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Chapter 30 - Tropical monsoon karren in Australia

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Introduction: the Tropical Australian Karst Areas

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 the climate becomes drier. 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 west (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. 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, 1987). Recent reviews of Australia's tropical karsts are provided in Spate & Little (1995) and Gillieson & Spate (1998).

Geological Settings

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 **Northwestern 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 Cainozoic soils. There are also lateritic & 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 *Aw* southwards through *BShw* to *BWhw* (Figure 2). On the east coast the seasonality decreases southwards and grades to the *Cfa* climate type. The rainfall varies from humid (e.g. Katherine) to arid (e.g. the southern part of the Barkly Karst Region), but with a pronounced seasonality with a five-month summer "wet" and a longer winter dry season (Figure 2). Significant variation in rainfall between years is a consequence of the "El Nino southern oscillation" effect. Potential evapotranspiration is substantially greater than actual rainfall throughout the region, giving a deficit in excess of 1000 mm per annum.

Most rain in the wet season falls either in short intense thunderstorms, or in occasional cyclonic events. Jennings (1967, 1983) suggested that solution during the wet season may therefore be equivalent to that of tropical humid climates even though the annual rainfall is low. So there is no need to invoke past wetter climates to explain features such as towers and the intense surface karren development.

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. Deciduous vine thicket may grow on the rocky limestone towers and grikefields.

Tropical karsts on 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 (Photo Z) 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 of steep-dipping limestone which alternate with insoluble rocks that are less resistant to erosion in this setting (Jennings, 1981, 1982). Some towers are surrounded by a limestone pediment or 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.

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.

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" (Photo B). Some towers have marginal depressions with active subsidence of the soil which are the result of aggressive water runoff from tower surface (Pearson, 1982).

Lithological controls

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. Danes, 1911) and has been discussed by many authors (Wilson, 1975; Marker, 1976; Lundberg, 1977a,b; Ford, 1978; Pearson, 1982;

Jennings, 1982; 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 'reef' limestone. He also noted that areas of excessive fracturing inhibit those karren that result from water flow over large surface areas.

Dunkerley (1988) compared runoff water and kaminitza 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 karren

The following 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) 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 **'sparite' or 'reef' limestone** towers are strongly dissected by solution and contain large grikefields, vertical sculptured walls and sharp pinnacles which make access difficult (Photo Z). 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 steep runnels to form intricately sculptured patterns of sharp pointed pinnacles up to 5m or more high (spitzkarren, Photo D). Solution dolines on the tower tops tend to be irregular forms with spitzkarren spires and internal drainage via grikefields. Some towers have stepped relief with risers and treads.

On sides of the towers and giant grikes extensive rillenkarren feed via steep runnels, 10-20 cm deep, into vertical wall karren that can be up to a metre deep (into the wall) and 40 m long (Photos Z & D). On steep slopes the rillenkarren are modified by cockling in places, and in extreme cases are replaced by deep pits similar in form to the "rainpits" of the flatter surfaces. Rinnenkarren (runnels) are listed by several authors but some appear to use this term for regenrinnenkarren or what is here called wall karren. Occasional decantation runnels occur below horizontal joints cutting into vertical walls.

On the more gentle slopes, which include steps and bevels, there are "rainpits", localised rosettes of rillenkarren, short irregular runnels, and small (up to 1 m wide) pans (kamenitza). Wilson (1975) reported that flat solution pans are common on tops of the towers, and noted that these always have a 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) summarised the results in Lundberg's (1977a) thesis, and also reported additional measurements giving flute lengths averaging between 17.3 and 29.8cm and widths of 16.9 to 18.5mm at three sites on the marble, whereas two 'sparite' sites had lengths of 31.3 & 35.6cm and widths of 18.5 & 23mm.

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 a sharp-ribbed and deeply recessed symmetrical form; 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 phototrophic karren which are grooves, sticks and spines oriented towards the light and found in the twilight zone of the caves and deep grikes (Photo X). These are a type of phytokarst eroded by algae. Individual spikes and grooves are between 2-50mm across, but can be up to 400mm long! Some spikes have cave coral 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 pan on top of one tower.

