COASTAL LIMESTONES

Ray Gordon
Director, Gordon Geological Consultants

ABSTRACT

The carbonate rocks that have been deposited in the coastal environment of western and southern Australia consist of two main types. Firstly and the most conspicuous are eolianites, which are wind blown limesands that have been cemented in place by calcium carbonate under subaerial conditions. The second group are the beachrocks, which consist of beach sand and gravel cemented in place. As beaches and sand dunes are often contiguous in the coastal environment, so eolianites and beachrocks are associated in present and past coastal environments, and along with shallow marine deposits, tufa, marls, travertines and coral reefs, make up the carbonate rocks that are known collectively as the coastal limestones. These rocks occupy over one quarter of the coastline of Western Australia over some 4000 km. They thus form a major part of the environment where most West Australians live. The limestones underlie the numerous development projects that are transforming the coastal region. The geology and properties of these rocks are however not well documented.

1 GEOLOGY

1.1 INTRODUCTION

Limesands that have been transported by the wind and accumulated in dunal deposits on a seashore in a warm climate become lithified in a weathering sequence which acts in the vadose zone with downward percolating, weakly acidic meteoric water causing the solution of surface grains with the eventual reprecipitation of $CaCO_3$ as cement lower in the dune. Progressive lithification, followed by leaching, acts on the wind-structured carbonate deposits to form a series of rock and soil types with characteristic and distinctive properties. Because of their coastal genesis as transverse and parabolic dunes the eolianites are largely linear features, persisting over tens of kilometres within a dunal complex, which may be half a kilometre wide. Local topography, soils, flora, wild life, industrial minerals, water supply, land use and geotechnical properties can all be determined by initial dune and shoreline morphology and the stage reached in the lithification and leaching sequence, which is governed by time, climate and topography and by changing sea levels resulting from global warming and cooling.

In places such as on the Swan Coastal Plain, five distinct dune ridges can be recognised, and even though they are in close proximity it is clear that they represent a series of successively ageing dune belts, probably emplaced at major interglacial high sea levels. This hypothesis is supported by dating on underlying shell and coral beds and by mineralogical findings of progressive ageing of the detrital sands from each dune system (Bastian, 1996) (Figure 1).

The beachrocks are more limited in their lateral extent, but regressing beach sequences can result in beachrocks extending tens of kilometres down dip and they may have a similar extent across strike. In some areas, such as the northwest coast of Western Australia, changes of sea level have resulted in the presence of offshore sequences of beachrocks and lithified dunes, which are more extensively developed than they are on the present land surface.

1.2 EOLIANITES

Eolianites consist of thinly bedded, cross-bedded calcareous laminae made up of well-sorted, well-rounded sand sized grains. A skeletal biogenic fraction is composed of fragments of molluscs, coralline algae, and foraminifera tests mainly of low Mg calcite but aragonite is initially present from the molluscan fragments. Subrounded to subangular grains of quartz often make up about 15 to 25% of the sand grain fraction. Deposited in-situ (authigenic) carbonate cement is the third mineralogical component.

The sequence of lithification and solution starts when shell grit and foraminifera are blown up from sea beaches to form dunal limesand deposits. Sub-aerial cementation produces a weakly lithified cemented calcarenite characterized by meniscus and rim cementation of the grains leaving up to 40% primary intergranular voids e.g. Safety Bay Sands. Subsequent pore filling produces a well-cemented calcarenite limestone.

Progressive diagenesis includes the dissolution of aragonite and the reprecipitation of low Mg calcite. Sequential solution or leaching usually is governed by the depth and access of the water table and follows the karstic pattern with initial enlargement of horizontal solution slots, then the formation of underground caves, swallow holes and dolines with the end product a leached amorphous remnant consisting of terrigenous quartz sands.

Eolianites show characteristic depositional structures, the most striking of which is cross bedding with thin bedded alternating laminae of fine and coarse grained layers. Eolianites have formed and lithified during periods of high sea level during the last five interglacials.

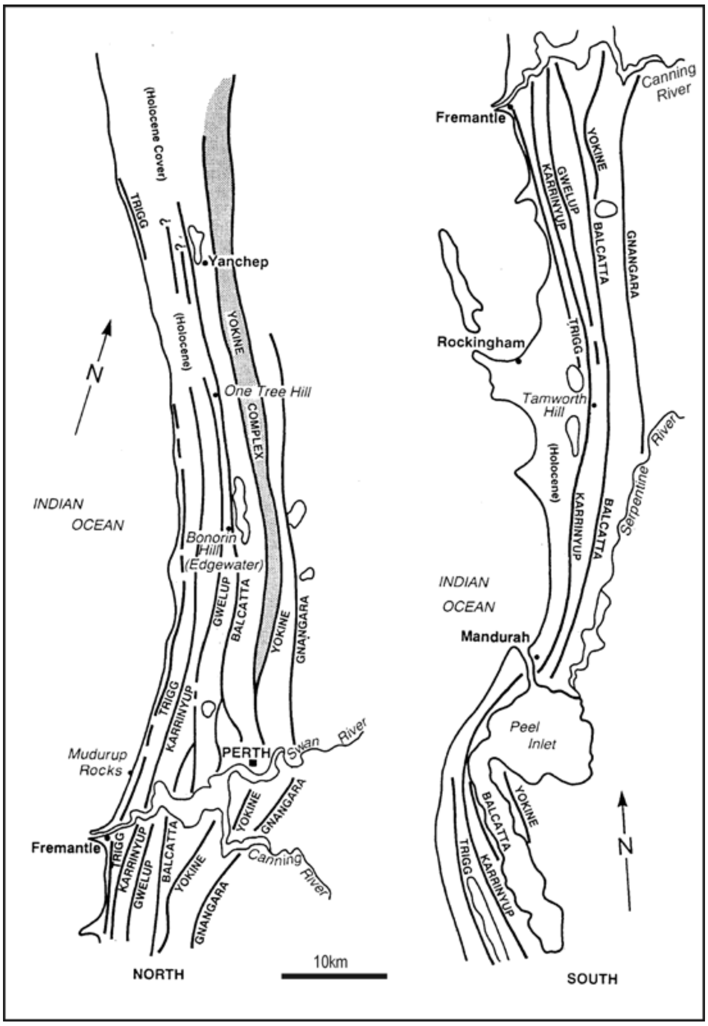


Figure 1: Dune Systems in the Perth region shown by trend lines (after Bastian, 1996).

1.3 BEACHROCK

Beachrock is a layered calcarenite (sand sized grains) or banded calcarenite and calcirudite (gravel and cobble sized carbonate particles), cemented with calcium carbonate, which occurs in one or more bands along the inter-tidal zone of tropical, subtropical or temperate beaches. Cementation is assumed to have occurred in situ beneath a thin sediment cover. The thin laminae dip seaward at angles coincident with the slope of the beach. Beachrock surfaces are marked by three distinct erosional features:

- Solution basins resulting from inter-tidal solution,
- Cracks and channels produced by the mechanical erosion and settlement along elongate joints and
- Potholes, which are the result of mechanical erosion.

Characteristic depositional features of beachrocks are laminated accretion beds that record the progradation of the beach over sub-tidal sediments. Vertical mollusc and work holes and branching crustacean burrows are often present. Keystone vugs or bubbles are also characteristic of beach rocks. Tabular or spherical cavities up to 5mm represent voids left by air bubbles escaping the sand mass following inundation during flood tides.

Eolianites and beachrocks can be distinguished because of the distinctive sedimentary structures and textures shown by the beachrocks. These include low angle laminated beds, bubble sand (keystone vugs), reworked beachrock clasts, marine borings and shell and gravel beds.

1.4 CORAL REEFS

Coral Reefs are an exotic member of the coastal limestones but they are important because the shells and corals can be dated by several methods to give a time framework to the coastal limestone sequence. The recognition of a coral reef at the mouth of the Swan River and its subsequent dating as Last Interglacial and recent exploration by drilling and by engineering works has been important in dating the overlying eolianites (Trigg Dunes) and the underlying shallow marine and beachrocks of the Minim Cove limestone. Coral reefs present challenges for development because of variability of strength and permeability.

1.5 TUFA TRAVERTINE AND MARL

Tufa and travertine are late stage products of the limestone sequence. Tufa is the name for granular deposits accreting to algal filaments and plant stems. It is dull and earthy in texture and highly porous once the algal frame rots away. Travertine is crystalline and dense layered calcrete that lacks a visible plant content, the plants having rotted away leaving visible holes. Marl is much more important, and is an industrial mineral. It accumulates in marl lakes. Former marl lakes with peat swamps and diatomaceous earth represent poor foundation materials and are present on the Swan Coastal Plain. Severe cracking developed in a small group of houses founded on marl and peat following the drawdown of the water table during the construction of the tunnels of the Graham Farmer Freeway.

1.6 DISCONTINUITIES

Unlike the ‘classical’ sedimentary and chemical limestones the eolianites and beachrocks are not broken up by numerous bedding planes, joints or faults. These discontinuities are of the greatest importance to the sedimentary and chemical limestones as they host and guide the solution conduits that form the essence of karstic dissolution. The eolianites and beachrocks do have natural joints, but they occur sparsely (30 m or so apart) and are generally vertical, at right angles or parallel to the dune direction. They are important as one of the few discontinuities of a limestone rock mass, and can guide rockfalls. The joints are probably formed by erosional unloading or possibly during diagenesis and lithification. The other main discontinuity is the bedding, and pseudo joints may form.

