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SPELEOGENESIS IN PLEISTOCENE LIMESTONES OF SOUTHEASTERN AUSTRALIA

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ABSTRACT

The extensive but relatively poorly consolidated Pleistocene carbonate dunes in southern Australia have developed areas of intensive karst development interspersed with extensive areas of limited cave and karst development.

Karst development on these eolianite ridges in southern Australia is dependent on several interrelated conditions: calcareous content of the limestone, its porosity, its ability to support a cavity and the availability of aggressive water capable of solution. Substantial variation in the karst development is found across southern Australia on the dunes and shows important differences in the number and type of caves present per volume of limestone, total passage length, passage orientation, passage size, and cave form. The karst features differ with the presence of distinctive features, such as bell holes and solution pipes, in some areas and their complete absence in others.

Although the dune karst is extensive in southern Australia, this overview concentrates on the karstic dunes of the western Otway Basin. The generalizations regarding karst characteristics and speleogenesis are consistent across the continent.

INTRODUCTION

The Cenozoic limestones of Australia include one of the world's most extensive areas of Pleistocene dune calcarenites. These extend along the west coast of Western Australia (WA) from Cape Range to Cape Leeuwin, and across the southern coast of the mainland Australia. Only limited deposits are found on the east and northern coasts (Figure 1). The dunes occasionally extend inland for up to over 100 km and overlie significant Paleogene and Neogene marine carbonates, some of which possess karst features. The karst features in the marine and eolian lithologies have some characteristics in common and others distinctly different. The earlier formed marine carbonates provide the source material for the overlying eolian lithologies.

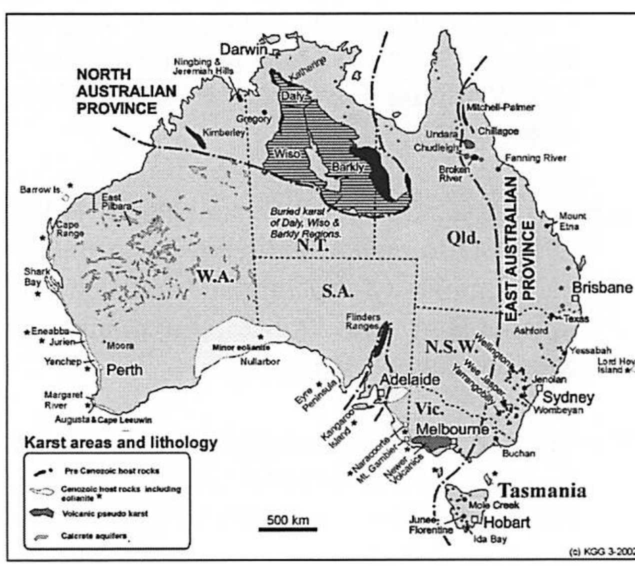

*Figure 1. Australian Karst Areas; eolianite areas indicated *. (After Grimes 2002)*

Jennings (1968) defined the processes involved in the simultaneous formation of karst features, including cave development, and lithification of the sediment as syngenetic karst. His syngenetic karst hypotheses were based on his observations of karst development in the relatively unconsolidated porous, permeable calcarenite dunes of Western Australia and South Australia and on the work by Bastian (1964), Sexton (1965) and Hill (1984). (Hill's work on Kangaroo Island was undertaken in the 1960s but only published posthumously in 1984). Since then further understanding of syngenetic karst in Australia has been undertaken by White (1989, 1994, 2000a) and Grimes (1994, 2002, 2004, 2006).

LOCATION AND GEOLOGICAL SETTING

Much of the research into dunes on the Australian continent has concentrated on either the quartz sand dunes of inland Australia or the spectacular surfing beaches of the east coast. The less studied but extensive calcareous dunes are often karstic; some, such as those in the lower southwest of WA, hosting large and well-decorated tourist caves.

The climatic conditions for the calcareous dune areas range through Arid, Temperate and Mediterranean climates. The most extensive karstic dunes, including those of the Otway Basin, are found in areas experiencing the dry summers and cool to mild wet winters of Mediterranean climatic conditions (Csb modified Köppen system).

The western Otway Basin lies on the southern Australian passive continental margin that formed during the Mesozoic continental break-up and seafloor spreading between the Australian and Antarctic plates. Extensive rifting, which controls the underlying geometry of the basin and the sediment accumulation, occurred from the mid-Jurassic to mid-Cretaceous and faulting continued into the late Cenozoic. The uplift of the Southern Australian continental margin (Dickinson et al., 2002) continues today.

The Gambier Karst Province is bounded by the coastline on the south and west, and the Dundas Tableland and associated high areas to the north and northeast (Figure 2). The diachronous eastern boundary, which is obscured by Cenozoic basalt flows, is defined by a lithological change from the Gambier Limestone to its lateral non-karstic equivalent, the Gellibrand Marl. This boundary is generally in the area of the Portland peninsula. Marker (1975) and Grimes et al. (1995) described the South Australian section of the Gambier Karst Province, and the former first established the area as an important karst province. In the western Victorian part of the province, investigations have focused on particular areas such as the Lower Glenelg National Park and Bats Ridge (White, 1994; 2000a, 2005). The karst province comprises extensive areas where cave and karst development is limited, interspersed with areas of atypical intensive karst development in both Oligo-Miocene cool water limestones, and the overlying the Pleistocene Bridgewater Group dunes, many of which have syngenetic karst development (White, 2005).

