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Epikarstic Maze Cave Development: Bullita Cave System, Judbarra / Gregory Karst, Tropical Australia

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Abstract

In the monsoon tropics of northern Australia, Bullita Cave is the largest (120 km) of a group of extensive, horizontal, joint-controlled, dense network maze caves which are epikarst systems lying at shallow depth beneath a well-developed karrenfield. The Judbarra / Gregory Karst and its caves are restricted to the outcrop belt of a thin bed of sub-horizontal, thinly interbedded dolostone and calcitic limestone – the Supplejack Dolostone Member of the Proterozoic Skull Creek Formation. Karst is further restricted to those parts of the Supplejack that have escaped a secondary dolomitisation event.

The karrenfield and underlying cave system are intimately related and have developed in step as the Supplejack surface was exposed by slope retreat. Both show a lateral zonation of development grading from youth to old age. Small cave passages originate under the recently exposed surface, and the older passages at the trailing edge become unroofed or destroyed by ceiling breakdown as the, by then deeply-incised, karrenfield breaks up into isolated ruiniform blocks and pinnacles and eventually a low structural pavement.

Vertical development of the cave has been generally restricted to the epikarst zone by a 3 m bed of impermeable and incompetent shale beneath the Supplejack which first perched the watertable, forming incipient phreatic passages above it, and later was eroded by vadose flow to form an extensive horizontal system of passages 10-20 m below the karren surface. Some lower cave levels in underlying dolostone occur adjacent to recently incised surface gorges.

Speleogenesis is also influenced by the rapid, diffuse, vertical inflow of storm water through the karrenfield, and by ponding of the still-aggressive water within the cave during the wet season – dammed up by "levees" of sediment and rubble that accumulate beneath the degraded trailing edge of the karrenfield. The soil, and much biological activity, is not at the bare karren surface, but down on the cave floors, which aids epikarstic solution at depth rather than on the surface.

While earlier hypogenic, or at least confined, speleogenic activity is possible in the region, there is no evidence of this having contributed to the known maze cave systems. The age of the cave system appears to be no older than Pleistocene.

Details of the speleogenetic process, its age, the distinctive nature of the cave systems and comparisons with other areas in the world are discussed.

Keywords: Tropical monsoon karst; network maze caves; epikarst; karren.

INTRODUCTION

The Judbarra / Gregory Karst (previously known as the Gregory Karst) lies at 16° south latitude within the Judbarra / Gregory National Park in the Northern Territory of Australia (Figure 1). It is an area of extensive network maze caves and well developed karrenfields at least 30 km long associated with a localised part of the Skull Creek Formation that has escaped secondary dolomitisation (Figure 2).

Serious cave exploration began in 1990 with the Operation Raleigh Expedition (Storm & Smith, 1991). Parts of Bullita Cave were first discovered in 1992 (Kershaw, 2005a,b, 2012). The Bullita Cave System is an unusual cave network enclosing more than 120 km of surveyed passages, making it a major system by international standards. Other caves to the north and south of the Bullita Cave System, including the Dingo Cave System (about 34 km of surveyed passages), are of a comparable nature, and the area as a whole had almost 220 km of mapped cave passage by 2011 (Kershaw, 2012). The cave systems have been described and speleogenetic models have been proposed in several short papers (Storm & Smith, 1991; Dunkley, 1993, Bannink et al., 1995; White & White, 2009). This report summarises the previous published information, and presents the authors' observations and opinions about the speleogenesis of the Bullita Cave System and the Judbarra / Gregory Karst area in general.

Climate and paleoclimates

The present climate is tropical monsoon with strongly seasonal contrasts (Figure 3; BOM, 2011a): very dry most of the year, but with a wet season from November to April, when the temperature varies from 24°C to 38°C (Dunkley, 1993). The annual rainfall at Bullita homestead is 810 mm (BOM, 2011a), falling in heavy bursts. Annual potential evapotranspiration is about 2000 mm (BOM 2011b). Consequently, the vegetation is a parkland savanna type, with narrow 'gallery forests' along the main streams.

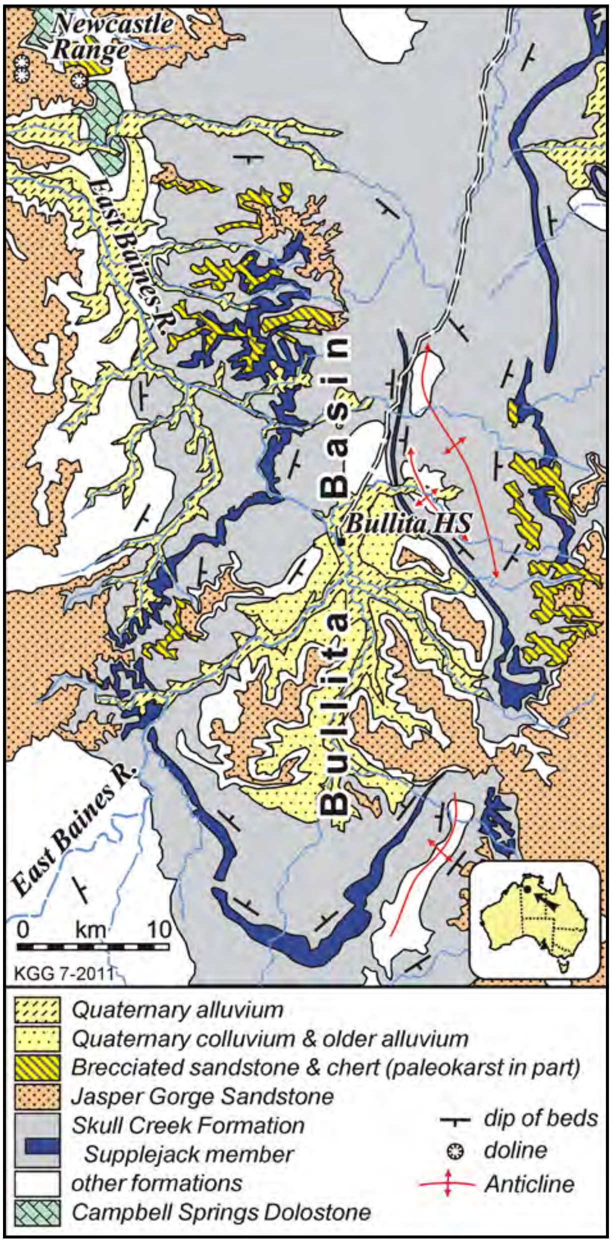

Figure 1: Geology of the Bullita Basin, Judbarra Karst area. Based on the Auvergne and Waterloo geological sheets (Dunster et al., 2000 and Sweet, 1973).

When considering the effect of climate on karst development one must allow for variations during the Pliocene and Quaternary. If only the recent past is considered, the study of the tufa deposits in Limestone Gorge indicates that drier and wetter periods alternated (Canaris, 1993), and a wetter climate may have prevailed 8-10 ka.

Information about earlier climatic conditions have been deduced from isotopic compositions of organic carbon in the sediments of Gregory Lake, situated 470 km to the SSW of Bullita (Pack et al., 2003), where the climate is presently semi-arid (rainfall: 300 mm/y, grass-land). The investigated lake section was 9 m thick and comprised the largest part of the Middle Pleistocene up to Recent, that is several 100 ky. The authors showed that the deepest strata recorded the wettest conditions of the stratigraphic section, with the land then covered by a closed-canopy forest. The dry conditions developed progressively after about 100 ka and more drastically in the last 20 ka. A wetter past climate is also indicated by terraces 20 m above the level of the present day Gregory Lake, which encompassed 4500 km^2 instead of 294 km^2

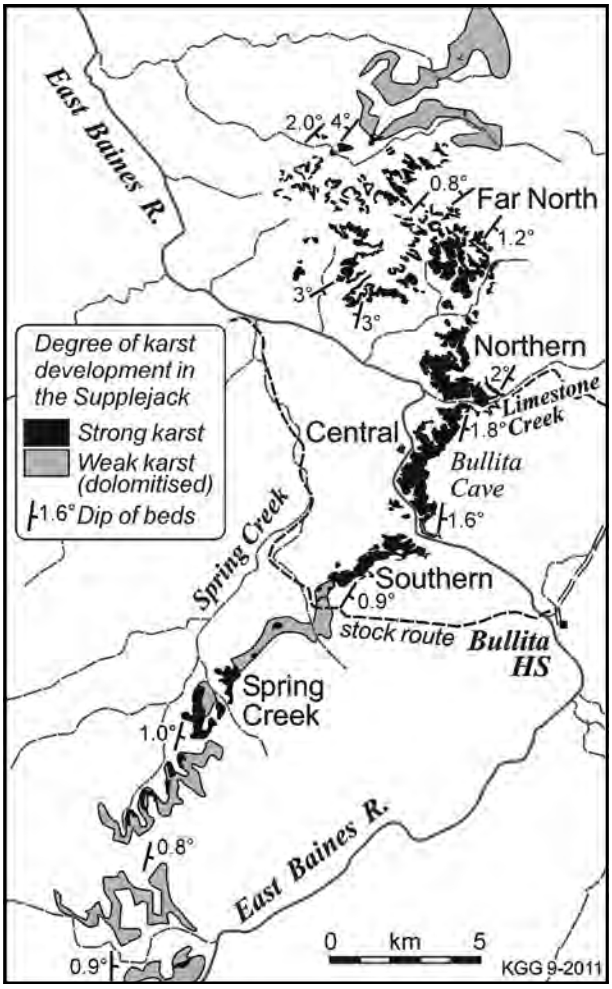

Figure 2: Location of the currently known extent of the Judbarra Karst, with named sub-areas. Based on air-photography and satellite imagery.

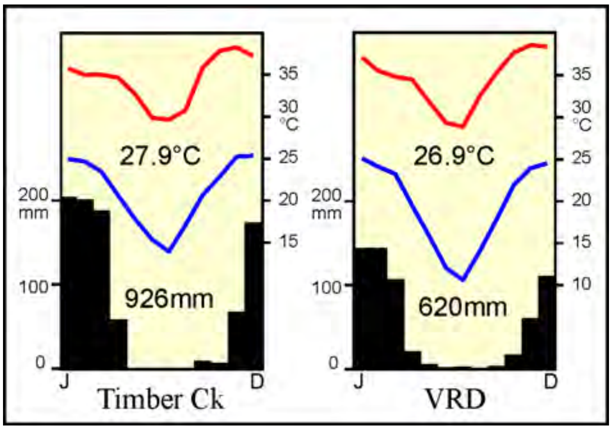

Figure 3: Climate charts for stations near the Judbarra karst. Monthly mean maximum & minimum temperature and monthly rainfalls, with annual averages in figures, are shown for Timber Creek, 50 km to the north, and Victoria River Downs (VRD), 70 km to the east. Data from BOM (2011a).

today. Since the Bullita area is situated much closer to the northern coast of Australia, it is reasonable to expect that at Bullita the climate was then also wet, probably even wetter than it was at Gregory Lake, with rainfalls in excess of one metre. Pack et al. (2003) also suggest that the rainfall was more widely distributed during the course of the year. During the last 2 million years the glacial-interglacial cycles caused an alternation of humid (interglacial) and dry (glacial) periods throughout the monsoon tropics (Kershaw et al., 2003).

Geology

The Judbarra / Gregory Karst area is developed in the gently dipping, unmetamorphosed Proterozoic Skull Creek Formation, 150-170 m thick and 1.6 Ga old (Sweet 1973, Beier et al., 2002; Figure 1). It mainly consists of centimetric to decimetric platy layers of carbonate and calcareous siltstone, with millimetric shale interbeds. Silicification occurs in places, forming chert nodules, but is not widespread. Thicker beds (typically 1 m) of massive carbonate are inter-stratified at regular intervals of a few metres, a setting typical in the upper part of the formation. One of these carbonate beds is much thicker (15-20 m) and constitutes the Supplejack Dolostone Member, which, together with an underlying shale bed, controls the formation of the Bullita Cave System (Figure 4).

Lower Skull Creek Formation

The Lower Skull Creek is about 120 m thick, but of main interest here is the top 20-30 m, which immediately underlie the Supplejack Dolostone Member, and which consists mainly of very-fine-grained, ivory-coloured, well-bedded dolomicrite. It has mostly been sampled on surface exposures, with the exception of three chips collected in the southernmost section of the Bullita Cave system (SOGS area, Figure 5). The carbonate generally consists of close to 100% dolomite, although 5 samples, out of a total of 19 collected, revealed 40 to 90% calcite (visual estimation of etched samples under the binocular microscope). The calcite-rich parts form thin seams interstratified in dolostone. Chert nodules are observed frequently.

Several thin (1-2 m) siltstone and shale beds are interstratified within the Lower Skull Creek, but only two significant ones have been observed in the caves. At the surface they are generally concealed under soil cover, but they are well exposed in the caves. The most important of them, the '**Upper Shale Marker**', lies immediately below the Supplejack Dolostone Member. It is about 2.5 m thick, well developed in both the Dingo Cave System (Bannink et al., 1995) and in Bullita Cave (Figure 6). At its base and on top there are massive dolomitic mudstone beds, 30 to 50 cm thick, which bracket a well bedded alternation of thin layers of calcareous siltstone and shale that are incompetent and easily eroded. A second shaly layer, the '**Lower Shale Marker**' occurs 10 m further down (Figure 12d).

Figure 4: View to west along the southern edge of Limestone Creek gorge, showing the karren field developed on the Supplejack Member and overlain by the Upper Skull Creek Formation, which has thin carbonate beds (dark bands) alternating with grassed slopes developed in the soft shale beds. [KGG]

Supplejack Dolostone Member

The Supplejack Dolostone Member has a distinctive outcrop pattern of cliffs and karrenfields that allows it to be easily identified and mapped (Figure 1). When seen from a distance, the 15 to 20 m thick unit appears massive, but in detail it shows a laminated to thin bedding (a few millimetres to hardly more than a decimetre thick, Figure 7). The beds are due to a well stratified alternation of dominantly dolomicrite and of dominantly calcitic limestone, generally also micritic. Quantitative estimations of 22 etched samples suggest a bulk average mineral composition of about 75% calcite (varying from 5% to nearly 100%), the remainder being mainly dolomite. Therefore, it appears that in the cave area the Supplejack carbonate may be classified as a dolomitic limestone. Paper-thin siltstone and clay seams are often inter-stratified at stratigraphic intervals of a few decimetres to more or less one metre.

The limestone portion is micritic, dark bluish grey. It may be entirely calcitic, but generally contains a small amount of very fine dolomite crystals disseminated in the calcitic matrix. The dark colour is due to organic matter, which is particularly abundant in the lower part of the member, where a foetid smell is produced when the rock is freshly broken.

In the field the dolomitic seams are easily distinguished from the limestone by their lighter colour (Figure 7). These lighter beds contain 50 to 100% of very fine dolomite (syngenetic or of early diagenesis), the balance being essentially calcite that constitutes the matrix of the tiny dolomite crystals (10 to 50 microns). When these beds are thicker, that is more than 3 cm, they are affected by syneresis cracks (Beier et al., 2002) filled with pure micritic limestone of the same nature as the associated limestone beds (Figure 7). These filled cracks, possibly developed during brief dessication phases following dolomitisation, represent 10 to 20% of the volume of the dolomicrite seams.