Microkarren are more extensive than suggested by earlier reports (Jennings, 1981, 1982; Dunkerley, 1983). 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 networks of irregular, discontinuous ridges which in turn break up into arrays of rasp-like teeth. 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 rills 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" (10mm or greater) can occur on one outcrop. There is also fine micro-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, as suggested by Jennings (1981, 1982). Solution by thin films of water, dew or light rain, seems the most likely origin (see discussion in Chapter 6 ?? EDITOR: please substitute appropriate cross-reference to the chapter on Microrills).

On the pediments there are smoothly rounded clints between soil-filled grikes (Photo B). 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 (kaminitza) 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 (Photo C). It would appear that these small pans have been draining downwards through fine cracks. Solution pipes also occur; typically elongated along a joint. In places soil erosion has exposed the grikes and other, generally rounded, 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 and spitzkarren pinnacles. Some large grike fields occur on the broader outcrops. The region has well developed small karren.

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 100m across, that is dissected into low spitzkarren and smoother areas of pans, "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 (Photo F). The rivulets 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 valley with some 2 m waterfalls. The channels have flat floors and steep sides which are usually undercut. Commonly they are from 0.5 to 2m 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 runnels, "rainpits" and solution pans developing on them.

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.

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 solution pans. 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, some of which connect with caves but apart from small patches of rillenkarren and "rainpits" it is essentially undissected. This may be a similar situation to that described below at the Gregory Karst - where a surface has not had time 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 are 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 pinnacles. Large rubble-choked grikes cut across the karren fields. Cave entrances are associated with the grikes or with large vertical solution pipes.

Other 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 31˚S, in northern NSW, which has a Cfa climate with an annual, rainfall of about 1700mm.

Tropical karsts in flat-lying carbonates, North-west Australia

Kimberley region, Western Australia.

The Kimberley Karst Region of northwestern Australia is also known 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 ranges of the Kimberley region and the flat plains of the 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 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

The surface karst landforms have been described in detail by Jennings & Sweeting (1963) and summarised in later papers by Jennings (1967, 1969), Williams (1978), Goudie & others (1989, 1990) and Gillieson & 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 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 & 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 more rounded hills and v-section valleys result. Jennings & Sweeting (1963) called these areas "merokarst" and excluded them from their main discussion.

Jennings & 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", Photo H). Widening of the giant grikes forms box valleys, with flat floor and vertical walls, which in turn coalesce to leave isolated towers and pinnacles within a broad pediment. Dolines are relatively uncommon.

Karren

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 kamenitza, "rainpits" and small patches of rillenkarren. This pavement is cut by a widely spaced network of deep grikes with fluted vertical walls (Photo H). The giant grikes are up to 7m wide, 33 m deep and hundreds of metres long and extend underground into fissure caves. As dissection becomes greater a rugged terrain of spitzkarren pinnacles develops (c.f. Photo K). 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, 1-2 m deep and wide and running vertically for 30-60m (Photo H). The pediments have solution pans and occasional shallow dolines and solution pipes.

Goudie & others (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 & others studied, the crucial 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 & others, Jennings & Sweeting (1963) noted the influence of bedding in disrupting rillenkarren development and breaking it into stacks of conical spitzkarren (c.f. Photo K).

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

Within the major gorges which cross the karst, wet season floods rise to heights of 10 m (Gilliesen & others 1991). The flooded sections of the gorge walls show well-developed scallops and strong etching of bedding and vertical joints to form cavernous slots and vertical grikes, along with spongework.

Ningbing and Jeremiah Hills

There have been no karst-specific reports published on this area of gently dipping Devonian and Carboniferous reef limestones. However, the geological report by Veevers & 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 (10-20°) 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 restricted to a thin (10-18 m) but extensive dolomite unit within the flat-lying late Proterozoic Skull Creek Formation (Sweet & others,1974 and Bannink & others,1995). There is obvious joint and bedding control of both the karren and the caves.

No detailed studies of the karren have been done, but Dunkley (1993 & pers. comm 1991) and Bannink & others 1995) provide brief descriptions. The top of the dolomite unit, where initially exposed by stripping of overlying non-karstic rock, is a smoothly-undulating stromotalitic surface with clints, exfoliation slabs and small karren features (Photo I). Away from the freshly-stripped contact these pavements evolve into a rugged grike-field, with grikes up to two metres wide and 15 m deep, large solution pans (up to 1m deep), and jagged spitzkarren. Corridors form from widened grikes in the final stage of dissection and a pediment surface appears on the valley floors. Relict runiform pinnacles occur locally (Photo J). Extensive joint-controlled maze caves underlie the dissected surface (Storm & Smith, 1991; Bannink & others,1995). Storm & Smith (1991) noted areas of phototrophic phytokarst fingers in the caves.

