Karren Book (in prep) xx-yy

Tropical monsoon karren in Australia

Ken G. Grimes.

RRN 795 Morgiana Rd., Hamilton, Vic 3300.
Regmap1@ozemail.com.au

This is the 2007 draft of a chapter submitted to a book on Karren being edited by Angel Ginés and others.

Further changes could occur.

Introduction: the Tropical Karsts of Australia

Karren in tropical Australia are strongly developed at all scales from microkarren to giant grikes and pinnacled towers, but with decreasing intensity and variety as one moves into the drier climates of the interior. However, the local effects of lithology, structure, cover and denudation history can create considerable variation.

Distribution

The tropical karsts of Australia can be divided into two structurally distinct provinces in the east and the northwest of the continent (Figure 1). A third province, the coastal dune limestones of southern Australia extends a short distance into the dry tropics of Western Australia but is not discussed here as the karren are poorly developed, and poorly documented (see Chapter 43 [‘Solution pipes & pinnacles...’ EDITOR please to substitute appropriate cross-reference]). There are also many areas of well-developed silicate karst, both as surface landforms and as caves, which will not be discussed here (see bibliography in Wray, 1997). Recent reviews of Australia’s tropical karsts are provided in Spate and Little (1995) and Gillieson and Spate (1998).

Geological Setting

The East Australian Karst Province is formed on strongly-folded, steep-dipping, Palaeozoic limestones and occasional marbles. These usually form narrow linear outcrops. They are impounded karsts (*sensu* Jennings, 1985), in which the drainage is largely controlled by allogenic streams which cross over, or cut through, the limestone belts with little loss of water underground. In the tropical part of this province the limestone beds tend to stand above the surrounding rocks as ridges and towers.

In the North Australian Karst Province the host rocks are flat-lying to gently folded Proterozoic dolomites and Palaeozoic limestones and dolomites. These form extensive regions, but in some the depth of the carbonate rock is limited to a few tens of metres. In some areas the carbonate rocks are well-exposed, with strongly karstified outcrops; others have extensive covers of Mesozoic and Tertiary sediments and younger soils (Figure 1). There are also laterite and silcrete capped deep weathering profiles. Chert nodules and beds are common in some of the carbonates and this can influence the degree of karstification.

Climate

Northern Australia has a tropical monsoon climate. The Köppen climate classes range from humid *Aw* southwards through drier *BShw* to arid *BWhw* (Figure 2). On the east coast the seasonality decreases southwards and grades to the *Cfa* climate type. The rainfall has a pronounced seasonality with a five-month summer “wet” and a longer winter dry season (see Figure 2, and BOM (2005) for further details). Most rain in the wet season falls either in short intense thunderstorms, or in occasional cyclonic events lasting several days. Significant variation in rainfall between years is a consequence of the “El Niño southern oscillation” effect. Potential evapotranspiration is substantially greater than actual rainfall throughout the region, giving a deficit in excess of 1,000 mm per annum.

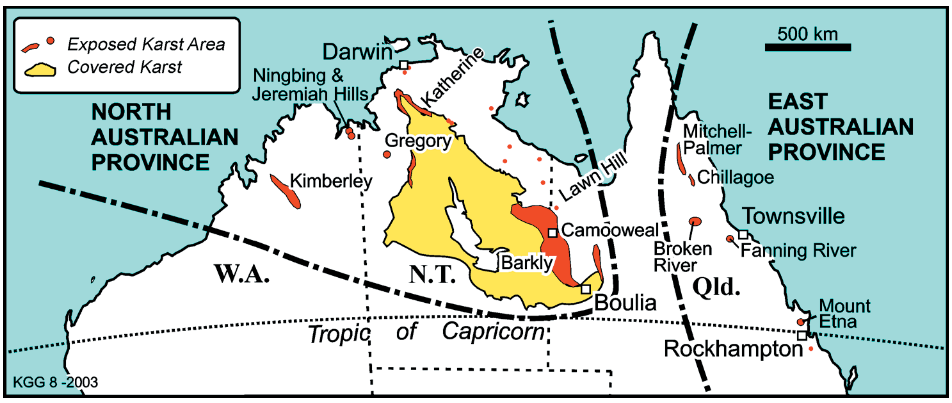


Figure 1: Location map of tropical karsts in Australia, showing the two main structural provinces. Karrenfields occur in the exposed karst, but not in the covered karsts.

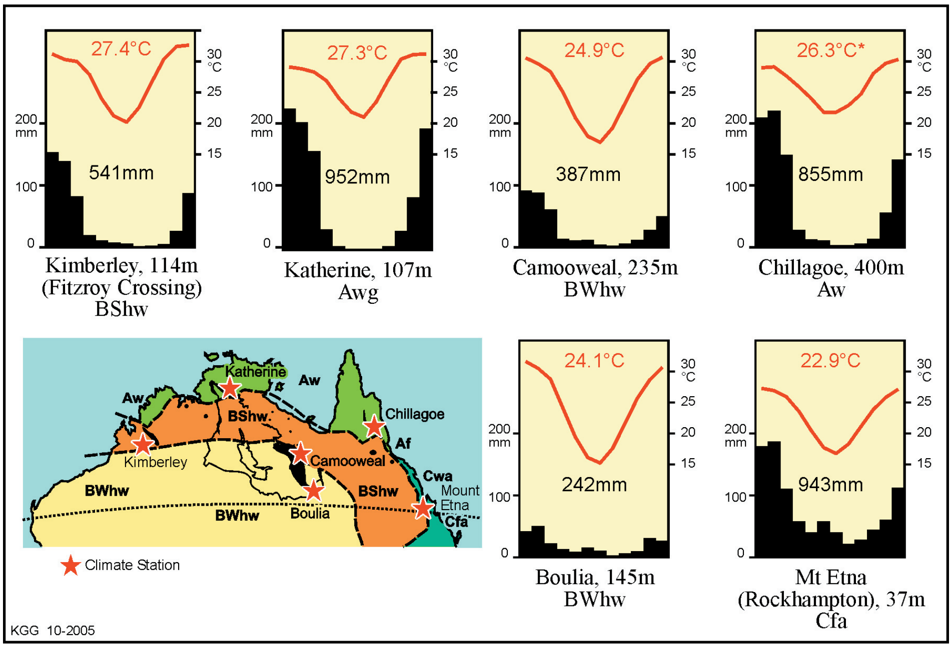


Figure 2: Monthly and annual mean temperatures and rainfall, and elevations for selected climate stations on tropical karsts. Station names are shown in parenthesis where this differs from the karst name. The Köppen climates for north Australia are also shown. Data from BOM (2005).

* Temperature data for Chillagoe is from 3 years only (Robinson, 1982).

Vegetation

Most of the region has a savanna woodland: denser and with more understory in the wetter parts, and more open in the arid regions. Open grassland is found in the dryer areas or where there is a heavy clay soil cover. Deep-rooted deciduous vine thicket may grow on the rocky limestone towers and karrenfields.

Steep-dipping limestones, East Australia

Chillagoe and Mitchell-Palmer.

The Chillagoe area is one of the better documented of the tropical karren in Australia (e.g Lundberg, 1977a; Ford, 1978; Pearson, 1982; Jennings, 1982; and Dunkerley, 1983). The area is best known for its serrated limestone towers – or 'bluffs' as they are locally called (Figure 3) which can reach up to 90 m high, though most are less than 50 m, and are from 100 m to over a kilometre long. The overall size and distribution of the towers are structurally controlled by the narrow lenses or fault-blocks of steep-dipping limestone which alternate with insoluble chert and other sedimentary rocks that are less resistant to erosion in this setting (Figure 4) – thus they are a special type of structural "tower karst" (Ford, 1978, Jennings, 1981, 1982). Some towers are surrounded by a limestone pediment (Figure 5) or by alluvium, but others rise immediately beside the (commonly faulted) contact with the surrounding rocks. The Mitchell-Palmer karst is similar to Chillagoe, but more remote and has larger towers but fewer pediments.

