A REGIONAL REVIEW OF COASTAL HAZARDS ALONG THE SOUTH WEST COAST OF WESTERN AUSTRALIA

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Geoscience Australia's Urban Geoscience Division, through its Risk Modelling Project and Cities Perth Project, is assessing the risks to Perth communities from a variety of natural hazards such as tropical cyclones, floods, earthquakes and landslides. This study is focused at the regional scale and involves a number of collaborators including the Bureau of Meteorology, the Fire and Emergency Services Authority of Western Australia and the WA state government department for Planning and Infrastructure. The ultimate objective of this research is to provide policy makers and hazard managers with decision support tools that will enable the better implementation of mitigation strategies. Ultimately these strategies will reduce loss of life, property damage and economic disruption from natural hazards.

1.2 COASTAL HAZARDS

The south west coast of WA comprises a series of exposed limestone headlands that are prone to the development of cliff lines and large overhangs. Coastal processes such as wind and water erosion in conjunction with salt crystallisation, and carbonate dissolution, make these cliffs highly susceptible to collapse.

The damaging impact that these unstable cliffs can have on the community was demonstrated on the 27th of September 1996, when four adults and five children were killed in a rockfall at Huzzas Beach, Gracetown. They were sheltering under a large overhang at the base of a limestone cliff, when the overhang collapsed without warning. At the time of the tragedy, this was the largest death toll for a rock fall or landslide in Australia, and equal to the number of lives lost in the 1989 Newcastle earthquake.

This tragedy highlighted the significance of coastal cliff collapse as a serious hazard along the southwest coast of WA. In response to this tragedy the coroner determined in his report 'That all authorities and bodies having responsibility for the coastal region of Western Australia in areas where there are cliffs should develop or adopt appropriate cliff management policies'. Many Local Government Authorities (LGAs) responded by employing geological and engineering consultants to investigate 'site specific' coastal limestone hazards. Some LGAs have acted to eliminate particularly hazardous areas by earthworks, blocking up caves, fencing and signage, but there are still areas that appear to have had little remedial work done.

1.3 PROJECT AIMS

As a part of the Geoscience Australia graduate program, this study has been conducted to investigate the nature of coastal hazards along the south west coast of WA, including the safety of the dune systems. This report is intended to provide a regional overview of coastal hazards along the south west coast, and is not designed to evaluate the stability of individual outcrops. This study was not intended to duplicate the work done by geological consultants, but to put these results into a regional context.

CHAPTER 2: GENERAL GEOLOGY OF THE COAST

2.1 INTRODUCTION

The coastline of the study area is approximately 300km in length, stretching from Gingin in the North, to Cape Leeuwin in the south (Figure 2.1). Beaches generally face northwest or southwest and are dominated by a series of exposed limestone cliffs and headlands, rock platforms, extensive dune systems and sandy beaches.

The coastline within the study area is composed of two main geological units (i) the Tamala Limestone; and, (ii) the Safety Bay sand. Both of these formations belong to the early Pleistocene to Holocene Kwinana Group (Playford *et al.*, 1976). They have been mapped at a scale of 1:50,000 by the Geological Survey of Western Australia (GSWA) in their Urban Geology Series and more recently in their Environmental Geology Series (Gozzard, 1989).

2.2 GEOLOGY

2.2.1 Tamala Limestone

The Tamala Limestone (LS1 on the Environmental Geology sheets) consists of coarse to medium-grained calcarenite, composed mainly of foraminifera and mollusc fragments, with some detrital quartz sand (Playford *et al.*, 1976). This limestone (otherwise known as the Tamala Eolianite) was formed from the cementation of the Spearwood Dune System by calcium carbonate (Playford *et al.*, 1976).

The Spearwood Dune System is a late Pleistocene formation (120ka) that comprises a series of coast-paralleling limestone ridges that were originally deposited as a transgressive sheet of coastal sand dunes (Gozzard and Smurthwaite, 1988). As sea levels fell, the shoreline retreated to the west. Shore parallel lines of dunes marks the successive position of the coast during this period. From 120 ka – 6.5 ka, the sea level was lower than the present day and a series of coast-paralleling islands and submerged reefs mark this lower sea level (Playford *et al.*, 1976).

