Hydrogeology and Speleogenesis Update, the Yanchep Cave Area, Western Australia

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INTRODUCTION

This article updates and modifies a paper of similar title (Bastian, 1991), introducing significant changes in terminology, with the reasons behind them.

The Yanchep cave area is situated approximately 50 kilometres north of Perth, and from 4 to 8 kilometres from the coast. The area is highly cavernous, and several hundred caves are known to exist within a relatively small area, much of which is incorporated within the boundary of the Yanchep National Park. The linear stream cave systems seen in the Leeuwin-Naturaliste block are controlled by the buried topography of a Precambrian basement (Bastian, 1964), however this factor is not present at Yanchep, where the underlying strata are unconsolidated sediments. There are peculiarities of the cave distribution at Yanchep, in particular the existence of a large tract of limestone country in the eastern part of the Park which is devoid of caves altogether.

REGIONAL GEOLOGY AND HYDROLOGY

The surface formation at Yanchep is a friable dune limestone (aeolian calcarenite or aeolianite) of Pleistocene age, the Tamala Limestone (Playford, Cockbain and Low, 1976). This is the same formation as that seen in the Leeuwin-Naturaliste belt, and is also an approximate equivalent to the Bridgewater Formation (Boutakoff, 1963) of southeast South Australia. A similar type of Pleistocene karst has been described from Bats Ridges in western Victoria (White, 1989).

The Tamala Limestone consists of a series of calcareous coastal dune ridges formed during successive interglacial high sea levels. In terms of geomorphic structure the ridges have been named collectively the Spearwood Dune System (McArthur and Bettenay, 1960), and at least five individual ridges have been recognised in the Perth region (Bastian, 1996). In contrast to the picture in southeast South Australia the ridges in most cases abut each other closely, with the younger ridge partially overlapping its older inland neighbour. However, there is one major interdune corridor in the Yanchep area, which is occupied by a chain of lakes, those within the National Park being Wilgarup and Yonderup Lakes, and Loch McNess. The younger ridge west of the lake chain is correlated by Bastian with the Balcatta Dunes of the Perth area, while the large limestone ridge to the east of the lake corridor correlates with the Yokine dunes.

In this part of the Perth Basin The Tamala Limestone abuts and overlies an extensive formation of sand, known as the Bassendean Sand (Playford and Low, 1972). This relationship contrasts markedly with most of the Leeuwin-Naturaliste area, where the unit generally rests upon impervious Archean metamorphic rocks, although the latter area does have pockets of pre-Pleistocene sands which have been buried beneath dune systems. The Tamala dune systems extend to about halfway across the Swan Coastal Plain; from thence to the Darling Scarp the surface formation is the Bassendean Sand.

The carbonate content in the aeolian calcarenite which makes up the Tamala Limestone has enabled solution and lithification to proceed rapidly, despite its geological youth, whereas the absence of carbonate from the underlying sand formation has left it in an entirely unconsolidated state. As a result the limestone rests upon loose porous sand. Also the contact between the two is not horizontal, but slopes westwards from relatively high levels at the eastern extremities of the limestone formation, to be well below sea level at the coast.

A large fresh unconfined groundwater resource has been identified in the region, known as the Gnangara Mound (Allen, 1981). This is a shallow body of groundwater with a mounded shape, which rises to over 60 metres above sea level between the Swan River and Gingin Brook, 70 kilometres to the north. Davidson (1995) dealt with the structure and hydrology of the Mound in the context of a general study on the groundwater resources of the Perth region.

Figure 1 is modified from the 1991 paper, showing the generalised surface geology of the area, including the Gnangara Mound.