Jennings, (1981, 1982) discussed the pediments, which, along with climatic control of tower form, had been given considerable emphasis in earlier work. He noted that, in fact, the pediments constitute less than half the tower perimeters. However, they are still active in many places and have cut back the tower flanks, in some cases reducing the tower to a scatter of fragments and ruins. The lower "scree" slopes of the towers are partly bedrock with a thin cover and Jennings (1982) referred to these ramps as "Richer denudation slopes" (Figures 4 & 5). Some towers have marginal depressions, with active subsidence of the soil into the epikarst, which are the result of aggressive water runoff from tower surface (Pearson, 1982).

The towers may be quite old. Robinson (1978), Jennings (1982), Webb (1996) and Gillieson et al. (2003) all discuss the age of the karst, noting the presence of isolated outcrops of quartz sandstone of possible Mesozoic age both on the tower tops, and around their bases. The conclusion is that the towers were already well-formed at the time of their burial during the early Cretaceous transgression, and were exhumed and further dissected during the Cainozoic.

Karren forms

While the climate would seem to be important for the overall abundance of karren forms in the area, lithology has been an important control on the detailed sculpturing of individual towers. This was recorded quite early (e.g. Daneš, 1911) and has been discussed by many authors (Wilson, 1975; Marker, 1976; Lundberg, 1977a,b; Ford, 1978; Pearson, 1982; Jennings, 1982; and Dunkerley, 1983, 1988). Unfortunately, there has been a lack of consistency in the lithological subdivisions recognised, and in the terminology used.

Jennings (1982) summarised the lithological control as producing poorly developed karren on the coarse-grained 'sugarstones' (a crumbly coarse-grained marble) and heterogeneous limestones, and a much wider range of well-developed karren on the fine-grained uniform limestones - known variously as 'sparite', 'fossil' or

Figure 3: Aerial view of the crest of a tower at Chillagoe. Showing large sculptured pinnacles and vertical wandkarren.

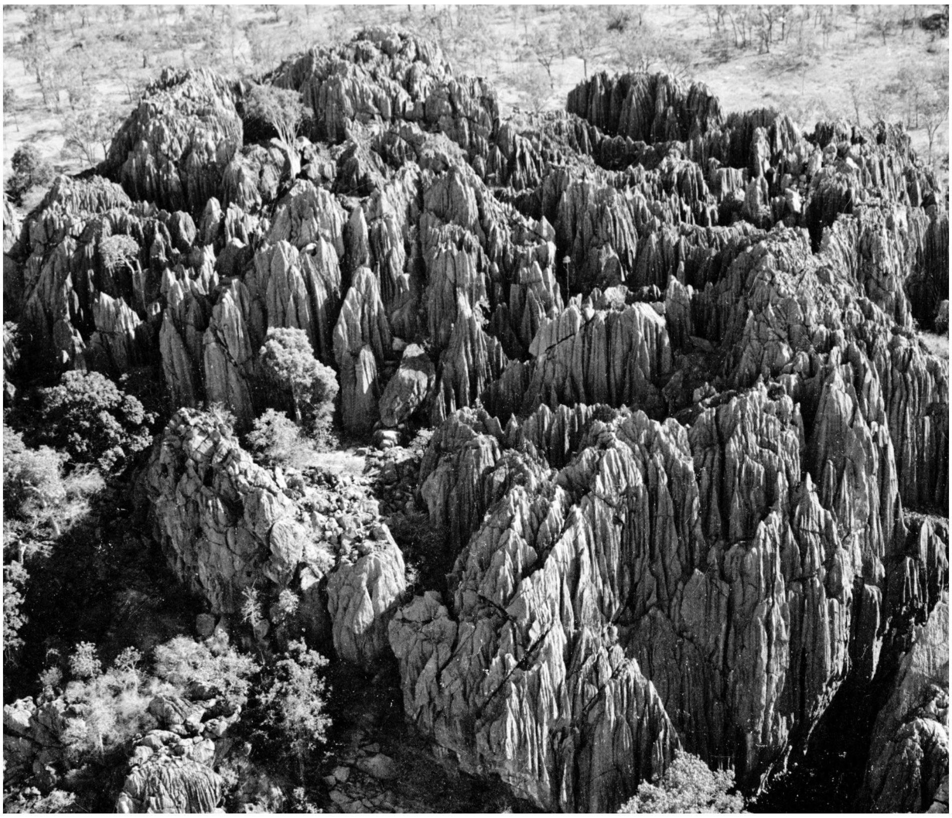
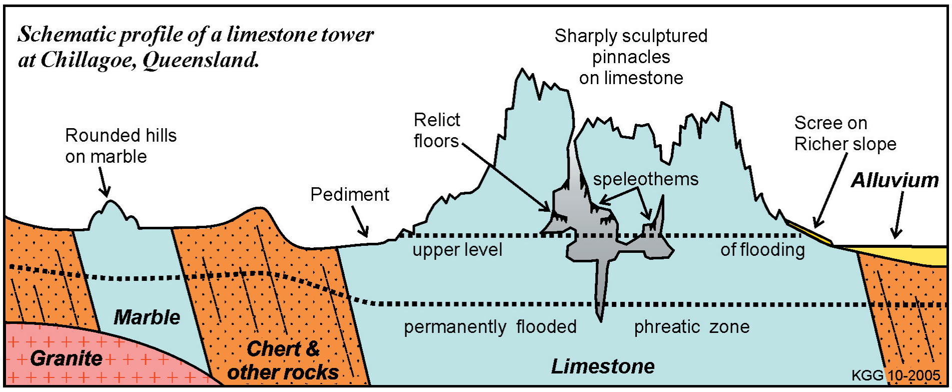


Figure 4: Schematic profile of a limestone tower at Chillagoe, Queensland. Based partly on a diagram in Robinson, 1978.



‘reef’ limestone. He also noted that areas of excessive fracturing inhibit those karren that result from water flow over large surface areas.

Dunkerley (1988) measured the chemistry of runoff water and kamenitza waters from rock surfaces on three lithological groups (coarse and fine-grained marble, and fine-textured “fossil” limestone) and found that the “fossil” limestone (41.9 ppm total hardness) and the fine-grained marble (41.3 ppm) were dissolving more rapidly than the coarse marble (34.1 ppm),. His detailed results have not yet been published.

The following description draws mainly on Pearson (1982) and Jennings (1982). The white, coarsely-crystalline, marbles (“sugarstone”) form smoothly rounded domes with exfoliation sheets that occasionally are raised to form A-tents. Some surfaces show a crazed pattern of fine cracks. Rillenkarren do occur on the marble, but are less well developed. Lundberg (1977a)

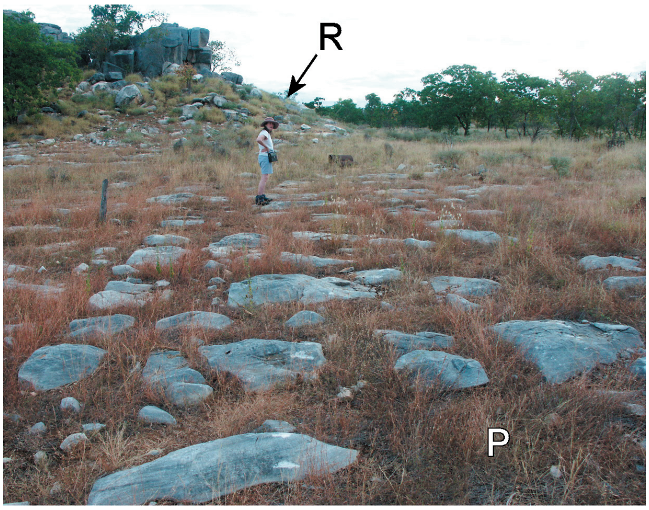


Figure 5: Pediment (P) with clints and soil-filled grikes at Chillagoe. In background is a small tower with a debris-covered Richer slope (R).

