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Black holes: caves in the Australian landscape

JOHN WEBB, KEN GRIMES AND ARMSTRONG OSBORNE

INTRODUCTION

On a world scale, Australia is not well-endowed with caves because, with the exception of the Nullarbor, it has relatively little limestone. By comparison, the United States and Western Europe have far more limestone and many more caves. Nevertheless, Australia's caves are world-renowned, both among the caving fraternity and the general public.

The huge passages and water-filled tunnels of the Nullarbor feature in numerous coffee-table books on Australian scenery, and have attracted many Australian and overseas cave-diving expeditions to the longest cave dive in the world, more than 6 kilometres. The caves, together with the Nullarbor's amazingly flat, treeless landscape and very large area (it is one of the largest outcrops of limestone in the world), have won it a nomination for World Heritage listing. Australia's most-visited caves are probably the Jenolan tourist caves, near Sydney; with their spectacular decoration and impressive limestone arches, they attract thousands of visitors each year. Australia's lesser-known limestone areas are notable for their variety and include many with fascinating scenery and exciting caves, such as the razor-sharp towers of north Queensland, the cold, deep shafts of southwest Tasmania, the carbonate dunes of southwest Western Australia, the clear cenote lakes of southeastern South Australia, and the ancient reefs of northwest Western Australia.

Australia's caves also have great scientific interest, and Buchan caves in eastern Victoria and Jenolan caves in New South Wales have given new insights into the evolution of the landscape of southeastern Australia. The stalagmites from many caves have been used to reconstruct past climates, and caves throughout Australia contain unique fauna and fossils (described later in this book). Australia also has interesting non-limestone caves, particularly the lava tunnels of north Queensland and western Victoria, some of which occur in basalt lavas that erupted relatively recently, during the past 20 000 years.

This chapter describes each of Australia's main limestone cave areas in order of the age of the limestone, starting with the oldest, and then goes on to look at non-limestone caves. However, before describing the caves themselves, the processes of cave formation are discussed, to provide the background information that makes it easier to understand the occurrence and significance of the caves.

THE FORMATION OF CAVES

Dissolution of carbonate rocks (limestone and/or dolomite) by water forms a particular type of landscape called karst. In order to understand how caves and other features of karst landscapes form, it is necessary to discuss the processes by which limestone and dolomite are dissolved.

Calcite (calcium carbonate, $CaCO_3$, the main constituent of limestone) and dolomite (calcium magnesium carbonate, $CaMg(CO_3)_2$) are sparingly soluble in pure water, but dissolve readily in acidic solutions. The most common acid in surface and groundwaters is carbonic acid, a weak acid that forms when carbon dioxide dissolves in water:

Reaction 1

$$\underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} \leftrightarrow \underset{\text{carbonic acid}}{H_2CO_3} \qquad (1)$$

Carbonic acid can then dissolve limestone (calcite) and/or dolomite:

Reaction 2

$$\underset{\text{limestone}}{CaCO_3} + \underset{\text{carbonic acid}}{H_2CO_3} \leftrightarrow \underset{\text{calcium}}{Ca^{2+}} + \underset{\text{bicarbonate}}{2HCO_3^-} \qquad (2)$$

Reaction 3

$$\underset{\text{dolomite}}{CaMg(CO_3)_2} + \underset{\text{carbonic acid}}{2H_2CO_3} \leftrightarrow \underset{\text{calcium}}{Ca^{2+}} + \underset{\text{magnesium}}{Mg^{2+}} + \underset{\text{bicarbonate}}{4HCO_3^-} \qquad (3)$$

Limestone is much more reactive than dolomite, but dolomite will still dissolve, and thick dolomite beds can contain substantial cave systems, for example, at Camooweal, northwest Queensland.

Rainwater dissolves carbon dioxide from the atmosphere according to reaction 1, and becomes naturally acidic, with an average pH of about 5.6 (note that a pH of less than 7 is acidic). When rainwater trickles down exposed limestone surfaces, its acidity gives it the capacity to dissolve vertical ridges and channels (rillenkarren) in the limestone, particularly in high-rainfall tropical climates (for example, Chillagoe, north Queensland, see photo 6).

Rainwater falling on soil will seep down to join the groundwater, absorbing additional carbon dioxide as it goes. Microbial decay of plant material in soil releases large amounts of carbon dioxide, so that air in soil contains about 30 times as much carbon dioxide as the atmosphere. Thus water in the soil is more acidic than rainwater, and once it comes into contact with limestone or dolomite, it will dissolve them according to reactions 2 and 3. In addition, organic acids (humic and fulvic acids) are released by microbial decomposition of plant material within soil, and can add significantly to the acidity of groundwater.

The acidified groundwater will dissolve limestone until its acidity is effectively neutralised and it becomes saturated, that is, it has so much calcium and bicarbonate in solution that it cannot dissolve any more limestone. The principle of saturation applies to any solid dissolving in water. For example, if so much sugar is added to a cup of coffee that no more can dissolve and some remains on the bottom of the cup, then the coffee is saturated. Waters undersaturated with respect to limestone are acidic and said to be aggressive, that is, they can dissolve more limestone. It takes some time for aggressive waters in contact with limestone to become saturated, and even longer if the waters are moving quickly through the limestone. Nevertheless, by the time the water leaves the limestone as springs, it is almost always saturated and lacks acidity.

Patterns of water flow and passage development

For large, extensive cave systems to develop, a substantial supply of aggressive water is required, often through a concentrated input such as a stream flowing onto limestone from adjacent or overlying non-carbonate rocks. Because this water has not previously been in contact with limestone, it is often acidic (aggressive) and can dissolve a considerable amount of limestone and form caves. As a result, many such streams disappear underground into cave systems through sinks in the stream bed soon after they cross onto the limestone, leaving dry valleys that flow only during floods. If the valleys do not continue off the limestone but end in a depression leading to a cave, they are called blind valleys. In Australia, sinking streams and their associated caves are common in the relatively small areas of older carbonate rocks surrounded by non-limestone lithologies.

In large areas of limestone, there is frequently no external source of water apart from rainfall, which seeps diffusely down through the soil. This aggressive water will tend to flow along particular pathways in the underlying rock; the pathways are determined by weaknesses such as fractures, so dissolution beneath the soil is often concentrated at particular points. With time, this process will form conical depressions called solution dolines, mostly tens to hundreds of metres across, that pock-mark the surface of a limestone terrain. Dolines may capture seepage over a considerable area, and this aggressive water will dissolve cave passages in the underlying limestone. Doline formation is thus contemporaneous with conduit development. As a result, dolines are often entrances to cave systems (see photo 1).

Aggressive water, whether it is trickling through a solution doline or flowing into the limestone through a stream-sink, will move down through the limestone until it reaches the watertable; below this level all cavities in the rock are filled with groundwater. Beneath the watertable the groundwater is not stationary, but flows slowly, generally toward the nearest topographic low point in the karst landscape, where it discharges from the limestone

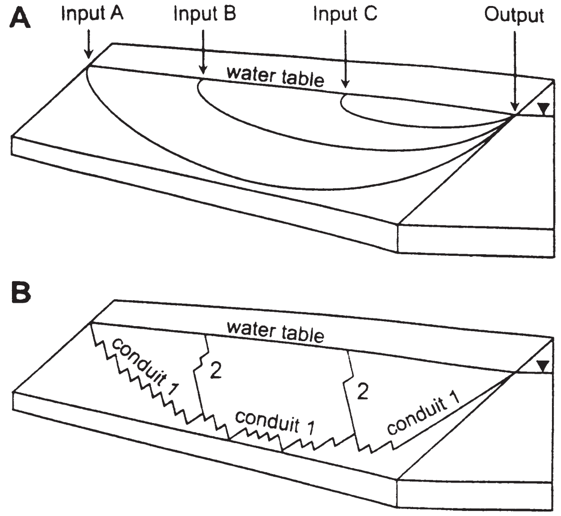


Figure 1.1

Phreatic loops in groundwater flow (A) and their reflection in the pattern of conduit development in limestone aquifers(B).

After Worthington, 2001

Photo 1:

Barwidgee Doline at Camooweal, Queensland. The channel in the background carries floodwaters from the Georgina River which have, over time, dissolved cave passages in the underlying limestone leading to the collapse of the doline.

Photo: K.G. Grimes

as a spring (also called an efflux). The location of the spring depends on topography and geology, but springs are often found at the edge of limestone outcrops, and along rivers and coastlines.

Groundwater movement between the input of aggressive water (doline or stream-sink) and the efflux (spring) is concentrated along a curved flow path called a phreatic loop (from the Greek *phrear*, a well). From the input, the groundwater moves slowly down, and then rises toward the efflux (Figure 1.1). The depth reached by the groundwater flow depends on the dip of the bedding of the limestone (the steeper the dip, the deeper the phreatic loop) and the distance between input and efflux (the greater the distance, the deeper the loop). For short flow paths and/or horizontally bedded limestone, the phreatic loop will be very shallow, and horizontal cave systems will form. For long distances between input and efflux and steeply dipping limestone, the depth of the phreatic loop will be considerable, in exceptional cases 1000 metres below the surface at the midpoint. Rapidly descending passages will form along the initial part of the flow path, and may later develop into subvertical shafts, such as those in the Junee–Florentine area of central Tasmania (Figure 1.2) or the caves around Camooweal (Figure 1.5).

Because the flow of aggressive water from the input is concentrated along the phreatic loop, limestone dissolution and cave formation occur predominantly along this flow path. Most caves in carbonate rocks form initially in this way, which is called phreatic development (that is, below the watertable). Dissolution of smaller passages will occur above and below the loop, but the largest cave passages will form along the preferred flow path. A large single-trunk passage may develop, or there may be several interconnecting passages at much the same level.

Once a passage is more than about 1 centimetre in diameter, water flows more rapidly through it. Thus most of the groundwater flow will be concentrated along a passage of this size, which will continue to enlarge, while nearby conduits, receiving relatively little flow, will remain small. As a result most of the passages within limestones are too small for humans to enter, although they may be very important as habitats for cave animals (see photo 2).

In large limestone areas there will be multiple inputs, for example, through numerous solution dolines. The caves developing from each input may join together downflow to form a trunk cave system feeding a major spring, in the same way that small tributary streams on the surface converge downstream to form a large river.

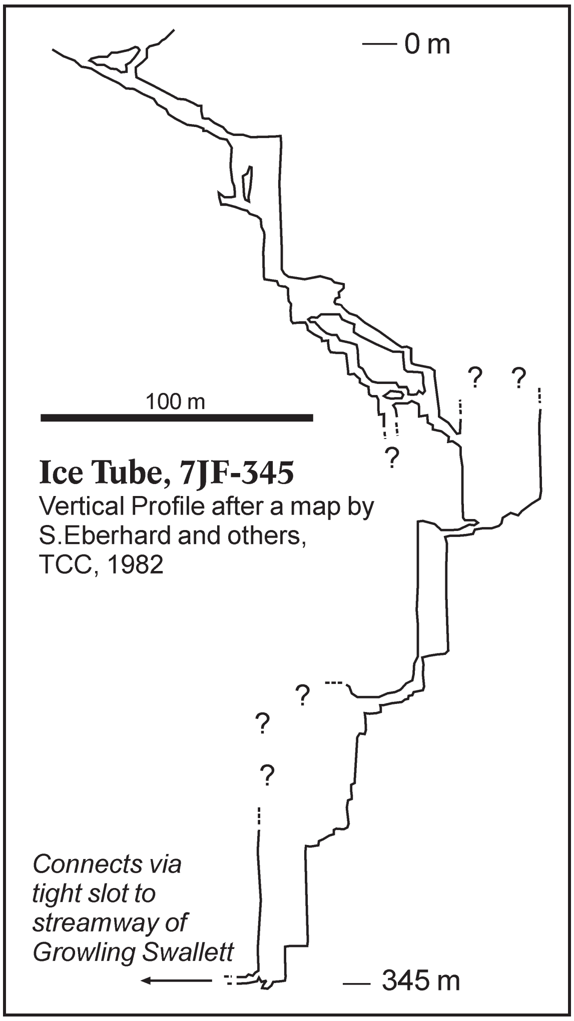


Figure 1.2

Profile of Ice Tube Cave, a sporting vertical cave system in the Junee area, Tasmania. This is typical of many of the deep cave systems in Tasmania.

Adapted from original survey drawn by Stefan Eberhard, Tasmanian Caverneering Club. 1982.

Photo 2

Initially, most of the groundwater makes its way through tiny passages, gradually enlargeing them along the main path, as seen here in these anastomosing tubes exposed along a bedding plane in Webbs Cave, Nullarbor, Western Australia. (10 centimetre scale).

Photo: K.G. Grimes

Occasionally, a single input may become a branching cave that feeds many springs, and more complex patterns can also occur.

The cave passages dissolved beneath the watertable may be more or less horizontal tubes with elliptical cross-sections and smoothly curved walls, or more sinuous in shape, extending vertically as well as horizontally, with large irregular scallops in the walls separated by limestone protuberances hanging from the ceiling (pendants) or rising from the floor. When these projections have numerous closely spaced holes dissolved through them, they are called spongework (see photo 3). The more irregular passages characterised by spongework were probably formed by slow-moving groundwater, driven by convection currents; in tubular passages the groundwater moves faster.

An additional factor that is important in the formation of some limestone caves is mixing corrosion. When two different waters, both saturated with respect to calcite, are mixed, the resultant solution is aggressive and can dissolve limestone. This process is particularly significant in the formation of caves along coastlines, where freshwater springs discharge into the sea. The mixing of seawater and fresh water, both saturated with respect to calcite, produces water that is aggressive and can enlarge the limestone passage from which the spring is discharging. The zone of mixing starts at the coast and works its way inland as the chamber enlarges. Thus caves developed at these locations are often largest at the coastline, and decrease in size upflow (inland). The mixing process may also be significant where downward seeping water reaches the watertable and mixes with groundwater, helping to dissolve horizontal cave passages at this level, although the importance of this process is disputed.

The effect of rock type and structure

Where a cave forms is partly determined by the composition and permeability of the limestone, and cave formation is obviously constrained by the presence of insoluble beds of sandstone or shale. Pure limestone is relatively easy to dissolve and often contains large caves and other solutional landforms. By contrast, clay-rich and sandy limestones are less amenable to karst development. Dissolution of these limestones releases clay, which can coat the walls of the developing caves and prevent further solution, or sand, which can block cavities as they form. As a result, caves frequently reduce in size or stop when they encounter impure limestones, and surface solution features are also poorly developed in, or absent from, these limestones. Where significant caves are developed in clay-rich limestones, they are usually guided by a major structural feature, such as the axis of a fold, for example, Anticline Cave at Buchan, Victoria (see colour plate 1). Almost no caves or other karst features are present in the sandy oolitic limestones of eastern Australia (described below), because of their high quartz sand content.

Some limestones contain small amounts of pyrite (iron sulphide). This mineral commonly forms in marine sediments rich in organic matter, as a result of microbial reduction of sulphate. It occurs as tiny scattered golden-yellow grains in many dark-coloured limestones. When pyrite is exposed to oxygen, in air or in groundwater, it oxidises and releases sulphuric acid, which is a strong acid, very effective at dissolving limestone. Thus relatively pure limestone beds containing small amounts of pyrite are very susceptible to dissolution and are called inception horizons, because cave development often occurs initially along these layers.

Cave formation is also influenced by the permeability of limestone (how quickly water can flow through it) and its porosity (the percentage of open space within the rock). Interconnected open fractures through the limestone can transmit water more quickly than the tiny pore spaces around the grains of the rock, and give limestone a high permeability. These fractures (also called joints) typically lie along bedding planes and perpendicular to them, and also form parallel to the axial planes of folds. Because groundwater in limestone moves rapidly along the joints, joint orientation and spacing have a major influence on cave development. Water flowing along a phreatic loop will preferentially follow joints along this pathway; the orientation of the joints will therefore determine passage directions (Figure 1.3). If the limestone bedding is dipping at a moderate angle, the joints parallel and perpendicular to bedding will also dip moderately, and along the phreatic loop the cave passages will switch from one joint set to the other, giving a zig-zag pattern (Figure 1.1).

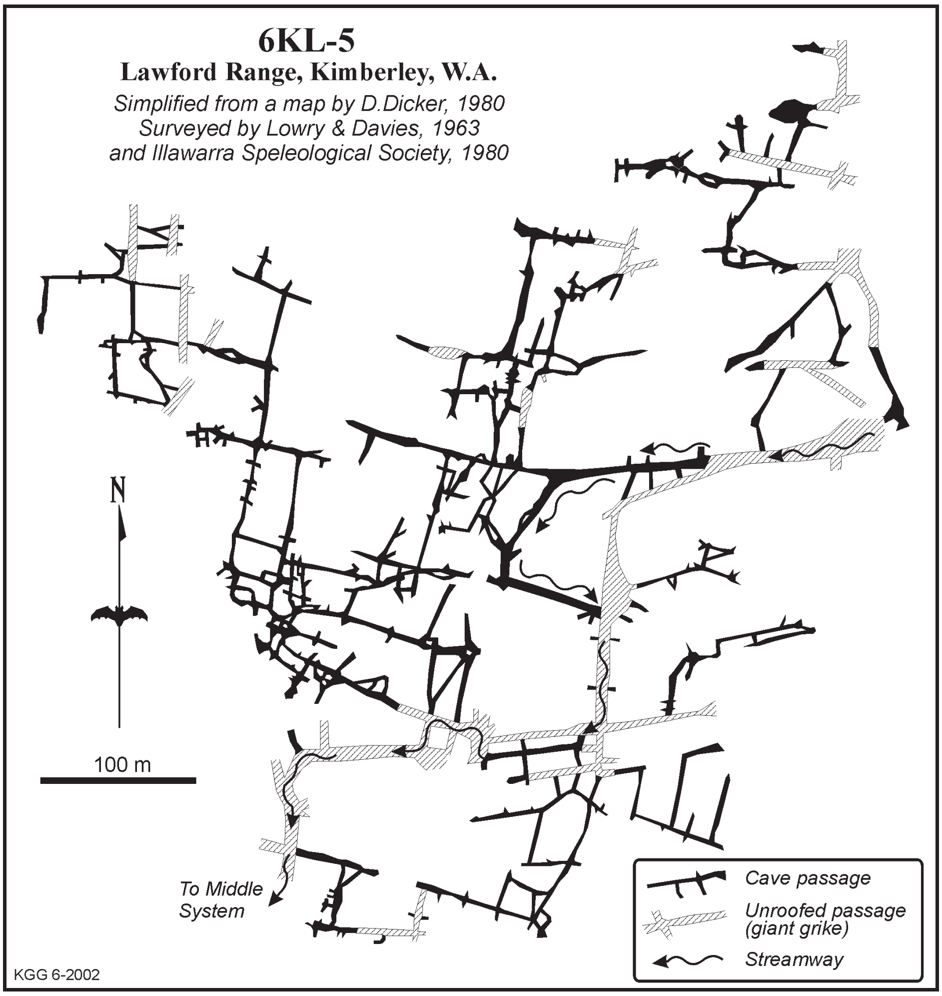


Figure 1.3

A major joint controlled cave system in the Kimberley of Western Australia developed beneath a “Giant Grikeland” surface. In many places the roof of the passage has connected to the surface to form deep, narrow fissures - the giant grikes.

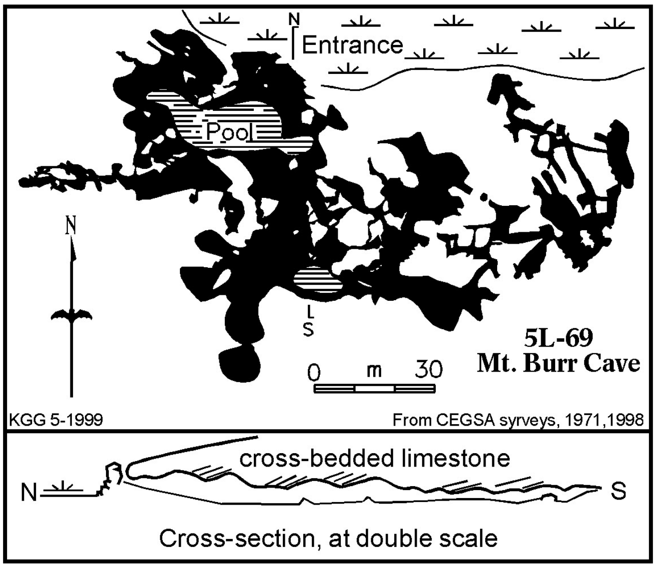


Figure 1.4

Mt Burr Cave, near Mt Gambier in South Australia, is a syngenetic maze developed in dune limestone next to a swamp. Acidic swamp water has seeped horizontally into the dune, dissolving irregular chambers.