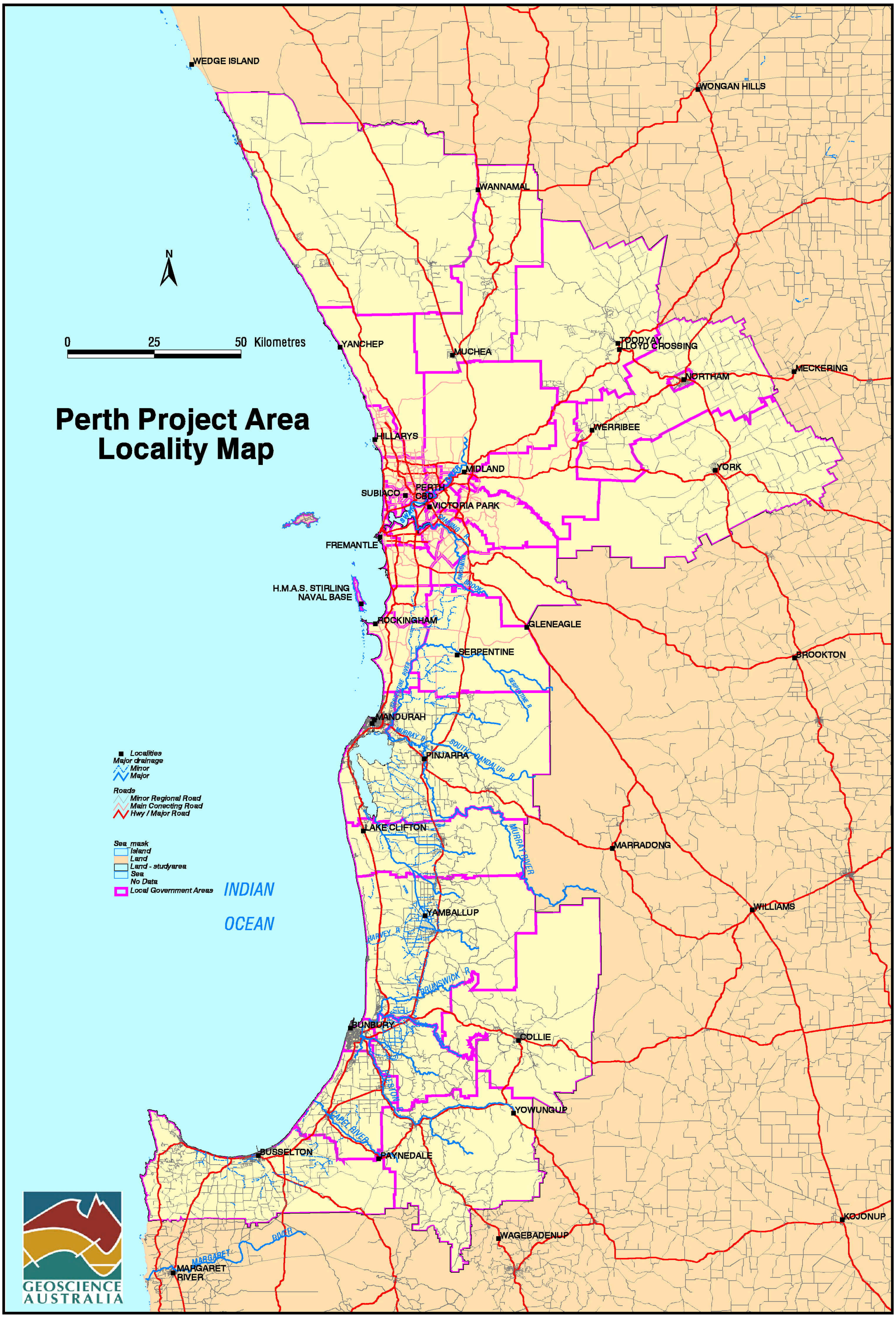

Figure 2.1: Location of the Perth study area is highlighted in yellow.

Paleosol (or fossi soil) layers, calcrete duricrust layers and calcified root structures are common features within the limestone. All three features are interlayered with the limestone and were developed during periods of sub aerial exposure.

Paleosol layers are light to dark brown in colour and can be up to 2 m thick, representing a hiatus in dune formation. They are unstratified, fine-grained calcareous soils that contain land snail shells and fossil cocoons of Weevils (Gordon, 1997). These periods of soil development allowed plants and trees to establish themselves within the dunes. The longer the hiatus in dune formation, the more extensive the vegetation.

Calcrete duricrust formation is a common feature of carbonate weathering and also forms during a hiatus in the dune building process. The duricrust forms when calcium carbonate from shells, is leached from the underlying layers of limestone and redeposited at the surface. The surface deposition of calcium carbonate forms a hard indurated caprock above the fossil soil layer, leaving the underlying limestone weak and friable. This calcium carbonate depleted layer weathers rapidly under the indurated caprock leaving hard calcrete casts and moulds of fossil roots as prominent features. This is known as the Zone of Roots (Gordon, 1999) and can be seen in extensive outcrops along the coastal fringe (Figure 2.2).

Figure 2.2 Hard calcrete casts and moulds of fossil roots can be seen in this outcrop of Tamala Limestone at site 6 (see Appendix A).

2.2.2 Safety Bay Sand

The Safety Bay Sand overlies the Tamala limestone and is Holocene (< 10 ka) in age. It occurs along the length of the study area and includes all of the modern dunes along the coastline. The beach ridge plain around the Rockingham area, as well as sand still being deposited are also a part of this unit.

The Safety Bay sand has an average calcium carbonate content of over 50% and is made up of shell fragments (mainly foraminifera and molluscs) with variable amounts of quartz and minor feldspar. This poorly to moderately consolidated sand can be weakly cemented below the dune surfaces, marking the first stage in conversion to eolianite (Playford *et al*. 1976).

The Environmental Geology map series produced by the GSWA has subdivided the Safety Bay sand into many different units based on their physical and mechanical characteristics. Only three of these subdivisions however occur along the coastline of the study area. These units are referred to as S1, S2 and S13 on the Environmental Geology maps and can be described as below:

S1 is most commonly found forming flat to gently sloping sandy beaches along the coast (Figure 2.3). The sand is calcareous fine to medium-grained, sub-rounded quartz and shell debris of eolian origin. This unit is not vegetated and has an elevation ranging from 0 – 25 m ASL (above sea level).

S2 also consists of fine to medium-grained, sub-rounded quartz and calcareous shell debris of eolian origin. This unit however, is most commonly found forming large undulating dunes with moderate to steep slopes ranging from ~10^o to >20^o (Figure 2.3) These vegetated dunes have an average elevation between 20 – 60 m but can reach heights of 140 m along the Naturalise coast.

S13 is predominantly found on beach ridge plains forming low (< 10m) undulating dunes. The unit consists of well sorted, medium-grained calcareous sand with rounded quartz and shell debris of eolian origin. The sands are variably thick and overlie limestone at relatively shallow depth.

Figure 2.3 Profile of Mindarie Beach in the City of Wanneroo. This beach is a typical example of the relationship between S1 and S2 Safety Bay Sands. S2 forms large dunes backing the gently sloping S1 beach.

2.3 COASTAL STABILITY

2.3.1 Introduction

The world's coastlines are dynamic systems in a constant state of flux. Through the process of erosion, transportation and deposition, the shape of the coastline changes, often slowly but sometimes very rapidly. The interaction between rock, water, wind and vegetation is responsible for the dramatic landforms we see along the coast today. Unfortunately however, these dynamic interactions can result in hazards that put our communities at risk.

2.3.2 Tamala Limestone

The Tamala Limestone is a soft porous rock that is highly susceptible to solution from weakly acidic water such as rainfall, seawater and groundwater. The carbonic acid in these waters causes the dissolution and removal of calcium carbonate in solution, resulting in a loss of carbonate from the limestone (Murck *et al*. 1997). This process is known as Karst weathering and occurs mainly along fractures and openings within the limestone rocks. Over time, large volumes of rock can be dissolved away, forming voids and zones of friable sand within the limestone. Sinkholes, caves and underground drainages are also characteristic of this type of weathering.