1.7 SUBAERIAL EXPOSURE

Subaerial exposure is generally a natural consequence for eolianites and three distinct facies can be formed, and in fact all three can develop in a limestone mass. These are (i) calcrete, (ii) fossil soils and (iii) karst.

Calcrete may be developed in an exposed limestone mass by a process of duricrusting with the sun pulling saturated bicarbonate solutions to the surface where the water evaporates and dense fine-grained calcite known as *caprock* is deposited. Thicknesses of up to 3 m are known, but most caprocks are about 1.5 m thick. The zone of carbonate depletion beneath the caprock is known as the zone of roots or rhizocretions zone, as plant roots either as molds or casts of calcrete stand out when the friable leached ground mass is exposed to erosion. Calcrete caprock is strong but the integrity of its surface is usually interrupted by solution tubes which are circular and up to 0.5 m in diameter. The tubes taper in with depth and may extend past the zone of roots into the cross-bedded limestone. The solution tubes are peripheral to the taproots of eucalypts growing in an overlying fossil soil. Solution tubes often become lined with thin concentric layers of calcrete sometimes to the extent that the tube is filled after the tree dies and thus tubes become residual columns when the weaker surrounding limestone is leached away. This is the origin of one of the types of pinnacles.

The fossil soil facies represent stand-stills in the dune building process, and they indicate a temporary diagenetic change of environment. The fossil soils are essentially much finer grained than the enclosing eolianites. They normally have an organic content and are not lithified, but may become partly cemented. Two distinct types of fossil soil are seen in the coastal limestones:

- A dark fine-grained, organic calcareous soil with calcified weevil cocoons and the land snail *Bothriembryon*. (Rendoll type soils).
- Terra rossa, which is a typically red brown sandy soil with significant fine sand content and a colouration of iron oxides derived from the coastal carbonates.

The karst facies developed in the eolianites is completely different from the classical karst model of Yugoslavia that has been described in textbooks. The relatively thin section of eolianites developed in coastal areas of Western Australia is without the overarching presence of joints, faults and folds that are the framework of classical karst. Groundwater does not find its way into eolianites from the ground surface by way of discontinuities and structures, rather it comes from a developed water table in a basal sand that encounters the limestone mass at one of the dune ridges adjacent to a interdune swale with lakes. Cave development commences as horizontal slots in the limestone, which enlarge until roof collapse occurs, and this process continues until a stable arch configuration is reached. Entry of surface water becomes possible from swallow holes, and in old age the caves fail through to the ground surface resulting in a collapse doline. The amount of cavernous ground in an eolianite rock mass is not discernable from the surface as only a few entrances to a cave system may be visible with a caprock covering. Karst development is largely confined to the west of the line where the ground water table intersects the basal areas of a cemented former dune ridge.

1.8 'NORMAL' WEATHERING

Apart from periods of subaerial exposure that initiate the calcrete, soil and karst facies, 'normal' weathering and exposure has a series of effects on a limestone mass. These include case hardening of newly exposed surfaces of faces or cuttings, selective leaching of coarse grained laminae, leaching with no case hardening of sand covered faces, and soil slotting or selective corrosion at the foot of an exposed limestone face or cliff.

1.9 THE TAMALA LIMESTONE FORMATION

The eolianites, beachrocks, shallow marine beds, coral reefs and marl are known collectively as the Tamala Limestone Formation. The genesis and history of the eolianite dune ridges that are conspicuously displayed within the coastal plain are governed by the periodic interglacials of high sea level that have occurred at approximately 110,000 year intervals throughout the Pleistocene. These glacial and interglacial episodes are also the cause of the formation of paleochannels that are driven by the lowering of sea level at Glacials, with low sea levels leading to river channels down-cutting to maintain grade. The palaeochannels of the Swan River can be distinguished because of extensive bridge site investigations in the Perth Metropolitan Area (Gordon, 2003). Three palaeochannels can be identified in some places, and they can be located in time because of their relationship to the various members of the beachrock and shallow marine deposits particularly the Minim Cove limestone and the alluvial Guildford Formation.

Some consideration should be given to timing of dune events and to nomenclature. The coral reefs at Rottnest and Fremantle, and dated shell beds at Peppermint Grove and Minim Cove, provide a basis on which to date the onshore and offshore dune systems. The second component is provided by recent research on the weathering of the mineral components of the various dune ridges.

Bastian (1996) has shown by mineralogical studies that the five onshore dune systems age progressively from west to east. There is a clear zonation due to progressive ageing of the soils with the sands originating from dissolution of a series of coastal dune belts emplaced at major interglacial high sea level points during the Pleistocene (Figure 1).

The youngest system (Trigg) on the coast overlies the Fremantle coral reef (130,000 YBP) Stage 5e, and the second youngest (The Karrinyup Dunes) overlies the Peppermint Grove Limestone dated at Stage 7 (Penultimate Interglacial). By analogy with the South Australian dune systems and the mineralogical ageing, the age of progressively older dune systems to the east can be inferred - Gwelup Dunes (Stage 9), Balcatta Dunes (Stage 11) and the Yokine Dunes (Stage 13). The offshore dunes or reefs have a similar spread. The Rottnest and Garden Island system overlies the Rottnest Limestone (130,000 YBP), which itself is underlain by the Coventry Reef – Rottnest line. Minden Reef is a beach ridge with no overlying eolianite.

This interpretation gives the Tamala Eolianite a range of 500,000 years B.P. and the older completely leached Bassendean Sands are possibly Stage 15 (540,000 to 600,000 YBP). The Ridge Hill Sand and the Yoganup Formation are early Pleistocene or Late Tertiary. The Guildford Formation infills the Penultimate Glacial Channels (6), and is eroded and cut by the Last Glacial Channel (2) so is 150,000 to 230,000 YBP. (See Gordon 2003 – this volume).

2 CLASSIFICATION AND STRENGTH TESTING

The classification chart for the description of Middle Eastern sedimentary rocks has been used in Western Australia to classify the coastal limestones consisting of eolianites and beachrocks. The scheme uses three parameters:

- Total carbonate content with divisions at 10%, 50% and 90%,
- 'Induration' with divisions into four strength categories and
- Grain sizes with divisions into four classes based on mud, silt, sand and gravel sizes.

The scheme has deficiencies in that:

- the estimates of carbonate content made in the field have to be confirmed or altered by laboratory analysis,

- inappropriate terms are used for the strength categories such as ‘soft’ and ‘hard’,
- the four strength divisions do not coincide with any international strength systems,
- laboratory testing of UCS strength is required to confirm or alter the field estimates of strength,
- the scheme uses the same rock name e.g. ‘limestone’ in different induration classes,
- the scheme includes a classification for crystalline limestone or marble but does not include notable coastal limestone constituents such as caprock (duricrusted) or calcrete (replacive or displacive) and
- it is too complex with three different parameters when two are sufficient i.e. strength can be added as a qualifier using accepted international standards.

To overcome the deficiencies of the Clark & Walker Classification a modified nomenclature system is proposed with the deletion of the ‘induration’ parameter, the removal of ambiguous terms, the addition of the calcrete facies and the separate use of strength data, based on accepted international standards as given in Table 1.

Table 1: Classification of Coastal Carbonates (after Gordon, 1997).

Material Type	**Total Carbonate Content**	**Grainsize (mm)** **Fine Grained**	**to**	**Medium to**	**Coarse Grained**
		0.02	0.06	2	60
Soils	100	CARBONATE MUD	CARBONATE SILT	CARBONATE SAND	CARBONATE GRAVEL
	0	CLAY	SILT	SAND	GRAVEL
Eolianites And Beachrocks	100	CALCILUTITE	CALCISILTITE	CALCARENITE	CALCIRUDITE
	90	Siliceous CALCILUTITE	Siliceous CALCISILTITE	Siliceous CALCARENITE	Siliceous CALCIRUDITE
	50	Calcareous CLAYSTONE	Calcareous SILTSTONE	Calcareous SANDSTONE	Calcareous CONGLOMERATE
Calcrete Facies		CAPROCK (Duricrust)		CALCRETED CALCARENITE	CALCRETED CALCIRUDITE
		Fluid Deposition (GROUNDWATER CALCRETE)			

Notes: Descriptions of the matrix and particle framework should be provided.
Coarser grains described as Clastic, Bioclastic, Oolitic etc.
Degree of cementation to be assessed preferably by hand and hammer tests and confirmed by UCS.
Lithological terms based on grainsize and carbonate composition only, and not by the degree of cementation, except by general correlation.
Percentage carbonate to be determined in the field by 0.1M HCl tests.

Strength characterisation of limestones and sandstones in international engineering and geological use are not standardised or uniform, and involve the division of strength classes in from four to seven categories. It is recommended that the seven-step classification standard of P.I.A.N.C. (Permanent International Association of Navigational Congresses), which is based on British Standard BS 5930, should be adopted for carbonate rocks. This Standard is based on the UCS test. The Australian Standard is unfortunately based on the use of the point load test, which is not appropriate for the coastal limestone rocks, which are of low strength. The implications are listed in Table 2.