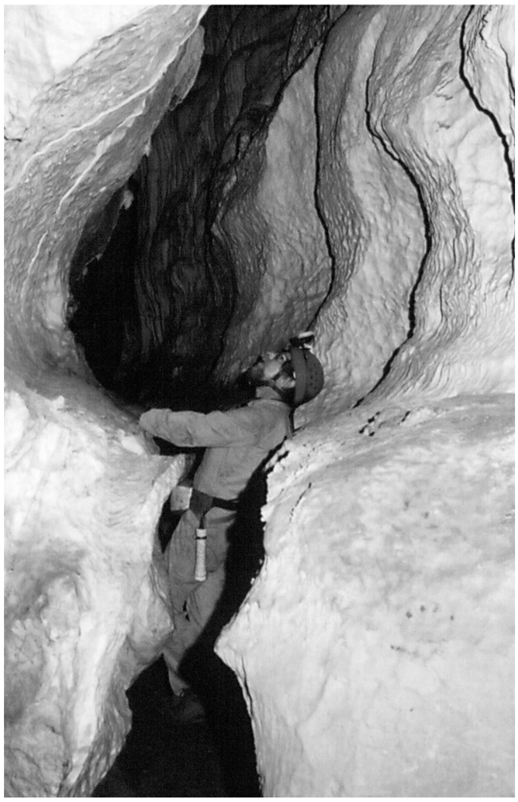


Photo 4

A typical ‘keyhole’ passage form, seen here in Wombeyan Caves, New South Wales, may be the result of vadose incision into the floor of an earlier phreatic tube. Note the wall scalloping caused by fast-flowing water.

Photo: K.G. Grimes

Photo 3

Phreatic pendants and spongework seen here in the roof of Mt Burr Cave, near Mt Gambier, South Australia, typically occur in cave passages that have been dissolved by slow-moving water beneath the watertable.

Photo: K.G. Grimes

In Australia, the Palaeozoic and older carbonate rocks are generally compact and well-cemented, so groundwater moves mostly along fractures, which therefore strongly influence cave development. The younger Tertiary limestones are often not well cemented, and groundwater can move through the pore spaces between the grains of the rock, but even in these limestones the joints often determine the orientation of cave passages. The youngest limestones in Australia, the Quaternary dune limestones, are lightly cemented and lack joints, so there is generally no preferred passage orientation (Figure 1.4).

Changing water levels and vadose caves

If the landscape remains stable for long periods of time, large cave systems will develop along the phreatic loop. If sea level rises or the ground subsides, the cave system may fall below the preferred phreatic pathway, and water movement in the passages will slow or stop, so cave dissolution ceases and fine-grained sediment may be deposited.

In contrast, tectonic uplift of the area or a fall in sea level will have more marked effects; the cave may completely drain and become air-filled, with a stream flowing along its floor. Such a cave is said to be vadose (from the Latin *vadosus*, shallow). Draining of a passage removes the buoyant support provided by the groundwater and often causes part of the cave to collapse, destroying the original passage shape. Large piles of rubble accumulate on the cave floor beneath an arched roof with a central horizontal or sloping section that represents a bedding plane in the limestone. If the cave collapse extends to the surface, it will form a steep-sided depression called a collapse doline.

The stream within a vadose cave will modify the original phreatic features. A vadose stream can flow faster than slow-moving phreatic water, and transports coarser grained sediment (sand and gravel) into the cave. Physical erosion by the stream is probably the dominant process in large vadose cave systems. It may incise a narrow canyon in the floor of the phreatic passage, giving rise to a keyhole cross-section, with a larger abandoned phreatic passage above a vertical vadose canyon (see photo 4). With time, the original phreatic passage forms may be obliterated.

The limestone walls of a vadose streamway are often scalloped, due to dissolution by the fast-flowing stream water. The scallops are relatively small (just a few centimetres across) and have a consistent size and shape, with a steeper upstream side. The size of the scallops is related to the speed of the water: the faster the flow, the smaller the scallops.

Above the stream the cave walls and roof may be partly or completely covered by stalactites and flowstone. These secondary carbonate deposits, called speleothems, are mostly composed of calcite, and are deposited from water dripping or seeping out of joints and pore spaces.

Once a drop in water level has drained a phreatic cave and turned it into a vadose system, a new phreatic cave will develop beneath the vadose passages, below the watertable. If another drop in water level occurs, this new phreatic cave will be drained and capture the cave stream from the overlying vadose passages, which may be completely dry and abandoned. By this continuing process cave systems can form as a series of tiers, one above the other, each representing a time period when the landscape was stable long enough for a substantial phreatic cave passage to form (Figure 1.5).

Thus it can be seen that most caves are predominantly phreatic in origin, and form below the watertable where no-one but cave divers can explore them. When the phreatic passages are drained, they are modified by collapse, stream incision, sediment deposition and speleothem formation, and may be almost unrecognisable. Nevertheless, most limestone caves will show evidence of their original phreatic origin if you look hard enough.

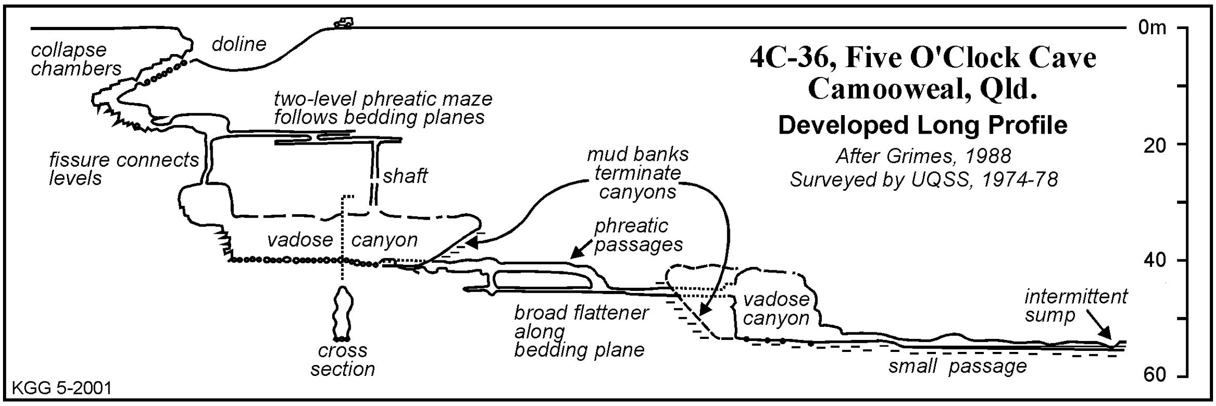


Figure 1.5

Five O'Clock Cave near Camooweal in Queensland shows a range of different passage types that developed at different levels controlled partly by soluble beds, and partly by changing watertables.

Some other processes of cave formation

The phreatic-vadose process described above is probably responsible for the formation of most of the caves in carbonate terrains. However, some caves have features that are inconsistent with this mode of formation. They may not be associated with obvious phreatic pathways, be too large or an unlikely shape, or contain secondary minerals, indicating that other processes have been at work. In general, these caves owe their origin to additional acidity or heat derived from a source deep within the earth's crust, often in combination with the normal carbonic acid processes.

In some cases there appears to have been an influx of carbon dioxide from an underlying chamber of molten magma; carbon dioxide is one of the dominant gases given off by magma as it crystallises. If there is a localised input of magmatic carbon dioxide into limestone from below, this can potentially dissolve a large cave system. The cenotes (collapsed caves with deep watertable lakes, see colour plate 38) in southeastern South Australia may have been dissolved by volcanic carbon dioxide associated with the nearby eruptions of Mount Gambier and Mount Schank.

In other cases the additional acidity is supplied by sulphuric acid, formed by the oxidation of hydrogen sulphide associated with oil and gas fields. Carlsbad Caverns, in New Mexico, USA, are believed to have formed in this way, and contain very extensive deposits of gypsum (calcium sulphate) along with some native sulphur. An additional factor is temperature, and hot springs have formed some caves. The higher temperature of hot spring waters may be due to circulation deep within the earth's crust, or to the presence of an underlying body of molten magma. As the hot waters rise and cool, they become aggressive, dissolving caves that are sometimes three-dimensional mazes with thick coatings of large calcite crystals on the walls and roof. No definite examples of caves formed by sulphuric acid or hot springs are known in Australia.

CAVES IN OLDER CARBONATE ROCKS

The older carbonate rocks in Australia are compact, mechanically strong rocks deposited during the Neoproterozoic (Late Precambrian, 545–1000 mya) and Palaeozoic (251–545 mya) eras. Unlike the Northern Hemisphere, limestones from the Mesozoic (65 -251 mya) are virtually absent in Australia.

Most older limestones in Australia were deposited in shallow marine environments and are made up of the skeletons of marine organisms, either embedded in calcite mud (which is produced predominantly by algae) or cemented together by fine calcite crystals. Relatively pure limestones with almost no clay or sand are generally massive, with widely spaced depositional layers (beds), often a metre or more apart. They contain fossils of brachiopods, gastropods, nautiloids, trilobites and, sometimes, early fish. Reefs are relatively uncommon and, where present, are generally composed of corals and sponges, including an extinct group of calcareous sponges called stromatoporoids (not to be confused with stromatolites, which have a much more irregular microstructure and were formed by cyanobacteria — blue-green algae). Caves intersecting beds rich in fossils may have spectacular displays in their walls (see photo 5).

Other limestones represent carbonate sand banks, for example, crinoidal and oolitic limestones. Crinoidal limestones are made of disc-shaped plates (5–20 millimetres across) from the stems of crinoids (sea lilies), and are sometimes called 'nuts and bolts' rock, because the crinoid stems resemble the shaft of a threaded bolt. Oolitic limestones are composed of spherical pearl-like oolites, 0.5–2 millimetres across, with thin concentric layers of calcite deposited around a central nucleus. Sometimes the crinoidal and oolitic limestones contain substantial amounts of quartz sand, which reduces their purity.

Clay-rich impure limestones generally have thin beds, about a centimetre thick, and are often rich in organic material, which gives them a dark, sometimes black, colour and a strong sulphurous smell when freshly broken. They were typically deposited in shallow marine environments such as lagoons and tidal mud flats. These thinly bedded limestones may be more fossiliferous than massive limestones, and contain abundant brachiopods and solitary corals.

Many of the older Precambrian carbonates in Australia are dolomites (also called dolostones), that is, they are made up of the mineral dolomite (calcium magnesium carbonate), rather than calcite (calcium carbonate), which dominates in limestones. Dolomites are often lighter in colour than limestones on a freshly broken surface, being cream or even pink, compared to blue-grey, dark grey or black for limestones. Dolomite typically forms by the replacement of the original limestone, and this may happen soon after the limestone was deposited. The additional magnesium frequently comes from seawater.

Marble is limestone that has been metamorphosed (recrystallised to a larger, more-even grain size), either by heat from a nearby large body of molten magma or by deep burial. Marble is generally pale-coloured or white, because heating drives off the organic compounds that give limestone its grey colour. Marble's coarser grain size means that it weathers differently to limestone, disintegrating into crystal sand and forming rounded outcrops (for example, Wombeyan, New South Wales), resembling the tors that form in granite. At Chillagoe, Queensland, there is a marked difference in appearance between the vertical, sharp-edged towers of grey limestone and the

Photo 5

This huge collection of fossils, including many large stromatoporoids and corals, is the remains of a Devonian reef deposited in what was then a shallow marine environment. Fanning River, Queensland (20 centimetre scale).

Photo: K.G. Grimes

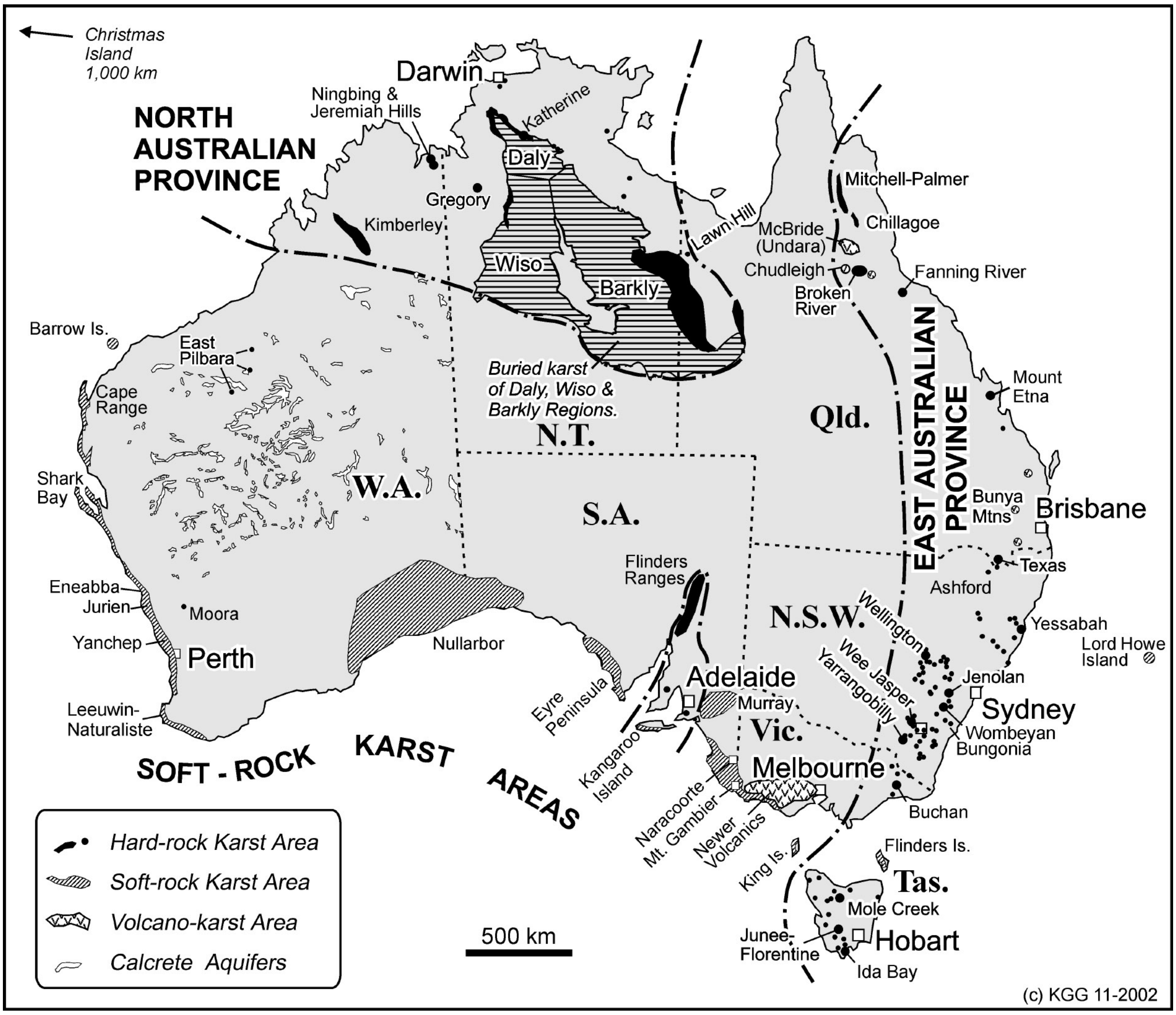


Figure 1.6

Karst areas of Australia. Map by K.G. Grimes

lower, rounded hills of white marble. The white colour and coarse grain size of marble give it high reflectivity and an aesthetically pleasing appearance in cave walls, particularly where it shows intense folding, for example, in Abercrombie Caves, New South Wales.

There are three broad regions of Australia with older carbonates (Figure 1.6). The most extensive is the East Australian Karst Province, which extends up the eastern highlands from Tasmania to north Queensland, and contains caves and karst in Ordovician to Permian limestones. These limestones belong to the Tasman Fold Belt. For convenience, the caves occurring in the Precambrian dolomites in Tasmania are described together with the younger nearby Tasman Fold Belt karsts. The North Australian Karst comprises a number of separate limestone and dolomite areas, extending from the Kimberley in Western Australia to the Barkly Tableland in far west Queensland. In South Australia, in the Flinders Ranges, Adelaide Hills and Yorke Peninsula, scattered caves are present in Precambrian and Cambrian carbonates. A few small caves are also present in Precambrian dolomites in Western Australia, for example, at Moora and in the East Pilbara.

In the North Australian and part of the South Australian Karsts, the carbonate rocks are mostly flat-lying or gently dipping, similar to most of the Tertiary limestones of Australia (described below). However, in the other areas, particularly the Tasman Fold Belt, the carbonates are commonly strongly folded, with vertical to steeply dipping beds, and outcrop as narrow bands of rock running through the landscape. In these folded limestones, caves may develop along the centre lines of folds, for example, Jenolan, New South Wales, rather than simply forming at the intersection of joints with particular beds (inception horizons), as is often the case in horizontal to gently dipping limestones.

East Australian karsts: Tasman Fold Belt

Many of Australia's best-known caves and karst landforms occur in Palaeozoic limestones of the Tasman Fold Belt, the geological province that underlies the highlands of eastern Australia and, before Australia split from Antarctica, continued southward into the Trans-Antarctic Mountains. From the Cambrian to the mid-Devonian

(550–380 mya), the Tasman Fold Belt consisted largely of chains of volcanic islands separated by troughs of deeper sea, and great thicknesses of marine sediments and volcanics were deposited. Limestones formed in the warm shallow seas surrounding the volcanic islands. Although volumetrically relatively minor, limestones occur through the whole length of the fold belt, from Precipitous Bluff and Ida Bay in southern Tasmania to the Mitchell–Palmer region of far north Queensland. All the large, better-known karsts of eastern Australia (for example, Mole Creek, Buchan, Jenolan, Mount Etna and Chillagoe) have formed in these limestones.

From the mid-Devonian to the Early Carboniferous (380–340 mya), a series of large-scale earth movements folded and uplifted large areas of the Tasman Fold Belt, turning what was ocean floor into dry land. Granites that intruded about this time produced marbles at Chillagoe and Wombeyan.

Exposure of the limestones at the surface allowed the formation of caves and other karst features in the Late Palaeozoic. Some of these ancient, sediment-filled cave passages (called palaeokarst) are exposed in the walls of caves that formed relatively recently, and outstanding examples of intersected palaeokarst occur in River Cave at Jenolan (see colour plate 2). It is moderately common for caves in eastern Australia to contain exposures of much older passages in their walls, but this is unusual for caves elsewhere in the world.

In the Late Palaeozoic there was little limestone deposition, apart from the formation of Carboniferous–Permian crinoidal and oolitic limestones in the cool shallow seas of eastern Tasmania, northeastern New South Wales and southeastern Queensland (Wallanbah Formation, Yessabah and Texas Limestones). There was no subsequent limestone formation in eastern Australia until the Tertiary.

Karst landforms

Most of the Palaeozoic limestones of eastern Australia occur as relatively small outcrops, often long and narrow in shape, and receive the bulk of their surface water as runoff from catchments in surrounding non-limestone rocks. Dry valleys, formed when streams are partly or wholly captured underground, are common. The dry valleys of the Jenolan River at Jenolan Caves and Lannigans Creek at Colong Caves lie above the active caves, and are probably periodically active when sediment fill blocks the flow through the caves and water is diverted back to the surface. Some streams have cut arches through the limestone, such as those at Jenolan Caves (see colour plate 5).

Surface solution sculpting (karren), both large and small-scale, is common on the pure limestones of the Tasman Fold Belt, even in low-rainfall areas such as Wellington, but is best developed on the tropical Chillagoe and Mitchell–Palmer karsts of north Queensland (see photo 6). The rillenkarren (flutes) on the latter limestones are razor-sharp, and separated by rinnenkarren (runnels) up to 30 centimetres deep; a fall when walking on the limestone can result in serious cuts and bruises. On the flatter limestone surfaces in north Queensland are solution pans (kamenitsa) up to 30 centimetres across, always with an outlet on one side.

Springs are common in the Palaeozoic limestones. Some represent the rising of streams originating off the limestone and captured underground by stream-sinks, others are fed entirely from rain falling on the limestone. The most impressive are found in Tasmania, for example, the sinking of Garth's Creek into Growling Swallett and its rising as the Junee River at Junee Cave nearly 10 kilometres away. Here, high rainfall coupled with relatively extensive areas of limestone have combined to produce large and active karst systems.

