2010). Multibeam sonar data were acquired using a Reson Seabat 101 multibeam sonar (Ierodiaconou, et al., 2007) and a Kongsberg EM2040C (Schimel, et al., 2015). Positioning was accomplished using a real-time differential GPS integrated with a positioning and orientation system for marine vessels (POS MV) for dynamic heave, pitch, roll and yaw corrections (± 0.1° accuracy). The final raster grid of the data has a 5 m horizontal resolution providing full coverage that captures the coastal terrain to depths of 80 m. The data were analyzed using the geographic information system software ArcGIS (v.10.3.1).

Areas along the modern coast with a slope > 20º were classified as cliffs following Hampton and Griggs (2004), and topographic profiles were spaced every 100 - 500 m. For smaller sections of cliffs (c. 3 km long), profiles were taken at shorter intervals (100 m) in order to quantify local variation and provide a statistically similar sample set for each section. From these topographic profiles, cliff height was measured as the vertical distance between the break in slope at the top of the cliff (where the near horizontal portion of the rock meets the rock face with an angle > 20º) and the break in slope at the base where the rock surface once again becomes < 20º (Figure 3.2). Each profile was subdivided into thirds for analysis of vertical variations (Figure 3.2). Statistical analysis was conducted in the Minitab 17 statistical software, using Tukey pairwise comparisons and ANOVA tests.

To classify submerged paleo-cliffs, the bathymetric elevation and slope data were used to identify areas of high relief (> 1.5 m) and high slope (> 20º). Backscatter data were then used to differentiate between rock and sediment. Since the submerged cliffs were much smaller than the onshore cliffs, the slope raster dataset was clipped and converted to slope point data, from which topographic cross-sections were extracted.

In the field, 300 rock hardness measurements were taken across the faces of cliffs of different lithologies in each of the five study areas using an L-type Schmidt Hammer in accordance with the recommendations of Goudie (2006). All surfaces were prepared with a carborundum wheel prior to testing, and a minimum of ten readings were taken at each site. Data were subsequently corrected for instances where the hammer was held away from the horizontal (Day, 1977), and anomalously low values were rejected on the basis of Chauvenet’s criterion for removing spurious data (Göktan and Ayday, 1993).

Figure 3.2 Example of cliff profile components used for individual measurements with example of dividing a cliff profile into thirds in order to take the slope of each section.
3.4 Results

3.4a Modern Coast

A total of 261 km of cliffs were identified and analysed across all five regions. Cliff height ranged from 3.9 to 152.5 m with an average of 27.4 +/- 17.7 m (Tables 3.1-3.5). The mudstone cliffs had the greatest mean heights, at 54.9 +/- 16.5 m. The granites had the largest range of heights, from 15.7 to 92.5 m, but the lowest cliffs overall with an average height of 18.5 +/- 8.0 m (Figure 3.3a). The Port Campbell Limestone (measured at Gibson Steps) showed the lowest rebound (r) values varying between 10 and 24 with an average of 17 (Table 3.6). When grouped by broad geology rather than specific named units, the granites had the highest average rebound value at 44, followed by the sandstones and mudstones averaging at 29, and the limestones having the lowest average at 17 (Figure 3c).

For the slope of the entire cliff face, gentler slopes (< 30º) were generally associated with harder rocks (e.g. granites), while the softer rock types (e.g. Cape Otway limestones) tended to have a higher mean slope (53.0 +/- 8.23º) (Figure 3.3b). However, there was no significant correlation found between cliff height and cliff slope (Figure 3.3e). The slope of the uppermost section of the cliffs tended to be the lowest with an average of 26.5 +/- 13.5º. The middle sections had the highest slopes (44.5 +/- 17.6º), while the bottom had a mean of 38.0 +/- 17.3º (Figure 3.3f). When grouped by lithology, the cliff tops were generally more gently sloping for all lithologies, with the highest found in the sandstones and mudstones (36.5 +/- 7.7º) and the lowest cliff top slopes being found in granites (13.9 +/- 6.4º). As for the middle of the cliff, the highest slopes were found in the limestone (69.1 +/- 15.8º) and the lowest in the granites (25.3 +/- 11.4º).

The morphology of the cliff toe on the extant coast often terminated on exposed bedrock shore platforms (21% of profiles), while others were buried by beaches, and some plunged below sea level. Shore platforms were found fronting the majority of cliffs comprised of sandstone, mudstone, and limestone. Platforms were generally absent for cliffs comprised of granite which often plunged below current sea level (Kennedy, et al., 2014). The sandstones and mudstones had the highest percentage of platforms present in front of the cliff profiles studied, at nearly 70%. The mean toe elevation for cliffs fronted by platforms ranged from +0.68 m for limestone cliffs to +2.36 m for sandstones and mudstones. For cliffs without platforms, granitic cliffs had the lowest base elevations at 0.64 m, while sandstone and mudstones terminated at a mean elevation of 2.01 m (Figure 3.3d).
Figure 3.3 Boxplots of (A) cliff height for all onshore cliff faces from top to toe, (B) cliff slope from top to toe, (C) rock hardness as tested with a Schmidt hammer as a proxy for compressive strength, (D) the elevation at the base of the cliff in relation to sea level, all with respect to main geologic type, (E) a scatterplot showing the relationship between cliff slope and cliff height, and (F) the slope variations between each section of each cliff face when divided into thirds vertically.
3.4b Submerged Coast

Submerged sea cliffs with slopes greater than 20° were present offshore of Discovery Bay, Port Campbell, and Wongarra (Figure 3.4) and were more gently sloping when compared to the onshore cliffs. The submerged cliffs were located an average of 4.1 km from the modern coastline, and the average depth for the base was -49.2 +/- 7.6 m. The mean slope for the submerged cliffs in all three localities was 31.3 +/- 8.9°, while the mean height was 7.4 +/- 3.8 m.

In Discovery Bay, the submerged cliff was 1.96 km from the modern coast and was the tallest of the submerged cliffs, with an average height of 15.1 +/- 3.4 m. The mean slope for this cliff was 32.5 +/- 9.5°, and the mean depth at its toe was -54.0 +/- 3.2 m. The onshore lithology for this region was primarily Bridgewater Formation (Higgins, 2011), and as the submerged cliff had a similar curvature and shape to the current coast in this section, it is interpreted to be composed of Bridgewater Formation as well.

The Port Campbell area contained three sets of submerged cliffs averaging 6.2 +/- 2.7 m in height. The toe of these cliffs averaged -48.4 +/- 8.8 m in depth. However, the set of cliffs closest to shore had a minimum depth of -26.5 m, while the cliffs farthest from the onshore shoreline had a maximum depth of -62.7 m. The mean slope of the submerged cliffs was 26.3 +/- 5.6°. Those cliffs found an average of 4.3 km offshore of the Peterborough region were also fronted by submerged sea stacks that sit between 50 to 60 m below present sea level (Bezore et al., 2016). The submerged cliffs on the west averaged a distance of 4.3 km offshore and those to the east were 5.0 km offshore.

Offshore of Wongarra, a submerged cliff comprised of Eumeralla Formation Sandstone was orientated parallel to the coast. The mean depth of the toe was -50.1 +/- 2.2 m, with a mean height of 8.5 +/- 3.8 m. The slope of the paleo-cliff averaged 21.4 +/- 1.4°, making it the lowest sloping cliff found offshore in this study.

As with the onshore cliffs, a Tukey pairwise comparison was conducted, the results of which showed three distinct groups with regards to lithology and slope. An ANOVA one-way analysis also showed a statistically significant difference between the slopes of the three sets of submerged cliffs based on their geology, with a P-value of 0.000 and an R-squared value of 31% (Tables 3.7 - 3.8)
Chapter 3. The Evolution of Sea Cliffs Over Multiple Eustatic Cycles in High Energy, Temperate Environments

3.5 Discussion

3.5a Cliff Morphology

The morphology of a cliff is controlled by the geological constraints (e.g. bedding, jointing, thickness, and compressive strength) that act either to enhance its strength and allow it to maintain a more vertical profile or to weaken its integrity and limit its height (Stephenson and Naylor, 2011). For example, the Port Campbell Limestone in Victoria is a large homogenous unit with horizontal layering. This allows for cliffs to be eroded by wave activity at the base while still having the compressive strength to maintain a vertical structure. The limestone is relatively soft (average $r = 17$) and erodes at a rate of 22 mm/yr (Bezore, et al., 2016), which means the cliffs maintain a relatively vertical profile as they retreat. However, the cliffs at Cape Paterson are also steep for the region with slopes averaging at 47.2° but had an average height 14 m lower than the limestone cliffs. In this case, the bedding of the Wonthaggi Formation at Cape Paterson dips north-west at 25 - 35°, which is broadly parallel to the orientation of the shoreline (Birch, 2003). This means that as the cliffs are exposed to erosional
forces, there is a higher chance that large blocks will be eroded through mass wasting, as evidenced by the boulders at the base of the cliffs (Hills, 1971). Another example is structural control of joint orientation within granites. Exfoliation joints orientated parallel to the granite dome appear to control the morphology in this study. The granitic cliffs had generally had lower, more plunging base elevations compared to the other lithologies. The lack of erosive features at lower sea levels attests to the 100,000 year scale of evolution for this lithology (Kennedy, et al., 2014). Thus, bedding and structural features, in addition to compressive strength, act as boundary conditions on cliff height (Trenhaile, 1987).

The presence of cliffs both on and offshore indicates the Victorian coast has been subject to similar erosional processes over multiple eustatic cycles. Submerged cliffs were discernibly high elevation topographic features in an otherwise low-relief environment and were assumed to be the same lithology as the extant coast based on established unit thickness (Krassay, et al., 2004; Boutakoff, 1963; Geological Survey of Victoria, 2001; Nicolaides, 1997). The submerged cliffs were more gently sloping and up to an order of magnitude shorter than those onshore. As the onshore and submerged cliffs were all found on an open coast exposed to Southern Ocean swell (McInnes, et al., 2016), the difference in morphology can be attributed to the erosional histories related to sea level fluctuations (Figure 3.5).

During the first stage of development, cliffs were carved into the landscape during a stillstand when marine erosive processes were stable for a sufficient period to truncate the exposed geology. These cliffs would appear similar to those seen on the modern coast. Subsequent climatic cooling and sea level regression stranded the cliffs above wave attack and exposed them exclusively to subaerial processes. This lead to accumulation of talus at the base of the cliffs. This stage of evolution would produce cliff profiles similar to those seen on the modern coast where wide beaches exist in front of cliffs, protecting them from waves and exposing them to primarily subaerial processes. The next stage would occur during a transgression, when sea level returned to elevations equal to when the cliffs first formed, returning them to the influence of marine processes. The initial cliffs would no longer be as vertical or have clearly defined slope breaks due to the period of subaerial exposure. Marine processes then acted to increase the slope as material was eroded. If sea level continued to rise, marine processes would then able to progressively erode higher on the cliff face with rates increasing as marine process acted on surfaces that have been subaerially exposed for longer periods of time. If sea level continued to rise further and the landform became submerged, material would still be removed at top of the cliffs while they remained under the wave base, although at lower rates than when the face was within the surf zone. As sea level rose higher still, cliffs would then be preserved once they were removed from the action of waves. As glacial climatic conditions returned, sea level would fall again, and the cycle would repeat (Figure 3.5). In Victoria, the rates of marine truncation were likely higher than observed on the modern coast, as the continental shelf would be narrower than today, allowing more wave energy to reach the shoreline (Shemdin, et al., 1980; Herbers, et al., 2000).
Figure 3.5 Diagram showing proposed process of cliff evolution progressing from cliffs being formed through marine and subaerial erosion during a sea level stillstand (A), to the cliffs being primarily controlled by subaerial processes as sea level falls (B), to cliffs being subjected to primarily marine erosion as sea levels quickly rise (C), to cliffs being submerged by high sea levels and no longer being exposed to erosion (D).

3.5b Using paleo shorelines as proxies for past sea levels

Unlike contemporary landforms, which have formed while sea level has been relatively constant, cliffs found submerged at depth have experienced alternating marine and subaerial processes across their entire face over multiple sea level cycles. In fact, numerical modelling using temporal scaling frameworks has suggested that the shift in process dominance, as determined by the rate of sea level rise, is more important than the magnitude of vertical movement in preserving landforms on continental shelves (Ashton, et al., 2011). Thus, the morphology of drowned cliffs is likely not as precise as their modern counterparts in constraining sea level elevation.

All the modern cliffs measured in this study had cliff toe elevations between -2.3 and 6.8 m relative to mean sea level. For the submerged cliffs, two groups occurred between -45.8 m and -62.7 m, and from -26.5 to -30.0 m. Thus, the modern coastal features act as a better proxy for sea level, given a variation of 4.5 m, compared to the maximum range of nearly 17 m for the cliff toe depths between 45 and 63 m depth. The cliffs found between 25 and 30 m depth, though, have a smaller variation of 3.5 m. The highest of the cliff toe elevations were primarily found in sandstone and mudstone lithologies, which may be attributed to the softer and more easily eroded nature of those rock types. Talus from in these softer rock types often obscures the base of the bedrock cliff in a topographic profile. In such cases, the cliffs have two effective bases, one at the talus-cliff face intersection and one at the talus-beach intersection. Slumping can also obscure paleo-shoreline features from previous sea level highstands during which sea level was higher than today. In this case, relict sea cliffs may be hard to differentiate from vegetated talus. The majority of the base elevations for the softer lithologies were either plunging or truncated by shore platforms at sea level. Cliffs without shore platforms, however, are the most accurate indicators of modern sea level, as platforms
Chapter 3. The Evolution of Sea Cliffs Over Multiple Eustatic Cycles in High Energy, Temperate Environments

may also be inherited features from previous sea levels and therefore not valid for defining modern sea level (Trenhaile, et al., 1999; Trenhaile, 2001).