There are a number of aspects that should be considered when making assessments of strength:

- Point Load Testing of eolianites and beachrocks does not give satisfactory, i.e. consistent, results especially of the more weakly cemented materials and the unconfined compressive strength (UCS) method should be the accepted standard, in spite of the preparation required. This emphasises the study made by Hawkins (1998), which showed that rocks of strength below 25 MPa should not be tested by the point load method.
- The onset of induration or case hardening on drying out means that carbonate cores have to be maintained at their in situ moisture content prior to being tested, otherwise apparent strength increases will occur.
- Another problem with point load testing is the fact that the correlation factor with UCS is a local one, varying from 4 to 11 on the WA coast. So that if point load testing has to be used because of lack of suitable sized core pieces, then a local correlation with UCS is necessary as precedents are not applicable.
- Other problems in the testing of eolianites and beachrocks for strength are a consequence of their anisotropic nature. In a typical site investigation of eolianites or beachrocks there is often a dearth or a complete lack of cores of suitable length for the UCS test. The cores have to be tested at right angles to the bedding which can be difficult with 35° bedding. Another factor is the complex strength profile resulting from cementation and leaching giving basically anisotropic structures.

- The fact that core pieces retrieved in drilling are usually of the strongest material from a particular layer, means that the strength results obtained are usually upper bound.
-

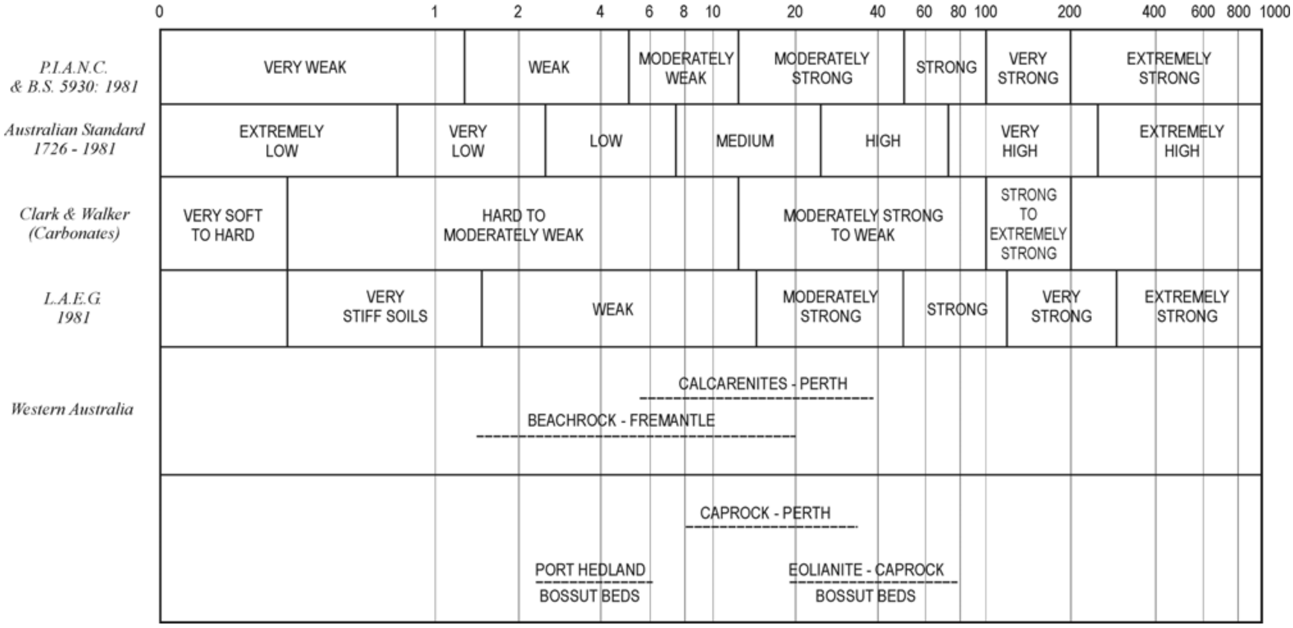


Figure 2: Comparison of Rock Strength Classifications.

3 SITE INVESTIGATION IN LIMESTONES

If the usual delays in approving a site investigation scope and budget occur, then the time available is compressed and this can result in a job done at minimum cost and maximum speed. Inadequate site investigations and poor drilling techniques are to blame for many construction problems that have subsequently occurred involving the coastal limestone rocks. Boreholes that are designed to recover samples for geotechnical testing should be rotary-cored holes of the largest possible diameter (at least over 70 mm) and should be drilled from a stable platform using drilling mud. Submarine drilling has limitations and cannot always be relied on. Inadequate logging by inexperienced people of core from holes drilled in coastal limestones has been the cause of many site investigations giving the wrong answers - there is no substitute for experience when producing such logs. Pressure, cheapness and inexperience amount to failures, and some examples are given in Table 2 which particularly addresses site investigations in a coral reef at the mouth of the Swan River.

Table 2: Continuing Problems at the Fremantle Coral Reef.

Year	**Project**	**Site Investigations**	**Geological Model?**	**Problems**
1895	Open Fremantle harbour	Adequate? 26(?) cored holes	None	Not needed – excavation by blasting followed by dredging.
1909-10	Graving dock	Apparently adequate (62 N sized cored holes) but core losses not shown	None	Project abandoned, cost millions, coral reef unsealable
1939	2000 ton slipway	None	None	Collapse during construction
1988	Dredging harbour	Comprehensive	Coral Reef	No problems
1996	Realign No.3 Berth	Numerous (17), but inadequately logged	None	Huge overruns in costs and time, corals not logged
2000	Maritime Museum foundations	6 boreholes, some inadequately logged, corals not identified	None, or the wrong one	Many piles had to be bored. Latent conditions claim. Cost blowout. Coral reef to blame.

4 CAPROCK PROBLEMS

Coastal limestones present formidable problems to engineering and development projects, mainly on account of complex variations of strength and continuity that are present in the rocks, and also because of the fact that limestone is soluble in water. This can give great variability and also give extreme permeability to the leached rock mass. Many construction problems have occurred because a capstone layer of integrity and considerable strength has been unexpectedly met with in an excavation or during piling. Caprock pinnacles or domed surfaces are another hazard for pile driving, causing the piles to lose verticality. Pile driving and dredging for port development have been particularly affected by inadequate site investigations, which did not detect the presence or nature of caprock material. Even more critical situations are present in offshore areas where a dredging project is to be performed, as inadequate investigations are unforgiving and costly. In some areas e.g. Mullaloo, two caprock layers are present close together with the lowest being the strongest.

4.1 CASE HISTORY – MULLALOO HEIGHTS STAGE 4

Mullaloo Heights is a housing development project that is located on the crest of the coastal limestone ridge about 1 km from Mullaloo beach. Stage 4 was constructed in 1977, initially with site clearing and land shaping and regrading including excavation of the main roads, then with the excavation of sewer trenches. The earthworks contractor who won the initial contract for site clearing, successfully regraded considerable areas of small caprock enhanced pinnacles (0.5 m) and excavated a road cutting some 6m deep that later became Dampier Avenue. No rock requiring blasting was encountered. The excavation showed minor and isolated caprock pinnacles in yellow sand over eolianite with solution pipes, with a zone of roots and horizontal bottomset beds and foreset beds dipping 30° to the north. Based on this experience, the contractor tendered for the Stage 4 sewer excavation contract in the same area.

No site investigations were undertaken by the consultant engineers who designed the subdivision, but they did indicate on a drawing what sort of limestone they were expecting in the Contract Documents (from Arbitration notes):

> *“**Rock***
> *Drawing 3110/C100 provides an assessment of the types of material through which excavation for the purpose of this Contract will be necessary. The Contractor shall allow in his Tender for excavating in material of the type indicated by this Drawing for individual sections of the work. The three assumed categories of excavation are:*
>
> ***Category 1**: Common excavation in sand or friable limestone suitable for excavation by Poclain or John Deere back hoe of similar type and condition to machines used in the Shire of Wanneroo for excavation of trenches for sewers and drains through sand.*
>
> ***Category 2**: Soft limestone of a type which can be ripped by a D8 or equivalent tractor with a two tine ripper. The rock is assumed to extend from the surface downwards and to become no more difficult to excavate at depth than it is at the surface.*
>
> ***Category** 3: Rock of category 2 type but situated not less than 1 metre below the existing surface of the ground. This is rock susceptible to ripping by a D8 tractor, which has in the course of earlier operations or natural drift been covered with material of category 1 type."*

The Contractor who had cleared the site was awarded the job and he commenced work on the sewer trenches with a Kato 1100 excavator with a 760 mm rock bucket. The trench was excavated one bucket width wide. Excavation proceeded regularly through a thin remnant of leached caprock and into leached limestone with caprock lined solution pipes between 1.5 m and 4.5 m thick. At a depth of between 2 m and 3 m a layer of yellow brown quartz sand (paleosol) was met, which was very weakly cemented. This proved to be about 2.5m thick overlying dense hard strong caprock, overlying calcarenite of wind blown origin with forset beds dipping at 36° to the east.