However, Susan White (pers. comm., 2003) observed that local variations in lithology and structure can modify that overall picture. In particular, stromatolitic beds elsewhere within the dolomite unit can also have relatively smooth surfaces. If we ignore small irregular and concentric ridges that are obviously from etching of stromatolite structures, the main karren forms on these surfaces include the following: shallow v-notches on joints evolving to small grikes, shallow runnels (2-3 cm wide) and scattered patches of "rainpits" and rillenkarren (Photo I). Microkarren are common on these stromatolitic surfaces, but not elsewhere (Susan White, pers. comm., 2003).

The best development of rillenkarren and spitzkarren are on the thicker beds where the surface is similar to that shown in Photo K. Thin-bedded areas have less rillenkarren as the etching of the horizontal bedding tends to over-ride the vertical flute development.

Daly Basin (Katherine)

This is an broad area of flat-lying early Palaeozoic limestone that has an extensive cover of Cretaceous sandstone and claystone and younger alluvium. Karst features are mainly restricted to the exposed limestones at the northern and western margins.

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 1-3m high, but up to 30m in places (Hamilton-Smith & others, 1989; Lauritzen & 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 & others, 1989). Solution pans 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 pinnacles and deep shafts, which is exposed within the occasional regolith-subsidence doline.

Barkly Karst Region (Georgina Basin)

This is the easternmost of the large covered karst basins. The rocks are mainly 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 most common 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 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 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 grikefields developed on belts of pure, thick-bedded and well-jointed limestone (Photo K).

One of the more accessible of these grikefields 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 surface between the deep grikes is strongly dissected by rillenkarren, steep runnels and spitzkarren (Photo K). Solution pans and "rainpits" also occur on flatter surfaces.

Gale and others (1997) described another grikefield 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" 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 and others (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 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 0.4 to 2.5cm 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 in larger joints or the bedding planes (Photo L). 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 an area 80 km NE of Camooweal. These included microrills, networks and rasp-like teeth, as well as fine pitting.

Further south, in the dryer area near Boulia (Figure 2), I found some very well developed microkarren on loose 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 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 karren are restricted to grikes and "rainpits" (AP Spate, pers comm).

Conclusion

Australia's tropical monsoon karsts have a number of surface features in common (Spate & Little, 1995): a positive relief with upstanding limestone towers, scarps and ridges, sometimes with adjoining pediments; extensive areas of bare limestone; strongly developed small-scale sculpturing, including extensive and deep grikefields, spitzkarren, a variety of sharply fretted pittings, rillenkarren, kamenitza and other forms. However all these become less well developed in the drier areas. Subsoil forms such as grikes, rundkarren, and pinnacles are exposed by soil erosion to form surface fields. Directional phytokarst forms and solution ripples occur in the twilight zones of the caves and giant grikes. Microkarren have been recorded from a number of areas 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 & Sweeting (1963, and Jennings in later papers) described a sequence of development for the Kimberly karst region, with gradation from undissected plateau through giant-grikefield, 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 & others, 1997). But this was not the original intention: Jennings & 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 & 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 (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 does not need to invoke past wetter climates. 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. In Australia, the history of long periods of exposure of many of the limestone areas 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.

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Chapter 30 - Tropical monsoon karren in Australia