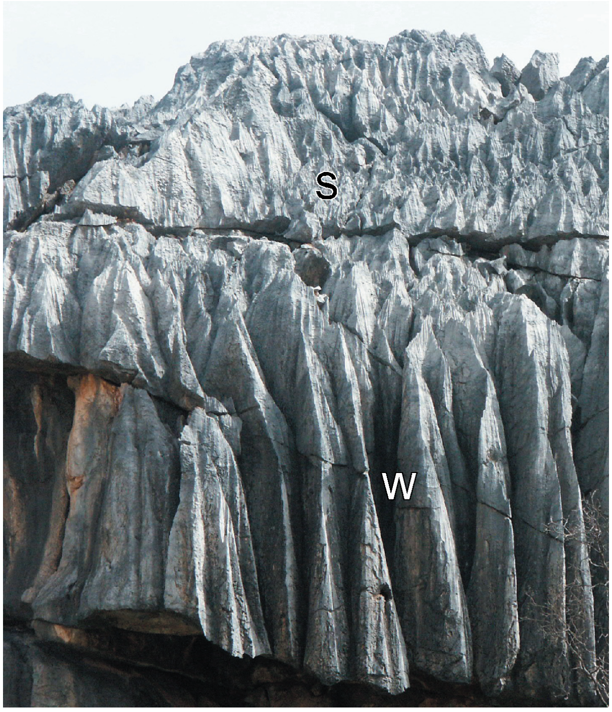


Figure 6: Spitzkarren (S) grading down to deep vertical wandkarren (W). On a tower in the Mungana area, Chillagoe. View is about 8 m high.

tabulated the differences in character between the rillenkarren on the 'sugarstone' and those on the 'sparite' limestones (see also summary in Jennings, 1982, p.25). The 'sugarstone' differed from the 'sparite' limestone in having pits and flutes that were narrower, shallower, more constant in form and less close-set and had more rounded ribs between them.

The finer-grained marbles have karren forms that are more similar to the 'sparite' limestone. However, the grain size of the marble can be quite variable over short distances, so the above distinctions need to be applied with some care.

The more widespread 'sparite' or 'reef' limestone towers are strongly dissected by solution and contain large grikes, vertical sculptured walls, fields of spitzkarren[1] and and large sharp-sculptured pinnacles which make access difficult (Figure 3) The following description refers mainly to these limestones (Jennings, 1982, pp 22-27).

Within the towers, giant grikes up to 10 m wide and 30 m deep connect to fissure-maze caves with numerous daylight holes. In places the grikes open out into karst corridors or deep steep-walled dolines of both solutional and collapse origin. The grikes combine with rillenkarren and wandkarren to form intricately sculptured patterns of sharp pointed pinnacles 5m or more high (Figure 3). Solution dolines on the tower tops tend to be irregular forms with fields of spitzkarren and internal drainage via grikes. Some towers have stepped relief with risers and treads.

On the sides of the towers and the giant grikes extensive rillenkarren feed via steep runnels, 10-20 cm deep, into vertical wandkarren that can be up to a metre deep (into the wall) and 40 m long (Figures 3 and 6). On steep slopes the rillenkarren are modified by cockling (see Chapter ?? - terminology, editor please to substitute appropriate cross-reference). Rinnenkarren (runnels) are listed by several authors but some appear to use this term for regenrinnenkarren or wandkarren (see Chapter ?? [Wandkarren - editor please insert appropriate cross-reference]). Occasional decantation runnels occur below horizontal joints cutting into vertical walls.

On the more gentle slopes, which include steps and bevels, there are "rainpits", localized rosettes of rillenkarren which grade to incipient spitzkarren, short irregular runnels, and small (up to 1 m wide) solution pans (kamenitza). Wilson (1975) reported that flat-floored solution pans are common on tops of the towers, and noted that these always have an outlet drain.

The rillenkarren have been studied morphometrically by Lundberg (1977a,b), Jennings (1982) and Dunkerley (1983). Jennings (1982) measured rillenkarren lengths on the 'sparite' that averaged 95 - 100 cm at three sites, with a SD of 48. Dunkerley (1983) summarized the results in Lundberg's (1977a) thesis, and also reported additional measurements giving flute lengths averaging between 17.3 and 29.8 cm and widths of 16.9 to 18.5 mm at three sites on the marble, whereas two 'sparite' sites had lengths of 31.3 and 35.6 cm and widths of 18.5 and 23 mm.

Two types of horizontal solution ripple were described by Jennings (1982, p.23): on underhangs and in the twilight walls of cave entrances there are sharp-ribbed and deeply recessed symmetrical forms; whereas on steep surfaces exposed by soil erosion of the pediment grikes there are more rounded and asymmetrical ripples that might have resulted from subsoil solution.

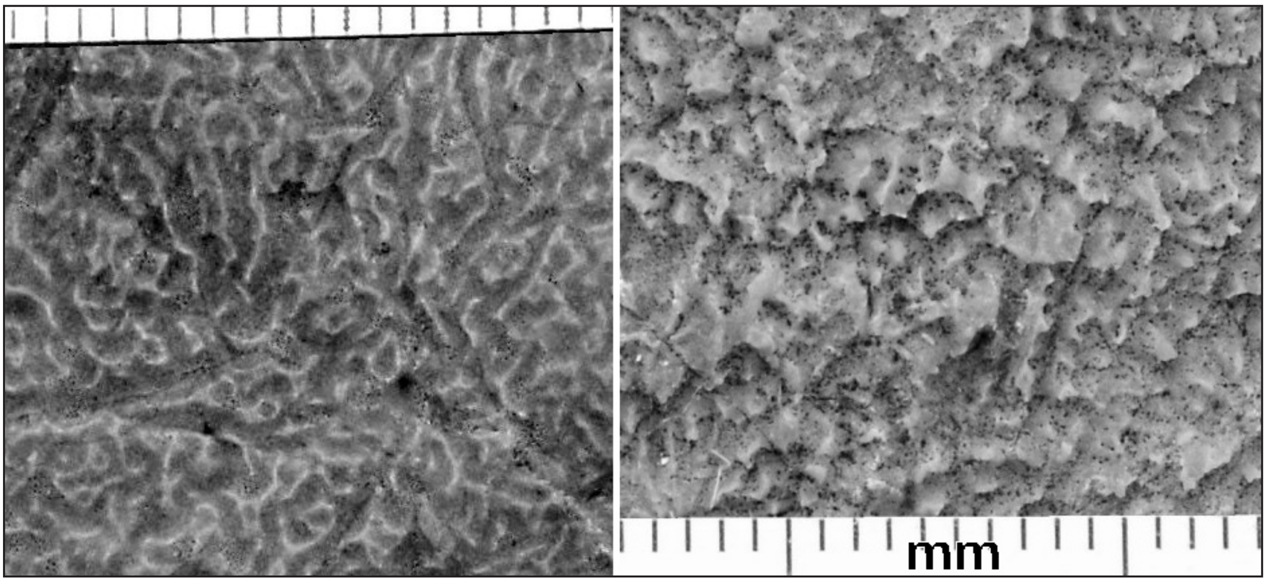
Jennings (1982, p.44-45) described phototropic karren which are grooves, sticks and spines oriented towards the light and found in the twilight zone of the caves and deep grikes (Figure 7). These are a type of phytokarst eroded by algae. Individual spikes and grooves are between 2-50 mm across, but can be up to 400 mm long! Some spikes have coralloid growths on their tips, or along their full length. Jennings (1982, p.45) described small needles, 10mm high and 1-2 mm thick, on the side of a rather deep solution pan on top of one tower.

[1] The term "spitzkarren" is used here for small to medium-sized pointed pinnacles that are sculptured by rillenkarren. In my usage these range from incipient rosettes of rillenkarren a few decimetres high to large pinnacles several metres high. However, I do not use the term for the "large sculptured pinnacles" which have more complex walls (with wandkarren) and are big enough to have clusters of smaller spitzkarren pinnacles on their crests.

Figure 7: Stereopair of phototropic spikes, with coralloid overgrowths, in the twilight zone of a cave entrance. A result of light-oriented algal corrosion. 10 cm scale-bar.

Figure 8: Solution pan on a pediment near Racecourse Tower, Chillagoe. It is formed from coalescence of smaller circular pans with central pits. 10 cm scale-bar.

Figure 9 (below): Microkarren on a pediment at Chillagoe. Left: micro-network of small furrows and bleached ridges; Right: rasp-like micro-teeth. Scales in mm.