Initially the second caprock was excavated by hand drilling and blasting as the excavator could not penetrate. However the yellow sand ran freely when shaken by blasting, which allowed the upper limestone to become undermined as much as 2 m and rockfalls of large size resulted into the trench. This unsafe situation caused a change of method. The trench was back-filled with sand, and a bulldozer was used to cut a trench, one blade’s width through the upper limestone and sand layers. No trouble was experienced in excavating the upper limestone but no penetration was possible with blade or single tyne ripper on a D8G dozer in the lower capstone already partially excavated by hand drilling and blasting. Airtrack machines were used to drill to sewer invert level and the limestone was removed by blasting.

The Contractor claimed for latent conditions as the profile encountered was unexpected and totally unlike the excavation easily made in the nearby road cutting. The lower capstone was stronger and harder than any of the engineer designated categories. When it came to litigation, engineering geological assistance was sought by the Contractor but the Engineer relied on his own expertise. The Contractor was granted his claim.

5 DEWATERING

5.1. GENERAL

The high porosity and large internal conduits and storage spaces created by leaching and erosion at the ground water table makes the coastal limestones a well-known aquifer in coastal areas. Equally the same features act as storages and conduits for ground and seawater and when excavations have to be made in coastal situations considerable problems have arisen if the dewatering works commence without adequate knowledge and with poor site investigations. Inflexible construction programmes are usually not geared to contend with massive dewatering situations that have not been anticipated.

5.2. CASE HISTORY – THE KWINANA POWER STATION DEWATERING

During the construction of the coal unloading hoppers at the Kwinana Power Station, which is located on the shores of Cockburn Sound, 15 km south of Fremantle, it was found that static water level was some 6.5 m below ground level and 6.5 m above the base of the excavation, which was 45 m long. The coastal limestone contained fossil soil (sand) bands, and the base of the excavation was in a capstone layer that required blasting, with a fossil soil sand layer immediately overlying. Dewatering equipment consisted of 4 submersible pumps working in casings in a sump, along with a well point system along the length of the excavation. A total of 10,000 m^3 of saline water per day was pumped out for a period of 70 days until the required construction was completed.

5.3. CASE HISTORY – THE FREMANTLE GRAVING DOCK

The attempted dewatering of a small section of the Perth Graving Dock located in a cavernous coral reef at the mouth of Fremantle Harbour is recounted in Ramsbotham (1913). Some 62 'N' sized holes were drilled, and the logs showed no core losses - which was not possible! Ramsbotham urged abandonment of the project after viewing the cores and the spoil from site dredging down to 15 m below sea level.

After severe problems with an investigation shaft it was decided to have a final trial by building the entire north wall of the designed dock, one compartment wide with a pump station. A total of 1872 steel sheet piles (18.3 m long) was used involving 14.5 km of driving. Three 380 mm centrifugal pumps with a total capacity of 1000 l/sec were used to clear the enclosed area. Pumping started on November 16, 1911 and continued without intermission until the 23rd of July 1912. After the excavation reached a depth of 6 m hydrogen sulphide gas was encountered which caused extreme discomfort to the workers, some of whom went temporarily blind, others contracted eczema, and everyone “went a bad yellow colour and became very lean, suffering from general debility and having severe attacks of cramp.” (Ramsbotham, 1913) This gas was probably caused by decaying seaweed.

Following blow-ins in the pumping well, a system of drilling and grouting under pressure was adopted. Drilling was done by hand, and systematic grouting was commenced at a grouting pressure of around 520 Kpa and with an average take of 1.2 m^3 of grout per hole. At about 19 m two caverns were encountered, with vertical openings of 9 m and 4.5 m respectively. A back-pressure of around 65 Kpa was encountered in one hole, and this suggested that a sudden blow-in could cause disaster for all men working below. Some 29 tonnes of cement and 6 tonnes of ashes was forced into the major cave without filling it, even though the leakage stopped. It was concluded that if similar conditions were encountered over the rest of the dock area it would take eight years to complete the job with the pumping equipment available. Once more Ramsbotham recommended that the site be abandoned, and this time his advice was accepted. The total cost was a staggering £725,000, which nearly bankrupted the infant colony and the only benefit was that the harbour was deepened in the area. This salutary lesson showed that the coralline limestone had extensive cavities and was highly variable in strength, facts that were observed by Ramsbotham from his first view of the cores.

6 ABRASIVENESS

Highly abrasive beachrocks which are deleterious to excavating machinery, especially dredgers, have resulted from the presence of large angular quartz grains or gravels, especially in cemented calcirudites and calcarenites or in interbedded sandstones. Litigation has been the order of the day but to date no documentation has resulted correlating angularity, size and percentage quartz with abrasion.

7 TUNNELLING IN COASTAL LIMESTONES

7.1 INTRODUCTION

There are few tunnels in Western Australia compared with other states such as New South Wales and Victoria, where hilly and even mountainous conditions are present. The rock mass of the coastal limestones is relatively easy to tunnel and excavate. It is usually the caprock and pinnacled surface areas that present difficult conditions. However the eolianite rock mass has its own characteristic set of defects, and these occasionally provide a unique set of problems for roof stability.

The hazards of tunnelling in the coastal limestones are shown in the three case histories presented:

- Whalers Tunnel, Arthur Head, Fremantle.
- Secret Tunnel, Arthur Head, Fremantle.
- Beenyup Tunnel, Perth Metro area.

7.2 CASE HISTORY – THE WHALERS TUNNEL

The Whalers Tunnel, the first underground structure in the State was built in ‘soft rock’ through Arthur Head by prisoners from the overlying Round House in 1837. The tunnel was 66 m long and 3.6 m wide and 3.6 m high and it linked the important whaling industry that was the backbone of the State economy in the 1830s to the town of Fremantle. The geology of Arthur Head and its erosion and quarrying are given by Gordon (2001).

In 1837, Henry Reveley the engineer of the colony reported to Governor Stirling that the Fremantle Whaling Company was constructing a temporary jetty on Bathers Beach and he recommended the cutting of a tunnel through Arthur Head to open a direct passage to High Street. He considered that the tunnel could be constructed by the prisoners housed in the Round House in six or eight months. *"The expense of making an open practicable road round the bay and even the rocks would be very great and communications circuitous, but by cutting a tunnel through the soft rock under the Jail Hill ... about 80 yards in length and in the precise direction of the high (sic) street of Fremantle the communication will become direct and the expense will not exceed £130. The rock is very soft but sufficiently solid to carry the superincumbent weight without risk or danger and is always perfectly dry"* (Reveley, 1837).

7.2.1 Neglecting a Heritage Tunnel

The Fremantle Whaling Company used the Whalers Tunnel to transmit supplies, men and product between Bathers Cove and Fremantle. A lookout on Arthur Head would alert the boat crews to the presence of whales and those captured would be towed back to the beach and processed. Mews Boat Shed flourished in Bathers Cove between 1840 and 1870 aided by the advent of pearling and the tunnel was extensively used. Later, larrikins and ladies used the tunnel to access Bathers Beach where the swimming areas were barely segregated by rocks. The tunnel was shortened in 1895 as the limestone area was used as a quarry to supply rock for the South Mole. In 1905, the tunnel floor was dug up and cables from the Power Station to the Car Barn in High Street and to the tramway system were laid. In 1916, a sewer was installed in the floor to service the Fruit Store established near the west end of the tunnel. In 1930, the western end was blocked and gates were fitted as the tunnel roof deteriorated.

In 1975, as part of the major restoration works funded by the Fremantle Port Authority the eastern tunnel was concrete lined with steel mesh reinforcing and sprayed with gunite for some 24 m. At the western end of the concrete lining where rockfalls were more apparent for some 8 m, remedial work consisting of mesh bolted on to the roof with openings and cavities being filled in and gunite was then sprayed on, in places up to 2 m thick. No remedial work was done at the extreme western end (8 m) and portal, apparently because the problem was too great, with visible open joints and rockfalls which caused the tunnel to be boarded off in 1997.

7.2.2 West End Defects

The opening of the tunnel in late 1999 for the purpose of a geotechnical and engineering geological survey was revealing. Circular root holes up to 200 mm in diameter, often vertical but many flatly dipping or horizontal, were found in abundance in the unlined areas of the tunnel walls and roof. They had a filling of wet sand derived from the zone of roots. The water content was acidic from fertilizer applied to the lawn above and saline, and salt crystals were found in isolated circular patches on the gunite cover in the lined sections, obviously below root holes. The unlined circular root hole openings were diverted along bedding planes and were obviously associated with an area of unstable roof near the junction of the Secret Tunnel. The roof there showed areas of leached limestone in the form of sand on bedding planes, and the CO_2 rich soil water in the root holes enhanced by acidic fertilizers used on the lawn above, had also entered into the coarser bedding planes to leach and weaken them and allow rockfalls (Figure 3).

In addition the Whalers Tunnel walls had dried out and contracted by the passage of air through the tunnel, leading to loosening of the walls and roof at openings or joint planes. This separated the tunnel walls and roof into a series of large blocks.

The subvertical and subhorizontal natural joints at the west end of the tunnel dominated the local stability, with open joints and intersections showing signs of separations or sagging. Many open joints were infilled with mortar. On the basis of this geotechnical survey a plan for remediation was formulated. The first consideration was stability and safety, the second was to show heritage methods values and to give people a chance to see parts of the first underground structure in the State.