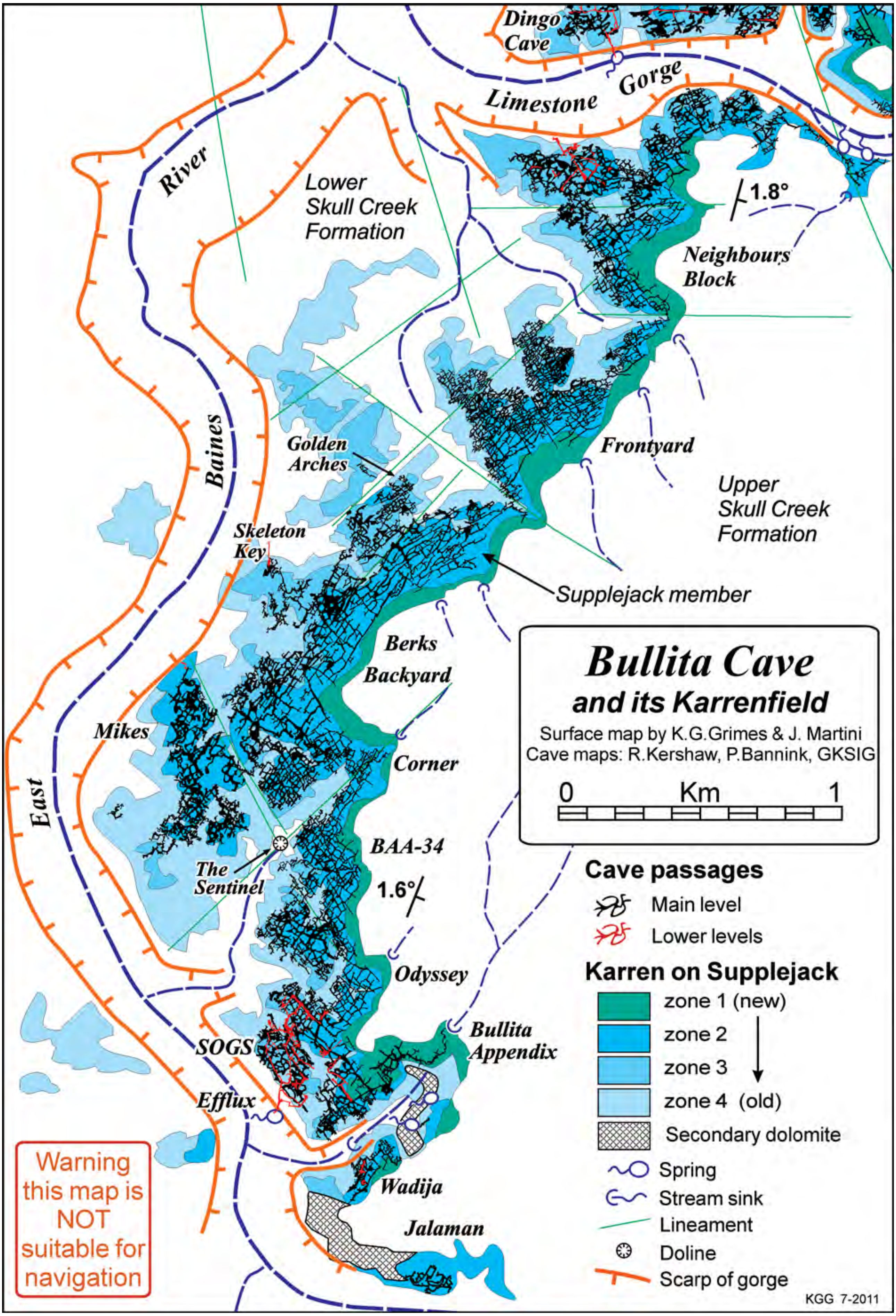

Figure 5: Bullita Cave and its karrenfield. Compilation from cave maps by Kershaw and Bannink, and personal field observations. *View Google Earth at 16° 3.8'S, 130° 23.0'E, Eye-height 13000m.*

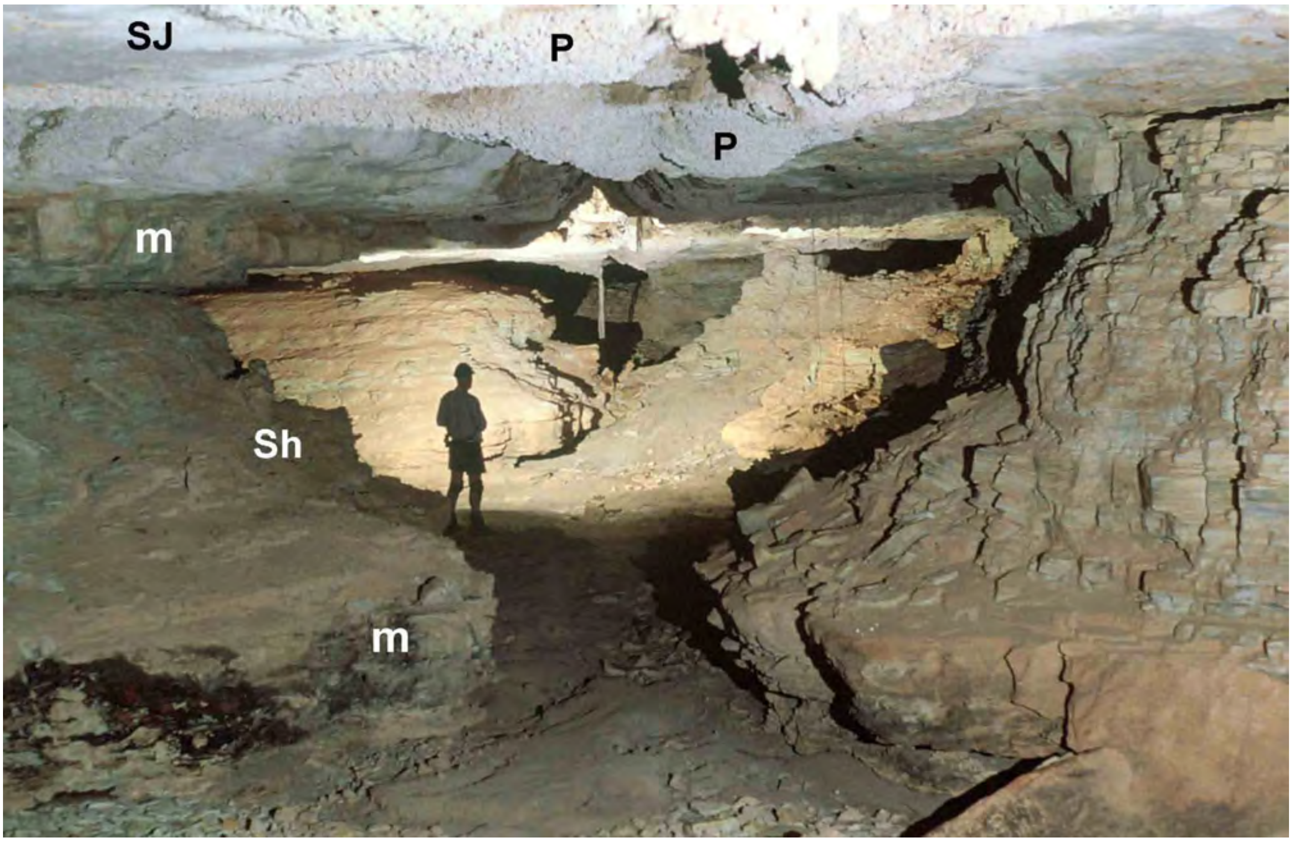

Figure 6: Shale passage (cf. Figure 18e). Note entire thickness of Upper Shale Marker is exposed (Sh), limited at base and on top by more massive mudstone (m). Horizontal ceiling is base of the Supplejack carbonate (SJ). Note popcorn (P) deposited on both sides of initial crack in ceiling. Three Presidents area, in Neighbours Block, Bullita Cave System. [JEJM]

Figure 7: Texture of Supplejack carbonate. Micritic limestone is bluish grey and dolostone is reddish-brown. Limestone forms seams and fills syneresis cracks, standing in relief with respect to dolostone. Passage wall in Frontyard section of Bullita Cave System. [JEJM]

Figure 8: Chert Marker (to left of upper caver) at main entrance of Mike's section. On top note absence of stromatolitic domes, already removed by dissolution. At bottom chaotic accumulation of blocks in collapse structure. [JEJM]

Figure 9: Large stromatolite domes on top of the Supplejack Member have been recently exposed by erosion of the soft shale of the Upper Skull Creek Formation. Note there is only incipient karren development here, at the leading edge of karren zone 1. [KGG]

Both the limestone and the dolostone often show millimetric to centimetric primary cavities filled with sparite, probably developed during a late diagenetic stage. In this case the dolomite and calcite crystals are larger, up to one millimetre or more. Very small (~0.1 mm) authigenic, hyaline, bipyramidal quartz crystals have been occasionally observed dispersed in the carbonate.

The Supplejack Dolostone Member contains two widespread stratigraphic markers, which are easily identifiable in the field, even at a distance. One is a 2-3 m thick zone, particularly rich in small chert nodules, that occurs 3 to 4 metres above the base of the member (Figure 8). The second is a 2-3 m thick stratigraphic interval of large stromatolite domes marking the top of the member. They are particularly spectacular on the upper surface of the Supplejack, where large domes 5-12 m across and 1-2 m high are exposed by the erosion of the overlying brown siltstones and shales of the upper Skull Creek Formation (Figure 9).

Secondary dolomitisation in the Supplejack

Apart from the syngenetic dolostone described previously, the Supplejack Dolostone Member locally underwent younger secondary dolomitisation, which may cut across the stratification and irregularly invades the member. This seems extensive elsewhere in the region, but in the Bullita Cave System it is generally absent except for the southernmost extremity of the cave (Figure 5). The dolomitised rock can be easily recognised in the field by its coarser crystalline texture (sand sized, 0.1 to 1 mm), its whitish colour, the depressed topography and the lack of well developed karren. Its extent can be mapped from aerial photographs and Google Earth satellite imagery. This metasomatism generally does not affect the original micritic dolostone seams, which can still be distinguished clearly in the field by their much finer texture. At the southern end of the cave system, where the secondary dolomitisation reaches the top of the member (Figure 5), one observes veins and irregular cavities filled with calcite, dolomite and barite. The barite forms up to 5 cm long radiating [001] blades. Very porous, brittle, ferruginous gossanous material, possibly developed after sphalerite weathering, also has been observed. At least here, the secondary dolostone is therefore of hydrothermal origin and is perhaps contemporaneous with the lead mineralisation regionally observed in the Supplejack Dolostone Member (Sweet, 1973; Dunster et al., 2000; Beier et al., 2002) and which might be related to the Mississippi Valley Type.

It is worth noting that the type section for the Supplejack Dolostone Member was measured in an area of strong secondary dolomitisation (where the Bullita Stock Route crosses the member, Sweet (1973), see Figures 2 and 17). This might explain why this member has been commonly described as a dolostone by the geologists who mapped the area (Sweet, 1973, Beier et al., 2002). Indeed, they wrote that the dolostone was ‘medium or coarsely crystalline, probably recrystallised’ and that ‘primary finer texture is preserved only in some areas’. Thus we have retained ‘dolostone’ in the formal stratigraphic name as that would seem to be the dominant lithology at the regional scale, even though not within the karst area.

Based on Google Earth imagery, to the southwest of the stock route it is possible that the member is heavily dolomitised over a strike length of 4.5 km, until the limestone reappears in the Spring Creek Karst (Figure 2). Similarly it is possible that further south, as well as along the eastern limb of the Bullita Basin, the secondary dolomitisation has affected the Supplejack extensively. Its real extent, however, remains to be ascertained in the field.

Upper Skull Creek Formation

The Upper Skull Creek, 30-40 m thick, differs considerably from the sequence below the Supplejack. It consists of a rhythmic alternation of more or less 1 m thick beds of slightly dolomitic limestone (10-35% dolomite), and about 3 m thick beds of calcareous siltstone and shale which are generally poorly exposed. However, two thicker beds of limestone (3-4m) have been mapped 20 to 30 m and 40 m higher up in the sequence. They are widely extensive within the Bullita Basin (e.g. Figure 17, and figure 4 of Grimes, 2012a).

Paleokarst Sandstone

In the Far North area (Figures 2, 10), belts of loose, brecciated quartz sandstone fill linear trenches which are unconformably inset into undisturbed outcrops of the Skull Creek Formation (Grimes, 2012b). They are interpreted by Grimes (2012b) as a paleokarst breccia, possibly formed from deposits of the younger Jasper Gorge Sandstone that subsided into structurally controlled solutional cavities in the Supplejack. Similar material may occur on the ranges to the south of the Spring Creek area. This breccia must postdate the Jasper

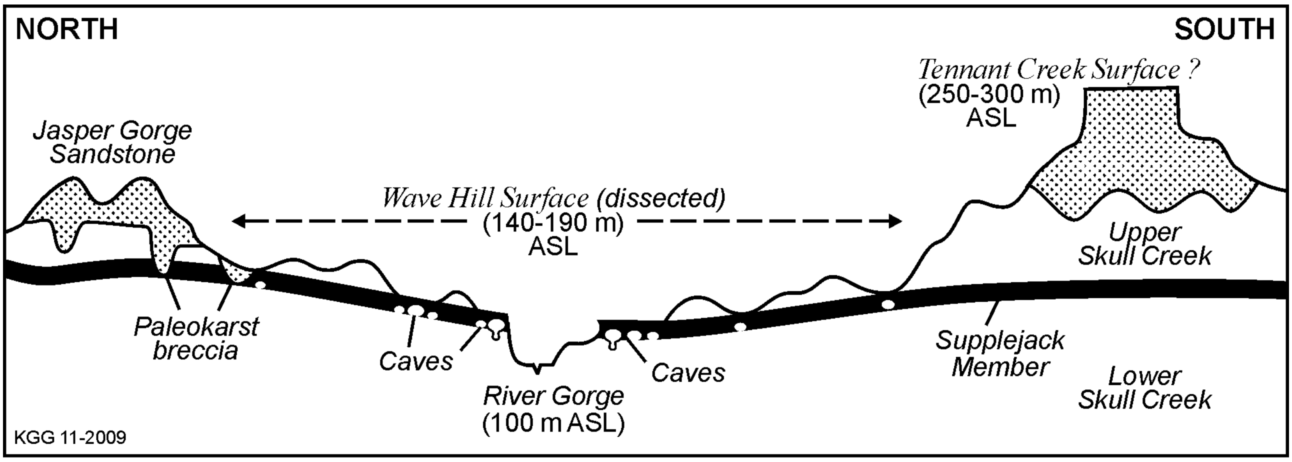

Figure 10: Schematic profile showing relationships between old land surfaces, stratigraphy and cave development in the Judbarra / Gregory Karst.

Gorge Sandstone (about 850 Ma, Dunster et al., 2000), and the loose nature of the breccia suggests a relatively young age. However, it must pre-date the present erosional cycle as the modern valleys are cutting across the paleokarst belts.

Structure

At a regional scale the Supplejack Member lies within a N-S elongated structural basin, about 50 km long, and 30 km wide, referred to here as the Bullita Basin (Figure 1). The main karst areas are on the western side of this basin, where dips are gentle, generally less than 2 degrees, except in the Far North area where dips are up to 4 degrees and there are several broad anticlines and synclines along NE-SW axes (Figure 2). On the eastern side of the basin the Supplejack displays steeper dips. In the cavernous area where the Bullita Cave System is developed, the structure is regularly monoclinal, with the strata dipping 1.2 to 1.8° ESE, that is close to horizontal.

The most prominent jointing directions, which are well defined on aerial photographs, are about 035° and 135°, less commonly 095° (figure 4 in Grimes, 2012a). At outcrop scale these three joint sets are well marked in the well bedded dolostone of the Lower Skull Creek Formation, which disintegrates into triangular and rhombic slabs, and they also control the grikes in the karrenfield of the Supplejack. Some of the most prominent lineaments visible on aerial photographs may be faults, but with displacements of not more than a few metres. For instance, in the Golden Arches area a vertical displacement of 2-3 m has been observed in the NE oriented fault separating the northern part of Berks Backyard from the block of karst developed to the NW of it (Figure 5).

The land surface, present and past

The present topography results from the dissection of old peneplains by an integrated network of valleys. It is flat to hilly, except for steeper slopes and cliffs along the incised East Baines River and some of its most important tributaries such as Limestone Creek and the creek south of SOGS (Figure 5), but this incision does not extend more than a few kilometres upstream. Next to the Bullita Cave System the main stream, the East Baines River, flows northward at an altitude of about 100 m above sea level. The Bullita Cave and karrenfield are developed between the altitudes of 110 m and 145 m (Figure 10).

At a smaller scale, the strata resistant to erosion are the carbonate beds, which form small stepwise escarpments. These scarps are moderately prominent in the Lower Skull Creek. The most spectacular cuesta, however, is formed by the Supplejack Dolostone Member. The thin limestone beds of the Upper Skull Creek protrude as obvious regularly-spaced scarplets (Figure 4).

At a broader scale, there are several old land surfaces recognisable that could assist in the interpretation of the denudation history of the area (Figure 10). In a regional study of old land surfaces in the Northern Territory, Hayes (1967) mapped residuals of his late Cretaceous to early or mid Tertiary ‘Tennant Creek Surface’ in this area. This could correspond to the surfaces at the top of the ranges, about 220-250 m ASL in the Far North area and 270-300 m ASL in the far south. However, the southern plateaux are, in part, structurally controlled by the top of the resistant Jasper Gorge Sandstone, so some caution is needed in interpreting these as old land surfaces (Figures 1 & 10).