The accuracy of the drowned cliff toe is further complicated by the fact that the observed elevation today may be influenced by many eustatic cycles, rather than just a single stillstand. The potential variation in elevation may therefore also be a function of depth, as the deeper the profile the more eustatic cycles that may have influenced land formation. This could explain the different margin of error between the -50 m paleo-shoreline (16.9 m) and the -30 paleo-shoreline (3.5 m) (Figure 3.6).

Figure 3.6 (A) Map of Victoria from Port Campbell to Lorne, showing the location of the -30 m and -50 m depth contours and how closely they match the paleo-shorelines including the submerged cliffs. (B) Reconstructed sea level curve (Grant et al., 2014) for the past 250 thousand years with the base depths for submerged cliffs. This curve was created through analysis of the U/Th-dated speleothem δ¹⁸O record for the Red Sea.

If the maximum variation in elevation is assumed (16.9 m) for the submerged cliffs, this means that two distinct paleo-shorelines occur in Victoria, at 30 and 50 m below present. While the ages of these paleo-shorelines was not dated as part of this this project, we can infer their timing of formation from established global eustatic curves (Bloom and Yonekura, 1990; Voris, 2000; Grant, et al., 2014). At -50 m, an interstadial occurred at 70 – 80 ka, and at both 50 and 170 ka interstadials were -80 and -70 m lower than present, all of which are within the error bands of our proxy. The morphology of the cliffs suggests multiple periods of exposure of these features, so it is most likely that these landforms date back to at least 170 ka. Highstands at 130-110 ka, 100 ka, and 80 ka were likely responsible for the primary evolution of the -30 m shoreline.

3.6 Conclusions

Sea cliffs are erosional features that are constantly exposed to weathering processes both from the sea and the atmosphere. This study provides quantitative evidence that the morphology and erosional patterns of cliffs depends heavily on their lithologic characteristics. Cliffs with the higher
slopes tended to be the taller cliffs, which can be attributed to softer, more easily eroded rock types. Cliffs composed of rocks such as Port Campbell Limestone were easily eroded by waves but possessed enough compressive strength to maintain the weight of the overlying cliff material above the base to erode without constant mass erosion at the top, allowing fast eroding, tall cliffs to form. On the other hand, the harder the rock type, such as the granitic cliffs studied, the lower the slope, due to the much higher resistance to erosion and much slower rate of chemical weathering taking place on the surface of these cliffs.

While the cliffs at modern sea level in Victoria have been formed and shaped through erosive processes over the past 7,000 years, the submerged cliffs found offshore indicate that this coastline has been an erosive zone over multiple eustatic cycles. Using the base of onshore cliffs as a sea level proxy can provide information as to the sea level when the cliffs formed within +/- 4.5 m, making this method a more useful constraint on paleo-sea level than submerged cliffs, which give a more variable range of base depths at 16.9 m. Much like how the cliffs found at modern sea level were formed, the submerged cliffs were also shaped through wave and subaerial erosion when sea level was roughly 50 m below modern levels. After their initial formation at sea level, these paleo-cliffs were then stranded above sea level for thousands of years, exposed to primarily subaerial processes that influenced their shape and size, making what may have once been vertical cliffs transform to more rounded, slumped morphologies. Then, as sea level began to rise, it rose at such rapid rates that rather than wave erosion having enough time to greatly impact the cliff shapes again, the rising waters submerged and preserved the cliffs with their slumped and gently sloping forms intact.

3.7 Acknowledgements

We thank Parks Victoria for funding the capture of the multibeam sonar data used in this study. We thank members of the crew Sean Blake and Dr Alex Rattray of Deakin University’s research vessel Yolla for assistance in the collection of the multibeam sonar data. We thank the Department of Environment and Primary Industries Department of Environment and Primary Industries coordinated imagery program for access to the georegistered aerial photography and the Future Coasts Program for access to the LiDAR data. We thank Ian Atkinson from Geoscience Australia and Nicole Bergersen from Acoustic Imaging Pty Ltd for technical support provided during MBES data capture and analysis. Rhiannon Bezore was supported by the Melbourne International Research Scholarship from The University of Melbourne. Thank you as well to Peter Clark for assisting in cartography.
### Table 3.1 Cliff height measurements for all onshore cliffs with respect to geology

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Mean Cliff Height (m)</th>
<th>Maxi mum Cliff Height (m)</th>
<th>Minimum Cliff Height (m)</th>
<th>Standard Deviation (σ)</th>
<th>Mean Elevation at base of cliff (m)</th>
<th>Maximum Elevation at base of cliff (m)</th>
<th>Minimum Elevation at base of cliff (m)</th>
<th>Standard Deviation (σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridgewater Formation</td>
<td>28.40</td>
<td>72.70</td>
<td>3.91</td>
<td>19.11</td>
<td>2.66</td>
<td>6.10</td>
<td>-1.46</td>
<td>1.54</td>
</tr>
<tr>
<td>Demon’s Bluff</td>
<td>28.17</td>
<td>88.80</td>
<td>6.07</td>
<td>17.47</td>
<td>2.42</td>
<td>6.17</td>
<td>-0.09</td>
<td>1.42</td>
</tr>
<tr>
<td>Eumeralla Formation</td>
<td>24.48</td>
<td>152.45</td>
<td>4.50</td>
<td>22.09</td>
<td>2.27</td>
<td>5.78</td>
<td>-0.76</td>
<td>1.19</td>
</tr>
<tr>
<td>Lilly Pilly Granite</td>
<td>19.88</td>
<td>37.03</td>
<td>10.54</td>
<td>6.14</td>
<td>-0.08</td>
<td>1.87</td>
<td>-0.92</td>
<td>0.71</td>
</tr>
<tr>
<td>Mount Norgate Granite</td>
<td>28.61</td>
<td>50.37</td>
<td>6.23</td>
<td>10.97</td>
<td>1.87</td>
<td>5.81</td>
<td>-1.51</td>
<td>2.07</td>
</tr>
<tr>
<td>Mount Singapore Granite</td>
<td>18.52</td>
<td>26.78</td>
<td>10.72</td>
<td>8.04</td>
<td>0.35</td>
<td>1.43</td>
<td>-0.75</td>
<td>1.09</td>
</tr>
<tr>
<td>Pebble Point Formation</td>
<td>38.60</td>
<td>61.99</td>
<td>24.74</td>
<td>20.37</td>
<td>2.55</td>
<td>4.18</td>
<td>0.45</td>
<td>1.91</td>
</tr>
<tr>
<td>Pember Mudstone</td>
<td>54.86</td>
<td>84.21</td>
<td>31.05</td>
<td>16.47</td>
<td>2.24</td>
<td>4.28</td>
<td>0.99</td>
<td>1.50</td>
</tr>
<tr>
<td>Port Campbell Limestone</td>
<td>36.32</td>
<td>68.81</td>
<td>9.81</td>
<td>15.00</td>
<td>1.72</td>
<td>6.36</td>
<td>-0.65</td>
<td>2.00</td>
</tr>
<tr>
<td>Sealers Cove Granite</td>
<td>25.33</td>
<td>41.09</td>
<td>13.81</td>
<td>8.88</td>
<td>0.64</td>
<td>5.72</td>
<td>-0.81</td>
<td>1.47</td>
</tr>
<tr>
<td>Torquay Group</td>
<td>24.09</td>
<td>42.15</td>
<td>7.67</td>
<td>10.63</td>
<td>2.18</td>
<td>4.59</td>
<td>0.12</td>
<td>1.24</td>
</tr>
<tr>
<td>Vereker Granite</td>
<td>29.84</td>
<td>51.20</td>
<td>13.95</td>
<td>10.37</td>
<td>0.85</td>
<td>4.56</td>
<td>-1.54</td>
<td>1.52</td>
</tr>
<tr>
<td>Wilsons Prom Granite</td>
<td>24.47</td>
<td>37.98</td>
<td>15.89</td>
<td>5.52</td>
<td>1.40</td>
<td>4.56</td>
<td>-2.26</td>
<td>1.83</td>
</tr>
<tr>
<td>Wongthaggi Formation</td>
<td>22.60</td>
<td>56.88</td>
<td>4.14</td>
<td>12.52</td>
<td>3.07</td>
<td>6.82</td>
<td>0.02</td>
<td>1.43</td>
</tr>
<tr>
<td>Woolamai Granite</td>
<td>53.48</td>
<td>92.47</td>
<td>15.67</td>
<td>27.30</td>
<td>2.98</td>
<td>5.74</td>
<td>0.26</td>
<td>2.01</td>
</tr>
</tbody>
</table>
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Table 3.2 Mean elevations of cliff slopes

<table>
<thead>
<tr>
<th>Lithologic Unit</th>
<th>Mean slope of entire cliff face (°)</th>
<th>Standard deviation</th>
<th>Minimum slope of entire cliff face (°)</th>
<th>Maximum slope of entire cliff face (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone or Mudstone</td>
<td>37.19</td>
<td>17.11</td>
<td>5.72</td>
<td>86.04</td>
</tr>
<tr>
<td>Limestone</td>
<td>52.99</td>
<td>8.23</td>
<td>6.54</td>
<td>86.85</td>
</tr>
<tr>
<td>Granite</td>
<td>28.15</td>
<td>7.12</td>
<td>6.76</td>
<td>71.87</td>
</tr>
</tbody>
</table>

Table 3.3 Mean elevations of cliff bases for both cliffs fronted by shore platforms as well as those not fronted by platforms.

<table>
<thead>
<tr>
<th>Lithologic Unit</th>
<th>Mean elevation at base of cliffs with platforms (m)</th>
<th>Standard deviation</th>
<th>Minimum elevation at base of cliffs with platforms (m)</th>
<th>Maximum elevation at base of cliffs without platforms (m)</th>
<th>Mean elevation at base of cliffs without platforms (m)</th>
<th>Standard deviation</th>
<th>Minimum elevation at base of cliffs without platforms (m)</th>
<th>Maximum elevation at base of cliffs without platforms (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone or Mudstone</td>
<td>2.36</td>
<td>0.96</td>
<td>-0.097</td>
<td>3.96</td>
<td>2.01</td>
<td>0.94</td>
<td>-0.76</td>
<td>3.99</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.68</td>
<td>1.14</td>
<td>-0.098</td>
<td>1.99</td>
<td>0.88</td>
<td>1.13</td>
<td>-0.65</td>
<td>3.12</td>
</tr>
<tr>
<td>Granite</td>
<td>1.85</td>
<td>1.04</td>
<td>0.26</td>
<td>3.45</td>
<td>0.642</td>
<td>1.53</td>
<td>-2.26</td>
<td>3.99</td>
</tr>
</tbody>
</table>

Table 3.4 One-way ANOVA with Tukey Pairwise Comparison analysis of onshore cliff slopes for the entire face of the cliff using the following conditions:
Null hypothesis: All means are equal
Alternative hypothesis: At least one mean is different

<table>
<thead>
<tr>
<th>Factor</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>95% CI</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone</td>
<td>141</td>
<td>52.99</td>
<td>23.20</td>
<td>(50.24, 38.17)</td>
<td>A</td>
</tr>
<tr>
<td>Sandstone or Mudstone</td>
<td>1113</td>
<td>37.19</td>
<td>17.11</td>
<td>(36.21, 38.17)</td>
<td>B</td>
</tr>
<tr>
<td>Granite</td>
<td>393</td>
<td>28.15</td>
<td>11.99</td>
<td>(26.50, 29.80)</td>
<td>C</td>
</tr>
<tr>
<td>Basalt</td>
<td>3</td>
<td>17.58</td>
<td>10.14</td>
<td>(-1.30, 36.46)</td>
<td>B, C</td>
</tr>
</tbody>
</table>

Significance level: \( \alpha = 0.05 \)

Equal variances were assumed for the analysis.

<table>
<thead>
<tr>
<th>S</th>
<th>R-sq</th>
<th>R-sq(adj)</th>
<th>R-sq(pred)</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.67</td>
<td>12.82%</td>
<td>12.66%</td>
<td>12.40%</td>
<td>80.70</td>
<td>0.000</td>
</tr>
</tbody>
</table>
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Table 3.5 One-way ANOVA with Tukey Pairwise Comparison analysis of onshore cliff slopes when segmented into thirds using the following conditions:
Null hypothesis: All means are equal
Alternative hypothesis: At least one mean is different
Significance level: $\alpha = 0.05$

<table>
<thead>
<tr>
<th>Factor</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>95% CI</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top 1/3</td>
<td>550</td>
<td>26.52</td>
<td>13.46</td>
<td>(25.16, 27.88)</td>
<td>A</td>
</tr>
<tr>
<td>Mid 1/3</td>
<td>550</td>
<td>44.51</td>
<td>17.60</td>
<td>(43.15, 45.87)</td>
<td>B</td>
</tr>
<tr>
<td>Bottom 1/3</td>
<td>550</td>
<td>38.03</td>
<td>17.29</td>
<td>(36.67, 39.39)</td>
<td>C</td>
</tr>
</tbody>
</table>

Equal variances were assumed for the analysis.