7.2.3 Rockfalls

The rockfalls that have occurred in the past in the Whalers Tunnel left large voids that were infilled with mesh and gunite at the west end over some 16m, while the main bulk of the Whalers Tunnel to the east was given a concrete shell with a gunite surface. (FPA in 1975) The rockfalls that have occurred at the west end are governed by natural joints and by the leached bedding planes.

7.2.4 Remedial Works

The remediation of the Whalers Tunnel was undertaken by Arup Geotechnics working under a WA Government grant. When the Whalers Tunnel had been geologically surveyed it was decided by the Tunnel Management Committee (which consisted of five architects) that the 16 m of tunnel at the west end should be stripped of gunite, mesh and mortar infill to reveal the bare bones of the tunnel as a limestone heritage feature. This work was difficult and dangerous and two roof falls occurred as the supporting elements were removed. Certain infill features had to be left for stability and to show the scope of past work. The geotechnical design for roof support consisted of a series of semi-circular steel forms that fitted against the tunnel roof with a spacing of 2 m. These were held in place by four radial ground anchors each some 3 m long. The holes for the anchors were meant to be cored, but no suitable diamond core rig was available that fitted into the tunnel. A proposal was made to use a rotary percussion rig but this was rejected as being unsafe because of vibrations, and a rock roller bit was used to make the holes.

The tunnel at this time had no support in the west end, and was drying out after years of being covered with gunite and shut off from outside contact. Three trial anchors were constructed in the concrete lined section of the tunnel, and these were loaded to failure as a basis for the contract anchors. However during acceptance testing a significant number of the installed anchors failed and had to be replaced. Extensive forensic investigations were made to determine the cause of the failures including the use of a borehole camera to determine the condition of the failed holes. The reasons for the failures were:

(i) Some of the anchors themselves were defective.

(ii) Some of the anchor holes were drilled along or intersected root holes that created too much space for the anchor grout to set. This defect should have been apparent during the grout injection but no records were kept of grout take.

(iii) No geotechnical supervision of the initial anchor installation works was allowed, but the final replacement which was under geotechnical control had no problems. Between the anchored forms, a Perspex roof was placed to catch any small rockfalls and to allow the rugged roof surface to be seen.

7.2.5 Uniqueness

The Whalers Tunnel is an unique structure and apart from its historical importance it is one of the few public places in Western Australia where it is possible to see non-karstic limestone in three dimensions.

Henry Reveley wrote to the Governor in 1837. *"The rock is very soft but sufficiently solid to carry the superincumbent weight without risk or danger and is always perfectly dry"*. However he could not be blamed for overwatering and fertilizing the Round House lawn, which was a prime cause of leaching along bedding planes in the tunnels.

7.3 CASE HISTORY SECRET TUNNEL

7.3.1 Introduction

The Secret Tunnel, sometimes erroneously referred to in the past as the Pilots Tunnel, runs from an entry at the base of the limestone cliff at the rear of the garden of the Gunners Cottage down into the Whalers Tunnel.

A local cut-down of the Arthur Head limestone headland northwest of the Round House formed the former Fort Arthur military complex, which was constructed in 1906 and was used in both World Wars with gun emplacements and living quarters for military personnel.

7.3.2 Description of the Tunnel

The Secret Tunnel was constructed in about 1938 as part of the preparations for World War II. The purpose of the tunnel was to enable quick access for the soldiers, boat pilots, gunners and their families living in the Fort Arthur area to reach Whalers Tunnel, which was to be used as an air raid shelter.

The Secret Tunnel is about 15 m long and has an average declination down to the south of 15°. At the junction with the Whalers Tunnel it has a similar crown elevation of approximately 6.5 AHD, and the average width is approximately 1 m and the average height is 2 m. There is a step down of 1.4 m from the floor of the Secret Tunnel to the floor of the Whalers Tunnel. The Secret Tunnel and Whalers Tunnel meet directly under a segment of the outer wall of the Round House. The Secret Tunnel underlies the Round House wall for approximately 7 m (Figure 3).

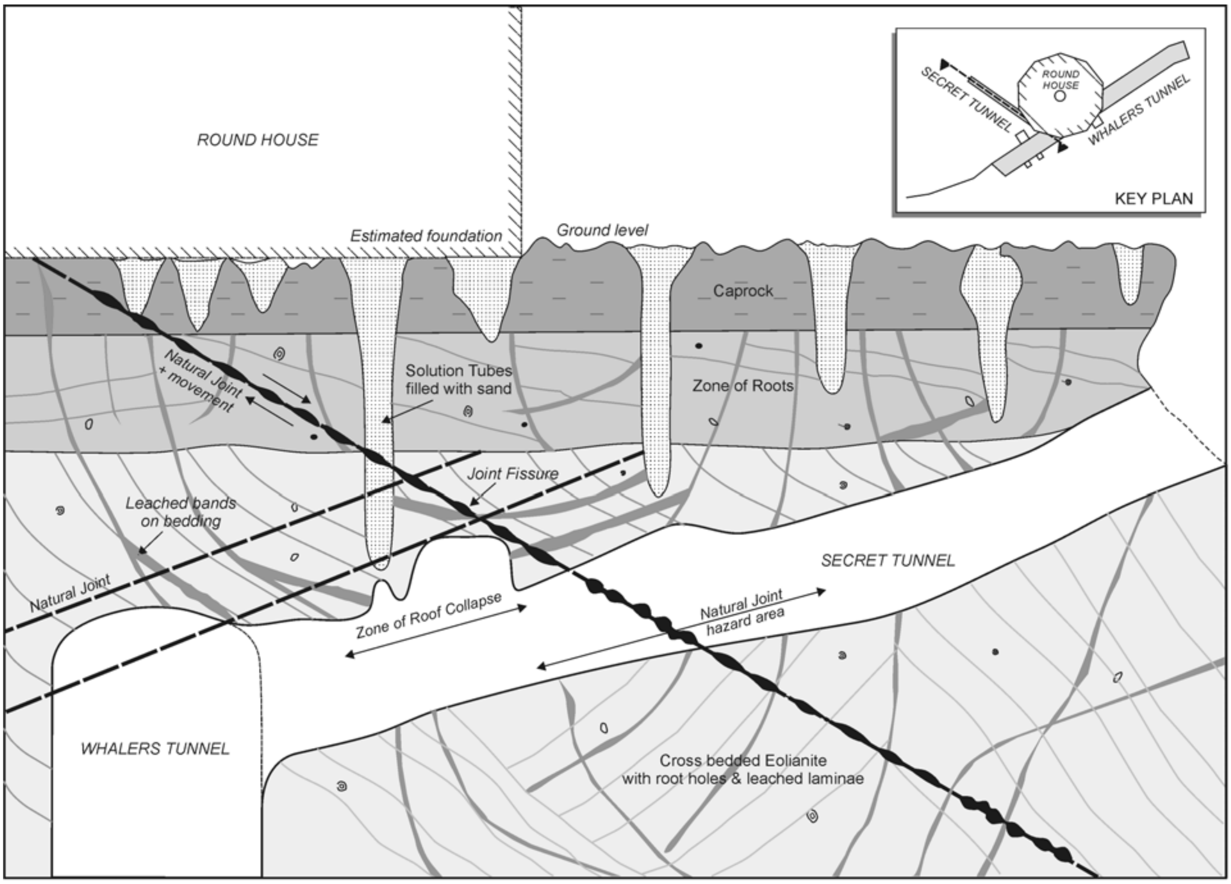


Figure 3: Arthur Head - Long Section through Secret Tunnel.

7.3.3 Geological and Geotechnical Survey

The Secret Tunnel was examined by a geological and geotechnical survey carried out in June 2000. The survey had been in progress for a few minutes before it became apparent that the tunnel was in a hazardous, indeed dangerous condition because of the condition of the roof. This caused the survey to be drastically abbreviated, and all future access to the tunnel was prohibited.

7.3.4 Root Holes

In addition to the solution tubes Arthur Head has a unique feature – the presence of numerous root holes up to 200 mm in diameter now filled with sand. This suggests that at least two varieties of eucalypts flourished on the headland, one with taproots (tuarts) and one with numerous spreading roots (jarrah). Most of the root holes are about 50 mm in diameter, and they are a late addition to the limestone rock mass as their direction and inclination is dominated by the bedding dips in the lithified dune. Only the largest holes have a thin lining of calcrete.

The sand infill in the root holes is derived from the zone of roots and is damp and saline in the interior of the rock mass as shown by salt crystals that have formed in the surface of the gunite lining of the Whalers Tunnel.

These root holes and the solution tubes act as conduits that bring surface water runoff, mostly excess water from lawn watering into the limestone interior. The water is saline and is charged with CO_2 from the soil root zone and with acidic fertilizer from the cultivation of the lawns.

7.3.5 Leaching of Bedding Layers

This acidic soil water acts as a leaching agent and it enters into the limestone at or along more permeable laminae, especially the coarser grained layers, which are not fully lithified and are more vulnerable to leaching. These layers become leached to weakly cemented sand of low strength and thus become weaknesses in the rock mass and they allow the separation and fall of slabs of rock, which have obviously dropped into the underground openings of the Whalers and Secret Tunnels.

