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Surface Karst Features of the Judbarra / Gregory National Park, Northern Territory, Australia

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Abstract

In the monsoon tropics of northern Australia, a strongly-developed karrenfield is intimately associated with extensive underlying epikarstic maze caves. The caves, and the mesokarren and ruiniform megakarren are mainly restricted to a flat-lying, 20 m thick, unit of interbedded limestone and dolomite. However, microkarren are mainly found on the flaggy limestones of the overlying unit. These are the best-developed microkarren in Australia, and possibly worldwide.

A retreating cover results in a zonation of the main karrenfield from a mildly-dissected youthful stage at the leading edge through to old age and disintegration into isolated blocks and pinnacles at the trailing edge. Cave undermining has formed collapse dolines and broader subsidence areas within the karrenfield. Tufa deposits occur in major valleys crossing the karrenfield. The karrenfield shows some similarities to other tropical karren, including tsingy and stone forests (shilin), but in this area there has not been any initial stage of subcutaneous preparation.

Keywords: Karst; karren; tsingy; stone forest; microkarren; ruiniform; epikarst; tufa; tropical; Australia.

Introduction

The Judbarra Karst lies within the Judbarra / Gregory National Park in the Northern Territory of Australia (Figure 1). This area was previously known as the Gregory National Park (and Gregory Karst).

This paper describes the surface karst features of the area and compares them with other tropical karsts. It builds on brief descriptions in Dunkley (1993), Bannink et al. (1995) and Grimes (2009). The Judbarra Karst also has extensive epikarstic maze caves underlying the well-developed karrenfield (Martini & Grimes, 2012). Subjacent karst collapse dolines and paleokarst features are also associated with sandstone units in the area (Grimes, 2012).

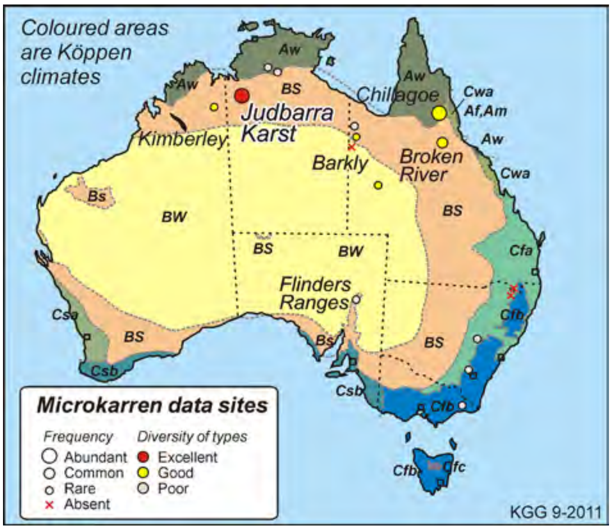

Figure 1: Location of the Judbarra Karst, with climate zones and other known microkarren sites in Australia.

Climate

Northern Australia has a tropical monsoon climate. The Köppen climate class for the Judbarra Karst region is semi-arid BShw (Figure 1). The present rainfall at Bullita homestead is 810 mm but a wetter climate may have prevailed 8-10,000 years ago (Canaris, 1993). The rainfall has a pronounced seasonality with a five-month summer 'wet' and a longer winter dry season (see Figure 2, and BOM (2011) for further details). Most rain in the wet season falls either in short intense thunderstorms, or in occasional cyclonic events lasting several days. Potential evapotranspiration is substantially greater than rainfall throughout the region, giving a deficit in excess of 1,000 mm per annum.

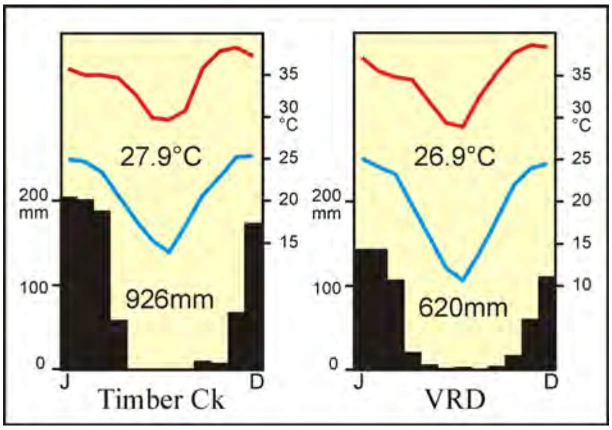

Figure 2: Climate of the Judbarra Karst area. Monthly mean maximum & minimum temperature and monthly rainfalls, with annual averages in figures, are shown for Timber Creek, 50 km to the north, and Victoria River Downs (VRD), 70 km to the east (BOM, 2011).

Vegetation

The area has a savanna woodland with narrow 'gallery forests' following the major streams. Scattered deep-rooted fig trees grow on the otherwise bare limestone karrenfields.

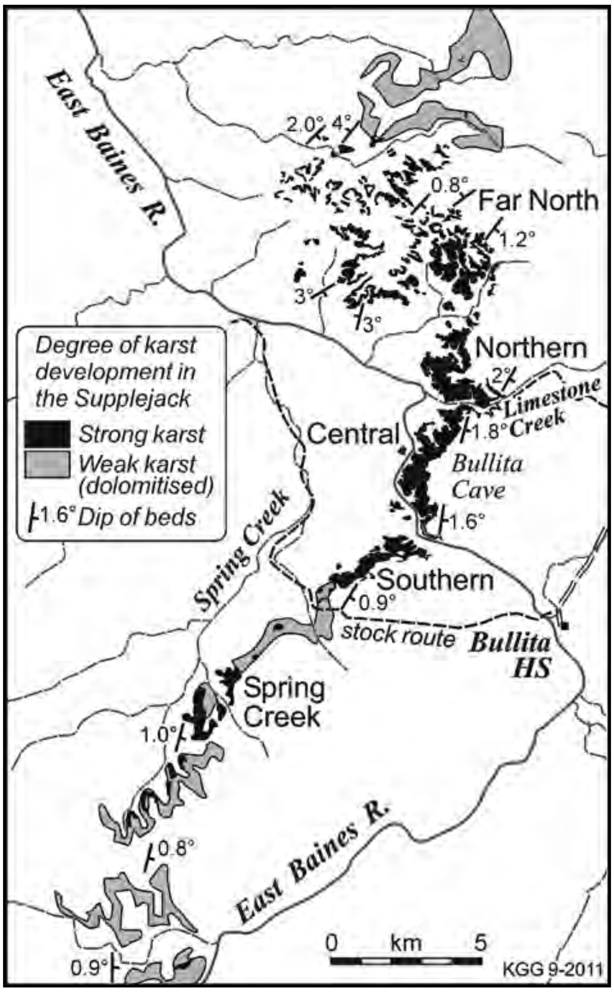

Figure 3: Location of the karrenfields (black) and named sub-areas within the Judbarra / Gregory Karst. (from Martini & Grimes, 2012).

Tropical karst and karren

Tropical karsts have a wide range of surface features, ranging from large towers down to microkarren. The largest features – e.g. polygonal karst, cone karst and towers are more characteristic of the wet tropics, and most tropical karst studies have been done in those climates. In the monsoon tropics of Australia, polygonal and cone karsts are absent, and the towers are restricted to a few areas, such as Chillagoe. The most common surface development is of grikefields grading locally to ruiniform relief: giant grikes, pinnacles and stone city or stone forest (Grimes, 2009).

Geology

The geology of the karst area (Skull Creek Formation and Supplejack Member) has been documented by others (Sweet et al., 1974, Dunster et al., 2000), and most recently by Martini & Grimes (2012).

The Judbarra Karst is developed in the gently dipping, unmetamorphosed Proterozoic *Skull Creek Formation*, 150-170 m thick (Sweet et al., 1974, Dunster et al., 2000; Figures 3, 4 & 5). It mainly consists of thin to medium bedded carbonate and calcareous siltstone, with laminae of shale. Thicker beds (typically 1 m) of massive carbonate are inter-stratified at intervals of a few metres. One of these carbonate beds, the Supplejack Member, is much thicker (15-20 m) and hosts the main karrenfield and caves (Martini & Grimes, 2012).

The Lower Skull Creek Formation is about 120 m thick. The upper part, which immediately underlies the Supplejack Member, consists mainly of very fine grained, well bedded dolostone (Martini & Grimes, 2012). The calcite-rich parts form thin seams interstratified in dolostone. A 3 m thick *shale bed* at the top of the unit is important for speleogenesis as it both initially perched the watertable, and later was easily eroded by vadose flow (Martini & Grimes, 2012).

The Supplejack Member has a distinctive outcrop pattern of cliffs and karrenfields that allows it to be easily identified and mapped (Figures 3, 4 & 5). Much of the unit has a laminated to thin bedding alternating between dolomicrite and calcitic limestone (see Martini & Grimes, 2012), but the upper parts tend to be thicker bedded. On outcrops the thin-bedded zones of the Supplejack tend to disrupt the development of rillenkarren and wandkarren on vertical faces (e.g. the tops of the blocks in Figure 13e). These thin-bedded areas also tend to have more chert nodules than are found in the more massive beds.

In some areas a later secondary dolomitisation occurs in parts of the Supplejack and this inhibits karren and cave formation (Martini & Grimes, 2012, and Figure 3). This is extensive outside the area shown in Figure 3, and is responsible for the restriction of the Judbarra Karst development to that localised area.

The Upper Skull Creek Formation, 30-50 m thick, consists of a rhythmic alternation of metre thick beds of slightly dolomitic limestone (10 to 35% dolomite), and thicker (~3 m) beds of soft calcareous siltstone and shale, which are generally poorly exposed (Martini & Grimes, 2012; Figure 6). However, occasional thicker beds of limestone (3-4 m) have been mapped higher up in the sequence (e.g. 's+1' unit on Figure 4). The thinner limestone beds form slabby outcrops and tessellated pavements (Figure 7).

Stromatolites

Stromatolites are common in the carbonate sequence. They are particularly well developed 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 soft brown muds of the Upper Skull Creek (Figures 6 & 8, and figure 9 in Martini & Grimes, 2012). The larger stromatolites have smaller laminated structures within them. Elsewhere, within the Supplejack and in the carbonate beds of the Skull Creek Formation, there are many smaller stromatolites, ranging down to polygonal groups with individuals only 10-20 cm across.