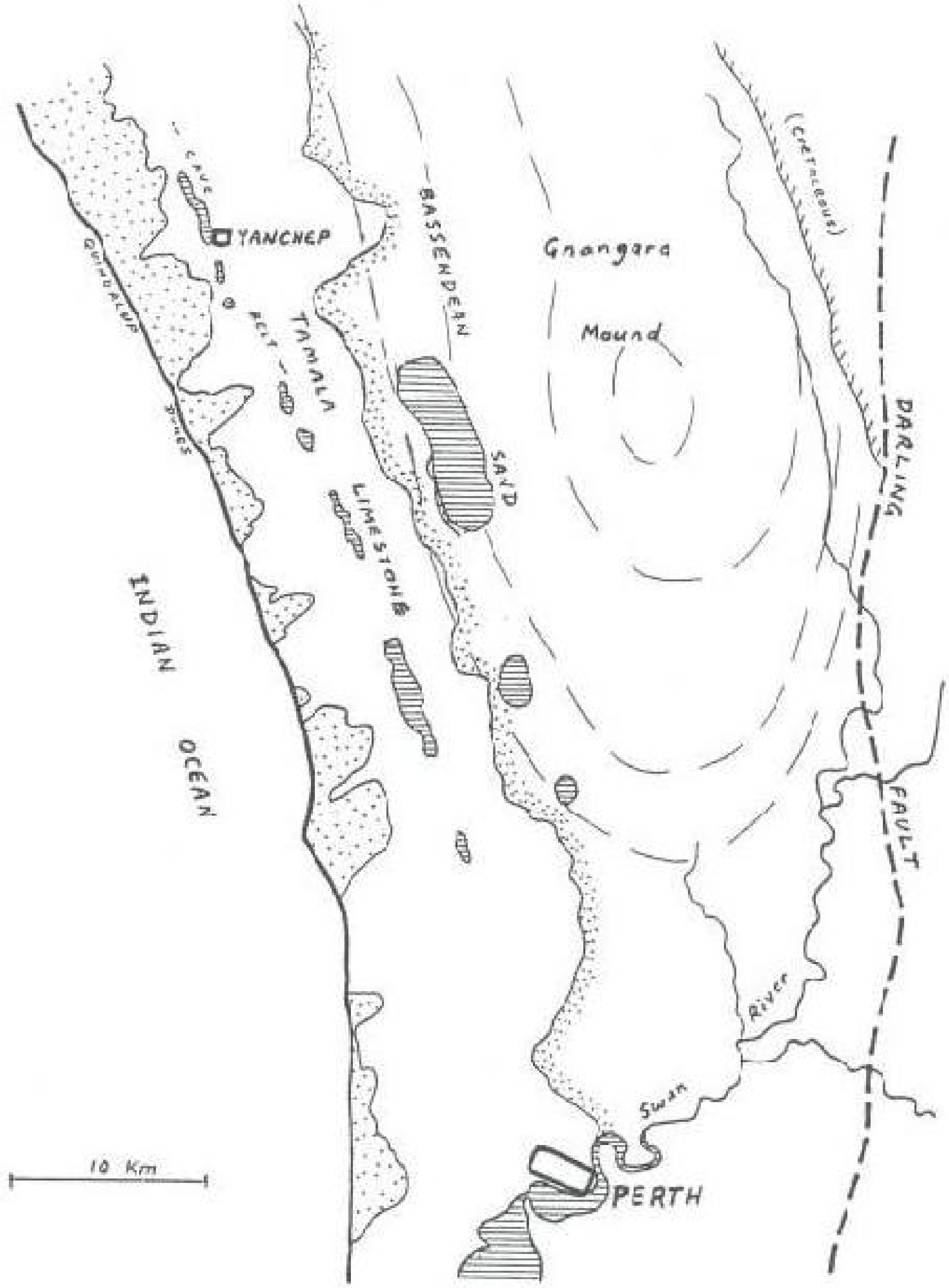

Figure 1 - Locality Plan
Watertable contours on the Gnangara Mound are shown schematically

The highest levels occur in an area east and southeast of Yanchep, resulting in radial groundwater movement from the Gnangara mound southwards towards the Swan River, and westwards towards the coast. The west-flowing sector takes the water into the Tamala Limestone, prior to discharge of the groundwater into the Indian Ocean. This process, operating in conjunction with the geological makeup of the region, leads to a unique hydrogeology, with several distinctive north-south zones.

SPELEOGENESIS

Cave development at Yanchep falls within the scheme described as syngenetic karst (Jennings, 1968), a sequence first proposed by the author (Bastian, 1964) from studies of caves in the southwest region. In this process cave development proceeds contemporaneously with the lithification of the dunes, and may already be well advanced by the time the material has become a reasonably firm limestone.

The groundwater relationships with respect to the limestone formation fall into five distinct zones aligned roughly parallel to the coastline. From east to west these are:

(i) Dry Substrate Zone
(ii) Cave Source Zone
(iii) Paraphreatic Cave Zone
(iv) Interdune Lake Chain
(v) Phreatic Cave Zone

Figure 2 shows a cross-section of the zones as modified from the 1991 paper.