<table>
<thead>
<tr>
<th>S</th>
<th>R-sq</th>
<th>R-sq(adj)</th>
<th>R-sq(pred)</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.23</td>
<td>17.40%</td>
<td>17.29%</td>
<td>17.09%</td>
<td>173.42</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Table 3.6 Schmidt hammer readings using compressive strength as a proxy for rock hardness. Readings were collected in the field and later corrected for hammer angle.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Mean Schmidt Hammer Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridgewater Formation</td>
<td>30.67</td>
</tr>
<tr>
<td>Demons Bluff</td>
<td>22.00</td>
</tr>
<tr>
<td>Eumeralla Formation</td>
<td>33.25</td>
</tr>
<tr>
<td>Mornington Volcanic Group</td>
<td>47.50</td>
</tr>
<tr>
<td>Newer Volcanics</td>
<td>27.20</td>
</tr>
<tr>
<td>Port Campbell Limestone</td>
<td>17.00</td>
</tr>
<tr>
<td>Wonthaggi Formation</td>
<td>30.14</td>
</tr>
<tr>
<td>Yanakie Granite</td>
<td>43.67</td>
</tr>
</tbody>
</table>
Table 3.7 Mean characteristics of submerged cliffs.

<table>
<thead>
<tr>
<th>Location</th>
<th>Geologic Unit</th>
<th>Mean Height (m)</th>
<th>σ</th>
<th>Maximum Height (m)</th>
<th>Minimum Height (m)</th>
<th>Mean Depth at base of cliff (m)</th>
<th>σ</th>
<th>Maximum depth at base of cliff (m)</th>
<th>Minimum depth at base of cliff (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discovery Bay</td>
<td>Bridgewater Formation</td>
<td>15.13</td>
<td>3.41</td>
<td>18.82</td>
<td>9.65</td>
<td>-54.01</td>
<td>3.23</td>
<td>-56.93</td>
<td>-49.16</td>
</tr>
<tr>
<td>Port Campbell</td>
<td>Port Campbell Limestone</td>
<td>6.21</td>
<td>2.65</td>
<td>12.39</td>
<td>1.53</td>
<td>-48.37</td>
<td>8.82</td>
<td>-62.73</td>
<td>-26.51</td>
</tr>
<tr>
<td>Wongarra</td>
<td>Eumeralla Formation</td>
<td>8.45</td>
<td>3.76</td>
<td>14.57</td>
<td>3.89</td>
<td>-50.15</td>
<td>2.20</td>
<td>-52.75</td>
<td>-45.78</td>
</tr>
</tbody>
</table>

Table 3.8 One-way ANOVA analysis with Tukey Pairwise Comparison of offshore cliff slopes using the following conditions:

- Null hypothesis: All means are equal
- Alternative hypothesis: At least one mean is different
- Significance level: $\alpha = 0.05$
- Equal variances were assumed for the analysis.

<table>
<thead>
<tr>
<th>Factor</th>
<th>N</th>
<th>Mean</th>
<th>StDev</th>
<th>95% CI</th>
<th>Grouping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Campbell Limestone</td>
<td>9292</td>
<td>26.34</td>
<td>5.61</td>
<td>(26.21, 26.47)</td>
<td>A</td>
</tr>
<tr>
<td>Eumeralla Formation</td>
<td>9292</td>
<td>21.44</td>
<td>0.07</td>
<td>(21.31, 21.56)</td>
<td>B</td>
</tr>
<tr>
<td>Bridgewater Formation</td>
<td>9292</td>
<td>31.71</td>
<td>9.28</td>
<td>(31.58, 31.84)</td>
<td>C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S</th>
<th>R-sq</th>
<th>R-sq(adj)</th>
<th>R-sq(pred)</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.26</td>
<td>31.00%</td>
<td>30.99%</td>
<td>30.98%</td>
<td>6261.04</td>
<td>0.000</td>
</tr>
</tbody>
</table>
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3.9 References


Boutakoff, N., 1963. The geology and geomorphology of the Portland area (No. 22). Department of Mines.


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CHAPTER 4

The Utility of Shore Platforms as Sea-Level Proxies in Microtidal, Temperate Environments
4.1 Introduction

Contemporary shore platforms are inter- to supratidal features found in rocky coast environments that develop through subaerial and marine erosion of sea cliffs (Trenhaile, 1987; Stephenson and Kirk, 2000a). Marine processes act to physically erode the rock surface, and also remove material already weakened by weathering (Matsumoto, et al., 2017; Matsumoto, et al., 2018). Wetting and drying cycles within the intertidal zone, combined with the presence of salt, mean downwearing rates are greatest in the high intertidal zone, decreasing rapidly towards low tide elevations (Stephenson and Kirk, 2000a; Kanaya and Trenhaile 2005). In microtidal environments this commonly results in semi-horizontal shore platforms (Stephenson, et al., 2013; Trenhaile, et al., 2015). Therefore, as erosive processes are greatest in the intertidal zone, shore platforms are often closely related to elevation of high and low tide and therefore mean sea level. This means they are important proxies for determining past sea level (e.g. Tasman Sea, Australia (Woodroffe, et al., 1995); Sicily, Italy (Scicchitano, et al., 2011), Lesvos Island, Greece (Vacchi, et al., 2012), Mexico (Trenhaile, et al., 2015), Red Sea (Inglis et al., 2019) Bahamas (Skrivanek and Dutton, 2018), and Scotland (Smith, et al., 2018).

Reconstructions of past higher sea levels have often used the cliff-platform junction or the mean elevation of the semi-horizontal surface as the height proxy. For instance, one study in Italy used marine terraces and wave-cut notches as indicators of the Marine Isotope Stage (MIS) 5.5 highstand (Ferranti, et al., 2006). In a review of global MIS 5 proxies, it was noted that the lower elevation limit for a shore platform in regards to sea level should be taken as the midpoint between mean higher high water and the breaking depth of significant waves (Rovere, et al., 2016). Another example are wave-cut notches in Central Greece that were used in conjunction with uplift rates to date the relative sea level at the time of their formation to roughly 6,000 years ago (Kershaw and Guo, 2001). In such cases there is often a contemporary surface from which comparisons can be made to extant sea level.

Over Quaternary timescales of landform evolution, shore platforms trend toward either an equilibrium state (Dickson, et al., 2013) whereby the entire platform surface migrates landward due to wave erosion (Trenhaile, 1974) or toward a static state in which the location of the seaward edge holds steady while cliff erosion continues, gradually increasing the platform width (Sunamura, 1983; Trenhaile, 2001). Numerical modelling suggests platforms tend to be narrower and steeper during glacial periods and wider with a gentler slope during interglacials (Trenhaile, 2001). It was also found that a reduction in slope gradients seaward on the slope will gradually affect the higher elevations on the erosional profile (Chao, et al., 2003). Many platforms are at least partially inherited from past interglacial cycles when sea level was close to present level (Trenhaile, 2001). This numerical modelling also found that platforms were eroded at all tidal levels during the Holocene and that slopes below modern sea level were eroded when
relative sea level was high while slopes above modern sea level were eroded when relative sea level was lower (Trenhaile, 2010).

Shore platforms as an active landform do however extend below sea level often to a depth approximating wave base (Kennedy, 2015). In microtidal Victoria, Australia the three types of subtidal morphologies were identified as being those with a gently sloping ramp, those with a defined seaward scarp, and those that extended seaward as a terrace (Kennedy, 2015; Kennedy, 2016). For all types, the landward edge is generally identified by either a cliff or is buried below the beach or hillslope talus, in which case it can be delineated as the slope becoming greater than 12-15°(Kennedy, 2015). Defining the seaward edge of shore platforms, however, is not necessarily a straightforward task, and there are five commonly used criteria for defining the seaward edge of a shore platform: 1) tidal elevation, 2) morphology, 3) sedimentology, 4) biology, and 5) wave processes (Kennedy, 2015).

For reconstructions of modern (7 ka to present) and past higher sea levels, the subtidal morphological features, such as the seaward edge, slope, and elevation in relation to sea level, is not often considered since the current intertidal zone provides a suitable vertical datum. For reconstruction of elevations of past lower sea level, however, where the boundary between the subtidal and intertidal is not known, this becomes problematic. This is because delineating a gently sloping seaward ramp from a gently sloping intertidal surface of similar angle without a tidal reference is very difficult. As a result, accurate calculation of interstadial and glacial-age shorelines often have large margins of error. To resolve this issue this study pairs analysis of drowned and contemporary shore platforms in a tectonically-stable temperate environment in order to assess the utility of submerged erosive rocky landforms as sea level proxies.

### 4.2 Regional Setting

This study focuses on four different rocky coast areas along the western half of the coast of Victoria, Australia 38°S to 39°S and 141° to 147°E 1. Port Campbell Coast: Peterborough to Wattle Hill, 2. Otway Coast: Cape Otway to Anglesea, 3. Cape Paterson Coast: Cape Schanck to Inverloch, and 4. Phillip Island) (Figure 4.1) where paleo-shorelines possibly formed during MIS 3 have been inferred (Boreed & James, 1993; Bezore et al., 2016). Tertiary marine carbonate mudstones dominate the shore in study area 1, while study areas 2 and 3 are composed of Cretaceous sandstones with interbedded siltstones and mudstones, (Birch, 2003). Phillip Island, in study area 4, is composed of basalt, granite, and sandstone (Birch, 2003; Higgins, 2011). A series of Pleistocene carbonate dune sequences mantle these
older lithologies across all study areas with outcrops in the intertidal zone around Peterborough in study area 1. Victoria is a relatively stable tectonic setting, with regional sea levels closely matching eustatic fluctuations (Murray-Wallace and Belperio, 1991; Pirazzoli, 1991; Murray-Wallace and Cann, 2007; Kennedy, 2014b).

The open coast is high energy with average wave heights of 2 - 3 m with winter swell reaching a maximum of 8 m at Wilsons Promontory (Hughes and Heap, 2010). Spring tidal range varies from 0.9 - 1.6 m (Bureau of Meteorology, 2017). The coast of Victoria is classified as a Mediterranean climate, with wet winters (minimum temperatures ranging between 12 - 15˚ C) and dry summers (maximum temperatures reach between 24 - 27˚ C) (Bureau of Meteorology, 2017).

### 4.3 Methods

This study uses bathymetric and terrestrial LiDAR data collected in 2007 using a LADS Mk II system with a GEC-Marconi FIN3110 inertial motion sensing system and a dual frequency kinematic geographic positioning system (kGPS). This dataset includes seamless terrestrial-marine mosaics from elevations of +10 m to depths of -80 m (Quadros and Rigby, 2010). The MBES survey was completed in 2013 with a Kongsberg Maritime EM2040C MBES and an Applanix POS MV WaveMaster 9.2 m and was post-processed to give a resolution of 0.5 m (Kennedy, et al., 2014a). The final raster grid of the data (2.5 m grid) has a 5 m horizontal resolution providing full coverage capturing the coastal bathymetry to depths of 80 m. This data set was collected in conjunction with Deakin University and Parks Victoria as
part of an offshore habitat mapping project (Ierodiaconou, et al., 2007). The data was analyzed using the geographic information system software ArcGIS V.10.1.

Sea cliffs were first identified as topographic features having slopes greater than 20° (after Emery and Kuhn, 1982; Hampton, 2004). Secondly, the data was classified into a binary raster using a slope threshold of 12°. This value was chosen as it is the maximum angle identified on surveyed platforms in Victoria (Kennedy and Milkins, 2015; Kennedy, 2016) and it lies between the threshold values of 10° of Matsumoto et al. (2017) and 15° of Trenhaile (2000). Finally, platforms were identified through comparisons with LiDAR backscatter data to ensure they were hard rock features rather than sediment, field survey, and aerial photography. For contemporary platforms the subaerial seaward edge was delineated by the mean low water spring elevation (MLWS) (Kennedy and Milkins, 2015). The demarcation between the landward portion and the seaward portion of the platforms was the halfway point along the horizontal profile (Kennedy and Beban, 2005) (Figure 4.2). For the Phillip Island and Cape Paterson study sites, MLWS is -0.6 m, while MLWS is -0.8 m for the Otway Coast (Bureau of Meteorology, 2017). When delineating the seaward edge of platforms, a morphological approach was undertaken as hydrodynamic conditions during their formation are unknown. This is particularly the case for platforms formed below current sea level. For the modern platforms, the edge was at a maximum of 10 m depth, as this is where active erosion of the bedrock ceases in Victoria (Kennedy, 2015).

Shapefiles were created for individual platforms in each study area and were used to delineate the platforms. The elevation and slope datasets were clipped to the individual platform shapefiles, converted

Figure 4.2 Example profile of a shore platform with the subhorizontal portion and seaward edge labelled as well as mean sea level (MSL) and mean lower water spring (MLWS) tide elevation for reference.
from raster layers to point shapefiles, and then analyzed using the Spatial Statistics tool in ArcGIS
(Figures 4.3-4.4). These zonal statistics were recorded for the entire platform surface from the landward
dge to the seaward edge of each identified platform. This process was repeated using a calculated
rugosity layer that was also clipped and converted to points for analysis. Transects were then created from
the landward edge to a depth of 10 m at intervals of 50 m along each section of mapped platform, for a
total of 946 profiles. Each platform transect was then subdivided into two sections: near-horizontal
platform and seaward edge. Slope and elevation in relation to sea level on the near-horizontal portion
were then completed for each section of the platforms using the transects to account for horizontal
variation in morphology. The elevations of the semi-horizontal platforms were then used as proxies for
sea level.

Statistical analysis was conducted in Minitab 17. ANOVA tests using Tukey pairwise
comparisons were conducted. The ANOVA method was used to best determine whether there were
statistically significant differences between the means of the independent groups of parametric data,
whereas the Tukey method was applied to highlight the variance between specific groups’ means by
comparing each pair of measurements against each other.

Figure 4.3 Example of methods used for Otway Coast shore platforms using elevation points across the face of the
platforms as well as transects spaced every 100m to measure the platform morphology.
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In the field, 300 rock hardness measurements were taken across the faces of cliffs of different lithologies in each of the five study areas using an L-type Schmidt Hammer in accordance with the recommendations of Goudie (2006). All surfaces were prepared with a carborundum wheel prior to testing with a minimum of 10 readings taken at each site. Data were subsequently corrected for instances where the hammer was held away from the horizontal (Day and Goudie, 1977) and anomalously low values were rejected on the basis of Chauvenet’s criterion, a statistical method for removing spurious data (Göktan and Ayday, 1993).