In conjunction with Karst weathering, which diminishes the structural integrity of the limestone, the unit is also vulnerable to mechanical weathering from wind and wave action. Wave action at the base of a cliff gradually erodes the limestone, undermining the cliff and developing an overhang (Figure 2.4). This process of erosion continues until the overhang becomes sufficiently undermined and collapses.

Rainfall can often be the trigger for an overhang collapse, such as the one at Gracetown in 1996. In a report to the Gracetown coroner, F.R. Gordon (1997b) stated that 'the eolianite cliff face has the capacity to absorb 30-40% water with the more sandy materials having higher absorptive capacities'. It was his view that 'the trigger for the rockfall was the heavy rainfall of the 27th and the antecedent days driving into the face, which increased the weight of the rock and sand mass by up to 40%'.

Figure 2.4 Wave action at the base of this cliff has initiated the development of an overhang.

Overhangs can also be developed from the action of wind, rainfall impact and salt spray erosion. These forces have the most impact on the softer more friable layers such as the Zone of Roots, therefore accentuating the differences between the layers of hard indurated caprock and the underlying Zone of Roots.

As the Zone of Roots weathers, the hard calcrete fossil roots are accentuated as the surrounding leached material is removed through erosion. Infilled solution pipes extending into the ZoR can act as columns to the caprock and provide support which may allow a large area to be eroded before collapse occurs (Gordon, 1997c).

2.3.3 Safety Bay Sand

Dunal systems formed by the Safety Bay Sand (S2), can be particularly hazardous if they are subject to erosion. The foredunes along the coastline are comprised of loose, unconsolidated sand with a natural angle of repose averaging around 30^0. When this angle of repose is increased due to erosion, the dune may become unstable and subside, therefore creating a hazard for people visiting the beach.

Erosion of dunal systems can occur through several processes. The first agent of dune erosion is that caused by wave action upon the seaward margin of a foredune (Figure 2.5). This natural process cuts into the base of the dune, increasing the angle of repose and exposing a crumbling cliff of sand. This process can dramatically increase the risk of collapse and is most common during winter storms.

Figure 2.5 The natural angle of repose for these dunes has been steepened to almost 90^o due to erosion.

Human impacts on the dune systems are a major cause of instability. The popularity of beaches for recreational activities means that human impact is inevitable. The stability of coastal sand dunes relies heavily upon the existence of vegetation. Dune vegetation acts as a barrier to surface wind speed, trapping blown sand and holding it in place. When vegetation is removed from the dune systems, erosion increases, as does the risk of subsidence. The direct impact of people on the dunes is primarily through trampling that occurs as people walk from the carpark over the dunes to the beach. This type of activity destroys the vegetation cover and may lead to the formation of blowouts or mobilise dunes that were previously fixed.

Other human activities that destroy the natural stability of dunes include horse riding, 4W driving, housing and industrial development, as well as digging into the foot of the dune. Recently, two children have been killed and two injured in Australia by digging or tunnelling into sand.

In each case of erosion, it is possible for a collapse to occur and hence there is a risk of injury or loss of human life should that collapse occur at a time when members of the public are present.

CHAPTER 3: A REGIONAL REVIEW OF COASTAL HAZARDS

3.1 INTRODUCTION

The geomorphology and geology of the coastline varies from north to south within the study area. The change in geological landforms is significant, and enables the coastline to be classified into four distinct areas (Figure 3.1). Each area selected represents a coastal area dominated by a set of similar broad morphological and process characteristics, and therefore, also represents a number of hazards that may be unique to that particular landscape.

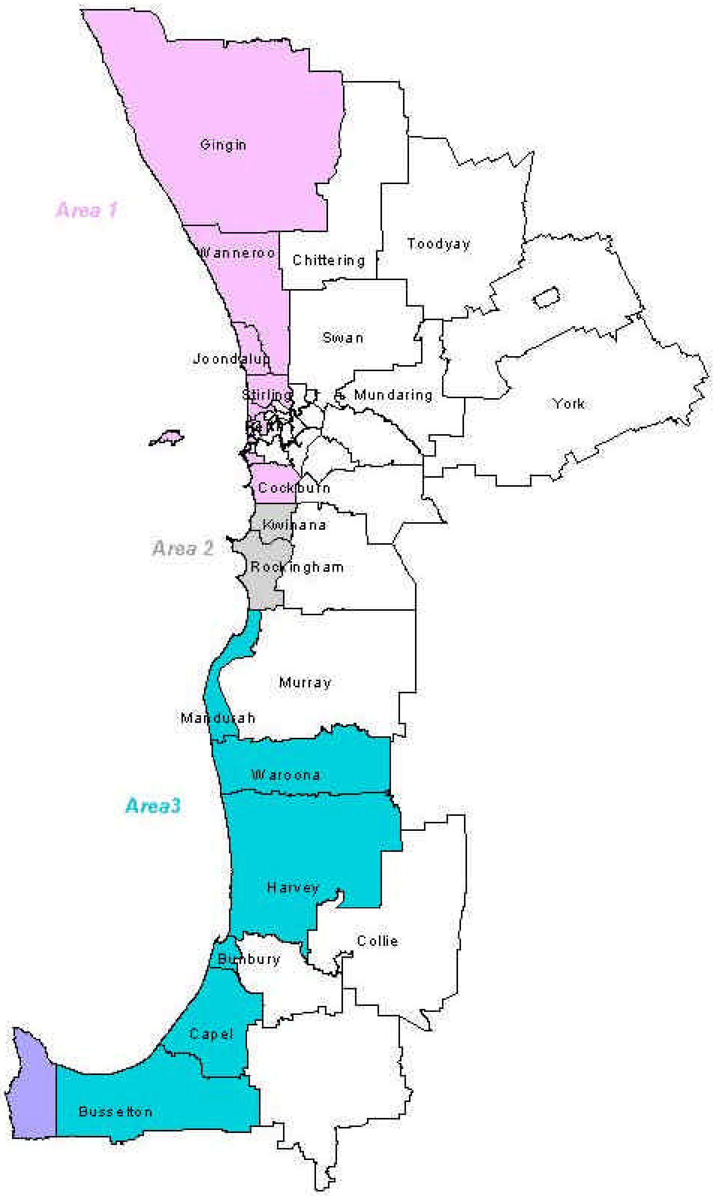

Figure 3.1 Location map showing the Perth study area, LGAs and the four subdivisions of coastline based on geological and morphological differences.