Microkarren are more extensive than suggested by earlier reports (Jennings, 1981, 1982; Dunkerley, 1983). The terminology used here is that suggested by Grimes (2007). The microkarren are most common on the flatter surfaces, especially on the gently rounded 'clints' of the pediments and on the steps of the towers. However, I found microrills and other forms on slopes up to 60 degrees. Some microkarren are superimposed on rillenkarren or "rainpits" (e.g. see photos 1-3 in Dunkerley, 1983); these appear to be secondary features modifying the initial coarser form. Linear microrills grade to micro-networks of irregular, discontinuous ridges which in turn break up into arrays of tiny rasp-like micro-teeth (Figure 9). I measured the following size ranges from a set of enlarged photographs: the microrills range from 0.2 to 2.8 mm wide, averaging 1.1 mm; the micro-teeth were spaced 0.5 to 3 mm apart, averaging 1.5 mm. Vertical relief is generally less than 1 mm; some microrills and micro-networks are extremely shallow and visible mainly by a slight bleaching of the crests. Circular micro-pits also occur as small as 1mm across, but show a greater size range and all gradations up to normal "rainpits" (10 mm or greater) can occur on one outcrop. There is also a very fine etching of structures such as irregular cracks, the crystal boundaries of the marbles, or the skeletal structure of fossil corals.

These small features have been under-reported because of their cryptic nature. They are most visible in areas lacking the ubiquitous thin grey algal coating, e.g. in the bare areas used by wallabies. However, they seem too extensive to be a consequence of corrosion by wallaby urine or dung, as suggested by Jennings (1981, 1982). Solution by thin films of water, dew or light rain, seems the most likely origin [EDITOR please add cross-reference to the chapter 6?? on Microrills)].

On the pediments there are smoothly rounded clints between soil-filled grikes (Figure 5). The clint surfaces may carry small areas of rillenkarren, but "rainpits" or smooth surfaces are more common, along with a range of microkarren. Solution pans (kamenitza) are less common. In one area, which appears to be flooded regularly, there were composite pans formed from coalescing smaller circular pans with small deep conical holes in their centres (Figure 8). It would appear that these small pans have been draining downwards through fine cracks. Subsoil solution pipes also occur; typically elongated along a joint. In places soil erosion has exposed the grikes and other, generally rounded, rundkarren and subsoil karren.

Broken River

This region is similar to Chillagoe, but differs in that the limestones here are not as steeply dipping, typically 50-70 degrees, and rather than high abrupt towers, they form long linear ridges dissected by grikes, spitzkarren and larger sculptured pinnacles.

Figure 10: A large, terraced, solution runnel on the crest of the Turtle Creek tower at Broken River. Terrace levels indicated by 1-3. Photo by A.P. Spate, 2003

The Turtle Creek Tower has some features of special interest. This broad, but steep-sided tower is topped by a bare plateau, including a broad solutional basin about 100 m across, that is dissected into low spitzkarren and smoother areas of kamenitza, "rainpits" and rillenkarren.

An unusual set of "interconnected solution rivulets" was first recorded within the basin by Godwin (1988). The following description is based on photographs and information provided by A. Spate and M. Godwin in 2003 (Figure 10). The rivulets are large runnels that form a branching contributory system of small flat-floored stream channels incised into the limestone floor of the basin and which leaves the basin via an increasingly deep channel with some 2 m waterfalls. The channels have flat floors and steep sides which may be slightly undercut. Commonly they are from 0.5 to 2 m wide and from 10 to 80 cm deep, The floor is generally bare limestone, but in places it has small pools. There are several terraces visible on the channel floors with the presently active channel in places being a narrow slot within a broader channel. The higher terraces, which are commonly paired, now have small rillenkarren, "rainpits" and kamenitza developing on them (Figure 10).

These channels appear to be dominantly solutional in origin. The wet season storms could produce sufficient runoff to allow some hydraulic erosion - though there is no sediment to provide abrasive tools. Algal material on the floors may have contributed to the undercutting of the walls – as happens in kamenitza.

Fanning River

This is a small karst area inland from Townsville that is developed on a 1 km wide low ridge of gently dipping Devonian limestone. The rock occurs in alternating zones of thick-bedded limestone with good karst development and poorly exposed belts of interbedded limestone, sandstone and shale with no karst features (Grimes, 1990). Dips vary from 10 to 70 degrees. The thick-bedded limestone has some grikes, rillenkarren, and kamenitza. However, surface solution sculpturing is not as well developed as in the Chillagoe and Broken River areas.

An unusual, dipping limestone pavement occurs in one place. This is a 12 degree dip surface formed by the stripping of a thinner-bedded muddy limestone from above a thicker-bedded calcirudite. The pavement has scattered grikes (0.5-2m deep and 2-20m long), some of which connect with caves, some relatively deep kaminitza with overflow channels on the downslope side, and small patches of rillenkarren and "rainpits"; but otherwise it is essentially undissected. This may be a similar situation to that described below at the Gregory Karst – where a surface has not been exposed for long enough to develop deep sculpturing.

Mt Etna

Mount Etna, rising 190 m above the surrounding plain, is the largest of several limestone ridges and hills that lie near the coast, just north of the Tropic of Capricorn (Shannon, 1970). These provide a borderline example of tower karst as the hills tend to be conical with a scree-covered base, and vertical cliffs are rare. The steep sides of the mountain are bare or covered with vine thicket and are strongly sculptured by a combination of rillenkarren and larger runnels to form spitzkarren. Large rubble-choked grikes cut across the karrenfields. Cave entrances are associated with the grikes or with large, vertical, solution pipes.

Other eastern areas

Mount Etna is at the southern limit of the tropical region, and lies just within the northern limit of the *Cfa* climate type. However, well-developed spitzkarren are found as far south as Kempsey, latitude 31ºS, in northern New South Wales, which has a *Cfa* climate with an annual rainfall of about 1,700 mm.

Figure 11: A giant grike, at least 5 metres wide, with collapsed blocks and deep vertical wandkarren. Above Mimbi Cave, Kimberley region. Note the relatively undissected plateau in the background. Photo by J. Jennings.

Flat-lying carbonates, North-west Australia

Kimberley region, Western Australia.

The Kimberley Karst Region of northwestern Australia is also referred to in reports as the "Limestone Ranges", "Napier Ranges" and "Fitzroy Basin" regions. It is an extensive belt of exposed Devonian reef that has had little folding (Playford, 1980). It lies at the junction between the rugged Proterozoic ranges of the Kimberley region and the flat plains of the Mesozoic Canning Basin to the south. Limestone ridges and plateau rise abruptly 30-90 m above the plains and extend for 290 km with a maximum width of 30 km. The plateau top is a dissected planation surface of probable mid Tertiary or Cretaceous age, but may contain older paleokarst features. Subsequent dissection in the late Tertiary and Quaternary has created the present karst landforms, along with gorges of superimposed drainage that cut across the limestone ranges.

Large-scale karst landforms (macrokarren)

The surface karst landforms have been described in detail by Jennings and Sweeting (1963) and summarized in later papers by Jennings (1967, 1969), Williams (1978), Goudie et al. (1989, 1990) and Gillieson and Spate (1998). The main scarp is an abrupt wall or cliff, deeply sculptured by various karren forms, as are the steep walls of the gorges, box valleys (bogaz) and giant grikes which extend into the plateau. In detail, the steepness and character of these walls is controlled by the lithology and structure of the different reef facies (Allison and Goudie, 1990). In particular, Jennings (1967) noted that the backreef facies tends to be impure (due to terrigenous components) and that reduces the degree of karstification so that one finds more rounded hills and valleys typical of fluvial erosion. Jennings and Sweeting (1963) called these areas "merokarst" and excluded them from their main discussion.

Jennings and Sweeting (1963) described an evolutionary sequence of dissection for the pure and well-jointed limestones (but not the merokarst). Progressive dissection and pediplanation has produced the following landforms on the pure limestones. Stripping of the original clay soil cover of the plateau leaves a relatively smooth rock surface with minor small karren features and scattered large, deep grikes ("giant grikeland", Figure 11). Widening of the giant grikes forms box valleys, with flat floor and vertical walls, which in turn coalesce to leave isolated towers and large sculptured pinnacles within a broad pediment. Dolines are relatively uncommon.