Hayes also mapped a lower ‘Wave Hill Surface’ of possible Miocene to Pliocene age, which might correspond to the lower gently undulating surface seen on either side of the East Baines River, at an elevation of 140-190 m ASL (Figure 10). This lower surface predates the incision of the present gorges of the river and Limestone Creek to about 100 m ASL.

The present gorges of the river and Limestone Creek suggest that there has been a recent phase of channel incision that might not have had a great deal of associated valley widening. ‘Recent’ must, however, predate the 8-10,000 BP dates on the older tufa deposits within Limestone Gorge and in an unnamed creek to the north west (Canaris, 1993).

DESCRIPTION OF THE KARST AND CAVES

Overview of the Judbarra/Gregory Karst

The Judbarra/Gregory Karst is the area of well-developed karst and caves associated with the Supplejack Dolostone Member of the Skull Creek Formation. Given that much of this is still poorly explored, the extent of the area is liable to change in the future, but for now the description will concentrate on the western side of the Bullita Basin (Figure 1). The component karst areas are in a strip about 30 km long, shown on Figure 2, but the best development and largest maze caves are in a 10 km belt that includes the Northern, Central and Southern karst areas. This paper concentrates on the Bullita Cave System of the Central Karst. The other areas are summarised briefly below, and the most informative ones are described in more detail later.

The Far North

This terrain has stronger relief than to the south with a more complex drainage pattern and so the outcrop belt of the Supplejack is narrow and forms a convoluted and discontinuous karrenfield (Figure 2). Karrenfields are reasonably well developed, but the narrow belts of exposed limestone reduce the potential for large maze caves. Nonetheless, several caves have been found on reconnaissance trips to the south-east of the area.

The Northern Karst area

A three kilometre long belt of meandering but continuous karrenfield lies to the north of Limestone Gorge (Figure 2). The karren are well developed (Figure 11) and overlie a set of large maze caves which total 34 km of passage length (Storm & Smith, 1991; Bannink et al., 1995; P. Bannink, pers. comm. 2006; Kershaw, 2012). The Dingo Cave system is of particular interest as it has four levels of development, and these are much more extensively developed than in Bullita Cave (Bannink et al., 1995). The northern part of the area is still incompletely explored.

The Central Karst area

This central part of the belt, the main topic of this article, runs for five kilometres between Limestone Gorge and the East Baines River, where it crosses the Supplejack outcrop belt (Figure 5). The northern boundary is the gorge of Limestone Creek (Figure 4) where the Supplejack forms vertical limestone cliffs. To the west the East Baines River is also incised into a gorge with intermittent cliffs. The land surface is a gently undulating plateau, possibly a part of the Wave Hill Surface (Figure 10), that lies 50-60 m above the stream-beds of the East Baines River and Limestone Creek. The karrenfield is broad and well-developed and underlain by the Bullita Cave maze system, with about 120 km of surveyed passage length in 2011, and several smaller caves that are not connected to the main system.

The Southern Karst area

A four kilometre long karrenfield runs south-west from the East Baines River (Figure 2). This has three significant maze caves, e.g. Claymore Cave at 6 km total passage length (Storm & Smith, 1991), but the area is still incompletely explored (Kershaw, 2012). The south-western end of the area, 1 km to the NE of the Bullita Stock Route, is defined as the point where well developed karst ceases as a result of secondary dolomitisation (see page 42) and is replaced by the 'mini-tower karst' (Figure 17).

The Spring Creek area

Much of this section of the Supplejack has only poor karst development as a result of secondary dolomitisation, but a few areas occur with better quality karren and cave systems (Figure 2). One part of this area, the Spring Creek Karst, will be treated in more detail in the section dealing with the caves description (page 53).

The East Baines River Valley (upstream section)

South across the divide and into the valley of the upper part of the East Baines River the Supplejack may have been extensively modified by secondary dolomitisation (Figure 2). This and the narrow outcrop width has inhibited karst development apart from a few small areas of karren and one known cave (BAA39, with 450 m of passage).

The Newcastle Range Karst

This area is about 30 km northwest of Bullita Cave (Figure 1). Several large collapse dolines occur on the top of a plateau of Jasper Gorge Sandstone, and are described by Grimes (2012b). The geological map (Dunster et al., 2000) shows that the sandstone is underlain at depth by the Campbell Springs Dolostone so the sinkholes are probably a subjacent karst effect. This area is in a separate geological setting and should not be considered as part of the Judbarra Karst.

Surface karst morphology

Evidence of superficial karst dissolution, mainly in the form of karren, is widespread on the Skull Creek Formation. Other classic superficial features such as funnel-shaped dolines, poljies or swallow-holes are missing or rare. At a large scale the morphology is characteristic of a fluvio-karst with an integrated surface drainage (Dunkley, 1993). The distinction between mesokarren, megakarren and microkarren is important as these have different distributions in the area (Grimes, 2012a). The best mesokarren by far are developed on the Supplejack dolomitic limestone and megakarren are restricted to this unit. Outside the Supplejack Dolostone Member there are well-developed microkarren in the upper part of the Skull Creek Formation (Grimes, 2007, 2009), but little mesokarren except on the occasional thicker bed mentioned above. The karren of the Judbarra/Gregory Karst are discussed in more

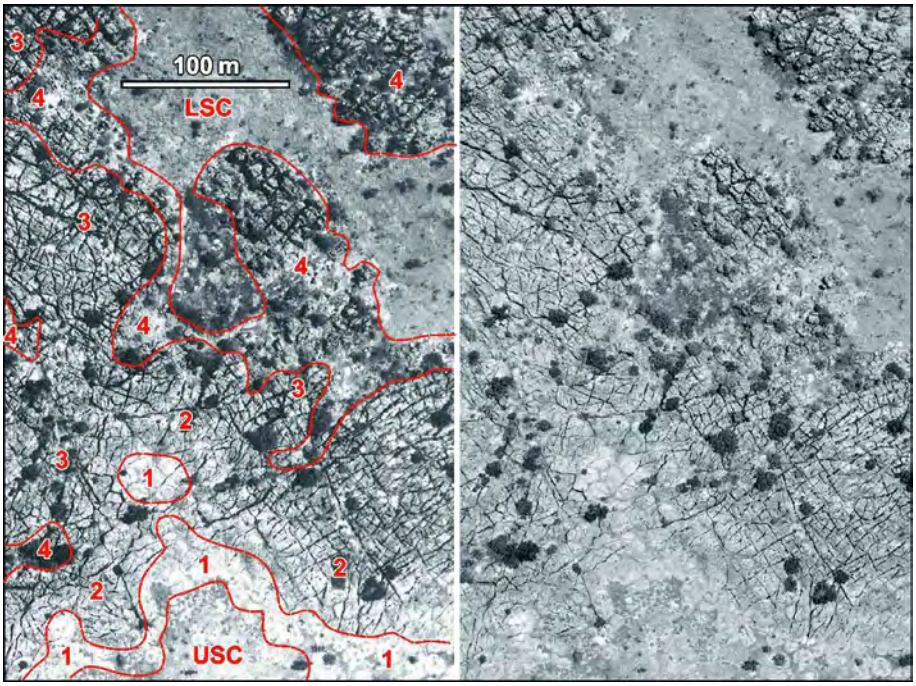

Figure 11: Stereo air photos of the karren field above Dingo Cave (Northern Karst Area), showing the zones 1-4.

LSC is Lower Skull Creek,

USC is Upper Skull Ck

detail elsewhere (Grimes, 2009, 2012a), so here we will concentrate mainly on the relationship between the karrenfield and the cave development.

The karrenfield forms a contorted and irregular band which is spectacularly displayed on aerial photographs and satellite imagery. Its width varies from 100 m to 900 m and the section hosting the Bullita Cave System is 4 km long and roughly oriented north-south (Figure 5). That section is interrupted in the north by the gorge of Limestone Creek and in the south by the East Baines River, but continues for several kilometres beyond to the north and south-west (Figure 2). As the very gentle dip of the Skull Creek is eastwards and as the general slope of the land is westwards, the denudation of the Supplejack from beneath its Upper Skull Creek cover proceeds eastwards.

The Supplejack is more mechanically resistant to erosion than the Upper Skull Creek Formation. The limestone beds of the latter only form small scarplets and the benches are too thin to have developed a well marked karst morphology before being eroded away. The surface of the Supplejack is almost entirely rocky,

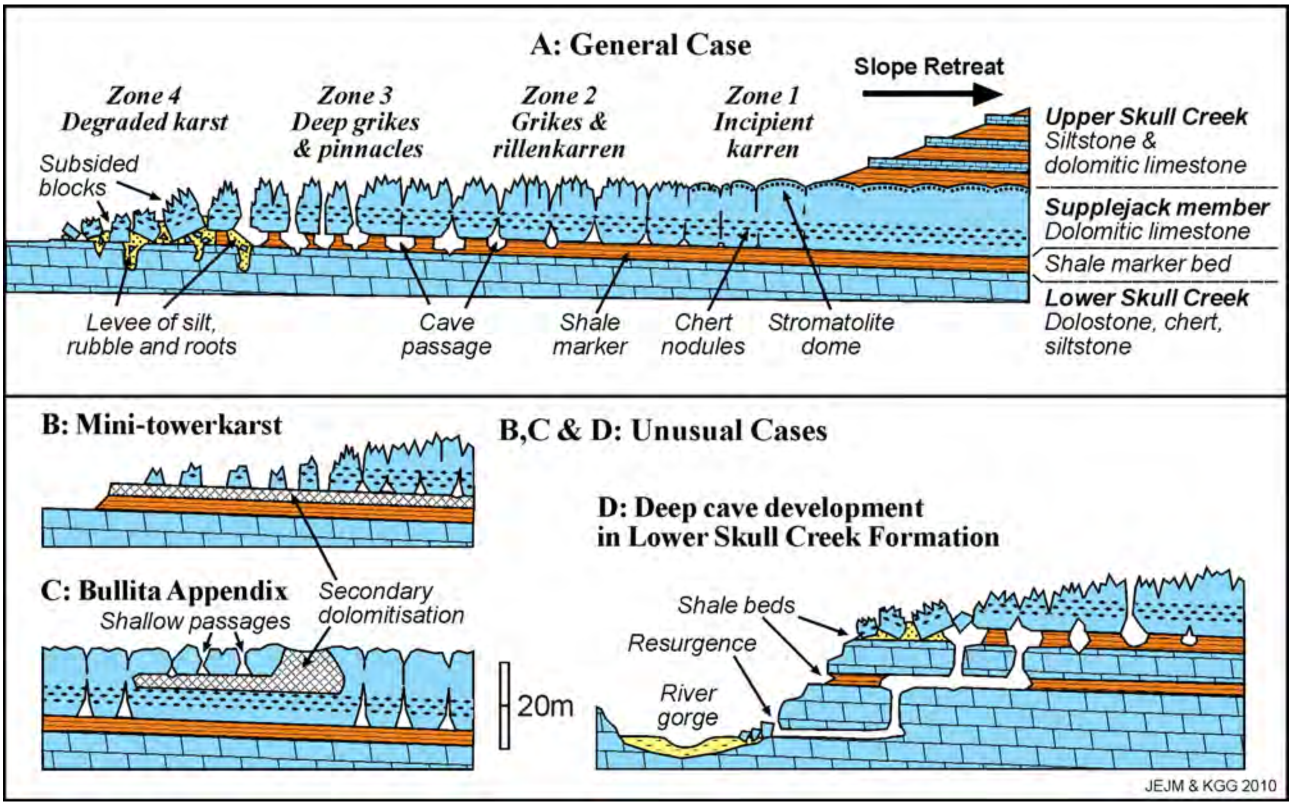

Figure 12: Idealised profiles of the Judbarra karst. Explanation in text. Vertical scale magnified about 3 times.

Figure 13: Residual spitzkarren pinnacles and small towers. Note the cherty marker bed in lower half of of face. Golden Arches, Berks Backyard, central Bullita Cave system. [KGG]

with practically no soil cover and with sparse vegetation. On the Supplejack, under which the Bullita Cave System is formed, one may distinguish four zones of karren morphology, related to the degree of karst development and grading from one to the other (Figures 5, 11 and 12). From east to west, that is, youngest to oldest, they are as follows:

Zone 1: The contact between the Supplejack and the Upper Skull Creek is well defined and sharp. Where the upper unit has been most recently removed by erosion, there is a band generally less than 100 m wide in which the surface is relatively smooth apart from the broad stromatolite mounds (Figure 9). This zone has only incipient mesokarren development (shallow rillenkarren and rainpits, and small narrow grikes), but has well-developed microkarren. Away from the contact, increasing dissection produces small spitzkarren up to 0.3 m high, and grades to zone 2.

Zone 2: Further westwards the exposed surface of the Supplejack becomes more rugged, grading into a classic karrenfield with rillenkarren, kamenitzas, grikes and spitzkarren up to 1 m high (Grimes, 2012a). In this zone the domal stromatolites are progressively dissolved away. There are occasional narrow connections from the grikes to the cave passages below.

The karren morphology is more controlled by its limestone component than its dolostone one, which is quantitatively minor. In most cases the rills reveal no evidence of differential dissolution rates between the limestone and dolostone seams, even though one would have expected dolostone to protrude with respect to limestone since dolomite has a much lower dissolution rate. Under the binocular microscope, however, it appears that the dolomite is in fact standing in relief, but only at the microscopic scale. On the dominantly dolomitic seams, after weathering, the tiny crystals of this mineral form a spongy, friable material, which rapidly disintegrates. This is mainly due to calcitic matrix dissolution. In the case of monomineralic dolostone, however, this apparent similar rate could be due to penetrative dissolution along crystal boundaries, a well known dolomite property. Moreover, this penetrative action can greatly increase the reactive surface, giving a false impression of faster rate, should one only consider the wall surface at a macroscopic scale. Under the binocular microscope it also appears that tiny black particles of organic matter are scattered on the rock surface. They are responsible for the generally dark appearance of the Supplejack outcrops. These particles are probably a remnant from algae or lichen, which were growing during the monsoon season. Other features visible under the binocular microscope are tiny mammillary buds and crusts of opal that have grown on sharp points and karren ridges. The opal results from the dissolution of silicate impurities in the Supplejack carbonates, followed by evaporation to dryness.

Zone 3: The previous zone grades into a field of pagoda-like spitzkarren pinnacles averaging 2 m high, separated by deep grikes developed along the joint system, which makes the surface very difficult to cross. Collapse dolines floored with chaotic large blocks, generated by breakdown of wide chambers, are common. At this stage of the karst development, although about half the volume of the dolomitic limestone has been dissolved, the top of the pinnacles remains stratigraphically not far below the top of the Supplejack, generally not more than 5 to 6 m. In the field the amount of dissolved carbonate above the pinnacles could be estimated visually from the thickness of dolomitic limestone still present above the cherty marker, as for instance at the Golden Arches (Figure 13).

Zone 4: The last and oldest zone is the 'degraded karst', where the dissolution of the Supplejack dolomitic limestone has proceeded further. The surface has

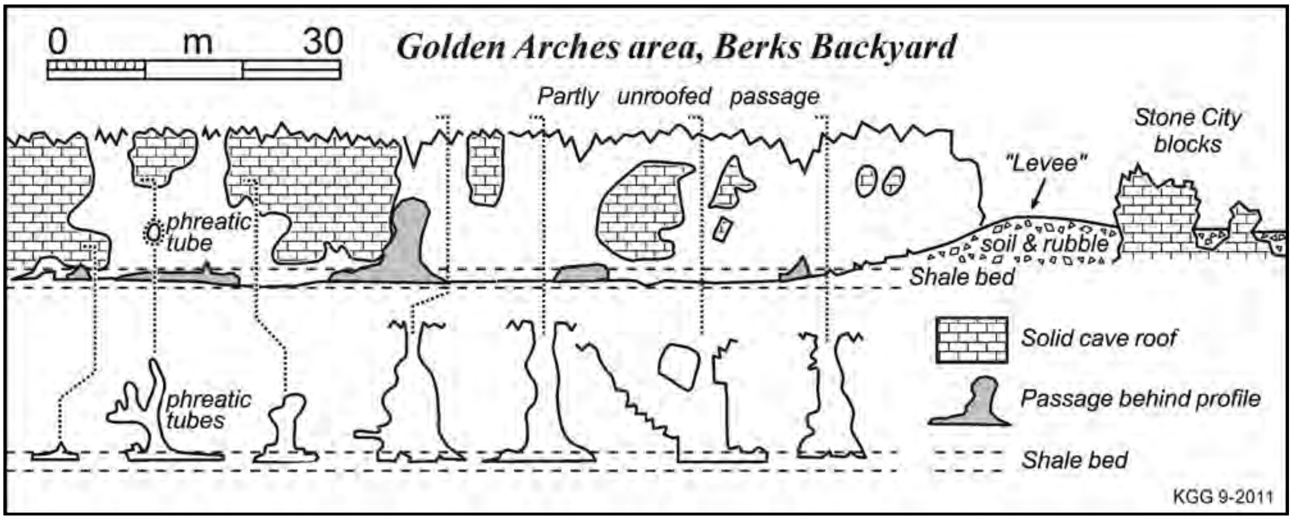

Figure 14 (above) Profile and cross-sections of a partly unroofed passage beneath karren zones 3 and 4 in the Golden Arches area. Note the rubble mound at the right-hand end which would form a 'levee' damming wet season flood-waters within the cave. The surface karrenfield is shown diagrammatically. Figure 15 is a photo of the right-hand end of the passage looking towards the rubble mound.