The high mechanical strength of the Palaeozoic limestones has resulted in the development of impressive cliffs and canyons. Bungonia Gorge, New South Wales, with its broad upper valley, narrow inner canyon and sheer

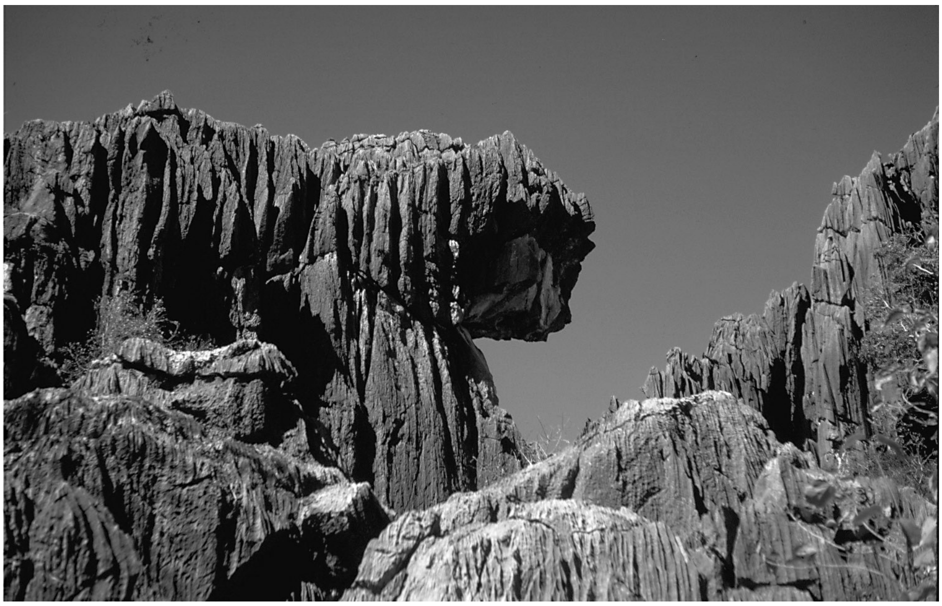


Photo 6
Surface solution sculpting results in karren, or fluting, and is common on the pure limestones of the Tasman Fold Belt. The dramatic large-scale karren forms seen here are a feature of Queenslander Tower, Chillagoe, Queensland.
Photo: J.L. Samuel

Photo 7

With its broad upper valley, narrow inner canyon and sheer cliffs, Bungonia Gorge, on the Shoalhaven River, New South Wales, is an outstanding example of canyon development in Palaeozoic limestone. Karst springs have been left hanging on the valley sides as the stream cut downward.

Photo: Elery Hamilton-Smith

cliffs up to 285 metres high, is an outstanding example of canyon development (see photo 7). Limestone outcrops frequently stand as bluffs above the surrounding landscape. The most impressive examples are the towers of north Queensland (see photo 8), which are quite distinct in appearance from limestone outcrops elsewhere in the Tasman Fold Belt. These individual steep-edged towers rise up to 100 metres above the surrounding flat plains, and can be 4 kilometres long and 1 kilometre wide. Solution along vertical joints and bedding planes within the towers has produced grikes (vertical slots), up to 10 metres wide and 30 metres deep.

Dolines are common in some areas. At Buchan, Victoria, there is an extensive doline field of conical depressions formed by solution, as well as some steep-sided dolines resulting from collapse into an underlying cave system. There is an even larger area of doline karst at Mount Cripps, Tasmania, but it is obscured by a cover of thick rainforest.

Caves

The southernmost caves of the Tasman Fold Belt, in Tasmania, are in the Ordovician Gordon Limestone, which outcrops in three main areas, Mole Creek, Junee and the southwest. At Mole Creek, more than 200 caves occur in a limestone area about 20 kilometres long by 10 kilometres wide. These include the well-known show caves Marakoopa and King Solomon's Caves. Kubla Khan (see colour Plate 6), one of the biggest caves in the area, consists of large breakdown chambers and stream passages, and is extraordinarily well decorated with enormous columns, forests of stalactites and stalagmites, and rimstone dams more than 2 metres high. A trip through this cave is never to be forgotten. To prevent damage to the cave through overuse, access is restricted.

The Junee karst contains some of the most challenging caves in Australia — cold and wet, with numerous vertical drops and difficult climbs and squeezes (Figure 1.2). The deepest caves known in Australia at the time of writing are here— Niggly Cave and the Growling Swallett system — both about 350 metres deep. Much of the

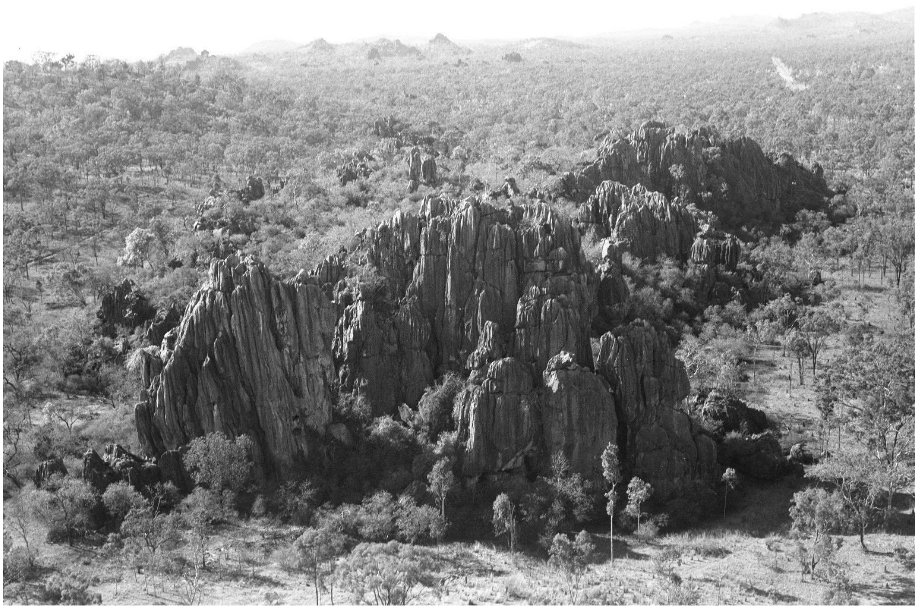


Photo 8

The Tower of London Bluff is just one of the highly distinctive limestone outcrops that occur around Chillagoe, Queensland. These steep-sided towers rise up to 100 metres above the surrounding flat plains.

Photo: K.G. Grimes

area is covered in dense rainforest because of the high rainfall, and exciting discoveries of new caves are still being made.

The southwestern karst, which lies in the Southwest Tasmania World Heritage Area, contains one of the longest caves in Australia, Exit Cave. It is a large network cave with a permanent stream and probably more than 40 kilometres of passages, which are up to 30 metres wide and high. Several deep shafts drop into these passages from the surface of the hillside above.

Precambrian dolomites in Tasmania contain a number of caves, including Hastings Cave in the south of the state; this is the only Australian show cave formed in Precambrian dolomite. Deep caves are present on Mount Anne, developed in alpine dolomite karst with entrances at altitudes of almost 1000 metres. The most extensive, Anne-A-Kananda, reaches 340 metres in depth and has an impressive doline entrance leading into a large chamber, below which are numerous rockfall passages and vertical shafts, one of them more than 100 metres deep. Many of the caves on Mount Anne are characterised by highly unstable areas of loose rock, possibly related to the effects of glaciation 18 000–20 000 years ago, when glaciers covered substantial areas of Tasmania.

In Victoria, Silurian and Devonian limestones are restricted to small areas in the centre and east of the state. The largest outcrop is at Buchan, where cave development can be more closely related to the development of the surface landscape than elsewhere in eastern Australia. The caves at higher levels here are phreatic mazes that formed beneath the Buchan River when it flowed some 200 metres above its present level about 40 mya. Subsequent incision by the river drained the caves and they have been abandoned ever since. The caves at lower levels along the Buchan River and its tributaries include the show caves Fairy Cave and Royal Cave, which consist of structurally guided phreatic passages strongly modified by stream incision. The flat roofs evident throughout these caves mark former positions of the watertable, and can be correlated with river terraces along the Buchan River nearby. Dating of speleothems and sediments within the caves indicates that even the lowest cave level, only a few metres above the Buchan River, formed more than 750 000 years ago.

In New South Wales, caves occur in more than 90 karst areas in the Palaeozoic limestones. Most of these contain only a few small caves. The five most cavernous karsts, with more than 100 recorded caves, are Bungonia, Jenolan, Wee Jasper, Wombeyan and Yarrangobilly (Figure 1.6). At Bungonia Caves, deep shafts and complex caves have developed in a limestone plateau that is mantled by sediment. Several of the caves contain high levels of carbon dioxide in the air, released by decay of organic material washed into the cave. The caves drain to a spring perched 190 metres above the floor of the adjacent Bungonia Gorge (see photo 7).

Jenolan, Wombeyan and Yarrangobilly caves occur in areas of high topographic relief and have been greatly affected by surface streams, which have washed significant quantities of sand and gravel into the caves. As this sediment filled and partly blocked passages and chambers, it forced water up against the ceiling, forming flat solutional ceilings as the cave grew upward. These caves also contain large active breakdown passages and high, domed chambers, circular in plan, called cupolas, such as the Temple of Baal at Jenolan Caves. Calcite speleothems are abundant, along with superb examples of aragonite, hydromagnesite, dolomite and gypsum speleothems.

At Wee Jasper there are several substantial caves, including Dip Cave, a structurally controlled network cave, Punchbowl Cave, with large chambers and horizontal ceilings, and Careys Cave, a large and well-decorated show cave that must be one of the best-kept secrets among the show caves of eastern Australia.

On the western slopes of the Great Dividing Range there are several small areas of limestone, the best known of which is near Wellington. The caves here are strongly guided by joints and bedding and entirely phreatic in origin. The wall and ceiling morphology includes spongework, large irregular scallops and bedrock pendants. There is no evidence of vadose incision by running water.

The caves at Wellington contain finely laminated clays and graded-bedded sands and conglomerates, deposited in the still water of ponds by slumps from sediment banks surrounding the pools. In the Wellington Caves Phosphate Mine, the sands comprise bone debris from the faeces of carnivorous bats, which inhabited the caves in the past. The caves also contain red silts, washed into the entrances and deposited as sediment cones. The red silt was probably blown into the Wellington area from central Australia by dust storms during the Pleistocene; dating of the oldest silt gave an age of about one million years. At Wellington and other localities, the red silt contains significant deposits of fossil bones, including those of giant kangaroos, diprotodontids (the size of a small rhinoceros) and other megafauna. These bone beds were initially excavated by the early explorer Thomas Mitchell, and the bones recovered were sent to London and later examined by Charles Darwin.

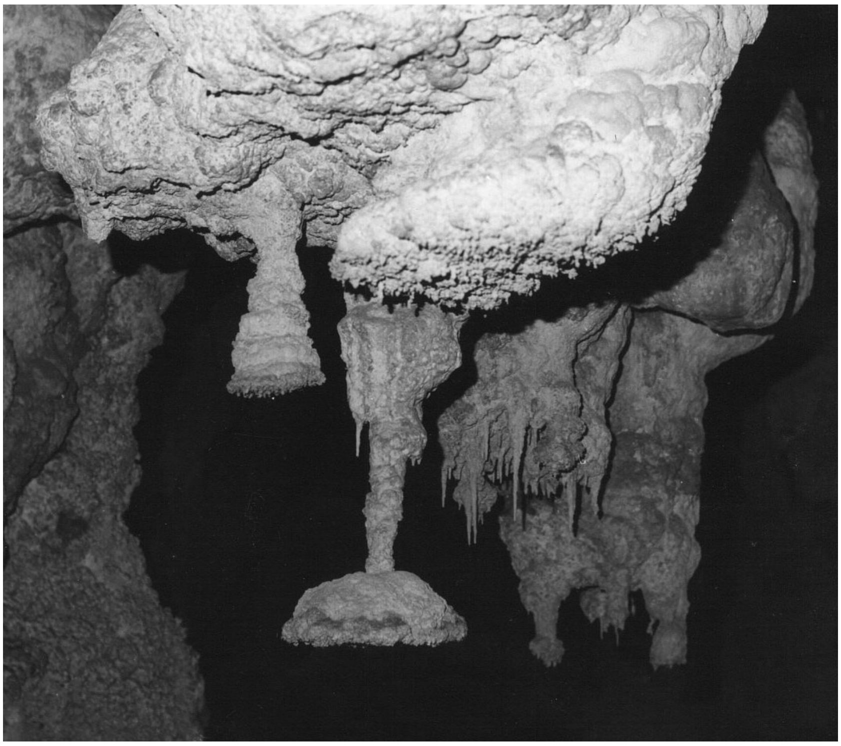
The caves of the Carboniferous and Permian limestones of northeastern New South Wales and southeastern Queensland are relatively small, structurally controlled network systems; only a few capture a permanent surface stream underground. Most of the caves in the small limestone area near Texas, in southeastern Queensland, have been flooded by a dam.

In Queensland there are four main karst areas, Mount Etna, Broken River, Chillagoe and Mitchell–Palmer (Figure 1.6), all with large numbers of caves. Mount Etna, a conical residual limestone hill near Rockhampton,

Photo 9

Stalactites are common in almost all the Chillagoe and Mitchell Palmer caves, Queensland. When they terminate in a flat subhorizontal plane covered in small cave coral, as seen here in Queenslander Cave, they are called 'suckerpads' or 'elephants feet'.

Photo: K.G. Grimes



has been quarried for limestone for cement, which has seriously damaged several of the caves. Two main styles of caves have been recognised here, deep vertical shafts and structurally guided horizontal caves. A large colony of the little bent-winged bat lives in Bat Cleft on the side of Mount Etna, and the bat flight out of the cave in the evening is a spectacular sight.

The Broken River Karst has many limestone ridges with well-developed karren and caves. At Fanning River the main cave has spectacular exposures in the walls, displaying the features of the original reef and lagoon where the limestone was deposited; in places the walls show abundant large stromatoporoids and corals (see photo 5).

The adjoining Chillagoe and Mitchell–Palmer areas are by far the largest of the eastern Australian karsts. The limestone towers (see photo 8) here are densely cavernous, and hundreds of caves are known. In general the highest, largest towers have the most extensive cave systems; the longest cave has more than 6 kilometres of passages. The caves are mostly mazes of interconnected phreatic chambers with directional control from both joints and vertical bedding. Typically, cave entrances are in the sides of towers. Most passages are rifts, that is, they are more or less straight, much taller than they are wide, and becoming narrower as the upper walls slope toward each other. Passages frequently connect upward with surface grikes (open joints), so daylight chambers are common. Where the walls are not covered with secondary calcite deposits, they are smoothly rounded and display typical phreatic solution features, such as pendants, large irregular scallops and spongework. The floors of the caves mostly lie at or slightly below the level of the plain outside the cave, and are more or less flat and covered with silt and/or rubble. Originally the passages probably narrowed downwards in the same way that they narrow upwards; the lower half or third is therefore filled with sediment. A few caves terminate downwards in narrow rifts that carry permanent water at a level some 15 metres below the surrounding plain.

Secondary calcite deposits (speleothems) are abundant in almost all Chillagoe and Mitchell–Palmer caves. The most abundant form is cave coral, which appears as rough knobbly protrusions, usually only a few centimetres long. Stalactites are common and many terminate not in a point but as a flat subhorizontal plane covered in small cave coral. Such stalactites are called 'suckerpads' or 'elephants' feet' (see photo 9). The speleothems generally have a chalky, porous, 'dead' appearance, even though they may be actively growing, because evaporation plays a major role in the calcite precipitation, due to the very well-ventilated nature of the caves. A few of the Chillagoe and Mitchell–Palmer caves contain translucent and coloured speleothems, with the waxy surfaces characteristic of high-humidity environments; these caves are small and/or have only a few entrances, so they have limited air circulation allowing high humidities to develop.

The walls of many Chillagoe and Mitchell–Palmer cave entrances and daylight chambers have been etched, leaving sharp prominences the size of pencils or narrow sticks that all point in the same direction, toward the light. This surface feature is called phytokarst and is produced by algae (and/or cyanobacteria) eating into the limestone.

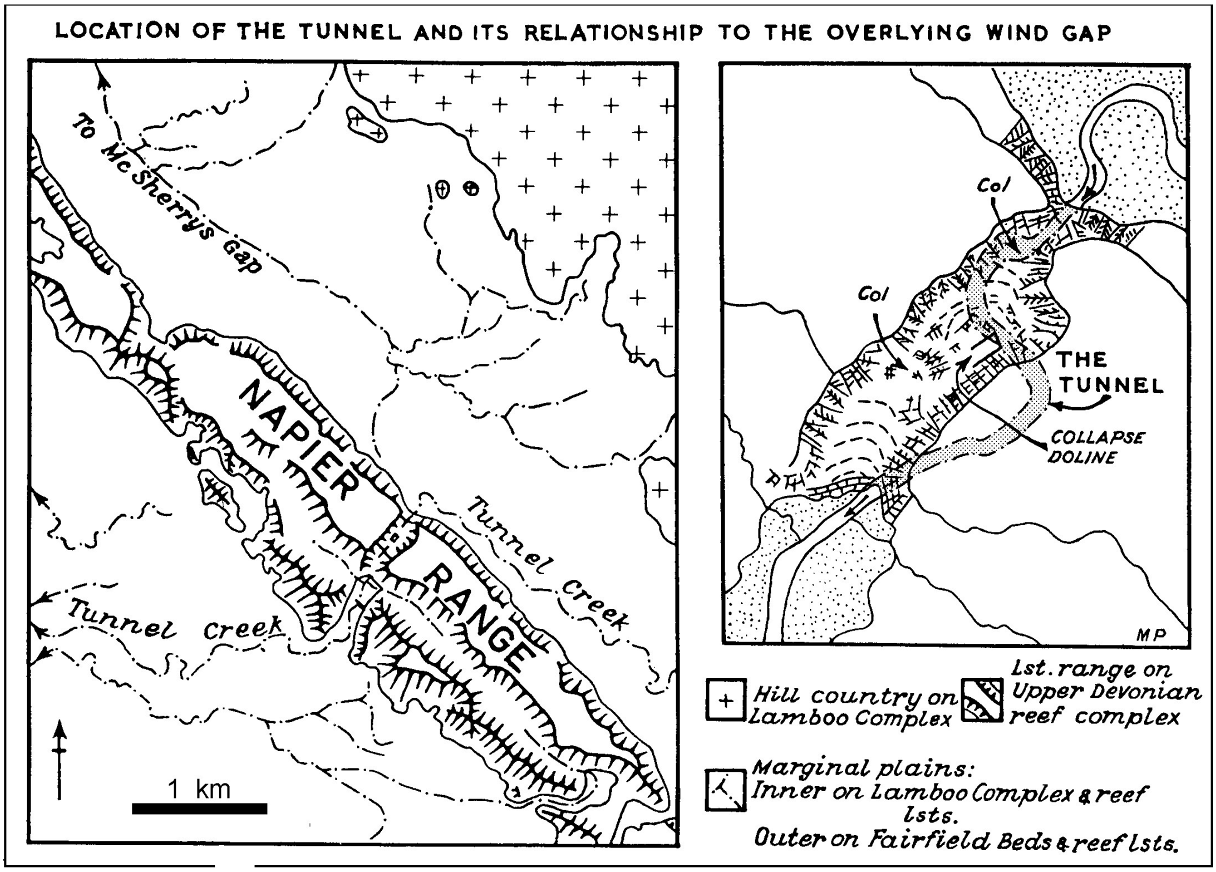


Figure 1.7

The Tunnel has cut through the Napier Range in the north of Western Australia, capturing its flow from a surface valley. *After Jennings and Sweeting, 1963*

North Australian karsts

The tropical north Australian karsts are mostly medium to large areas of horizontal to gently folded, well-cemented limestones and dolomites of Late Precambrian, Cambrian and Devonian age. The present climate is tropical monsoonal to semi-arid, so most areas receive the bulk of their rainfall in two or three months during summer, when there may be extensive flooding, including inundation of the lower levels of the caves. The surface landforms show strong similarities with the Chillagoe and Mitchell–Palmer karst in the tropical northern part of the Tasman Fold Belt. In the west are the limestones of the southwestern Kimberley and the Gregory dolomite; farther east are the larger areas of Cambrian dolomites and limestones of the Barkly Tableland and around Katherine, mostly covered by younger sediments (Figure 1.6).