Structure

Bedding dips are gentle, and those shown on Figures 3 and 4 have been calculated from the intersection of

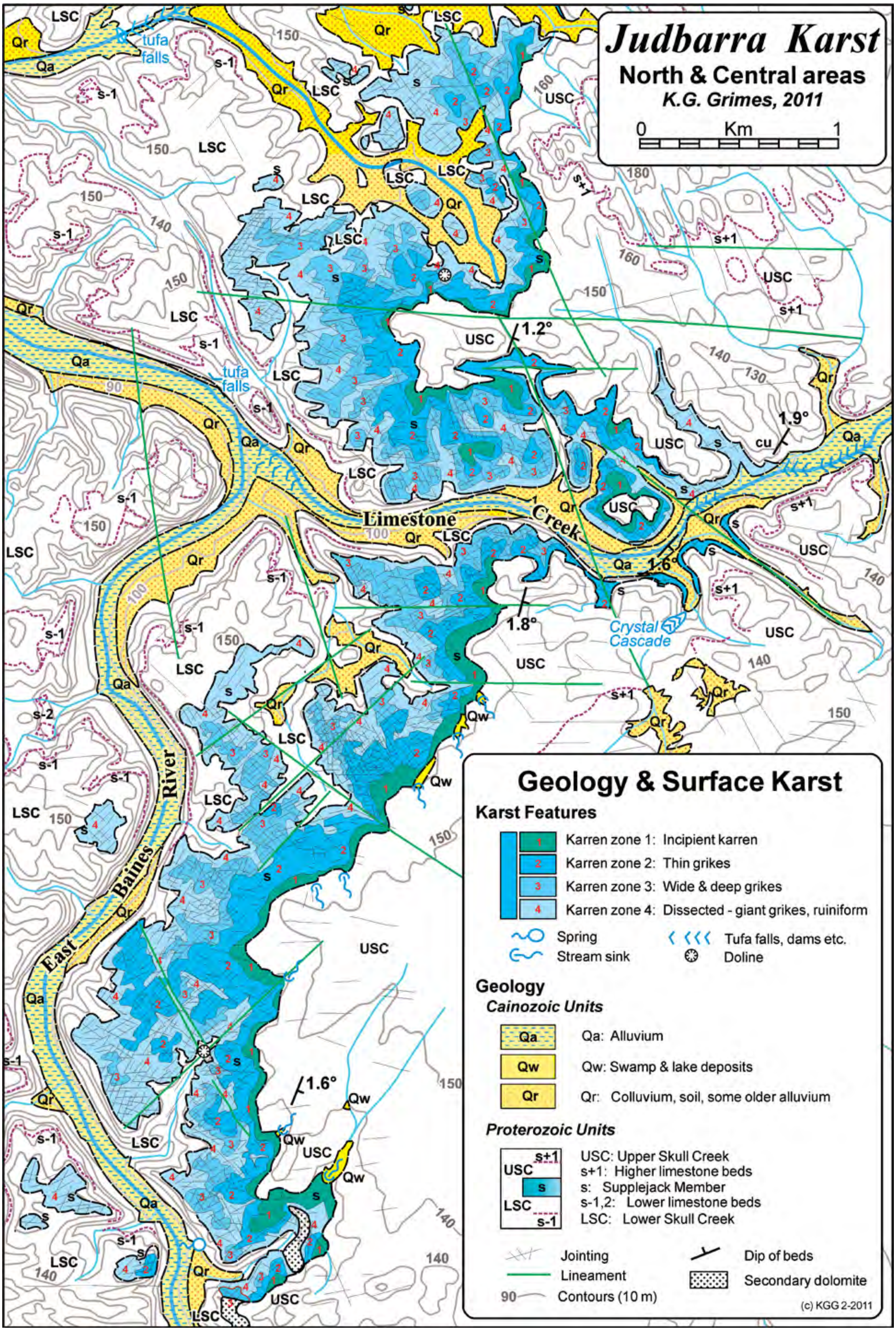

Figure 4: Geological and Surface Karst map of the Central and Northern areas of the Judbarra Karst. Based mainly on air-photo interpretation.

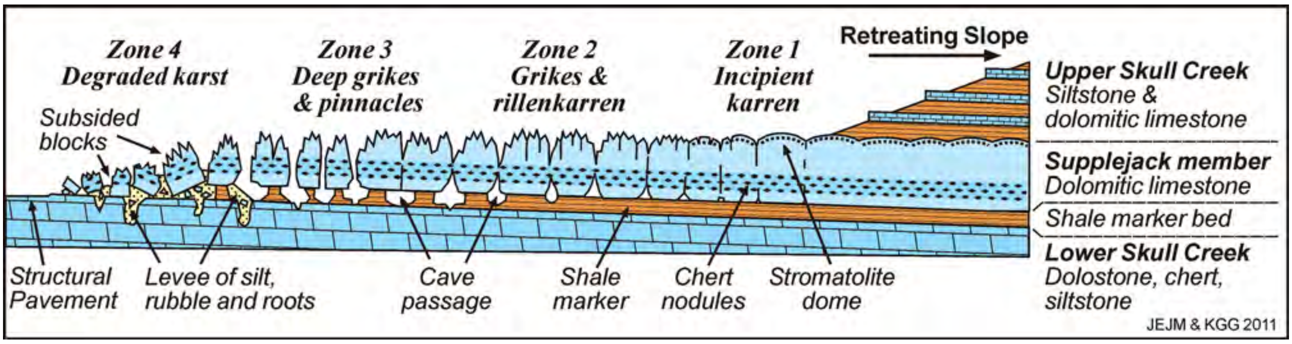

Figure 5: Diagrammatic cross-section of the karrenfield, showing the four zones, and geological units.

Figure 6: Stromatolite domes at top of the Supplejack, exposed by retreat of the overlying Upper Skull Creek Formation – being soft shale (pale grass) alternating with 1 m beds of resistant limestone (dark).

Figure 7: A tessellated pavement, with microkarren, on a thin limestone bed in the Upper Skull Creek Formation. 10 cm scale bar.

contour lines with the outcrop line at the top of the Supplejack[1]. In the central area, in the vicinity of Bullita Cave, the beds dip between one and two degrees to the ESE. Further north the dips vary but are still shallow, reaching up to 4 degrees, with several broad gentle anticlines and synclines along NE-SW axes (see Figure 3).

1 Structural and geological maps are available online at http://helictite.caves.org.au/data.html

Figure 4 shows joints and lineaments. The joint (grike) density on the Supplejack karrenfields is denser than can be shown at this scale, so the patterns have been generalised. However, this gives a useful overview of the structures which are controlling the grikes and the cave passage beneath them.

The most prominent jointing directions are about 035° and 135°, less commonly 095°. Typical joint spacings seen on the surface are 0.2 to 1 m (Figure 10a) but only some of these form the large grikes visible on the air-photos.

When the cave map is superimposed on the 1:8000 scale air-photos, some surface grikes correspond to cave passages, but there are many additional grikes in the areas between the mapped passages. Some of these appear on the cave walls as tight joints. Martini & Grimes (2012) discuss the possibility of pre-karstic widening of some initial joints (to a few centimetres), which might have accelerated the initial stage of karren formation at the leading edge of the karst.

Some major lineaments cross the grikefield and adjoining country (Figure 4) and could be formed by close-spaced joint-sets or faults. These can form flat-floored box valleys (Figure 13c, and see page 28).

Younger, Quaternary deposits

Narrow belts of alluvium (*Qa* on Figure 4) follow the main valley floors, with occasional slightly higher terraces visible beside the East Baines River. Colluvial slope deposits (*Qr*) are common in the stronger relief of the far northern area, and beside the main rivers. Areas of soil cover (*Qr*) related to the mud beds in the Upper Skull Creek are common on the gently undulating plateau surfaces to east and west of the river in the Central (Bullita Cave) area.

Where short streams flow off the Upper Skull Creek onto the karrenfield these sink into narrow fissures and have some associated swampy areas (*Qw*) which appear to flood briefly during the wet season.

Tufa deposits of Limestone Creek and elsewhere have been described by Canaris (1993) and are described briefly later (page 29).

The Landscape

The present topography is a result of long-term vertical erosion to form an integrated network of valleys and shorter-term horizontal slope retreat with progressive exposure of the top of the Supplejack, and migration of its outcrop belt – this is ongoing at present.

The Judbarra Karst region and its subregions (Figure 3) are described in Martini & Grimes (2012). The karst is mainly restricted to the outcrop belt of the gently dipping Supplejack Member. Extensive maze caves underlie the dissected surface and there is a close relationship between the surface and underground evolution of the area (Storm & Smith, 1991; Bannink et al., 1995; Martini & Grimes, 2012).

In the central part of the karst region (Northern, Central and Southern karst areas) the land surface is a gently undulating plateau, possibly a part of a late Tertiary peneplain (figure 10 in Martini & Grimes, 2012), which lies at elevations between 130 and 150 m.

The Supplejack has only a gentle dip so its outcrop belt, and karrenfield, tend to follow the contours (Figures 3 & 4). In areas of gentle slopes, as in the central part, this results in a broad outcrop belt, and extensive karrenfields and caves (Martini & Grimes, 2012). However, in the Far North (Figure 3), where there are high ridges with steep slopes, the Supplejack outcrop belt is much narrower, less than 100 m across, and frequently interrupted by sheets of colluvial material moving down from above. Nonetheless, karren are still well developed.

The present gorges of the East Baines River and Limestone Creek suggest that there has been a recent phase of channel incision, to an elevation of 100 m ASL, that might not have had a great deal of associated valley widening (and therefore of slope retreat above the karrenfield). 'Recent' must, however, predate the 8-10,000 BP dates on the older tufa deposits within Limestone Gorge (Canaris, 1993; see Tufa, page 29)

Surface Karst

Karren and other surface karst features are widespread on the Skull Creek Formation, and particularly common on the Supplejack Member. Brief descriptions have appeared in Dunkley (1993), Bannink et al. (1995) and Grimes (2009). At a large scale the morphology is characteristic of a fluvio-karst with an integrated surface drainage (Dunkley, 1993).

The most obvious and distinctive feature is the Supplejack karrenfield, which forms a contorted and irregular band which is spectacularly displayed on aerial photographs and satellite imagery (Figure 3, and view Google Earth at 16° 4.0'S, 130° 23.0'E, eye-height 13 000 m). Its width varies from 100 m to 900 m. The karren can be divided into four zones of increasing dissection (see below).

As the very gentle dip of the Skull Creek is eastwards and as the general slope of the land is westwards, the exposure of the Supplejack from beneath its Upper Skull Creek cover proceeds eastwards (Figure 5). The karrenfield is therefore diachronous, being youngest in the newly exposed zone 1, and oldest in zone 4 where it is disintegrating. The overall age, i.e. that of the oldest parts of the karrenfield, is uncertain, but Martini & Grimes (2012) use several approaches to deduce that the karren and underlying caves are not older than the Pleistocene.