4.4 Results

4.4a Shore platforms at modern sea level

Intertidal platforms occur in three study areas (2, 3, and 4) (Figure 4.1), comprising around 170 km of the coastline. Platforms represented entirely by a subtidal ramp were identified in the field and satellite imagery in the Port Campbell region (study area 1) extending up to 165 m from the shore fronting 40-80 m high limestone cliffs. Suspended sediment within the surf zone however limited LiDAR acquisition, thus preventing the use of this area in the analysis.

Rugosity showed the least variation across the platforms, ranging from 53.54 in the Cape Paterson to 57.30 along the Otway coast (Figure 4.5; Table 4.1). Basalt platforms had an average elevation of -0.33 +/- 0.42 m and the lowest mean slopes at 0.71 +/- 0.69° and lowest maximum slope at
0.62°. Sandstones and mudstones had maximum slopes of 11.95° with an average slope of 1.27 +/- 1.56° and showed more variation in elevation with a mean of -0.21 +/- 0.54 m. For each lithology, the landward half of the platform tended to have a higher slope than the seaward section. In the case of all platforms, not accounting for lithology, the mean slope of the landward sections was 1.67 +/- 1.87°, while the mean slope of the seaward sections was 1.33 +/- 2.82°. With regards to lithology, sandstone and mudstone platforms had the highest mean slopes for the landward sections (1.08 +/- 1.23°) as well as the seaward sections (1.35 +/- 1.67°) (Table 2). Average Schmidt hammer readings were r = 29.01 for sandstones and mudstones and r = 52.35 for basalts (Table 5).

Figure 4.5 Histogram showing rugosity, slope, and elevation in relation to mean sea level of the shore platforms in each study area as measured by converting raster to points and calculating zonal statistics for each individual platform from landward edge to seaward edge.

There was not a significant difference in elevations based on lithology amongst sandstone, mudstone, and basalt platforms (Table 4.2). The maximum elevations for all lithologies were within 2 m of modern sea level, with sandstone and mudstone platforms having the highest maximum elevation of
1.72 m (Table 4.2). The mean elevation across the surface of the platforms varied by less than 0.4 m between lithologies, and all mean elevations were less than 1 m from mean sea level. The sandstone and mudstone platform elevations were closest to sea level at -0.22 +/- 0.54 m, while the mean for basalt platforms was -0.33 +/- 0.42 m (Table 4.1).

While the intertidal platform surfaces may be nearly horizontal, the seaward edges varied from gently sloping ramps to almost vertical scarps (Table 3). The sandstones and mudstones had the highest maximum seaward edge slopes, reaching up to nearly 90° with an average of 16.71 +/- 18.71°. Of all the lithologies, the basalt platforms had the lowest mean and maximum seaward slopes, at 9.37 +/- 16.56° and 86.88°, respectively. These results did not show a statistically significant difference in terms of slope, given that the seaward edge was nearly vertical in all cases.

**4.4b Shore platforms below modern sea level**

Platforms were found at the base of four submerged cliffs located offshore of Port Campbell, Wongarra, Lorne, and Anglesea. These platforms had low sloping platform surfaces that tended to have gently sloping seaward edges (Figure 4.6). The features offshore of Port Campbell had a less defined subhorizontal profile and were found in shallower depths compared to the other three locations. The Wongarra platforms had a distinct subhorizontal surface, with clearly defined landward and seaward edges and were the widest of the offshore platforms. The platforms at Lorne were narrow and showed differential erosion, leading to a discordant coastal pattern. Anglesea had wide, gently sloping platforms that tapered off seaward with no clear seaward edge (Figure 4.6). The platforms found offshore of Port Campbell have a mean slope 3.31 +/- 2.8°, making them the steepest, while those offshore of Wongarra have the lowest mean slope at 1.05 +/- 0.81° (Figure 4.7). The shallowest depth recorded was near the edge of the cliff-platform demarcation in the Port Campbell location, with a depth of -38.06 m. The deepest recorded depth of an offshore platform was also in Port Campbell, at -57.18 m. The other offshore platforms had smaller ranges of depths, with Wongarra ranging from -49.89 to -56.29 m, Lorne from -46.39 to -53.14 m, and Anglesea platforms from -52.22 to -56.07 m depth (Figure 4.8; Table 4.4).
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A

B
Figure 4.6 Paleo-shore platforms located in front of submerged cliffs offshore of Port Campbell (A), Wongarra (B), Lorne (C), and Anglesea (D). Platform seaward edges are denoted by a black outline for viewing purposes.
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Figure 4.7 Anova One-Way Analysis using Tukey comparisons showing a significant difference between the slopes of each of the offshore platforms.

Figure 4.8 Anova One-Way Analysis using Tukey comparisons showing a significant difference between the depths below modern sea level of each of the offshore platforms based on their location.
4.5 Discussion

4.5a Shore platforms at modern sea level

Subaerial shore platforms in Victoria are all near horizontal, and form within 2 m of present mean sea level. They therefore can be considered a relatively reliable proxy for Holocene sea level, which has varied by around 2 m on this coast (Bryant, 1992). The morphology of contemporary shore platforms can sometimes be partly inherited from previous highstands (Young and Bryant, 1993; Brooke, et al., 1994; Trenhaile, 2002; Chao, et al., 2003; Kennedy, 2010) and in Victoria MIS 5 was up to 6 m above present. Platforms elevated above the current intertidal zone, left behind by higher sea levels, were not found in this study, so it is possible that today’s surfaces may be partly inherited from this period. Regardless as whether these older surfaces have been worn down to present intertidal elevations or eroded completely, the extant platform morphology can be considered to be primarily a product of contemporary erosive processes.

On a global scale, the gradient of platforms generally increases with rock hardness, and platforms tend to only develop in rocks with rebound values between 15 - 50 (Trenhaile, 2005; Thornton and Stephenson, 2006). Overall this study did not support this, as sandstone and mudstone (r = 28.74) platforms had higher slopes compared to basaltic (r = 52.35) platforms (Figure 4.9; Table 4.5). Globally, platform elevation is positively correlated with rock hardness (Sunamura, 1992; Dickson, et al., 2004; Thornton and Stephenson, 2005), while other studies have shown that rock structure also has significant influence over elevation (Trenhaile, 1978; Naylor and Stephenson, 2010). In this study, however, there was not a strong correlation between rock strength and platform elevation. When analyzing the entirety of mapped platforms (total of 11,963,496 m² in area), a Pearson correlation value of 0.068 and a p-value of 0.190 were calculated, meaning the correlation is not statistically significant on a regional landform scale (Figure 4.9). When analyzed for each lithology, sandstones and mudstones showed the highest correlation (R = 0.157, p = 0.008), while basalt platforms had negative correlations but also were the least significant (R = -0.152, p = 0.314) (Figure 4.10).
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In the case of the Victorian basaltic platforms, the measured hardness was lower than other basaltic platforms in Australia, such as those found on Lord Howe Island (Dickson et al., 2004). However, elevation was within the expected trends given the hardness. The relative softness of the Victorian basalt is most likely due to its young age (late Tertiary), olivine-rich composition and emplacement mechanism (Birch, 2003). In addition, block plucking appears to be a major erosive process (Gill, 1972) in contrast with a significant component of granular-scale downwearing occurring on the sandstone units (Stephenson et al., 2012, Yuan et al., 2018). The extent and thickness of lava flows is
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another common limiting factor for platforms formed in basalt and in Victoria this most likely contributes to the overall elevation of the platforms.

Just as the horizontal portion of the platforms varied, so did the morphology of the seaward edge. In this study, each of the three seaward edge types of Kennedy (2016) were found, but there were also many cases of a composite form. This was often the case for platforms that extended 80 - 100 m from their landward cliffs which had both a reef-like profile, in that the surface was gently sloping with high rugosity, as well as having a well-defined seaward cliff. These variations in morphology create complications in using platforms as sea level proxies, as there has to be a standardized set of parameters in place to ensure that the same elevation is being measured no matter the morphological type. It is suggested for contemporary platforms, that the elevation be treated as the average elevation measured between the landward edge of each platform and MLWS.

4.5b Shore platforms below modern sea level

The shore platforms found submerged offshore are assumed to have the same lithology as the onshore platforms due to the maximum burial depths of each onshore lithology being within the range of the maximum depth of the offshore feature (as per Krassay, et al., 2004; Boutakoff, 1963; Geological Survey of Victoria, 2001; Nicolaides, 1997). The submerged platforms have similar physical characteristics to their onshore counterparts, with mean slopes less than 4°, although for these platforms mean depths occur within an 8 m range. The platforms are all found at the base of submerged paleo cliffs, meaning it is likely that the platforms likely formed under similar processes as to contemporary features. Platforms in general are not quickly eroding features, but rather they require timescales on the order of several hundreds to thousands of years to form (Stephenson et al., 2013). Platforms formed in more erosion resistant rocky types take longer to form but are more likely to withstand multiple sea level changes, whereas those formed in softer lithologies take less time to form but are more likely to be completely eroded over eustatic cycles (Hills, 1971; Sunamura, 1973; Trenhaile, 2002). For the submerged Victorian platforms sea level would have moved vertically across their profile numerous times, exposing them to varying amounts of marine and subaerial erosion. These erosional patterns are most likely the cause of the greater vertical extent of the platforms when compared to the present shoreline (Trenhaile, 2002; Chao, et al., 2003).

The elevations for the horizontal surface of all the onshore platforms extended from 1.72 m above sea level to 3.57 m below sea level, a range of 5.29 m. For all the offshore platforms, the range was much larger at 19.12 m (-38.06 to -57.18 m). The shallowest platforms, offshore of Port Campbell, are inferred to form in
the same limestone unit that forms the subtidal ramps observed in the field within the surf zone. As the subaerial portion of the profile is not present on the contemporary coast, and therefore not a reliable indicator of sea level, we can assume that these submerged platforms are equally poor eustatic indicators. Therefore, the Wongarra, Lorne, and Anglesea offshore platforms are a much more accurate tool for measuring sea level. The offshore depth range, then, is 7 m, ranging from -49.69 m to -57.18 m. This confines sea level to -52.64 +/- 1.44 m depth across all the sites at the time of their formation.

Sea level has been 50-60 m below modern levels for 27% of the past 150,000 years (Figure 4.11), including for thousands of years during MIS 3, providing enough time for the true platforms to form (Bloom and Yonekura, 1990; Voris, 2000; Grant, et al., 2014). It is also possible that the shallower offshore platforms in the Port Campbell study area represent a different highstand when sea level was 30-40 m lower than today, such as 100,000 years ago during MIS 5. Sea level has also risen and fallen multiple times within that time period, meaning that all of the paleo platforms were likely repeatedly exposed to marine and subaerial erosive conditions across their entire profile for different periods of time. It appears that this movement has allowed platforms to be formed, but their resultant morphology is less reliable as a sea level proxy than their contemporary counterparts on the modern coast.

Figure 4.11 Sea level curve for the past 250 ka (adapted from Grant, et al., 2014), showing the average depths of shore platforms found offshore at -30 m and -50 m in comparison to mean sea level (MSL).
4.6 Conclusions

Shore platforms are subhorizontal rocky shoreline features that signify a long-term erosional coastal environment. Shore platform morphology, especially the elevation of the subhorizontal surface, can be attributed to boundary conditions such as dominant erosion processes and lithology. In Victoria, Australia, these features are common along the modern coastline in sandstone, mudstone, and basalt lithologies. As this study discovered, they are also found offshore, submerged at -50 m depth as remnants of paleo-sea levels. The paleo-platforms have a similar morphology and lithology to the platforms found along the modern coast, meaning that they likely formed under similar boundary conditions when sea level was -50 m below present.

This study shows, the elevation can also provide valuable information as to sea level fluctuations and the longevity of these cycles over time. The shore platforms found within 2 m of sea level are believed to be modern coastal features. The offshore platforms, on the other hand, have been submerged below sea level and exposed subaerially many times over the past and therefore act as a less reliable or accurate proxy for sea level but can still provide constraints within 7 m for an approximate age of 60,000 years old.

4.7 Acknowledgements

We thank Parks Victoria for funding the capture of the multibeam sonar data used in this study. We thank members of the crew Sean Blake and Dr Alex Rattray of Deakin University’s research vessel Yolla for assistance in the collection of the multibeam sonar data. We thank the Department of Environment and Primary Industries Department of Environment and Primary Industries coordinated imagery program for access to the georegistered aerial photography and the Future Coasts Program for access to the LiDAR data. We thank Ian Atkinson from Geoscience Australia and Nicole Bergersen from Acoustic Imaging Pty Ltd for technical support provided during MBES data capture and analysis. Rhiannon Bezore was supported by the Melbourne International Research Scholarship from The University of Melbourne.

4.8 Tables

Table 4.1 Platform rugosity values taken from points generated from slope data for each study site.

<table>
<thead>
<tr>
<th>Location</th>
<th>( N_{\text{rugosity}} )</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otway Coast</td>
<td>1048575</td>
<td>57.30</td>
<td>14.94</td>
</tr>
<tr>
<td>Phillip Island</td>
<td>592332</td>
<td>56.12</td>
<td>16.13</td>
</tr>
<tr>
<td>Cape Paterson</td>
<td>230525</td>
<td>53.54</td>
<td>18.17</td>
</tr>
</tbody>
</table>
Table 4.2 Intertidal platform slope and elevation characteristics for each lithologic unit.