3.2 GEOGRAPHY AND PHISOGRAPHY OF THE STUDY AREAS

3.2.1 Study area number 1

Area no.1 encompasses the coastline from Naval Base (just north of Rockingham) to the northern most limit of the study area in the Shire of Gingin. The coastline within this area is almost linear with a constant north to northwest trend and has a typical absence of large bays and protruding headlands. Coastal geology within this area alternates between sandy beaches backed by Tamala Limestone cliffs (<6 m) with a rocky platform at their base and sandy dune systems (S2). Dunes vary in height along the coast and are usually between 5 and 50 m tall.

The length of coastline within this area is approximately 150 km and about 15 % of this is composed of Tamala Limestone. Although this area also contains extensive dune systems, it is the large area of coast backed by limestone cliffs (LS1) that distinguishes it from the rest of the study (Figure 3.2).

Figure 3.2 Typical exposure of Tamala Limestone within study area no.1. The cliffs in this photo are 3-4 m tall and are located at site 4 (see Appendix A).

3.2.2 Study area number 2

Area no. 2 extends south from area no.1 to Mandurah (~50km) and is characterised by large cuspate promontories composed of very low (< 1-2m) dunes (S13). These dunes are part of a prograding foredune plain that is influenced by the diffraction of waves around the offshore islands and reef. Tombolo development has occurred, and is still occurring, linking offshore islands to the mainland. There is only one occurrence of coastal limestone in the area, and that is on a former island captured by tombolo development.

3.2.3 Study area number 3

The coastline between Dunsborough (just east of Cape Naturaliste) and Mandurah defines study area no. 3 and is approximately 75km in length. From Mandurah to Bunbury, the coastline is almost linear with a constant south to south east trend. From Bunbury to Dunsborough, the coastline sweeps around in a south westerly and then to a north westerly direction, forming a large north facing bay. The coastal landscape throughout this region is characterised by long narrow sandy beaches backed by vegetated dune systems (Figure 3.3) and back barrier swamps. In the area immediately south of Mandurah, the beaches are interspersed with minor limestone headlands. Dunes range in size from 2m - 60m with foredunes typically around 2m in height. There are no major cliffs in this area.

Figure 3.3 Site 13 is a typical example of the sandy beach and low foredunes that characterise area no.3.

3.2.4 Study area number 4

Area no. 4 occurs in the Naturaliste region, which is a belt of relatively rugged country between Capes Leeuwin and Naturaliste. The area extends from Cape Naturaliste to the southern edge of the Perth study area, about 10 km north of Gracetown. This area is significantly different to the others because it is floored by Archaen basement rock of granite-gneiss. It has a rocky coast with hard cliffs and small sandy beaches. Gneissic rock shore-platforms and headlands, along with limestone cliffs dominate the coastline. Limestone cliffs are significantly higher in this region, reaching heights above 10 m.

3.3 COASTAL HAZARDS

3.3.1 Field Investigations

The regional variation in geology and geomorphology of the coastline was inspected over a period of 3 days. The aim of this investigation was to gain an appreciation for the different landforms in the area and their associated hazards. It was *not* our intention to undertake detailed geotechnical assessments. A total of 18 sites were visited (Figure 3.4) and a brief description and photo of these sites can be found in Appendix A.

3.3.2 Study area no.1

Area number 1 contains both limestone backed beaches as well as dune backed beaches. The most noticeable hazards within this area are associated with the Tamala Limestone.

Visual examination of several outcrops revealed great variability in the limestone. While some cliffed areas appear quite fresh and consolidated, others exhibit extensive weathering, mainly due to dissolution and removal of calcium carbonate.

The most obvious feature pertaining to the cliff hazard, are the large limestone blocks that have separated from the parent body and fallen onto the beach (Figure 3.5). These limestone blocks can be up to $1m^3$ in dimension. The timing of collapse is not known, however in certain instances, variations in the colour of the exposed rock formations indicate recent fracture.

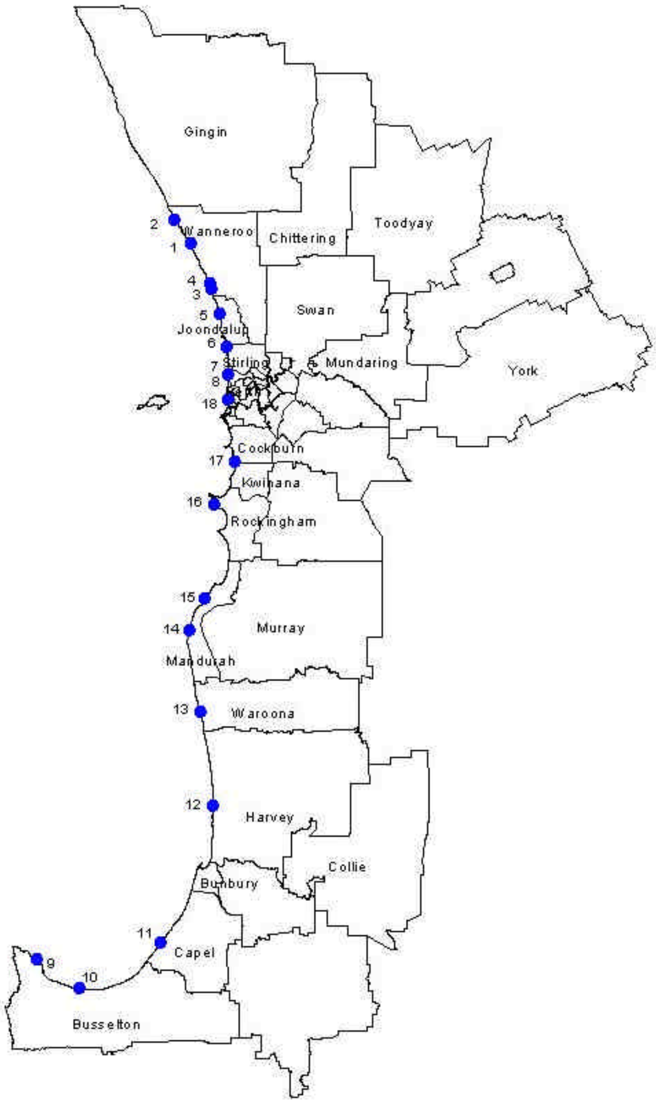

Figure 3.4 Sites visited during a 3 day field investigation.