There is no soil cover on the karrenfield beyond a narrow (<10 m) fringe where the Supplejack is first exposed. The insoluble part of the muds from the overlying Skull Creek is washed down through small impenetrable grikes and fissures to the incipient passages of the cave beneath.

None of the karren features, apart from the broad stromatolite domes, predate exposure to the surface. The genesis of the karren is entirely subaerial, which differs from some theories proposed for the development of shilin (stone forests) and tsingy karrenfields (see discussion on page 30).

Martini & Grimes (2012) discuss the surface micro-morphology and lithological controls on solution in the karren-fields. The karren morphology is controlled more by its limestone component than its dolostone one, which is quantitatively minor. In most cases the sculpturing reveals no evidence of differential dissolution rates between the limestone and dolostone seams, except at the microscopic scale.

Terminology

Karren nomenclature and size groups

The nomenclature of karren types is complex (Ginés, 2004, Ginés et al., 2009). Angel Ginés (pers. comm. 2005), suggested a division into several size ranges:

- *Nanokarren*: Microscopic features – recognisable through a 1 mm grid (i.e. widths significantly less than 1mm)
- *Microkarren*: Small-sized rills and pits – recognisable within a 1 cm grid (microrills, etc).
- *Mesokarren*: Normal-sized karren – recognisable within a 1 m grid (rillenkarren, kamenitza. runnels, grikes, etc.).
- *Megakarren*: Large-sized karren – recognisable within a 10-100 m grid (giant grikes, pinnacles, box valleys, etc.).
- *Karrenfield*: Composite landforms – involving a variety of karren types in a range of sizes, including ruiniform terrain (see below).

Note that Grimes (2007, 2009) used *macrokarren* for the 10 m grid, but *megakarren* seems to have had more usage (e.g. the karst entry in the German wikipedia (http://de.wikipedia.org/wiki/Verkarstung) uses *megakarren* for metre-sized karren). These large-scale karren have also been called *megalapies* (e.g. Salomon, 2009).

In the present study, the distinction between micro-, meso- and megakarren is important as these have different distributions in the area (Table 1). The best mesokarren by far are developed on the Supplejack dolomitic limestone, and megakarren are restricted to this unit. Outside the Supplejack Member there are well-developed microkarren in the Upper Skull Creek Formation, but few mesokarren, except on the occasional thicker bed mentioned above (see Geology, page 16).

Ruiniform relief is a broad term (Mainguet, 1972) used for sharply dissected, structurally controlled, composite landscapes of the giant grikefield, stone city and stone forest type, which are characterised by numerous vertical-faced blocks and pinnacles of rock separated by joint-controlled fissures or wider eroded areas. The term *ruiniform* has been mainly used in describing sandstone landforms (e.g. Young et al., 2009) which are of possible parakarst origin, but similar joint-controlled forms occur on carbonate karst, e.g. shilin, tsingy and labyrinth karst (Ford & Williams, 2007; see pp. 323, 335, 391) and *ruiniform relief* is used here as a broad term to include all the sub-types.

Karren zonation.

The karrenfields on the Supplejack show a zonation (first recognised by J. Dunkley in an unpublished report, 1991) which results from progressively longer periods of exposure at the surface after slope retreat has removed the overlying muddy beds of the Upper Skull Creek; the zones are migrating towards the retreating contact. This zonation starts with incipient karren development on recently exposed surfaces and continues through progressively deeper dissected karren to a final ruiniform stage of isolated blocks and pinnacles at the outer edge (Zones 1 to 4, see Figures 4, 5, 8, 9).

The changes from one zone to the next are gradational and the boundaries shown on Figures 4 and 8 are somewhat subjective. A study of the map (Figure 4) and air-photos (Figures 8 & 9) illustrates this gradational character, and also shows that while zone 1 is a continuous belt on the eastern edge, zone 2 is less continuous, and zones 3 and 4 have a much less consistent pattern which includes embayments and inliers of zone 4 within the younger zones.

From East to West, that is, youth to old age, the karren zones are as follows.

Karren Zone 1

The youngest zone is a freshly-exposed surface, up to 100 m wide, formed on the top of the Supplejack by stripping of the overlying Skull Creek Formation. It is initially a smooth surface with well-preserved stromatolite mounds (Figures 6 & 8).

This zone has only incipient mesokarren development (Figure 10a), but has well-developed microkarren. The surface quickly becomes sculptured by incipient rillenkarren (Figure 10a) with superimposed microkarren (Figure 11d). Etching of joints and bedding produces splitkarren and eventually small grikes (Figure 10b). Kamenitza are common, but not as large as seen in zone 2.

Away from the contact, increasing dissection produces small spitzkarren up to 0.5 m high, and grades to zone 2.

Karren Zone 2

In Zone 2 the stromatolite domes are still recognisable locally, but are strongly dissected by a variety of mesokarren, including numerous large kamenitza (up to 2.5 m wide and 0.4 m deep) and spitzkarren up to 1 m high (Figure 10c). Grikes are wider and deeper; averaging 2 m deep, but with considerable variation, including occasional narrow connections to the cave passages below (Figure 10c). Drainage from the spitzkarren is by short runnels connecting the kamenitza and feeding to the grikes (Figure 12e).

The transition to zone 3 is quite gradual and irregular.

Karren Zone 3

Zone 3 has wider and deeper grikes (Figure 10d), and connections to the cave become more common, though still narrow. Traversing the surface is difficult. The dominant features between the grikes are fields of pagoda-like spitzkarren pinnacles sculptured by rillenkarren and up to 2 m high (Figures 10d & 12c). Wandkarren, cockles and horizontal solution ripples appear on the grike walls and the sides of the larger spitzkarren (Figure 12c).

Undermining by the caves below has formed either occasional collapse dolines where only a single block of grikefield has disintegrated, or broader areas of mass-subsidence (see Figures 13b,d).

Karren Zone 4

In the oldest zone the surface has become completely dissected and megakarren features appear. Giant grikes 1-5 m wide penetrate to the cave floors 10-15 m below and divide blocks of rock up to 20 m wide with smaller grikes and strong spitzkarren on the tops (Figure 10e), and wandkarren, rillenkarren and cockles on the walls (Figure 14). As the giant grikes widen, and cave undermining destroys some blocks, one gets a ruiniform topography of isolated blocks, many of which are tilted (Figures 13e & 15). Finally there is an abrupt change to a broad flat-floored structural pavement developed on the Lower Skull Creek with only scattered ruiniform blocks and sculptured pinnacles (Figures 5, 8 & 13e). The width of zone 4 is irregular; sometimes over 100 m wide, but can be completely missing.

Along major lineaments or minor faults, dissolution was more intense, with development of long box valleys which cut across all zones of the karren-field but tend to become wider towards the more mature stage. They are partly responsible for the narrow necks between the various sectors of the Bullita Cave (see Martini & Grimes, 2012)

Vertical Zonation

In addition to the lateral zonation, one also sees vertical variations controlled by the bedding thickness and presence of chert nodules (Figure 13e). In the thin-bedded, chert-rich unit (Figure 5) the bedding forms numerous horizontal notches which disrupt the vertical flow of water down the walls of the grikes and stone city blocks. This inhibits development of rillenkarren and,

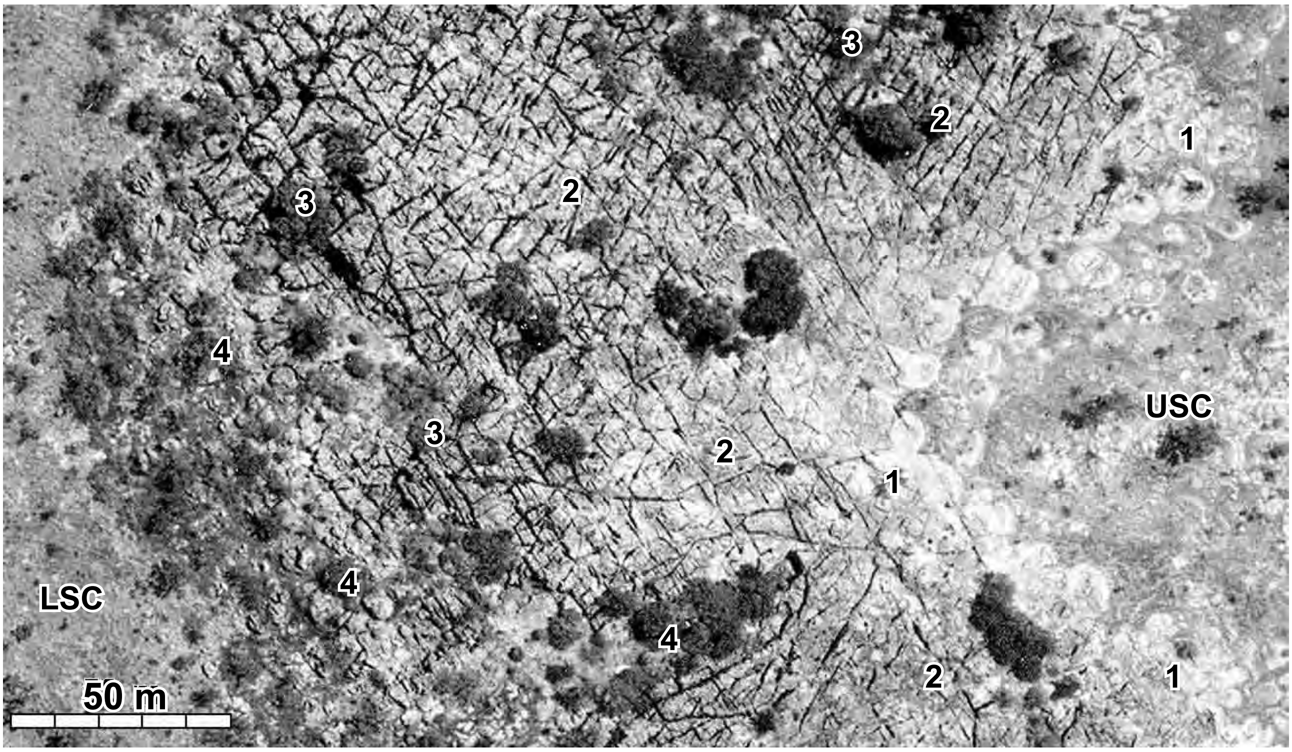

Figure 8: Air-photo of karrenfield developed on the Supplejack Member in the Northern Area. Zones 1 - 4 indicated by numbers. 'USC' is Upper Skull Creek, 'LSC' is Lower Skull Creek. Pale circular patches in zone 1 are stromatolite domes. *Air photo (c) Northern Territory Government, 1989*.