Ken G. Grimes

FIGURES

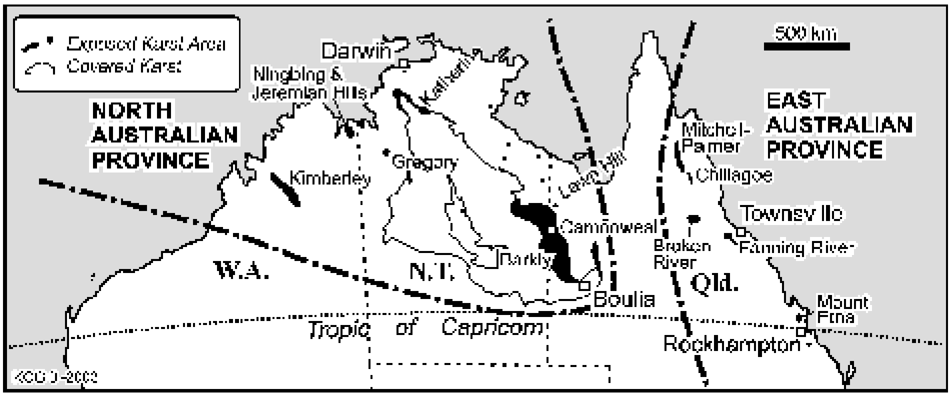

Figure 1: Location map of tropical karsts in Australia, showing the two main structural provinces..

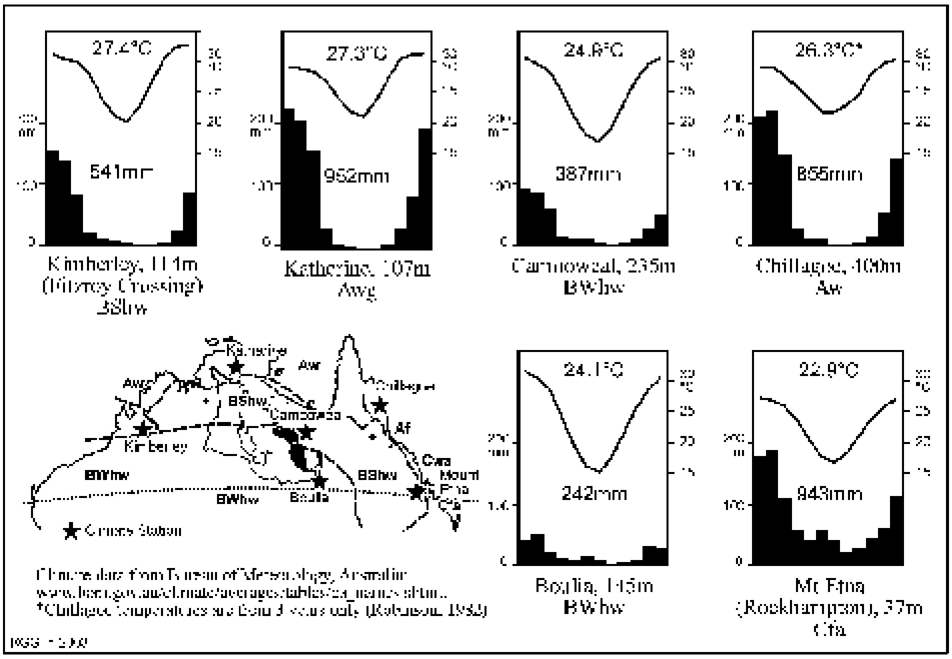

Figure 2: Monthly and annual mean temperatures and rainfall for selected climate stations on tropical karsts. The Köppen climates for north Australia are also shown.

Tropical Karren in Australia - Figures.