<table>
<thead>
<tr>
<th>Lithologic Unit</th>
<th>Mean slope (°)</th>
<th>Standard Deviation</th>
<th>Max. Slope (°)</th>
<th>Min. Slope (°)</th>
<th>Mean elevation (m)</th>
<th>Standard Deviation</th>
<th>Max. Elevation (m)</th>
<th>Min. Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone/Mudstone</td>
<td>1.27</td>
<td>1.56</td>
<td>11.95</td>
<td>0.0025</td>
<td>-0.21</td>
<td>0.54</td>
<td>1.72</td>
<td>-2.22</td>
</tr>
<tr>
<td>Basalt</td>
<td>0.71</td>
<td>0.69</td>
<td>0.62</td>
<td>0.0044</td>
<td>-0.33</td>
<td>0.42</td>
<td>0.49</td>
<td>-1.59</td>
</tr>
<tr>
<td>Granite</td>
<td>2.49</td>
<td>2.58</td>
<td>11.71</td>
<td>0.0074</td>
<td>-0.57</td>
<td>0.74</td>
<td>1.06</td>
<td>-3.40</td>
</tr>
</tbody>
</table>

Table 4.3 Slope measurements for all shore platform seaward edges with respect to lithology.

<table>
<thead>
<tr>
<th>Lithologic Unit</th>
<th>Mean Slope (°)</th>
<th>St.Dev.</th>
<th>Max. Slope (°)</th>
<th>Min. Slope (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone/Mudstone</td>
<td>16.71</td>
<td>18.71</td>
<td>91.34</td>
<td>0.05</td>
</tr>
<tr>
<td>Basalt</td>
<td>9.37</td>
<td>16.56</td>
<td>86.88</td>
<td>0.64</td>
</tr>
<tr>
<td>Granite</td>
<td>15.62</td>
<td>14.04</td>
<td>88.17</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Table 4.4 Characteristics of paleo-shore platforms found in each of the four locations

<table>
<thead>
<tr>
<th>Offshore Location</th>
<th>N (slope)</th>
<th>Mean slope (°)</th>
<th>Standard Deviation</th>
<th>N (depth)</th>
<th>Mean depth (m)</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port Campbell</td>
<td>20272</td>
<td>3.31</td>
<td>2.80</td>
<td>21232</td>
<td>-46.51</td>
<td>4.44</td>
</tr>
<tr>
<td>Wongarra</td>
<td>15408</td>
<td>1.05</td>
<td>0.81</td>
<td>15410</td>
<td>-52.88</td>
<td>1.06</td>
</tr>
<tr>
<td>Lorne</td>
<td>5383</td>
<td>1.78</td>
<td>1.49</td>
<td>5432</td>
<td>-51.35</td>
<td>0.84</td>
</tr>
<tr>
<td>Anglesea</td>
<td>4076</td>
<td>1.54</td>
<td>0.73</td>
<td>4076</td>
<td>-54.29</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Table 4.5 Schmidt hammer readings using compressive strength as a proxy for rock hardness. Readings were collected in the field and later corrected for hammer angle.

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Mean Schmidt Hammer Reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridgewater Formation</td>
<td>30.67</td>
</tr>
<tr>
<td>Demons Bluff</td>
<td>22.00</td>
</tr>
<tr>
<td>Eumeralla Formation</td>
<td>33.25</td>
</tr>
<tr>
<td>Mornington Volcanic Group</td>
<td>47.50</td>
</tr>
<tr>
<td>Newer Volcanics</td>
<td>57.20</td>
</tr>
<tr>
<td>Wonthaggi Formation</td>
<td>30.14</td>
</tr>
<tr>
<td>Yanakie Granite</td>
<td>43.67</td>
</tr>
</tbody>
</table>
4.9 References


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CHAPTER 5

MIS 3 Paleo-Shoreline of Victoria, Australia
5.1 Introduction

Sea level is not static, but rather it rises and falls over eustatic cycles as the Earth’s climate switches between glacial and interglacial periods. Eustatic sea level changes have been well documented using radiometric dating of fossil corals, speleotherms, and paleo-deposits (Grant, 2014; Lisiecki, et al., 2009; Rohling, et al., 2008; Rohling, et al., 2009; Rohling, et al., 2014;). Regional studies, however, rely on localized proxies to reconstruct past sea levels specific to specific study sites. During periods of relatively stable sea level, referred to as highstands and lowstands, coastal landscapes are preferentially formed as the erosive action of waves and tides can act at a specific elevation for a prolonged period of time. These landforms then act as proxies for previous sea levels. Along hard rock coasts such features are erosional in origin and include sea cliffs, shore platforms, sea stacks. In shallow, warm marine waters, depositional coral reefs also provide more precise constraints on paleo-sea levels and more accessible working environments for collecting data.

Global eustatic sea level variations over the past 220 ka, since Marine Isotope Stage (MIS) 7, have seen sea level vary by over 125 m, ranging from about -120 m below to +5 m above present elevations (Rohling, et al., 2014) (Figure 5.1). During these fluctuations significant land formation has occurred during the relatively stable interglacial periods of MIS 7, 5 and 1. Average sea level elevation during this period has however been around 50 m below present meaning that erosional and depositional coastal processes have most often been occurring at lower elevations than today (Boreen and James, 1993). Significant stable periods below present sea level are termed interstadials and these occur when the climate is relatively warmer during an otherwise glacial period (Broecker and Denton, 1990). These periods of stability have occurred at around 14.7 +/- 93, 23.3 +/- 298, 27.8 +/- 416, 28.9 +/- 449, 32.5 +/- 566, 33.7 +/- 606, 35.5 +/- 661, 38.2 +/- 724, 40.2 +/- 790, and 41.5 +/- 817 ka (Andersen, et al., 2006; Rohling, et al., 2009), leading to development of coastal landforms at 50 - 60 m depth around the globe, such as submerged ridges in Western Australia (Brooke, et al., 2010), and reefs in Oahu (Fletcher and Sherman, 1995), and the western Indian Ocean (Camoin, et al., 2004). These submerged landforms also act as valuable habitat for marine life (Rattray, et al., 2009; Monk, et al., 2010) and are therefore important for fisheries (Jalali, et al., 2015). They are also important in planning for offshore infrastructure for the energy and communications industries (Roarty and Roarty, 2008; Lech, et al., 2016).
The modern coast of Victoria, Australia is a temperate environment with high wave energy (Flocard, et al., 2015), which is not conducive for providing high accuracy and high precision sea-level proxies, such as the coral reefs. In such temperate environments it is erosional landforms that are most commonly used for the reconstruction of past climatic and oceanographic conditions (Sivkov, et al., 2011; Jara-Muñoz, et al., 2015; Cawthra, et al., 2016). Such studies have led to inferences regarding a MIS 3 shoreline along Victoria’s coast based on submerged river channels, ridges, and cliffs (Boutakof, 1963; Bloom and Yonekura, 1990; James and Borch, 1991; Bird, 1993; Beaman, et al., 2008; Brooke and Sext, 2010), yet little investigation has been conducted on the precise morphology of this old shoreline. Other erosional landforms identified on this old shore are composed of sea stacks (Bezore, et al., 2016, Ch. 1), cliffs (Bezore, et al., in progress, Ch. 2) and shore platforms (Bezore, et al., in progress, Ch. 3), and this chapter uses these proxies to examine the morphology of this erosional shoreline and its similarity to the modern shore.

The following is a review of sea level over the past 220,000 years, highlighting studies that have used landforms or biological samples as sea level proxies. This study contributes to the historic sea level curve data by adding constraints to the sea level curve for Victoria, Australia, specifically during MIS 3.

**Quaternary Sea Level**

Changes in eustatic sea levels prior to the 19th Century were controlled primarily by phase sequences within Milankovitch cyclicity (Pillans, et al., 1998). For example, starting roughly 1.5 ma, the periodicity of glaciations switched from a 41 kyr cycle to a 100 kyr cycle, due in part to tropical
semiprecession cycles moving to higher latitudes (Rutherford, 2000). Sea level changes in the Quaternary have been due primarily to the periodic exchange of mass between ice sheets and oceans (Lambeck and Chappell, 2001). This period has been marked by an increase in both the amplitude of sea level changes between interglacial and glacial periods as well as the duration of glacial cycles, with glaciations lasting about 100 kyr followed by interglacial periods lasting 10-15 kyr (Murray-Wallace and Woodroffe, 2014). From about 25-22 ka, the climate and corresponding sea levels fluctuated greatly leading up to the next glaciation (Imbrie, et al., 1992). For example, Quaternary sea levels were 30 – 40 m below present between 97-116 ka and between 85-10 ka and were 70-90 m below present between 30-60 ka and 12-15 ka (Brooke, 2017). The Last Glacial Maximum (LGM) peaked 22-19 ka, when land ice volumes were at their maximum extents. During this time, sea levels were significantly lower globally and were between 110-130 m below modern sea level in Australia (Yokoyama, et al., 2000). During this time, temperatures were up to 8° cooler than present in southeast Australia, and rain fall reached minimum levels for the LGM from 14-12 ka (Williams, et al., 2009).

**Holocene Sea Level Proxies**

Evidence for post-glacial transgression in Australia include in situ reef growth, tree stumps, and mollusc shells (Lambeck, 1990) (Table 5.1). Sea level studies in north-eastern Australia show that sea levels peaked 1.0 – 1.5 m above modern sea level by 7,000 years ago before regressing to modern levels 2,000 years later (Lewis, et al., 2008). In Victoria, the Holocene highstand was 2.0 m above modern levels (Gill, 1983), with evidence such as relict tubeworms dated at ~5,570 years old being found 1.5 m above present sea level at Cape Liptrap (Haworth, et al., 2002). In Melbourne, Victoria, the analysis of wood samples, tree stumps, and fresh water peat has given an upper limit on sea level rise in the area at 9,000-7,000 years ago (Lambeck, 1990). Port Phillip Bay, Victoria saw its Holocene highstand maximum at 4 m above present about 1,000 years before other Victorian coastal regions, such as Warnambool which reached a maximum of only 1 m above present or headlands like Wilson’s Promontory and Cape Howe which reached maximum levels much later (Lambeck and Nakada, 1990). One study using foraminiferal biofacies found in late Oligocene stratigraphic sequences in southeastern Australia show a strong consistency with global eustatic sea levels and glaciations at that time, with alternating bands of shallow water and deep water species (Li, 2003). Work done in southern Australia shows that relative sea level during the Holocene was very site specific but did follow the global pattern of rapid sea level rise (~16 mm/yr) due to de-glaciation in the early Holocene, reaching present levels around 6,400 years ago, and then regressing by about 1-3 m variably across different regions (Belperio, et al., 2002).
Pleistocene Sea Level Proxies

Pleistocene sea level reconstruction studies in Australia have relied on the analysis of submerged paleo-coastal features and the radiocarbon dating of offshore sediments and fossils, as sea level has been lower than present levels over the past 250 ka, apart from during Marine Isotope Stage 5e (124-119 ka) (Rohling, et al., 2014). All of the work in this review focuses on MIS 5e onwards, as very few studies have any dates for Australian proxies prior to this period. Work done on the Great Barrier reef showed drowned shelf edge reefs between 40-70 m depth and terrace step features at 78 - 114 m depth that are believed to have formed during the last pulse of sea level rise about 20-10 ka, but it was also noted that they may represent growth during earlier sea level oscillations prior to and after 120 thousand years ago (Beaman, et al., 2008). Submerged features deposited during the Last Glacial Maximum in Australia include beach rocks; shallow marine, intertidal, and subaerial sediments; and shallow water corals all found 130 - 150 m below present sea level that have all been dated to be 18,000-20,000 years old (Chappell, 1987). One study focusing on the Otway Basin in western Victoria cites a late Pleistocene highstand in the area from 60-26 ka (-50 m), followed by a subsequent drop from 26-17 ka (-120 m) based on radiocarbon dating of shelf sediments (Boreen and James, 1993). This was followed by a sea level transgressive period from 17-10 ka, which slowed but continued to infill shallow embayments on the Otway shelf from 10-6.5 ka (-120 to 0 m), after which sea level stabilized close to present levels (Boreen and James, 1993).

Marine Isotope Stage 3

Marine Isotope Stage 3 was the period between 60 and 25 ka, marked by fluctuating climatic conditions with sea levels ranging between 60 to 90 m below present (Siddall, et al., 2008). During this stage interstadial warming periods called Dansgaard-Oeschger (DO) events are recorded in ice cores which show sea surface temperature increases of 8 - 15° (Dansgaard, et al., 1993; Siddall, et al., 2008; Van Meerbeeck, et al., 2008). Sea level in MIS 3 can be split into two major highstands of -60 m for the first half of the period and -80 m for the second half, with 4 minor fluctuations of 20 - 30 m. Paleo-shoreline locations and morphology during this time would have been a significant determining factor in early human habitation on the Australian continent. Human migration to Australia began at the beginning of MIS 3, with coastal settlements being established by 45 ka, perhaps aided by wet conditions across the continent during this climatic period (Tobler, et al., 2017; Kemp, et al., 2019).
5.2 Regional Setting

Victoria, is located in southeastern Australia between 38°S to 39°S and 141° to 147°E (Figure 5.2). Mean average wave height of 2 - 3 m occurs derived from Southern Ocean swells along the western parts of the state (Flocard, et al., 2015) to 2 m along the eastern section of coast with winter swell reaching 8 m (averaging 2m) at Wilsons Promontory (Hughes and Heap, 2010). Mean Spring Tidal range varies from 0.9 - 1.6 m along the study area of coast (Bureau of Meteorology, 2017). The coast is a Mediterranean climate, with wet winters with minimum temperatures between 12 - 15˚ C and dry summers with maximum temperatures between 24 - 27˚ C (Bureau of Meteorology, 2017).