On the southwestern edge of the Kimberley region are ranges of Devonian limestone, containing some of the world's best-preserved fossil reefs of this age. The reefs have not been folded or faulted to any extent, and the barrier reefs, atolls and lagoonal limestones are still more or less in their original positions, with their fossils clearly visible. A low-relief land surface was eroded across the limestone ranges in the Tertiary; uplift, perhaps in the Miocene, has allowed erosion and dissection of this old land surface. The rivers that existed in the Tertiary cut down into the limestone to form gorges that cross the present ranges, for example, Geikie Gorge and Windjana Gorge. In one case the river was diverted underground to form The Tunnel, a large meandering stream cave, leaving the old valley abandoned at a higher level (Figure 1.7).

Broad-scale erosion of the old land surface on the Kimberley limestones has formed a variety of landscapes. 'Giant grikelands', limestone outcrops criss-crossed by a grid of open joints, represent the least dissected areas; with time the narrow grikes widen to more open box valleys ('ruined cities'). Further erosion leaves isolated limestone towers up to 50 metres high, surrounded by low-level flat rock surfaces (pediments) that extend away from the abrupt edge of the towers. Bare rock exposures are extensive on the limestone bluffs, and are strongly sculpted into an array of karren forms, including abundant rillenkarren.

Caves in the southwestern Kimberley are generally hosted by the massive reef and fore-reef limestones, most commonly as small cliff-foot chambers and short fissures extending from grikes. Large joint-controlled maze systems also occur beneath the giant grikelands. For example, the cave shown in Figure 1.3 has 8.5 kilometres of surveyed passages, and in the wet season a stream zigzags through it. This cave is also of interest in that it has developed in the back-reef lagoonal limestones.

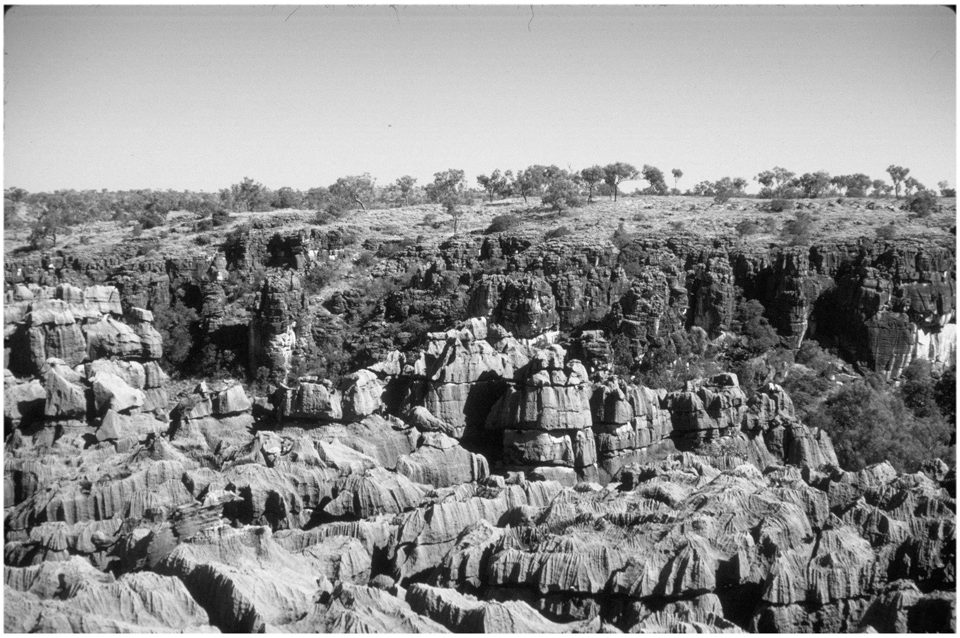


Photo 10

The Colless Creek Grikefield, near Lawn Hill Gorge, lies on the edge of the Barkly Karst. A large incised tributary gorge can be seen behind the grikefield with a flat Tertiary plateau surface in the distance.

Photo: K.G. Grimes

Some caves contain permanent pools and lakes, and exploration of one requires a duck-under followed by a long swim. Freshwater crocodiles have been reported in surface streams in the area! Springs fed by the cave systems emerge along the flanks of the ranges, and may be associated with extensive tufa deposits.

The Gregory Karst is a small area of thin flat-lying Proterozoic dolomite that currently contains Australia's longest cave, Bullita Cave. This is a complex close-spaced maze system with 88 kilometres of mapped fissure passages that run beneath the well-developed surface grikefield. The cave includes unroofed sections (that is, giant grikes), so some might argue that it is really several caves. Other Proterozoic dolomites in the Northern Territory have small caves and karst features, as well as paleokarst breccias.

The Cambrian carbonates of north Queensland and the Northern Territory are very extensive, but largely covered by thin Mesozoic and Cainozoic sediments. Surface karst and enterable caves are restricted to the limestones of the northwestern margin near Katherine (Daly River Basin), and dolomites and limestones of the eastern edge at Camooweal and Lawn Hill in Queensland (Barkly Karst). In these areas the carbonates are better exposed and rainfall a little higher.

At Katherine, the Cutta Cutta Caves have been open to tourists for some time and are complemented on the surface by grotesque limestone pinnacles that rise abruptly from the flat, soil-covered plain. To the east are warm springs at Mataranka and associated tufa deposits on the Roper River. The caves are typically shallow horizontal phreatic systems; some form joint-controlled mazes but others are more random in plan and show bedding control. They are typically warm and humid, so caving in this region generally involves large amounts of sweat.

In northwestern Queensland and the adjoining part of the Northern Territory is the Barkly Karst, predominantly a gently rolling tableland of flat-lying dolomites covered by an impermeable black clay soil. Scattered collapse dolines and stream-sinks, where the soil has been stripped away, form localised areas of dolomite outcrop and represent the only surface karst development. The Camooweal area contains the highest concentration of karst features in the region, with about 30 caves, at least eight of which extend 70–80 metres below the surface to the regional watertable (Figure 1.5). The caves are simple collapse chambers extending from the dolines or else descend as a series of alternating horizontal levels and vertical shafts or fissures that can reach to watertable lakes. The passages are often strongly joint-controlled and generally devoid of speleothems. At the lowest levels the larger systems tend to radiate out in bifurcating distributary patterns of hot, muddy crawlways. Many areas show strong spongework effects, suggesting slow phreatic solution in the past. The four separate horizontal levels in the caves, about 20–30 metres apart vertically, include an active flooded section up to 30 metres below the watertable, and might represent successive development of phreatic loops. The abandoned upper levels contain occasional meandering canyons incised by the strong wet-season floods that also transport gravel into the lower passages. The regional gradient of the watertable is to the south, and the caves appear to trend dominantly in this direction also, toward the Georgina River.

At the northeast margin of the Barkly Karst, near Lawn Hill, the dolomites are replaced by limestone. The broad downwarping of the earth's crust that formed the Gulf of Carpentaria allowed streams to cut down through the limestone, giving rise to large gorges. The best known, Lawn Hill Gorge, contains a beautiful, tree-lined river, fed by large, permanent springs, and dammed into a series of pools by extensive tufa deposits. Grikefields are well developed over parts of the limestone (see photo 10), and have associated maze caves. In the same area the remarkable vertebrate fossils of the World Heritage Riversleigh site are found partly in palaeokarst cave fill. The well-preserved bones give a fascinating insight into the diverse fauna that inhabited the forests of the region in the Tertiary, and include strange extinct animals like *Thingadonta*.

Late Precambrian–Cambrian carbonates of South Australia

The carbonate rocks of South Australia are similar to those of the Tasman Fold Belt to the east in being mostly folded linear bodies surrounded by non-karst lithologies. However, they lie in a drier climate, are formed in older rocks (Late Precambrian to Cambrian), and dolomites are more common. In the Flinders Ranges, thin, folded limestone beds are scattered along the full 400-kilometre length of the region, and a variety of caves has formed depending on the local structure and topographic setting. These include both linear systems in steeper dipping beds, and mazes in more gently dipping carbonates. There are some old, ridge-top caves that must date from much earlier landscapes, and also a partly flooded system with a lake that extends 18 metres below the present watertable. Wooltana Cave was once a major roosting site for the Ghost Bat, and contains large amounts of bat guano (mined in the past for fertiliser) and mummified bats preserved by the dry climate. The disappearance of the Ghost Bat from the Flinders Ranges was probably related to climate changes over the past few thousand years and not to human interference.

Farther south, a few scattered caves occur in folded limestones and dolomites of the Adelaide Hills, including the controversial Sellicks Hill Quarry Cave, which was blasted in 1993. On Yorke Peninsula, Corra-Lynn Cave is an extensive multilevel maze that has formed in jointed, flat-lying Cambrian limestone. The cave has more than 13 kilometres of surveyed passages but covers an area only 450 metres by 250 metres.

How old are the caves?

When the caves in the Palaeozoic limestones were formed has long been a matter of debate and controversy. Until the early 1980s, the conventional view was that these caves were no more than a few hundred thousand years old, because they looked similar to Northern Hemisphere caves of this age. However, many Australian caves occur on the tops of hills, far above the present streams and watertable, so they must be much older than this. In 1982, Joe Jennings recognised that the history of many caves is complex and extends back a considerable time into the past. Studies over the past 20 years have demonstrated that in several cases the landscapes surrounding the caves are ancient, perhaps 90–100 million years old around Jenolan and Yarrangobilly, and possibly twice this age at Chillagoe. Dating of the landscape at Buchan indicates that the oldest caves there were in existence 40 mya, and the palaeokarst passages exposed in the walls of caves at Jenolan are older still. Some modern caves appear to be ancient caves that have been re-excavated; in other cases the caves represent younger features of very old landscapes. The simple question, ‘How old are the caves?’ rarely has a simple answer.

CAVES IN TERTIARY LIMESTONES

At the beginning of the Tertiary, about 65 mya, Australia lay well to the south of its present position. At this time Australia had begun to split from Antarctica, so an ocean basin had opened up between the two continents. Throughout much of the Tertiary the ocean along Australia’s southern margin was warm to cool temperate, and was frequently warmer than at present.

The shallow waters along this margin supported and continue to support abundant marine life, including many organisms with skeletons of calcite, such as bryozoans, forams, echinoids (sea urchins) and calcareous red algae. Wave energy breaks the skeletons of the dead organisms into sand-sized grains, and together with those skeletons that were already sand-sized (such as forams), these accumulated to form extensive Tertiary limestone deposits on the continental shelf along the southern, and to a lesser extent western, margins of the Australian continent. The southern Australian Tertiary limestones are the largest area of temperate water limestone in the world, and continue to accumulate today. On the floor of Bass Strait extensive bryozoan mounds are growing at present, and calcite sands are building up nearby.

These temperate limestones are quite different from tropical and subtropical limestones, which are dominated by corals and calcareous green algae that have hard parts composed of aragonite. Aragonite is easily dissolved in rainwater, so when tropical limestones are exposed to weathering by uplift or a fall in sea level, the aragonite skeletons within them are quickly dissolved, and the dissolved carbonate can then reprecipitate within the pore spaces in the limestone as calcite cement. Thus tropical limestones are typically well cemented and resistant to erosion. By contrast, temperate limestones contain little aragonite because the skeletal grains within them are almost all calcite. Calcite is less readily dissolved by rainwater, so when temperate limestones are exposed to weathering, there is less precipitation of cement in the pore spaces between the sand-sized grains. Thus temperate limestones are frequently not well cemented and quite porous. Caves formed in these limestones are generally subject to frequent collapse, because of the relatively low strength of the surrounding rock, and the sediments on the cave floors are usually composed of sand grains derived from the breakdown of the limestone.

The Australian Tertiary temperate limestones accumulated in a number of different basins around the edge of the continent, but only three, known as the Eucla and Otway Basins and the Exmouth Sub-basin, contain karst with significant cave systems. These, in turn, are called the Nullarbor, Gambier and Cape Range karsts. Only the Exmouth Sub-basin has suffered significant folding since deposition of the sediments; in the Eucla and Otway Basins the limestones are mostly flat-lying.

Nullarbor karst

Landscape and climate

The best-known and most-studied of the Tertiary karsts is the Nullarbor and, because it contains a number of unique and fascinating features (sufficient to be nominated for World Heritage listing), it will be described in some detail. It has an area of about 200 000 square kilometres, making it one of the largest outcrops of limestone in the world (Figure 1.6). The Nullarbor Plain is astoundingly flat, with the longest stretch of straight railway in the world (478 kilometres). The surface slopes very gently seaward from 240 metres above sea level in the northwest, and terminates abruptly at the Great Australian Bight in a cliff-line 40–90 metres high that extends more or less continuously for nearly 900 kilometres. The cliffs fall sheer into the sea, except in two areas in the centre and west, where there are coastal plains (Roe and Israelite Plains respectively). The climate ranges from semi-arid along the coast (up to 400 millimetres rainfall) to very arid in the north, where rainfall is less than 150 millimetres and the mean maximum January temperature is 35^{o} Celsius. Potential evaporation greatly exceeds rainfall, increasing from 2000 millimetres near the coast to 3000 millimetres inland. Most rain occurs as light falls, but occasional heavy storms can cause local flooding. The coastal belt has a warm, semi-arid climate that supports small trees (mallee eucalypts and myalls). The Eyre Highway runs almost entirely through this coastal woodland, giving travellers a false impression of Nullarbor vegetation. Most of the Nullarbor Plain is treeless; its name, from the Latin words meaning ‘no trees’, was coined in 1867 by an early explorer, EA Delisser. The dominant plants are bluebush, saltbush and tussock grasses. The soils are thin, stony, well-drained loams and sands. Over much of the plain erosion has stripped away the soil, leaving bare stone pavements.

Geological history

The limestone of the Nullarbor is flat-lying and can be divided into three units deposited at different times. The oldest and thickest is the Wilson Bluff Limestone (up to 300 metres thick); it was deposited in the Middle–Late Eocene (from about 43–36 mya) across the entire Nullarbor in relatively quiet, shallow, cool temperate waters. In the Early Oligocene (about 35 mya) the sea withdrew from the Nullarbor, and the surface of the Wilson Bluff Limestone was exposed to weathering and erosion for probably 10 million years, forming a prominent surface soil. This soil is clearly visible in the sides of the dolines at Koonalda and Old Homestead Cave.

From the Late Oligocene to Early Miocene (about 25–23 mya), the sea returned and deposited the 100-metre-thick Abrakurrie Limestone, but only in the central Nullarbor area. The sea then retreated but returned in the Middle Miocene (about 15 mya) to deposit the Nullarbor Limestone, a relatively thin blanket (maximum 45 metres) of limestone, similar to the Abrakurrie Limestone, but covering the entire Nullarbor region. This limestone contains a greater variety of fossils than the older limestones, including occasional patches of corals (although no reefs formed).

The sea withdrew for the last time about 14 mya, and soon afterwards the Nullarbor region was gently uplifted. Later sea level rises eroded the coastal cliffs and formed the Roe and Israelite Plains. During the 14 million years that the surface of the Nullarbor Limestone has been exposed, a thickness of only 30–70 metres of limestone has been eroded away, the greatest erosion occurring closest to the coast, where rainfall is highest.

During the deposition of the limestone, the climate was warm with a strongly seasonal rainfall, and the vegetation on the nearby hills consisted of monsoon woodland (similar to that in northern Australia today) with pockets of rainforest. The climate became increasingly dry about 5 mya, but there was a warm, wet episode from about 5–3 mya. The present level of dryness, with extensive development of sand dunes in central Australia, was achieved only about 1 mya.

Groundwater

The Nullarbor Plain lacks surface water, but contains substantial quantities of groundwater. The watertable slopes very gently toward the coast; in the north it is only 30–45 metres below the surface, but close to the coastal cliffs it is as much as 90 metres down. As the groundwater flows slowly southward, its salinity increases from 1000–4000 milligrams per litre TDS (total dissolved solids) to 5000–20 000 milligrams per litre near the coast. (Normal drinking water should have less than 500 milligrams TDS per litre and sheep can drink water as salty as 14 000 milligrams TDS per litre). The south-flowing groundwater receives progressive additions of saline water seeping from above, which represents rainwater concentrated by evaporation. In addition, there is probably an input from salt spray blown inland from the waves crashing against the coastal cliffs. Groundwater closest to

Photo 11

Among the most spectacular features of the Nullarbor Plain, Western Australia, are its dolines and caves. Seen here is the large, steep-sided collapse doline of Kestrel 1, which formed when the roof of a large cave fell in.

Photo: Ken Boland

the coast, beneath the Roe Plain, has a salinity of 30 000 milligrams TDS per litre, approaching that of seawater (35 000 milligrams TDS per litre).

Surface karst features

The surface of the Nullarbor Plain is not completely flat. It rises and falls several metres between clay-floored depressions up to a kilometre wide, separated by stony ridges of the same width. The ridges are frequently aligned parallel to jointing in the underlying limestone. The Nullarbor surface is covered with a layer of calcrete, a hard, white, cemented crust generally about a metre thick, formed by precipitation of fine-grained calcite within the soil.

A few old river courses (palaeochannels) run southward across the northern and western parts of the plain as meandering, often clay-floored channels. These represent southerly extensions of palaeochannels incised into the low hills of very old basement rocks around the plain, particularly to the north and west. These old river courses probably first formed in the Cretaceous (perhaps 100 mya). At times the rivers may have extended southward across the Nullarbor for 100 kilometres or more, before the water seeped into the porous limestone to become part of the groundwater.

Small-scale solutional sculpting on the limestone outcrops is restricted. Irregular shallow solution pans are common on calcreted limestone pavements, and these often contain water after rain. Vertical pits up to 10 centimetres deep are found in the limestone along cliff-lines, but solution fluting (rillenkarren) is never well developed.

Dolines and caves

Apart from its great extent, remarkable flatness and lack of trees, the most spectacular features of the Nullarbor are its dolines and caves, although, given the vast size of the Nullarbor, the number of these is really rather small. More than 150 collapse dolines are present, mostly within 60 kilometres of the coast, as steep-sided, closed depressions 2–35 metres deep and 10–240 metres across (see photo 11). A large proportion are partly or wholly walled by cliffs, which may be overhanging. Many are degraded; erosion since the original collapse has weathered the sides and partly filled the dolines with sediment. However, some are still actively collapsing, as shown by a recent rockfall in Weebubbie doline. Some dolines lead to caves, but many do not.

Caves in the Nullarbor, like the dolines, are mostly restricted to the coastal belt and there are about 100 that have significant passage lengths. They vary in depth and form, but extensive collapse is a feature of most caves, and in many this has completely obscured the original phreatic form of the cave. The breakdown passages so formed are irregular in outline, with flat, bedding plane roofs and rubble (rockfall) floors, and they can be very large; the biggest is the main hall of Abrakurrie Cave, 300 metres long, 30 metres wide and 15 metres high (see colour plate 4 and Figure 1.8). Collapse is prevalent, probably for two reasons. First, the limestone is poorly cemented and structurally weak, so it collapses readily. Second, the arid climate on the Nullarbor promotes salt weathering, which weakens the limestone still further. Salt weathering occurs when evaporation of groundwater within the pore spaces of the limestone causes salt crystals to precipitate; these wedge apart the fossil grains and break the cement binding them together. Within caves this process detaches particles from the cave walls, sometimes enlarging the caves upward as domes, and depositing sand on the cave floor. In Mullamallang Cave this sand has been blown into dunes, and in places forms 'coffee-and-cream', banks of sand streaked with cream and dark brown.

However, a number of caves still contain original phreatic passages, and the best developed of these is Old Homestead Cave (Figure 1.9), which is also notable for being 100 kilometres from the coast, at the northern edge of the caverniferous part of the Nullarbor. Old Homestead Cave is the longest Nullarbor cave, with about 30 kilometres of surveyed passages; the farthest points of the cave are about 4 kilometres apart in a straight line.