Figure 3.5 Large limestone blocks (<1m^3) have separated from the cliff and fallen on to the beach (Site 5).

Overhangs or cantilevers along the leading edge of outcrops are common features. It is a certainty that these overhangs will eventually collapse, but the timing of these events is almost impossible to predict. Gordon (1997a) states that 'Geotechnical assessments cannot anticipate the magnitude of a major trigger such as cyclonic rain on a porous limestone cliff'. It can therefore be said that structures that may appear stable now, may not be stable after periods of intensive rainfall.

Other features seen within the limestone include cracks and fissures, along with solution piping. This piping was apparent at most sites, but was most noticeable at site 5 where the limestone was riddled with solution tubes up to 60 cm in diameter (Figure 3.6).

Figure 3.6 Solution piping is a common feature within the Tamala limestone. At site 5, these solution tubes were up to 60cm in diameter.

3.3.3 Study area no. 2

Area 2 stretching from Mandurah to Naval Base is dominated by a beach ridge plain and does not have any hazardous cliff lines. The area has a very low relief and has subsequently been used for residential developments. The major hazard associated with this area is the removal of vegetation in developed areas, and the subsequent loss of vegetation in surrounding areas due to increased recreational pressures and road development. While not necessarily threatening to life, this loss of vegetation destabilises the dune systems and can result in the development of blowouts, leading to frequent incursions of mobile sand into residential developments.

3.3.4 Study area no. 3

Large vegetated dune systems dominate the coastline within this area. Field investigations revealed some potential hazards associated with these dunes. In some areas there has been significant loss of vegetation and blow out development. Of particular concern is the effect of public pressure on the dunes, primarily through trampling caused when accessing the beach.

Erosion as a result of wave action is also occurring, cutting into the foredunes and shaping the face into cliff-like structures (Figure 2.5). The increased angle of repose in these cliffs will significantly increase the risk of subsidence occurring.

Another concern for this area is related to public awareness. Digging or tunnelling at the base of a dune is particularly hazardous as it disturbs the natural stability of the dune, increases the rate of erosion, and makes the dunes highly susceptible to collapse.

3.3.5 Study area no. 4

Gneissic rock shore-platforms and headlands, along with limestone cliffs dominate the coastline of this area. Field investigations did not extend into this region and there are no detailed site descriptions. However, the hazards in this area are mainly related to the Tamala Limestone, which forms cliffs that are significantly higher in this region. The weathering and erosion features of these cliffs are similar to those in study area no.1 and therefore pose similar hazards.

CHAPTER 4: MINIMISING COASTAL HAZARDS

4.1 INTRODUCTION

A large number of variables are involved when a tragedy occurs due to cliff collapse. Due to the random nature of the physical processes operating, it is impossible to predict when a tragedy will occur, however we can minimise the risk, by reducing the hazard.

Most local governments have implemented strategies in attempt to reduce the hazard associated with coastal landforms. The erection of fencing and signs around dangerous cliff areas has been quite extensive, and the mobility of sand in blowout areas has been reduced through the process of brushing. A large number of these preventative and remedial measures have been employed to comply with the recommendations of geological and engineering consultants. There are however, still many areas that have been neglected. Fenced areas often have alternative entries and some particularly hazardous beaches have no warning signs.

4.2 GEOTECHNICAL REPORTS

Following the Gracetown tragedy, most local governments with costal cliff lines employed geotechnical consultants to inspect and assess coastal landforms that may be of concern to public safety. These reports were quite comprehensive, documenting the stability of the coastline and recommending options for maximising public safety and minimising risk to the LGA. Table 3.1 provides a list of all the LGAs with coastal outcrops of Tamala Limesone.

The City’s of Wanneroo, Joondalup, Stirling and Mandurah, along with the Town of Cottesloe and the Shire of Busselton have all had one or more of these geotechnical assessments. We are however, not aware of any reports completed by the Cities of Freemantle, Nedlands or Cockburn, the Shire of Gingin, or the Town of Mosman Park (this does not mean to say that these reports do not exist, it simply means that we have not been able to source any). If there have in fact, been no geotechnical assessments completed within these LGA’s, we do recommend that they reassess their need for an inspection of coastal cliff hazards.

Table 3.1 Local Government Areas with coastal outcrops of Tamala Limestone.

LGAs with coastal outcrops of Tamala Limestone	
Shire of Gingin	Town of Mosman Park
City of Wanneroo	City of Freemantle
City of Joondalup	City of Cockburn
City of Stirling	City of Mandurah
City of Nedlands	Shire of Busselton
Town of Cottesloe	

4.3 MINIMISING COASTAL LIMESTONE HAZARDS

4.3.1 Introduction

There are several preventative and remedial measures that can be taken by LGAs to minimise the number of hazardous cliff areas along the coastline. These measures are discussed in detail in many of the geotechnical reports, and provide a variety of options ranging from community education through to the use of explosives. These preventative and remedial measures are summarised and discussed below.

4.3.2 Education

Education is probably the most important factor in maximising public safety. If people are aware of the dangers associated with the coastal limestone, then most people will respond by avoiding precarious locations.

In a report to the City of Wanneroo by Gordon Geological Consultants (1997a), it is suggested that the educational process should begin with the City Rangers and their employees. This would better enable employees to provide reliable information to the public concerning coastal hazards and unsafe areas. It would also be extremely beneficial to educate children about coastal hazards through the process of school visits and presentations.

Equally important in educating the public is the availability of information in the form of pamphlets and poster boards. Examples of these types of pamphlets are the ‘Shore

Safety' pamphlet produced by Geosciensce Australia and the 'Coastal Hazards' pamphlet produced for Rottnest Island. Other LGAs have produced similar literature and this information should be available at all tourist information and accommodation booking centres.

4.3.3 Warning Signs and Fences

Local Government Authorities have been quite active in erecting a variety of signs warning the public about limestone hazards. These warnings range from prohibitive signs such as 'Keep Out' and 'No Entry' (Figure 4.1), to more informative signs specifically warning people not to walk over the cliffs and not to shelter under overhangs (Figure 4.2).