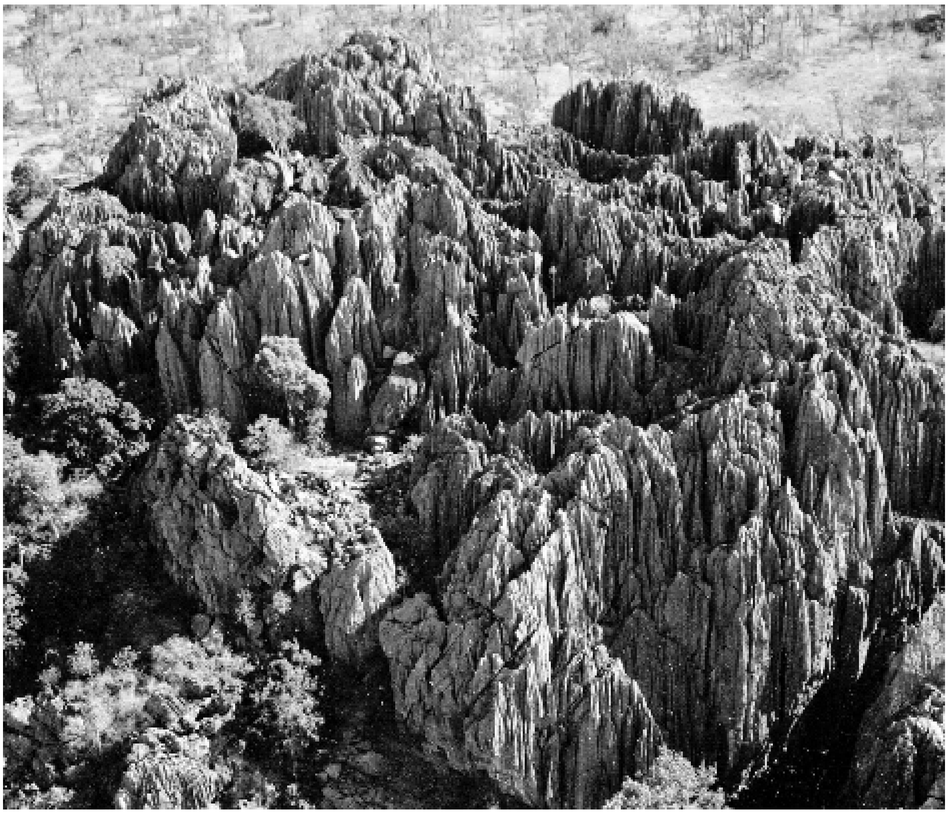

Photo Z: Aerial view of the crest of a tower at Chillagoe. Showing large grikes, pinnacles and vertical wall karren.

Figure B: Pediment with clints and soil-filled grikes at Chillagoe. In background is a small tower with a debris-covered Richer slope.

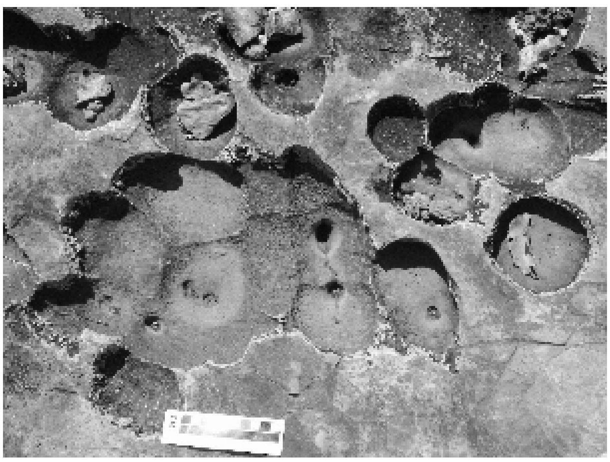

Figure C: Solution pan on a pediment near Racecourse Tower, Chillagoe. It is formed from coalescence of smaller circular pans with central pits. 10 cm scale-bar.

Tropical Karren in Australia - Figures.

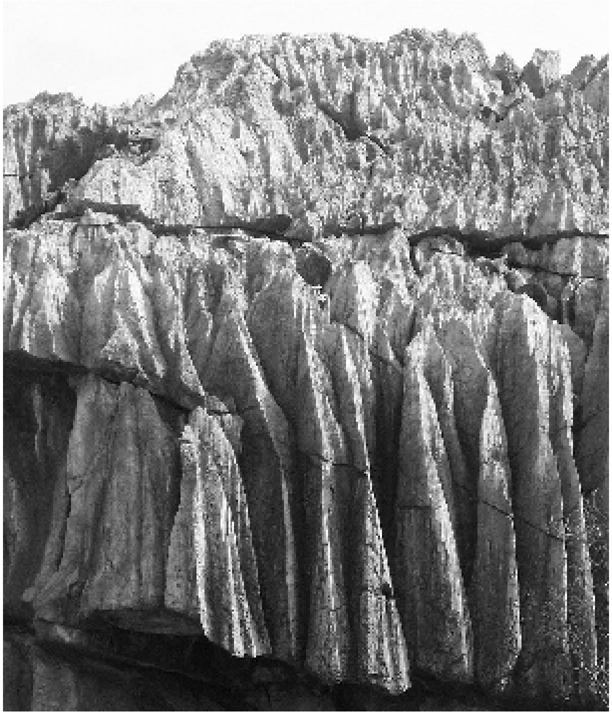

Figure D: Spitzkarren pinnacles grade down to deep vertical wall karren. On a tower in the Mungana area, Chillagoe.