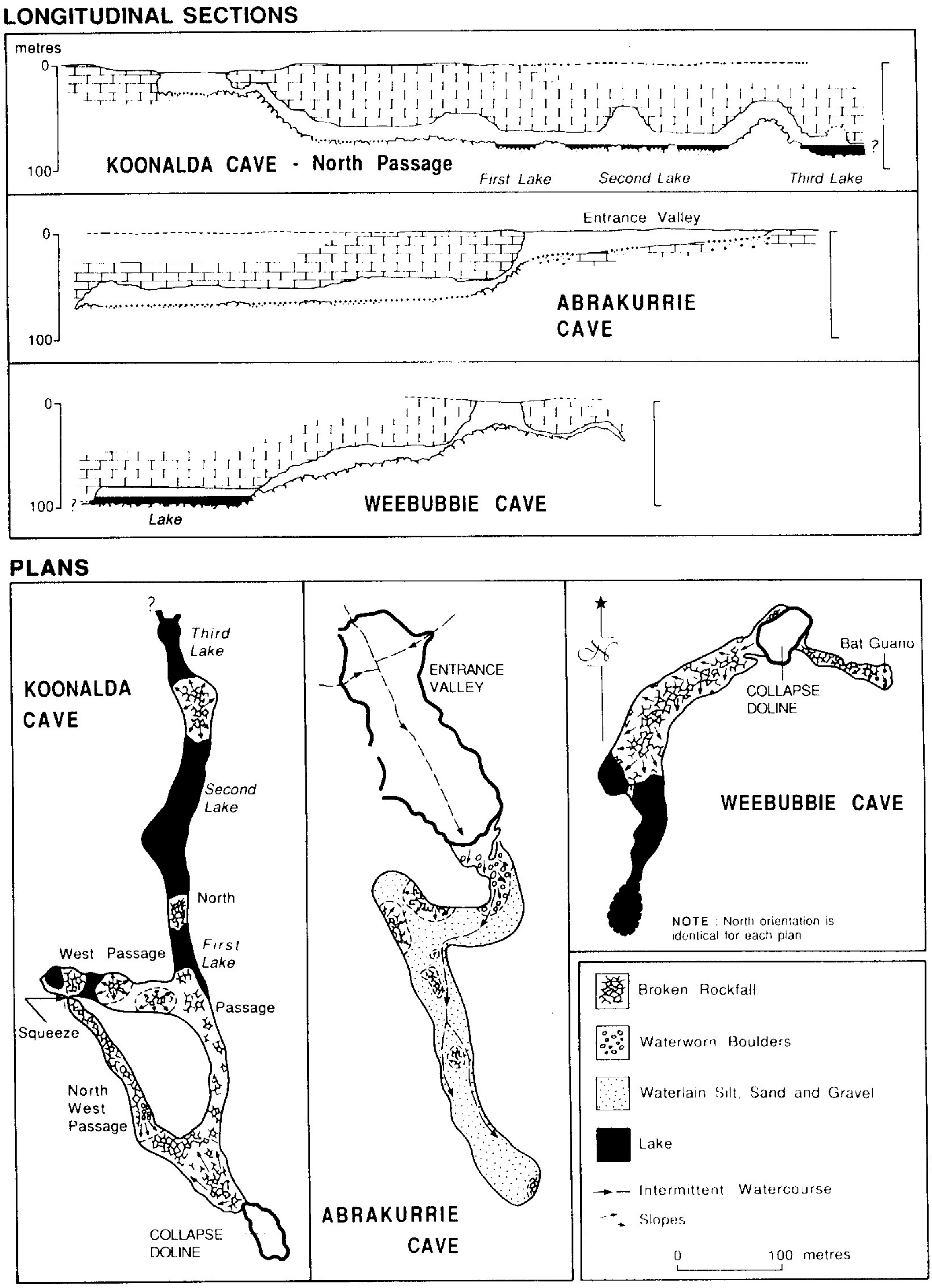


Figure 1.8

Long profiles and plans of three large caves on the Nullarbor Plain, Western Australia.

From Gillieson & Spate, 1992.

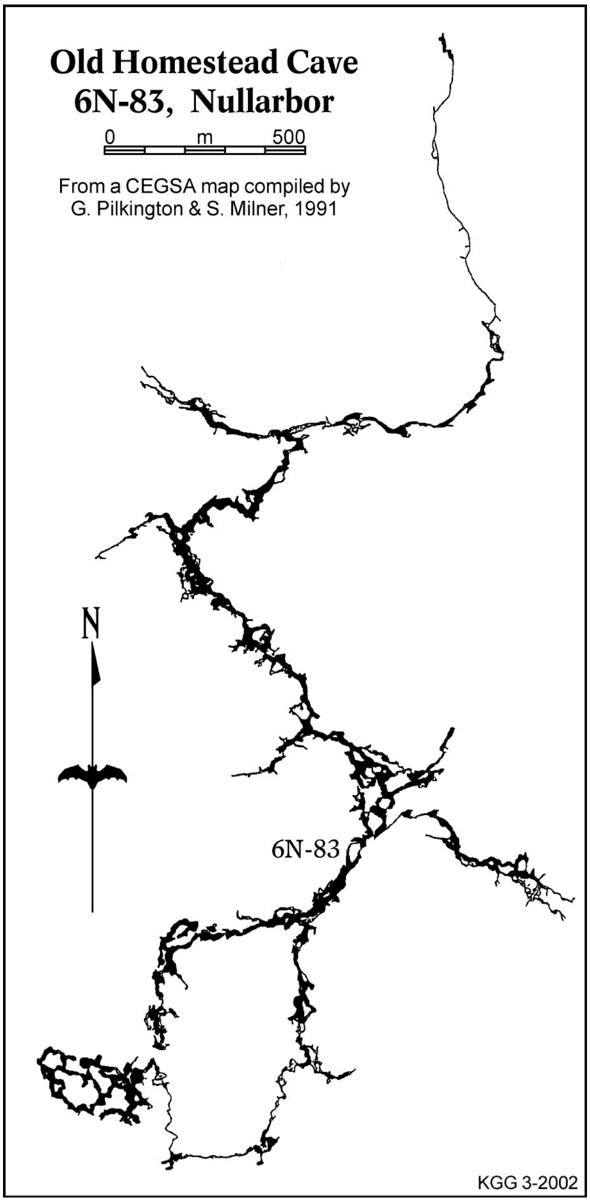


Figure 1.9

Old Homestead Cave, Nullarbor Plain, Western Australia, is a phreatic maze in detail, but has an overall meandering, joint-controlled plan at the broad scale. An additional 9 kilometres of passage has been explored since the original of this map was compiled by CEGSA in 1991.

Photo 12

Old Homestead Cave is the longest cave of the Nullarbor Plain, Western Australia, with about 30 kilometres of surveyed passages. In this phreatic passage large-scale wall scalloping and spongework can be clearly seen.

Photo: Ken Boland

Overall the cave trends north–south, but individual passages follow joints that run generally either northwest–southeast or northeast–southwest. The cave is entered through a double collapse doline; the rockpile leads rapidly downward to a very extensive horizontal phreatic system developed on two levels, lying about 63 metres and 70 metres below the plain. The phreatic passages often show large-scale wall scalloping and spongework with projecting rock blades and pendants (see photo 12), and may have flat roofs (not bedding planes). The cave lies more or less directly south of an old river channel on the surface of the plain; this channel represents the southerly extension of a palaeochannel cut into the basement to the north. Thus it seems most likely that Old Homestead Cave formed where water sank into the porous limestone at the termination of the old river course, and a phreatic system developed at or just beneath the watertable (the flat roof marks the watertable at the time). The cave formed along joint planes, its overall north–south orientation determined by the coastward flow of the groundwater. The cave drained when the watertable dropped (due to uplift of the plain or a fall in sea level), and collapse probably began almost immediately, forming breakdown chambers within the cave. In one of these chambers collapse continued until it breached the surface, creating the doline that is now the cave entrance.

A different, larger form of phreatic passage is present in Cocklebiddy Cave. This cave is also entered through a collapse doline and a steep talus slope leads to a large breakdown chamber, at the far end of which is a lake of clear, salty, blue-green water. The water-filled passage beyond this has been shown by divers to extend more than 4 kilometres; parts have collapsed, but some sections represent a large phreatic tube, up to 40 metres across and 30 metres high, with a subcircular cross-section. This passage formed by dynamic phreatic processes, that is, slow continuous movement of large volumes of water. It is substantially larger than the phreatic passages in Old Homestead Cave, perhaps because it is closer to the coast, and may represent a trunk system that had several tributary systems of the size of Old Homestead Cave. A drop in the watertable has partly drained the passage, removing the roof support and probably causing most of the collapse.

The caves described so far are all deep caves, extending 50–120 metres below the surface of the plain; some are deep enough to reach the watertable, and contain lakes of saline water. They are almost all formed in the Wilson Bluff Limestone (the entrances are generally within the Nullarbor Limestone).

There are also a number of shallow caves, less than 30 metres deep. Some have formed entirely within the Nullarbor Limestone, others extend downward into the underlying limestones. They are common on the eastern end of the plain and there are several north of Mundrabilla Homestead. Most are low collapse chambers, and their most notable feature is the presence of abundant dark brown to black calcite stalactites, stalagmites and flowstone. The Nullarbor is the only area in Australia where calcite decoration of this colour is so common. Stegamites, vertical shields of black calcite growing upward from the floor, are found in a few caves. The black calcite speleothems have been dated as more than 350 000 years old; at present they are being broken down by salt crystallising in cracks (see photo 13). Chemical studies have shown that the black colour is due to organic compounds (see Chapter 2), similar to those that stain swamp water a tea colour. This may indicate the presence of swamps on the plain at the time; perhaps the wet climatic phase about 3–5 mya could have been responsible for the black calcite deposition. Until the black calcite can be dated accurately, this remains very speculative. Black calcite is also present in a few of the deep caves, but most of these are almost devoid of calcite decoration.

The limestone close to the surface of the plain is honeycombed with small cavities of irregular-shape, generally less than 20 centimetres in diameter, as well as narrow sinuous tubes that are mostly concentrated along bedding planes and joint surfaces. These tubes may fork and rejoin to form a complex anastomosing pattern (see photo 2). In Webbs Cave these tubes also occur along a fracture plane through a large flowstone boss of black calcite. The tubes may have formed due to solution beneath the watertable or enhanced dissolution along tree roots. More work is needed to determine their origin.

Also present in the near-surface limestone of the Nullarbor are perhaps 100 000 blowholes, smooth-walled vertical tubes within the limestone, up to a metre across, and generally only a few metres deep (see photo 14). They are so-called because air draughts blow in and out of them, often strong enough to blow a hat into the air, or make a flag held across the hole flutter vertically (see colour photo 3). When the weather changes because a low or high pressure system moves across the plain, the surface air pressure decreases or increases, forcing air to blow out of or suck into the blowholes respectively. Some blowholes lead into large caves, but most connect only with small voids such as those mentioned above. Many blowholes resemble the solution pipes in Quaternary limestones, and could have formed in a similar manner, that is, beneath trees (see Quaternary section below). Alternatively, blowholes may form by upward doming from the small underlying cavities, due to erosion of the limestone by salt wedging (described above).

Decoration in the caves, apart from the black calcite already mentioned, is largely restricted to formations composed of gypsum and salt, also known as halite. Gypsum forms golden-yellow stalactites, as well as encrustations and curving crystal clusters ('flowers'). Salt occurs as white or clear crusts, straws and columns, often with smooth glassy surfaces from which project tiny cubic crystal shapes, as well as curving, wire- or hair-like helictites. The abundance of these minerals reflects the current arid climate; salt speleothems, in particular, will form only when the cave atmosphere is very dry. Dating of a gypsum and two salt speleothems gave ages of

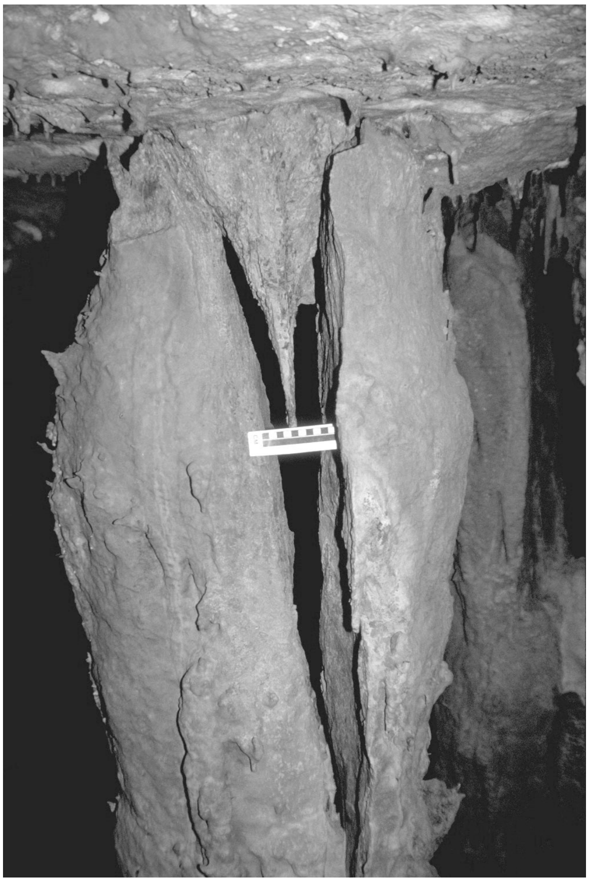


Photo 13

The old calcite speleothems in Webbs Cave, Nullarbor, Western Australia, are being broken as a result of pressure from salt that crystallises in the cracks and wedges them apart (10 centimetre scale).

Photo: K.G. Grimes

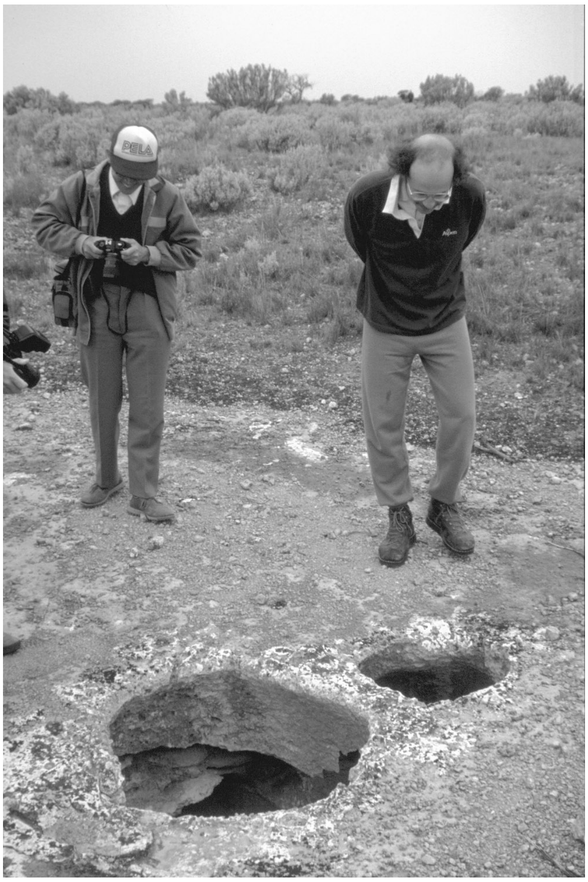


Photo 14

Eyeball Blowhole, one of thousands of similar vertical openings that dot the surface of the Nullarbor Plain, Western Australia. Draughts of air blow in and out of them as the barometric pressure at ground level rises and falls.

Photo: K.G. Grimes

about 185 000 years and less than 40 000 years respectively, providing independent evidence that the present level of dryness in the Nullarbor caves was reached within the past million years (only recently in geological terms).

Aboriginal usage of caves throughout Australia was generally restricted to camping, artwork and rituals in the entrance sections or overhangs; dark zones were avoided. However, one of the Nullarbor caves, Koonalda, was the site of extensive mining over the past 30 000 years by Aborigines, who took flint nodules from the cave walls, well within the dark zone. The flint breaks to give a sharp edge and was used for stone tool manufacture. The cave walls also show early artwork, in the form of wavy lines and other patterns created by dragging the fingers over the soft limestone.

History of cave formation

There is some cave formation on the Nullarbor occurring at present; in particular, there are periodic collapses within the caves, aided by salt crystallisation due to the current arid climate. However, there is probably little active cave dissolution going on now, because groundwaters and cave waters are all saturated with respect to calcite, that is, they cannot dissolve more limestone. Rainwater floods into the caves after heavy storms and, although this water can dissolve calcite, its effect is apparently relatively small, as shown by Old Homestead Cave. In this cave a system of small passages, often only tens of centimetres high and wide, slopes gently away from the entrance; the passages are superimposed on the larger, horizontal phreatic system. It seems likely that these small passages formed due to rainwater input into the cave after the doline entrance had collapsed.

Some cave dissolution is also occurring at present due to mixing corrosion. When rainwater flows into a lake cave, it forms a lighter surface layer of water, up to a metre thick, on top of the heavier saline water of the underground lake. As the two different water bodies mix, they form water with a new composition that can dissolve calcite. This process (mixing corrosion) is probably responsible for the notches in the walls around some lakes, notably in Cocklebiddy Cave. Nevertheless the effects of present-day mixing corrosion seem to be relatively small.

The main phase of cave formation was in the past. Cave development could have started when falling sea level exposed the Wilson Bluff Limestone to weathering from 35–25 mya, before deposition of the Abrakurrie and Nullarbor Limestones. However, it is likely that the caves formed after the last retreat of the sea and uplift of the Nullarbor Plain about 14 mya. The caves could have been forming more or less continuously for the past 14 million years, and for a large part of this time, the climate was wetter than at present; the present level of aridity was reached only about 1 mya. However, if the climate has been wetter in the past, why isn't there more karst development? Why are there so few caves and dolines, given the vast size of the Nullarbor? Why is the surface so flat, and why is there so little solutional sculpting?

It may be that flat plains of porous limestone cannot readily develop extensive underground and surface karst features, no matter what the climate. The Gambier Karst in South Australia and Victoria is a flat plain of porous, flat-lying limestone about the same age as the Nullarbor, with very gentle groundwater gradients, and has now, and probably always has had, about double the rainfall of the Nullarbor. However, like the Nullarbor, it also has relatively few caves and karst features, given its size, and little surface solution sculpting. There are probably two factors involved. First, the porosity allows substantial groundwater flow through the porous limestone itself, even though flow beneath the watertable is concentrated along a few joints that become caves. By contrast, in well-cemented, low-porosity limestones such as those of the Palaeozoic karst areas of Australia, groundwater flow is concentrated entirely along joints and faults, allowing greater cave development. Second, the flat outcrops of the limestone plains are unsuitable for the extensive formation of vertical solution sculpture such as fluting.

The flat roofs in the phreatic sections of caves like Old Homestead indicate that at least some and probably most cave formation on the Nullarbor occurred in the shallow phreatic zone, at and just below the watertable at that time. The fact that most caves are developed at only one level indicates that the watertable was stable throughout their development. However, Mullamallang shows two levels separated by about 25 metres vertically, and the shallow caves probably formed at a different level to the deep caves, reflecting different positions of the watertable caused by sea level fluctuations and/or uplift of the plain. Some caves, such as Old Homestead, probably started to form where old river courses sank into the porous limestone. Larger caves closer to the coast may represent trunk systems that had several tributaries of the size of Old Homestead Cave.

As noted already, most caves and dolines occur within 60 kilometres of the coast. This may reflect the fact that there has always been relatively greater rainfall near the coast; the additional rainfall would probably promote cave development. However, the belt of cavernous limestone lies parallel to the coast, and this is not the region of highest rainfall. The amount of rain decreases progressively along the coastline from southwest to northeast. Instead, salt spray, blown a more or less uniform distance inland from the waves breaking on the coastal cliffs, may be responsible. Salt crystallisation would weaken the limestone (as described above), making caves in the coastal region more susceptible to collapse, opening entrances into them and forming dolines. So there may be many caves farther from the coast, but entrances into them have not been opened by collapse. It is notable that Old Homestead Cave, about 100 kilometres from the coast, has relatively little breakdown.

Gambier Karst

The Otway Basin, which extends from Kingston and Bordertown in southeastern South Australia eastward to Melbourne in central Victoria, accumulated large thicknesses of sediments, including limestones, through much of the Tertiary. The Gambier and Port Campbell Sub-basins, in southeastern South Australia and far-western Victoria respectively, contain the extensive cave and karst development of the Gambier Karst, and will be described in some detail below. In the eastern part of the karst region there are relatively few caves, despite a large area of limestone, partly because of an extensive cover of younger basalt lavas. There are minor clusters of caves around Warrnambool and Timboon, and at Port Campbell the 60-metre coastal cliffs of limestone form the spectacular scenery of the Twelve Apostles and contain a few wave-modified caves. To the north of the Gambier Sub-basin are the extensive Tertiary limestones of the Murray Basin, but again caves are sparse and mostly in or near the cliffs along the Murray River. The largest, Punyelroo Cave, starts in the river cliff and has 2000 metres of sand-floored horizontal joint-controlled passages with local collapse areas.

Landscape and climate

South of Mount Gambier the Gambier Karst is a flat limestone plain that slopes gently to the coast and is crossed by sand dunes up to 30 metres high. To the north of Mount Gambier and around Naracoorte are plains at higher levels, with heights of around with heights of about 60–70 metres and 85–100 metres respectively. The well-preserved volcanic cones of Mount Gambier and Mount Schank rise more than 120 metres above the plain. The climate is Mediterranean, with warm dry summers and cool wet winters. Rainfall decreases from 800 millimetres around Mount Gambier to 550 millimetres near Naracoorte, as the annual mean temperature increases from 13.2^{o} to 14.4^{o} Celsius.