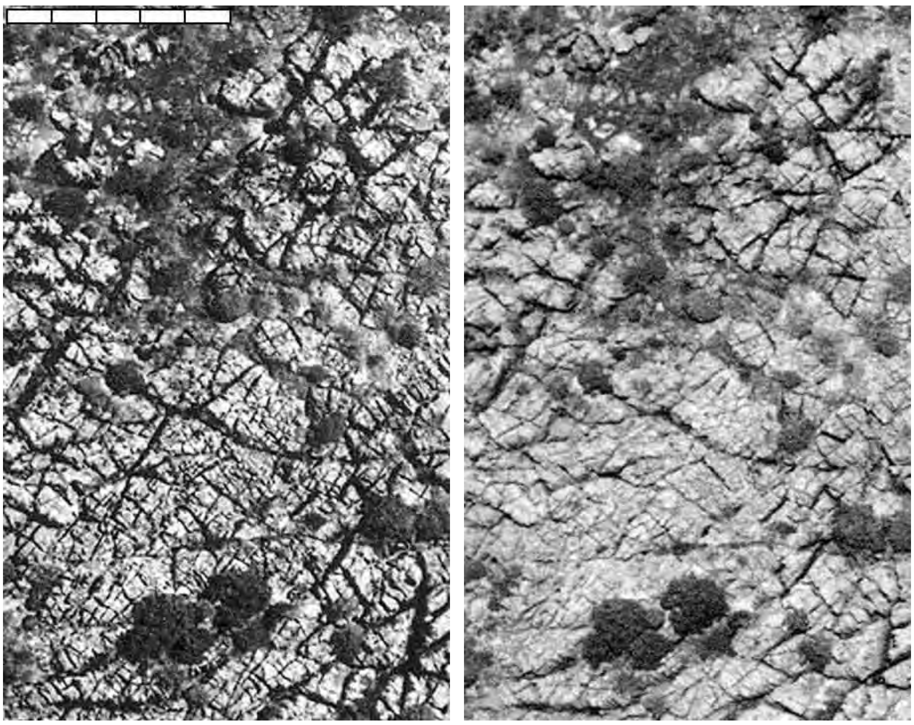

Figure 9:

Stereoscopic view of karrenfield in the Northern Area. Zone 3 (bottom) is grading to Zone 4 (top). Note the hierarchy of grike patterns – giant grikes separate blocks which have sets of smaller grikes and spitzkarren on their tops. 50 m scale bar.

Additional stereoscopic views appear in Grimes, 2009 (fig.13) and Martini & Grimes, 2012 (fig.7).

Air photos (c) Northern Territory Government, 1989.


a
b
c
d
e

Table 1: Distribution, abundance and size of karren types in the four karren zones of the Supplejack Member, and the Upper and Lower Skull Creek Formation (USC & LSC, respectively).

	USC	Zone 1	Zone 2	Zone 3	Zone 4	LSC
microkarren	a, l: <0.6mL	c, m	r, s	r, s	vr	r-c?, m
stromatolite domes	r, m	a, l: 5-12m W, <2m H	r (dissected)	–	–	–
tessellated pavements	c, s	r, s	–	–	–	r, s
splitkarren = v-notches	c	a	r	r	vr	c
rainpits	r[1]	r-c	c	r	r	r [1]
rillenkarren	r, s[1]	c, s: <0.2m L	a, m: <0.9m L	a, l: <2m L	a, l: <2m L	r, s [1]
trittkarren	–	r, s	–	–	–	–
kamenitza	?[1]	c, m: <0.8mW, <0.2m D	a, m-l: <2.5mW, 0.4m D	c, m: <2mW, <0.4m D	c,m: <1mW, <0.4mD	r, s
runnels	–	r, s	c. s	a, s-m	?	–
spitzkarren	–	r, s: <0.3m H	c, s: <1m H	c, m: <2m H	c, l: 1-5m H	–
bedding slots	c, s	c, s	c, s	c, m	c, l	c, s
cockles	–	r (modifying rillenkarren)	?	r	r	–
grikes[2]	r, s; c, m[1]	r, s: <1m W, <0.5m D	c, m: <1.5m W	c, l: <4mW	c, G: 2-6m W	- ; r, m [1]
wandkarren	–	–	–	r: <3mV	c, m-l: <5mV	–
solution ripples	–	–	–	r	r	–
dolines	–	–	–	r, m	c, m-l	–
box valleys	–	Cut across all zones but more common in zones 3 & 4. Floors are on LSC				
ruiniform relief: giant grikes, pinnacles, stone city etc.	–	–	–	–	c, l-G.	–
Abundance: –, absent; vr, very-rare; r, rare; c, common; a, abundant. Size: s, small; m, medium; l, large; G, giant. Size refers to the most significant dimension (L, length; W, width, H, height; V, vertical length). [1] The type is more common on the occasional thick limestone bed in the LSC & USC [2] In zones 2-4, maximum grike depth is that of the cave floors; width is a better guide to size						

to a lesser extent, wandkarren. Gale et al. (1997) report a similar control of detailed sculpturing by bedding thickness in a part of the Barkly Karst, Queensland, as do Knez & Slabe (2001) for the shilin stone forests of China.

Microkarren

Microkarren are finely-sculptured forms, typically recognisable within a one cm grid, that appear to occur mainly in arid climates – but not necessarily hot-arid, since they have been reported from Greenland and Tibet (Davies, 1957; Waltham, 2004). However, these cryptic forms are poorly documented and it is too early to make definite statements about their distribution.

Figure 10 (facing page): The karren zones.

a: Zone 1, near the advancing edge. Incipient rillenkarren, rainpits and splitkarren.

b: Zone 1 to 2 transition. Kamenitza and incipient spitzkarren, some small grikes in background.

c: Zone 2. Small, but well-developed grikes and spitzkarren.

d: Zone 3. Deep grikes, tall spitzkarren.

e: Zone 4. Giant grikes separate blocks with pagoda spitzkarren on top. Wandkarrren on sides of grikes.

Microkarren are best developed on gentle slopes, but some microrills occur on slopes up to 60° and short decantation microrills occur on the vertical sides of cobbles and slabs.

No detailed studies of their genesis have been made, but solution by thin films of water, dew or light rain, with surface-tension effects, may be their most likely origin (e.g. Ford & Lundberg, 1987; Ginés, 2004; Ford & Williams, 2007, p.323-4; Gómez-Pujol & Fornós, 2009). However, Rhys Arnott (Ranger at the Gregory National Park in 2005) said that dew is rare in the Bullita area. Possibly the high humidity during the wet season allows films of water to remain on the surfaces after rain for longer periods than in other climates. Some forms, e.g. micro-pits and simple etching of structures, may

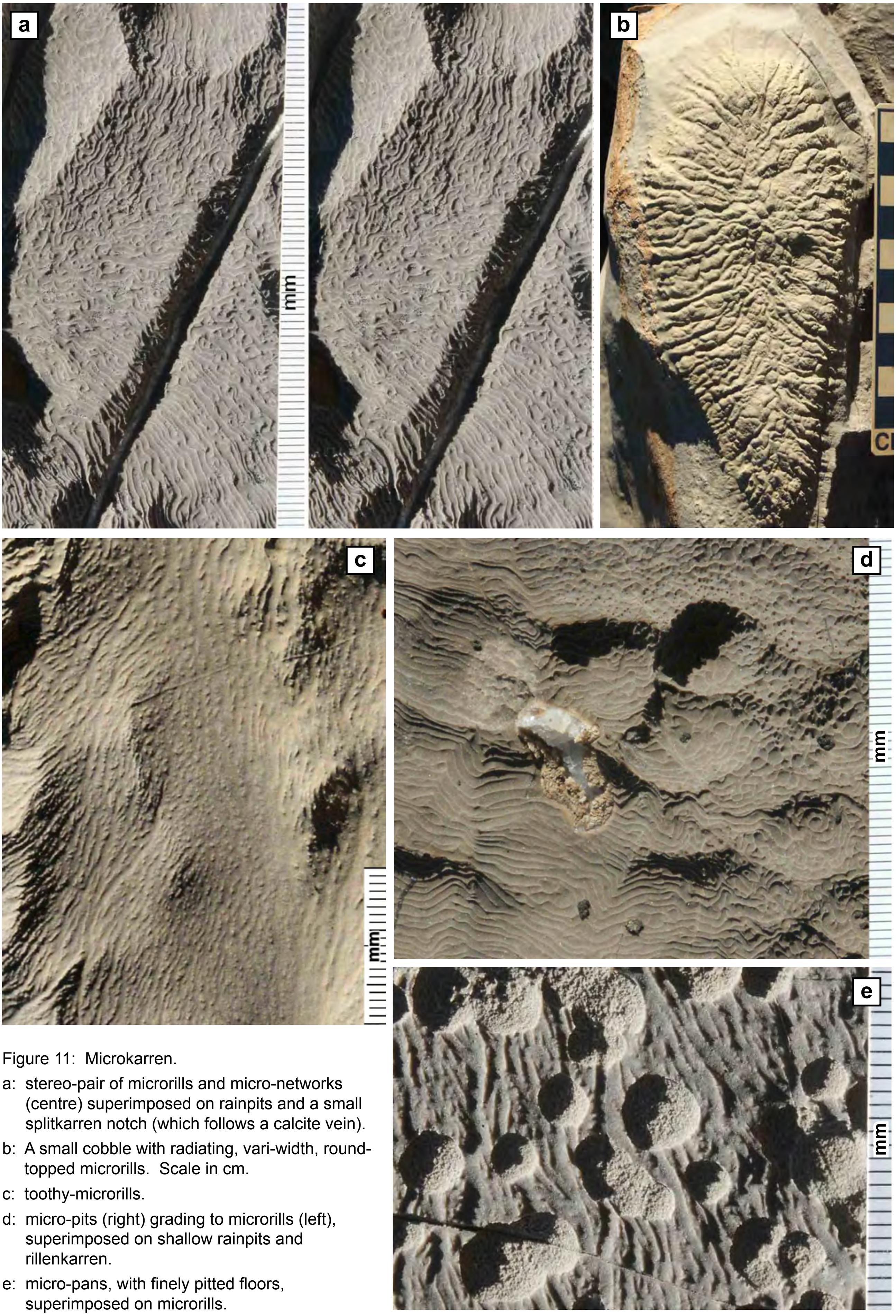

Figure 11: Microkarren.

a: stereo-pair of microrills and micro-networks (centre) superimposed on rainpits and a small splitkarren notch (which follows a calcite vein).

b: A small cobble with radiating, vari-width, round-topped microrills. Scale in cm.

c: toothy-microrills.

d: micro-pits (right) grading to microrills (left), superimposed on shallow rainpits and rillenkarren.

e: micro-pans, with finely pitted floors, superimposed on microrills.

be polygenetic and are not always associated with other types of microkarren.