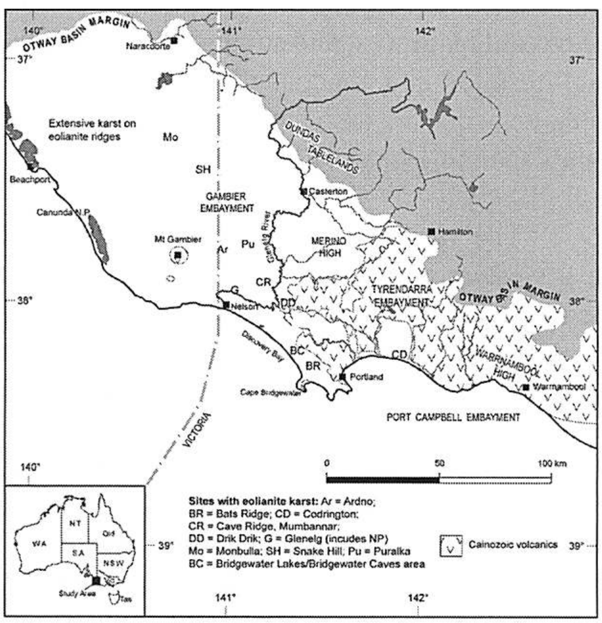

Figure 2. Western Otway Basin: eolianite karst areas

Sediments comprising two non-carbonate facies underlying the carbonate-rich Heytesbury Group were deposited during cycles of marine transgression and regression from the Late Mesozoic to the Pliocene. The marine regression in the Late Miocene led to the end of Heytesbury Group carbonate deposition through gradually shallowing seas (Benbow et al., 1995; Holdgate and Gallagher, 2003). Uplift at the end of the Miocene (Dickinson et al., 2002) led to subaerial exposure and associated karstification at the top of the Gambier and Port Campbell Limestones (Benbow et al., 1995). A transgression of the Late Tertiary sea affected both the Otway Basin and the adjacent Murray Basin to the north, depositing siliceous shoreline sediments (Loxton-Parilla Sands) in both basins. During the Pleistocene, as the sea regressed, the bioclastic carbonate beach, barrier and sub-parallel calcareous dune complexes were deposited over extensive areas of the western Otway Basin in a high-energy coastal environment with barrier dunes and associated lagoons. Dune building occurred from at least 1.3 Ma through to present times, where suitable conditions of sediment supply are available. The gradual uplift of the coastal plain west and south of the Kanawinka Fault resulted in a punctuated, time-transgressive eolianite sequence associated with sea-level high stands spanning most of the Pleistocene (Belperio et al., 1995).

The western Otway Basin represents the most western part of the Western District Volcanic Province, which was subjected to Quaternary volcanism from the Pliocene (Holdgate and Gallagher, 2003, Cupper et al., 2003) to the 4 to 5 ka eruptions of Mount Gambier and Mount Schank (Sheard, 1995). Recent tectonic movements have substantially affected the landscapes, e.g. the 60 m displacement of Pleistocene dune limestone on the Swan Lake and Kentbruck Faults (Boutakoff, 1952; Coulson, 1940). Consistent with the post Mid Pleistocene movement along faults is the termination of some dunes against fault escarpments, e.g. at Drik Drik. The spacing of the calcarenite dunes east of the Kanawinka Fault is less than to the west within the Gambier Embayment, where the rate of tectonic uplift was less.

LITHOLOGY OF THE BRIDGEWATER GROUP

The series of parallel, WNW-NW-trending Pleistocene strandline eolianite dune and shoreline systems, separated by interdune flats and alluvium, overlie the Tertiary sediments throughout southwestern Victoria and into South Australia (Belperio et al., 1995; Coulson, 1940; Cupper et al., 2003; Kenley, 1971). These were originally described as Bridgewater Formation (Boutakoff and Sprigg, 1953) but elevated to group status in Victoria (Orth, 1988) as equivalent eolianites to the east, were subdivided into a number of distinct formations (Gill, 1988). In the South Australian section of the basin this unit is still described as the Bridgewater Formation. This paper uses the Victorian nomenclature for the whole basin.

The Bridgewater Group is a range of coastal beach, dune and interdune facies deposited in shallow tidal, dune and lagoon environments (Kenley, 1988; Orth, 1988; Trounson, 1985) during the sea-level fluctuations spanning most of the Pleistocene. The South Australian calcareous dunes have been extensively dated by thermoluminescence (TL) and optical luminescence (OSL) methods. The TL dates range from ~61 ka to ~725 ka in age but older undated dunes are present (Banerjee et al., 2003, Huntley et al., 1993a; Huntley et al., 1993b; Huntley et al., 1994; Huntley and Prescott, 2001). In Victoria fewer dunes are dated but extend back to at least the Mid Pleistocene, with dates of ~500 ka at Warrnambool and ~300 ka near Portland (Oyston, 1996; White, 2000b). These dunes young towards the coast and their height and degree of separation decrease inland. The dunes are characterized by large-scale dune cross bedding. In a few cases, horizontally bedded beach sediments can be seen as part of the sequence. Where a number of dunes are superimposed, the maximum thickness is about 45 m, but thicknesses of between 15 to 25 m are more common.