The most spectacular features of the landscape are the cenotes, circular cliffed collapse dolines that puncture the limestone plain and contain deep lakes (see colour plate 38). The cenotes provide the only surface water in the

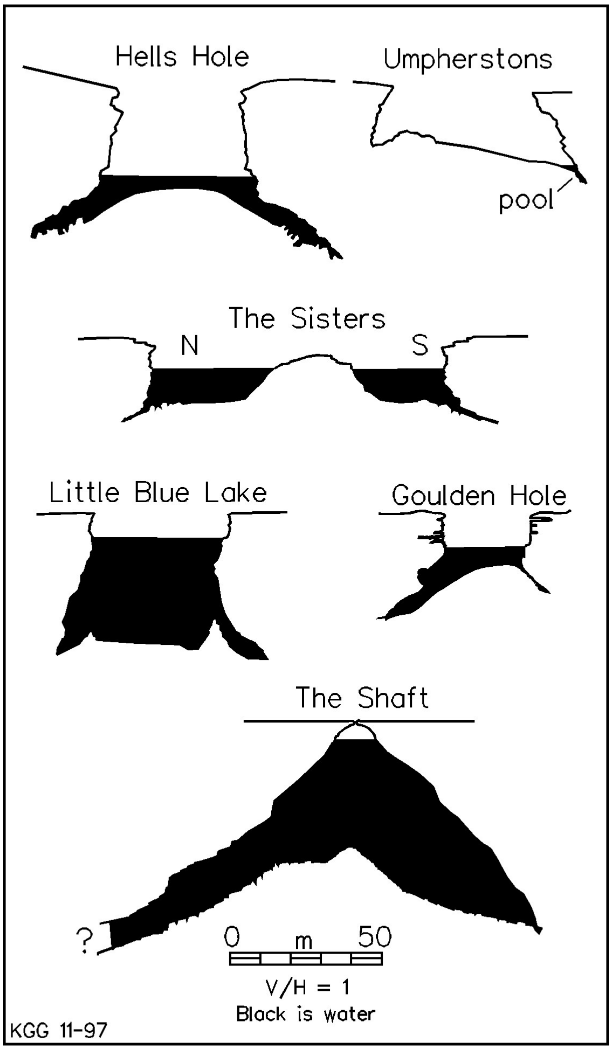


Figure 1.10

Cross-sections of some cenotes in the Mt Gambier area of South Australia. These are collapse dolines that extend below the watertable. The Shaft shows the situation just before the roof of a large cavern falls in.

area, and so were the first points of white settlement. They are up to 60 metres in diameter, and are surrounded by walls up to 30 metres high. The lakes are floored by rubble cones, often covered by a thin layer of sediment, and may be very deep; the deepest, The Shaft, has been dived to about 90 metres (Figure 1.10). Growing underwater on the walls of some dolines, mostly in water depths of less than 10 metres, are stromatolites (from the Greek words *stroma* to spread or cover, and *lithos* stone). These are crusts, columns or plates of laminated, very fine-grained calcite, precipitated by mats of cyanobacteria (blue-green algae) growing over their surfaces. The largest stromatolites are columns several metres long that grow diagonally upward toward the light from the cenote walls. Stromatolites are one of the most ancient life forms on earth; fossil examples more than a billion years old have been found in northwestern Australia. Today, large stromatolites are rare. Marine examples are found in Shark Bay, Western Australia, but the Mount Gambier stromatolites are among the largest freshwater stromatolites known.

The crystal-clear water of most of the cenotes makes them attractive diving locations, but they are potentially very dangerous. Some of them are very deep, and the narrower cave passages may silt up rapidly when disturbed. In the 1960s several divers drowned in the cenotes in a series of separate accidents. Diving in them is now restricted to divers with a recognised cave-diving qualification.

Geological history

The Gambier Limestone accumulated from the latest Eocene to the earliest Middle Miocene (about 38–15 mya) on an open marine shelf. Although the sea level rose and fell during this time interval, the ocean floor was not exposed to weathering for any lengthy period of time (unlike the Nullarbor). The limestone is composed predominantly of sand-size fossil fragments, and has a high permeability, so large volumes of groundwater can be pumped out of it.

The Gambier Limestone is essentially flat-lying, and thins northward from a maximum thickness of about 300 metres at the present coastline. It has been offset along two northwest–southeast trending faults, the Tartwaup and Kanawinka Faults, near Mount Gambier and Naracoorte respectively. Both faults have moved in the past few million years; the uplifted northeastern sides are topographically higher.

The sea withdrew from the Gambier Sub-basin about 15 mya (the same time as on the Nullarbor), and the limestone was exposed to weathering until about 5 mya (Early Pliocene). At that time, the sea level rose again, flooding the Gambier Sub-basin as well as the Murray Basin to the north to create a vast inland sea. This deposited a thin sand layer in the Naracoorte area before retreating about 2–3 mya.

Over the past million years, the sea level has risen and fallen many times, depositing a series of parallel northwest-trending calcareous sand dune ridges across the limestone plain (see Quaternary limestones). At the same time the Gambier Sub-basin has been gently uplifted, causing the Glenelg River, which flows across the eastern edge of the sub-basin, to incise a gorge in its lower reaches, where 35-metre cliffs line the river. Also over the past million years there have been several small basaltic eruptions in the area. The most recent formed the volcanic cones of Mount Gambier (perhaps about 23 000 years old) and Mount Schank (about 5000 years old). Blue Lake at Mount Gambier is a crater lake resulting from an explosive eruption that blasted through the Gambier Limestone.

Groundwater

Apart from the Glenelg River, which rises in the Grampians to the north, outside the karst region, the Gambier Sub-basin has no surface drainage network and virtually no perennial surface streams. Rainfall soaks quickly into the porous limestone through the thin soils and limestone pavements to recharge the groundwater, particularly in winter when evapo-transpiration is at a minimum and rainfall is at a maximum. The watertable slopes gently toward the coast, except along the Kanawinka and Tartwaup Faults, where it has a steeper gradient. Inland the watertable may be up to 15–25 metres below the surface, but along the coast it appears at ground level at springs and swamps.

The groundwater is high quality (low salinity) and extensively used for irrigation, domestic and industrial uses, particularly as there are few surface water resources. The abundance of good-quality groundwater has made this area the most productive agricultural region in South Australia. However, dolines have often served as convenient disposal sites for contaminated waste, including sawmill wastes, sewerage, cheese and paper factory effluent, resulting in pollution of the aquifer. Nitrate levels in the groundwater are high, probably due to pollution from agricultural activities, but the water is still safe for drinking.

Blue Lake at Mount Gambier is famous for turning from grey/green to intense blue in November each year, and back again in the following April/May. The blue colour is due to the precipitation of very fine calcite crystals in the surface water of the lake over this period. These crystals reflect the sunlight falling on the lake water, particularly the blue wavelengths. The sudden onset of calcite precipitation is due to warming of the surface water in the summer months, causing the dissolved carbon dioxide in the water to be given off into the atmosphere. When the amount of dissolved carbon dioxide in the water drops below a certain level, precipitation of calcite results and the water turns blue. As the surface waters cool in autumn, the crystals become denser and sink, mixing with the underlying less-saturated waters. Calcite precipitation stops, and the water turns grey.

Discharge of groundwater from the limestone occurs mostly through springs; the best known are Ewens Ponds and Piccaninnie Ponds, which have large flows of about two and one cubic metre(s) per second respectively. At Piccaninnie Ponds the spring rises from a deep shaft that has been dived to a depth of 90 metres; elsewhere the springs issue from small dolines, caves or swamps, and some bubble out of the sand on the beach. The larger springs flow to the sea as small creeks, which have often been artificially modified to drain adjacent swamps. Submarine springs have also been reported at a small distance from the coast.

Surface karst features

The limestone is mostly covered by thin red-brown (terra rossa) soils, except in the swampier areas, where the soils are sandier and grey. South of Mount Gambier there are extensive areas of limestone pavement, where the soils have been stripped away. The pavements show rounded subsoil solution forms, as well as flat, shallow solution pans and some small-scale solution fluting (rillenkarren). Along the coast, limestone outcrops have a hackly appearance with small spines and pits, due to attack by microbial filaments and salt.

Caves

Caves in the limestone are concentrated in three main areas: southeast of Naracoorte, around Mount Gambier, and along the Glenelg River. Apart from the Naracoorte caves, karst features are scattered and, overall, uncommon, given the extensive area of limestone present. However, numerous shallow surface depressions on the plains may be partly karstic in origin.

Many of the entrances to the Naracoorte caves are vertical solution pipes less than a metre across and up to 20 metres deep; others are collapse windows. Both open into horizontal systems of collapse chambers floored by rubble cones and connected by low, wide, solutionally sculpted passages, often partly filled with sediment. Sand from dunes on the surface sometimes falls into the caves through solution pipes, to form distinctive sand cones within the passages (see colour plate 11). The sand plugging the pipes may collapse from time to time to form a surface sinkhole; one such subsidence was triggered by a farmer driving his tractor across the paddock.

Phreatic passages, sometimes with spongework, are present, particularly in the lower levels near the watertable, where they may be partly filled with clay. Caves that reach the watertable have still, shallow pools with calcite rafts on the surface; the level of these lakes has fluctuated over time in response to changes in the regional watertable. The longest cave, Victoria Fossil Cave, has more than 3000 metres of an extensive rambling network of large collapse chambers and smaller connecting passages, some very well decorated. Victoria Fossil Cave is so named because it contains one of the largest accumulations of Pleistocene fossil vertebrates in Australia. In the past, the solution pipe entrances to some chambers acted as pit traps; animals that fell in were trapped and died there. Even today, surface dolines formed by collapse into an underlying cave can trap cows and sheep. In Victoria Fossil Cave, large, now-extinct animals such as thylacines (Tasmanian Tigers), marsupial lions (Thylacoleo), giant kangaroos and diprotodontids fell into the cave, and their very well preserved skeletons litter the floor in places. The fossils accumulated in several episodes during the Middle Pleistocene (100 000–400 000 years ago). The old pitfall entrances down which the animals fell are now completely sealed with sediment.

Dating of the calcite stalagmites and flowstone in the Naracoorte caves has shown that calcite deposition occurred during times when the climate was relatively wet. The most recent of these wetter phases finished about 20 000 years ago, and there is little speleothem deposition occurring in the caves at present.

Naracoorte cave passages show a preferential northwest–southeast alignment, more or less parallel to the Kanawinka Fault, and probably representing the predominant joint direction. The density of cave development at Naracoorte is atypical for the Gambier Karst. It has been linked to the locally steep gradient of the watertable, resulting from the uplift along the Kanawinka Fault, but this theory is now regarded as doubtful.

In contrast to the Naracoorte caves, the caves around Mount Gambier are of two types. The most common are joint-controlled, phreatic systems, mostly running northwest–southeast, parallel to the Tartwaup Fault; in fact, a line of elongated dolines follows the surface trace of the fault. Passages are usually narrow vertical fissures, but phreatic tubes, circular or oval in cross-section, are present in some caves, and collapse domes also occur. Englebrecht Cave (Figure 1.11) has a long section of collapsed passage that includes one large collapse dome. The walls in some caves show incuts and undercuts left by old watertables. Because the watertable is now quite close to the surface in this area, many caves have water-filled sections. Tank Cave, the longest of these, has more than 5 kilometres of almost entirely underwater passages explored by divers, and an extensive maze of large phreatic tubes and collapse domes as much as 14 metres below the surface.

The second type of cave in the Mount Gambier area comprises large, water-filled collapse passages that run off some of the cenotes. These are rubble-floored and trend downward until the floor, which represents a continuation of the rubble pile in the centre of the cenote, eventually meets the roof. These caves are not very long, extending less than 120 metres from the overhanging edge of the cenote lake, and do not intersect enterable phreatic caves.

The cenotes and their associated caves appear to have an unusual origin. They have some similarities to the collapse dolines on the Nullarbor; the latter would be cenotes, with lakes exposed to the surface, if the watertable there were 10 metres or less below the surface (as it is at Mount Gambier). However, in contrast to the Nullarbor collapse dolines, the Gambier cenotes never open into phreatic passages, and they extend to depths (about 90

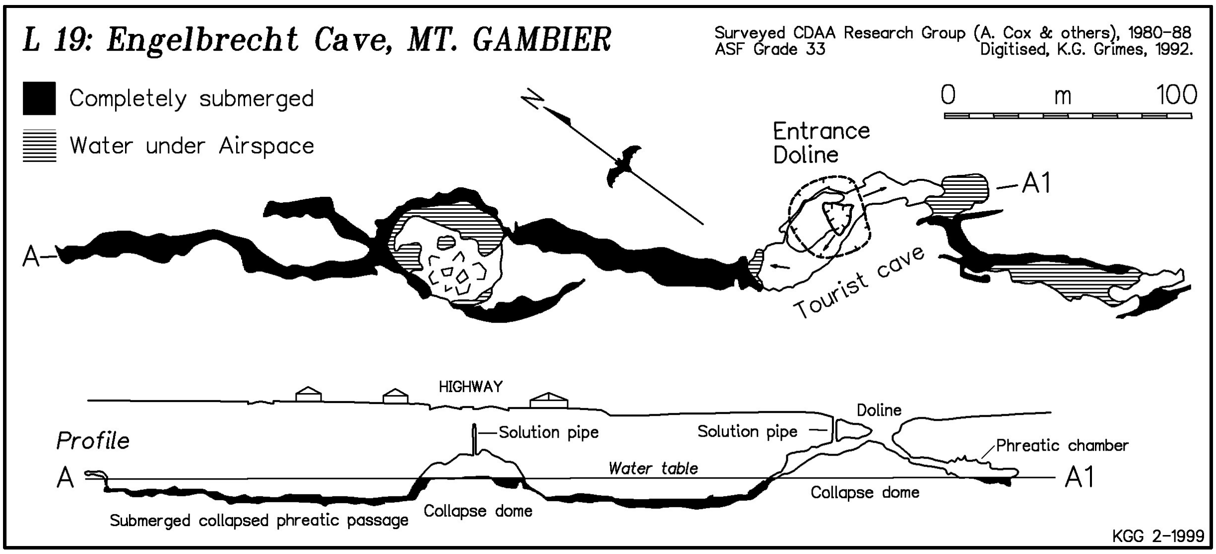


Figure 1.11

Engelbrecht Cave is a mainly flooded system that runs beneath the city of Mount Gambier, South Australia.

metres) far below the level at which the known phreatic systems around Mount Gambier are developed. They could have formed by collapse into caves formed deep in the limestone when sea level was very low (for example, it was about 120 metres below its present height 18 000–20 000 years ago). However, cenotes are rare, and occur predominantly in two clusters west and northwest of Mount Schank. These factors suggest a different origin to the phreatic caves in the area. One hypothesis is that the cenotes could have formed by collapse into large cavities dissolved in the limestone by carbon dioxide coming up from deeper in the earth's crust, along with the basaltic magma that caused the volcanic eruptions in the area.

About 15 kilometres east of Mount Schank is a borehole (Caroline 1) drilled into the sediments beneath the limestone. At a depth of about 2.5 kilometres, this borehole intersected a large reservoir of carbon dioxide trapped in the pore spaces of sandstone. Isotopic studies have shown that this carbon dioxide is volcanic in origin, and was probably given off by the basalt magma responsible for the eruptions at Mount Gambier and Mount Schank. Some of this carbon dioxide could have risen along fractures into the limestone and dissolved into the groundwater to form carbonic acid; this acid could easily have eaten away large enough caves in the limestone to form cenotes when they collapsed.

Another style of cave is present along the lower reaches of the Glenelg River on either side of the Victoria/South Australia border. These caves are mostly vertical fissures; some contain phreatic tubes and collapse chambers. Many have entrances in the limestone cliffs of the Glenelg River Gorge. Most are aligned northwest–southeast, but at Drik Drik the caves trend more or less north–south, reflecting the change in the dominant joint direction in the limestone from west to east. One of the longer caves, Princess Margaret Rose Cave, is well decorated, and some caves have bone deposits. In a few cases a surface stream has entered a cave and enlarged it by vadose erosion. Presumably cave development is mostly along the river because the gradient of the watertable was steepened here as the river incised its gorge, thereby increasing the groundwater flow along joints in the limestone and dissolving the caves.

In general, the caves of the Gambier Karst are not well decorated, as continuing collapse of the soft wall rock destroys many speleothems. Nevertheless, there are individual caves or parts of caves that have abundant stalactites, stalagmites and flowstone, and the Gambier Karst has more caves with decoration than the Nullarbor Karst, probably reflecting the higher rainfall. The growth and clearing of pine plantations around Mount Gambier has had a noticeable effect on the stalactites in the underlying caves; when the pine trees are growing they use so much water that the watertable drops and the stalactites dry up. After the trees are removed, the watertable rises and water droplets reappear on the stalactite tips.

History of cave development

It is uncertain when cave development around Naracoorte and Mount Gambier began, but it could have started when the sea retreated and first exposed the limestones to weathering about 15 mya. Cave formation may have slowed when the sea returned about 5 mya and covered the area for 2–3 million years. About 900 000 years ago the sea advanced across the area for the last time, forming a sea cliff and sand dunes at Naracoorte, and the caves may have been flooded by this rise in sea level. Blanche and Alexandra Caves contain columns and flowstone (not yet dated) that have been extensively dissolved, exposing their internal layering, and suggesting that the caves were flooded after the speleothems had formed. The Naracoorte caves have remained dry since the last sea level rise 900 000 years ago. In Victoria Fossil Cave the oldest flowstones, growing directly on the floor of a chamber, are more than 500 000 years old.

At Mount Gambier the cenotes may be substantially younger than the phreatic caves in the area, and collapse is still occurring in some. One opened in the middle of a road near Allendale in the mid-1800s, and in 1971 attempts to fill it in were finally abandoned. The road was diverted around it; the hole was fenced in but defiant. The collapse of Hells Hole, a large cenote east of Mount Schank, penetrated a 200 000–250 000-year-old sand dune, so it occurred after this date. The stromatolites in the cenote lakes started growing only 6000–8000 years ago; this represents the time during the last sea level advance when the water level became high enough for the cenotes to fill with water. If the caves beneath the cenotes were dissolved by carbon dioxide given off during the Mount Gambier/Mount Schank eruptions, they could have developed about the time of the eruptions, in the past 25 000 years. The actual collapse of the cenotes may have been triggered when the underlying caves were drained by the low watertables 18 000 mya to 20 000 mya, corresponding to the last major sea level fall caused by the advance of the glaciers. Further dating is necessary to resolve this question.

Cape Range Karst

Cape Range forms a limestone peninsula 16 kilometres wide and 80 kilometres long on the northwest coast of Western Australia, 1300–1400 kilometres north of Perth (Figure 1.6). It is composed of Tertiary limestones deposited on an open marine shelf from the Late Oligocene to the mid-Miocene (from 25–30 mya to 15 mya). The oldest limestone, the Mandu Limestone, is a chalky white rock with low porosity and permeability. The overlying pinkish-yellow Tulki Limestone makes up the bulk of the Cape Range, and is more porous. The youngest mid-grey

Trealla Limestone caps the northern and western parts of the range. The fossils in the limestones, including forams, bivalves, snails, sea-urchins, algae, bryozoans and sponges (and, in the Trealla Limestone, corals), are similar to present-day sea life around the peninsula (there is a coral reef growing offshore at the moment).

About 15 mya earth movements began that uplifted the limestones and folded them gradually into a broad gentle arch (anticline) running north–south down the centre of Cape Range. Cut into the western (seaward) side of the range are four benches (terraces), the lowermost bordering the present coastal plain. It was formed during a time of high sea level about 125 000 years ago, when the open ocean waves carved a bench into the seaward side of the emerging limestone range, and coral reefs then colonised the terrace.

The crest of Cape Range is gently undulating and rises to 314 metres. The flanks are gently sloping but are dissected by deeply incised canyons that contain flowing water only after heavy rain. About 40 per cent of the rainfall in the area comes from intense tropical cyclones. The overall annual rainfall is low (about 250 millimetres) and temperatures are high; for example, the mean maximum and minimum January temperatures are 33° and 23° Celsius respectively. Given the present aridity, it is remarkable to find in the headwaters of one creek a small stand of *Livistonia* palms, a relic of past wetter climates. Much of the Cape Range is devoid of soil cover, and a calcrete surface is extensively developed. Limestone pavements with varying degrees of small-scale solutional sculpture are common.