There is some local lithological control. Microkarren seem to form best on fine-grained (lutite) limestones, such as those of the Upper Skull Creek. On the laminated stromatolite outcrops one can see better development of microrills on the finer-grained paler laminae than on adjoining darker (organic rich?) and coarser-grained laminae. In some outcrops where there are adjoining areas of light brown dolomite and grey limestone, the microkarren seem to form better on the limestone, but on other outcrops we find microkarren developed equally on both lithologies.

Within the Judbarra area the best development of microkarren is on the flaggy to slabby outcrops of fine-grained dolomitic limestone in the Upper Skull Creek Formation (Figure 7), where there is little competition from mesokarren. That unit has the best array of microkarren found anywhere in tropical Australia (Grimes, 2007, 2009; Figure 1); nearly every outcrop has examples (Figure 11).

However, microkarren do occur within the main karrenfield of the Supplejack Member. They are common in zone 1, where the limestone surface has just emerged from beneath a cover. As the surface becomes dissected by mesokarren in the older zones the microkarren are mainly lost, but examples still occur on spitzkarren crests or associated with rillenkarren and rainpits on gentle slopes (Table 1).

Appendix 1 gives detailed descriptions of the subtypes of microkarren, which are illustrated in Figure 11.

Microkarren elsewhere in Australia

There are still insufficient data on the distribution of microkarren in Australia (Figure 1). However, some generalisations are possible. They seem to form best on fine-grained limestones, although there is an exception on coarse marble at Chillagoe (Grimes, 2009). Microkarren are most common and best developed in the monsoon tropics, and possibly in semi-arid areas further south (e.g. the Flinders Ranges, R. Frank, pers. comm., 2009).

In the wetter eastern karsts they are uncommon and are poorly developed where they do occur. The most common types there are toothy microrills, micro-teeth, micro-pitting and a variety of simple etching effects.

In some areas, there seems to be preferential formation on limestone as against dolomite. This is best seen at Camooweal in the Barkly karst (NW Queensland, Figure 1) where the Camooweal Dolomite has no microkarren apart from etched micro-notches (see figure 19 in Grimes, 2009), even though it is finer grained than limestones 60 km to the NE which have well-developed microkarren (Reto Zollinger, pers. comm.).

At Chillagoe and Broken River, bleached patches where the grey biofilm had been removed by animal urine have well-developed microkarren (Jennings, 1981, 1982; Grimes, 2009), but that might be partly because the microkarren are easier to see where the biofilm is absent. The possible connection between micro-pans and wallaby faecal pellets suggested by Grimes (2007, 2009) is still unproven. At Broken River, the wallaby camps had abundant pellets and bleaching associated with obvious microrills, but no micro-pans were found there. Viles (2009, p.42-43) mentions bleaching by wallaby urine in connection with mesokarren in the Kimberley, but does not mention microkarren.

Mesokarren.

The best development of mesokarren is in the karrenfields of the Supplejack Member. However, some mesokarren are developed on the thicker limestone beds of both the Upper and Lower Skull Creek (units s+1, s-1, s-2 on Figure 4). There is a broad array of types and the size and character vary across the four karren zones. Twilight zone sculpturing occurs in the caves and giant grikes, and includes photo-tropic spikes.

Table 1 summarises the distribution and sizes of the different types across the four karren zones. Appendix 1 gives detailed descriptions of each type, some of which are illustrated in Figure 12.

Megakarren

Ruiniform relief

Ruiniform relief is defined in the introduction (page 20), and includes composite landscapes of the giant grikefield, stone city and stone forest type.

In the Judbarra Karst ruiniform relief characterises zone 4 (Figures 8, 9, 10e. 13a,e, 15). Once the grikes have cut down to the base level provided by the shale bed, erosion proceeds with the low ground expanding at the expense of the high ground. Thus grikes expand to giant grikes, then stone city streets and finally broader areas separating isolated pinnacles and blocks. The high ground shrinks from broad sculptured blocks to smaller narrow pinnacles which finally break up into piles of smaller rotated blocks and rubble. Isolated small blocks and pinnacles can survive well out onto the structural pavements or valleys beyond the main karrenfield (Figure 13e). Dense fields of tall pointed pinnacles, such as characterise the tsingy, and the shilin stone forests of China, are less common. Details of the components of this sequence are given in Appendix 1 (page 36).

The pattern of grikes is a hierarchical one with smaller grikes nested between the giant grikes. The giant grikes have a spacing of 4-20 m, and are easily visible on the air photos (Figures 8, 9). Some extend as lineaments for several hundred metres. This larger pattern may be partly inherited from the pattern of hollows separating the stromatolite mounds at the top of the Supplejack

Figure 12: Mesokarren.

a: Kamenitza with smooth floor and black algal peelings. Note etched polygonal stromatolite structures on floor.

b: Kamenitza with pitted floor and grey biofilm. (10 cm scale bar).

c: Flat-floored grike in zone 3. The walls have cockles and horizontal solution ripples, as well as bedding-plane notches. Hammer for scale.

d: Trittkarren formed by aggressive seepage across the surface of zone 1.

e: Dendritic pattern of runnels between incipient spitzkarren and a few small kamenitza. Zone 1. 10 cm scale bar.

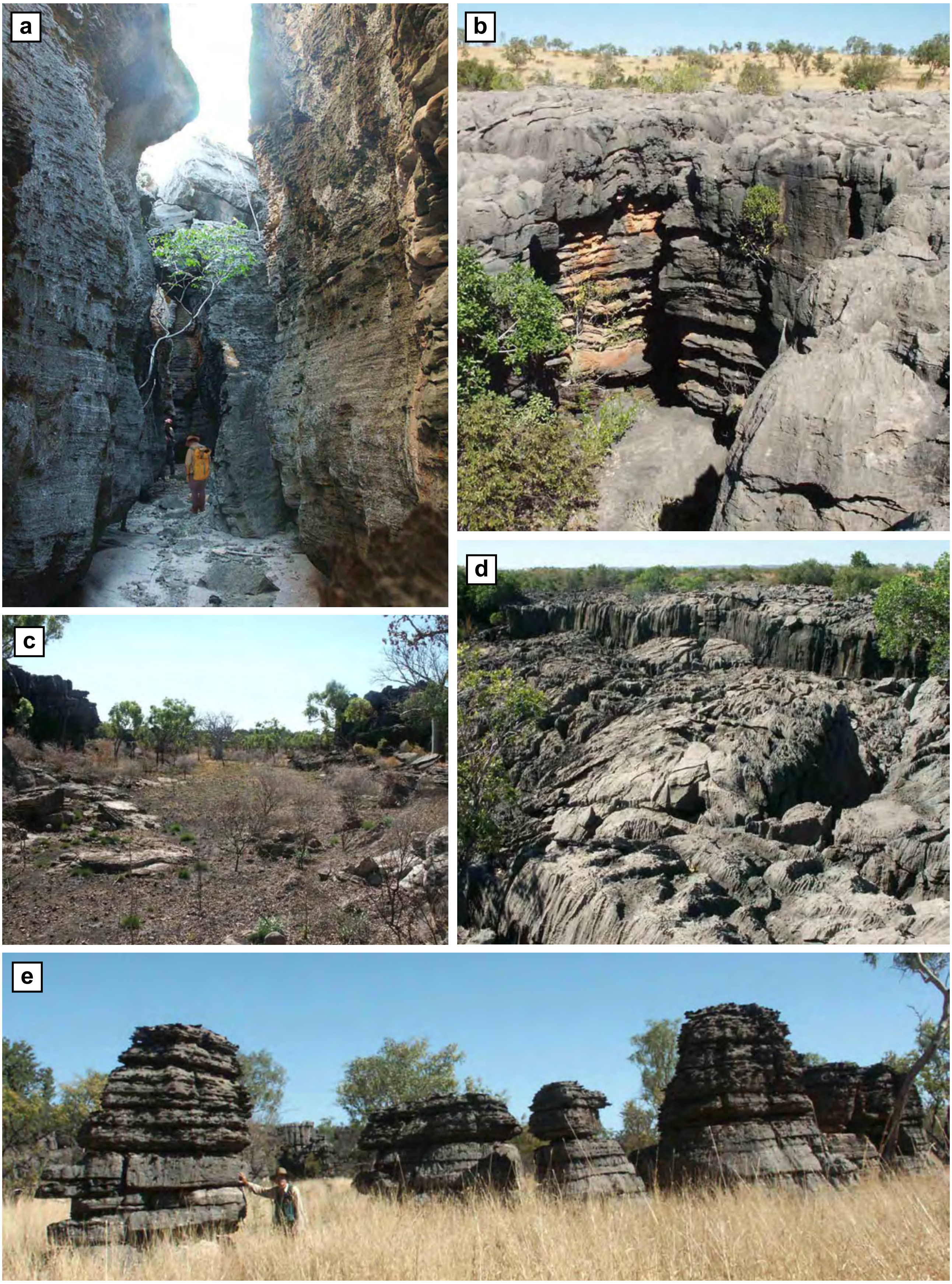

Figure 13: Megakarren.

a: Giant grike, formed by unroofing of a cave passage.

b: Collapse doline, bordered by grike walls. Northern area.

c: Box valley, 40 m wide, near the Golden Arches (Central Karst area).

d: Cave undermining has caused 1.5 m of subsidence in front of the background scarp.

e: Isolated stone forest blocks on a pavement. Note how the upper thin-bedded, chert-rich, unit inhibits vertical fluting in comparison with the thicker beds below.