Mesokarren forms

The surface sculpturing can be quite intense to form inhospitable jagged ridges and spires. In the undissected parts of the plateau the smooth surface has kamenitzas, "rainpits" and small patches of rillenkarren. This pavement is cut by a widely spaced network of deep grikes with fluted vertical walls (Figure 11). The giant grikes are up to 7 m wide, 33 m deep and hundreds of metres long and extend underground into fissure caves. As dissection becomes greater a rugged terrain of spitzkarren and larger sculptured pinnacles develops (c.f. Figure 18). Rillenkarren are ubiquitous, but their intensity and character is controlled by the local lithology, structure and slope (see below). On the vertical walls there are large vertical solution runnels (wandkarren), 1-2 m deep and wide and running vertically for 30-60 m (Figure 11). The pediments have kamenitza and occasional shallow dolines and subsoil solution pipes.

Goudie et al. (1989) discuss some lithological and other factors controlling the development of the rillenkarren, which are only well-developed on certain beds. The limestones are all hard and have little primary porosity, but, of the factors which Goudie and others studied, the important control on the occurrence of rillenkarren appeared to be the purity (insoluble residue) and the homogeneity (as revealed by thin section study). The difference is mainly one of the fabric and the cement type: in particular, rillenkarren develop best in the absence of fabrics characterised by bioclasts, ooids, and an excess of ooids over intraclasts. They are also related to an absence of micritic cement. Other factors statistically associated with rillenkarren were low levels of dolomite and a sparite cement that is less equant than elsewhere. In addition to the factors measured by Goudie et al. (1989), Jennings and Sweeting (1963) noted the influence of bedding in disrupting rillenkarren development and breaking it into pagoda-like stacks of conical spitzkarren (c.f. Figure 18).

Goudie et al. (1989, p.101 and figure 3) also recorded that the karren types vary with gradient of slope: shallow slopes (0-30º) tend to be pitted and have kamenitza. Grikes are scattered across these "pavements" and some may be filled with tufa deposits. Moderate slopes (30-55º) have bifurcating (dendritic) rillenkarren which become parallel as the slope steepens (55-80º). The steepest slopes (>80º) are described by Goudie and others as having "boxy forms" (cockling?).

Within the major river gorges which cross the karst, wet season floods rise to heights of 10 m (Gillieson et al., 1991). The flooded sections of the gorge walls show well-developed scallops and strong etching of bedding and vertical joints to form cavernous slots (splitkarren, *sensu* Ford & Williams, 1989, p.380) and vertical grikes, along with spongework.

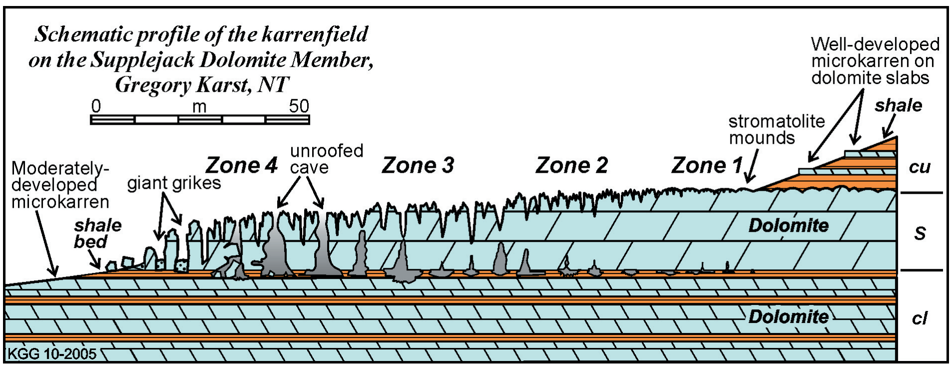


Figure 12: Schematic profile of a karrenfield in the Gregory Karst, Northern Territory. cu, upper Skull Creek Formation; S, Supplejack dolomite member; cl, lower Skull Creek Formation. Zone 1, Incipient karren; Zone 2, moderately-developed grikes and spitzkarren; Zone 3, deep grikes and large spitzkarren; Zone 4, giant grikes, unroofed caves, sculptured pinnacles.

Ningbing and Jeremiah Hills

There have been no karst-specific reports published on this area of gently-dipping Devonian and Carboniferous reef limestones, which is also known as the East Kimberley. However, the geological report by Veevers and Roberts (1968) has photographs of outcrops of the different carbonates which show the distinctive fluted, pinnacled and cavernous tower structure seen in other areas. There is also a suggestion of both lithological and structural control on the character of the solutional sculpturing. A photo of the fore-reef breccia of the gently dipping (10-20º) Westwood Member shows unusual smooth-surfaced cones and pinnacles from 1 to 4 m high. These could be uncovered subsoil features, but as the outcrop is in an area of low relief in a prograding coastal plain the potential for soil erosion seems limited.

Gregory Karst

In this area karst and karren are largely restricted to a thin (10-18 m) but extensive dolomite unit, the Supplejack member, within the flat-lying late Proterozoic Skull Creek Formation. The Skull Creek Formation is also dominantly carbonate, but less pure and thinner bedded (Sweet et al.,1974 and Bannink et al.,1995). Apart from the Supplejack member, the Skull Creek Formation has only poorly developed mesokarren, but it has well-developed microkarren, especially in the upper part. Figure 12 illustrates the geological structure and the resulting karren. Extensive maze caves underlie the dissected surface (Storm and Smith, 1991; Bannink et al.,1995). There is obvious joint and bedding control of both the karren and the underlying caves.

Only brief descriptions of the karren have been published previously (Dunkley, 1993; Bannink et al., 1995). The karrenfields on the Supplejack member show a zonation which results from progressively longer periods of exposure at the surface. This starts with incipient karren development on recently exposed surfaces adjacent to the contact with the overlying Skull Creek Formation and continues through progressively deeper dissected karren to a final stage of "ruined cities" of isolated pinnacles at the outer edge (Zones 1 to 4 on Figures 12 and 13). The zones are gradational and the boundaries shown on Figure 13 are only approximate. This developmental sequence has similarities to that described by Jennings and Sweeting (1963) in the Kimberly region, but at a smaller scale.

Zone 1 has well-preserved stromatolite domes (up to 12 m wide and 2 m high) exposed by stripping of the overlying rock. The surfaces are smooth or sculptured by incipient "rainpits" and rillenkarren with superimposed microkarren (Figure 15). Etching of joints and bedding forms splitkarren. There are scattered kamenitza and small grikes.

Away from the contact, increasing dissection produces small spitzkarren up to 0.3 m high, and grades to zone 2. There the stromatolite domes are still recognisable locally, but are strongly dissected by a variety of mesokarren, including numerous kamenitza (up to 2 m

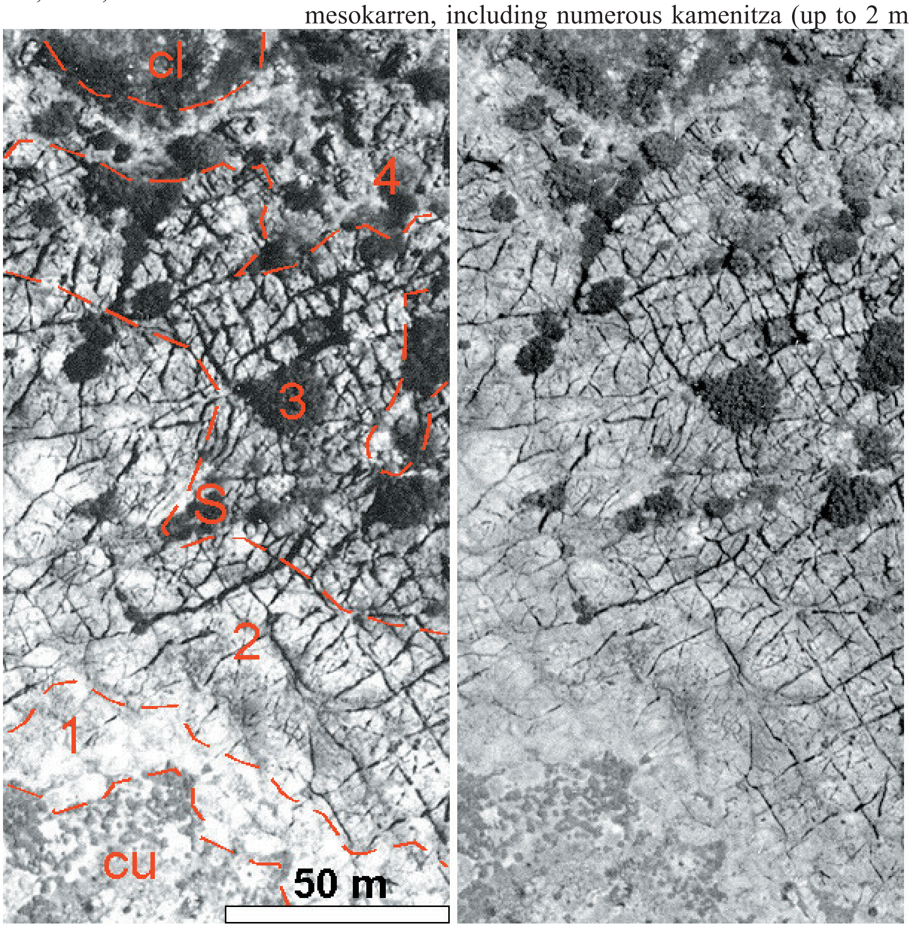


Figure 13: Aerial stereo-pair of a karrenfield in the Gregory Karst. Numbers 1 - 4 refer to the zones shown on Figure 12. The main karrenfield is on the Supplejack member; cl and cu are outcrops of the lower and upper Skull Creek Formation, respectively. Note subsided areas in centre (S) - a result of cave undermining. Original air-photos copyright Northern Territory Government, 1989.

