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The Drowned Apostles: The Longevity of Sea Stacks over Eustatic Cycles

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ABSTRACT

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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). 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 preferrentialy 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 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 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) is Port Campbell Limestone overlaying the Gellibrand Marl

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(Geological Survey of Victoria Report 103, 1995). 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 south-west 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).

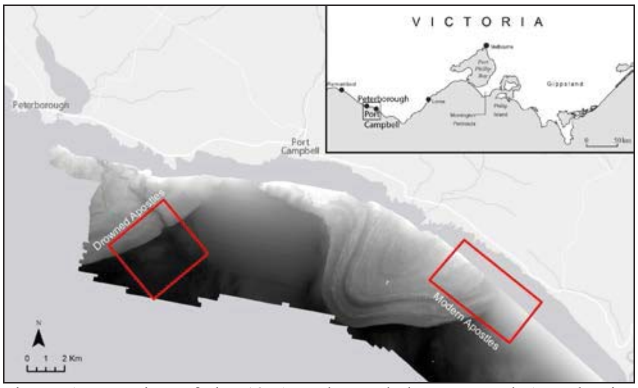

Figure 1. Location of the 12 Apostles and the Drowned Apostles in Victoria, Australia.


Figure 2. Aerial photo of the 12 Apostles Port Campbell, Victoria.

METHODS

This study uses bathymetric and terrestrial LiDAR data collected in 2007 using a LADS Mk II system with a GEC-Marconi FIN3110 intertial 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˚ 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 Port Camp

The morphological features identified in the LiDAR data were then measured and analysed in ArcGIS. Cliff erosion was analysed 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 polyline 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 apostles. 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.

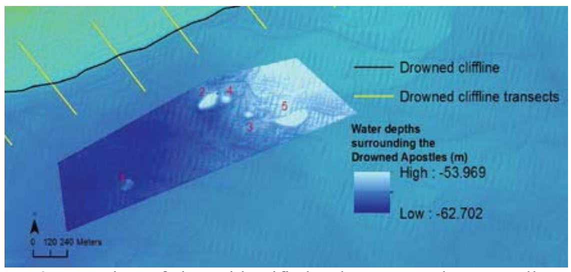

Figure 3. Location of the 5 identified paleo-sea stacks, as well as the transects used to measure the drowned cliffs backing them.

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 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 1).
The current stacks sit at an average distance of 118.65 m offshore (Table 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 902.88 - 21,564.60 m²), and the average perimeter was 275.79 m (range of 127.07 - 599.72 m) (Figure 6). The drowned Apostles are found farther seaward from their respective shoreline than the modern Apostles, at an average distance of 655.32 m from the drowned cliff (Table 1).

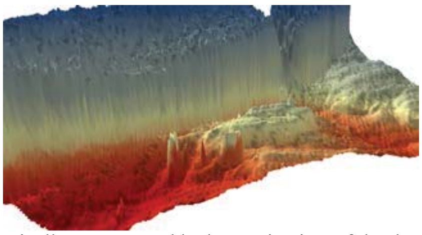

Figure 4. Vertically exaggerated bathymetric view of the drowned sea stacks and paleo-cliffs behind them.

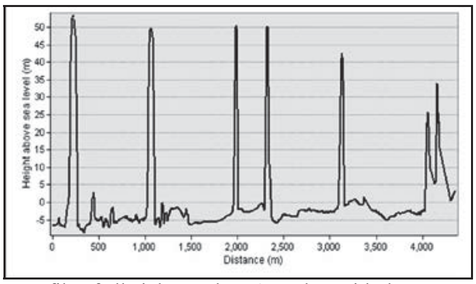

Figure 5. Profile of all eight Modern Apostles, with the westernmost stack (Modern Apostle 1) shown on the left.

The sea cliffs also vary in height, with the drowned cliffs averaging 13.60 m high, which gives a sea stack height to cliff height ratio of 0.32. Compared to the modern cliffs, the drowned cliffs are more rounded and have a lower angle toe with an average cliff face slope of 29˚. The water depths surrounding the

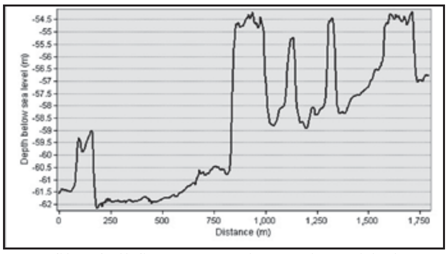

Figure 6. Profile of all five Drowned Apostles, with the westernmost stack (Drowned Apostle 1) shown on the left of the graph.