Australia tends to follow global sea level trends quite closely. This can be attributed to the fact that it is an intraplate continent, located far from the tectonic activity found at plate boundaries (Murray-Wallace, 2002). While there is some localized tectonic uplift along the coast of southern Australia and in Tasmania, Australia is considered to be a relatively tectonically stable continent, removed from continental ice sheet, meaning that uplift and subsidence of the coast are negligible in relation to Milankovitch-scale sea level changes, which are on the order of up to hundreds of meters of elevation change in comparison to less than a few meters of tectonic elevation change (Belperio, et al., 1995).

From the west to east, the coast is divided into the following five regions based on the bathymetric data available for this study and offshore features found: Discovery Bay, Port Campbell, Wongarra, Lorne, and Angelsea. The regions contain three dominant lithologies: mid-Miocene limestone, Cretaceous non-carbonaceous sandstone, and Tertiary marine carbonate mudstone (Birch, 2003).

5.3 Methods

Bathymetric and terrestrial LiDAR data collected in 2007 was collected using a LADS Mk II system with a GEC-Marconi FIN3110 intertidal motion sensing system and a dual frequency kinematic geographic positioning system (kGPS). This dataset includes seamless terrestrial-marine mosaics from elevations of +10 m to depths of -25 m (Quadros and Rigby, 2010). Multibeam sonar data were acquired using a Reson Seabat 101 multibeam sonar (Ierodiaconou et al., 2007) and a Kongsberg EM2040C (Schimel, et al., 2015). Positioning was accomplished using a real-time differential GPS integrated with a positioning and orientation system for marine vessels (POS MV) for dynamic heave, pitch, roll and yaw corrections (± 0.1° accuracy). The final raster grid of the data has a 3 m horizontal resolution providing full coverage.
capturing the coastal bathymetry to depths of 80 m. The data was analyzed using the geographic information system software ArcGIS v.10.3.1.

For the paleo-sea cliffs found submerged beneath modern sea level, a minimum slope of 20° was also used to map these topographically high features on an otherwise horizontal sea floor surface, and a break in slope of less than 20° was used to measure the location of the base of the cliffs (after Bezore, et al., in progress A). As for submerged shore platforms, a maximum slope of 12° was used to identify and map the subhorizontal erosional platforms. The elevation of the subhorizontal surface was then taken to be the elevation of sea level at which it was formed through erosion. As the paleo-platforms that were found were submerged at depth, rather than using a tidal approach to delineate the seaward edge, a morphological approach was used, marking the edge as a break in slope of greater than 12° (after Bezore, et al., in progress (Chapter 4). For sea stacks, these features were identified as columnar pillars on an otherwise low-topography surface and a break in slope of less than 20° was used to define the base of each stack (after Bezore, et al., 2016 (Chapter 2)). The shoreline features found submerged offshore are assumed to have the same lithology as the onshore platforms due to the maximum burial depths of each onshore lithology being within the range of the maximum offshore feature depth (Krassay, et al., 2004; Boutakoff, 1963; Geological Survey of Victoria, 2001; Nicolaides, 1997). All hard rock landforms found below modern sea level were confirmed to be composed of rock, rather than sediment, using a backscatter data set.

5.4 Results

Paleo-landforms were discovered in this study along the coast of Victoria, including sea cliffs, shore platforms, sea stacks, river channels, and estuary basins. These features were found in primarily 30 - 60 m depths offshore of twelve locations (Figure 5.3; Table 5.2).
Figure 5.2 (A) The coast of Victoria in southeast Australia, showing the study extent from Warrnambool in the west to Wilsons Promontory in the east. (B) All locations and types of paleo-shoreline features found offshore of the modern coast of Victoria, Australia.

The offshore zone between the border of South Australia and Victoria east to Discovery Bay is characterized by low bathymetry and bedrock substrate. It is largely devoid of rocky outcrops or topographic highs. At Discovery Bay, a paleo-sea cliff occurs with a mean depth at its base of 54.0 ± 3.2 m, (49.2 to 56.9 m) (Figure 5.3). The cliff edge is an average of 1.96 km from the modern coast, and the cliff face is well defined with a slope of 32.5 ± 9.5°. The paleo-cliff matches the headland shape of the modern cliffs and increases in height from west to east, with a steep face across the entire cliffside.

Continuing to the east, the substrate returns to being low-profile (＜2°) and sediment covered. This continues on until the mouth of the present-day Fitzroy River, at the Narrawong Coastal Reserve. Here, a lava tube tracks seaward in a southeast direction for 7.5 km southeast, and a basin feature extends from 1.6 km offshore to about 8.5 km offshore with a total area of 29.3 km² (Figure 5.4). The lava tube begins nearshore as a narrow, bedrock confined channel and meanders southeast, staying tightly confined. A lava plain is visible surrounding the channel, extending nearly 6 km across, with 5 km of that total on the
southwest plain that is nearly 40 m in depth and a less smooth surface than the surrounding sea floor due to even sediment deposition across the surface.

Moving further eastward, the seafloor is flat (< 2°) and is primarily exposed bedrock with some sand cover until Warrnambool, where there is a paleo-river channel extending 4.4 km southeast from the mouth of the Hopkins River. This paleo channel runs close to the shore, ranging from about 0.13-0.87 km from the coast and covering 1.56 km². There are two wedge-shaped bedrock outcrops in the middle of the channel as well, with areas of 0.05 km² and 0.03 km² (Figure 5.5).

![Figure 5.3 Location and depths of the paleo-cliffs found offshore of Discovery Bay](image)
Figure 5.4 Location and depths of a lava tube (white dashed line) and flood plain (red dashed line) offshore of the Narrawong Coastal Reserve.

Figure 5.5 Location and depths of paleo river channel (white dashed line) the Hopkins River in Warrnambool.
At Port Campbell, there were three submerged cliffs, one facing 45° away from the modern coast and two comprising opposite sides of a headland, averaging 
-48.4 m +/- 8.8 in depth at their base (Figure 5.5). The set of cliffs closest to shore had a minimum depth of -26.5 m, while the cliffs farthest from the modern shoreline had a maximum depth of -62.7 m (Figure 5.6). The large headland is formed by two cliffs, each nearly 5 km long, which mark the edge of an embayment between them, which extends east to west for nearly 7 km across and narrows in the middle at Port Campbell Bay. The western cliff also has a river channel running through it, extending from onshore at the river mouth of the Curdies River. This paleo-channel extends 5.7 km offshore from -14 to -51 m depth and runs southeast from the modern shore, before terminating at the base of the cliffs. The intersection of the river and cliff face also appears to be an incised river valley estuary due to the immediate deepening to -61 m seaward of the river mouth (Figure 5.7).

Shore platforms occur at the base of the western-most and eastern-most paleo-cliffs, with depths of -38.06 to -57.18 m. The slopes average 3.31 +/- 2.80°, making them the steepest paleo-platforms found in this study. Due to the cliffs backing them, the landward edge was clearly defined, as was the seaward edge (Figure 5.8).

The only paleo-sea stacks found in this study were offshore of the modern Twelve Apostles (Figure 5.9). Five separate stacks were identified, all within 175 m of one another. The depth at the base of the stacks ranged from -58.11 to -62.12 m below modern sea level, with an average depth of -59.72 m (Bezore, et al., 2016). Compared to the modern Twelve Apostles at Port Campbell, these sea stacks were about ten times shorter and four times wider, but they still maintained a clear columnar profile. Because of their tall, pillar shaped morphology, they were not considered to be islets or eroded islands.
Figure 5.6 Location and depths of the paleo-cliffs found offshore of Port Campbell.

Figure 5.7 Location and depths of the river channel (channel and tributaries shown in white dashed line) found offshore of Port Campbell, extending out through the cliffs seen in Figure 5.
Figure 5.8 Location (shown by black boxes) and depths of the paleo-platforms found offshore of Port Campbell. Inset shows a 3D rendering of the platforms in the eastern location box.
Moving east from Port Campbell, the sea floor returns to a low relief unconsolidated sediment plain until southwest of Wattle Hill a where a paleo-river channel occurs. This channel runs parallel to the modern coast for 2.53 km and does not appear to connect to any modern day river. The sediment surrounding the channel looks to be anastomosing in form while the river is bedrock confined, which is an uncommon combination (North, et al., 2007). It has a complex pattern extending landward and seaward from the channel for a total area of 47.08 km² (Figure 5.10). The remainder of the offshore region between Wattle Hill and Cape Otway is flat and featureless, primarily covered by sand.

**Figure 5.9** Location (shown by black box) and depths of the paleo-sea stacks, dubbed the “Drowned Apostles” found offshore of Port Campbell (Bezore, et al., 2016). Inset shows the paleo-sea cliffs fronted by the five sea stacks, sitting at nearly 60 m depth.
Figure 5.10 Location and depth of a paleo-river channel (black dashed line) running parallel to the modern coast and surrounded by deposited sediment offshore of Wattle Hill.

Bearing roughly 45° degrees from the tip of Cape Otway when looking north, there runs a long, narrow, nearly straight feature that may be either a dyke or a fault, reaching 5.93 km seaward and trending in a slightly southwest direction. Just over 2 km to the east of this feature are two partially linked depressions that can be interpreted as paleo-estuaries, given their proximity to the modern coast and similar morphology to contemporary estuaries. The depression closest to the coast (0.5 km offshore) is 0.32 km² and -4.71 to -19.84 m, while the other is 0.22 km² and sits 1 km offshore with depths of -19.52 to -26.48 m. The last erosional feature in this region is a slumping ridge extending from the eastern side of Cape Otway to the southwest in a linear fashion. This ridge is low sloping (< 20°) and runs for nearly 8 km with elevations of about -44 m while on either side of the ride, depths are closer to -37 to -40 m (Figure 5.11).
Figure 5.11 Location and depth of paleo-estuary basins, a ridge, and possible dyke system off the headland at Cape Otway.

Between Cape Otway and Wongarra, the substrate is primarily flat with no surface irregularities, with sediment deposits making the only topographic variations. At Wongarra, however, more bedrock paleo-features were discovered, including a cliff with slopes greater than 20° (Figure 5.12). The Wongarra paleo-cliff had a mean depth at the base of 50.1 +/- 2.2 m below sea level (range -52.7 to -45.8 m). This submerged cliff looked morphologically similar to the sea cliffs found onshore in Wongarra as well, with more gently sloping faces (21.4 +/- 1.4 °), although the average height was lower than cliffs onshore at only 8.5 +/- 3.8 m. The submerged cliffs in Wongarra also had paleo-shore platforms fronting them, with depths on the platforms ranging from -49.9 to -56.3 m (Figure 5.13). The platforms were low sloping, wide features, with an average slope of 1.05 +/- 0.81° and a width of 0.3 km at the widest point. These features were most likely heavily jointed at one point, as they have split into three individual platform surfaces.
Figure 5.12 Location and depths of the paleo-cliffs found offshore of Wongarra. Insert shows an oblique view 3D rendering of the sea cliffs, with shore platforms sitting seaward of the cliffs.
Figure 5.13 Location and depths of the paleo-platforms found offshore of Wongarra. Insert shows 3D rendering of the area highlighted by the black box, showing low sloping, segmented shore platforms.

Just northeast of Wongarra, there is a paleo-channel found offshore of the mouth of the Kennett River (Figure 5.14). This paleo-channel extends eastward out to sea for 2.43 km and has depths ranging from -4.5 m to -42.8 m at its terminus. The channel begins nearshore at 0.27 m wide before narrowing to 0.05 m after about 1 km seaward and then widening slightly again to 0.12 m in width at the paleo-river mouth. There is a significant amount of sediment deposited around the channel, especially on the southern side, totaling 2.43 km² in area. It is also possible that the river channel has been incised into a fan-shaped bedrock outcrop, leaving a distinct contact surface between the two lithologies.
Continuing northeast, the next location of a well-defined shoreline is found offshore of Lorne. Here a shore platform that ranged in depth from -46.4 to -53.1 m was found (Figure 5.15). The platform in this location was narrow and steep compared to onshore platforms near Lorne, with widths ranging between 0.06 m to 0.2 m and a mean slope of 1.8 +/- 1.5°. While this platform feature is fronting a topographic high, the high is not classified as a cliff due to the mean gradients being less than the 20° minimum slope used for the classification.
Figure 5.15 Location (black box) and depths of the paleo-platforms found offshore of Lorne. Inset shows 3D vertical exaggeration rendering of the narrow, relatively steep shore platforms.

The next area of interest for paleo-features is in Anglesea, where there are shore platforms, a paleo-river channel, and a large paleo-estuary basin. The paleo-platforms in this region were -52.22 to -56.07 m below modern sea level and have a broad, gently sloping profile with a ramp-like morphology (Figure 5.16). The slope of these platforms average 1.54 +/- 0.73° and have widths from 0.07-0.18 km. Just north of the platforms, near the mouth of the Anglesea River, a paleo-river channel extends 2.02 km southeast and has a meandering path that is 2.70 km in total length. The depths at the landward section start at -12.5 m, reach -22.0 by the midpoint, and end at -29.3 at the river mouth. The banks are about 6 m higher than the channel at the landward end and then taper off by the mouth to only 3 m higher than the channel. This paleo-channel also terminates in a paleo-estuary basin, which has an area of 1.01 km² and slightly raised edges encompassing the basin, especially on the landward side. This oblong shaped basin has a southwest to northeast orientation with a width of 1.73 km in that direction and depths of about -35 m below sea level at the very center while the landward portion is -31 m and the seaward section is -36 below sea level. (Figure 5.17).
Figure 5.16 Location and depths of the paleo-platforms found offshore of Anglesea. Inset shows 3D rendering of location highlighted by black box, showing wide, ramp-like shore platforms.