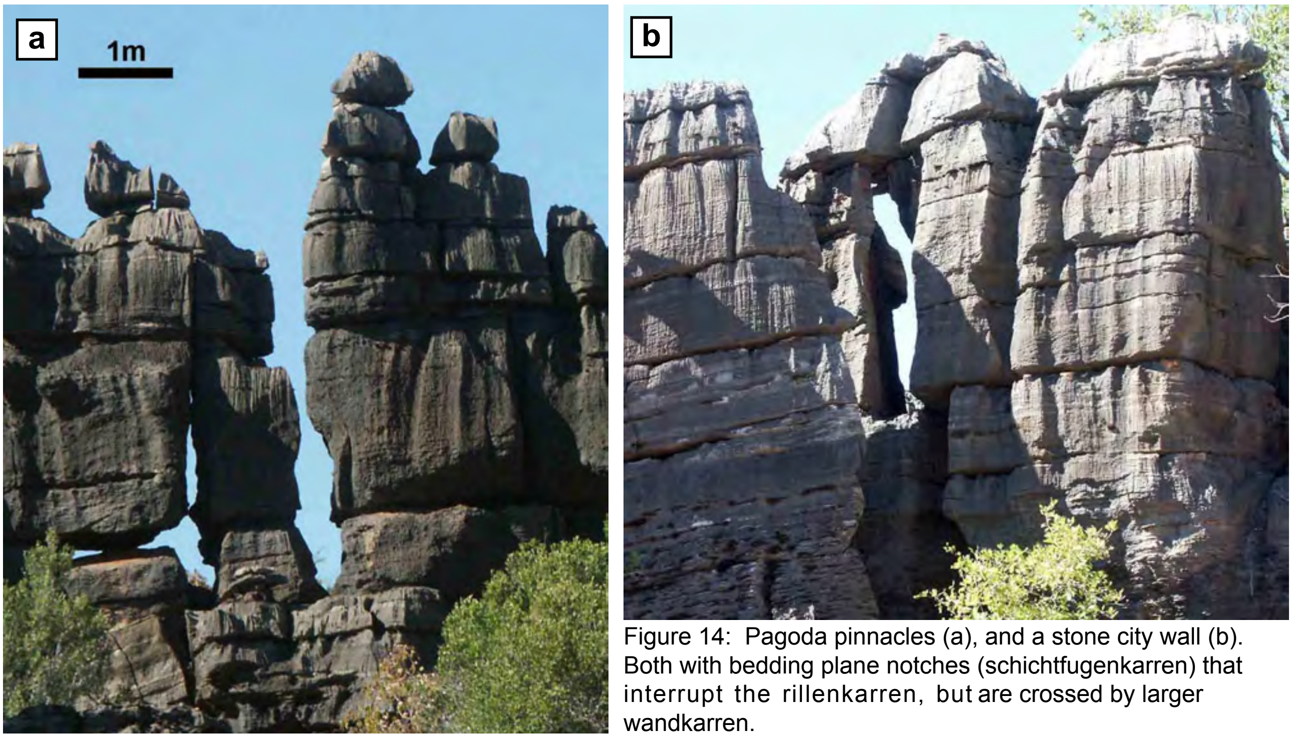

Figure 14: Pagoda pinnacles (a), and a stone city wall (b). Both with bedding plane notches (schichtfugenkarren) that interrupt the rillenkarren, but are crossed by larger wandkarren.

Figure 15: Degraded karst in zone 4. A ruiniform stone city with rotated blocks and a mound of rubble and soil that forms a 'levee' at the edge of the karrenfield.

(Figure 8). The tops of the blocks between the giant grikes have a pattern of smaller grikes (1-3 m wide, and spaced 1-5 m). The tops are further sculptured into fields of sharp spitzkarren, separated by narrow runnels and broader kamenitza (Figure 10e). This hierarchical pattern is well shown on the stereo photos (Figure 9).

Dolines

Collapse dolines and broader areas of mass subsidence are a common result of undermining of the karrenfield by cave development (Martini & Grimes, 2012). Figure 13d shows part of a broad closed depression resulting from undermining and subsidence of the whole karren surface, and Figure 13b shows a small vertical-walled sinkhole where a single grike-bounded block has disintegrated (Northern area, see Figure 4). In the southern Bullita Cave area, The Sentinel (a large boab tree) is in a closed depression at the junction of two lineaments (Figure 4).

Broad karst valleys or corridors

Flat-floored, steep-walled, box valleys (or karst corridors), 10 to nearly 200 m wide but less than 20 m deep, follow lineaments or surface drainage lines (Figure 13c). These disrupt the karrenfield and segment the underlying caves. The floors are usually rocky structural pavements cut on the top of the Lower Skull Creek formation (see foreground of Figure 13c), but may have a thin cover of colluvial soil or alluvium.

In the Far Northern karst area, several large, straight, flat-floored valleys appear to be eroding along narrow bodies of a paleokarst breccia (Grimes, 2012) which in turn follow major lineaments, possibly fault zones.

Structural pavements and pediments

The shale bed beneath the Supplejack member provides a base level for development of the karrenfield. Adjacent to the East Baines River and some major tributaries we find valleys cut below this level, but generally downward erosion of the karrenfield ceases when it reaches the shale bed and is replaced by widening of the grikes to produce the ruiniform terrain. The shale bed itself is removed, but a flat structural pavement is left on the top of the Lower Skull Creek. This is similar in appearance to pediments which occur in some other tropical karsts of Australia, e.g. Chillagoe (Jennings, 1981, 1982) and the Kimberley (Jennings & Sweeting, 1963), but in the Judbarra Karst the structural control is more obvious and the term *pediment* is less justified.

Tufas

The tufa deposits of Limestone Creek have been described and mapped by Canaris (1993). Canaris recognised at least two stages of tufa growth: relict tufas and modern tufas.

Relict tufas

The relict tufas are the most widespread, in places extending across the full width of the valley. They have thicknesses up to 3 m, and can rise high above the younger actively-forming deposits. They are well lithified, and resistant to erosion. This is partly responsible for the 8 m drop over a series of stepped terraces in the bed of Limestone Creek where it joins the East Baines River (Figure 4). Canaris reported radiocarbon ages of 8-10 ka from the relict tufas. That would have been a period of wetter climate.

Canaris (1993) reported a large relict tufa fall on a 15 m cliff on the north side of the river downstream from its junction with Limestone Creek (Figure 4). The 'Crystal Cascade' is a smaller waterfall with tufa deposits in a side valley of Limestone Creek; it is only active during the wet season.

Modern tufas

The modern tufas began growing in the present stream channels about 1600 BP (Canaris, 1993). Canaris noted two types of modern tufa: those which form transverse bars across the stream flow, and lithoclast tufas. The transverse type is the more common and these are autochthonous; they have grown in situ to form stepped terraces and sinuous barrages. Lithoclast tufas form by cementation of stream gravels. Canaris reported them forming pedestals in the creek bed at the upstream end of Limestone Gorge.

Figure 16: A small waterfall over a 5 m high tufa wall. Located in the far north-west of Figure 4.

A set of well-formed tufa walls, falls and pools occurs along the main creek that drains south from the Far North area (The north-west corner of Figure 4). In July 2005 the largest waterfall was flowing at about 5 L/s over a 5 m high tufa wall into a deep pool (Figure 16). The pool sides are coated with soft, crumbly, bubbly, white tufa. An overhang of the dam wall on the north side has tufa stalactites beneath it.

In several places seepage water running out from the Supplejack - Skull Creek contact and across the slabs at the top of the Supplejack (karren zone 1) has formed small 'paddy-field' terracettes of two types. A constructional form has small rounded tufa ridges a few cm high and wide damming the terraces, and indicates precipitation from saturated water. The other type appear to be wholly corrosive in form and comprise shallow steps with or without low rims (Figure 12d and see Trittkarren in Appendix 1, page 35).

Discussion

Microkarren

The Judbarra Karst has the best array of microkarren found anywhere in tropical Australia, particularly on the slabby outcrops of the Upper Skull Creek Formation. Not only are there well-developed examples on every outcrop, but there is a broad range of types to be seen.

Favourable factors seem to be the climate (semi-arid monsoon), the lack of competing mesokarren (a consequence of the thin limestone beds alternating with soft calcareous muds), and the fine grain size of the rocks (a calcilutite). The rock composition may also be a factor, as in some outcrops there seems to be a preference for formation on the limestones rather than on adjacent dolostones, but this is not universal.

Zonation of karrenfields

The evolution of the surface karrenfield and the cave beneath are intimately related (see also Martini & Grimes, 2012). Both show a trend from youth to old age. As slope retreat removes the overlying sediments of the Upper Skull Creek to expose the Supplejack Member, both the cave and the karrenfield zones migrate in that direction with their youngest parts at the leading edge, and the oldest parts disintegrating at the trailing edge to form a structural pavement on the Lower Skull Creek.

At the advancing edge the freshly exposed surface of the Supplejack Member has a surface of broad smooth domes that is the original depositional surface of the stromatolite mounds. There has been no pre-exposure stage of solutional preparation beneath the cover that would be comparable to that suggested for some other tropical karrenfields, such as the shilin stone forests or the tsingy (see below).

Microkarren are common on the initial surface (zone 1) and rainpits and incipient rillenkarren quickly appear, along with small solution slots (splitkarren) along the joints. With time the karren become more deeply incised, with kamenitza and runnels feeding to small grikes. Progressively larger grikes become the dominant features, with spitzkarren pinnacles and smaller grikes on the tops of the intervening clint blocks. Finally, in zone 4, the grikes connect with the ceilings of the evolving cave passages to unroof them, and form giant grikes separating blocks and towers with strongly dissected surfaces. Undermining by the widening cave passages causes subsidence and rotation of the blocks. The karren surface breaks up into a stone city and finally only scattered blocks and pinnacles remain on a flat structural pavement.

Zoned karrenfields elsewhere in Australia

Superficially similar karrenfields occur on many of the flat-lying carbonates of tropical Australia (Grimes, 2009), but a zonation is generally much less obvious.

West Kimberley: Jennings and Sweeting (1963), and Jennings (1967, 1969), described a comparable zonation of surface development for the West Kimberley karst region, with gradation from undissected plateau with a black soil cover through giant-grikefields, box valleys, and towers to a final low-level pediment. Maze caves, such as Mimbi Cave (figure 38 in Playford, 2009), are present beneath the giant grikefields. However, the Kimberley sequence is at a larger scale; the limestone beds there are up to 90 m thick, as against only 20 m for the Supplejack Member at Judbarra. The Kimberley also differs in details; for example the giant grikes are present almost from the start, separated by relatively smooth-topped blocks, and an integrated surface drainage via narrow box valleys appears early in the development. The limestone is a large barrier reef, and the lithologies of the different reef facies have an important influence on the karst character. There is also a strong paleokarst influence with many exhumed Permian sub-glacial karst forms; including, possibly, some of the giant grikes (Playford, 2002, 2009).

Barkly Karst: The Colless Creek grikefield at the northern edge of the Barkly Karst region (Figure 1; Grimes, 2009; Gale, et al., 1997) is a small area beside an incised gorge about 45 m deep. In detail it has many karren features similar to Judbarra, and has a maze cave formed beneath it, but the zonation is less systematic and appears to be more related to exposure of different beds than to a progressive denudation. This is one of several small karrenfields scattered across the northern edge of the Barkly Karst region. The karrenfield described by Gale, et al. (1997) is in a separate small area further west, where lithological and structural control seem more important than progressive denudation. The influence of bedding thickness reported by Gale, et al. (1997) is similar to that seen at Judbarra.