Wire fences have been constructed around some of the more hazardous areas and are often used in conjunction with prohibitive signs such as 'Keep Out' (Figure 4.1). Railed walkways can also be an effective way of ensuring that the public walk on designated paths and stay out of hazardous areas.

Figure 4.1 A variety of prohibitive signs in conjunction with wire fences have been constructed to keep people out of hazardous areas.

While signs and fences cannot guarantee that everyone will observe the warnings and be responsible, they do inform people of the dangers, and discharge in whole, or in part a duty of care. In general, LGAs have implemented the use of signs and fences quite effectively, however there are some localities where more work could be done. For example, at site 15 (see Appendix A) located in the City of Mandurah, highly weathered limestone outcrop forms 3-4 m cliffs with clear evidence of undercutting and the development of overhangs. There are large sections of rock that have separated from the cliff, and some of these are encroaching on to the public staircase that provides access to the beach (Figure 4.3). There did not appear to be any warning signs at this site, despite recommendations to do so in a draft safety audit for the City in 1997. It may be possible however, that these signs have been removed or are still in the process of being developed.

Figure 4.2 An example of an informative sign within the City of Wanneroo. This type of sign does not deny public access, but alerts people to the dangers associated with limestone cliffs.

Figure 4.3 Limestone blocks encroaching on to a stair way that provides the public with beach access.

4.3.4 Catch fences and catch ditches

Catch fences and ditches are not used as frequently as other preventative measures, but are put into operation to prevent falling blocks from rolling down slope onto a road or path.

4.3.5 Limestone blocks and spalls

Cut limestone blocks and limestone rubble of various sizes (also known as limestone spalls) can be used to infill spaces such as caves or those under overhangs. The placement of these materials under hazardous areas can provide support to the overhang and help prevent potential rockfalls. These materials cannot be moved without the use of mechanical equipment, and therefore prevent the public from sheltering under these areas. This method is a commonly suggested remedial method.

4.3.6 Mechanical removal

Loose or unstable blocks of limestone are extremely hazardous in frequently used areas. Removing loosened blocks or rolling them down the slope using mechanical equipment such as a backhoe bucket can reduce the risk of rockfall. This remedial method has been suggested for several localities by geotechnical consultants.

4.3.7 Demolition

If no other method is appropriate to remediate a particular hazard, then demolition may be the only available option. This can be achieved in one of two ways, either by using chemical expanders, or as a last resort, explosives.

Chemical expanders can be poured into drill holes within the rock to be demolished. The material then hardens and expands causing cracks to form systematically. The rock may break unaided along the drill lines, or can be easily removed with a hammer or backhoe bucket.

There are extremely few recommendations to use explosive force to remove dangerous overhangs or demolish caves. Explosives are dangerous to use and can cause damage to and weaken adjacent rock structures causing widespread cracking.

4.4 MINIMISING COASTAL DUNE HAZARDS

4.4.1 Introduction

The main hazard associated with coastal dunes is an increase in the natural angle of repose through the process of erosion. When this angle of repose is increased, the dunes may become unstable and collapse, therefore creating a hazard for people visiting the beach. Another consequence of dune erosion is the mobilisation of sand, which can inundate roads and houses, creating a problem for residents.

All of the LGAs within the study area have coastal dune formations, and therefore need to consider their stability as a serious issue. While the draft safety audit produced by the City of Mandurah mainly focused on limestone headlands, a small section of the report was devoted to foredune stability. Although very general, its inclusion in the report highlights the significance of coastal dunes as a hazard to the community.

4.4.2 Education

As with coastal cliff lines, we can minimise the risk associated with coastal sand dunes by educating the public about the related hazards. Once again, these sorts of community programs should be specifically targeted towards school children in the form of school visits. Information should also be contained within tourist information brochures and appropriate signage displayed at beaches. There are a number of other preventative and remedial measures that can be undertaken to ensure the stability of our dune systems and these are listed below.

4.4.3 Artificial walkways

Providing the community with designated walkways over the dunes will help minimise the damage to surrounding areas. Walkways are most effective if they are clearly visible to the public, and this will depend on the nature of the walkway. If a regularly used track has been worn into the dunes, then this should be roped off to ensure people stay on this path and do not disturb other areas of the dunes. Alternatively, artificial walkways can be constructed using railway sleepers or pine timbers. It can also be appropriate to use suitable quantities of shell or bark to form a walkway. All options provide a pathway that will give the dunes some protection from erosion.

4.4.4 Brushing and revegetation

Brushing is remedial method used to encourage the regeneration of vegetation within the dune systems. This method involves the spreading of tree prunings around the de-vegetated area to protect the sand dunes from the direct impact of wind and to help stabilise the sand. The prunings also facilitate the capture and establishment of wind blown seeds within the sand, accelerating the growth of new vegetation. Brushing can be used by itself to encourage new vegetation growth, or in conjunction with manual sowing or planting of dune grass. In addition to revegetation, brushing also makes access to the areas more difficult and deters people from using them.

4.4.5 Sand fences

In areas where large quantities of sand are being blown out of the dunes, sand fences can be used to rapidly accumulate sand within the area. These fences can be constructed out of perforated plastic and erected at right angles to the direction of the prevailing wind. These fences act to slow down the wind sufficiently enough for sand particles to settle out. When enough sand has accumulated to rebuild the dunes, revegetation must occur to stabilise the dune and to prevent further blow outs.

4.4.6 Regrading dune surfaces

When the face of coastal sand dunes becomes over-steepened due to wave action or aeolian processes, there is an increased potential for these dunes to collapse. Particularly hazardous dunes may need their surface regraded to a natural, less steep angle of repose. This will greatly reduce the potential for collapse.

4.5 HERITAGE VALUES

4.5.1 Introduction

The Tamala Limestone cliffs and the dunes of the Safety Bay Sand can pose a serious hazard to the community. It is not uncommon to see hazardous areas altered or removed in the interest of public safety. It must be noted however, that these geological and landscape features may also be areas that have significant natural or cultural heritage values.

4.5.2 Natural heritage values

Any area that has a particular importance to a group of people can be determined to have heritage values. Natural heritage sites are natural areas that are important for present and future generations in terms of their scientific, social, educational, aesthetic and life-support value.