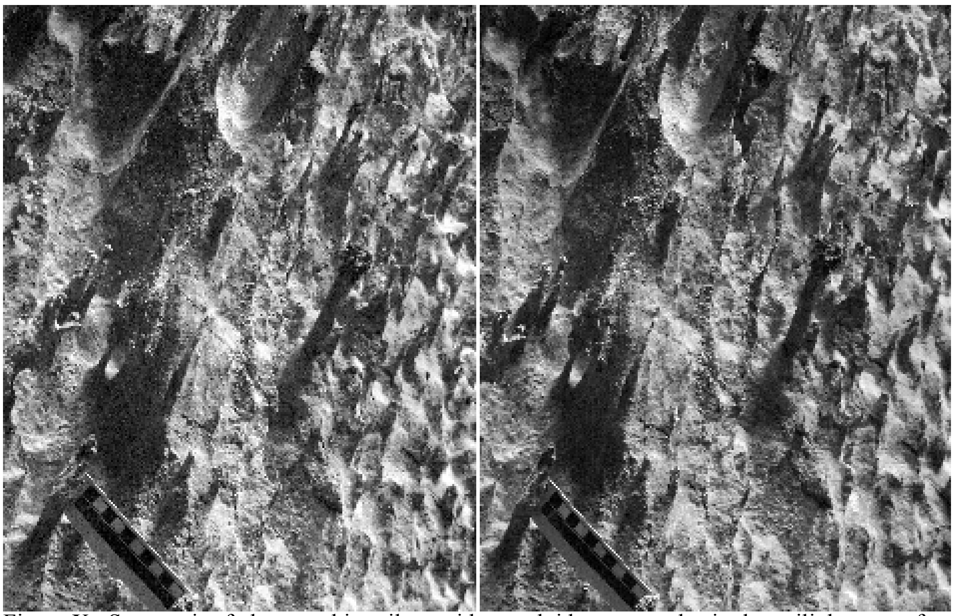

Figure X: Stereopair of phototrophic spikes, with corraloid overgrowths, in the twilight zone of a cave entrance. A result of light oriented algal corrosion. 10 cm scale-bar.

Tropical Karren in Australia - Figures.