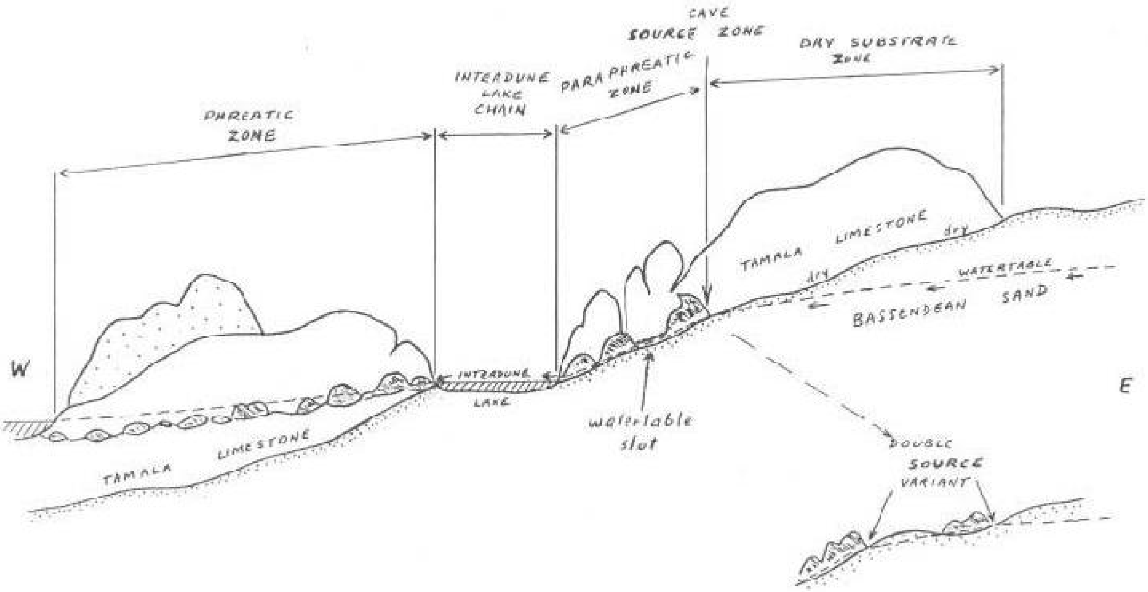

Figure 2 - Schematic east-west cross-section

(i) Dry Substrate Zone

This replaces "Subjacent watertable zone" as used in the former article, with a term that focusses more clearly on the reason for the absence of caves. In the zone, extensive tracts of the dune limestone lie as a relatively shallow veneer over the non-calcareous sand substrate, with the water table being located in the sand, generally well below the base of the limestone. For example, Drillhole NE72, located approximately 3 kilometres ENE of the Yanchep Park office, passed through 40 metres of limestone followed by 14 metres of dry sand below the base of the limestone, before intersecting the water table (Gozzard, 1982). It is debatable as to how much of the rain falling directly upon this zone reaches the water table: it is the opinion of the author that much of it remains perched in closed off solution pipes.

Even at the springtime maximum the water table does not rise sufficiently to reach the base of the limestone. Since there is no contact of groundwater with the limestone, solution at the base of the limestone is virtually nil and there is no cave formation. The zone is devoid of surface cave indications, and the dominant vegetation is heath. Karstification is limited to surface phenomena only, such as solution pipes and pinnacles; the pipes characteristically close off with depth.

(ii) Cave Source Zone

As outlined in the section on geology, the base of the Tamala Limestone descends westwards to be below sea level at the coast. This basal surface is steeper than the natural gradient of the water table, which cannot go below sea level. Hence the water table intersects the base of the limestone. Being virtually free of dissolved carbonate, the groundwater can dissolve the limestone vigorously, hence this line is marked by a sharp onset of solutional activity.

I had for some time been attempting to give a suitable title for the zone along which the groundwater makes its first contact with the limestone. In the 1991 paper I used the term: "Cave Threshold", but subsequently realised that this expression was already in regular use for the entrance area of a cave, where partial light penetrates. Due to seasonal fluctuations of the water table the actual point of groundwater contact fluctuates within a rather narrow zone, which therefore has been redefined as the "Cave Source Zone" (Bastian, 1996a). As a result of this activity a semi-continuous belt of caves is developed, manifested by the appearance of collapses, dolines, and fissures, with numerous enterable caves. A profound vegetation change is also seen, in the appearance of tuart (*Eucalyptus gomphocephala*), which thrives in broken limestone ground with access to the water table, and the understorey as a whole becomes denser in response to the increased accessibility of water.