Figure 14: Isolated pinnacle, about 5 m high, at outer edge of zone 4 in the Gregory Karst. Photo by N. White, 1992.

wide and 0.4 m deep) and spitzkarren up to 1 m high. Grikes are wider and deeper - averaging 2 m deep, but with considerable variation, including occasional narrow connections to the cave passages below.

The transition to zone 3 is quite gradual. Zone 3 has wider and deeper grikes, and connections to the cave become more common, though still narrow. Traversing the surface becomes difficult. Spitzkarren are dominant and up to 2 m high. Wandkarren appear on the grike walls and the sides of the larger spitzkarren.

In zone 4 the surface has become completely dissected. Giant grikes 1-5 m wide penetrate to the cave floors 10-15 m below and separate blocks of rock with strong spitzkarren on the tops and wandkarren, rillenkarren and cockles on the walls. As the grikes widen, one gets a "ruined city" topography of isolated blocks, many of which are tilted. and finally an abrupt change to a broad flat floored valley on the lower Skull Creek Formation with only scattered blocks and sculptured pinnacles (Figure 14).

Kamenitza are common in zones 2 and 3 but also found in the other zones, reaching up to several metres wide and 0.4 m deep. These can form chains linked by short runnels The flat floors have two types of surface associated with different algal types: smooth, bare rock floors are associated with curled fragments of a black algae, and pitted floors are coated by the usual thin, grey, hard film of algae that covers most of the rock surface. The pitted floors comprise both pits and cones, 2-5 mm wide and 2 mm deep/high. Larger "rainpits" form hackly floors in places. Etched stromatolite structures make small ridges on some floors.

In the twilight zone of cave entrances and at the base of the giant grikes there are phototropic spikes and solution ripples similar to those described at Chillagoe (c.f. Figure 7).

Microkarren occur within the main karrenfield. They are common in zone 1, but also occur in the other zones, usually at the tops of spitzkarren and associated with rillenkarren and "rainpits". However, the best development of microkarren in the Gregory Karst is on the flaggy to slabby outcrops of dolomite in the upper Skull Creek formation, where there is little competition from mesokarren.

Microkarren are best developed on gentle slopes. They include microrills up to 60 cm long, typically 1-2 mm wide, and straight to sinuous (Figure 15) or locally tightly meandering (Figure 16). Micro-pits have a full size range from less than 1 mm wide and deep up to 20 mm (i.e. they grade to "rainpits"). A broad range of sizes can occur within a single outcrop. On gently-domed surfaces micro-pits occur on the crest and grade to microrills on the slopes. Micro-teeth and micro-networks (as seen at Chillagoe, Figure 9) are less common. Small shallow micro-pans are 2.5 - 8 mm wide but only 1-2 mm deep and are superimposed on pre-existing microrills (Figure 17). These have finely pitted or toothed floors. Micro-tessellations (spaced networks of shallow etched cracks, see photo 3 in Grimes, 2007) are also superimposed on other microkarren.

Katherine (Daly Basin)

The Katherine area is at the northern end of the Daly Basin, a broad area of flat-lying early Palaeozoic limestone that has an extensive cover of Cretaceous sandstone and claystone and younger alluvium (Figure 1). Karst features are mainly restricted to the exposed limestones at the northern and western margins of the basin.

Most outcropping limestone forms pavements of grikes and clints or, in more strongly dissected areas, widening and deepening of the grikes has converted the clints to pinnacles and small towers that are typically 1-3 m high, but up to 30 m in places (Hamilton-Smith et al., 1989; Lauritzen and Karp, 1993; Karp, 2002). The surfaces of the pinnacles and towers are sculptured by deep "rainpits" and rillenkarren grading to spitzkarren in the more dissected areas. Locally the pitting becomes very intense to form a sharp fretted surface analogous to coastal phytokarst (Hamilton-Smith et al., 1989). Kamenitza up to two metres across are also common and some have outlet channels. Beneath the sandy cover there is a well-developed epikarst surface of narrow smooth-surfaced pinnacles and deep shafts, which is exposed within the occasional soil-subsidence doline.

Further south, the rainfall is lower, and outcrops around the edge of the basin have only hackly surfaces

Figure 15: Microrills superimposed on shallow rillenkarren on a horizontal slab in the upper Skull Creek Formation, Gregory Karst Region. Scale bar marked in cm.

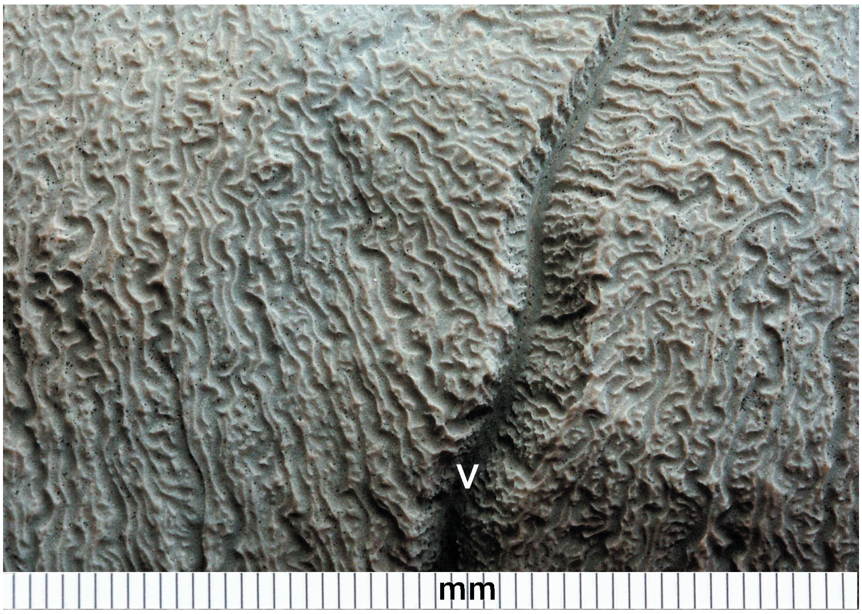


Figure 16: Tightly meandering microrills and a v-notch (V) following a joint. On a cobble in the upper Skull Creek formation, Gregory Karst Region. Scale in mm.

Figure 17 (below): Shallow micro-pans, with finely pitted and toothed floors, superimposed on microrills. Gregory Karst Region. Scale in mm

with deep “rain-pits” ranging in width from 3 mm to 20 mm.

Barkly Karst Region (Georgina Basin)

This is the easternmost of the large covered karst basins (Figure 1). The rocks are mainly Palaeozoic flat-lying dolomite with some gently folded limestones around the basin margins which have the best exposures of surface karst (Grimes, 1988). The climate ranges from semi-arid in the north to arid in the south (Figure 2) and karren are best developed in the wetter northern part.

The Dissected Northeastern Edge

Much of the northeastern edge of the karst region is a dissected Tertiary plateau (Grimes, 1988; Williams, 1978) with the major streams incised as a superimposed drainage pattern. Between these is a dense pattern of

Figure 18: The Colless Creek karrenfield, Barkly Karst, Queensland. In the foreground a thick-bedded limestone is dissected into deep grikes and spitzkarren. Beyond the gorge of Colless Creek is a plateau developed on a less pure and thinner-bedded limestone.