Bridgewater Group calcarenites are well-sorted, fine- to medium-grained, laminated bioclastic carbonate sands (biosparite grainstones) composed of clasts of carbonate and quartz along with some fine clay derived from reworking of the underlying Tertiary sediments (Boutakoff, 1963; White 2005). Thin section and mineralogical analyses show that the chemical composition of Bridgewater Formation is typically variable (Kenley 1971; Coulson 1940; White, 1984, 2005) and are variably cemented with calcite. In some areas e.g. Naracoorte and Glenelg River areas, the dunes have relatively little quartz (<10%) compared to elsewhere, e.g. Bats Ridge, in western Victoria, where up to 28% quartz is present (White, 1984). This reflects the highly calcareous underlying source rocks of the Gambier Limestone and the lack of a nearby river inflow providing a source of quartz; the Glenelg River bed load lacks significant amounts of quartz. Although generally variably cemented (Holdgate and Gallagher, 2003), where the karst develops the dunes are better cemented e.g. Bats Ridge, western Victoria (15 to 30% cement) (White, 1984), Naracoorte up to 34.0 %, Drik Drik 12% - 24% (White, 2005). In some cases, at least two episodes of cementation can be differentiated and both rim and infill cement are present (White, 2005) (Figure 3).

Non-calcareous interdune facies are important in restricting vertical recharge and diversion of surface water into the dune ridges. In this context miscellaneous alluvial (e.g. Mosquito Creek) and lacustrine (e.g. Bool Lagoon) sediments within the sequence have local significance. The Bridgewater Group is also covered in places by either the siliceous sand sheets of the Pleistocene Mallanganee Formation (Boutakoff, 1963) or calcareous beach and dune complexes along the coastal margin (Discovery Bay Sands, Bridgewater Bay Sands) (Kenley, 1971).

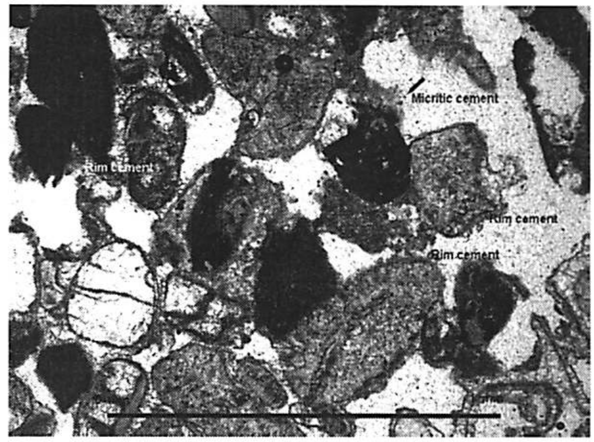

Figure 3. Thin section micrograph, Bridgewater Group eolianite at Drik Drik. Carbonate bioclasts, quartz, and both rim and infill cement. Scale bar 1mm

KARST DISTRIBUTION

The dunes in specific localities show a range of syngenetic karst features, including caves. Those localities include Bats Ridge, Codrington, Mumbannar, Puralka, Ardno, Monbulla, Snake Hill (Berryman and White, 1995; Jenkin, 1988; Kenley, 1988; Grimes et al., 1995; White, 1997).

Old coastal cliffs, such as at Bridgewater Caves above the Bridgewater Lakes and in the Swan Lake area, show evidence of the Pleistocene sea level changes. Some of the present coastal cliffs have well developed coastal karren (lapies) and there are a few small sea caves, which were primarily formed by wave action. There are good exposures of solution pipes, either with or without soil, e.g. in the coastal cliffs at Coonunda National Park and Cape Bridgewater (Grimes, 2004).

CHARACTERISTICS OF KARST

Distinctive characteristics of syngenetic karst on calcareous dunes include: development of an indurated layer in the dunes, shallow caprock caves, irregular horizontal mazes, caves that are either dominated by collapse domes or "inclined fissures", with little or none of the original solutional passage remaining and "flank-margin caves" in coastal situations. The caves are modified by extensive collapse, solution pipes, bell hole development, and extensive speleothem deposition, in particular, moonmilk.

Caprock (Kankar)

The indurated caprock (kankar) is essential for the development of caves in the dunes. This caprock does not show clear evidence of either biological activity or pedogenic processes and is not a soil calcrete. The original sand dunes stabilize quickly in subaerial conditions, but have insufficient strength to resist collapse after even relatively small amounts of material have been removed by solution. The caprock forms as the result of solution and redeposition of $CaCO_3$ under subaerial coastal dune conditions. The cap rock thickness is typically between ≈0.5 m and 1 m and is visible in cave entrances where a cross-section of the dune is obtainable (Figure 4).

Figure 4. Caprock above entrance and swampy area in foreground, Milliways Cave (CD 28), Codrington Victoria. (Photo: N.White).

Rock beneath this indurated layer is less cemented and softer than the cap rock itself (White 1994, 2005). Although the caprock hardness is still low compared with many other cavernous limestones (Day 1981), it has sufficient strength to hold up the roof when caves are formed. Hardness and cementation identified by Schmidt Test Hammer measurements and thin section analysis, indicates that the cap rock is significantly harder and more cemented than the underlying, less-consolidated limestone. Generally, where the cap rock exists, the caves, where present, form beneath it. However, fresh collapses are a characteristic feature in the caves, and are usually not composed of indurated limestone. The cap rock then should be seen as a bed of dune limestone, which has sufficient strength to withstand complete collapse when caves and hollows are dissolved beneath it. The cave entrances exposing cap rock can be seen are just below the ridge of the dune (Figure 4).