Since the solutional attack must commence along the whole line of groundwater contact, it results in a loosely integrated cave system, with a distinct north-south elongation in plan. Continuity is however interrupted by breakdown features, somewhat analogous to a lava tunnel which has been broken by collapse into numerous segments. Chamber sizes tend on the whole to be larger than in other parts of area, because of the powerful solutional attack of the groundwater at the point of first contact with the limestone. Caves within this zone include Yanchep Cave (YN16), Catacombs Cave (YN8), and the eastern end of Crystal Cave (YN1), while the eastern (north-south) arm of Boomerang Gorge is an excellent example of a collapse feature developed along this trend.

Primary solution features are rarely seen, as the pervasive collapsing which occurs in the friable limestone means that most of the accessible caves are above the primary speleogenetic level. The most frequent cave form is the "inclined fissure" (Bastian, 1964), but open arched chambers are also common, due to complete dissolution of collapsed ceiling rock.

(iii) Paraphreatic Cave Zone

Westwards from the Cave Source Zone the base of the Tamala Limestone continues to maintain a gradient which on the whole is slightly steeper than the natural gradient of the water table.
The strong solutional activity which now occurs at the base of the limestone creates extensive cave systems, into which the groundwater discharges as a network of subterranean seepages, being fed into the streambeds from a slight excess of hydrostatic pressure.

Open streams fed from these seepages are able to transport the discharging groundwater much faster than it can percolate through the sand formation, thus the typical stream is in effect a sheet of fast moving groundwater. When functioning normally, the streams accommodate seasonal variations in the water table, by simply increasing or decreasing their rate of flow through relatively slight rises or falls in stream depths, respectively. Thus, instead of the pronounced annual fluctuations of the water table seen in central parts of the Gnangara Mound, water tables in this zone maintain an almost constant level[1].

Loss of hydrostatic pressure in the stream seepages means the water table is unable to penetrate the limestone, but instead follows down the sloping contact between the two formations until it has descended to not far above sea level. The relative gradient of the water table depends upon the slope of this contact plane.

Caves in this zone are not formed within the epiphreatic level (which by definition is the level of *intermittent* saturation, in which caves are subject to seasonal inundation). However, they do not fit a standard vadose model either, because vadose streams flow in conduits at levels above the zone of water saturated rock. These Yanchep cave streams are, by contrast, genetically linked to the water table within the underlying sand. In the 1991 paper the term "exophreatic" was proposed, but this is now regarded as an inaccurate term to cover the situation, as the water doing the dissolving is not outside (*exo-*) the phreas but remains at all times an integral part of the phreas. Instead, the term *paraphreatic*[2] has been substituted to reflect more accurately the locus of solution activity (*para* = from, alongside). *Paraphreatic* is defined as the condition in which the base of a limestone formation is in contact with a saturated non-calcareous aquifer, with a slight excess of hydrostatic pressure. It is essential to the paraphreatic condition that the intake area of the aquifer be relatively low, as any marked excess of pressure, such as in subartesian conditions, would cause the water table to invade the limestone, leading to the development of normal phreatic caves.

Also in the earlier paper the zone was described as a "Groundwater Escarpment", to highlight an apparent oversteepening of the water table in this zone. However, water table contours in the Yanchep area, derived from Water Corporation monitoring bores, confirm that the steepening is only slight and is not consistent, depending as it does upon undulations of the limestone/sand interface. The term has been dropped.

Although most caves in the region display the inclined fissure structure (Bastian, 1964) or complex variants thereof, the primary form in paraphreatic caves is a broad *watertable slot* with a horizontal ceiling. These slots typically have only a few centimetres space for the streams to run between their limestone ceiling and sandy bottom. As cave systems develop, the streams then continue to dissolve any limestone which may have collapsed into the water. Due to the friability of the limestone this eventually becomes the main means of cave enlargement: a typical ceiling in caves of the Paraphreatic Zone has no solution carved features, the only solution features being those at the base level, where a stream may be seen issuing from its slot. Since the stream beds are actually on the underlying sand formation, they are invariably shallow with a bottom of clean washed sand. Rotational Collapse of fallen roof blocks in the stream beds, as described by Caffyn (1973) can be seen in a number of places.