Comparison with the tsingy

The tsingy of Madagascar have also formed on flat-lying limestones in a tropical monsoon climate (Salomon, 2009; Veress et al., 2008, 2009). However, they have a generally higher rainfall – between 1000 and 2000 mm/a for the best-developed examples at Bemaraha and Ankarana, as against 810 mm at Judbarra (Veress, et al., 2009). The tsingy have the same array of deep grikes and sculptured crests as in karren zones 3 and 4 at Judbarra. However, the tsingy grikes are much deeper: up to 120 m at Bemaraha, but only reaching 11 m at Ankarana, which is more comparable with Judbarra. This great depth is partly because there is a greater thickness of limestone available and no inhibiting shale bed, and partly because of a history of a dropping watertable. The tops of the tsingy are much sharper than at Judbarra, being narrow pointed cones and blades; possibly this is a consequence of the stronger rainfall. There is a greater variation in lithological control also; Salomon (2009) reports that some lithologies form cone karst (kuppen), mogotes and towers rather than tsingy.

Salomon (2009) suggested that the giant grikes of the tsingy originated as subsoil fissures and were exposed by erosion of the soil, with some subsequent deepening. However, Veress et al., 2008, 2009, suggest an alternative genesis for the tsingy that involves both the collapse of pre-existing cave ceilings and downward incision of the grikes by rainwater dissolution to join up with the caves. The latter model has similarities to the evolutionary sequence at Judbarra where there has been no subsoil preparation (Martini & Grimes, 2012). However, the cave genesis beneath the tsingy differs (Veress, et al., 2008). The underlying caves there show mainly phreatic features and have formed at several levels. They appear to have formed beneath a watertable that has dropped progressively over time. In contrast, at Judbarra the shale bed has had an important influence, both on the cave development, and in restricting the depth of the karren. Cave undermining of the surface karren by erosion of the shale bed is a special feature of the Judbarra Karst.

Comparison with the shilin stone forests

Compared to Judbarra, the stone forests of Shilin and elsewhere generally have a scenery dominated by pinnacles rather than large grikes; and the pinnacles are more densely spaced, taller, narrower and more pointy (Knez & Slabe, 2001; Song & Liang, 2009). In parts of zone 4 at Judbarra we do get some tall pagoda spitzkarren pinnacles similar to those at Shilin (e.g. Figure 14a), but they are not common. However, some of the stone forests (e.g. the Naigu stone forest, illustrated by Knez & Slabe, 2009, p. 441) have smaller pinnacles and form a mass more akin to the tops of the Judbarra zones 3 and 4.

The shilin pinnacles had an important stage of subsoil preparation prior to erosional exposure of the pinnacles and their further sculpturing by rainwater. At Judbarra the only relief on the newly exposed limestone surface is that of the broad stromatolite domes (Figure 6). There has been no stage of subsoil preparation, and all the sculpturing is a result of rain falling directly into the bare rock and then draining down the fissures.

Conclusion

The main factors influencing the development of the karren are:

The lithology: The rock is mainly a finely-interbedded limestone and dolomite – both lithologies form karren. However, areas of secondary diagenetic dolomite inhibit all karren and cave formation. Chert bands and nodules inhibit the mesokarren but not the megakarren. The microkarren appear to form best on isolated thin beds of fine grained limestone in the Upper Skull Creek Formation where mesokarren do not compete.

Structure: Joints and bedding planes guide the formation of some linear karren (grikes and bedding slots in particular), and horizontal bedding planes can disrupt the run of rillenkarren on steep slopes. The larger box valleys may be following fault zones. The gentle dip of the beds, and its relationship to the landsurface slope, has resulted in the main karrenfield forming a meandering band – narrow where dips and/or slopes are steeper, and broader where they are more gentle (Figure 3).

Denudation history: The overall terrain is the result of vertical erosion of a set of old land surfaces, but the detailed zonation of the karrenfield is a result of lateral slope retreat. This has produced a diachronous surface grading from youth at the advancing edge to old age and decay at the trailing edge, as discussed above. At Judbarra there is no evidence of an initial subsoil stage of preparation, such as is reported in the shilin stone forests.

Climate: Generally speaking, carbonate rocks are upstanding in tropical monsoon areas. Other rock types weather and are eroded relatively rapidly, whereas in the carbonate areas there is an early development of griked surfaces and underground drainage so the remaining surface is relatively unaffected and upstanding.

The abundance of microkarren is a puzzle, as existing models for their origin generally invoke thin films of water from dew or spray. There is no dew in this area, and the rainfall is generally heavy but intermittent. Possibly the high humidity in the wet season leaves the rock surface damp for longer periods than in other climates?

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Appendix 1
Detailed Karren Descriptions

This appendix provides detailed descriptions of specific karren types found in the area. Table 1 (page 23) summarises their distribution and size ranges across the karren zones.

Microkarren

Microkarren Types

Laudermilk & Woodford (1932) described four types of *Rillensteine* (another name for the most conspicuous types of microkarren). However, their classification is difficult to apply and there are many other types of microkarren which they do not describe. Here I use the broader, descriptive, field classification suggested and illustrated by Grimes (2007).

Microrills: Narrow grooves, running down gentle slopes. Typically 1 mm wide, less than 1 mm deep, and a decimetre long. However, they can be up to 60 cm long. They vary from straight, to sinuous, to tightly meandering. There may be some branching, both contributory and distributary, depending on whether the slope is spreading or focussing the rills. There are two sub-types. The most common type is regular in width, sharp-ridged, with parallel sides, and can be straight, sinuous or meandering (Figure 11a,d). The less common type, mainly found on the gently domed surfaces of cobbles, is variable in width (fanning out and widening downslope) and can have either sharp or rounded ridges (Figure 11b). Microrills grade to micro-networks.

Micro-networks: These are similar to microrills, but more densely branched to form an irregular or elongate network rather than long linear runs (Figure 11a, and see photos in Grimes, 2007, 2009). They grade in turn to micro-teeth.

Micro-teeth: In these the network of grooves has become so densely branched that the interfluves have been reduced to isolated sharp, rasp-like, conical or faceted teeth about 1 mm wide and less than 1mm high. See photos in Grimes (2007, 2009).

The ridges between micro-rills can also break up into chains of elongated teeth – a type I refer to as *toothy microrills* (Figure 11c). Toothy microrills are uncommon in the Judbarra karst, but in the more humid karst areas of eastern Australia, where microkarren are poorly developed, they are the most common type.

Micro-pits: Hemispherical to conical pits occur in a wide range of sizes from 1 mm wide and deep, up to 20 mm wide (i.e. to normal rainpits). A broad range of sizes can occur within a single outcrop. Possibly there are several modes of formation for these and only some would be related to other (surface-tension) microkarren. On gently-domed surfaces micro-pits tend to occur on the crest and grade to microrills on the slopes (Figure 11d and see photos in Grimes, 2007).

Micro-pans: Shallow pits, 5-10 mm wide, but only 1-2 mm deep. They have flat to slightly concave floors that can be smooth or have fine micro-pits or teeth. They are commonly superimposed as scattered clusters on other microkarren (Figure 11e). This superimposition suggests that they form after the other types. A possible origin might be concentrated solution beneath pellets of wallaby dung – but this has not been confirmed.

Micro-decantation rills: These run down the vertical side of a cobble, becoming smaller as they descend – implying a loss of aggressiveness or of moisture as they descend from their source at the top. They are commonly coarser than the microrills that feed them.

Micro-tessellations: Narrow U-section notches in lines or networks. They commonly disrupt other pre-existing microkarren and appear to be following a cracking or crazing pattern that is superficial (<2 mm), not deep as in joints. See photos in Grimes (2007).

Micro-notches: Irregular V-section notches that follow cracks in the rock (a micro-version of splitkarren). They have a broad range of sizes (see figure 19 in Grimes, 2009). These are an etching of rock structures (see below).

Etched rock structures: Various structures of fossils, crystals, cracks or bedding may be etched out: negatively or positively, and sharply or more rounded. These effects reflect the structure or texture of the rock, and may be unrelated to other microkarren. They are widespread in most karst regions, and are particularly common on sub-soil surfaces. They are listed here for completeness, but are probably genetically unrelated to the distinctive surface tension forms.

Double-sided cobbles

The underside of loose cobbles is usually smooth or pitted, but it is not uncommon to find ones with microrills and other microkarren. These rills tend to be more rounded and more shallow. Possibly some cobbles have been kicked over by animals and the initial sculpture smoothed against the soil. However, Lauritzen (1981) demonstrated experimentally that 1-2 mm wide rills could form in contact with moist silt and sand, so these could form directly on an underside against damp soil.

Relationships between microkarren and mesokarren

Microkarren do not compete well with mesokarren (rillenkarren, etc), but the two can co-exist: typically with microkarren superimposed on shallow rillenkarren, rainpits and splitkarren on flatter surfaces (Figure 11a,d). Where the mesokarren are only incipient, as in zone 1, it is difficult to tell whether the superimposed microkarren are forming subsequently or contemporaneously. Some microrills are continuous across the sharp crests of rainpits and rillenkarren (Figure 11a,d).

Relationships between microkarren types

The micro-rills, -networks, -teeth and -pits are forms that grade into each other. It is common to find on undulating surfaces that the crests have micro-pits or micro-nets that grade to linear or meandering microrills on the slopes. In the hollows, networks and pits may reappear or there may just be a smooth surface. Micro-teeth are an extreme case of micro-nets where the grooves of the network overlap to leave only small faceted teeth in place of longer ridges. The micro-pans and micro-tessellations appear to be always late-stage features that are superimposed on other microkarren.

Some observed successions of micro- and mesokarren in the Bullita area are:

- Some microkarren postdate micro-notches.
- Micro-tessellations postdate most types of microkarren. Photo in Grimes, 2007.
- Shallow micro-pans postdate most types of microkarren. Figure 11e.
- Microkarren (microrills, micro-teeth, etchings & micro-notches) are superimposed on shallow incipient rillenkarren and rainpits. However, the microkarren may be penecontemporaneous in the early stage of incipient rillenkarren development. Figure 11a,d.
- Some microrills are continuous across pre-existing splitkarren. Figure 11a. However, some splitkarren postdate microrills.
- Some microrills are continuous across the sharp crests of rainpits and rillenkarren. Figure 11a,d.
- Rainpits occasionally postdate microrills.

Mesokarren

Rillenkarren: Rillenkarren are solution flutes – the most common and distinctive of the karren (Ginés et al., 2009; Ford & Lundberg, 1987). They are best formed and most common as a component of the spitzkarren (q.v.). They also occur as simple parallel linear flutes on the sides of the larger grikes and cliffs, though on steep slopes they tend to be modified by cockling (q.v.) or interrupted by bedding notches ('Schichtfugenkarren'; Figure 14). Rillenkarren also occur as small shallow incipient flutes on the Upper and Lower Skull Creek pavements and on the zone 1 pavements, often with microrills superimposed on them. Dimensions range from 8-30 mm wide, 1-22 mm deep and up to 2 m long (the maximum length downslope is generally limited by horizontal bedding notches). The deepest and longest rillenkarren are on steep slopes in zones 3 and 4, but there is not a strong correlation between depth and slope.