7.3.6 Natural Joints

Apart from the bedding, natural joints are one of the few rock structures that subdivide the limestone rock mass. Natural joints are usually planar fractures without displacement that occur intermittently in the coastal limestones. They are often vertical or steeply dipping and occur with wide spacings. They may be infilled with sheet calcrete but are still weaknesses that control rock breakage. They are formed during lithification and are the result of erosional loading and unloading.

The natural joints at Arthur Head consist of three sets:

- Sub-parallel to the original topography at the southern end of the domed dune complex and dip to the south at 10° to 30°,
- At the northern end of Arthur Head dip north at about 30° and
- A vertical set of about 5 joints intersects the west end of the Whalers Tunnel striking, north-south.

Two of the joints exposed in the cut cliff face south of the Whalers Tunnel have opened up by settlement of the cliff on an undercut soil slot and these separations or openings are being monitored by glass slides. The Secret Tunnel intersects a natural joint dipping down to the south at 30° that has also sustained some movement (Figure 3).

7.3.7 The Natural Joint Area

A major natural joint is met at the mid point of the length of Whalers Tunnel. It has a dip of 30° to the south and has a slight curvature concave to the south. The joint consists of a series of open slots up to 20 mm wide and 200 mm long alternating with a series of tight joints with limestone on limestone. Clearly movement of some 100 mm has occurred as the joint was originally planar. The sense of movement is that the upper block moved down to the north. There is one interesting historical fact that may be correlated with this movement. In July 1873 several thousand tons of rock were dropped from the southwest face of Arthur Head for use in the Long Jetty. The blasting vibrations caused the development of a large crack in the floor of the Round House and alarmed the female prisoners on the upper floor of the jail so much that they had to be transferred to Perth Gaol (Fremantle Compendium).

The projected position of the joint plane in the Pilots Tunnel intersects the Round House and would possibly run across the courtyard south of the well. For the movement of 1873 to have broken the caprock is alarming but there is no present day activity in the form of blasting that will happen in the precinct in the future. The only possible comparable movement could be from seismic shaking, which caprock normally attenuates. However the opened and moved joint is a major discontinuity that could interact with other weaknesses to exacerbate stability problems. In any case the immediate roof of the tunnel adjacent to the natural joint is at risk of a local fall with added problems from an adjacent leached zone.

7.3.8 The Collapsing Roof Area

This area of roof fall is located over some 7 m at the lower end of the tunnel ending some 1.2 m from the Whalers Tunnel. The rockfalls that have occurred have been the result of leaching of bedding planes to a very weakly cemented sand with acidic liquid carried mainly by root holes.

The rockfall from the roof will continue until the supply of acidic water is cut off and the roof assumes a stable configuration. The falls will eventually reach the zone of roots layer about 1.25 m above the top of the present roof, which is weak, and then only the caprock would remain. But the caprock is probably cracked on the natural joint (?), so the long-term scenario is for possible problems to the Round House and the short-term prognosis is for more falls from the tunnel roof.

7.3.9 Conclusions

The Secret Tunnel has uncertain heritage values, and no recommendations were made in the Heritage Documents. What is the heritage value of a tunnel with no documented history and which is inaccessible? Geologically it has interest especially in the natural joint, but it is dangerous and access should be prevented, while a decision is made on its future. The Secret Tunnel could be stabilized and strengthened but all forms of support must be positive not passive. In other words spraying gunite on the roof may only add to the weight of a block that has relaxed into the opening and its fall may be accelerated. Rock bolting, mesh and gunite is an option with anchoring in the caprock layer.

A decision on the future of the Secret Tunnel is required as there are possible long-term problems for the overlying Round House if nothing is done. To date (08/2003) nothing has been done.

7.4 CASE HISTORY – BEENYUP TUNNEL

There are definite problems in tunnelling into and along the upper layers of a buried eolianite ridge where the surface of the rock mass is pinnacled capstone with solution holes and the material on a shallow tunnel line can thus vary from cohesionless sand to zone of roots limestone to capstone lined solution pipes within a metre or so.

Stapledon (1983) and McInnes (1979) have provided information on the construction problems and on the subsequent arbitration case concerning the Beenyup Tunnel, which is some 3.4 km long and extends from the Beenyup Sewerage Waste Water Treatment Plant to the Indian Ocean, 25 km north of Perth. The Tunnel is circular and 2 m in diameter and is fully lined.

A comprehensive site investigation was mounted by the WA Water Corporation, before and during construction, including auger drilling and NQ^3 and PQ^3 diamond core drilling, along with extensive laboratory testing. From this well conducted exploration the materials likely to be encountered at tunnel level were estimated as given in Table 3.

Table 3: Materials to be encountered.

Material	Strength	likely % at location
SAND	(cohesionless)	36%
ROCK	low to high strength	60%
CAVITIES		4%

(See Figure of Stapledon, 1983)

The contractor elected to use a heading type tunnel machine. Problems arose in the tunnelling operation when passing from loose sand, which was present between pinnacles, into the capstone pinnacles themselves. Vibrations from the tunnelling machine when excavating through the caprock caused sand runs round the shield, which was not adequately hooded. The runs extended up to the ground surface where craters formed, and the heading machine was on occasions partly buried.

An arbitration case was brought under a Clause 12 Claim (Unforeseen Adverse Conditions). The Claim was decided in the contractors favour. This was in spite of the fact that the Principal had provided extensive factual data collected by specialists over a long time, whereas the contractor did not, and apparently was not expected to, obtain specialist help when interpreting this data during a short tender period (Stapledon, 1983). There were several other unsatisfactory aspects of the way this arbitration proceeded, for example legal tactics caused the suppression of expert opinions that would have given a balanced view of the geological and geotechnical nature of the materials.

8 DREDGING

Dredging is a problem area for coastal development as all the dredging projects on the WA coastline on limestones up to 1989 ended in litigation except those done at Port Hedland on a cost plus basis. The dredging of Fremantle Harbour in 1989-90 was accomplished without litigation, because the lessons of the past were acted on and the risks were shared with the dredging companies by involving them in the site investigations. (See Tutton 2003 – this Volume).

9 ROCKFALLS, TOPPLING, LANDSLIDES

9.1 TYPES

Geological Hazards, which are hazards of geological origin that impact on man and his activities, can be divided into two categories:

- the spectacular rapid onset, intensive hazards that catch the media headlines (Volcanic eruptions, earthquakes, rockfalls) and,

- the slow onset, pervasive, quiet, geohazards that cause widespread distress (loss of soil, rising saline groundwater, subsidence).

The geohazards endemic to the coastal limestones are rockfalls and topples from cliffs, overhangs and caves, landsliding of sand above limestone cliffs and karstic collapses and subsidence.

9.2 CHANGE IN THE COASTAL ENVIRONMENT

On a seacoast there are many agents of change and erosion. Nothing remains the same on a coastline, but on a limestone coast the changes are especially dynamic because of facies variability and its particular vulnerability to solution. Limestone is a soft rock that will dissolve in weakly acidic water such as rainfall, sea spray, seawater, and groundwater. In addition, there are three other powerful agents for change summarized in Table 4.

Table 4: Agents of Change affecting Coastal Limestones

Marine erosion	Subaerial erosion	Human activity
Notching	Wind, rain and trees	Traffic exposing new faces
Salt crystallisation	Rainfall impact	Digging - sand and fossils
Hydraulic impact	Rainfall weight	Lighting fires under overhangs
Pneumatic effects	Soil and root zone. CO_2	Quarrying
Abrasion		

There is very little that can be done to avoid marine erosion or to prevent subaerial erosion from occurring. With the impact of people on the limestone environment however, the problems that have been created are all avoidable. Overuse of holiday areas with unrestricted foot traffic such as on the area near the Basin on Rottnest Island, Hamelin Bay and Gracetown have caused huge local blowouts to develop. The loose sand in the blowouts has become ammunition for sand blasting, and subaerial erosion has accelerated, and increased the risk of rockfalls and topples on adjacent cliffs.

Table 5: Mechanisms causing rockfalls and topples in Coastal Limestones.

Mechanism
Caprock Failure On Zone Of Roots (Undercut)
Soil Slotting At Base Of Cliff Or Outcrop
Root Wedging Especially From Tuarts
Thinned Caprock Zones Undercut From Below
Cliff Failure On Fossil Soil Bands
Falls From Fossil Soil Bands
Eroded Basal Layers – Notches & Calcirudites
Boulder Fall From Cliffs
Bedding Plane Failure
Surface Water Runoff Destabilizing Locally
Blow Outs Providing Sand Blasting
Cliff Collapse with Filled Solution Tubes

In Table 4 the causes of the coastal erosion of limestones are outlined, and in Table 5, the various mechanisms directly causing rock falls and topples are listed.

In all cases, the trigger for failures is rainfall.

10 KARSTIC PROBLEMS

There are two areas in the south of the State where karst is active, resulting in underground solution, caves, swallow holes and dolines. These are (i) the Lake Joondalup – Yanchep belt, and (ii) the inland belt of older eolianites on the ridge between Capes Naturaliste and Leeuwin. The Joondalup – Yanchep belt is some 2 to 3 km wide and contains hundreds of caves and dolines (Figure 4). The public caves of Yanchep National Park are the best known – Yanchep, Nambiddy, Crystal, Yonderup and Cabaret Caves, but caves equally as large and with significant ornamentation occur throughout the karstic zone.