The south-west coast of Western Australia has some spectacular limestone cliffs and dune systems that demonstrate natural processes at work. These features not only illustrate the effects of present exposure to climate and earth forces, but also document past geological processes. In conjunction with their scientific and educational value, these landforms are also the habitat of many species of plants and animals, and are areas of natural beauty.

When making decisions on appropriate hazard prevention and/or remedial measures, the natural heritage value of our coastline should be taken in to account. Consider if there are there any rare or endangered species of plants or animals living in the area, or if the geological formation may be important for scientific or educational purposes. No one wants to see all of the spectacular cliffs, caves and overhangs altered or removed by explosives or excavators. Equally, no one wants to see a myriad of signs and fences. A balance must be reached between hazard mitigation and preserving the natural environment.

For example: When using limestone blocks and spalls to fill in spaces under overhangs and in caves, the more natural the limestone looks the better. It is preferable to use blocks with rugged faces, rather than cut faces. Uncut blocks with more or less flat faces on bedding planes are a good option. When building a limestone wall it is essential to have the mortar the same colour as the limestone to provide a natural look.

2.5.3 Indigenous heritage values

Cultural heritage, in particular, Indigenous heritage, is something that can be found in almost all, natural areas. For more than 60 000 years, Aboriginal and Torres Strait Islander people have left signs of their occupation in Australia. Indigenous people's heritage is an important element of the whole of Australia's heritage. Their heritage is something that is of continuing significance, creating and maintaining continuous links with the people and the land.

If there are hazardous areas within a site that has particular significance to the Indigenous people, then their consultation should be the first step towards finding an appropriate remedial method.

2.5.4 The Heritage Council of Western Australia

The Heritage of Western Australia Act 1990 requires Local Government Authorities and State Government Agencies to seek the advice of the Heritage Council if they are considering development of a place that is entered in the Register of Heritage Places. Work may not proceed before advice has been received and the work must comply with the advice.

Advice can also be sought from the Heritage Council in regard to proposed development of non-registered places. This advice can be sought at the discretion of the owner or developer, Local Government Authority or State Government Agency. In these instances the advice is for consideration only and is not binding.

2.5.5 Conclusions

Australia's heritage, shaped by nature and history, is an inheritance passed from one generation to the next. Our heritage helps us to understand and tell stories about this land and its people.

In planning for the future, it is important to ensure that all elements of significance are protected. Hazard mitigation and remediation must strike a balance between conserving our natural and cultural heritage values and increasing safety along our coastline. If done correctly, our coastline will remain a beautiful and safe place for everyone to enjoy for many years to come.

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APPENDIX A: SITE DESCRIPTIONS

Site number:	**1**
Location:	1.5 km south of Yanchep Lagoon
GPS:	0370544 / 6506865
Geological unit:	Safety Bay Sand, S1 backed by S2

Description: Narrow (<10m) sandy beach backed by large extensive dunes characterises this area. Foredunes are well-vegetated approx 5-8 m tall. Scattered along the waters edge are limestone outcrops ~ 50cm high and of varying diameter.

Site number:	**2**
Location:	Two Rocks
GPS:	0365481 / 6514219
Geological unit:	Safety Bay Sand (S2), Tamala Limestone (LS1)

Description: Two Rocks beach is a narrow (10-15 m) sandy beach, backed by low (3-5 m) hummocky dunes. A large limestone island sits just off the beach in the water. There are several blocks (1-2 m^3) as well as evidence of undercutting, including an archway that has been eroded by wave action.

Site number: **3**

Location: Mindarie Beach

GPS: 0377069 / 6492532

Geological unit: Safety Bay Sand, S1 backed by S2

Description: Mindarie is a long, wide sweeping beach backed by large (6-10 m) vegetated dunes. There are no limestone cliffs developed on this beach, but there are however, numerous limestone sections protruding from within the sand dunes and some cliffed headlands to the north. One particular outcrop protruding from within the dunes is about 5-6m wide and approx 4m tall. There are some large ($1m^3$) blocks of limestone that have broken off from the main body and toppled to the ground. A sign has been erected at the top of the staircase in the car park, warning people that there is a risk of rockfall and that paths should be used at all times.

Site number: **4**

Location: Quinns Rock Beach

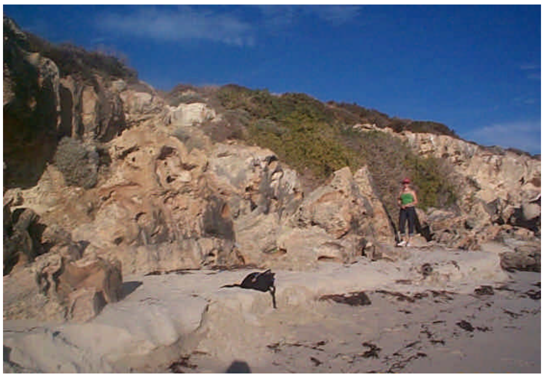
GPS: 0376504 / 6494237

Geological unit: Tamala Limestone (LS1)

Description: There is a very narrow (<10m wide) sandy beach, backed by low (~5 m) dunes. At the southern end of the beach, vertical limestone cliffs approx. 3-4 m tall form a series of headlands along coast. Access to the cliff areas is limited as they front straight on to the water. There is evidence of wave undercutting and the development of small overhangs. There are several large (>1m^3) blocks of limestone scattered around the base of the limestone which provide evidence for collapse. There is a large sign at the top of the car park warning visitors that this is a rock fall risk area.

Site number:	**5**
Location:	Immediately south of Ocean Reef Boat Harbour
GPS:	0379629 / 6485055
Geological unit:	Tamala Limestone (LS1)

Description: This site is characterised by a small sandy beach backed by highly weathered limestone cliffs (~5 m tall). The beach is littered with very large (1-2 m^3) blocks of limestone derived from collapse. The cliff face appears to be quite fresh in a number of places which is evidence for recent topples. The limestone is extremely porous exhibiting large solution tubes <60 cm in diameter. A fence has been erected part way around this area, but does not surround it, making the beach easily accessible. There are no warning signs in the immediate vicinity identifying the cliff as a hazard.



Site number: **6**

Location: North Beach between Castle St. and Malcom St.