Caprock (kunkar) is well developed throughout the area, and plays a modifying role in terms of the cave morphology. Upwards stoping generally stops at the base of the caprock level, resulting either in extensive fissure complexes below the caprock or, less commonly, open chambers with subhorizontal ceilings. These complexes may virtually honeycomb a hill which has outwardly few or small entrances giving access to the system beneath.

(iv) Interdune Lake Chain

After the water table has descended by about 6-7 metres down the limestone/sand contact, the cave streams efflux onto the main lake chain. These are of the groundwater throughflow type (Davidson, *op.cit.*), and with a mean level of around 7 metres above sea level, afford a natural boundary between the water table regime east of the lakes and that to the west.

The lake chain interposes a significant modification to the hydrological system. In the winter peak period (June - August) the peat-clogged lakes are generally not able to discharge the amount of water entering them from the numerous effluxes along their eastern side. This in most cases results in a distinct winter rise in lake level which exceeds the rise in the streams feeding them, during which period the lakes in effect function as natural dams.

In the limestone hill barriers between the lakes, where dune lobes of younger western dunes have bridged across to the older dune system, there are several cave streams which traverse the barriers from east to west, thereby skirting the lakes. Thus, water dye tracing (Bridge 1969) failed to show a water connection between the lakes, although the water from the Loch Overflow (YN13) was detected in Mambibby Cave (YN12) about a thirdway across the gap.

The lake water exits via several natural cave spillways (Allen, 1981). These are cave systems which are exceptionally well developed and relatively free of organic matter, enabling them to take strong winter streams when the lake level rises. These disperse into cave labyrinths in which water movement is almost stagnant, and which are typically floored by thick deposits of peat. Caves of this type have been found along the western shores of Yonderup and Wilgarup Lakes and between Loch McNess and Yonderup Lake. This sluggish dispersed movement then makes its way to the coast, to emerge eventually as submarine seepages.

Figure 3 shows the main effluxes and inflow points found along the lake margins. Note that these are very incomplete, due to dense swamp vegetation and snake hazards: the number recorded along the northern flank of Loch McNess is due to a severe bushfire in 1991 which temporarily afforded easy movement and visibility.