Cave form

The caves are of two common plan forms: simple single linear passages or chambers and single-level caves. The caves vary from a few meters in length, e.g. at Bats Ridge from 10 m at BR 19 to over 1.5 km in River Cave (BR 4).

The linear caves e.g. Chimney Cave, Bats Ridge (BR 1) (Figure 5) typically show low sinuous linear passages, low, flat, wide chambers (flatteners) and occasional collapse. They show extensive horizontal development that may be due to preferential erosion of soluble sediments along the water table of occasionally horizontal bedding planes. The spongework maze systems e.g. River Cave (BR 4), are dominated by interconnected solution cavities of varying size and irregular geometry. They also have low, flat, wide chambers (flatteners) and occasional collapse.

Caves are primarily formed at or near the water table by lateral solution, perhaps assisted by mixing corrosion. Much of the groundwater in the Otway Basin is saturated or nearly so in CaCO3, but the acidifying action of the swampy dune swales has probably been important in the creation of conditions of undersaturation of calcite resulting in aggressive solutional conditions. Surface water tends to be undersaturated in calcite+ but is only present during relatively short periods and is there- fore not a major factor in current cave development. Percolation water, on the other hand, is relatively saturated in calcite and results in the deposition of calcite speleothems in the existing caves. The caves have been formed primarily at times of higher water tables, probably during a period of wetter conditions (relative to today) in the late Pleistocene.

Collapse

Successful cave development is dependent on the strength of the overlying rock. In this case, it is the tensile strength, particularly of the cap rock, which enables caves to remain rather than completely collapsing. Many caves have been modified by collapse, often resulting in domed roof structures. Large collapse domes commonly obscure much of the original solutional cave shape, although the general linear or maze pattern of most caves can still be identified. Collapse material may almost completely fill the cavity leaving only limited "inclined fissures", with little of the original solutional passage remaining. In some areas, e.g. Codrington, an entire cave has collapsed and no underground cavity now exists, just a jumble of rocks.

Hill (1984) developed a two-stage scheme based on tension and shear processes for the formation of collapse domes in dune limestone at Kelly Hill Caves, Kangaroo Is. S.A. First, tension cracks appear towards the top of a dome so there is less support. The load is transferred to the periphery, where shear stress is increased. This builds up to the critical level of ultimate shear stress and shear occurs along the periphery as a final collapse. The cavity is effectively displaced towards the surface and structural stability is achieved for at least a time.

Collapse is one of the major entrance types and is generally located about 10m below the ridge crest and beneath exposed caprock. Multiple entrances for a cave system are common.

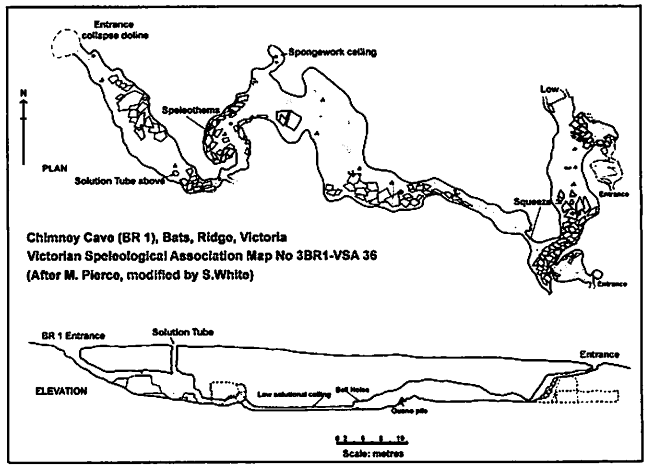

Figure 5. Map: Chimney Cave (BR 1), Bats Ridge, Victoria (After Pierce and VSA, 1974).

Solution Pipes, Soil Pipes and Bellholes

The presence of both solution pipes and bell holes (avens) is characteristic of caves in dune limestone (Jennings 1968). Soil-filled pipes not associated with caves are common across the Gambier Karst Province. They are sometimes associated with rhizomorphs (calcified small root structures), which are quite fragile and easily destroyed by erosion.

Solution pipe entrances are vertical and usually smooth sided cylindrical tubes varying from 0.2 to 3.5 m in diameter. These penetrate from the surface and intersect cave passages. They can be found as single pipe entrances, e.g. BR 58 (Chimney Cave) or as multiple closely spaced pipes, e.g. Tom-the-Cheap's Cave BR 9 (Figure 6). They typically have a thinly cemented rim, often only a few millimetres thick.

Solution pipes are dissolved by downward focused vertical flow of undersaturated water (Lundberg and Taggart, 1995). They are usually subsoil karst features often associated with vertical joints; however, the absence of joints in the dune calcarenites of southern Australia indicates that their presence is not essential. Solution pipes are a distinctive and widely reported feature of the softer more permeable limestones, e.g. Cretaceous

Chalk of Europe (Lamont-Black and Mortimore, 1999) and Pleistocene eolianites (Jennings, 1968).

Figure 6. Solution pipe entrances, Tom-the-cheap's Cave, (BR 9), Bats Ridge, Victoria. (Ladder indicates scale) (Photo: N.White).