Several hundred caves have been documented from the area. Most have developed in the Tulki Limestone in the ranges, but there are also small caves on the coastal plain, extending through the thin coastal plain sediments into the underlying Tulki Limestone. Some coastal caves contain permanent water. Of the caves in the ranges, most are vertical solution pipes, often modified by collapse. Only a few, such as Wanderers Delight, also have horizontal development in the form of extensive, low, joint-controlled passages. Some cave entrances are within large, shallow dolines; these divert substantial amounts of rainwater into the caves during cyclones, eroding the passages and depositing coarse, well-rounded gravels. Many caves have calcite decoration, but very little is currently active.

The Cape Range caves are remarkable for the rich fauna that lives in them, including fish, insects, spiders, shrimps, millipedes and land snails; it is among the world’s most diverse cave faunas. There are 39 species of animals that have specific adaptions to the cave environment (troglobites), such as loss of eyes. For example, a blind fish and a blind eel have been recorded from the permanent pools in the coastal caves. The fauna is largely a relict from times of higher rainfall, when tropical forest covered this region. As the climate dried out, the forest disappeared and was finally lost from the gorges about 2 mya. Many animals that formerly lived on the forest floor retreated to the moister, cooler cave environments, where they have survived to this day.

The first well to strike oil in Western Australia (Rough Range 1) was drilled just to the east of Cape Range in 1953, but no petroleum was produced until the 1980s. Wells were also drilled in Cape Range, but no significant petroleum finds were made.

CAVES IN QUATERNARY LIMESTONES

In Australia, Quaternary limestones are widespread as beach dunes from southwest Western Australia to Wilson’s Promontory, including Kangaroo and King Islands, and are also present on Lord Howe Island (Figure 1.6). These dune limestones are similar to the Tertiary limestones already described, in that they are porous, poorly cemented, and composed of well-rounded grains of fossils with calcium carbonate shells that inhabited the shallow water environments along the southern Australian coast from the Early Tertiary to the present (as described previously). The shells and skeletons are broken up by wave action, washed ashore onto the beaches, and then blown into dunes behind the beaches by the prevailing winds, which are predominantly strong westerlies across southern Australia. In Victoria there is an additional contribution to the beach sand from the erosion of Tertiary limestones that outcrop in cliffs along the coast. The quartz sand within the dune limestones was mostly washed down to the coast by rivers, and derived from erosion of granites and metamorphic rocks inland.

The carbonate dunes form ridges parallel to and just inland from the coast, rising up to 40 metres above the beach in Victoria, and to more than 100 metres in Western Australia, where the winds are stronger and blow more continuously. At Cape Leeuwin, the wind blows at more than 30 kilometres per hour for about 50 per cent of the time, whereas at Portland in western Victoria the wind exceeds this velocity only about 15 per cent of the year. Where the Western Australian dunes have advanced inland over rising hills, their crests may be 200 metres above sea level. The dunes contain well-developed steeply dipping cross-bedding. Each cross-bed represents the downwind slip-face of the dune; sand is blown up the upwind side of the dune, and then avalanches down the lee side, burying the downwind face as a cross-bed. As the dune migrates downwind, it progressively forms these steeply dipping cross-beds.

During the past million years of the Quaternary, the sea level has risen and fallen many times as the polar ice sheets retreated and advanced. Carbonate dune systems formed during times of high sea level like the present. When the glaciers advanced, sea level fell; for example, about 18 000–20 000 years ago ice sheets covered much

Photo 15

Carbonate dunes often contain vertical tubes opening to the surface, such as these, exposed by erosion at 'The Petrified Forest', Cape Bridgewater, Victoria. The pipes, known as solution pipes, can be soil-filled or hollow; their origin is not completely known.

Photo: K.G. Grimes

of North America and Europe, and sea level fell to about 120 metres below its present level. As the glaciers melted and sea level rose, the advancing waves pushed the beach in front of them, like a giant bulldozer. When sea level reached its maximum, the position of the coastline was stable for a time, and the prevailing winds were able to blow the beach sand into dune ridges behind the beaches.

In southeast South Australia and western Victoria the coastal region is being forced upward very slowly by tectonic forces within the earth's crust. As a result, each dune formed during a sea level maximum became topographically a little higher by the time of the next sea level rise, so that it was generally not reworked by the waves and remained preserved as a linear ridge. The dune systems formed by the many sea level maxima during the Quaternary now extend across the coastal plain as low ridges parallel to the shoreline, separated by swamps or lakes.

Where the coastline is stable and not being uplifted, for example, in southwest Western Australia and much of Victoria, the dune systems constructed during successive sea level maxima stacked up on top of each other, forming deposits of dune limestone more than 100 metres thick in Western Australia. Dune sands of different ages may be separated by soil horizons. When sea level falls and the beach dunes are abandoned, they are subjected to weathering processes. Dissolution of fossil fragments in percolating groundwater releases dissolved calcium carbonate that can then be precipitated as thin rims of calcite cement around the grains within the dune. This cement does not generally completely fill the pore spaces, so the bulk of the dune is poorly cemented and very porous; it is often possible to break up the limestone in your hands. More cement may be precipitated close to the surface of the dune, and additional cementation may occur in the form of a hard calcrete crust. The strengthened surface layer formed in this way is often called a cap rock.

The carbonate dunes often contain solution pipes (see photo 15), which are vertical tubes or cones opening to the dune surface; they are generally up to a metre in diameter, with smooth, well-cemented walls. These pipes extend down into the dune limestone, typically for 2–5 metres, but up to 20 metres in places. They are soil-filled or hollow and hollow pipes often open into cave chambers below. Solution pipes frequently contain root moulds, as tubes of calcite-cemented sand precipitated around roots that later rotted away. The origin of solution pipes is not completely known, but the following process is probably responsible in many cases. When rainwater falls on large trees growing on limestone, it tends to run from the leaves to the branches to the main trunk. The rainfall

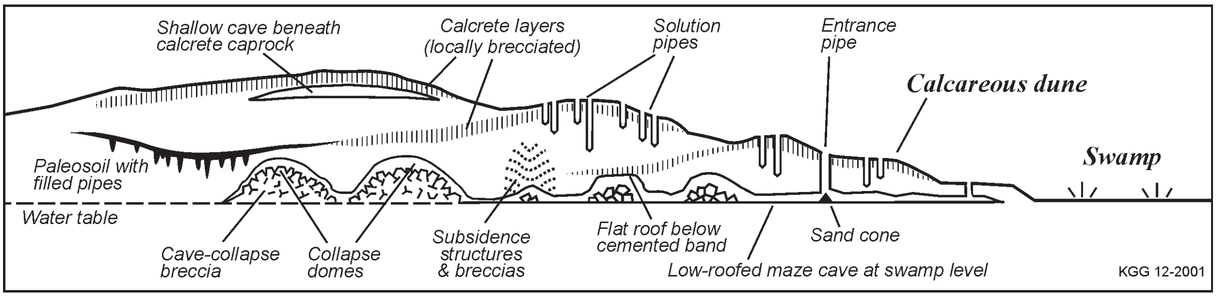


Figure 1.12

Features of syngenetic karst in a dune limestone result from solution occurring at the same time as the sand is being cemented into a soft rock.

intercepted by the leaves flows down the trunk, where it seeps into the soil. This groundwater beneath the tree has carbon dioxide and organic acids added by the tree roots, giving it an increased ability to dissolve limestone and form a solution pipe directly below the tree. The solution pipe will fill with soil as it is slowly dissolved, and at least some of the calcium carbonate in solution will precipitate nearby to form the well-cemented walls of the pipe. The soil within the tube may later be washed away if a cave has developed beneath it.

There is relatively little surface karst development on dune limestones, because of the poor cementation and the presence of a sandy soil, composed of quartz sand left behind after the calcium carbonate grains in the limestone have been dissolved. On more cemented dunes there may be bare limestone pavements, particularly if the native vegetation has been cleared. Where hardened cap rock is exposed, irregular pitting or small areas of rillenkarren may develop. Joints in the cap rock are occasionally evident as linear or polygonal networks of ribs with cracks along them. Dolines are frequently present, formed either by soil slumping down solution pipes or by collapse. Collapse dolines are up to 45 metres across and may have overhanging walls formed of projecting cap rock.

Cave development in dune limestones is dependent on several factors. First, the limestone must be sufficiently pure, although it is not nearly as pure as Palaeozoic limestone. The cavernous dune limestone in western Victoria has 70–90 per cent calcium carbonate; cavernous Palaeozoic limestone in eastern Victoria has generally more than 90 per cent calcium carbonate. The high porosity of the dune limestone means that less dissolution is required to form a cavity, so the quartz sand left behind as the limestone dissolves is less likely to clog the caves as they form.

Second, as for any caves in limestone, a more or less consistent supply of aggressive water is required. This input can be provided by lakes and swamps, directly by streams, or by groundwater seeping out of an adjacent non-carbonate aquifer. Swamp water appears to be particularly aggressive, due both to carbonic acid (from microbial degradation of organic matter, which releases carbon dioxide) and organic acids (humic and fulvic acids).

Third, the limestone must be sufficiently well cemented that solutional cavities do not collapse before they became very large; older dunes are generally better lithified than younger ones. For near-surface caves, the hardened cap rock often provides additional strength to support the roof.

Because in carbonate dunes the process of limestone cementation is occurring just prior to, or even at the same time as, cave dissolution, the term syngenetic, coined by Joe Jennings in 1968, is often used to describe karst development in such limestones (syn, together; genetic, origin). These processes are rapid (in geological terms), occurring over a few hundred thousand to perhaps a few thousand years. This is in contrast to cave formation in the Palaeozoic and Tertiary limestones of Australia, where cementation of the limestone occurred hundreds to tens of millions of years before cave formation.

Quaternary dune limestone is widespread along the southern Australian coast, but contains caves only in southwest Western Australia (where they are especially abundant and well decorated), Kangaroo Island, Eyre Peninsula and the Mount Gambier area (all in South Australia), western Victoria, and Lord Howe Island. Even in these areas caves may be restricted to a particular dune ridge.

Because the Quaternary limestone is not well cemented, cave chambers and passages within the dunes are characterised by virtually ubiquitous collapse (Figure 1.12), and original solutional passage walls may be difficult to find. Entrances are either collapses where the roof has completely fallen in, or solution pipes. The roofs of collapse chambers are often broadly dome-shaped, with the walls and roof only a few metres from the top of the rubble mound filling the chamber. One of the best examples is Kelly Hill Cave on Kangaroo Island, which consists of roughly circular, symmetrical collapse domes up to 60 metres in diameter. The sides of the domes are narrow fissures dipping at 40–60^{o} and blocked off by rubble at the bottom. In Western Australia, inclined fissure caves, representing one side of a collapse dome like Kelly Hill Cave, are common. They consist of passages with a rubble floor and steeply sloping roof, often representing a cross-bed within the dune. In some Western Australian caves, collapse has followed a weakness within the limestone caused by the presence of a buried soil horizon. In stream caves, the collapse rubble that falls into the stream is often dissolved and removed, leaving large chambers.

The morphology of the caves varies according to the extent of the dune limestone, the source of aggressive water and its flow direction. Because the limestone has a high, uniform porosity and does not contain jointing to any extent, the direction of groundwater flow is determined almost solely by the slope of the watertable, which generally flows downhill. Where the flow is slow, irregular mazes with sculpted walls develop (Figure 1.4 and see photo 3); occasionally there may be sinuous passages (Figure 1.13).

At Bats Ridge in western Victoria, the dune system dates back more than 800 000 years, but caves are restricted to one dune about 300 000 years old that is relatively pure (it lacks internal soil horizons). The cavernous dune ridge parallels the coast, and on its inland side are small spurs separated by swampy hollows. The largest caves are developed directly adjacent to these swamps, as shallow sinuous systems with multiple entrances and low, flat, wide chambers often modified by collapse. The overall cave direction is toward the southeast, that is, downhill toward the coast, but there is little preferred orientation of cave passages, reflecting the lack of jointing in the limestone. The longest cave has more than 1.5 kilometres of passages but extends only 400 metres in a straight line, because it is a maze confined to the single dune ridge. The caves are developed at two separate heights, reflecting different water levels in the swamps in the past; the watertable is now 0.5–1.8 metres below the swamp floor, although this partly reflects artificial lowering by agricultural drains constructed in the area.

In southwest Western Australia, the largest area of dune limestone, 80 kilometres long and up to 7 kilometres wide, is on the Leeuwin–Naturaliste Peninsula, where it overlies Precambrian granites and gneisses. The dunes, blown by the strong westerly winds, have migrated and blocked some of the stream valleys eroded into the Precambrian basement, forming lakes or swamps. The larger streams have maintained their courses through the encroaching dunes, forming valleys with steep walls up to 60 metres high. The smaller streams have formed cave systems, which can extend for hundreds of metres as linear, sinuous stream passages oriented down the watertable gradient, sometimes following buried valleys on the basement surface (Figure 1.13).

In the southernmost part of the peninsula (around Augusta) the caves are located in the oldest, most inland dune system, which is composed of relatively well-cemented limestone. The caves form multilevel complexes with up to several kilometres of passage, sometimes as network mazes; the Jewel-Easter Cave system is more than 8 kilometres long. Well-developed spongework is prevalent in the cave walls, indicating dissolution by slowly moving water; the presence of a large, horizontal roof over a chamber in Jewel Cave indicates that dissolution

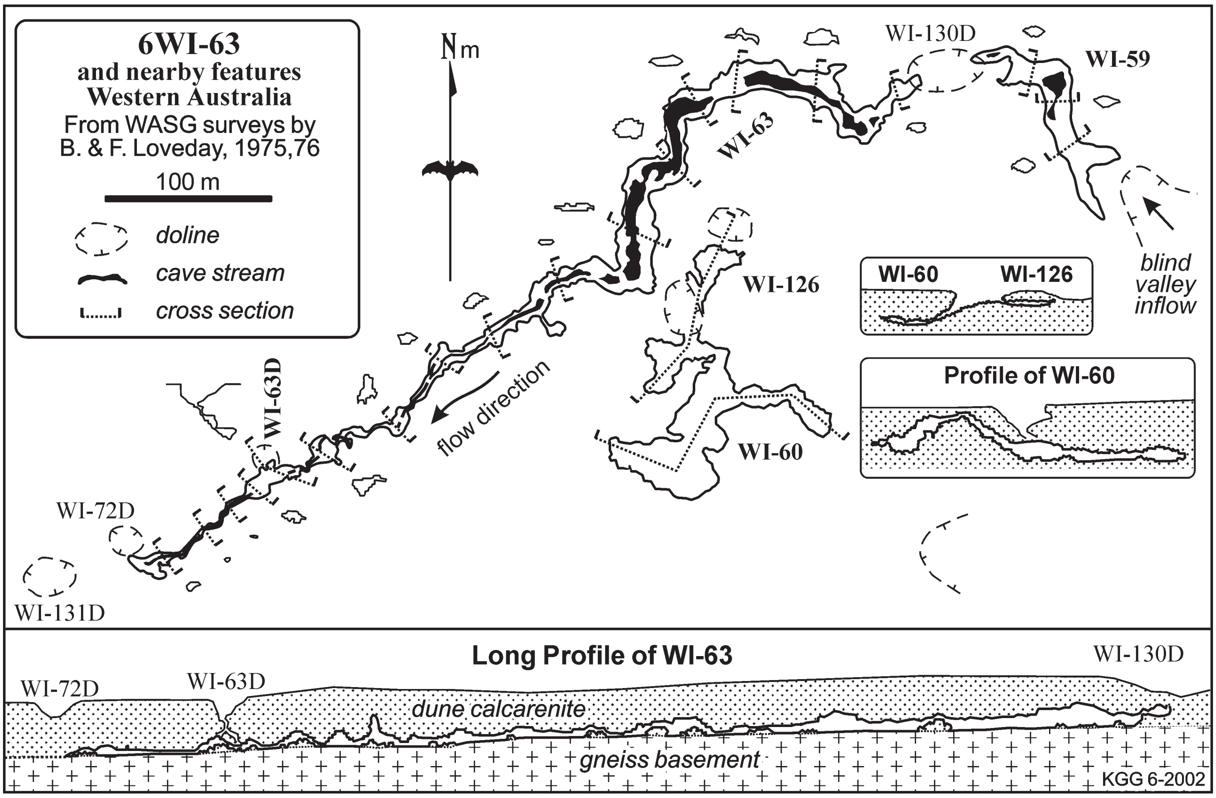


Figure 1.13

A linear stream cave (WI-63) follows the contact between dune limestone and impermeable gneiss. By contrast, the neighbouring cave system (WI-126 and WI-60) is more typical of caves in dune limestone, being a series of large collapse domes with little of the original dissolutional cave remaining.

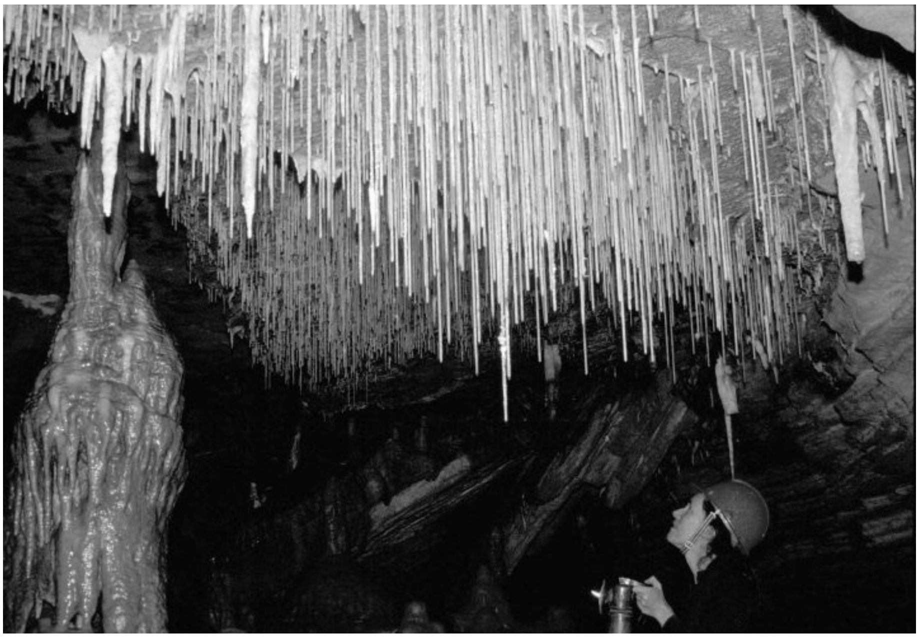


Photo 16

Thousands of straws and stalactites decorate the ceiling of a dune limestone cave in South Australia. They form as a result of water percolating through the whole surface area of the porous roof.

Photo: K.G. Grimes

extended up to the watertable. The groundwater flow paths may have extended deeper into the limestone than elsewhere in this region, because around Augusta the dune limestone is sufficiently thick that deeper flow paths are possible. By contrast, farther north in the Leeuwin–Naturaliste Peninsula the limestone is often thinner and cave floors may expose and be slightly incised into the underlying basement (Figure 1.13). It has been proposed that in the southern part of the Leeuwin–Naturaliste Peninsula, earthquakes along the Darling Fault to the east may have intermittently tilted the landscape, so that the major drainage across the dune fields was diverted progressively south, forming successive cave systems as it did so.

At Yanchep, north of Perth, the dune limestone overlies not Precambrian basement but porous, unconsolidated, non-carbonate sand. Inflow to the limestone occurs not from swamps or surface streams but as diffuse groundwater flow from below, where the watertable in the underlying sand intersects the base of the limestone. Where this inflow occurs, a semicontinuous north–south belt of caves, characterised by collapse domes, has developed; on the surface there are collapse dolines and a distinctive vegetation characterised by tall eucalypts. To the east, where the watertable lies below the limestone, there is no cave development and no eucalypt forest. The caves transport the groundwater away faster than it can percolate out of the sand, steepening the dip of the watertable; this follows the base of the limestone coastward for about a kilometre, until it meets a chain of interdune lakes. On the coastal side of the lakes are several sinks where water drains into cave systems characterised by solutional features such as broad flat ceilings with roof pendants. The size of these caves decreases toward the coast, as the aggressiveness of the water within them is decreased by dissolution of the limestone.