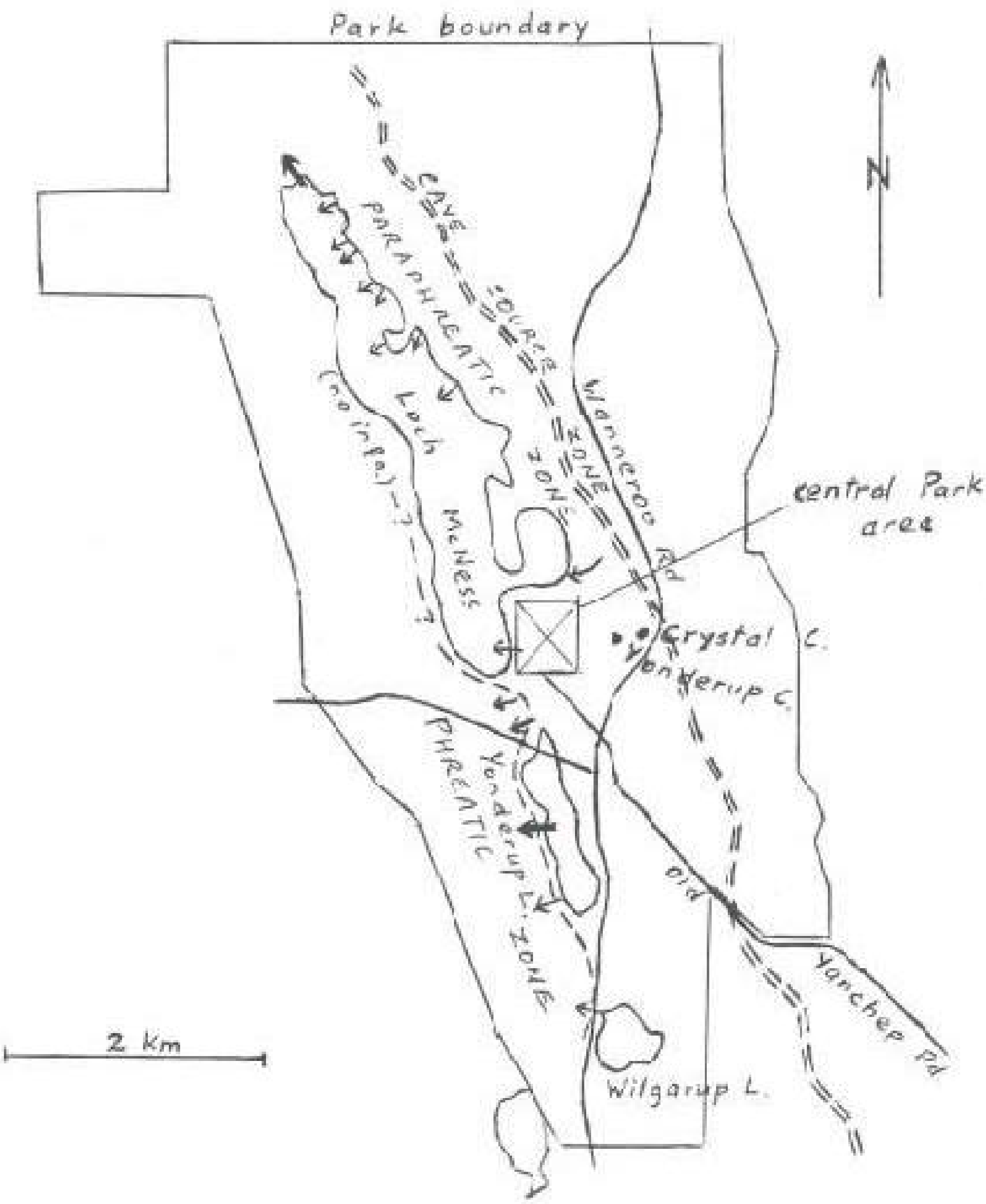

Figure 3 - Cave zones, effluxes and inflows in the Yanchep National Park area

The main cave spillway of Loch McNess is at the northern end of the lake, taking a vigorous winter stream which runs northwestwards to bypass the mainly blocked western shore of the lake. That this lake drains northwards was a feature observed by one of the early settlers in the district, Henry White (Milligan, 1903). The cave labyrinth named Loch Overflow (YN13) at the southern end of the lake does not actually draw surplus water from the lake as its name would imply, but is fed directly by a sheet of seepages from the east. The water in the lake is slightly alkaline; a set of pH readings taken at various points in the lake ranged from 7.6 to 8.1 (McComb and McComb, 1967).

At Yonderup Lake two major spillways have developed, one about halfway along the western shore of the lake, and another at the southern end. The spillway system on the western shore takes such a strong flow that a clear sandy floored channel crosses the lake to the inflow point, making it virtually a river within the lake. These two spillways have become so effective in draining the lake that it has an almost constant level summer and winter, which at 6.0 metres is a full metre lower than Loch McNess. Wilgarup Lake has a single inflow point at its northwestern corner, which appears to have silted up, and is not draining the lake very effectively: with the result that the lake level is higher than either of the others.

(v) Phreatic Cave Zone

A younger component of the Tamala Limestone - the Balcatta Dunes - forms the main lake frontage on the western side of the lake chain. The base of the limestone formation continues to descend, and eventually goes below sea level nearer the coast. The groundwater therefore must invade the formation, resulting in a radical change in the type of flow in the cave systems. Thus, instead of shallow streams flowing down the contact plane between the limestone and sand, the water movement changes to normal phreatic conditions.

Apart from the actual spillway points, where water levels reflect the fluctuations in lake level, the water table in this zone shows only a small annual variation, until the area subject to tidal effects is reached. A radial pattern can be identified originating from the various spillway points along the western shores of the lakes (Bastian, 1989). This pattern is soon lost as the water disperses throughout the zone in its movement towards the coast. A progressive lessening in subsurface karst phenomena can be observed toward the west, evidently due to increasing carbonate saturation of the cave waters. Cave distribution becomes more sparse and cave dimensions likewise tend to gradually diminish, with fewer or smaller collapses managing to break through to the surface. No caves have been accessed within several kilometres of the coast.

In this zone true phreatic solution features make their appearance, in which solution profiles can be observed, not just dissolved ceiling rock. An excellent example is the tunnel labyrinths of Concinna Cave (YN166) in the southern part of the Park. Instead of shallow streams these caves have ponded lakes, complex tunnel labyrinths, broad flat ceilings with roof pendants, and concave solution pockets. Caves fed from the lakes typically have heavy peat deposition in the tunnels.