Figure 15 (left): Partly unroofed cave passage forms a giant grike in degraded karst (zone 4). Mound at rear is the 'levee' material. Golden Arches, Berks Backyard, central Bullita Cave System.
View is looking to right along the profile of Figure 14. [KGG]

Figure 16 (below): Degraded karst (zone 4).
Note rotated blocks resting on undisturbed Lower Skull Creek dolostone (light coloured) in foreground.
NW of the Golden Arches, Bullita Cave System. [KGG]

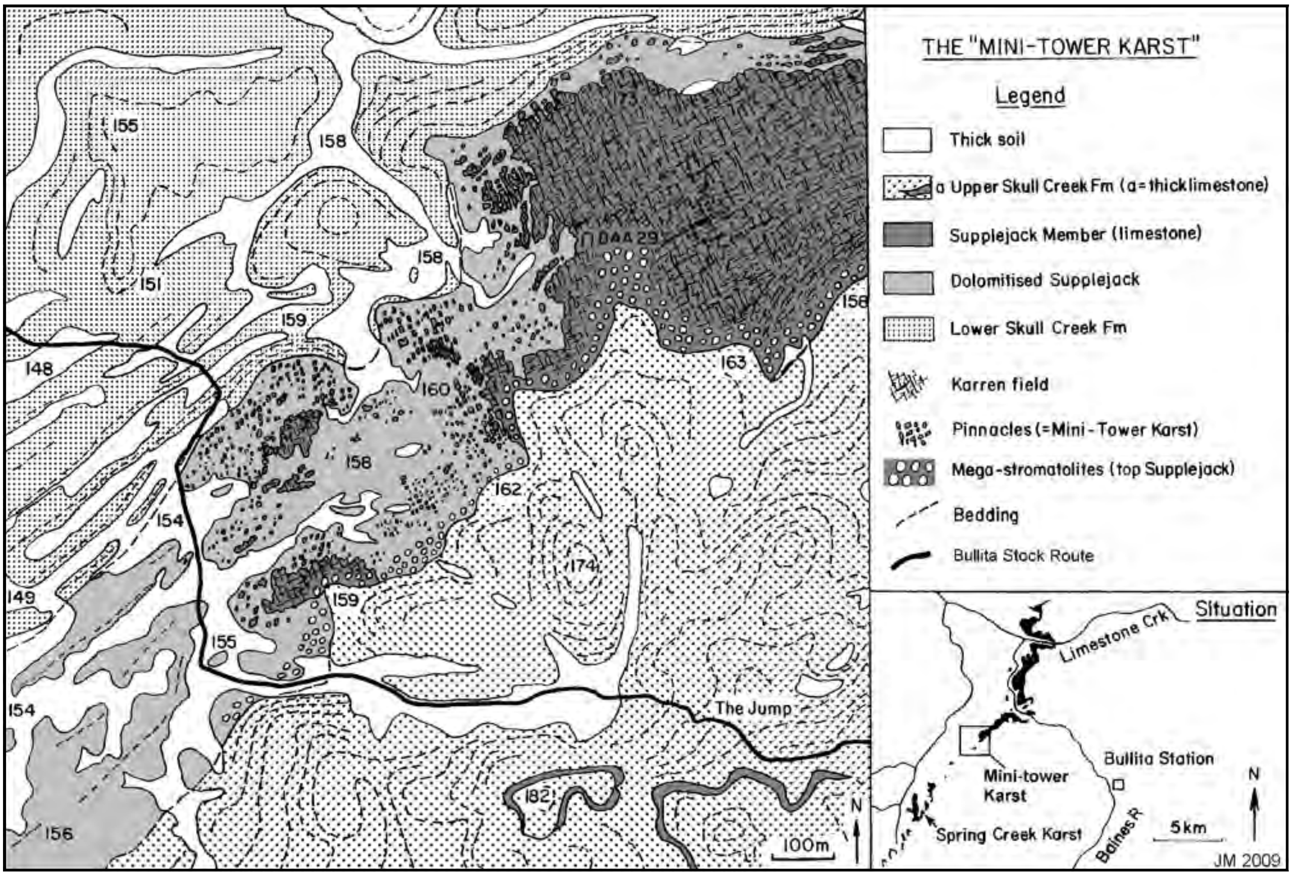

Figure 17: Map of the Mini-Tower Karst, after Google Earth satellite imagery and some field checking. Altitudes in metres. *View Google Earth at 16° 6.1'S, 130° 21.1'E.*

become completely dissected and megakarren features appear. Giant grikes 1-5 m wide penetrate to the cave floors 10-15 m below, separating pinnacles and blocks of rock which have strong spitzkarren on the tops and sculptured walls (Figures 13, 14 and 15). As the grikes widen, one gets a ruiniform or 'ruined city' topography of isolated blocks, many of which are tilted (Figure 16), and finally an abrupt change to a broad flat-floored structural pavement on the lower Skull Creek Formation with only scattered blocks and sculptured pinnacles, which eventually degenerate into chaotic boulder fields. The boulders have even rolled down the slopes, where the latter are steep, that is, along the main streams. The width of this zone is irregular, sometimes over 100 m wide, but may be missing, for example on both sides of Limestone Gorge and along most of the cliffs dominating the Baines River.

At the outer edge of the degraded karst, one characteristically observes Supplejack blocks showing dips tilted in all directions, but resting on structurally undisturbed Lower Skull Creek carbonates (Figure 16). This suggests that the latter formation was little or not at all affected by karstification. Another characteristic of the degraded karst is that the cracks and irregular voids between blocks are most generally filled with silt and rubble to a thickness up to 10m. This material forms barriers to the drainage of the caves, as discussed later in the sections on cave sediments (page 54) and hydrology (page 54).

Along major joints or minor faults, dissolution was more intense, with development of long trenches, which have widths varying from 5 to 10 m or more, ranging from giant grikes to bogaz and box valleys. They are observed within all zones of the karrenfield, but tend to become wider towards the more mature stage. In many instances the giant grikes display irregular floors and are partly filled with silt, the same way as in the degraded karst (see above), with large boulders protruding from the floor. Wide shallow grikes with an undisturbed dolomitic limestone floor have also been observed (see figure 12c of Grimes, 2012a). The fact that the grikes did not always reach the base of the Supplejack is also demonstrated by cave passages developed under them. This indicates that the large grikes do not develop only from the collapse of cave passages at the base of the Supplejack, but also from dissolution from the top down.

The Mini-tower Karst

At the south-western end of the Southern area, and immediately to the north-east of the place where the Bullita Stock Route crosses the Supplejack Dolostone Member, an interesting and unusual karst area was discovered by J.Dunkley. It consists of a field of widely spaced pinnacles, which appears to result from the degeneration of the karrenfield. It is different and much more extensive than the other 'ruined cities' observed further north. It is nearly one kilometre long and is referred to here as the *Mini-Tower Karst* (Figures 12b and 17). Field work, mineralogical study and remote sensing mapping shows that the Supplejack is here extensively invaded by secondary dolomite, which spared localised lenticular beds of primary dolomitic limestone, which are generally only a few metres thick. On the Google Earth satellite images, the dolomitised parts appear as white pavements, often retaining the typical jointing observed in the karst. The limestone pinnacles and the larger blocks are resting on this pavement. Here again the unaltered limestone is protruding on account of its mechanical resistance to erosion, which is greater than the friable, poorly karstified secondary dolostone, as discussed previously in the geology section (page 42).

Description of the caves

The following description concentrates mainly on the Bullita Cave System (Figure 5), which is the largest studied in the Judbarra / Gregory Karst.

This system consists of an intricate and dense maze of joint-controlled passages developed exclusively under the karrenfield: primarily under karren zones 2 and 3, with only incipient small passages under zone 1, and becoming unroofed or destroyed by roof breakdown under zone 4 (the degraded karst). However, under zone 4 the limit of cave development is less easy to delineate than under zone 1. Indeed, exploration and survey has been mainly focussed on extending the main system, with less priority on potential caves in isolated zones of less degraded karst, which are unlikely to connect physically to the main passage network but are speleologically part of the system. As the passages develop at shallow depth (about 5 to 20 m), the connections to the surface through grikes are very numerous, producing probably well over 1000 ceiling entrances. The consequence is that the daylight penetrates into the cave in many places, to such an extent that in some sections, artificial light is hardly necessary. Tree roots, mainly from fig-trees (Figures 24 and 25), are ubiquitous in the passages developed in the Supplejack Dolostone Member and in the Upper Shale Marker, but are less common in the lower levels. Their abundance is related to the very shallow nature of the system. The roots hang free from the ceiling to the floor, then penetrate the cave soil or creep horizontally in search of moisture, sometimes over long distances.

The general layout of the Bullita Cave System is irregular, as the cave consists of a chain of discrete sectors of maze interconnected by a few passages, sometimes by only a single narrow crawl. This imparts a necklace structure to the cave map, with the sectors representing the beads. Specific names have been given to these sectors, such as ‘The Frontyard’, ‘Backyard’ and ‘Neighbours Block’ (Figure 5). At the surface, the

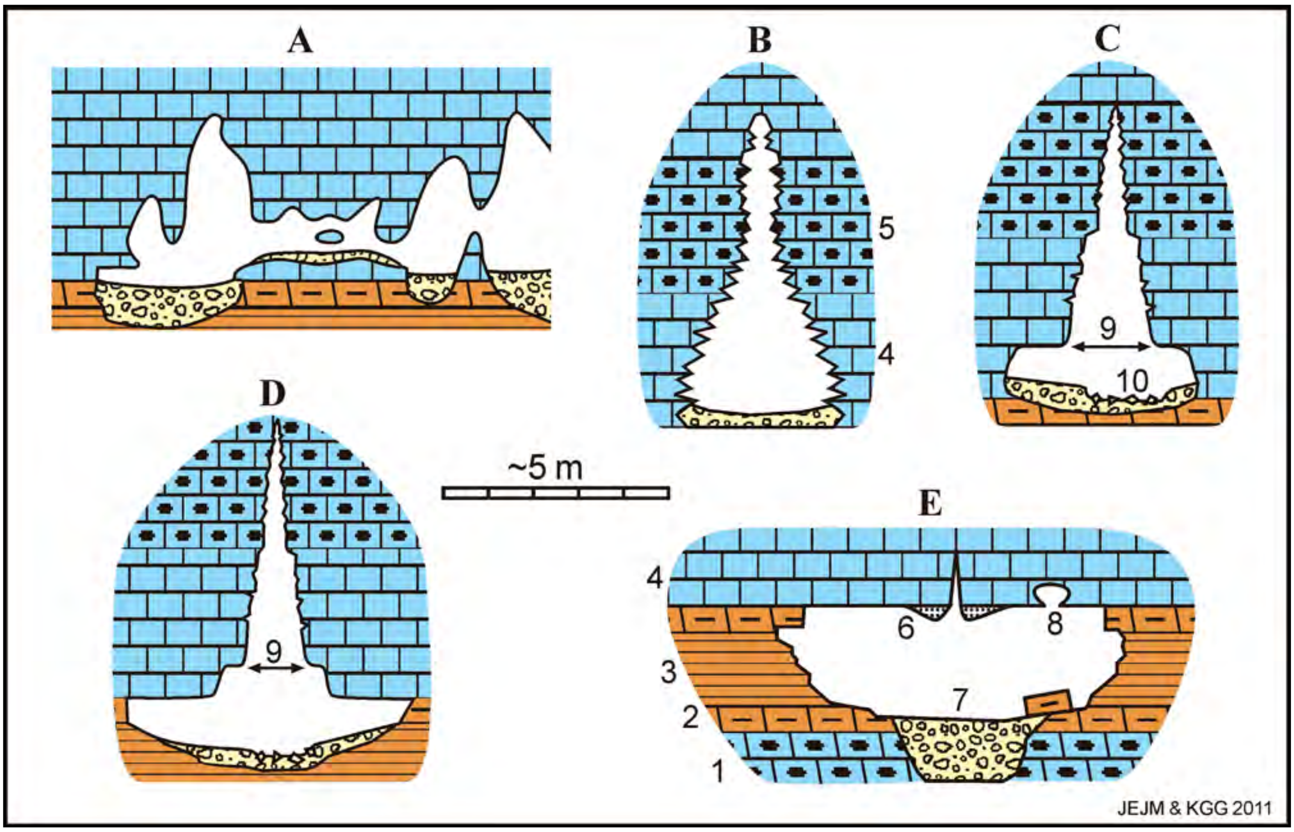

Figure 18: Types of passage sections: A: phreatic passages (ex. FrontYard, c.f. Figure 21); B: Ledgy A-form passage that widens downward (c.f. Figure 19); C: Tented passage showing bevelled ceilings and incipient ledges (ex. from Front Yard, c.f. Figure 20); D: Inverted-T form resulting from erosional expansion in the shale bed (c.f. Figure 23); E: rectangular shale passage (c.f. Figure 6).
Lithology: 1: dolostone, more or less cherty; 2: dolomitic mudstone; 3: dolomitic siltstone and shale; 4: dolomitic limestone; 5: cherty dolomitic limestone; 6: popcorn; 7: alluvial and residual filling; 8: ‘omega’ tube; 9: bevel at old watertable; 10: stream bed.

Figure 19: A-fissure passage with ledge development (c.f. Figure 18b).
Odyssey area in Bullita Cave System. [KGG]

Figure 20: 'Tented' type passage that widens downward towards a bevel (b) in the side walls one metre above the floor (c.f. Figure 18c). Note stream bed between two alluvial banks. The horizontal grooves and ridges on the upper wall are from differential corrosion of limestone and dolomite beds.
Frontyard block, northern Bullita Cave System. [JEJM]

Figure 21 (above): Phreatic tubes (p) 2-3 m above the base of Supplejack limestone and two undercuts in the lower part of the picture: the higher one (b) affects the very base of the limestone (0.5-0.6 m thick) and the lower one (s), much more pronounced, is due to mechanical removal of the Upper Shale Marker.
Frontyard block. Bullita Cave System. [KGG].