GPS: 0381914 / 6474767

Geological unit: Tamala Limestone (LS1)

Description: Some of the limestone cliffs within this area appear to have crumbling rock faces. Pitting caused by dissolution is evident in some outcrops, along with overhang development and loosened blocks of limestone. Calcified root structures can be seen quite clearly in one outcrop, and is an excellent example of the Zone of Roots. Fences have been erected around dangerous areas and warning signs are displayed.

Site number: **7**

Location: Floreat Beach

GPS: 0382316 / 6466206

Geological unit: Safety Bay Sand, S1 backed by S2

Description: This site is characterised by a long narrow (~10-15m wide) beach backed by low (< 5m tall) vegetated dunes with a slope of approximately 30^{o}.

Site number:	**8**
Location:	City Beach
GPS:	0382341 / 6466087
Geological unit:	Safety Bay Sand (S1)

Description: This site consists of a wide flat sandy beach. The area has been artificially developed with a stone wall and grassed BBQ/play area backing the beach. There are no natural hazards from limestone cliffs or sand dunes at this site.

Photo of site 7

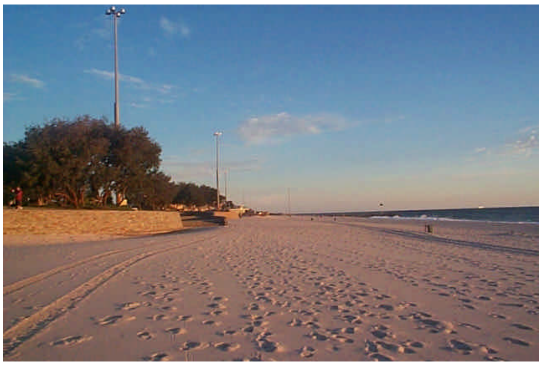


Photo of site 8

Site number:	**9**
Location:	Meelup Beach
GPS:	0322449 / 6283597
Geological unit:	Safety Bay Sand (S1) and Granite Gniess (GN)

Description: Meelup Beach is a small sandy cove in between two rocky headlands. The headlands are composed of large rounded granite gneiss boulders. The narrow beach has a very gentle slope and is backed by a grassed reserve with many trees and a car park. There are no cliff lines or sand dunes at this site.

Site number: **10**
Location: Broadwater
GPS: 0335537 / 6274775
Geological unit: Safety Bay Sand, S1 backed by S13

Description: The beach at this site is quite narrow (10–15 m) and very flat. Backing the sandy beach are some well vegetated low dunes, no more than 2 m high. The dunes are well stabilised by trees and grasses and do not present a threat to the community.

Site number: **11**
Location: Peppermint Grove Beach
GPS: 0361080 / 6289159
Geological unit: Safety Bay Sand, S1 backed by S2

Description: Peppermint Grove is a sandy beach, 10-20 m wide backed by small <1m foredunes with moderate vegetation cover. The foredunes grade into larger (>6m) dunes backing the beach that are densely vegetated and appear to be well stabilised.

Photo of site 10

Photo of site 11

Site number: **12**
Location: Binningup Road
GPS: 0377460 / 6331445
Geological unit: Safety Bay Sand, S1 backed by S2

Description: Long, narrow sandy beach with shore parallel foredunes 3-5 m in height. Dunes are moderately vegetated and are quite steep with an angle of repose around 45^{o}.

Site number: **13**

Location: Preston Beach

GPS: 0373603 / 6360932

Geological unit: Safety Bay Sand, S1 backed by S2

Description: Preston is a narrow sandy beach, < 10 m wide backed by small < 4-5m foredunes with moderate vegetation cover. The foredunes have a gentle slope of 10-20^{o} and grade into larger (>10m) dunes backing the beach that are densely vegetated.

Photo of site 12

Photo of site 13

Site number: **14**

Location: Tims Thickett Road

GPS: 0370112 / 6386302

Geological unit: Safety Bay Sand, S1 backed by S2

Description: The foredunes along this narrow beach are 4-5 m high and front on to the waters edge. Their angle of repose is around 70-80^{o}, giving them a cliff like appearance, which is most likely caused by wave erosion. The dune systems backing the beach are extremely large reaching heights well over 20 m. There is evidence of de-vegetation and blowout formation, however these are being remedied through the use of brushing.

Site number: **15**

Location: Gretel Drive, 2km North of Falcon Bay

GPS: 0374892 / 6395996

Geological unit: Tamala Limestone (LS1)

Description: The limestone outcrop in this location is part of a natural headland (< 3-4m high). The limestone fronts directly onto the water with some narrow areas of beach at the base of the cliffs. Weathering features are highly developed at this site, with rock surfaces being extremely jagged and porous. There is clear evidence of undercutting and the development of overhangs, as well as fractures and piping in the rock. Large sections of rock have separated from the parent rock and lay scattered around the base of the cliffs. There are also large separated rocks (> 1m^3) encroaching on to the staircase that provides access to the beach. There are no signs erected at this site warning the public about the condition of the limestone or the risk of rockfall.

Site number: **16**

Location: Mersey Point Reserve

GPS: 0377965 / 6425528

Geological unit: Safety Bay Sand, S2 backed by S13

Description: Small narrow beach with gently sloping 2-3 m dunes. The area backing the beach has been levelled to form a picnic reserve.

No Photo

Site number: **17**

Location: Challenger Beach

GPS: 0384527 / 6438843

Geological unit: Tamala Limestone (LS1)

Description: Challenger beach is a flat and narrow sandy beach backed by < 4 m high limestone cliffs. At the base of the cliff there are numerous blocks of limestone ranging in size up to 2 m^3. There does not appear to be any major overhang development or cave formation. A 'rockfall risk' sign has been erected at the top of the beach.

Site number: **18**

Location: South Cottesloe Beach

GPS: 0382113 / 6458087

Geological unit: Tamala Limestone (LS1)

Description: This large area of limestone outcrop is extremely weathered showing many dissolution features such as pitting and piping. Three small interlinked-caves have formed along a bedding plane within the limestone. The individual caves are about 1 ½ metres deep, 1-2 m wide with a height of roughly 1/2 metre. Two residual columns support the front section of the cave formation. Variations in the colour of the exposed rock formation indicate recent fracture. This is supported by several large blocks (<1m^3) of separated rock. A general council sign has been erected at the entrance to the beach outlining prohibited activities and general warnings. The risk of rock fall is one of these warnings.