Figure 5.17 Location and depths of the paleo-channel (axis shown by white dashed line) found offshore of Anglesea, terminating in a paleo-estuary basin (black dashed line).
Farther east along the coast, at the river mouth of Barwon River, another paleo-river channel extends off the modern coast. This paleo-channel terminates 4.24 km southeast offshore and appears to separate into four branches at the southeast portion. The main channel is the widest section, with the widest portion reaching 0.81 km across, while the smaller branches measures only 0.10-0.20 km across. The deepest portion is in the southern branches at 34.6 m (Figure 5.18).

The offshore zone beyond Anglesea is largely devoid of any topographically high features, being composed of sandy substrate or low relief bedrock with slopes less than 1° and depths ranging less than 0.5 m. The only point of interest is offshore of Phillip Island, where a series of large sand ridge features sit about 2.5-3.5 km off the southwestern tip of the modern shoreline. The features were identified as being sand or sediment rather than rock through analysis of the backscatter data. This ridge system does not classify as cliffs, as the slopes are under 20°, but they stand about 5 m tall with a depth of -48.5 m at the base and -37.7 m at the top. They range in width across the top from 0.3 to 0.5 km and average 2.4 km long. It also appears that there is another possible ridge sitting directly landward of the ridge system with a distance of only 0.5 km between them, and both run southwest to northeast at roughly 45° to the modern coast (Figure 5.19).
5.5 Discussion

The -50m shoreline in Victoria is extensive, being exposed as erosional landforms for nearly 80 km in length across the contemporary shelf. These erosional landform account of 8.1% of the 991 km length of the coast at the -50m contour (Figure 5.20). In comparison, the modern coast is 2,512 km long, nearly 50% of which are classified as rocky. This discrepancy in the existence of rock formations along the modern coast compared to the submerged paleo-coastline can be attributed to the sea floor being a depositional environment where sand and sediment dominate, whereas the modern coast is exposed to ongoing erosion that exposes bedrock and carries sediment alongshore and offshore. The similarity of existence and morphologies of these rocky landforms indicate the long term predominance of energetic wave conditions on this shoreline. In many cases the paleo-shoreline is up to 6 km offshore, but in some instances the landforms are connected to the contemporary shore through paleo-channels, as evidenced by the proximity to contemporary onshore features like rivers and by sediment depositional features, such as alluvial fans, linking the modern system to the drowned features.

The sea cliffs, shore platforms, and sea stacks found submerged offshore of Victoria were formed when sea level was 50 - 60 m below present, corresponding with sea level during the beginning of MIS 3 (Siddall, et al., 2003; Rohling, et al., 2014). Sea level has been 50 - 60 m below modern levels for 27% of the past 150,000 years, including for thousands of years during MIS 3, providing enough time for these
landforms to be eroded from the rocky coast (Bloom and Yonekura, 1990; Voris, 2000; Grant, et al., 2014). Between 65 - 62 ka, sea levels ranged between 80 - 85 m below modern sea level, then rose over 3 ka to peak at -40 m at the beginning of MIS 3. It then fell to 70 - 80 m below present until about 40 ka and then rose to roughly 60 m below present from 39 ka onwards until dropping at 30 ka and staying at -80 m until the boundary with MIS 2 (Last Glacial Maximum (LGM)) (Shackleton, et al., 2000; Chappell, 2002; Siddall, et al., 2008).

The age of the shoreline is initially inferred as MIS 3 based on previous work (Boutakof, 1963; James and Borch, 1991; Bird, 1993). There is also the possibility that some of the morphology of the submerged cliffs could be attributed to erosion during the Younger Dryas regression, when sea levels began to rise after the Younger Dryas glaciation ended in Australia around 11,100 years ago, marking the point of continued warming lasting until the early Holocene (Andres, et al., 2003). While sea level was at around 50 - 60 m below present during this time (Grant, et al., 2014), it was actively rising the whole time. This means that wave activity likely had an impact on the morphology of the cliffs now found offshore but was not likely to have been the sole cause of the cliff formation. The size of the landforms would suggest that they required a still stand on the order of hundreds to thousands of years to create, much as the modern shoreline has formed in the past 6,000 years since sea level stabilized, thus an interpretation of MIS 3 age would be more realistic.

The paleo-river channels and estuary basins would have formed when sea level was 30 m below present and would have taken considerable time to form, on the order of hundreds to thousands of years, depending on the geology and discharge rates. Those formed in softer lithologies, such as sandstones, or in high discharge environments could have been formed quicker than those in harder rock types. Over the past 250,000 years, sea level has been -30 m for 67% of the time, spanning six separate events (Chappell and Shackleton, 1986; Voris, 2000). The two predominant highstands that had sea levels of -30 m for thousands of years were around 80,000 years ago and before that from 107,000-98,000, which was the single longest stillstand in the past 250,000 years (Brooke, et al., 2017). After their formation during these sea level highstands, the channels and estuaries would have been 30-90 m above sea level over the next 71,000 years (Chappell and Shackleton, 1986). During this time, they would have been exposed to only subaerial processes and likely subject to some sediment infill. The next time that sea level was near the -30 m shoreline features was not until 9,000 years ago, when sea level was already consistently rising after the LGM. Meltwater Pulse 1C would have submerged the features by 8,000 years ago, when sea level rose at about 0.05 m/yr, which would be fast enough to preserve them beneath sea level without significant infill of sediment over time (Hopely, 2011) (Figure 5.21).
For the contemporary shoreline at current sea level, landform evolution is driven by wave processes, both in direct erosion as well as in removing eroded material. This is observed in the cliff profiles being marine dominated, as seen in the Port Campbell region where cliff slopes reach nearly 90° (Bezore, et al., in progress, Ch.2). It therefore can be assumed that the submerged shoreline was formed under similar process conditions to those which formed the modern coast, although during this time, the Bass Strait was likely mostly exposed as a land bridge, as its average depth is 60 m below modern sea level (Lambert, et al., 2008; Kemp, et al., 2019). This would have led to a different wave regime than that seen today, with regards to both wave direction and angle.

Sea level has however oscillated since MIS 3 (Figure 5.21), meaning that the landforms have been submerged and exposed repeatedly after their initial formation. Sea level fluctuations were accompanied by climatic variations on land as well. In Australia, the climate varied spatially and temporally until 50 ka, after which the climate switched to a mostly wet environment until 40ka, at which point most of Australia became predominantly dry for the remainder of MIS 3, apart from southeastern Australia which remained relatively wet (Harle, 1997; Kemp, et al., 2019).

While wave attack eroded the rocky coast and formed the coastal features, the much wetter climate would have also increased subaerial erosion of the features as they formed as well. As sea level began to rise
over the features, storms moving onshore could have also reworked the surfaces at shallow depths. When sea level fell, leaving the landforms to be exposed to primarily subaerial processes, and each subsequent exposure to wave attack and subaerial processes would leave behind a more rounded, less distinct profile, leaving the paleofeatures with a less vertical morphology than their modern counterparts. It is also possible that the paleo-shoreline features, specifically the shore platforms, as they are nearly horizontal, were buried by sediment over time during sea level lowstands and then smoothed by post-glacial marine transgression. Upon sea level rising quickly at the end of the LGM, wave attack once again dominated and reshaped the landforms, but as it rose quite rapidly, the features were able to be preserved at depth and will retain their current morphology until sea level exposes them once again.

![Sea level curve](image)

**Figure 5.21** Sea level curve adapted from Grant, et al., 2014 shown in blue with the sea level proxy dates from studies around Australia (see Table 5.1) shown in red in Inset A.
5.6 Conclusions

The coast of Victoria, Australia has been an actively eroding rocky coast over multiple eustatic cycles. During the first half of MIS 3, the Victorian coastline looked much like today’s modern coast, only 60 m below modern sea level and 6 km offshore. Shore platforms, hard rock cliffs, and even sea stacks were being eroded from the rocky coastline, evolving over thousands of years during the sea level high stand, much as the modern coast has evolved over the past 8,000 years. As these features formed through wave attack, they were also eroded above sea level by wetter than present climatic conditions, including increased precipitation and high winds. As the climate began to dry and sea level began to drop during the second half of MIS 3 and into the Last Glacial Maximum, the coastal landforms were preserved above sea level until the end of the LGM. At this point, sea level began to rise rapidly enough to submerge and continue to preserve the paleo-shoreline features at depth, leaving the relict coastline 60 m below sea level today. Subsequent changes in sea level, primarily after the LGM, have also left behind remnants of a previous shoreline, such as river channels and estuary basins around 30 m below sea level. These features are much younger and have not been exposed to subaerial processes since their submergence some 8,000 years ago, leaving their morphology much as it was when they first formed.

5.7 Acknowledgements

This work was partly funded by the Australian Research Council (LP130100204). We thank Parks Victoria for funding the capture of the multibeam sonar data used in this study and for allowing used of the resultant data. This study was also made possible by Deakin University and through the University of Melbourne through the Melbourne International Research Scholarship.
### 5.8 Tables

**Table 5.1** Location, depth, and age of various sea level proxies, compiled from studies focused on sea level history for Australia.

<table>
<thead>
<tr>
<th>Location</th>
<th>Proxy Type</th>
<th>Depth (m)</th>
<th>Age (yrs) Or Epoch</th>
<th>Reference</th>
</tr>
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<tr>
<td>Great Barrier Reef, Australia</td>
<td>-Coral reefs -Terrace step</td>
<td>-40 to -70 m depth (corals)</td>
<td>12-10 ka</td>
<td>Beaman, et al., 2008</td>
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<td></td>
<td></td>
<td>78-114 m (terrace step)</td>
<td>20 ka</td>
<td></td>
</tr>
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<td>-Shallow, intertidal, and subaerial sediments -Shallow water coral</td>
<td>-130 to -150 m</td>
<td>20-18 ka</td>
<td>Chappell, 1987</td>
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<td>-Wood samples -Tree stumps -Fresh water peats</td>
<td>-20 m</td>
<td>10-8 ka</td>
<td>Lambeck, 1990</td>
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<td>-Offshore ridge</td>
<td>2.5 m</td>
<td>6 ka</td>
<td>Chappell, et al. 1982</td>
</tr>
<tr>
<td>South Australia, Australia</td>
<td>-Benthic foraminifera</td>
<td>-22 m</td>
<td>40-31 ka</td>
<td>Cann, et al., 1988</td>
</tr>
<tr>
<td>Great Barrier Reef, Australia</td>
<td>-Shallow marine formed ooids</td>
<td>-100</td>
<td>16.8 ka</td>
<td>Yokoyama, et al., 2006</td>
</tr>
<tr>
<td>Warrnambool, Australia</td>
<td>- Molluscs</td>
<td>7.5</td>
<td>125-110 ka</td>
<td>Gill, 1988</td>
</tr>
<tr>
<td>Northwest Shelf, Australia</td>
<td>-Tidal sediments</td>
<td>-80 -88 -118 -120 -110 to -100 -95</td>
<td>48 ka</td>
<td>Yokoyama, et al., 2001</td>
</tr>
<tr>
<td>Sahul Shelf, between Northern Territory, Australia and Papua New Guinea</td>
<td>-Submerged shorelines</td>
<td>-100 -75</td>
<td>15 ka</td>
<td>Bloom and Yonekura (1990)</td>
</tr>
<tr>
<td>Sydney, Australia</td>
<td>-Mangrove roots</td>
<td>1</td>
<td>7 ka</td>
<td>Thom and Roy, 1985</td>
</tr>
<tr>
<td>New South Wales, Australia</td>
<td>-Organic fragments</td>
<td>-22</td>
<td>6.7 ka</td>
<td>Umitsu et al., 2001</td>
</tr>
<tr>
<td>Torres Strait, Australia</td>
<td>-Submerged incised valley</td>
<td>-30 to -50</td>
<td>33.8 ka</td>
<td>Harris, et al., 2005</td>
</tr>
<tr>
<td>Rottnest Shelf, Western Australia, Australia</td>
<td>-Submerged ridges</td>
<td>-25 to -30 -50 to -60</td>
<td>100-80 ka 60-27 ka</td>
<td>Brooke, et al., 2010</td>
</tr>
<tr>
<td>South-eastern Australia</td>
<td>-Fossil molluscs</td>
<td>-130 to -150</td>
<td>20 ka</td>
<td>Ferland, et al., 1995</td>
</tr>
<tr>
<td>Northern Territory, Australia</td>
<td>-Sediments</td>
<td>-14.84 to -13.95</td>
<td>125.7 ka</td>
<td>Reeves, et al., 2008</td>
</tr>
</tbody>
</table>
Table 5.2 Offshore paleo-shoreline landforms discovered and analyzed in this study, including feature type and maximum depth at the base of each feature.