Four methods of concentrating the flow have been proposed: stem-flow, tree root influence, water accumulating on surface hollows, and uneven cementation of the hardpan. These methods are not mutually exclusive, and all four may occur at one locality to produce solution pipes (Grimes, 2004). In all cases, once the flow is concentrated at a point, solution will progressively deepen a vertical pipe beneath that point. The cemented rim of the pipe is formed by lateral movement of water away from the pipe in the initially porous limestone. Solution pipe formation by upward migration of bell holes appears unlikely as a major mode of formation as the solution pipes would generally have a more flared base than is observed. Random intersection of solution pipes and bell holes is possible, and this may explain the rare solution pipes with constrictions, which have previously been explained as more resistant lithology despite no apparent obvious lithological differences. The relationship between the downward development of the solution pipes and the bell holes is unclear but are probably not related and the two features formed independently. Modification of solution pipe entrances has occurred by solutional widening, where sub-vertical solutional grooves are evident on the pipe walls, or, more commonly, by varying amounts of collapse, resulting in a collapse entrance.

Bell holes are cylindrical cavities with long vertical axes, varying between 0.3 to 1 m in diameter and 0.5 to 1.0 m deep, tapering upwards (Figure 7). They are a widespread feature of ceilings of caves in dune limestone in southern Australia, are not found on walls and are not associated with jointing in the cave ceilings.

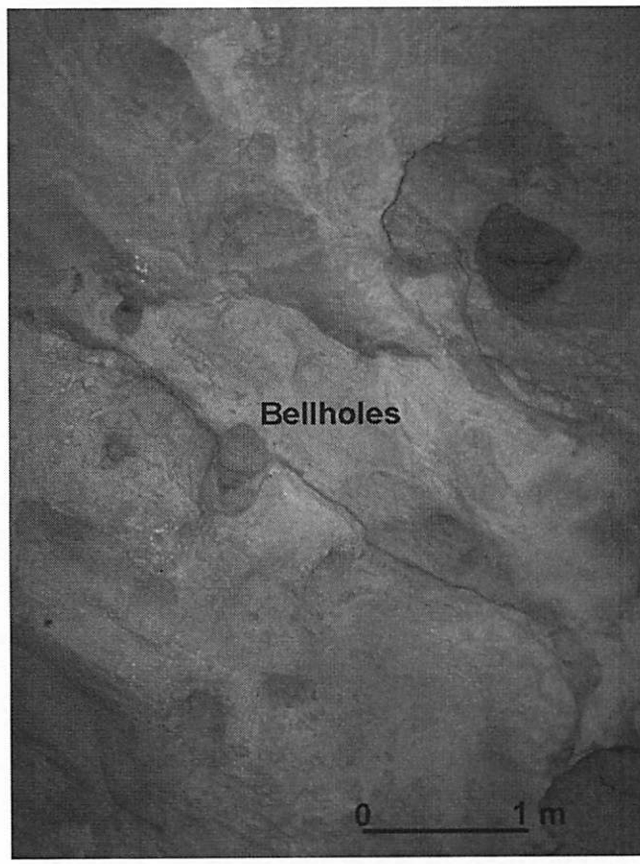

Figure 7. Bellholes in roof Chimney Cave (BR 1), Bats Ridge, Victoria (Photo: J. Mylroie). Scale bar ~1m.

Examples of the tops of bell holes are found on ceilings, subject to collapse, indicate that they are a solutional feature predating collapse. Bell holes in the dune limestone caves of the Otway Basin are more vertical and cylindrical than conventional ceiling pockets, which are often associated with fissures (Slabe, 1995). Bell holes have been explained in several ways, (cf. Lauritzen and Lundberg, 2000) including by condensation erosion in conjunction with microbial initiation in tropical conditions (Tarhule-Lips and Ford, 1998), and by a combination of vadose percolation and a phreatic process functioning in a laminar or slow-moving turbulent flow regime (Dogwiler, 1998). However more work is required to document their extent and understand their formation in the Otway Basin eolianites. They are not associated here with tropical conditions and have formed during the glacial/interglacial conditions of the Pleistocene.

Palaeosols

Soil pipes are present in many areas of Bridgewater Formation (Boutakoff 1963; Blackburn et.al. 1965) and are considered an integral part of the stratigraphy (Kenley 1988). They are absent from some of the intensively karstified dune areas e.g. Bats Ridge calcarenite ridge, although solution pipes without soil are present. The absence of soil-filled pipes may be due to the purity of the limestone, in that there are relatively low amounts of insoluble residues present. This suggests the areas with most intense karstification as expressed in the existence of caves, are those where the eolianite has the highest carbonate content.

Speleothems

Many caves show extensive calcite redeposition as speleothems including moon-milk, many of which are intermittently active (Figure 8). The most ubiquitous deposition of calcite is in the form of moonmilk, composed of calcite crystals with high water content between the crystals. It is found extensively across all areas of dune limestone karst e.g. Bats Ridge (White, 1989).