Figure 22 (above right): 'Omega' type of tube at the very base of the Supplejack Member – perched above the shale bed, which was later eroded away.
Claymore Cave, Southern Karst. [KGG]

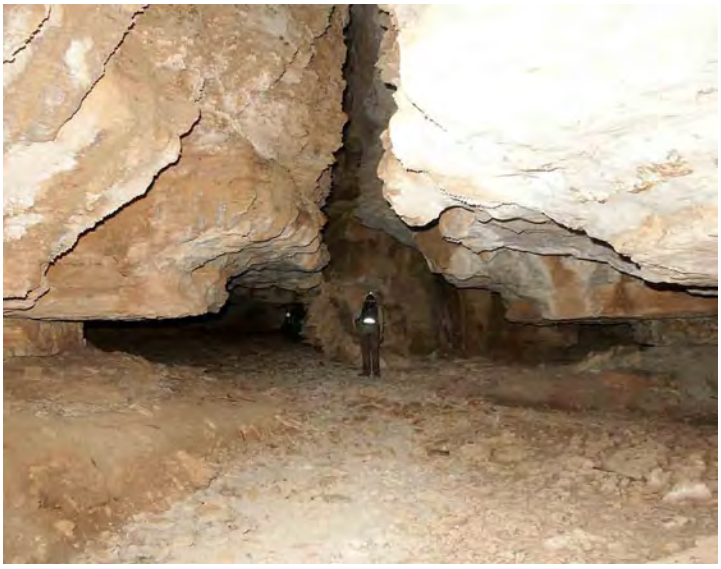

Figure 23 (right): Typical 'inverted-T' passage. A narrow vertical fissure following a joint in the Supplejack Member changes to a broad basal slot in the shale bed. Note wet-season streamway in foreground.
Claymore Cave, Southern Karst. [KGG]

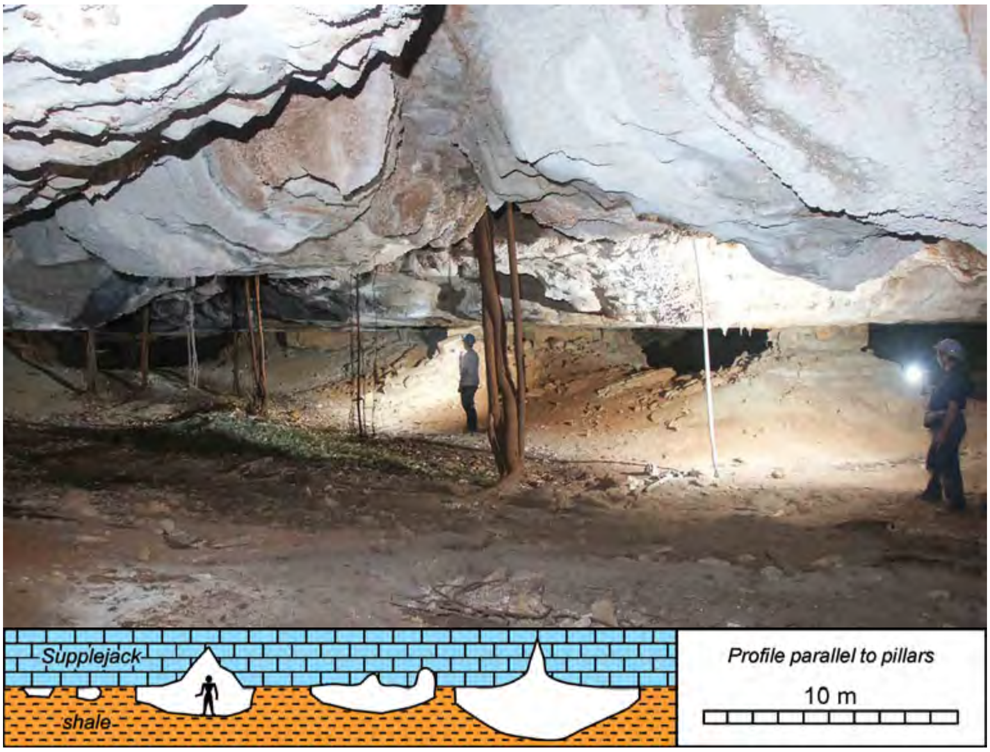

Figure 24: Advanced stage of lateral shale erosion, leaving shale pillars supporting the ceiling. Note roots entering via narrow fissures developed along an initial joint.
Hermitage Grange, in Backyard section, Bullita Cave System.
The cross-section is parallel to the line of pillars, and continues to right of the photograph.
[KGG]

narrow links between the sectors generally correspond to the ends of large grikes and minor valleys, that is, to constrictions of the karrenfield.

The main passage types

There are three broad types of passages that have a morphology closely controlled by the stratigraphy of the host rock (Bannink et al., 1995):

1. the type developed in the lower strata of the Supplejack Dolostone Member;
2. the type due to excavation of the 2-3 m thick Upper Shale Marker;
3. the type developed stratigraphically deeper in the well bedded dolostone and in the Lower Shale Marker of the Lower Skull Creek Formation (Figure 12d); these lower levels are best developed in Dingo Cave (Bannink, et al, 1995) and in the SOGS section of the Bullita system.

Supplejack Passages (type 1): In this first type, although passages are observed at all stratigraphic heights in the member, they are mostly concentrated at its base, even within the incipient zone 1 (Figure 12). This has been well confirmed by four profiles[1] surveyed across the cave system. Where the Supplejack Dolostone Member's base is not exposed in the passages, its proximity can be ascertained by the elevation of the chert nodules marker above.

Commonly the passages form fissures developed along joints; these display triangular sections which vary from narrow fissures tapering upwards (the 'A-type', Figures 18b, 19) to the 'tented passages' of Bannink et al., (1995) that widen significantly towards the base where they intersect the top of the shale bed (Figures 18c, 20).

A typical phreatic morphology is frequently observed, particularly in the Frontyard and in the Golden Arches, and is characterised by wider passages with roof pendants, solution bells and ellipsoidal horizontal tubes not controlled by jointing (Figures 18a, 21). Some horizontal 'phreatic' tubes run just above the contact with the underlying Shale Bed and suggest a perched watertable at that level. Later erosion of these down into the shale bed has left ceiling half-tubes with a distinctive 'omega-shaped' cross-section (Figure 22). Typically the best development of this phreatic morphology occurs in the 3-4 basal metres of the Supplejack. In this case, the walls generally display a narrowly corrugated surface, which is lithologically controlled: the millimetric to decimetric dolomite-rich laminae are more corroded than the limestone ones, which project up to 3 cm. The syneresis cracks filled with limestone, developed in thicker dolomicrite beds, also protrude and form small sub-vertical partitions (Figure 7). In the most common type the passages are simply A-form with walls exhibiting ledges developed at decimetric intervals and projecting horizontally for up to half a metre (Figures 18b, 19). Here too the interval between ledges seems most often developed from recessive dolostone seams.

The vadose or phreatic origin of the ordinary smooth-walled tented passages cannot be ascertained from their morphology. The only definite vadose morphologies seen within the Supplejack are horizontally bevelled ceilings and undercut walls close to the base of the member, as observed in the SW part of the Frontyard (Figures 18c,d; and 20) and in Claymore Cave. They

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[1] Plots of these profiles are available on the *Helictite* web site: http://helictite.caves.org.au/data.html.

Figure 25: Cave development in Lower Skull Creek Formation. Note from top down: the horizontal ceiling formed at the base of the Supplejack Member; the Upper Shale Marker (S) forming a wide slot immediately under the ceiling; then a 6-7 m deep trench in Lower Skull Creek dolostone; underlain in turn by the Lower Shale Marker forming an undercut behind the distant caver.

The central group of hanging roots is about 10 m long.

SOGS section, southern Bullita Cave System. [JEJM]

suggest lateral dissolution in a pool with a stable water level (Rossi et al., 1997).

Shale passages (type2): The second type of passage is developed in the Upper Shale Marker and is perhaps the most common one in the Bullita Cave System (Figures 6 and 18e). Due to lateral excavation of this soft, incompetent horizon by vadose flow, 'rectangular passages' (Bannink et al., 1995) have formed with heights not exceeding 3 m, but with widths in places reaching 30 m. The 'inverted-T' passage type is another typical result, with a narrow fissure in the Supplejack expanding to a broad horizontal slot in the shale bed (Figures 18d, 23). In extreme cases, only pillars of shaly material are left to support the ceiling and the passage network merges into wide but low chambers, which are reminiscent of a coal seam excavated by mining (Figure 24). An axial joint is generally visible on the flat ceiling. This joint is open to widths varying from millimetric to metric.

Morphologies hybrid between the types 1 and 2 are common; A-type and elliptical phreatic passages in the base of the Supplejack have expanded downwards into the shale bed to form the inverted-T, tented and omega forms described above (Figures 12a, 18).

Lower Level Passages (type 3): In the Bullita Cave System, most of the passages are developed in the Supplejack Dolostone Member and in the Upper Shale Marker. Less common are passages that are locally entrenched into the Lower Skull Creek dolostone, but generally at not more than a few metres below the Upper Shale Marker. These are generally found close to the degraded karst zone and in the vicinity of steeply entrenched valleys and gullies, for instance in the Backyard, in the Skeleton Key and in the northern reaches of Mike's section (Figure 5). The development in these parts of the system is generally of shallow trenches extending down from the floor of broad shale passages which are poorly interconnected horizontally.

Only in the southern section of the Bullita Cave System (SOGS, Figure 5) is the Lower Skull Creek more deeply affected by karst dissolution (Figures 12d, 25, 26). In the Dingo Cave System (Figure 5), they play a more important role (Bannink et al., 1995) and up to four cave levels are recorded there. The access to these lower levels is via trenches and pits. The passages differ from those of type 1 and 2 in being smaller, narrower and forming simpler networks (Figure 26) and do not seem to develop at stratigraphic depths much greater than about 20 m below the floor of the upper shale passages, that is the East Baines River level. Some of them have formed immediately above the Lower Shale Marker in the SOGS Section. Here in cross-section they are 1-2 m high, 1 m wide, 'phreatic' looking and not obviously controlled by jointing. Their floor is resting on the top of the shale, although the latter is generally masked by alluvial silt. It is interesting to note that passages in the Lower Skull Creek have been observed only under presently karstified Supplejack. For instance, extensive prospecting of the Lower Skull Creek dolostone cliffs of the left (west) bank of the East Baines River, above which the Supplejack has been almost entirely eroded (Figure 5), failed to disclose any cave entrance (L. Robinson and N. White, pers. comm.).

Relationships between the caves and the surface karst

The three types of passage are partly related to the surface karst morphology. As a general rule, type 1 passages are developed under karren zone 2, but end eastwards more or less against zone 1 (Figure 12a). In the close vicinity of zone 1, the passages get smaller and thinner and eventually become impenetrable for a caver. In a few cases these crawlways end against very narrow chimneys connected to the surface. An exception to this rule occurs in Dingo Cave, where a few passages

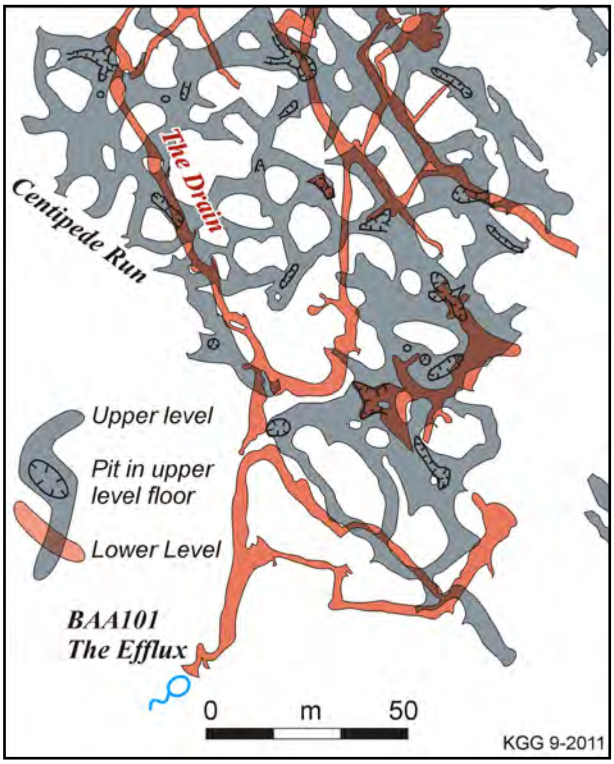

Figure 26: Different passage styles in the upper and lower levels of the SW part of SOGS, Bullita Cave System. From maps compiled by R. Kershaw, GKSIG.

have developed under Upper Skull Creek cover for short distances. The type 2 shale passages are developed further westwards, mostly under karren zone 3. Still further west the boundary of the cave system coincides with the start of the degraded karst (zone 4). Close to this limit the shale passages get very wide, tend to collapse due to lack of roof support (Figures 12a, 15 and 16) and often degenerate into a chaos of huge blocks. This collapsing process explains the generally tilted attitude of the pinnacles and boulders, as described in the surface karst morphology section (page 46). Furthermore, the western edge of the cave system is also due to the widespread filling of the cavities by rock debris and silt. In this area of degraded karst, 'islands' of relatively undisturbed limestone and caves survive. In some cases, the cavers have connected these isolated cave passages to the main system via underground routes through areas of chaotic breakdown which are only indirectly related to solutional speleogenesis. Conversely, 'islands' of degraded karst, where the passages have been destroyed, may be completely surrounded by intact passage mazes, for instance in the BAA34 sector (Figure 5).

Regarding the compartmented nature of the cave system, it has been observed that each sector of maze has a tendency to possess its own type of passage morphology (M.Sefton, pers. comm.), especially when considering the variations of the passages within the Supplejack. For instance, the well-developed phreatic morphology, with practically no prominent ledges on the walls of the passages, is characteristic of the Frontyard sector (Figure 21). In this sector the particularly dense maze development (Figure 5) is perhaps also related to this phreatic morphology. In other parts of the system, for instance in BAA34, A-type passages with prominent ledges are common (Figure 19). In the Neighbours Block the dominant morphology is the shale passages (type 2, Figure 6), often with very little dissolution at the ceiling.

Other cave styles

The Bullita Appendix: An unusual case of cave development is observed at the south-east end of the Bullita cave system, in the 'Bullita Appendix' (Figure 12c). Here, a several metres thick layer of secondary dolostone is inter-stratified in the middle portion of the Supplejack Dolostone Member, over a 300 m strike length. The dolostone seems to have acted as an aquitard, thus preventing deeper speleogenesis, and today still rapidly conveys the water to two resurgences (Figures 5 and 12c). Therefore, caves are only developed within the 6 m thick top portion of the Supplejack, where the passages display a rather narrow A-fissure sub-type. These passages are developed mainly under karren zone 1, which is an exception to the general rule. Immediately to the SW of the last resurgence, the dolomitisation extends up to the top of the Supplejack over a length of 60 m. This interruption of the limestone seems to have acted as a barrier to speleogenesis, explaining the failure to find underground connections between Bullita and nearby Wadija Cave (Figure 5). Immediately south of Wadija, the entire Supplejack interfingers rapidly into secondary dolostone. The dolomitisation is complete over a strike length of 200 m, and then progressively grades back into primary dolomitic limestone up to Jalaman Cave (Figure 5).

The Spring Creek Karst

The Spring Creek Karst lies beyond a 4.5 km dolomitised gap, which separates it from the Southern Karst area (Figure 2). Since it is remote from Bullita Cave in the Central Karst and shows some differences, it is informative to describe it in some detail. Here, the thickness, the stratigraphy, the very gentle eastwards dip of the Skull Creek Formation and the detailed stratigraphy of the Supplejack Dolostone Member, are very similar to the sections studied 14 km to the NE, in Limestone Gorge. From its contact with the Upper Skull Creek, this relatively small karst develops several long (400-800 m) tongues of karren, separated by shallow valleys floored by the Lower Skull Creek. Compared with the areas north of the Bullita Stock Route, the surface morphology is flatter and not affected by the same deep post-Wave Hill incision. The altitude (170-175 m) of the karst, however, is higher than for the Bullita System. To the southeast it abuts against a residual hill culminating at 260 m. The karren shows a zonal sequence comparable with the Bullita System, but with the exception of zone 4, which is poorly developed or missing. Furthermore, tilted blocks of karren, resulting from the collapse of type 2 shale passages, have not been observed.

The caves of the Spring Creek area were still poorly explored at the time of the authors' field inspections in 2007, but could yield a potential 20-30 km of passages. In one interesting cave (Gothic Arch Cave) 3.4 km of cave passage was surveyed in 2007. The passage network (type 1) extends from the northwest end of the north-eastern tongue of the karrenfield and terminates 400 m southwards, not far from the contact line with the Upper Skull Creek Formation. It is entirely developed within the Supplejack and never reaches the Upper Shale Marker. Close to the northwest tip of the tongue the floor of the passages lies about 1.5-2 m below the cherty marker. Southwards the sub-horizontal floor transgresses through stratigraphically higher strata and in the middle part of the system the passages are entirely within the cherty marker. Here the walls are characterised by thin protruding ledges. Close to the southern termination, before the passages get smaller and end, they lie above this marker and exhibit thick and widely spaced ledges. These discordant passages cut across nearly half of the stratigraphic thickness of the Supplejack.

Cave sediments

The detrital sediments covering the passage floors have both endogenic and allogenic origins. The endogenic material originates from the residuals left after the dissolution of the Supplejack dolomitic limestone and after the weathering and erosion of the Upper Shale Marker. The residuals released from the Supplejack are mostly chert nodules and finer material such as dolomite, and minor quartz and clay minerals. The Upper Shale Marker produces relatively large platy fragments of carbonate rock and siltstone, together with finer sediments (silt and clay). These detritals are then reworked and transported as alluvials by the cave streams.