This photo is typical of many outcrops of flat-lying thick-bedded carbonates in tropical Australia.

modern dendritic surface drainage with v-section valleys and rounded interfluves which is developed on impure limestone and dolomite with abundant chert as nodules and thin beds. This is equivalent to the "merokarst" of the Kimberley region (Jennings and Sweeting, 1963) and lacks significant karst or karren, though there are scattered caves and dolines. Within this terrain occasional distinctive dark bands show up on the air photos – these are karrenfields developed on belts of pure, thick-bedded and well-jointed limestone (Figure 18).

One of the more accessible of these karrenfields is on the north side of Colless Creek a kilometre above its junction with Lawn Hill Creek, just west of Lawn Hill Gorge (Grimes, 1978, 1988). There, the flat-lying, thick-bedded, pure limestone bed is about 45 m thick and large grikes connect down to joint-controlled fissure caves. The structure is similar to that at Gregory (Figure 12) The surface between the deep grikes is strongly dissected by rillenkarren, steep runnels and spitzkarren (Figure 18). Kamenitza and "rainpits" also occur on flatter surfaces.

Gale et al.(1997) described another karrenfield 12 km further west which had relatively thin (about 2 m) beds of pure and thick-bedded limestone interbedded with less pure, closer-jointed and medium-bedded cherty limestone beds. There, the grikes have widened to form small flat-floored "box valleys" (their usage) a few metres across and a "ruined city" of narrow walls and small "towers" up to 4.5 m high. The "towers" and walls are capped by the thick-bedded limestone, but the grikes have cut below this several metres into the underlying thinner bedded and less pure limestone. Gale et al. (1997) interpret the flat floors as corresponding to an impermeable bed which converted the downward erosion of the joints to lateral corrosion which widened the grikes.

The southern, arid, region

The more arid, and less dissected parts of the Barkly Karst have relatively poor karren development. Possibly this is partly because much of this country is developed on dolomite.

Camooweal lies at the boundary between the semi-arid *BShw* and arid *BWhw* climates (Figure 2). Here, the dolomite strata are horizontal and thick to medium and occasionally thin bedded. They have well developed vertical joints that result in a blocky to slabby outcrop with narrow grikes and clints. Other karren are restricted to "rainpits" and fine etching of structures. The "rainpits" occur mainly on slopes and vertical faces, and tend to follow the bedding structure. Sizes are variable, typically ranging from 4 to 25 mm across and they can form hackly surfaces. The flat tops of beds are generally smooth or finely etched but some small "rainpits" occur. The etching can be quite detailed, following nets of very fine cracks, and forming deeper v-notches (splitkarren) in larger joints or the bedding planes (Figure 19). Colour variations in the cream-coloured dolomite indicate that weathering has penetrated a few mm in from the major cracks. Occasional poorly-developed rillenkarren and runnels are seen, usually only a few decimetres long. Reto Zollinger (pers comm, 2003) found microkarren in a more dissected area 80 km NE of Camooweal. These included microrills, micro-networks and rasp-like micro-teeth, as well as fine pitting. Micro-pans and micro-tessellations were superimposed on the microrills and micro-teeth.

Further south, in the dryer area near Boulia (Figure 2), I found some well-developed microkarren on cobbles of limestone. The upper, horizontal, surface had radiating micro-rills 0.5 - 2.0 mm wide, and linear micro-rills also ran down the vertical sides, but became less pronounced

Figure 19: Fine etching of cracks (splitkarren) in dolomite near Camooweal, Barkly Karst, Queensland. Pen is about 15 cm long.

downward – suggesting a decantation process. The underside of a loose specimen had fine pits (0.5 - 2 mm) where it had been in contact with the soil. In this arid region larger mesokarren are restricted to grikes and "rainpits" (Andy Spate, pers comm).

Conclusion

Australia's tropical monsoon karsts have a number of surface features in common (Spate and Little, 1995). There are extensive areas of bare limestone. The macrokarren have a positive relief with upstanding limestone towers, pinnacles, scarps and ridges, sometimes with adjoining pediments. The mesokarren are very well developed and include extensive and deep grikes, spitzkarren, rillenkarren, kamenitzas, a variety of sharply-fretted pittings, and other forms. However all these become less well-developed in the drier areas. Subsoil forms such as grikes, rundkarren, and smooth-surfaced pinnacles are locally exposed by soil erosion to form surface fields, as at Chillagoe. Directional phytokarst forms and solution ripples occur in the twilight zones of the caves and giant grikes. Microkarren have been recorded recently from a number of areas, and are particularly well-developed in the Gregory Karst, but because of their cryptic nature it is too early yet to make deductions about their true distribution.

However, the local effects of lithology, structure, cover and denudation history can create considerable variation within that broad tropical theme.

A semi-arid tropical monsoon model?

Jennings and Sweeting (1963), and Jennings in later papers, described a sequence of development for the Kimberly karst region, with gradation from undissected plateau through giant-grikes, box valleys, and towers to pediment. Jennings (1967) said "it may be that here there is a semi-arid tropical monsoonal karst type." Some later writers have taken this sequence to be a purely climatic model, arguing for or against it on that basis (e.g. Williams, 1978; and Gale et al., 1997). But Jennings and Sweeting (1963) also noted local lithological and structural controls and specifically excluded the impure limestones from their discussion as those formed a quite different "merokarst" terrain. The Jennings and Sweeting sequence is only applicable to areas of hard, pure, thick-bedded, jointed and flat-lying limestones in a tropical monsoon climate. Other constraints may also apply: e.g. time for the full sequence to evolve, and a dissected plateau with limited vertical relief. Even within such areas, variation in lithological and structural factors, and the history of denudation can result in quite distinctive landforms and karren styles.

When considering climate, Jennings (1967, 1983) noted that although many of these areas are semi-arid the rainfall is concentrated into a short wet season and frequently falls as brief intense storms. So intense solutional sculpturing of the surfaces, comparable to that of more humid climates, is not inexplicable – one would not need to invoke past wetter climates. However, this idea is opposed by theoretical modelling by Szunyogh (2005) which suggests that long periods of gentle rain should be more effective for denudation than short intense falls. Higher temperatures in tropical regions could also speed the reaction rates, and there may be a greater input from biological activity – including micro-organisms and algal coatings. However, in Australia what is probably more important is the history of long periods of exposure of many of the tectonically stable limestone areas. which could compensate for the slower rates of sculpturing.

However, Jennings (1981) argued for moderation in applying both climatic, and other (e.g. lithological) influences to karst morphology. The truth will usually lie between the extreme views; climate, lithology and structure have all contributed to greater or lesser degree to the character of Australia's tropical karsts. Each area needs to be interpreted according to its local setting.

Acknowledgements

Andy Spate reviewed an early draft and provided information and photos of many of the areas. He also made available a collection of photos taken by Joe Jennings. Susan and Nicholas White, Mick Godwin and Reto Zollinger provided information, photos and specimens from several areas. Les Pearson commented on the Chillagoe text. Angel Ginés discussed the nomenclature and Bernie Smith discussed etchings and "rainpits". Jacques Martini discussed the karren zones in the Gregory Karst. Two anonymous reviewers helped improve the final text. Sources of photographic figures are acknowledged in the captions, all unacknowledged photos are my own.

References

Allison, R.J. and Goudie, A.S., 1990: The form of rock slopes in tropical limestone and their associations with rock mass strength, *Zeitschrift fur Geomorphologie*, 34(2): 129-148.

Bannink, P., Bannink, G., Magraith, K., and Swain, B., 1995: Multi-level maze cave development in the Northern Territory. *in* Baddeley, G. [ed], *Vulcon Preceedings, 20th Conference of the Australian Speleological Federation.* Victorian Speleological Association, Melbourne. pp. 49-54.

BOM (Bureau of Meteorology, Australia), 2005: Climate. <http://www.bom.gov.au/climate/averages/>

Daneš J.V., 1911: Physiography of some limestone areas in Queensland. *Proc. Roy. Soc. Qld*. 23: 75-86.