A distinctive feature is the presence of a pronounced high water mark on the cave walls. This is particularly well seen in Loch Overflow Cave (YN13) and several others, in the form of a solution carved ceiling with numerous roof pendants, generally around one metre above present day levels. Deep notches on cave walls and on the pendants directly below these ceilings show that the level was maintained for some time. Broad flat-roofed chambers similar to the "Flat Roofed Lake" in the Augusta Jewel Cave are widespread in Loch Overflow Cave.

It is suggested that the high water level was brought about by an interglacial high sea level, which forced water tables near the coast to rise. The most probable time for this to have occurred would have been the major interglacial high sea level at about 120,000 years before present. Support for the antiquity of the high water level is afforded by the presence of old corroded cave decorations, with younger decoration superimposed on it.

The widespread nature of this phenomenon is evidenced by its presence in the Augusta cave area, having all the features mentioned above, including old corroded decoration and superimposed younger decoration. It is noteworthy that the high water level at Augusta is clearly higher than in any Yanchep cave. The probable reason for this is that the Augusta caves would have been particularly close to the coast at times of high sea level, resulting in a rise of the water table to match that of the ocean. Bermuda, virtually antipodeal to this region, reveals the same sequence of events in its caves. Harmon et al (1983) report the imprint on speleothems of the interglacial high sea level in the period 125,000 to 120,000 years B.P., and suggest a sea level rise of approximately 5 metres occurred at that time.

Paraphreatic/Phreatic Transitions

Because the limestone base is undulating there is no sharp demarcation between the two. Inaccessible watertable slots having vertical openings of only a few centimetres, in which the only solution carved rock will be the ceiling of the slot, grade into accessible mud tunnels having small roof pendants. Slightly deeper penetration of the limestone by the groundwater gives rise to scolloped ledges, larger pendants, and alcoves with a corrosion profile, but still lacking a rock floor to the main tunnels. The tunnel labyrinths of Loch Overflow Cave (YN13) are almost wholly of this type. As the base of the limestone deepens, the profile likewise deepens, resulting in full solution carved chambers floored by solid rock.

Again, the undulating substrate of the limestone formation causes variations in detail of the zonation. Depressions in the sand substrate which had become filled in with the calcareous dunes, result in hollows where the groundwater has invaded the limestone to produce an isolated pocket of phreatic caves, surrounded by caves with shallow paraphreatic streams. Of particular note is a group of phreatic caves in the limestone tract between Loch McNess and Yonderup Lake, which have developed within the swale that formerly occupied this strip prior to dunes advancing across it and separating the lakes. The most well known of these is Water Cave (YN11) near the south end of Loch McNess.

Mass Subsidence

There is one aspect of speleogenesis at Yanchep which deserves special mention. The limestone formation in this area is thin: the total thickness of Tamala above the sand substrate may range from around 50 metres to as little as 10 metres or even less. The pervasive groundwater contact with the base of the limestone can undermine it so extensively that there may be a complete loss of integrity of the limestone, from bottom to top of the formation. This effect can spread laterally to encompass a wide area. Once this happens, the rock as a whole begins to settle *en masse* as it is being dissolved from beneath. Such areas may be described as undergoing *mass subsidence*.

This phenomenon begins to manifest itself in an *early stage*, in which caves will have lost the "inclined fissure" form, consisting instead of fortuitous spaces amongst massive breakdown blocks. Pendant decoration in such caves frequently reveals extensive areas of leaning ceiling, showing that essential loss of integrity has occurred *above* the cave. A common feature seen on the surface is groups of vertical or near-vertical rifts, resembling the crevasses of a glacier, showing that the ground is effectively in a broken condition. There is a large rift (YN115) high on the hillside west of Yonderup Lake, showing that the eastern half of the ridge - which superficially appears intact - is actually already beginning to tilt towards the lake.

This is followed by an *advanced stage*, in which the rock is breaking down into smaller and smaller blocks, until finally no enterable caves can be found in the mass of subsiding limestone. Boomerang Gorge is a relic of a former cave whose collapsed ceiling rock has been almost wholly dissolved away, leaving only tumbled blocks of caprock along its flanks. The surface also becomes increasingly bare, due to the loss of soil down the multitude of cracks, and instead of the usual terrain of caprock pinnacles projecting through the soil what is revealed is a surface of disoriented blocks and boulders.