Depending on the size of the catchment surfaces upslope from the karrenfield, the allogenic source may predominate in some sectors of the cave system. The related alluvium, as observed in the small stream beds at the surface, consists of gravel, sand, silt and clay entering the cave system close to its eastern limit near the junction of karren zones 1 and 2. This material accumulates in the passages below during the flood periods and is more or less evacuated by streams as the floods recede. Very often one observes that the fine sediments are deposited both on the banks of stony stream beds and as very thin layers on the ledges of the tented passages, at all elevations above the bottom. False floors of speleothem, originally deposited on alluvium that has since been eroded away, have been observed, especially in the lower levels of the system developed in the southern sectors (SOGS). There is also an example of a false floor in BAA34, relatively close to the surface contact line with the Upper Skull Creek.

The most important volume of sediment has accumulated in the degraded karst (zone 4), where it fills the spaces between pinnacles and huge collapsed blocks. These sediments are thick, reaching perhaps 10 m in places and seem to surround and limit the cave system nearly everywhere along its western edge. The result is that the great majority of the 'easy' access points to the cave from the adjoining valleys are up over sediment mounds and then down through descending entrances located at the periphery of the system (Figures 12a, 14 and 15). Horizontal entrances are exceptional, but include the cliff entrance at the northernmost end of Mike's Section (Figures 5, 8). This sedimentary filling consists of Supplejack boulders and rubble of all sizes in a matrix of sand, silt and clay. Samples have been collected from shallow digs (50 to 70 cm) at two entrances (BAA 65 and 70, respectively in Berks Backyard and in the southern Frontyard). These revealed grey to beige silt penetrated by very dense networks of roots, most generally from the small tree *Celtis phillippinersis*, which characteristically grows on the sedimentary filling of the degraded karst. This tree is one of several species reported on this karst (Storm & Smith, 1991). Close to the surface the silt is grey, rich in organic matter and snail shells, but less so at depth where it turns beige. The silt fraction is composed of very fine quartz, carbonate, clay and a minor amount of white, fibrous, friable fragments, which are a few millimetres long at the most. Under the microscope these are seen to be made of a hyaline isotropic mineral, with a regular cellular texture. It remains unchanged after ignition. Very probably it represents ashes or wood silicified by opal replacement of plant particles.

Thus the sedimentary filling in the degraded karst is composite, consisting partly of material of in situ origin, such as dolostone and limestone fragments, vegetation debris, and snails, which is partially of allogenic material, such as silt and clay. During flooding, this latter fine material might add to the previous accumulations by deposition and infiltration. The very dense root networks contribute greatly to stabilise and protect these deposits from erosion. These sedimentary accumulations are contemporaneous with the final evolutionary stage of the karst (zone 4) and are somewhat reminiscent of natural levees which in flood plains tend to confine rivers within their bed. In the case of the Bullita Cave System, these 'levees' might contribute to pond and retard the draining of flood water accumulated in the cave, as discussed below in the Hydrology and Speleogenesis sections of this report.

Hydrology of the cave systems

Exploration is restricted to the dry season, when the systems are almost completely dry. However, in Bullita Cave there is abundant evidence that, during the wet season, streams are active and flooding occurs. This can be deduced from numerous streambeds (Figures 20, 23), from sediments covering survey markers left during previous expeditions, and from recent waterlines marked by small snail shells and leaf debris sticking to walls. The flooding can reach a height of several metres in some places. For example, an automatic camera left in the cave in 2002 by L. Robinson and N. White and designed to be triggered by rising floodwater was found to have been totally inundated when retrieved the following year. No permanent pool has been encountered in the Bullita Cave System. This is in contrast to the Dingo System, where the watertable has been reached in a few places in its lowest level (Bannink et al., 1995).

It is possible that today, in the type 1 Supplejack passages developed under the karren zone 2, complete flooding might sometimes occur, whereas further west, in the type 2 (shale) passages, vadose stream activity is dominantly the rule today. In these latter parts of the cave the water may converge towards channels developed in the dolostone of the Lower Skull Creek Formation, e.g. in SOGS, which act as drains connecting to the incised valleys of the East Baines River and Limestone Gorge (Figure 26). As these narrow passages must convey large volumes of water, many of them should be temporarily flooded up to the roof and function in a 'seasonal floodwater regime'.

Inputs

Water enters the Bullita Cave System in two ways: diffuse autogenic and localised allogenic (Bannink et al., 1995). The diffuse input is by direct infiltration via karren fissures and crevasses. The allogenic source is from surface runoff on the Upper Skull Creek Formation and the water enters the cave system where it reaches the karrenfield (Figure 5). Most of the small rivulets entering the karst appear to sink through karren crevasses rather than through well defined swallow-holes. The only spectacular swallow-hole is located near the southern end of the Bullita Cave System, close to the Appendix, and absorbs a much larger volume of water, as it has a longer tributary stream (see Figure 5).

Concerning the entire system, the surface of the non-karstic allogenic catchment area, measured on the topographic map, is slightly greater than that of the karrenfield. However, on the Upper Skull Creek Formation a portion of the rain slowly infiltrates the soil, then is taken up by the vegetation or evaporates, thus reducing the amount of runoff. In contrast, in the karrenfield, most of the rain rapidly sinks underground with a minimum loss to evaporation. Moreover, the allogenic contribution to the apparent total input of the system can be further reduced in that the large catchment area feeding the 'Appendix swallow-hole' should be practically discounted, as due to the ESE dip of the Supplejack, most of the water from this stream is forced to flow SSW and, therefore, rapidly reappears at two resurgences (Figure 5) without contributing to feed the main cave system. In conclusion, it seems very likely that today the diffuse autogenic input via the karrenfield is quantitatively the most important. This is supported by the fact that within the maze system no specific morphology can be clearly correlated with the location of allogenic inputs.

Only two water sinks located in the Lower Skull Creek Formation have been observed. One is a swallow-hole along the streambed just north of Wadija Cave (Figure 5), where the water sinks between large dolostone boulders, but which does not seem able to absorb all the stream during peak flow. The second one consists of a depression at the intersection of two major joints or faults within the karrenfield (at the Sentinel, Figure 5), but it is not fed by a well established stream.

Outputs

The only well documented resurgence, the Efflux, is located at the southern end of the Bullita Cave System (Figures 5, 12d, 26). It is obviously the most important one, and is relatively deeply entrenched (20-25 m) into the Lower Skull Creek. Moreover, it has cave passages connecting it to the main part of the system. At the north-western extremity of the Berks Backyard Section (Skeleton Key, Figure 5), a long passage heading north is entrenched into the Lower Skull Creek, but only a few metres below the Upper Shale Marker. That might be a drain leading to an, as yet, unlocated resurgence. It is also highly likely that a large number of minor, cryptic resurgences drain the system during the wet season. Two of these can be observed at the northernmost end of the Bullita system, in Limestone Gorge at the base of the Supplejack Dolostone Member (Figure 5). At the opposite end of the system, two resurgences have been mentioned previously south of the Bullita Appendix (page 53, Figure 5).

Storage

One might think that Bullita Cave would be well-drained in a vadose environment, given that it lies adjacent to the incised channels of the East Baines River and Limestone Creek and that the outcrop belt of the Supplejack is dissected at regular intervals by valleys that cut down to the base of the formation and drain to the river. However, this is not entirely so, and there is ample evidence given above for flooding to several metres depth during the wet season. The accumulation of sediments (stones and silt) at the edge of the degraded karst (zone 4), as described in the section on cave sediments (page 54), could help explain this seasonal flooding. These 'levees' may have acted as more or less impermeable dam walls, which could keep floodwater in the cave for weeks to months during the wet season. The silting has also affected some major grikes, which could then have functioned as dykes partitioning the cave into hydrologically separate compartments. It also appears possible that the water-tightness of these 'dykes' and 'levees' is variable from one block to another, which means that some compartments remain flooded for a longer time than for the others. This might explain the difference of passage morphology from one sector to another, as mentioned in the description of the cave passages (page 51).

Spring Creek Karst

In the case of the Spring Creek caves, the stratigraphically discordant behaviour of the network, as described in a previous section (page 54), could be in part related to the general flatter relief on the Lower Skull Creek. Moreover, this karst is separated by a secondary dolostone zone and by a long distance from the deeply incised valleys in the north. Therefore the karst should be less well drained than in the case of the Bullita System. At Spring Creek this should favour phreatic development along a horizontal, disconformable water-table. This may also explain the lack of development of type 2 passages in the Upper Shale Marker.

Speleothems

Compared to most caves in the world, classic dripstone-type speleothems, such as Ca-carbonate stalactites, stalagmites, and draperies, are relatively uncommon and volumetrically small. This is probably a consequence of the lack of surface soil, which normally produces CO_2; high CO_2 in soil generates solutions supersaturated in calcite and aragonite when they enter a cave, where the pressure of this gas is usually much lower, especially when well ventilated as the Bullita Cave System most certainly is. Mineralogically, the stalactites, stalagmites and flowstone seem to consist exclusively of calcite, as should be expected since the host rock is dominantly calcitic. A few well developed gypsum flowers have been observed in Claymore Cave, in the Southern Karst. This seems a rare occurrence and none have been reported in Bullita Cave itself.

In the Bullita System, the most common speleothems are coralloids (popcorn, cave coral) as moonmilk-like crusts on the ceiling and walls (Figure 27). Loose white powder on the floor seems to derive from the disintegration of the moonmilk crusts. Twelve samples were collected and analysed by XRD (at La Trobe University, Melbourne), which revealed only calcite. Aragonite was detected only in small, hard, white efflorescences growing, not in the cave, but at the surface on the pinnacles in several places. As the country rock in Bullita is a magnesian limestone, containing calcite and dolomite, and as popcorn is an evaporation-type speleothem, one would have expected to detect species such as aragonite, hydromagnesite, or huntite. However, even moonmilk-like material was seen to be microcrystalline calcite, whereas such chalky material commonly consists of Mg carbonates where the country rock is Mg-rich and the climate dry. This suggests that the initial solutions entering the cave from the karren surface must have been exceptionally low in Mg.

This preponderance of calcite in evaporative speleothems can be explained by the generally rapid transit of rainwater from surface to cave floor, leaving little time for dolomite to be substantially dissolved. At equal saturation level, the dissolution rate of dolomite is much slower than for calcite (Dreybrodt, 2004a); therefore calcite will be preferentially dissolved. As suggested previously (page 46), the dolomite crystals are probably freed by calcite dissolution and mechanically transported, without providing much magnesium to the solutions before reaching the cave floor. This process

Figure 27: Large coralloid speleothem masses may indicate seasonal alternation of flooded and dry conditions in ‘Lost in Space’ cave, Spring Creek karst area. Chamber is about 70 cm high. Photo by Alan Pryke.

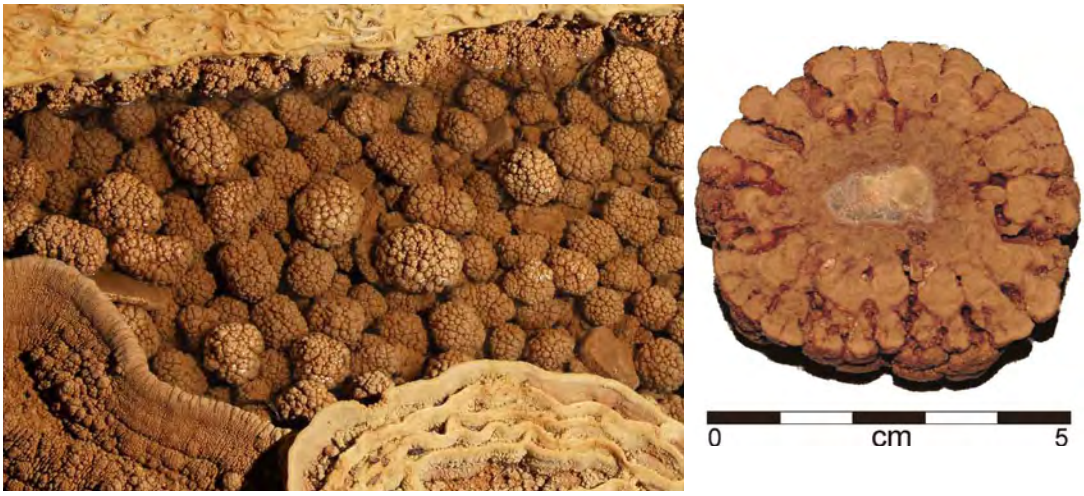

Figure 28: Large knobby nodules sitting loose in a pool (left) and a cross-section of one specimen (right).

Photos by Mark Sefton.

could also explain the apparently higher corrosion of the dolostone seams exposed on the passage walls, which were described previously. Therefore, the solutions ponding in the passage system were possibly more under-saturated in dolomite than in calcite.

On the ceiling of the rectangular shale passages, popcorn characteristically grew symmetrically on both sides of the crevasse developed along the axial joint (Figures 6, 18c). Close to the joint it may reach several decimetres in thickness, but tapers further away. Popcorn has been deposited by evaporation to dryness of a thin film of water creeping from the joint across the walls. However, close to the plane of the crevasse the popcorn may be corroded, in places very sharply cut with vertical striations in continuity with the runnels on the crevasse wall. This suggests that initially the water might have been more supersaturated, when the narrow crack was transmitting the flow more slowly than at present, and that dissolution prevailed later when the fissure had been more widely opened. Alternatively, the strong, less-saturated, wet season flows might be eroding material deposited by slower more-saturated seepage between storms.

Gours and flowstone floor with ‘mini-rimstone dams’ (micro-gours) are locally well developed, particularly at the southern end of the system (SOGS). Pisoliths resembling classic cave pearls, although generally imperfectly round, have also been observed. One peculiar type of pisolith is the ‘coral balls’, found filling only one in a cluster of rimpools (information from M. Sefton, Figure 28). They are up to the size of tennis balls and covered with 5 mm long protruding knobs. A section of one revealed a limestone fragment at the core and radiating coralloid rods with concentric growth laminae. The balls are unattached and, therefore, probably formed in an agitated environment. Although their exact conditions of genesis remain unclear, deposition in an environment alternating between subaquatic and sub-aerial (evaporation) seems the only explanation. Similar balls have been observed in China (Zhu Xuewen, 1988).

One of the most spectacular dripstones is the ‘Pendulite’, which formed when the tip of a long stalactite reached a rimpool surface and within the water developed a bulbous piece of shelfstone. Bulbous speleothems in the lower levels of SOGS, and in the Spring Creek caves may be sub-aqueous ‘cave clouds’ that grew in a large perched, periodic pool.

An unusual speleothem is the ‘volcano’ observed in the Frontyard near the entrance BAA71. It is a conical mound of clay pellets, 50 cm high and 1 m in diameter, with a shallow ‘crater’ on top. In the crater the pellets have been coated with a crust of carbonate, deposited by water dripping from the ceiling. Another ‘volcano’ has been observed in the Golden Arches Section (BAA87, Figure 5). It is smaller and a tongue of white calcified pellets ‘flow’ from the crater, like lava. The genesis of the ‘volcanoes’ is not clear. Possibly they started to form under a dripping site, on a flat floor of clay pellets, which were cemented underneath by calcification. Subsequent erosion of the remaining unconsolidated pellets left a cone of more resistant material.

DISCUSSION

Speleogenesis

For all the caves of the Judbarra / Gregory Karst, the broad style of the networks is very reminiscent of joint-controlled phreatic mazes. However, even in the early reports on Bullita Cave (Dunkley, 1993) and Dingo Cave north of Limestone Gorge (Bannink et al., 1995), the authors perceived that the direct, vertical influx of water plays an important speleogenetic role, since cave development occurs almost exclusively where the surface karrenfield is well developed. They were of the opinion that the origin of the system was mainly vadose, with reference to the large volume of cavity formed by the erosion of the shale beds and the subsequent cutting down into the carbonate underneath, forming streamways and canyons. As phreatic style features were not as frequently observed, they visualised those as forming in a minor initial phreatic phase controlled by the two shale beds, which may have acted as aquitards. For Bannink et al. (1995), the origin of the phreatic phase was not clear, but might have been caused locally by the damming effect of collapses, which induced flooding. The authors of both papers visualised an ongoing speleogenetic process, evolving at the rate of surface denudation, meaning that the youngest stage (narrow passages in the base of the Supplejack Dolostone Member) and the senile stage (sinking of the underground streams into deeper drains developed in the Lower Skullcreek Formation) have been active simultaneously in different parts of the cave system. The degree of maturity of the cave passages coincides with the degree of evolution of the karst surface, both being related to the length of time the Supplejack was exposed to weathering (Figures 12, 29). This speleogenetic model is still largely valid, but some aspects need further discussion. These aspects are treated in the five sections which follow.