Dunkerley, D.L., 1983: Lithology and micro-topography in the Chillagoe karst, Queensland, Australia. *Zeitschrift fur Geomorphologie,* 27: 191-204.

Dunkerley, D.L., 1988: Solution and precipitation of limestone in the Chillagoe karst and opportunities for dating landscape development. *17th Biennial Conference of the Australian Speleological Federation*. 112-117.

Dunkley, J.N., 1993: The Gregory Karst and caves, Northern Territory, Australia. *Proceedings of the 11th International Congress of Speleology,* Beijing. 17-18.

Ford, D.C. and Williams, P.W., 1989: *Karst Geomorphology and Hydrology*. Unwyn, London. 601 pp.

Ford, T.D., 1978: Chillagoe - a tower karst in decay. *Trans British Cave Research Assoc.* 5: 61-84.

Gale, S.J., Drysdale, R.N., Scherrer, N.C., and Fischer, M.J., 1997: The Lost City of North-west Queensland: a test of the model of giant grikeland development in semi-arid karst. *Australian Geographer,* 28(1): 107-115.

Gillieson, D.S., Smith, D.I., Greenaway, M., and Ellaway, M., 1991: Flood history of the limestone ranges in the Kimberley region, Western Australia. *Applied Geography*. 11: 105-123.

Gillieson, D.S., and Spate, A.P., 1998: Karst and Caves in Australia and New Guinea, *In* Yuan Daoxian and Liu Zaihua [eds.], *Global Karst Correlation*, Science Press, Beijing PRC and VSP Press, Utrecht NL, pp. 229-256.

Gillieson, D., Nethery, J., Webb, J., Godwin, M., O'Keefe, C., and Atkinson, A. 2003: *Field Guidebook: Limestone and Lava*. 15th Australasian Conference on Cave and Karst Management, Chillagoe and Undara, Queensland, May, 2003. Australasian Cave and Karst Management Association. 43 pp.

Godwin, M., 1988 [editor] *Broken River Karst: a speleological field guide, North Queensland.* Unpublished report by Chillagoe Caving Club and Queensland National Parks and Wildlife Service, Cairns. 134 pp.

Goudie, A.S., Bull, P.A. and Magee, A.W., 1989: Lithological control of rillenkarren development in the Napier Ranges, Western Australia, *Zeitschrift fur Geomorphologie, Supplementband,* 75: 95-114.

Goudie, A.S., Viles, H.A., Allison, R.J., Day, M.J., Livingstone, I.P., and Bull, P.A., 1990: The geomorphology of the Napier Range, Western Australia, *Transactions of the Institute of British Geographers*, 15(3): 308-322.

Grimes, K.G., 1978: Colless Creek and Lawn Hill Gorge. *Down Under (Newsletter of the University of Queensland Speleological Society).* 17(2): 45-49.

Grimes, K.G., 1988: The Barkly Karst Region, North-west Queensland. *17th Biennial Conference of the Australian Speleological Federation*. 16-24.

Grimes, K.G., 1990: Fanning River Karst Area: Notes on the geology and geomorphology. *Queensland Department of Mines, Record* 1990/7 (unpublished). 31 pp.

Grimes, K.G., 2007: Microkarren in Australia – a request for information. *Helictite*, **40(1):** 21-23.

Hamilton-Smith, E., Holland, E., Mott, K, and Spate, A., 1989: *Cutta Cutta Caves Nature Park - Draft Plan of Management*. Unpublished report by the Australasian Cave Management Association for the Conservation Commission of the Northern Territory.

Jennings, J.N., 1967: Some karst areas of Australia. *in* Jennings, J.N., and Mabbutt, J.A., [eds] *Landform Studies from Australia and New Guinea*. Australian National University Press, Canberra. 256-292.

Jennings, J.N., 1969: Karst of the seasonally humid tropics in Australia. *in* Štelcl, O. [ed] *Problems of the Karst Denudation*. Supplement for the 5th International Speleological Congress. Institute of Geography, Brno. pp. 149-158.

Jennings, J.N., 1981: Morphoclimatic control - a tale of piss and wind or the case of the baby out with the bathwater? *Proc. 8th Int. Congress Speleology.* 1: 367-8.

Jennings, J.N., 1982: Karst of northeastern Queensland reconsidered. *Tower Karst, Chillagoe Caving Club, Occasional Paper*, 4, 13-52.

Jennings, J.N., 1983: The disregarded karst of the arid and semiarid domain. *Karstologica.* 1(1): 61-73.

Jennings, J.N., 1985: *Karst Geomorphology*. Blackwell, Oxford. 293 pp.

Jennings, J.N., and Sweeting, M.M., 1963: The Limestone Ranges of the Fitzroy Basin, Western Australia. *Bonner geographische Abhandlungen,* 32: 60 pp.

Karp, D., 2002: Land degradation associated with sinkhole development in the Katherine region. *Department of Infrastructure, Planning and Environment, NT. Technical Report 11/2002.* (unpublished.)

Lauritzen, S.E., and Karp, D., 1993: Speleological assessment of karst aquifers developed within the Tindall Limestone, Katherine, N.T., *Power and Water Authority, NT. Report 63/1993* (unpublished.)

Lundberg, J., 1977a: *The geomorphology of Chillagoe limestones: variations with lithology*. Unpublished M.Sc thesis, Australian National University, Canberra. 175 pp.

Lundberg, J., 1977b: An analysis of the form of Rillenkarren from the tower karst of Chillagoe, north Queensland, Australia. *Proc. 7th. Int. Congr. Speleology.* 294-6.

Marker, Margaret E., 1976: A Geomorphological Assessment of the Chillagoe Karst Belt, Queensland. *Helictite* 14(1): 31-49

Pearson, L.M., 1982: Chillagoe karst solution and weathering. *Tower Karst, Chillagoe Caving Club, Occasional Paper*, 4, 58-70.

Playford, P.E., 1980: Devonian "Great Barrier Reef" of Canning Basin, Western Australia. *American Association of Petroleum Geologists, Bulletin.* 64(6): 814-840.

Robinson, T., 1978: A question of age. *Tower Karst, Chillagoe Caving Club, Occasional Paper*, 2: 18-36.

Robinson, T.W.L., 1982: Limestone solution experiment at Chillagoe. *Tower Karst, Chillagoe Caving Club, Occasional Paper*, 4, 71-76.

Shannon, C.H.C., 1970: Geology of the Mt Etna area. *in* Sprent, J.K., [ed] *Mount Etna Caves.* University of Queensland Speleological Society, Brisbane. 11-21.

Spate, A.P., and Little, L., 1995: Is the conventional approach to karst area management appropriate to tropical Australia. *in* Henderson, K., Houshold, I., and Middleton, G., [eds] *Proceedings of the 11th Australasian Conference on Cave and Karst Management.* Australasian Cave and Karst Management Association, Carlton South, 68-84.

Storm, R., and Smith, D., 1991: The caves of Gregory National Park, Northern Territory, Australia. *Cave Science,* 18(2): 91-97.

Sweet, I.P., Mendum, J.R., Bultitude, R.J., and Morgan, C.M., 1974: The geology of the southern Victoria River Region, Northern Territory. *Bureau of Mineral Resources, Australia, Report.* 167. 143 pp. with maps.

Szunyogh, G., 2005: Theoretical investigation of the duration of karstic denudation on bare, sloping limestone surfaces. *Acta Carsologica*, 34(1): 9-23.

Veevers, JJ., and Roberts, J., 1968: Upper Palaeozoic rocks, Bonaparte Gulf Basin of Northwestern Australia. *Bureau of Mineral Resources, Australia, Bulletin*, **97.** 155 pp. + folded maps.

Webb, J: 1996: *Chillagoe Field Trip Excursion Guide*. 7th Australia and New Zealand Geomorphology Group Conference. 21 pp.

Williams, P.W., 1978: Interpretations of Australasian Karsts. *In* Davies, J.L., and Williams, M.A.J., [eds] *Landform evolution in Australia*. Australian National University Press, Canberra. 259-286.

Wilson, P.A., 1975: Observations on the geomorphology of the Chillagoe limestones. *Proc 10th biennial conf, Aust Speleol. Federation.* 69-73.

Wray, R.A.L., 1997: A global review of solutional weathering forms on quartz sandstones. *Earth-Science Reviews*. 42: 137-160.