Some re-solution of speleothems occurs at levels indicating a standing water table level of aggressive water in the caves. In many cases

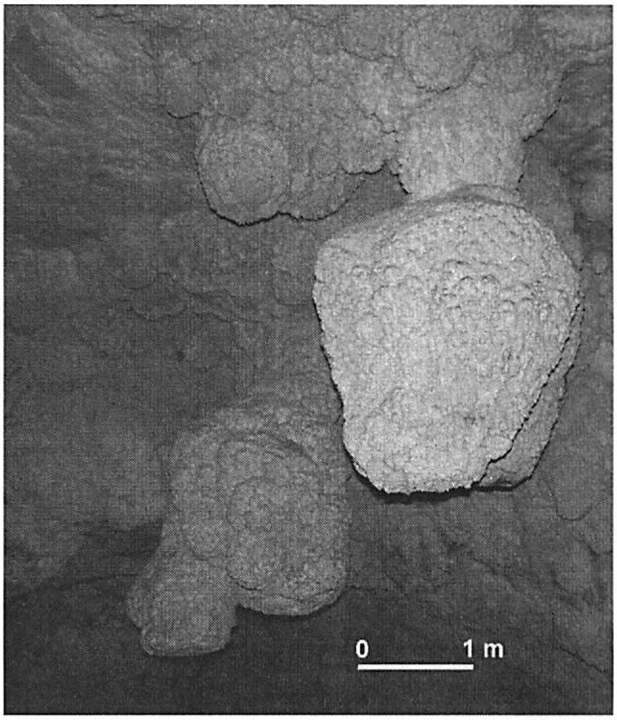

Figure 8. Extensive moonmilk Chimney Cave (BR 1), Bats Ridge, Victoria (Photo: N.White). Scale bar ~1m

this no longer occurs due to the draining of the swamps e.g. the Eumeralla River at Codrington. Currently, only under extreme flood conditions, if then, could water levels reach a height capable of spelothem dissolution.

Flank margin caves

The presence of Flank Margin Caves (FMC) (Mylroie & Carew, 2000) in this setting is possible but their identification on the coastal areas of dune calcarenites has been complicated by the continental uplift of the passive continental margin. More detailed research and documentation needs to be obtained to clarify this but caves such as Taragal (Bridgewater) Caves (P1) (Figure 9) show many of the characteristics of FMC, especially the irregular form of interconnected "mixing chambers". The name refers to the tendency for these caves to cluster at the island margin, but similar clustering can occur along the edge of

FIGURE 9. Probable Flank Margin Cave, Taragal (Bridgewater) Caves (P1), Portland, Victoria (Photo: J. Mylroie)

dune ridges adjacent to swamps that provide aggressive water (Eberhard, 2004).

HYDROLOGY

There is limited surface drainage, and the Glenelg River with its incised valley and gorge is the only major stream. Most of its tributaries in its karstic tract are subsurface streams. Several springs occur in the areas close to the present coast, issuing from small, submerged dolines, caves, or on the present beach, and others have been reported offshore (Marker, 1975). Coastal springs, often with tufa deposits, also occur on the coastal cliffs, e.g. Cape Bridgewater. The absence of extensive surface drainage combined with the swampy interdune swales result in a complex interaction between coastal groundwater conditions and speleogenesis. The position of the caves within the dune can reflect a previous higher water table. Surface features include enclosed depressions, which are often swale lakes modified by solution.

SPELEOGENESIS

In eolianite dunes, percolating rainwater dissolves the unconsolidated carbonate clastic sand to limestone by the alternating processes of dissolution and re-deposition of calcium carbonate. Surface solution results in a soil depleted in carbonate but enriched in the insoluble grains (e.g. quartz). Underneath this soil, a cemented caprock forms in the top of the dune. Where the dune contains paleosols this caprock may be duplicated. Downward movement of percolating water may result in solution pipes where the water is focused, but where the water is less concentrated the caprock is increasingly cemented. Although some concentration of water may occur associated with vegetation roots, it is not clear that this is always the case. The development of caves is dependent on conditions promoting solution, which include the purity of the limestone and the availability of sufficiently aggressive groundwater under the cap rock.

The caves develop as a result of lateral solution at or near the water table, due to the increased aggressivity of water, which is itself the result of increased acidity and/or mixing corrosion. The present position of the caves may relate to previous water table levels.

The caves are subsequently modified particularly by collapse but also where inflow of swamp water from the interdune swales occurs at times of high water tables. The drainage modifications since European settlement of the area also have an effect on the karst.

CONCLUSIONS

Syngenetic karst, as presented by Jennings (1968) and later workers (e.g. Grimes, 2006), is described as cave development while the sediment consolidates; speleogenesis and lithogenesis are concurrent. Quaternary eolianites (eolian calcarenites) show the best development of syngenetic karst in southern Australia, but other permeable calcarenites e.g. the Oligo-Miocene Gambier and Nullarbor limestones, often develop distinctive syngenetic features e.g. solution pipes, caprock and extensive collapse modification, which are evidence of karst processes in poorly consolidated and variably cemented limestones rather than specifically eolianite karst.

The characteristic landforms of syngenetic karst are associated with the processes of dissolution and collapse on Pleistocene calcarenite strandline ridges (White, 2000a; Grimes, 2006). This includes extensive cap rock (kankar) development, which formed as the result of solution and re-deposition of calcium carbonate under sub-aerial conditions. The caves are shallow and often sinuous with horizontal development, and have formed under the cap rock. The caves have multiple entrances, low, flat, wide chambers, solution pipes, bell-holes, moonmilk and extensive weathering of wall surfaces. Collapse modification is extensive. The position of the caves within the dune can reflect a previous higher water table. Surface features include enclosed depressions, which appear to be swale lakes modified by solution.