1: Possibility of deep seated phreatic influences

In the Supplejack Dolostone Member of the Bullita Cave System, the phreatic passages are better developed than in Dingo Cave north of Limestone Gorge. For this reason Dunkley (1993) put more emphasis on the role of phreatic development, which was considered by Bannink et al. (1995) to be only a short transient phase. Dunkley proposed a development within a confined aquifer, under Skull Creek cover, that was independent of the later vadose phase. This was suggested by the presence further north on the Newcastle Range of sinkholes (Figure 1, Dunster et al., 2000) which suggested deeply seated karst dissolution – but that is in a quite different geological setting (described previously in the Newcastle Range Karst section, page 44). In the case of the Bullita Cave System, the passages get smaller and peter out before reaching the contact line between the Supplejack and the Upper Skull Creek (Figures 5, 29), often ending with narrow impenetrable chimneys leading to the surface. Almost no penetrable phreatic passages seem to extend under the upper Supplejack cover. A localised exception is in northern Dingo Cave, where one long, low-roofed passage within the shale bed extends for 300 m beneath a cover of Skull Creek Formation. However, in that case, speleogenesis is controlled by upstream recharge generated from another part of the Supplejack karrenfield – the passage is merely shortcutting beneath a ridge of cover (Peter Bannink, pers. comm. 2006).

The model of speleogenesis in a confined aquifer seems further unlikely as the observed phreatic passages are dominantly positioned within the lower third of the Supplejack Dolostone Member, at or within a few metres of the Upper Shale Marker (Figures 18a, 21 and 22). This restriction of phreatic development to close to the base of the dolomitic limestone is further supported by the morphology of the tented passages and by the nature of the hydrological regime. They are narrow at their top and get progressively wider downward, which fits with a model of temporary flooding: the residence time under water is shorter on top than at the base.

The only explanation left, if development had occurred in a deeply seated aquifer, would be that the lack of passages extending under Upper Skull Creek cover is only apparent and that they exist to the east of the cover limit line, but are filled up by the allogenic sediments abundantly entering the cave system from the ESE side of the karst field. This hypothesis, however, remains to be demonstrated in the field and is not supported by the observed absence of frequent and well developed phreatic passages up to the top of the Supplejack. The model described in the following section might better explain the observed phreatic morphology.

2: Possible pre-karstic widening of joints by mixing of solutions

A hypothetical possibility is that the initial joints were widened before the main speleogenetic phase. Such a process could have taken place by mixing of solutions close to the Supplejack-Upper Skull Creek contact line. There the slow moving solutions filling the original joints under Upper Skull Creek cover would mix with the karst waters. The most efficient mixing model would be if there were reducing solutions, containing H_2S from hypogene origin, which might have oozed laterally in scanty supply from the part of the Supplejack Dolostone Member still covered by the Upper Skull Creek Formation, and which may have then entered the flooded environment under the incipient karren of zone 1 (Figure 29). There, oxidation and corrosion would have taken place, which would have enlarged the joints to at least a few millimetres and thus greatly facilitated the initiation of penetrable passages by vertical flow from the karrenfield.

The possibility of these reducing solutions is supported by the presence of organic rich, black, foetid limestone in the basal Supplejack. Moreover pyrobitumen and sulphides have been reported in the Skull Creek Formation (Beier et al., 2002). Such a process has been observed elsewhere: in the fissures of an aquifer developed in Lincolnshire Limestone, rich in organic matter and finely disseminated pyrite (Lowe et al., 2000). In that case, detailed studies demonstrated joint widening by sulphide oxidation, which, however, did not lead to proper speleogenesis. The rare occurrence of gypsum efflorescences in Claymore Cave suggests that sulphides are present in the dolomitic limestone, presumably in the form of pyrite. However, without any field evidence, this initiation model remains hypothetical for the time being.

3: Phreatic development by lithological control and wet-season ponding

The shale bed immediately underlying the Supplejack is important both as an aquitard and as an easily-eroded incompetent bed. The shale bed may have controlled the level of initial phreatic speleogenesis by providing a perched watertable, which is seasonally very variable, as observed. The omega-shaped tubes in the roof of the larger chambers may have formed at that stage

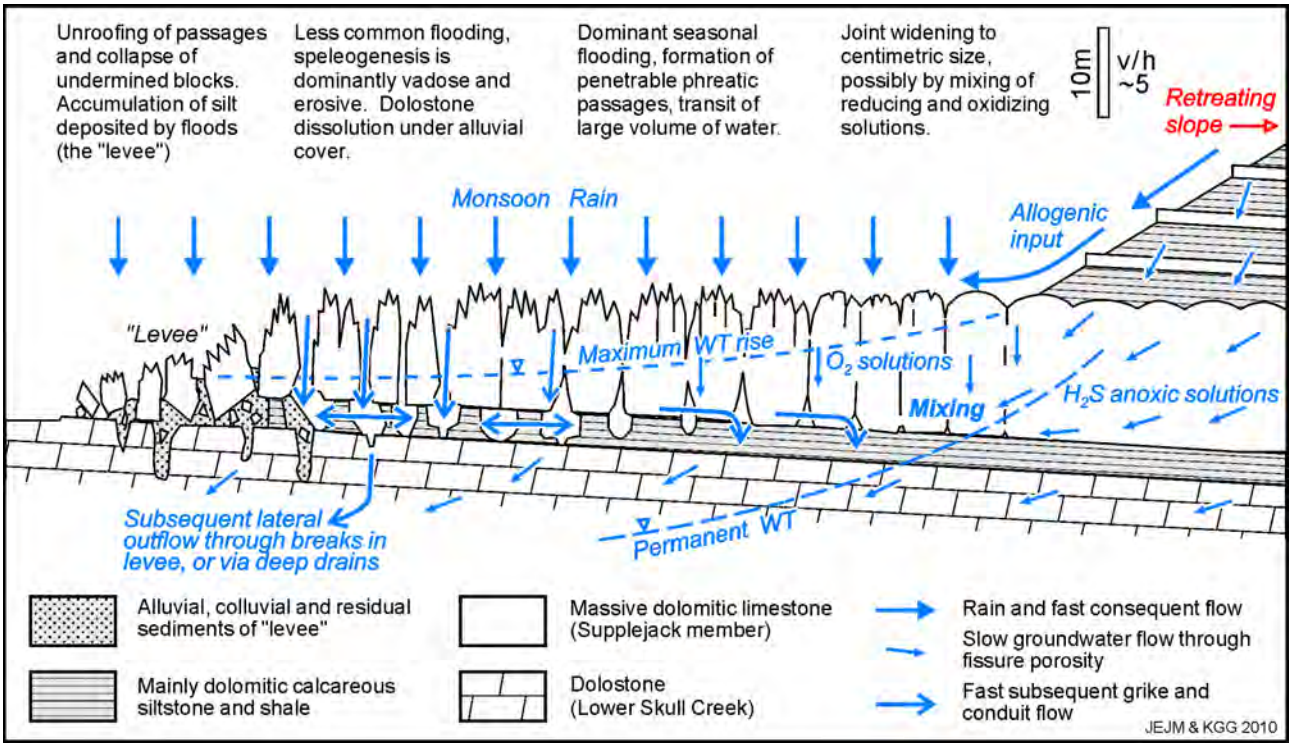

Figure 29: Speleogenetic model. Vertical scale magnified about 5 times.

(Figure 22). Once these initial tubes, fissures and tented channels become large enough to carry strong flows, physical erosion would have cut down into the incompetent shale bed and then sideways to create larger passages, which follow the pattern of the initial joint-controlled channels in the overlying dolomite. Physical erosion of the incompetent shale by wet season flood waters is active at present – as indicated by the stream channels on the passage floors and the abundance of angular shale fragments as a bed-load in those channels (Figures 6 and 20).

This influence of the shale bed has strong analogies with the essentially vadose caves of the Sorbas gypsum karst in Spain (Calaforra & Pulido-Bosch, 2000) and with the 'Contact caves' of West Virginia, USA (Palmer, 1974, 2009, and see also p.235 & 240 in Palmer, 2007). Both those areas have a first stage of phreatic evolution of proto-conduits just above the shale, followed by a second stage in which the predominant process has become vadose mechanical erosion of the soft shale beds.

The 'levees' and sediment-filled grikes described in the cave sediments section (page 54), together with the Upper Shale Marker, may help to explain the development of larger scale seasonal phreatic conditions. This would be a better alternative to the deep seated phreatic model. These 'levees' could keep floodwater in the cave for weeks to months during the wet season. As already mentioned the effectiveness of these 'dykes' and 'levees' may have varied from one block to another, so that some compartments remained flooded for a longer time than for the others. For instance, the Frontyard, with its well developed phreatic morphology, could have been in the past such a relatively poorly drained compartment.

This seasonal flooding means that there is an annual alternation of phreatic and vadose conditions, with a period of minimal activity during the dry season.

4: Effect of cave soil on speleogenesis

For a better understanding of the speleogenesis, it is also necessary to consider carbonate dissolution under soil cover. In the case of the Bullita Cave System, with the exception of the deep passages in SOGS (Figure 12d), the bulk of the system is developed within the epikarst. Compared with the rest of the world, this is unusual. Moreover, the soil does not cover the surface, as in most cases, but the cave floors. The potential speleogenetic contribution from the soil seems evident when the chemical aspect of karst dissolution is considered. At the surface and in the cave system, which is well ventilated, the solubility of calcite and dolomite should be controlled by CO_2 values, which cannot be far above the atmospheric level (0.03%), that is, in the region of 50-60 mg/L (Palmer, 1991). In contrast, the CO_2 level must be much higher (1-10%) in the cave soil, consisting of karst residuals and alluvials plus organic matter (such as leaves and dead tree roots). The CO_2 is generated by bacterial decay of organic matter and also directly released by living roots (Dunkley, 1993), which are well developed in the cave system (Figures 24 and 25). There the carbonate minerals' solubility can rise considerably (200-400 mg/L).

The contrast in potential dissolution between the two environments is even greater if one considers the residence times of the solutions. On the surface and in the largely open cracks connecting to the cave, the residence time of water must be very short during torrential monsoon rainfalls. The water would reach the cave still under-saturated in calcite, and very largely so for dolomite, as suggested by the corrosion of popcorn described in the speleothem section (page 56). In contrast the cave soil would remain wet for a much longer time, all of which suggests that the amount of calcite and dolomite dissolved in the soil environment may be estimated to be at least one magnitude higher than the amount in the open cave above.

The higher potential for dissolution enlargement of the channels filled with soil or alluvials, however, is somewhat lessened for several reasons:

1. dissolution of alluvial fragments of carbonate rock and fine dolomite grains released by dolomicrite weathering;
2. recycling of the calcium pumped to the surface by the vegetation;
3. the rate of calcite dissolution is also lessened by the reduction of the active surface area of water in contact with the filled cavity wall, due to detrital particles and to the slow movement of ground water, which makes the dissolution dominantly diffusion controlled.

A less efficient than expected dissolution of limestone under soil cover has been predicted and measured by Dreybrodt (2004b). Due to lack of data at Bullita, it is not known to what extent the speleogenesis under soil and residual cover is lessened in this case.

The development of passages in the Lower Skull Creek dolostone is in part due to dissolution under alluvial and residual cover from the cave soil and from the ‘levees’. In the case of a development of a cavity filled with soil, even if water does not occupy all the porosity (that is, an unsaturated aquifer), the dissolution is active over the entire wall-sediment contact and is not restricted to the floor, as in open passages. Should this filling be subsequently removed, the cavity will, therefore, display a morphology reminiscent of a phreatic passage. Such a model could be an alternative to explain the apparent phreatic morphology of some of the passages in the Bullita Cave System. The presence of dripstone false floors, mostly developed in the Lower Skull Creek (e.g. SOGS), supports the idea that some passages may have evolved further while filled up with detrital material that has been subsequently eroded by streams, or removed by withdrawal from underneath (the hopper model).

5: The unusual nature of the caves in the Judbarra/ Gregory Karst

The surprising nature of these caves is that dense interconnected networks of large passages are developed at shallow depth exclusively under practically the entire surface of a karrenfield. Elsewhere in the world, thin layers of shallow-dipping limestone comparable to the Supplejack Dolostone Member, and resting on a layer easily amenable to erosion, are not rare. However, to the authors’ knowledge, they generally do not host accessible caves comparable to the Bullita Cave System. World wide, there are many horizontal, joint controlled mazes, which are developed under karrenfields at variable depths. Compared to the Bullita System, however, they are generally not controlled by aquitards, but by watertables. Most of the time they are not restricted to the extent of a karrenfield, are not necessarily developed in the epikarst and do not display such lengths of connected passages (120 km).

The only karst closely resembling the Judbarra one seems to be the Bemaraha tsingy field in Madagascar (Veress et al., 2008; Salomon, 2009). There are some differences, however, as the Bemaraha limestone is much thicker, purer and not limited by an impervious layer at shallow depth. The karstogenic process proposed is also different, as phreatism is more important than at Bullita: the watertable was originally close to the surface and then several levels of passages formed by progressive lowering. Concurrent de-roofing followed this process leaving narrow grikes, reaching a maximum depth of 120 m.

In order to form systems similar to Bullita, it appears that at least two conditions are essential:

1. thin limestone resting on a thin subhorizontal shale bed;
2. monsoon rainfall regime (infiltration rate and style);

They are commented on in detail as follows.

In the **first** condition, thin limestone on a shale bed, it is important that an aquitard be present at shallow depth in order to constrain speleogenesis within the decompression zone, that is the epikarst. Indeed in thicker limestone, the passages would develop in the hypokarst where, due to a higher degree of hierarchicalisation (Klimchouk, 2000), the channel network would not be as dense as in the case of Bullita.

The **second** favourable condition is the monsoon rainfall regime, which prevails in the Judbarra region. It fosters slow surface dissolution. Once the joints are sufficiently enlarged and once the surface is free of soil cover, rainwater rapidly sinks underground, where it retains much of its dissolution potential. As the rain events are mostly torrential and of short duration, coupled with a strong evapo-transpiration, the karren should remain wet only for a limited number of days a year: conditions that measurably slow surface lowering (Dreybrodt, 2004b). As the caves remain flooded for longer times, most of the dissolution has occurred at this level. In contrast, where a karst is covered with soil or is barren but exposed to a temperate or cool humid climate, with moderate rainfalls widely spread over the year, the rate of the surface lowering is about one magnitude faster than for Bullita. These latter conditions are unfavourable for the formation of Bullita-type epikarstic systems.

Age of the cave system

The age of the formation of the cave has not been discussed at length by other authors, who only estimated it to 'be of very great antiquity' (Dunkley, 1993), probably with reference to the relicts of large phreatic-shaped passages partly dismantled by surface erosion, such as the Golden Arches (Figures 14, 15). In order to estimate the age of the Bullita Cave System, one has to accept that, with only very rare exceptions, the cave is developed exclusively where the Supplejack Dolostone Member has been stripped bare of its Upper Skull Creek cover (Figures 5, 12a, 29).

Concurrent timing of cave and surface karst evolution

The age of the cave is diachronous in that new passages are being initiated at the advancing eastern edge (under zone 1) at the same time as old passages are being unroofed and destroyed at the trailing western edge (zone 4). What we are discussing is the maximum time taken for a passage to go from youth to old age and destruction.

Where the cave system comprises small incipient passages close to the Supplejack – Upper Skull Creek outcrop line, the age may be accepted as the most recent, being equivalent to the time necessary for a primary crack to be enlarged into a crawlway negotiable by cavers. The minimum age must also correspond generally to the time necessary for this outcrop line to retreat eastwards for a distance of 50-100 m (Figures 5, 12a and 29). On the other hand the maximum age must be reached where the passages are being destroyed by advancing surface dissolution and collapse due to excessive widening of the shale passages, near the transition between zone 3 and the degraded karst (zone 4). Here the age of the passages is equivalent to the time necessary for the original Supplejack – Upper Skull Creek contact line to have retreated from the actual degraded karst boundary to its present day position (a maximum of 900 m). At the zones 3-4 transition about half of the mass of the Supplejack Dolostone Member (taken vertically) has been dissolved. The rare cases where the cave extends down into the Lower Skull Creek carbonates under the degraded karst and even beyond, are not taken into consideration here.