Eventually the limestone is reduced to isolated hummocks, either surrounded by swamp or by extensive tracts of residual yellow sand, and ultimately the limestone will disappear altogether. A considerable volume of residual sand is released from the dissolving limestone, and accumulates as aprons round the remnant hills. There is evidence that this has already occurred along much of the eastern side of Loch McNess, in the occurrence of extensive tracts of residual sand. Most of the effluxes along this side of the lake have eroded short stream channels through these sand tracts en route to the open water, which is mainly to be found along the western side of the lake. As a result of this process the lakes at Yanchep have been enlarged peripherally, so as to become much larger than their original sizes.

FOOTNOTES

1. N.B.: Due to a severe and progressive fall in the water table from local human causes since the early 1990's, water table data have become increasingly anomalous, and at present (2002) do not represent the normal situation for the locality. Many streams with a history of reliable flow are now drying out in the summer, while others have dried out altogether.
2. Ken Grimes (*pers.comm.*) has pointed out that the term had been published by Tratman in the late 1950's, but has never come into use. The term is reinvented here because the prefix is the best that can be used to cover the situation described.

BIBLIOGRAPHY

ALLEN, A.D. (1981). Groundwater resources of the Swan Coastal Plain, near Perth, Western Australia. In: Groundwater Resources of the Swan Coastal Plain (1981). *Proceedings of the symposium*, 29-80. Perth: C.S.I.R.O. Division of Land Resources Management.

BASTIAN, L.V. (1964). Morphology and development of caves in the southwest of Western Australia. *Helictite* 2: 105-119.

BASTIAN, L.V. (1989). Newly indexed caves and entrances in Yanchep National Park. *The Western Caver* 29: 8-13.

BASTIAN, L.V. (1991). The hydrogeology and speleogenesis of Yanchep. Australian Speleological Federation Inc. *Preceedings of the 18th Biennal Speleological Conference* 1991: 19-24.

BASTIAN, L.V. (1996). Residual soil mineralogy and dune subdivision, Swan Coastal Plain, Western Australia. *Australian journal of earth sciences* 43: 31-44.

BASTIAN, L.V. (1996a). Speleogenetic controls at Yanchep. *The Western Caver* 36: 13-19.

BOUTAKOFF, N. (1963). The geology and geomorphology of the Portland area. *Geological Survey of Victoria Memoir* 22.

BRIDGE, P.J. (1969). Water tracing Yanchep. *The Western Caver* 13(4): 124-125.

CAFFYN, P. (1973). Rotational collapse of blocks in the caves of the South West. *The Western Caver* 13(4): 130-132.

DAVIDSON, W.A. (1995). Hydrology and groundwater resources of the Perth region, Western Australia. *Geological Survey of Western Australia, Bull*. 142.

GOZZARD, J.R. (1982). Yanchep Sheet 2034 IV, Perth Metropolitan Region, Environmental Geology Series, *Geological Survey of Western Australia*.

HARMON, R.S., MITTERER, R.M., KRIAUSAKUL, N., LAND, L.S., SCHWARCZ, H.P., GARRETT, P., LARSON, G.J., VACHER, H.L., and ROWE, M. (1983). U-series and amino-acid racemization geochronology of Bermuda: Implications for eustatic sea-level fluctuation over the past 250,000 years. *Palaeogeogr., Palaeoclimatol., Palaeoecol*. 44: 41-70.

JENNINGS, J.N. (1968). Syngenetic karst in Australia. In: Jennings J.N. & Williams P.W.: Contributions to the study of karst, 5: 41-110. *Research School of Pacific Studies Australian National University*.

MCARTHUR, W.M., and BETTENAY, E. (1960). Development and distribution of soils of the Swan Coastal Plain, Western Australia. *CSIRO Australia Soils Publication* 16.

MCCOMB, J.A., and MCCOMB, A.J. (1967). A preliminary account of the vegetation of Loch McNess, a swamp and fen formation in Western Australia. *Jour. Roy. Soc. West. Aust*. 50: 105-112.

MILLIGAN, A.W. (1903). Lake Yanchep. *The Morning Herald*, Perth, March 7, 1903.

PLAYFORD, P.E., and LOW, G.H. (1972). Definitions of some new and revised rock units in the Perth Basin. *Geological Survey of Western Australia Annual Report* 1971: 44-46.

PLAYFORD, P. E., COCKBAIN, A.E., and LOW, G.H. (1976). Geology of the Perth Basin, Western Australia. *Geological Survey of Western Australia Bulletin* 124.

WHITE, S. (1989). Karst features of Pleistocene dunes, Bats Ridges, western Victoria. *Helictite* 27(2): 53-71.