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REFERENCES

Banerjee, D., Hildebrand, A.N., Murray-Wallace, C.V., Bourman, R.P., Brooke, B.P. and Blair, M. 2003. New quartz SAR-OSL ages from the stranded beach dune sequence in south-east South Australia. Quaternary Science Reviews, 22: 1019-1025.

Bastian, L. 1964. Morphology and development of caves in the Southwest of Western Australia. Helictite, 2: 105-119.

Belperio, A.P. Benbow,M.C. Callen, R.A. Drew, G.J. Love. D.N. Rogers, P.A. Preiss, W.V. Sheard. M.J. Smith, P.C. Stone, M. & Walker, S. 1995. Quaternary. In: J.F. Drexel and W.V. Preiss (Eds), The Geology of South Australia. South Australia Geological Survey Bulletin 54. Adelaide, pp. 219 - 280.

Benbow, M.C., Alley, N.F. and Lindsay, J.M. 1995. Tertiary: Introduction. In: J.F. Drexel and W.V. Preiss (Editors), The Geology of South Australia. Bulletin 54. The Geological Survey of South Australia, pp. 151

Berryman, S. & White, S. 1995. Karst in recent dunes, Codrington, Victoria. In Baddeley, G. (ed), Vulcon Precedings, (20th ASF Conference), Victorian Speleological Association, Melbourne. pp. 23-31.

Blackburn, G., Bond, R.D., & Clarke, A.R.P. 1965. Soil development associated with stranded beach ridges in South-east Australia. CSIRO Australia Soil Publication, 22: 1-65.

Boutakoff, N. 1952. The Structural Pattern of South-West Victoria. Mining and Geological Journal Victoria, 4(6): 21-29.

Boutakoff, N. 1963. The geology and geomorphology of the Portland area. Memoir 22, Geological Survey of Victoria, Melbourne.

Boutakoff, N. and Sprigg, R.C. 1953. Summary report on the petroleum possibilities of the Mt Gambier Sunklands. Mining and geological journal Victoria, 5(2): 28-42.

Coulson, A. 1940. The sand dunes of the Portland district and their relation to the post-Pliocene uplift. Proceedings of the Royal Society of Victoria, 52(2): 315-335.

Cupper, M.L., White, S. and Neilson, J.L. 2003. Quaternary: ice ages - environments of change. In: W.B. Birch (Ed), Geology of Victoria. Geological Society of Australia Special Publication 23, Geological Society of Australia (Victoria Division), pp. 337-359.

Day, M.J., 1981. Rock Hardness and landform development in the Gunung Mulu National Park, Sarawak, E. Malaysia. Earth Surface Processes and Landforms 6: 165-172.

Dickinson, J.A., Wallace, M.W., Holdgate, G., Gallagher, S.J. and Thomas, L. 2002. Origin and timing of the Miocene Pliocene unconformity in southeast Australia. Journal of Sedimentary Research, 72(2): 288-303.

Dogwiler, T. J 1998. Analysis of Bell Hole Morphology and Distribution: A Tool for Evaluating Formational Processes. MSc Thesis, Department of Geosciences Mississippi State University, Mississippi, U.S.A.

Eberhard, S.M. 2004. Ecology and hydrology of a threatened groundwater-dependent ecosystem: the Jewel Cave karst system in Western Australia. PhD thesis Murdoch University, Western Australia. Downloadable from: http: //wwwlib.murdoch.edu.au/adt/browse/ view/ adt-MU20051010.141551 (17 Mb)

Gill, E.D. 1988. Warrnambool - Port Fairy District. In: J.G. Douglas and J.A. Ferguson (Editors), Geology of Victoria. Geological Society of Australia, Victoria Division. Melbourne, pp. 374-379.

Grimes, K.G. 1994. The South-East Karst Province of South Australia. Environmental Geology, 23: 134-148.

Grimes, K.G. 2002. Syngenetic and Eogenetic Karst: An Australian Viewpoint. in Gabrovšek, F. [ed] Evolution of Karst: from Prekarst to Cessation. Inštitut za raziskovanje krasa, ZRC SAZU, Postojna. pp. 407-414.

Grimes, K.G. 2004. Solution pipes or petrified forests? Drifting sands and drifting opinions. The Victorian Naturalist, 121(1): 14-21.

Grimes, K.G. 2006. Syngenetic Karst in Australia: a review Helictite 39(2): 27-38.

Grimes, K.G., Hamilton-Smith, E. and Spate, A.P. 1995. South East Karst province of South Australia, Australian Caves and Karst Management Association.

Hill, A.L. 1984. The origin of the Kelly Hill Caves, Kangaroo Island, S.A. Helictite, 22(1): 6-11.

Holdgate, G.R. and Gallagher, S.J. 2003. Tertiary: a period of transition to marine basin environments. In: W.B. Birch (Editor), Geology of Victoria. Geological Society of Australia Special Publication 23, Geological Society of Australia (Victoria Division), pp. 289-335.

Huntley, D.J., Hutton, J.T. and Prescott, J.R. 1993a. Optical dating using inclusions within quartz grains. Geology, 21: 1087-1090.

Huntley, D.J., Hutton, J.T. and Prescott, J.R. 1993b. The stranded beach-dune sequence of south-east South Australia: A test of thermoluminescence dating, 0-800 ka. Quaternary Science Reviews, 12: 1-20.