Age deductions from chemical denudation rates

Karst denudation rates have been measured world-wide by a number of methods, which have, however, proven to be of variable reliability (Gunn, 2004).

The best way to calculate this rate in any area is to ascertain three parameters: rainfall; deep infiltration; and water chemistry. The rate is expressed as the thickness of a limestone sheet dissolved per unit time and comprises three parts: the carbonate dissolved at the surface; in the epikarst; and in the endokarst. At a world scale 75 to 90% of the denudation takes place at the surface and in the epikarst (White, 2000). This means that these numbers are applicable for Bullita since the cave is dominantly developed within the epikarst, assuming that the hypokarst portion is negligible. Unfortunately, in the case of Bullita the data necessary for an accurate calculation of the denudation rate are approximate or missing: only the present rainfall is fairly well known (810 mm at Bullita homestead), but no precise data are available about the potential evapo-transpiration (about 2000 mm/a, BOM 2011b), nor of the chemical composition of the deep aquifer (only accessible in Dingo Cave) or of the water transiting though the system during summer flooding.

Therefore, the only way to estimate the denudation rate is by comparison with other areas of more or less similar rainfall and climatic type. The denudation may then be estimated by simple comparison of Bullita annual rainfall (810 mm) with curves and regression lines from various areas in the world. Three comparable results are 19.5 mm/ka (Lang, 1977), 33 mm/ka (Pulina, 1974) and 50 mm/ka (White, 2000). In Yucatan and Madagascar, the denudation was estimated to be 20-30 mm/ka for rainfalls of the same order of magnitude as at Bullita (Salomon, 1997). In conclusion, it appears from these data that a denudation rate around 20 mm/ka seems a reasonable estimate for Bullita. Taking into account that the cave system is dominantly developed in the epikarst, this represents a 20 m thick limestone layer per million years, which is the total thickness of the Supplejack. If, as proposed above, the cave passages are destroyed when about half of the limestone is dissolved, this would reduce the age of the oldest part of the cave to 0.5 Ma.

This rate, however, is only valid under the present day climatic conditions. It has been mentioned previously that conditions were more humid than now during most of the middle Pleistocene, which suggests even higher denudation rates in the past. However, Bullita differs from normal karsts in possibly having a fast hydraulic transit; so that, at the resurgences, the average water hardness might not be as high as in the classic cases. For instance, in an extreme case, if the average composition was equivalent to equilibration in atmospheric pCO_2, the age could rise to something like 2 Ma for the cave and 4 Ma for total dissolution of the limestone. These are the maximum ages to consider. Future wet season water analysis in the cave and at the resurgences, for instance by automatic sampling, would be informative.

The numbers quoted above, however, apply to the total karstic denudation. As the Bullita case is complex, it is necessary to distinguish dissolution in the karrenfield from that in the cave, in the soil covering the passage floor and in the 'levees'.

The tablet method can roughly evaluate the difference between these various karst environments. It measures the dissolution of thin limestone plates, that are exposed to rain within, on, and above the soil (Gams, 1989). The measurements in the air and on the ground surface are only representative of the lowering of the pinnacle tops since, like the tablets, the tops rapidly shed rain water. In fact the pinnacle sides receive both rain and flowing water from the upper surface, thus explaining the evolution of their shape towards sugar loaf profiles.

World data from tablets in the air and on the ground (Gams, 1989) indicate a lowering of 4.5 to 4.7 mm/ka for subtropical humid to semi-arid climate (rainfall: 445 mm/a) and 1.8 to 2.3 mm/ka for subtropical arid and semi-arid climate (197 mm/a). More local data from Chillagoe, Queensland, where the annual rainfall of 855 mm, is characterised by a monsoon regime similar to Bullita, give denudation rates of 2.0 to 2.4 mm/ka (Gams, 1985).

For the Bullita Cave System, a lowering of the pinnacle tops of about 5 m is observed at the stage where the passages are destroyed by a combination of dissolution, collapse and silting. From the above denudation rates, it appears that under the present day climate the corresponding lowering time should be 2 to 3 Ma. As expected, these times are well in excess of the previous numbers deduced from the total denudation. Under the more humid and probably cooler conditions of the past, encompassing parts of the Pliocene and Pleistocene, higher rates are more likely. Moreover, as seen previously (page 46), the physical erosion of the dolomite particles, which represent a non-negligible portion of the limestone, is also contributing to hasten the denudation of the karren.

Finally, one has to consider the rate of dissolution in the degraded karst (zone 4). In the 'levees' forming a great part of the 'matrix' of the blocks and pinnacles in this zone, the higher CO_2 content and the longer residence time of water suggest that the carbonate dissolution there should be more important than in the karrenfield and even than in the open cave. Based on the tablet method, the dissolution should be 3 to 6 times greater than that of the surface (Gams, 1985, 1989). As already stated in the section dealing with speleogenesis (page 60), however, finer-grained detrital carbonates in these soils are lessening this rate as far as the walls are concerned, but to an extent which cannot be estimated. Nevertheless, the relatively narrow degraded karst zone, probably not wider than a quarter of the width of the Supplejack outcrop band (Figure 5), suggests that the large boulders are rapidly dissolved in contact with the sedimentary filling of the 'levees'. This means that the age of the complete dissolution of the Supplejack will not be considerably older than the age for the cave and less than the value of 4 Ma quoted above.

In conclusion, the age of the oldest passages can be estimated to be between 0.5 and 2 Ma, that is Pleistocene. The total dissolution of the Supplejack limestone might be completed after a time not considerably longer than these numbers. From the data at present in hand, it appears that the cave is quite young, a conclusion which can be updated only when more field observation becomes available. This conclusion is to be taken as a working hypothesis.

Age deductions from regional denudation history

The age of the caves can also be estimated from the progression of the erosion surfaces. The Bullita Cave System developed after dissection began to destroy the presumed Miocene-Pliocene Wave Hill Surface (140-190 m ASL – see 'Land surfaces' section on page 43 and Figure 10) which suggests a Pleistocene speleogenetic age. In the Spring Creek karst area south of the Bullita Cave System, very similar caves developed, but at the higher altitude of 175 m. Their genesis and age, however, should be similar, since both result from the same karstic denudation and slope retreat processes.

The rate of slope retreat should not have had an important impact on the speleogenetic age, except that the karren zones described previously might be wider or shorter according to this rate. In the cases of a fast retreat (steep slope), the oldest zones may be 'amputated', as for instance at some places in Limestone Gorge and along the East Baines River, where the degraded karst (zone 4) has had no time to develop.

In conclusion, it appears that the age of the caves estimated from morphological evolution is in agreement with the maximum value of 2 Ma suggested by chemical denudation.

Note that we are not considering here the age of the paleokarst breccias, nor that of the subjacent karst of the Newcastle Range, which are in different geological settings (Grimes, 2012b).

The complex karstification of dolostone

In the Judbarra / Gregory karst, field evidence suggests that the micritic dolostone of the Lower Skull Creek is poorly affected by deep-seated karst dissolution, except in some places where it is overlain by dolomitic limestone of the Supplejack which in contrast is well karstified. Under a climatic type comparable to Australia, control by rainfall has been observed in northern South Africa and Namibia, where well developed endokarsts occur in calcite-free dolostone, but only where the rainfall is relatively high (Martini, 1985; Martini et al., 1990). In the more arid area of Namibia only the limestone formations show endokarstic developments, as in the Judbarra / Gregory Park.

The case of Bullita may seem more complex, as speleogenesis in dolostone occurs exclusively under the karstified Supplejack limestone. However, this can be related to the fact that the karrenfield on the overlying dolomitic limestone drains underground where large volumes of water are retained during the rainy season. As the water is stored for a significant time in the cave systems, the situation is equivalent to a higher rainfall regime.

Therefore, compared to limestone, the control of karstic dissolution of dolostone seems more sensitive to rainfall and evapo-transpiration. Nevertheless, at a world scale the process remains somewhat paradoxical. For instance, in the Alpine karst, which is developed in a humid and cold climate, important cave systems are hosted in Triassic limestone resting on thick dolostone which acts as an impervious layer (Audra, 2000). Here dolostone is resistant to karst dissolution, in spite of a very humid climate. In this case, the low temperature is apparently the factor impeding karst development. In Bullita the more resistant behaviour of secondary dolostone is also not easy to explain (page 42). As a general rule other factors may play a role, such as local hydrothermal activity, past wetter conditions, karstification time duration, crystal size, Fe-Mn replacement in the dolomite lattice, and width of the initial jointing. Moreover, to make the story even more complicated, the rate of dolomite dissolution is more complex than for calcite (Palmer, 1991, 2007) and is still not fully understood (Dreybrodt, 2004a).

CONCLUSION

Distinctive features of the karst and caves

Distribution of the karst

Karst and cave development is mainly restricted to parts of the outcrop belt of the 20 m thick Supplejack Dolostone Member (Figures 1 and 2). The Supplejack has a well-developed karrenfield and associated underlying shallow horizontal maze caves, which show all stages from youth to old age within the width of the karrenfield (100-900 m). The cave system is mainly developed in the lower part of the Supplejack limestone and within a 3 m shale bed marking the top of Lower Skull Creek Formation, with localised deeper levels in the latter formation (Figure 12).

Lateral zonation of the karrenfield and the caves

The karst zones (Figures 5 and 12a) show a progressive evolution over time, and it is deduced that, as a result of lateral denudation, the zones are migrating eastward to follow the retreating contact with the overlying shaly Upper Skull Creek. In zone 1, recently exposed from under the impervious cover, the initial karren are shallow, and beneath the surface there are only incipient small cave passages, mostly impenetrable. Zones 2 and 3 show progressively deeper dissection of the karrenfield and corresponding growth of the cave passages within the Supplejack and in the underlying shale bed. Numerous visible connections appear between the surface grikes and the underlying cave passages. In zone 4, the degraded karst, both the karrenfield and the cave system break up into giant grikes and ruiniform blocks, more or less chaotic, as a consequence of widening and downward cutting of the grikes as well as ceiling breakdown in cave passages developed by erosion in the shale bed. In this degraded karst zone, accumulation of rubble and finer-grained material in the space within grikes, in relict caves and in chaotic zones, form ‘levees’ which impound wet-season rainwater within the cave system.

The Caves

The caves are extensive shallow, sub-horizontal, dense network maze systems (Figures 5 and 12). In plan, they show joint control and a lateral evolution in passage style that is linked to the development of the overlying karrenfield (see above). In depth, the cave levels are controlled by lithology and lithology-controlled hydrology: in particular the impermeable and incompetent shale bed beneath the Supplejack which in great part confines cave development to the epikarst zone. High-level passages within the Supplejack include ‘phreatic’ style tubular passages which are intersected by vertical fissure passages along the joints. The latter may connect to the surface grikes and also widen downwards, in places displaying bevelled ceilings. These passages are most common in the lower third of the Supplejack, and include the ‘omega’ tubes immediately above the shale bed which are now exposed in the ceilings of the cave chambers. The main cave development has been along the shale bed. There is evidence that this level floods extensively during each wet season. The Supplejack and Shale passages have expanded horizontally rather than in depth to form distinctive tented or inverted-T cross-section shapes, with flat ceilings or undercuts at the contact between the soft shale and the base of the Supplejack. Locally, large chambers occur with scattered shale pillars supporting the roof.

In some places, generally near the incised gorges of the East Baines River and Limestone Creek, lower cave levels have developed down to 20 m below the main shale bed, within the Lower Skull Creek dolostones and a second shale bed (Figure 12d).

There is considerable sediment in the shale-bed passages, both locally derived from the shale, and entering from above. This includes much organic material and active roots. The epikarst ‘soil’ zone is here, in the cave, rather than on the bare rock surfaces of the karrenfield.

Age

There is no direct evidence of the age of the cave systems which show a diachronous development from youth beneath the recently exposed zone 1 to old age and decay in zone 4. However, regional considerations and comparisons with other areas of similar climate, lithology and structure suggest that the age of the current cave system, from youth to old age, is not older than Pleistocene.

Controlling factors

The geological setting

Structural influences are the shallow dips and the well-developed jointing. The most important lithological factor is an impermeable and incompetent subhorizontal shale bed, 20 m below the karren surface, which has restricted development of the cave to the shallow epikarst zone. The shale bed initially perched the watertable, forming phreatic passages within the Supplejack, and later was easily eroded by vadose streams to form a major sub-horizontal drainage system.

The composition and the texture of the carbonates have influenced the rate and nature of dissolution. The presence of thinly interbedded dolomicrite and micritic calcitic limestone within the Supplejack may be a factor in restricting the main karst development to that unit. The carbonates in the Lower Skull Creek are mainly dolostones, and the Upper Skull Creek is mainly siltstone and shale with only thin beds of carbonate. Within the Supplejack belt, karst is further restricted to those beds that have not been modified by secondary dolomitisation (Figure 2).

The surface geomorphology

The present terrain is a result of long-term vertical erosion, which includes development and later dissection of two possible old land surfaces which may provide limits to the overall age of the caves and karst (Figure 10); and of shorter-term horizontal slope retreat with progressive exposure of the top of the Supplejack, and subsequent sequential development of both the karrenfield and the underlying cave – this is ongoing at present.

The bare rocky surface of the karrenfield has an important influence on fast water input to the caves (see hydrology, below) and the lack of surface soil means that the epikarst soil zone is now within the cave. The incised gorges have provided a greater potential gradient for the nearby watertables, which may have promoted the localised development of lower levels in the caves.

The hydrology

The present tropical monsoon climate has a strongly seasonal rainfall characterised by brief torrential storms. Pleistocene climates would have been wetter (interglacials) and drier (glacials). Most of the present water flow and speleogenesis occurs during the wet season, when the area is practically inaccessible. Thus most of the following is deduced rather than observed.

There is a strong need to monitor the wet season processes, possibly by using flood-proof data-loggers that would be installed and recovered during the dry season.

Fast, vertical, diffuse, autogenic input of rainwater occurs through the numerous fissures of the karrenfield. Only limited solution occurs during the short transit time, so the water is still aggressive on arrival within the cave. Lesser allogenic inputs occur at the leading edge of karren zone 1 where channelled runoff from the impermeable beds of the Upper Skull Creek enters the karrenfield via numerous small fissures, and possibly some inputs also come from deep confined origins, which are probably reducing. Mixing of these three waters beneath the leading edge of the karrenfield may have assisted in passage initiation under zone 1 (Figure 29).

Within the cave systems there is an early stage of a perched aquifer above the shale bed, with subsequent enlargement of joints within the Supplejack by vertical vadose flow and widening of their lower parts by seasonally ponded water. The rubble and sediment ‘levees’ at the trailing edge of the degraded karrenfield cause seasonal ponding of aggressive rain water within the cave. This water forms both open pools and cave streams and also soaks into the cave sediments and rubble. It would be responsible for solutional enlargement of the lower parts of the fissures within the Supplejack, of the carbonate material within the shale beds and of the carbonate rubble and sediments that have occupied the cave passages in the ‘levees’. Organic activity within the cave sediments may make the ‘soil’ water more aggressive, but the diffuse flow through the sediment would also somewhat slow the rate of solution of the cave walls in contact with the sediments. Both the seasonal flooding, and the solution at the soil-rock contact may explain some of the ‘phreatic-like’ patterns seen on the cave walls. Horizontal vadose stream flow through the cave systems during the wet season has eroded the shale bed, undermining the overlying limestone to contribute to the collapse in zone 4.

Apart from the Efflux, which is a major, but seasonal, spring beside the river, fed from a low-level passage system (Figure 5), outflows from the system are mostly cryptic and only active during the wet season.

While it is possible that there may have been earlier minor speleogenetic activity in a hypogenic, or at least a confined aquifer setting, there is no evidence of this having contributed to the known maze cave systems.

To summarise

The caves of the Judbarra / Gregory Karst are epikarst maze systems lying at shallow depth beneath a well-developed karrenfield. There is a strong link between the evolution of the karren and of the underlying caves. The character of the karst is controlled firstly by the geology: both the lithology of the Supplejack and, most importantly, the presence of a horizontal shale bed which has restricted cave development to shallow depths which are connected directly to the surface karrenfield; and secondly, by the combination of climate and hydrology, with rapid vertical inputs of wet season storms resulting in aggressive water ponding within the cave, so that an unusually large part of the dissolution occurs near the base of the limestone, rather than at the surface.

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