Drowned Apostles span from 58.11 - 62.12 m depth with an average depth of 59.72 m (Table 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 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 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 1. *Dimensions of each drowned and modern sea stack.*

	Height (m)	Length (m)	Width (m)	Area (m²)	Perimeter (m)	Dist. from cliff (m)	Depth stack base (m)
Drowned Apostles							
1	3.32	70.45	57.55	4,346.00	274.35	788.51	62.12
2	6.47	98.78	117.24	1,1034.48	423.18	484.72	60.74
3	3.95	25.17	38.27	902.88	127.07	524.44	58.33
4	4.25	48.10	67.02	3,071.88	228.96	691.51	59.35
5	3.90	116.33	207.94	21,564.60	599.72	787.40	58.11
12 Apostles							
1	67.45	95.68	66.75	7,900.24	354.84	65.26	-10.74
2	12.98	34.53	38.50	1,410.87	146.02	141.29	-5.77
3	56.92	57.43	70.14	4,433.83	247.76	152.14	-7.75
4	53.80	57.96	40.74	2,536.41	205.47	120.64	-2.88
5	54.49	25.82	31.99	1,091.61	130.72	178.29	-2.60
6	47.78	61.00	41.57	1,952.43	191.25	49.40	-3.65
7	30.34	41.37	44.92	1,387.81	142.85	159.40	-2.61
8	38.73	45.22	38.01	714.42	127.32	82.78	-4.78

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 (Nicolaides, 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.

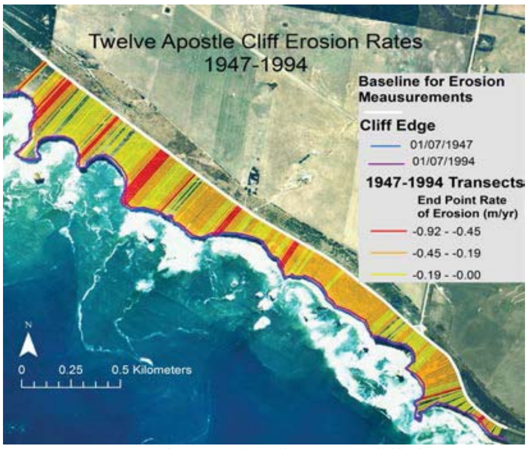

Figure 7. Erosion rates of the modern limestone cliffs from 1947 - 1994.

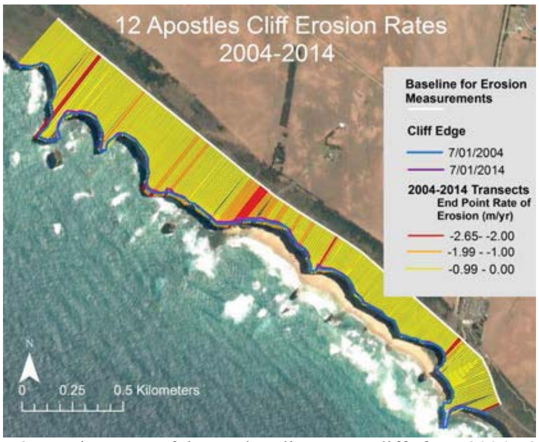

Figure 8. Erosion rates of the modern limestone cliffs from 2004 - 2014.

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. Therefore, using the formation depths and a relative sea level curve extending back over the past 250 kyr, the most likely age of formation of the drowned Apostles was during the Marine Isotope Stage 3 (MIS 3) (60-27 ka) (Figure 9).

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 interstadial 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.

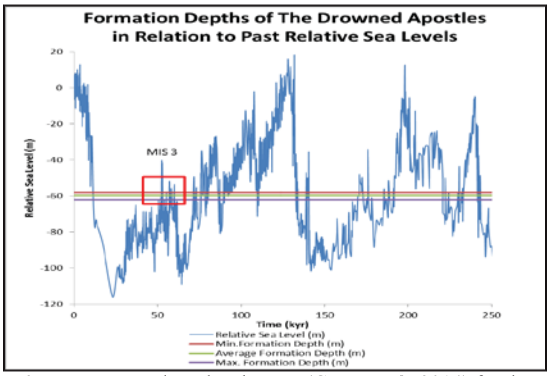

Figure 9. Reconstructed sea level curve (Grant *et al.*, 2014) for the past 250 thousand years with the best fit for the age of formation of the drowned sea stacks based on the depth of water in which they sit currently.

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 trangression, 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.

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