<table>
<thead>
<tr>
<th>Closest Onshore Location</th>
<th>Feature Type</th>
<th>Maximum Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discovery Bay</td>
<td>Paleo-cliffs</td>
<td>57.2</td>
</tr>
<tr>
<td>Fitzroy River (at Narrawong Coastal Reserve)</td>
<td>Paleo-lava tube</td>
<td>40.2</td>
</tr>
<tr>
<td>Hopkins River (at Warrnambool)</td>
<td>Paleo-river channel</td>
<td>28.8</td>
</tr>
<tr>
<td>Port Campbell</td>
<td>Paleo-cliffs</td>
<td>62.7</td>
</tr>
<tr>
<td>Port Campbell</td>
<td>Paleo-sea stacks</td>
<td>62.1</td>
</tr>
<tr>
<td>Port Campbell</td>
<td>Paleo-river channel</td>
<td>51.0</td>
</tr>
<tr>
<td>Port Campbell</td>
<td>Paleo-shore platforms</td>
<td>57.2</td>
</tr>
<tr>
<td>Wattle Hill</td>
<td>Paleo-river</td>
<td>31.3</td>
</tr>
<tr>
<td>Cape Otway</td>
<td>Paleo-dyke</td>
<td>36.7</td>
</tr>
<tr>
<td>Cape Otway</td>
<td>Paleo-ridge</td>
<td>40.0</td>
</tr>
<tr>
<td>Cape Otway</td>
<td>Paleo-estuary basin</td>
<td>26.5</td>
</tr>
<tr>
<td>Wongarra</td>
<td>Paleo-cliff</td>
<td>52.7</td>
</tr>
<tr>
<td>Wongarra</td>
<td>Paleo-shore platforms</td>
<td>56.3</td>
</tr>
<tr>
<td>Kennett River</td>
<td>Paleo-river channel</td>
<td>42.8</td>
</tr>
<tr>
<td>Lorne</td>
<td>Paleo-shore platforms</td>
<td>53.1</td>
</tr>
<tr>
<td>Anglesea</td>
<td>Paleo-river channel</td>
<td>29.3</td>
</tr>
<tr>
<td>Anglesea</td>
<td>Paleo-estuary basin</td>
<td>36.0</td>
</tr>
<tr>
<td>Anglesea</td>
<td>Paleo-shore platforms</td>
<td>53.1</td>
</tr>
<tr>
<td>Barwon</td>
<td>Paleo-river channel</td>
<td>34.6</td>
</tr>
<tr>
<td>Phillip Island</td>
<td>Paleo-sand ridges</td>
<td>48.5</td>
</tr>
</tbody>
</table>
5.9 References


Boutakoff, N., 1963. The geology and geomorphology of the Portland area (No. 22). Department of Mines.


CHAPTER 6

Conclusions
6.1 Summary and Conclusions

The primary research question driving this dissertation was how interstadial shorelines are preserved over multiple eustatic cycles. To answer this overarching question, it was necessary to address what boundary conditions determine rocky coast morphology along the modern shoreline and how these erosional landforms evolve over multiple changes in sea level. This research focused on sea cliffs, shore platforms and sea stacks along the present-day coast of Victoria to provide insight into the boundary conditions and erosional processes forming these features at current sea level. Offshore of Victoria, the use of bathymetric sonar data allowed for a comprehensive mapping and analysis study of the same types of landforms but submerged at 50 m below sea level, providing an understanding of how they formed and of how their morphology changed over geologic time. Below are the key findings from each of the previous chapters and their broader implications and applications for the field of coastal geomorphology.

6.2 Chapter 2- Sea Stacks

Five paleo-sea stacks were discovered 6 km offshore of Peterborough, Victoria, roughly 12 km west of the modern Twelve Apostles. These submerged sea stacks are 60 m deep at their bases and stand about 10 m tall, making them a quarter of the height of their onshore counterparts. They are believed to be comprised of limestone and possibly sandstone and were formed much in the same way that the Twelve Apostles were formed over the past 6,000 years through wave attack at a cliff face, forming caves, arches, and eventually collapsing into free-standing sea stacks. Since their formation, the sea stacks have been exposed above sea level multiple times during sea levels lower than -50 m, with each exposure and re-submergence rounding and eroding the stacks, creating lower and wider profiles. While the modern sea stacks are all within 5 m of present sea level, the paleo-sea stacks have a range of 10 m for their depths, making them less accurate sea level proxies. The Drowned Apostles case study is the first research to definitively discover and analyze paleo-sea stacks preserved at depth. Previously, these features were believed to be so highly erosional that they would not be able to withstand multiple sea level cycles and would likely form and erode within a single sea level stillstand.

6.3 Chapter 3- Sea Cliffs

This chapter focused on the Victorian coastal region between Peterborough in the west to Wilsons Promontory in the east. Of this 501 km long section of coast, 261 km were classified as cliffs, using a minimum of 20° slope to qualify a feature as being a cliff. Cliffs were found in limestone, sandstone, mudstone, granite, and basalt lithologies. This study found that the morphology of cliffs were determined not only by the dominant erosive processes (marine or subaerial) acting on the cliff face, but also the lithology and especially the compressive strength of the rock itself. The height of a cliff was most
strongly confined by the shear strength of the rock and any structural weaknesses, meaning that more cohesive rock units with vertical bedding planes that were able to withstand overlying pressure would produce taller cliffs compared to more jointed and fractured or weaker lithologies. As for cliff slopes, this study found that softer rock types such as sandstones and limestones produced much steeper cliff faces compared to the harder rock types such as granites, which are influenced to a lesser degree by wave attack due to being more erosion resistant.

Submerged paleo-cliffs were also found at 50 m depth offshore of Discovery Bay, Port Campbell, and Wungarra. These cliffs also have slopes greater than 20°, although they all tend to be slightly more rounded and gently sloping than the cliffs onshore nearby in each case. The submerged cliffs were formed under the same erosional processes that formed the cliffs found on the modern coast, in that marine erosion was responsible for eroding the cliff face through wave attack and subaerial erosion was the dominant force above the reach of waves. Since cliffs form at or very near sea level, and the modern cliffs in this study were all within 8 m of sea level and the paleo-cliffs had a range of +/- 17 m depths at their bases, it can be assumed that the paleo-cliffs were formed when sea level was near their bases, 50 m below present sea level. Given that cliffs require on the order of a thousand years or more to form, this constrains the time of formation to the first half of Marine Isotope Stage 3. Another set of submerged cliffs was also found near 30 m below modern sea level, meaning that there is evidence for two distinct paleo-shorelines in this study area. Highstands at 130–110 ka, 100 ka, and 80 ka were likely responsible for the primary evolution of the -30 m shoreline.

6.4 Chapter 4- Shore Platforms

Shore platforms were found across 170 km of the Victorian coast in basalts, sandstones, and mudstones. These features all were within 2 m of modern sea level and all had slopes less than 12°. This study found that there was not a strong correlation between rock strength and platform elevation and that the lower elevation of the basalt platforms can instead be attributed to limited initial lava flow heights. The slope of the platforms were found to be largely controlled by the hardness and structural integrity of the rocks in which they form, however, with platform gradients increasing with rock hardness.

Paleo-shore platforms were also found offshore of Port Campbell, Wungarra, Lorne, and Anglesea. The platforms offshore of Port Campbell were backed by paleo-sea cliffs and had a mean depth of -47 m and a mean slope of 3°. While the shore platforms on the modern coast have formed over the past 6,000 years, except for those that may have been inherited from previous sea level high stands and preserved in the interim, the paleo-shore platforms would have formed when sea level was roughly 50 m below present. As was the case with the paleo-sea cliffs, the most likely age of formation for these features is MIS 3.
Given that sea level has risen above and fallen below -50 m multiple times since MIS 3, the continued exposure and re-submergence of the platforms has reshaped their morphologies and primarily responsible for their broader zone of formation. While the modern platforms were a more reliable proxy for sea level, the paleo-platforms can still provide an error bound of 7 m for MIS 3 sea level.

6.5 Chapter 5- MIS 3 Shoreline in Victoria, Australia

As seen in Chapters 3-5, there are clear geomorphic landform indicators of an MIS 3 -50 m paleo-shoreline offshore of present-day Victoria Australia. In addition to the paleo-sea stacks, cliffs, and shore platforms discovered above, there were also paleo-river channels and even estuary basins discovered. These submerged features were identified using the same classification methods used to identify their modern, onshore analogous landform types. For instance, sea cliffs were identified as tall linear rock features having slopes greater than 20°, shore platforms as being low lying hard rock bench features with slopes less than 12°, sea stacks as being columnar features comprised of hard rock, river channels as being sinuous incisions in bedrock usually ending in an alluvial shaped river mouth, and estuary basins as being oblong depressions located at or near river mouths. In total, erosional paleo-landforms comprised 8% of the -50 m contour offshore of the modern coast.

Offshore of the present-day Fitzroy River, a paleo-river was found extending 7.5 km southeast that was surrounded by a riverplain over 29 km² in area and reaches nearly 6 km wide. The bathymetry for the channel and the surrounding delta reach depths up to 40 m below modern sea level. There was also a paleo-channel offshore of Warrnambool, proximal to the Hopkins River mouth and reaching 4.4 km offshore to the southeast. This is also a shallower paleo-channel, only reaching -29 m depth at its deepest point.

In addition to the paleo-cliffs and shore platforms offshore of Port Campbell, there was also a 5.7 km long paleo-river extending offshore from the Curdies River in Peterborough. This channel has at least four clear branches extending off of the main channel, which appears to end at the base of the submerged cliffs in an incised river valley. At the base of the cliffs and river mouth is an estuary basin at -62 m depth about 6 km offshore.

At Wattle Hill is paleo-river channel that runs parallel to the coast, and unlike the other paleo-channels, does not have a distinct or recognizable modern river counterpart onshore. This channel is also notable and unique because it appears to be bedrock confined, but the channel is also anastomosing. The depositional pattern surrounding the channel seaward is also rather large and complex and comprises 47 km².
Offshore of Cape Otway were a number of paleo-features, including a possible dyke or fault extending from the modern coast to nearly 6 km offshore. There were also two paleo-estuary basins reaching -20 m and -27 m. Southwest of the basins sat a low sloping ridge with a base depth of -40 m and a height of about 4 m.

At Kennet River, there was another paleo-river channel, this time extending eastward from the modern coast for over 2 km and ending at -43 m depth. Along the southern side of the channel was a large sediment fan that extended the full length of the channel seaward, ending nearly -50 m below sea level at the seaward terminus.

A paleo-river channel and a rather large estuary basin were found offshore of Anglesea. The paleo-channel lies near the onshore river mouth of the Anglesea River and has a meandering path ending at -29 m depth. At the river mouth of this paleo-channel was found a large depression that represents a paleo-estuary basin, reaching a maximum depth of -36 m.

The Barwon River also feeds into a paleo-river channel that branches off into 4 smaller channels. An estuary basin that measured almost 0.7 km across and just over 1 km in length sat between the main channel before it branched off into the four smaller channels. At the deepest portion of the channels, the depths reached nearly -35 m below sea level.

Finally, offshore of the southwest tip of Phillip Island is a series of five paleo-ridges all running southwest to northeast at an oblique angle to the modern coast. The depth at the base of the bluff sitting furthest seaward was -49 m.

The presence of the paleo-landforms offshore of Victoria provides evidence for a long term high wave energy, erosional system for the region, spanning multiple sea level cycles. The depth at which the landforms are found beneath modern sea level can provide insight into past sea level changes in Victoria, as the depth at their base now is at or near the sea level at which they were formed. The majority of the paleo-features in this study, especially the hard rock features, were found at or very near -50 m depth, corresponding with a MIS 3 sea level of 50-60 m below present (Figure 6.1). The paleo-channels and estuaries tended to fall between 30-40 m depth, however, indicating that these features likely formed either 80 ka or between 107-98 ka. Following their formation, these features would have been 30-90 m above sea level until 9 ka. Since rising above these landforms around 8,000 years ago, sea level has not fallen below their formation depths, preserving them much as they would have looked when they first formed. Though the paleo-shoreline landforms are likely composed of the same lithologies as the modern coastal features in each study area due to the maximum thickness of each unit, differing lithologies in
addition to varying erosive processes over geologic time could have attributed to differences in the paleo-landforms’ morphology compared to the modern coast.

![Figure 6.1](image)

Figure 6.1 Histogram showing the frequency at which the paleo-landforms in this study were found at each depth. There is a clear binary depth trend showing the paleo-shorelines at -50 m and roughly -40 m below modern sea level.

After the initial formation of the MIS 3 landforms, sea level fell and left the landforms exposed to subaerial erosion above sea level. Until the Last Glacial Maximum, the MIS 3 shoreline would have been submerged and exposed multiple times (Figure 6.2), each regression and transgression reshaping and eroding the features to make them more gently sloping and shorter than their onshore counterparts (Figure 6.3). The frequency with which sea level was 30-40 m below sea level is nearly three times higher than it has been 50-60 m below modern levels. The shallower landforms would have also likely formed at least 20,000 years prior to the MIS 3 shoreline and been subjected to subaerial processes as stranded shorelines above sea level for over 70,000 years following their formation until nearly 9,000 years ago. Immediately following the end of the LGM, however, sea level would have risen quickly enough to once again erode the shorelines while still submerging it at a rate that allowed the features to be preserved at depth.
Figure 6.2 Histogram showing the frequency at which sea level has been at each stage compared to modern sea level (0 m on the x-axis).

Figure 6.3 Diagram showing proposed process of cliff evolution progressing from cliffs being formed through marine and subaerial erosion during a sea level stillstand (A), to the cliffs being primarily controlled by subaerial processes as sea level falls (B), to cliffs being subjected to primarily marine erosion as sea levels quickly rise (C), to cliffs being submerged by high sea levels and no longer being exposed to erosion (D) (Bezore, et al., in progress, Ch.2 Figure 7).
Increasing availability, both in the quality and the quantity, of bathymetric data allows for in depth analysis of submerged paleo-shorelines in a way that has not previously been feasible in many locations globally. The ability to measure morphological characteristics provides insight into how relict coasts formed, looked, and evolved during lower sea level highstands compared to the modern coast. Analysis of the onshore features found adjacent to these submerged shorelines allows for an analogous study of both how rocky coasts relate to the sea level in which they are formed and how they change morphologically in response to rising and falling sea levels over geologic time. In high-energy, wave dominated environments, especially in temperate climates where coral reef and other biological sea level proxies may not be available, submerged paleo-shorelines can provide constraints on past sea level high stands and help improve the accuracy of eustatic and regional sea level curves. As the coast of Victoria, Australia is in a relatively stable tectonic setting with a sea level history that closely matches eustatic trends, the paleo-shorelines analyzed in this study present constraints on the duration and amplitude of previous sea level highstands as well as presenting the possible depths at which other submerged features may be found globally.
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