Rainpits and other small pits: Not all small pits are formed by rain impact, though Ginés & Lundberg (2009) define *rainpits* specifically as being rain impact structures. However, they also describe other *etch pits* and *subsoil pits* which can overlap in size and shape. The small pits in the Judbarra area comprise all three genetic types. They are hemispherical pits with sharp edges, typically 1-3 cm across, but a broad range of sizes occurs (sometimes within a single rock surface) right down to micro-pits only 1 mm across (see photo in Ginés & Lundberg, 2009, p.174). See also *cockling*, described below, which occurs on steeper slopes and runnel floors.

True rainpits occur as small clusters on the crests of spitzkarren and grade to rillenkarren on the slopes. They are also found on the floors of some kamenitza and flat-floored grikes and on other sub-horizontal surfaces.

As well as on the main Supplejack karrenfield, rainpits also occur on the pavements of the Upper and Lower Skull Creek Formation.

Some small but deep conical and hemispherical pitting may be the result of etching by water seeping along bedding planes that have been later exposed at the surface (e.g. beneath loose slabs). Etched pits in a broad range of sizes occur on surfaces buried by soil, and may be exposed by soil erosion.

Cockling: Cockling is the term for hemispherical pits, similar to rainpits (see above), but found on steep to vertical walls and having a larger range of sizes. Cockles may be quite deep and sharp-edged. Cockles can also occur as modifications of the channels in rillenkarren, and in larger runnels. This type also occurs on the twilight zone walls of caves, where it may grade to solution ripples (see Twilight Zone, page 36).

Spitzkarren (pinnacles): I use the term spitzkarren broadly for all sizes of fluted beehive-shaped pinnacles ranging from a few decimetres up to several metres high and wide (Figure 10d,e, 14). They are composite forms with rainpits on the crest grading down to rillenkarren and then (on the larger examples) to wandkarren.

They form in fields, and are separated by grikes or by dendritic patterns of runnels which collect water from the spitzkarren (via rillenkarren) and feed it to a nearby grike.

In this usage, spitzkarren are the most common of the larger, composite, mesokarren forms at Judbarra, but are largely restricted to the Supplejack outcrops. However, there are a few small spitzkarren on the thicker 's+1', 's-1' beds of the Skull Creek Formation (see Figure 4).

The spitzkarren range in size from incipient clusters of radiating rillenkarren only 10-20 cm across and a few cm high (Figure 10b) in zone 1, through groups and fields of fluted pinnacles from a few decimetres to several metres high and wide (Figures 10c,d,e, 12c) to high isolated pagoda pinnacles in the stone city areas of the outer edges of zone 4 (Figure 14a). Typical dimensions for each zone are given in Table 1.

The larger spitzkarren have 'pagoda' shapes, with steps where the steep slopes and flutings are interrupted by bedding-plane notches (Schichtfugenkarren; see Figures 10e, 14).

Wandkarren (wall karren): Wandkarren occur as large, vertical, rounded channels on the walls of cliffs, grikes and the largest spitzkarren pinnacles, and extend down the vertical faces from the runnels between the spitzkarren (Figure 14b). They can be at least 4 m long (down the wall), and can continue uninterrupted across deep bedding notches (Schichtfugenkarren, e.g. Figure 14b). They are from 0.1-0.3 m wide (spaced 0.2-0.5 m) and 0.1-0.3 m deep into the wall.

The wandkarren at Judbarra are not as deeply incised into the walls as those seen in other karsts, both in tropical Australia (the Kimberley and Chillagoe, Grimes, 2009) and elsewhere (e.g Veress, 2009b). This may be because most of the drainage from the karrenfield rapidly feeds via numerous open grikes to the caves beneath and the runnels feeding to the wandkarren are only short.

Bedding plane notches (schichtfugenkarren): In the thicker bedded limestones, bedding planes can form deep horizontal notches, called *Schichtfugenkarren* (Veress, 2009b, p. 241). They occur in all zones, but are deepest in the walls of zone 4. They disrupt the flow of water down the walls so that patterns of vertical rillenkarren are terminated and restart below each notch (Figure 14). However, the larger wandkarren have sufficient water flow to carry across the notches without disruption (Figures 10e, 14b). Bedding notches also segment the larger spitzkarren to form a pagoda style (Figure 14a).

Kamenitza (solution pans): The solution pans are flat-floored basins, with steep to overhanging walls (Figures 10b, 12a,b). They have a broad range of depths and widths (up to 2.5 m wide and 0.4 m deep). Their outline can be roughly circular to very irregular. There is usually an overflow point, and they may form chains joined by short runnels that eventually feed to a grike (Figure 12e). The flat floors commonly have etched out linear or polygonal patterns of the stromatolites.

The pans have two types of flat floor:

1: Smooth and bare-surfaced with curled flakes of thick black to dark grey biofilm (Figures 10b, 12a).

2: Finely pitted with both positive cones and negative pits 2-5 mm wide and 2 mm deep (Figure 12b), or with larger hackles up to 2 cm wide and deep. These pitted floors have a thin grey biofilm similar to that seen elsewhere in the karrenfield.

Occasionally one sees spiky structures (micro-pinnacles) on the floor, some with coralloid overgrowths. There seems to be a correlation between the floor type and the type of biofilm present.

Kamenitza are mainly found in zones 2 and 3, but are also seen in parts of zones 1 and 4, and occasionally on pavements of the Upper and Lower Skull Creek Formation.

Trittkarren (solution steps): In a few places solution steps (trittkarren) form shallow 'paddy-field' terracettes where, in the wet season, sheets of aggressive seepage water have flowed from the upper Supplejack–Skull Creek contact across the slabs of the top of the Supplejack (karren zone 1). These are similar to *step trittkarren* (Veress, 2009a, who prefers, however, to restrict the term to areas influenced by snow-melt). The floors are smooth to cockled, and some steps have low rims (Figure 12d). Small tufa rims also occur in this situation (see *Tufa*, page 29).

Runnels (rinnenkarren, etc): The runnels are small sinuous to straight solutional gutters that drain water from the surface into the grikes. They typically form dendritic drainage patterns within fields of spitzkarren or connecting chains of kamenitzas (Figure 12e). The runnels on the Judbarra Karst are not as obvious as in some karst areas as they are not smooth and well-formed, but generally broken by cockling and steps and interrupted by broader kamenitzas. The floors are completely lacking in soil or sediment. There are no true meanderkarren.

Grikes (kluftkarren): Grikes are linear trenches formed by enlargement of vertical joints. They occur in all four zones, and come in a broad range of sizes. At the small end of the size range (zone 1) they grade down to splitkarren (v-notches, Figures 10a, 11a). In zones 2 and 3 the larger grikes (those visible on the air photos, Figures 8, 9) have a typical spacing of 2-5 m, but can get as close as 1 m. In zone 4, there are giant grikes that are five or more metres wide and 10-20 m deep (Figure 13a), which separate blocks 4-20 m across (see *megakarren*, below). The larger grikes have walls that are sculptured by rillenkarren, wandkarren, cockles and horizontal solution ripples (Figure 12c).

There is a hierarchy of smaller grikes between larger grikes (Figure 9, and see *Ruiniform* section in main text, page 25).

Splitkarren (v-notches): These small V- or U-section notches are formed by the solutional enlargement of joints and shallow cracks (Figures 10a, 11a). They can

Figure 17: Stereopair showing inclined phototropic spikes beneath a daylight hole in Claymore Cave (Southern area). Some are capped by thin chert seams.

have any orientation., and vary from 1 mm (microkarren notches) up to 10 cm wide and 20 cm deep. Larger ones would be called grikes if vertical, or bedding notches (Schichtfugenkarren) if horizontal. Some of the tessellated pavements of the Upper Skull Creek are patterns of splitkarren on a solid flagstone (left side of Figure 7).

Twilight zone sculpturing

In the twilight zone of the caves (entrances and daylight holes) there are solutional features that differ from those seen in the surface karrenfield or in the dark zone of the cave. These generally have a grey biofilm, similar to that found on the surface karren.

Phototropic Spikes: These are grooves, sticks and spines oriented towards the light and found in the twilight zone of the caves and deep grikes (Figure 17). They are a type of phytokarst eroded by biofilms which dissolve the rock beneath them but avoid shaded areas. Individual spikes and grooves are between 2-30 mm across, but can be up to 10 cm long. They may also have secondary coralloid growths on them. Some are capped by chert nodules which provided a shading effect (Figure 17). Phototropic spikes have also been reported in the giant grikes and cave entrances at Chillagoe (Jennings, 1981, 1982; Grimes, 2009).

Cockling: This is the same as the cockling seen on the surface (see above, page 34). It is particularly common on cave walls beneath roof holes that admit light and rainwater. Wall cockles grade to solutional ripples.

Solution ripples: On cave walls beneath daylight holes the cockling patterns may become organised into small horizontal ripples, with or without serrations.

Megakarren

Ruiniform features

In the ruiniform areas of zone 4 we find a progressive development of the following types.

Giant Grikes: The giant grikes are formed partly by incision and widening of surface grikes and partly by the unroofing of the cave passages in zone 4 (Martini & Grimes, 2012). The former have their flat to U-shaped floors in solid limestone above the level of the cave floor (Figure 12c). The latter have their floor near the level of the shale bed, and may have bridges of limestone where the roof has not been lost (Figure 13a). They can grade into partly to wholly roofed sections of cave passage.

Stone cities: Stone cities have a grid of streets and blocks of similar widths (5-20 m). The streets are enlarged giant grikes or small box valleys. Some blocks may be undermined and rotated (Figure 15). Only a few small remnants of caves are left.

Isolated towers, blocks and pinnacles: The final stage of decay leaves an open pinnacle field, or isolated and partly-disintegrated blocks and pinnacles scattered across broad structural pavements or valleys (Figure 13e).

The 'mini-tower karst' described by Martini & Grimes (2012) lies to the southwest of the Southern Area (Figure 3). It varies from a stone city comprising small blocks and pinnacles, 3-10 m wide and up to **6** m high, separated by streets of similar width; to broad pavements with scattered blocks. Its genesis is special, being tied to the presence of areas of secondary dolomite, which erodes easily, alternating with small lenses of unaltered limestone that form the blocks (Martini & Grimes, 2012).