There is increasing pressure for urbanization of the karstic limestone belt, which is picturesque with varied topography and large trees. However problems could be plentiful in the form of collapses during development and possibly later during residential occupation.

10.1 CAVE ROOF COLLAPSES

The collapse of cave roofs is a usual development in the formation of caves in the karstic environment. Caves are formed where the water table intersects the limestone rock mass. Initially horizontal solution slots are formed, and eventually the rock strength is overcome by the weight of the overhang and rockfalls occur. This process continues until a stable arch configuration is reached, often with a caprock roof.

Some of the caves presently show vast rock piles; in others the cave spaces have been cleared of rubble by the solution and erosion of cave streams. It is not a question of age or time that determines whether the fallen roof debris is removed or not, but factors such as the location and diversion of cave streams following collapses, and the possible lowering of the water table, which would make the cave inactive.

The nature of the limestone in the roof and its structures, the incidence of discontinuities such as natural joints and palaeosol bands and solution tubes and swallow holes are factors that have influence on cave roof stability. Internal collapses usually continue until the caprock layer is reached, which provide a stable cover. Consequently there are few entrances and in a karst area there may be many caves but few signs of their presence.

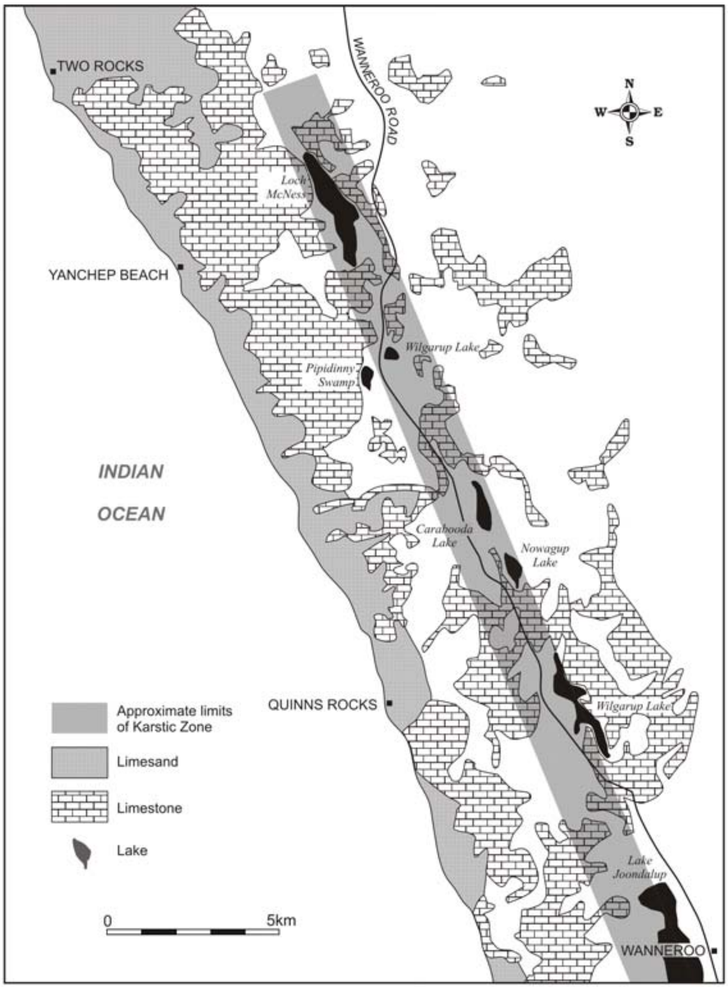


Figure 4: Joondalup – Yanchep Karst area.

It is also of importance to determine if self-healing of the cave roof and walls is occurring, with flowstone and other cave formations developing in the cave due to carbonate solutions in fissures, pipes and natural joints then depositing flowstone to reheal cracking and bind rubble piles together.

In general the stability of a cave can be assessed by observations on the incidence of straws, stalactites and flowstone in the roof and walls. If there are rubble piles on the floor and large raw-looking areas of roof alongside an area coated with well-developed stalactites or straws, then rockfalls have been active in the recent past. It is in these freshly exposed roof areas and in those immediately adjacent that further falls are most likely to occur.

As far as is known no fatalities have occurred from cave roof collapses in Western Australia. Some children have died in coastal limestone areas with tiny shallow caves and overhangs but it seems likely that the cause of the problem was sand runs down solution pipes. The assessment of cave roof stability is not an easy task as lighting is often poor, and cracking of the roof and upper walls may not be visible from the cave floor. Testing of the roof for drummy areas is usually not available to assess safety and in any case it is a method that is not definitive in a limestone roof where flowstone healing may be occurring. Forced scaling of a cave roof is not recommended as it often causes more problems than it solves, as the exposed roof is usually more strongly rehealed than the inner roof.

The 1968 Meckering Earthquake had a considerable impact on the public caves at Yanchep. Cabaret Cave was closed and Crystal Cave underwent extensive remedial works at the behest of the Mines Department. The works that were carried out would have been appropriate for a gold mine, but looked out of place in a tourist cave.

- A 30 m long tunnel was driven from the Pantheon Opening to the southern limb, with wooden sets, and the walls sprayed with dark grey cement coloured mortar which looks crude compared with the mellow browns and creams of the limestone.
- A culvert set of corrugated iron 14 m long was installed as an earthquake shelter.
- Numerous reinforced concrete props were installed. Unfortunately the reinforcing was too close to the outside faces, and in the humid cave atmosphere rust formed that split the props vertically which was similar to axial splitting from a heavy load and initially caused much concern.

10.2 KARSTIC SUBSIDENCE, COLLAPSE AND URBAN DEVELOPMENT

Spectacular sinkholes, caused by the collapse of an underground limestone gallery or by the failure of a surficial clay plug in a chimney (both usually activated by groundwater addition or lowering), are not a common feature of the karst area of the West Australian eolianites. In fact no catastrophic sinkhole appearances are known to have occurred in historic time.

However many small sinkholes up to 5 m in diameter are known to have suddenly appeared, especially in the Flynn Drive – Yanchep area (Figure 4). Most of these have been caused by the loss of a grass or root mat covering a pre-existing swallow hole or small doline. Local overwatering, breakage or leaking irrigation or house pipes are a common cause. Lowering the local groundwater level by new or by over pumping has also initiated collapses. Sand craters occur occasionally in suburban backyards in East Fremantle and Dalkeith. Heavy rainfall filling up storm water sumps also can cause the collapse of sand, filling solution tubes, and houses have been undermined in the Edgewater Area (Figure 5).

Caves can be a significant geological hazard. Slow subsidence due to progressive underground collapses is of relatively common occurrence at the present time, e.g. the Cabaret Cave area at Yanchep National Park. Some caves are quite dangerous as they have not reached a stable arch shape, e.g. Twilight Cave in Yanchep National Park.

Caves with a relatively strong caprock roof can develop into large caverns, and the risk of external collapse then slowly increases with time and the incidence of surface solution of the caprock. Often there are only a small number of entrances in solution tubes or swallow holes, which is misleading because it does not reflect the extensive amount or extent of caves beneath.

During the initial stages of a major housing or industrial development construction machinery could be at risk in karstic areas. Heavy machines like dozers and excavators could break into caves and compaction machinery could also be at risk.

The boundaries of the area of karstic rocks are well known and can readily be defined on a map. The speleologist group have maps and details of most known caves and dolines. Local government bodies should be made aware of the risks involved in approving a subdivision in such an area. It is only a matter of time before disaster strikes.