Caves in dune limestones often contain abundant speleothems. Because of the high porosity of the limestone, water percolation can occur over the entire ceiling, rather than being confined to joints as in Palaeozoic limestones. As a result, the cave roofs can be covered with thousands of straws and stalactites (see photo 16); this is particularly true of the caves in Western Australia. Individual straws in these caves may be up to 7 metres long, and helictites are also well developed. Cave pearls (oolites) commonly form around sand grains in pools on the cave floors, and may develop very rapidly (over about 20 years). In western Victoria the dune limestone caves are less well decorated; because the climate there is cooler, cloudier and wetter than in southwest Western Australia, groundwater percolating into the caves has not been concentrated as much by evapo-transpiration, and is less likely to precipitate calcite.

CAVES IN NON-CARBONATE ROCKS

Most caves form by solution of limestone/dolomite, but caves also form in a variety of non-carbonate rocks, both by solution and other mechanisms. A large variety of non-carbonate rocks can host caves, but here we will discuss only those that are most common in Australia: lava caves, sandstone caves, caves in granite, piping caves in soils and beneath duricrust layers, sea caves and, finally, fissure caves.

Lava caves

Lava caves mostly develop as tubes within basalt flows during eruption of the lava, while it is still fluid. Basalt lava is erupted at high temperatures (greater than 1000° Celsius) and flows easily and quietly, generally at speeds of several kilometres per hour. Basalt lavas can flow for long distances and build up lava plains (as in western Victoria), or shield volcanoes, which are very extensive with gentle slopes (for example, as in Hawaii).

Photo 17

Barkers Cave, Undara, Queensland. This large lava tube would originally have been filled with liquid lava, insulated from the air by a solidified ceiling. The cave we see formed when the movement of lava into the tube from the volcano stopped; the lava tube then drained, leaving this passage.

Photo: K.G. Grimes

Basalt lava has two forms, a very fluid type called pahoehoe, which cools to form smooth ropy surfaces on the lava, and a more viscous type, aa, which has a rough, blocky surface. Most lava caves form in pahoehoe flows. These flows move rapidly downhill from the eruption point (often a volcano), generally as lava tongues and channels that flow preferentially along low-lying parts of the landscape, for example, along pre-existing river valleys.

The roofing of surface channels to form lava tubes has been observed in active lava flows on Hawaii (Figure 1.14). Most commonly, the surface of the flow in the channel solidifies as a crust, which will eventually completely cover the flow. In addition, the outer edges of a channel chill rapidly and solidify, and overflows from the channel may form raised margins or levees that can build up and arch over to roof the flow. The flow roof is often covered and thickened by later lava flows. The casing of solidified lava around the flow insulates its central portion, which remains at a high temperature, and molten lava continues to move through what is now a lava tube. These insulated tubes can allow the lava to travel great distances (for example, 160 kilometres at Undara, in north Queensland). Small parts of the roof often collapse to form skylights, revealing the orange glow of the flowing lava in the tube below. When the eruption ceases, the movement of lava into the tube from the volcano stops; the lava tube may partly or completely drain, resulting in a lava cave, although most lava tubes probably remain full of solidified lava. The caves formed are typically single or sparsely branching, sinuous passages with oval cross-sections, and can be several metres high or wide. Large 'railway-tunnel' lava tubes of this type occur at Undara (see photo 17) and Byaduk, Victoria.

Smaller lava caves can originate by a different mechanism (Figure 1.15). Lobes of lava, extruded at the margins of a flow or overflowing from a channel, cool rapidly and can be completely enclosed by a thin surface crust. Ruptures in the crust can allow the lobe to drain, forming a cave. Because the lobes are often thin, stacked up on each other and interconnected, such caves are often mazes of low chambers and passages that fork and rejoin.

Drained lava caves have a number of characteristic features (Figure 1.16). The walls are lined with a glassy glaze that may show drips (lava stalactites) and vertical ribs; this lining flakes off easily and is often absent in older lava caves. Pasty lava may be extruded from behind the lining to form 'lava hands'. If the floor has solidified, lava stalagmites may build up beneath drips. Where blocks of partly solidified lava have begun to fall away from the walls or roof, sticky pull-apart structures form. Sub-horizontal tide marks along the walls form benches and shelves that mark the level of successive lava flows within the tube. The floor represents the last lava flow within the tube, and frequently shows a ropy pahoehoe surface.

After the eruption ceases, lava tubes are susceptible to collapse as the roof is weakened by weathering. This process forms entrances and breaks long tubes into segments but, nevertheless, lava caves many kilometres long are known overseas (for example, Kazumura Cave in Hawaii is 65 kilometres); the longest in Australia is Bayliss Cave in north Queensland (more than 1.3 kilometres).

If the throat of a volcano remains open after becoming extinct, it forms a shaft, and this represents a separate, rare category of lava cave. Such shafts are generally rubble-floored and may be lined with abundant lava stalactites; a good example is The Shaft, near Mount Eccles in western Victoria.

Small caves can also form in lavas by weathering processes after the eruptions have stopped. The boundary between different lava flows may be a zone of weakness, characterised by vesicular, altered lava and/or volcanic ash; this material is easily weathered to clay and washed away, particularly if exposed in a cliff-line. This process can produce overhangs and small caves, such as those in Bunya Mountains National Park in southeast Queensland.

Weathering of the basalt surrounding and overlying lava caves produces large amounts of clay, which is often washed into the caves and covers the floors. If bats inhabit the caves (often the case in Australia), large amounts of bat guano also accumulate on the cave floors. The phosphate from the guano can react with elements released by weathering of the basalt to produce a variety of rare phosphate minerals. For example, eight phosphate minerals have been recorded from Skipton Cave in western Victoria; four of these were first described from here and one is known nowhere else.

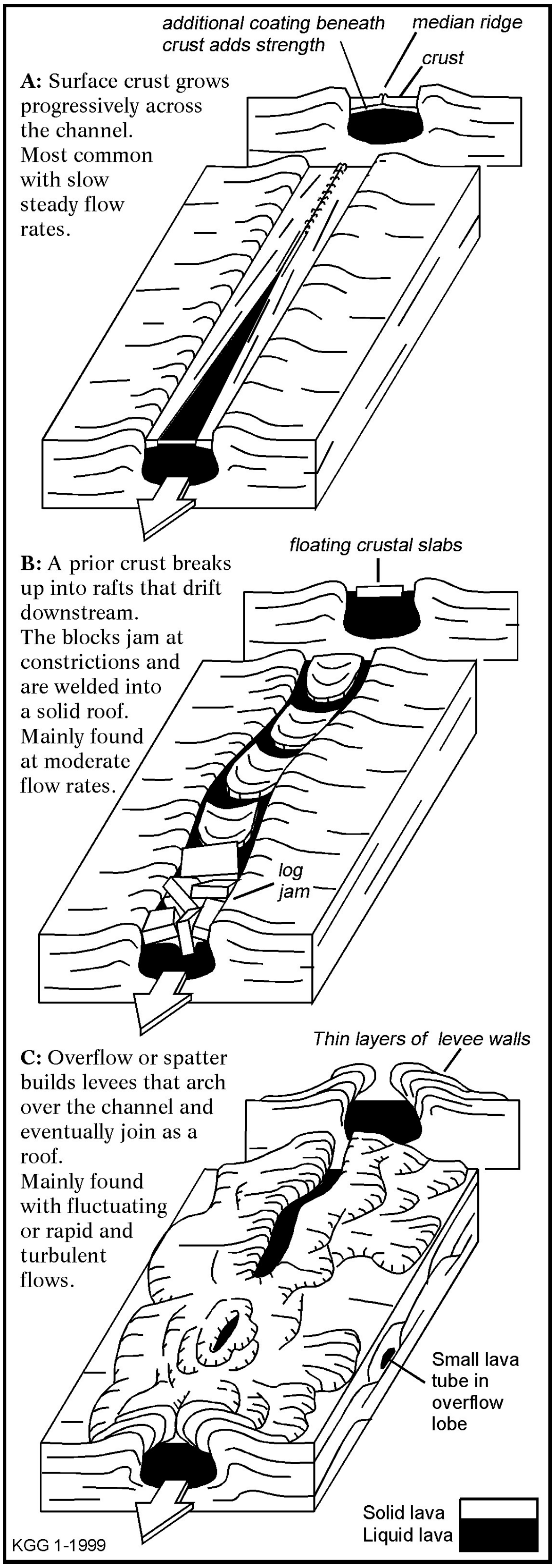


Figure 1.14

Three ways of forming a lava tube by roofing of a surface lava channel.

After Grimes, 1999

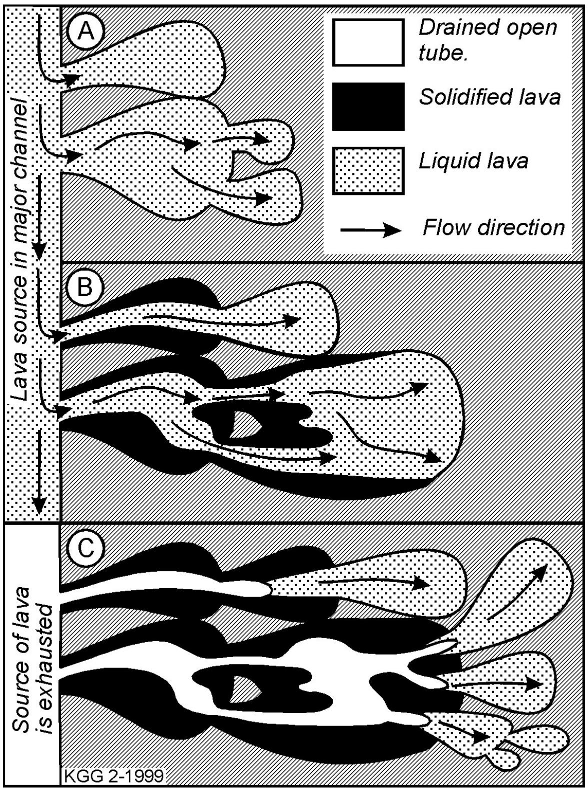
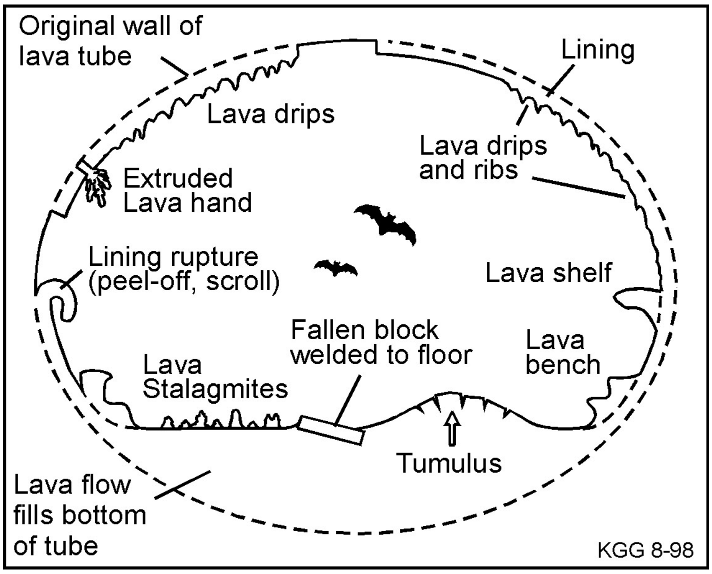


Figure 1.15

Complex lava caves formed by the progressive development and draining of multiple thin lava lobes.

After Grimes, 1999

Figure 1.16
Some distinctive features found in lava caves.



Lava caves rarely contain abundant speleothems, but small stalactites and coralloids of calcite and opal may form on the walls and roof from the calcium and silica released as the basalt weathers.

In Australia there are two basalt lava provinces that contain numerous lava caves, the Newer Volcanic Province of Victoria and the McBride Province of north Queensland (Figure 1.6). Isolated lava caves occur in other basalt areas of eastern Australia. The Newer Volcanic Province extends westward from Melbourne to just over the South Australian border (about 15 000 square kilometres) and eruptive activity occurred predominantly in the past 2 million years. The most recent eruption was probably 4000–5000 years ago at Mount Schank. Lava caves are scattered through the province. The most extensive are the lava tube systems of the Byaduk Caves in the Harmon Valley flow from Mount Napier, and the short but complex tubes in flows on either side of a major lava channel at Mount Eccles.

The McBride Basalt Province lies about 250 kilometres northwest of Townsville, and is smaller (about 6000 square kilometres) than the Newer Volcanics Province; volcanic activity started 8 mya, and the most recent lava flows are probably less than 10 000 years old. Within the 190 000-year-old basalts erupted from Undara Volcano are more than 60 caves representing very well preserved segments of two major tube systems extending 20–25 kilometres from the volcano.

The oldest Australian lava cave is in southeast Queensland, where a small remnant of a lava tube is preserved in basalts 22–24-million years old; the original glassy wall lining is still present in places.

Sandstone caves and karst

Quartz is the most common mineral at the earth's surface, mainly because of its great resistance to weathering. Nevertheless, quartz can dissolve slowly under some conditions, and quartz-rich rock types can form caves and surface karren features, in particular solution pans. Examples of karst and caves developed in quartz sandstones are known from the Northern Territory, Queensland and the Sydney area, as well as the Kimberley region of Western Australia, where the sandstone towers of Purnulu (Bungle Bungles) owe their origin partly to solution. Although solution may have been important in the initiation of the sandstone karst features in these areas, in general other processes (for example, mechanical stream erosion) have enlarged them to their present size and shape.

The largest sandstone cave in Australia, Whalemouth Cave in Western Australia, is associated with large grikefields and towers. It is a spacious stream cave, 220 metres long and 120 metres in total depth. The upstream end is fed from a sinkhole in a semi-blind valley and the water runs through in a series of falls, rapids and plunge-pools to emerge from a large opening (45 metres wide and 60 metres high) part way up a cliff.

Large collapse dolines, up to 50 metres wide and 15 metres deep, occur in lateritised Cretaceous sandstones and claystones of the Sturt Plateau in the central Northern Territory. Although these have been attributed to solution of the sandstones, collapse of caves in the underlying limestone/dolomite could be responsible.

Caves in granite

These caves result from weathering processes that are concentrated along joints (cracks) in the rock. Water seeping through the joints reacts with the biotite (black mica) and feldspar grains in the granite, altering these minerals to very fine-grained clay. The other common mineral in granite, quartz, is usually unaffected by weathering. The clay and quartz grains released by disintegration of the granite can be washed away, and this process gradually opens up the joints. The near-surface portion of a granite outcrop is most susceptible to this style of weathering, because with increasing depth, the joints are squeezed shut by the pressure of the overlying rock, and little if any water can percolate along them. Granite outcrops are usually cut by three sets of joints, two vertical sets at right angles to each other, and a subhorizontal set. Over a long period of time, removal of weathered granite along these joints results in the formation of rounded boulders (called tors), which overlie relatively unweathered granite outcrops. If a large amount of material is removed along the joints, the boulders may collapse onto each other.

Most granite caves are mazes developed among tors, which are either more or less in place or in an irregular jumbled pile. At Labertouche, in southern Victoria, a landslide containing a large number of granite tors blocked the floor of a valley. The stream within the valley has since eroded a passage through the boulders. It is easy to become lost in this cave, as it is in many granite boulder caves, because the cave passages are very irregular in shape and orientation, and all parts of the caves tend to look much the same. Two somewhat similar caves occur on Mount Buffalo in central Victoria; visitors can tour one of these, the Underground River.

Within solid granite outcrops, few joints ever become enlarged enough to form caves, presumably because the amount of water flowing along most of the joints is insufficient, but some caves do form in this way. Where developed along vertical joints, the passages are generally high, narrow and straight. In other cases, the caves have formed along inclined joints subparallel to the rounded surface of the outcrop, and are characterised by low, laterally extensive passages. Occasionally, these caves can capture surface streams, and mechanical abrasion within the stream can increase the passage size and change its shape. The best-known Australian examples are in Girraween National Park in southeast Queensland. Typically, granite caves contain few speleothems; the most common are small coralloids and stalactites of opal and calcite. Quartz sand often covers the floors.

Piping caves in soils and beneath duricrust layers

In soils and soft alluvial deposits the process of piping can form small caves by physically removing soil material along shallow subsurface conduits, but these are rarely enterable. Saline soils are particularly susceptible to this process, as they contain highly dispersive clay minerals that mix very easily with water. Water seeping through the subsoil can readily remove these clays in suspension; if the flow is forced to follow a particular path by topography or some other influence, a small cave may develop. Dolines may form at the surface, and these caves can occasionally capture surface drainage. Piping caves can form quite quickly (for example, in a single bout of rainy weather), and tend to have narrow, unstable passages. Because the host material is unconsolidated, they may change rapidly. They can be a problem in earth-walled dams, and relatively extensive piping caves are present in alluvium along Flagstone Creek in southeast Queensland.

More extensive caves can form by a similar process occurring beneath duricrusts, which are near-surface layers that form by cementation of, in general, the lower part of a soil profile. The cementing material can be silica, iron oxides and hydroxides, or calcite, and the duricrusts so formed are called silcretes, ferricretes (also known as laterites) and calcretes respectively. Duricrusts often form extensive, subhorizontal layers that are resistant to weathering and are very common in the Australian landscape; silcretes are particularly obvious as they cap many of the mesas (small plateaux) in central Australia.

The process of cave formation beneath duricrusts is the physical removal of the underlying, relatively unconsolidated material by piping. This typically forms overhangs along cliff-lines, but the hard roof occasionally allows more extensive, generally very low passages to develop, like those of caves near Ravensbourne in southeastern Queensland, Wedding Present Cave near Banana in central Queensland, and at Chittering in Western Australia.

SEA CAVES

Sea caves develop in cliff-lines along coasts, predominantly by mechanical processes rather than solution; nevertheless, sea caves can be present in limestone. For sea caves to form there must be appropriate bedrock structure and sufficient wave energy. Sea caves are mostly excavated along weaknesses within the rock, such as joints, bedding planes, faults or easily weathered rock types (for example, subvertical igneous dykes intruding the sandstone cliffs around Sydney). In addition, the bedrock must be sufficiently strong that the roof does not collapse as the cave develops.

The main agent of sea cave formation is wave energy. Breaking waves compress the air and seawater trapped in narrow cracks within the bedrock, and this hydraulic action can break off grains or whole blocks, which are then washed away. Waves also mechanically abrade the rock, continually tumbling sand and pebbles against the cliff-face. In addition, the rock may be weakened by water seeping out of joints in the bedrock, weathering the surrounding material, and by seawater evaporating from an exposed rock face, forming salt crystals that wedge apart the grains of the bedrock. Many of the animals that live on shore platforms can bore into, abrade or even dissolve the rock, and can remove surprising amounts of material.

Sea cave passages vary in size and shape. If the controlling influence on cave development is a narrow, subvertical structure (for example, joint, dyke), then the passage is typically high, narrow and straight. If a particular layer within the cliff is being preferentially eroded, then passages may be much wider and more complex in plan.

Sea caves are most common on high-energy cliffed coasts, particularly if the continental shelf is narrow and the tidal range is small, so wave energy is not dissipated. The southern Australian coast, which is subject to very high wave energies, contains numerous sea caves. Some of the best known are on the Tasman Peninsula, Tasmania, and around Sydney, but there are many sea caves along the Victorian coast, on Kangaroo Island, South Australia, and in the cliffs on the edge of the Nullarbor Plain. On the granite coastlines of north Queensland sea caves are common, but generally represent the interstitial spaces between granite tors.

Over the past million years there have been several rises and falls in sea level as the glaciers have retreated and advanced, so sea caves have formed at sea levels both higher and lower than at present. Drowned sea caves are known around Jervis Bay, New South Wales, and high-level sea caves are preserved at Cape Bridgewater in western Victoria.

Sea caves are occasionally well decorated with calcite speleothems, either when they have formed within limestone, or when limestone overlies the rock in which they have been excavated. Occasionally, wave erosion of a sea cliff breaks into a pre-existing limestone cave. This has happened at Tantanoola Cave, in southeastern South Australia; the cave has abundant calcite stalactites, and on the floor are well-rounded beach gravels with seal bones.

FISSURE CAVES

Behind the sandstone cliffs of the Sydney area are numerous high, narrow fissures that may be partly roofed by fallen sandstone boulders. These caves formed when large blocks of sandstone slid a small distance downhill over an underlying bed of shale, often rotating as they did so, and opening narrow fissures with matching surfaces on opposite walls. The clay content of the underlying shale makes it slightly slippery, particularly after heavy rain.

References

There was an editorial decision not to include references to the literature within the book chapters.
The book has a small ‘further readings‘ section which has limited relevance to this chapter.
I have, therefore, added a list of papers of interest on the following pages.
This is not complete, but will give you an introduction to the literature.

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