Huntley, D.J., Hutton, J.T. and Prescott, J.R. 1994. Further Thermoluminescence dates from the dune sequence in the southeast of South Australia. Quaternary Science Reviews, 13: 201-207.

Huntley, D.J. and Prescott, J.R. 2001. Improved methodology and new thermoluminescence ages for the dune sequence in south-east South Australia. Quaternary Science Reviews, 20: 687-699.

Jenkin, J.J. 1988. Geomorphology. In: J.G. Douglas and J.A. Ferguson (Editors), Geology of Victoria. Geological Society of Australia, Victoria Division, Melbourne, pp. 403-419.

Jennings, J.N. 1968. Syngenetic Karst in Australia. In: Jennings, J.N. and Williams, P.W. Contributions to the study of karst. Res. Sch. Pac. St. A.N.U. 5: 41-110

Kenley, P.R. 1971. Cainozoic geology of the eastern part of the Gambier Embayment, Southwestern Victoria. In: H. Wopfner and J.G. Douglas (Eds), The Otway Basin of southeastern Australia. Special Bulletin. Geological Surveys of South Australia and Victoria, pp. 89-155.

Kenley, P.R. 1988. Quaternary - Southwestern Victoria. In: J.G. Douglas and J.A. Ferguson (Eds), Geology of Victoria. Geological Society of Australia, Victoria Division, Melbourne, pp. 365-379.

Lamont-Black, J. and Mortimore, R.N. 1999. Predicting the distribution of dissolution pipes in the chalk of southern England using high resolution stratigraphy and geomorphological domain characterisation. In: B.F. Beck (Ed), Hydrogeology and Engineering Geology of Sinkholes and Karst. Balkema, Rotterdam, pp. 97-102.

Lauritzen, S.-E. and Lundberg, J. 2000. Solutional and Erosional Morphology of Caves. In: A. Klimchouk, D. Ford, A. Palmer and W. Dreybrodt (Eds), Speleogenesis: Evolution of Karst Aquifers. National Speleological Society Inc., Huntsville, Alabama, U.S.A., pp. 408-426.

Lundberg, J. and Taggart, B.E. 1995. Dissolution pipes in northern Puerto Rico; an exhumed paleokarst. Carbonates and Evaporites, 10(2): 171-183.

Marker, M.E. 1975. The Lower Southeast of South Australia: A Karst Province. Department of Geography and Environmental Studies, University of Witwatersrand, Johannesburg, Occasional Paper No. 13, 68 pp.

Mylroie, J.E. and Carew, J.L. 2000. Speleogenesis in Coastal and Oceanic Settings. In: A.

Kilmchouk, D.C. Ford, A.N. Palmer and W. Dreybrodt (Eds), Speleogenesis: Evolution of Karst Aquifers. National Speleological Society Inc., Huntsville, Alabama, U.S.A. pp. 224-233

Orth, K. 1988. Geology of the Warrnambool 1:50,000 mapsheet. 86, Geological Survey of Victoria.

Oyston, B. 1996. Thermoluminescence dating of quartz from Quaternary aeolian sediments in southeastern Australia. Ph.D. Thesis, La Trobe University, Melbourne, 299 pp.

Sexton, R.T. 1965: Caves of the Coastal Areas of South Australia, Helictite 3(3): 45-59.

Sheard, M.J. 1995. Quaternary Volcanic Activity and Volcanic Hazards. In: J.F. Drexel and W.V. Preiss (Eds), The Geology of South Australia. Bulletin 54. The Geological Survey of South Australia, pp. 264 - 268.

Slabe, T. 1995. Cave rocky relief and its speleological significance. Znanstvenoraziskovalni Center Sazu, Ljubliana, 128 pp.

Tarhule-Lips, R.F.A. and Ford, D.C. 1998. Morphometric studies of bell hole development on Cayman Brac. Cave and Karst Science, 25(3): 119-130.

Trounson, L. 1985. Diagenetic and pedogenetic features of Quaternary dune and beach deposits of the southwest Victorian coast. M.Sc. Thesis, University of Melbourne, Melbourne, 139 pp.

White, S. 1984. Karst landforms and their relationship to Pleistocene dune ridges, Bats Ridge, Portland, Victoria. Unpublished MSc. Thesis, University of Melbourne, Australia.

White, S. 1989. Karst features in Pleistocene dunes, Bats Ridge, western Victoria. Helictite, 27(2): 53-71.

White, S. 1994. Speleogenesis in aeolian calcarenite: A case study in western Victoria. Environmental Geology, 23: 248-255.

White, S. 1997. Karst of the Cainozoic limestones of the Otway Basin, Southeastern Australia, Fourth International Conference of Geomorphology. Supplementi di Geografia Fisica e Dinamica Quaternaria. Comitato Glaciologico Italiano, Italy, pp. 129-132.

White, S. 2000a. Syngenetic Karst in Coastal Dune Limestones: A Review In: A. Klimchouk, D. Ford, A. Palmer and W. Dreybrodt (Eds), Speleogenesis: Evolution of karst aquifers. National Speleological Society, Huntsville, Alabama, pp.234-23.

White, S. 2000b. Thermoluminescence dating of dune ridges in western Victoria. Helictite, 36: 38-40.

White, S. 2005 Karst and Landscape Evolution in parts of the Gambier Karst Province, Southeast South Australia and Western Victoria, Australia. PhD thesis, Latrobe University, Australia.