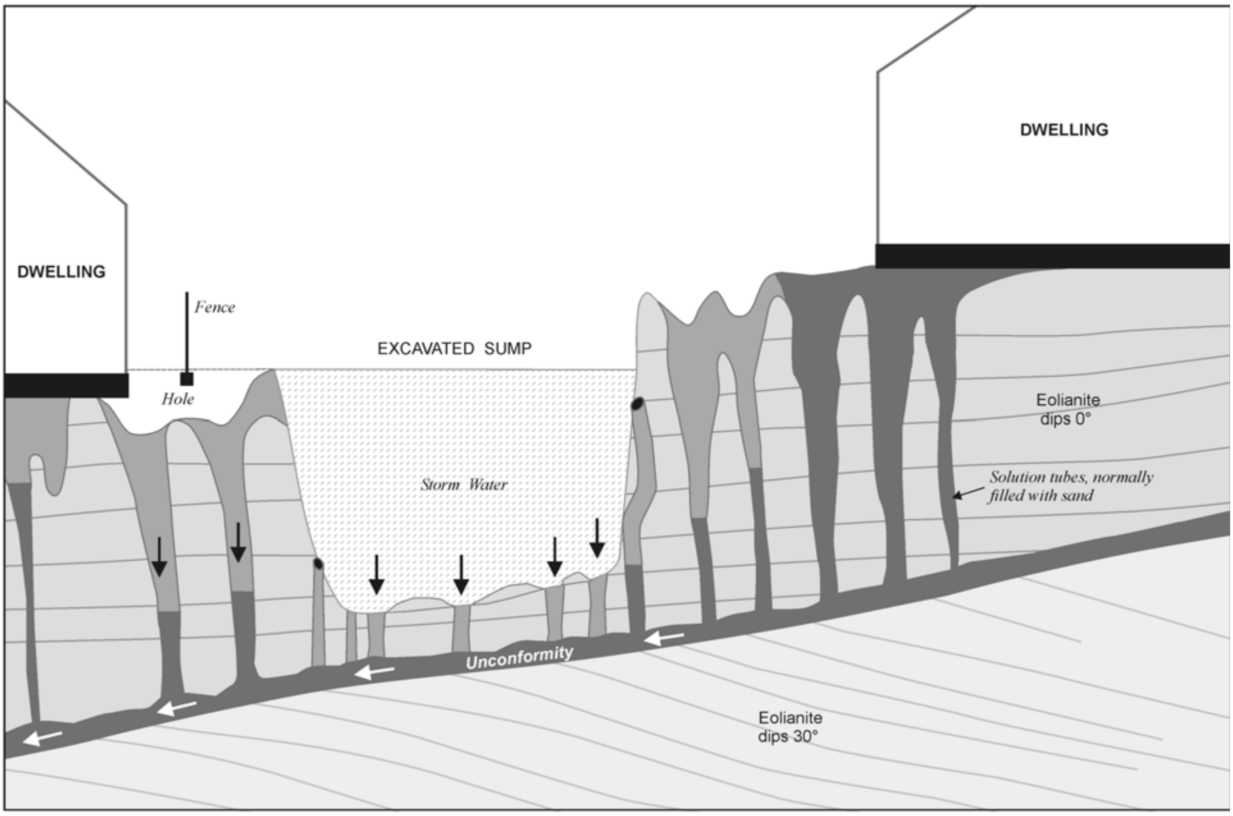


Figure 5: Subsidence caused by stormwater sump. Regatta Drive, Edgewater.

11 REFERENCES

Bastian, L.V., (1996). Residual soil mineralogy and dune subdivision, Swan Coastal Plain, W.A., *Australian Journal of Earth Sciences*. Vol. 43, pp 31-44.

Clark, A.R. and Walker, B.F., (1977). A proposed scheme for the classification and nomenclature for use in the engineering description of Middle Eastern sedimentary rocks. *Geotechnique*. Vol. 27, pp 93-99.

Gordon, F.R., (1997). Oakajee Port feasibility study. Department of Industrial Development WA. (Unpublished).

Gordon, F.R., (1999). The rockfall of Huzzas Cliff, Gracetown, Western Australia. *Australian Geomechanics*, Vol. 34, pp35-44.

Gordon, F.R., (2001). The formation use and conservation of Arthur Head, Fremantle. *Australian Geomechanics.* Vol. 36, pp 23-30.

Gordon, F.R., (2003). Sea level change and Palaeochannels in the Perth Area, *Australian Geomechanics.* This Volume.

Hawkins, A.B., (1998). Aspects of rock strength. *Bulletin of the Association of Engineering Geology and the Environment.* Vol. 57, pp17-30.

ICE (1991). Inadequate site investigation. Institution of Civil Engineers. Site Investigation Steering Committee Group. Thomas Telford, London.

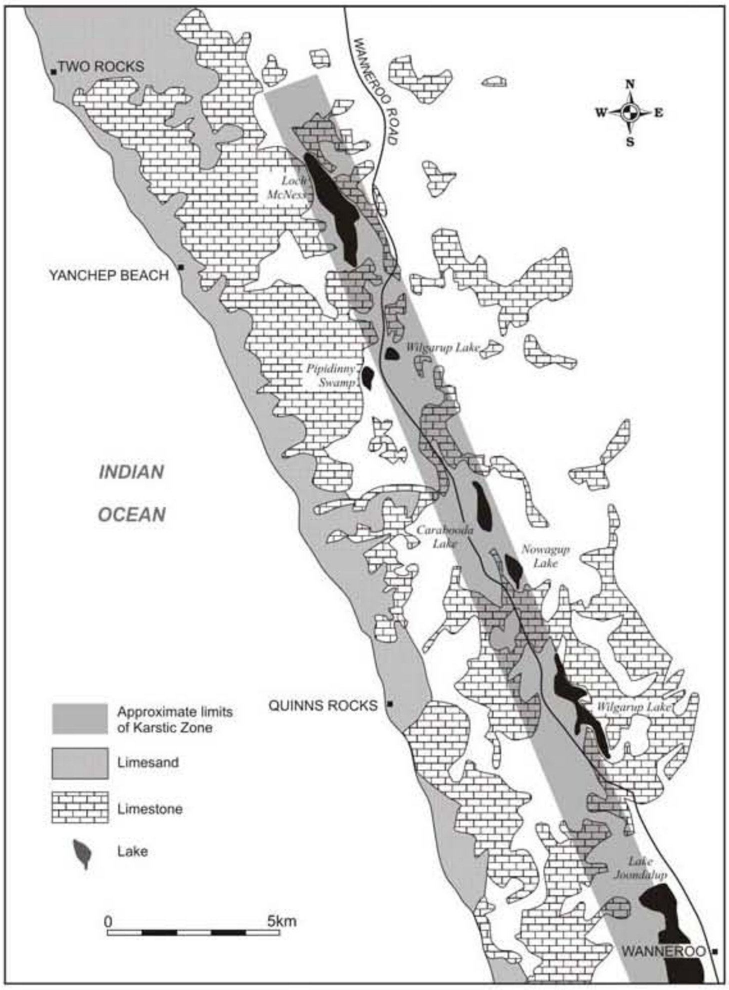
Kempin, E.T., 1953. Beach sand movement at Cottesloe, Western Australia. *Royal Society of Western Australia Journal.* Vol. 37, pp 35-58.

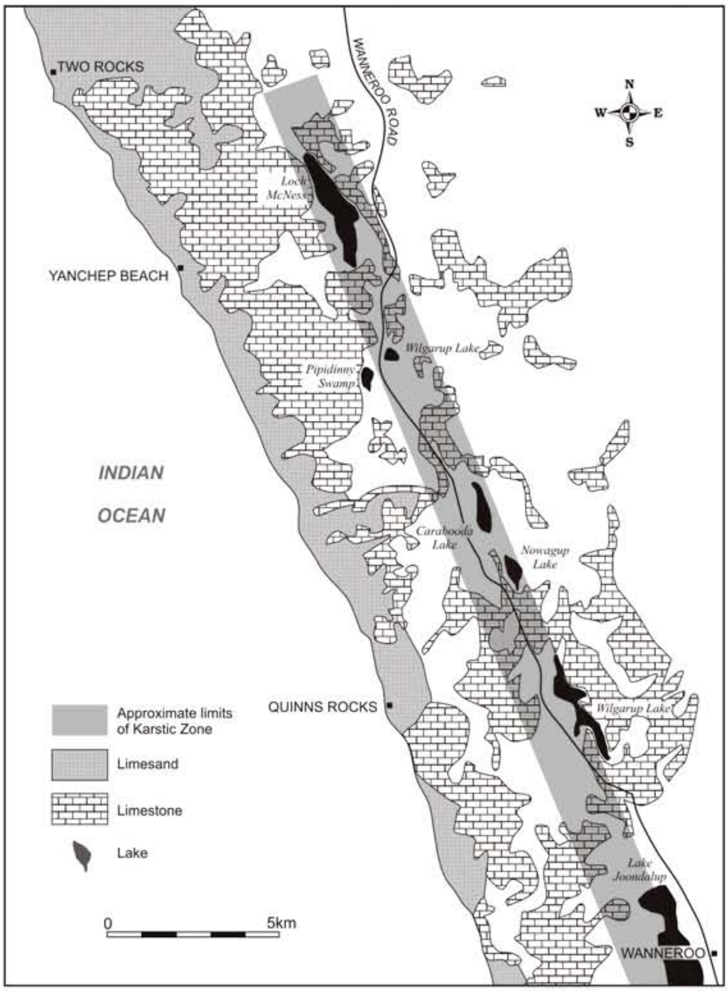
McInnes, D.B., 1979. Coastal limestone Western Australia, construction case histories. Institution of Engineers Australia Engineering Conference Papers, Perth.

Ramsbotham, J.F., 1913. The history of work done at the site of the Fremantle Graving Dock. *Transactions of the Liverpool Engineering Society.* Vol. 34, pp 319-366.

Reveley, H.W., (1837). Letter to the Governor, June 9th 1837.

Stapledon, D.H., 1983. The geotechnical specialist and contractual disputes. *Collected Case Studies in Engineering Geology.* Geological Society of Australia Special Publications.


TWO ROCKS
WANNEROO ROAD
N
W
E
S
Loch McNess
YANCHEP BEACH
Wilgarup Lake
Pipidinny Swamp
INDIAN
OCEAN
Carabooda Lake
Nowagup Lake
QUINNS ROCKS
Wilgarup Lake
Approximate limits of Karstic Zone
Limesand
Limestone
Lake
Lake Joondalup
0
5km
WANNEROO


TWO ROCKS
WANNEROO ROAD
N
W
E
S
Loch McNess
YANCHEP BEACH
Wilgarup Lake
Pipidinny Swamp
INDIAN
OCEAN
Carabooda Lake
Nowagup Lake
QUINNS ROCKS
Wilgarup Lake
Approximate limits of Karstic Zone
Limesand
Limestone
Lake
Lake Joondalup
0
5km
WANNEROO