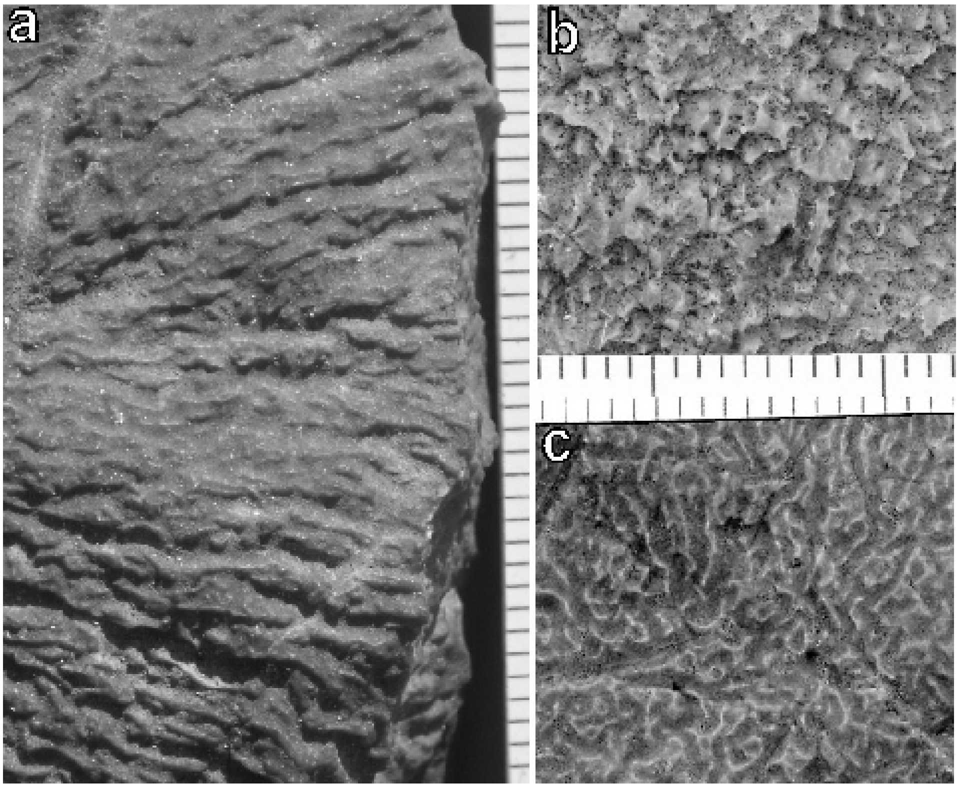

Figure N: Microkarren. a: linear microrills on a limestone cobble at Boulia; b: rasp-like teeth at Chillagoe; c: networks on a pediment at Chillagoe. Scales in mm.

Figure F: An incised solutional rivulet on the crest of a tower at Broken River. Note terraces. Photo by A.P. Spate

Tropical Karren in Australia - Figures.

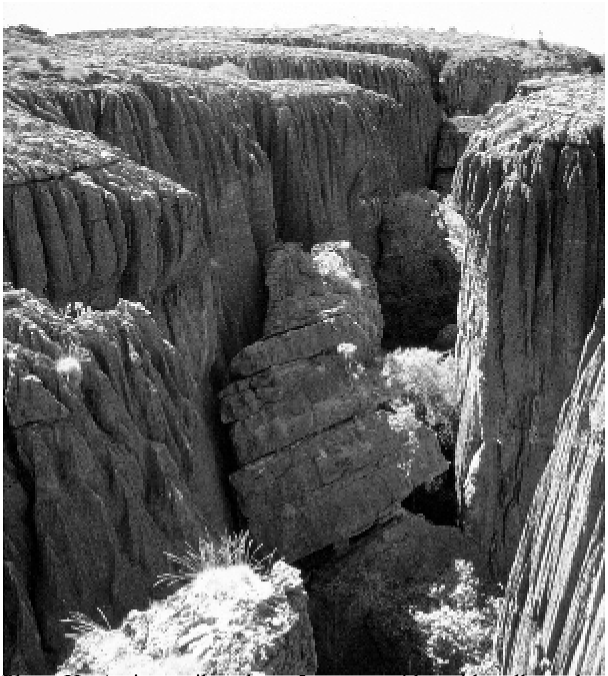

Photo H: A giant grike, about 5 metres wide, with collapsed blocks and deep vertical wall karren. Above Mimbi Cave, Kimberly region. Note the relatively undissected plateau in the background. Photo by J. Jennings.

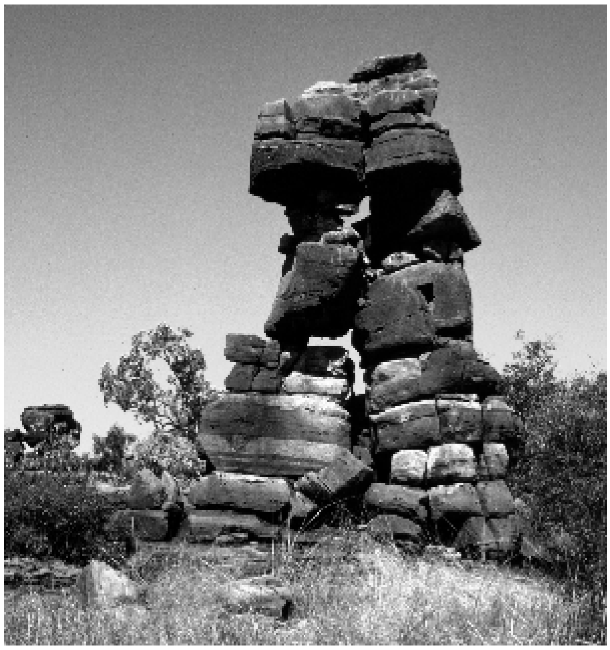

Photo J: Runiform pinnacle, about 5 m high, in the Gregory Karst. Photo by N. White, 1992.

Photo I: Smooth surface of stromatolite bed in the Gregory Karst has incipient grikes and shallow pits and runnels. Photo by N. White, 1992. Lens cap for scale.

Tropical Karren in Australia - Figures.

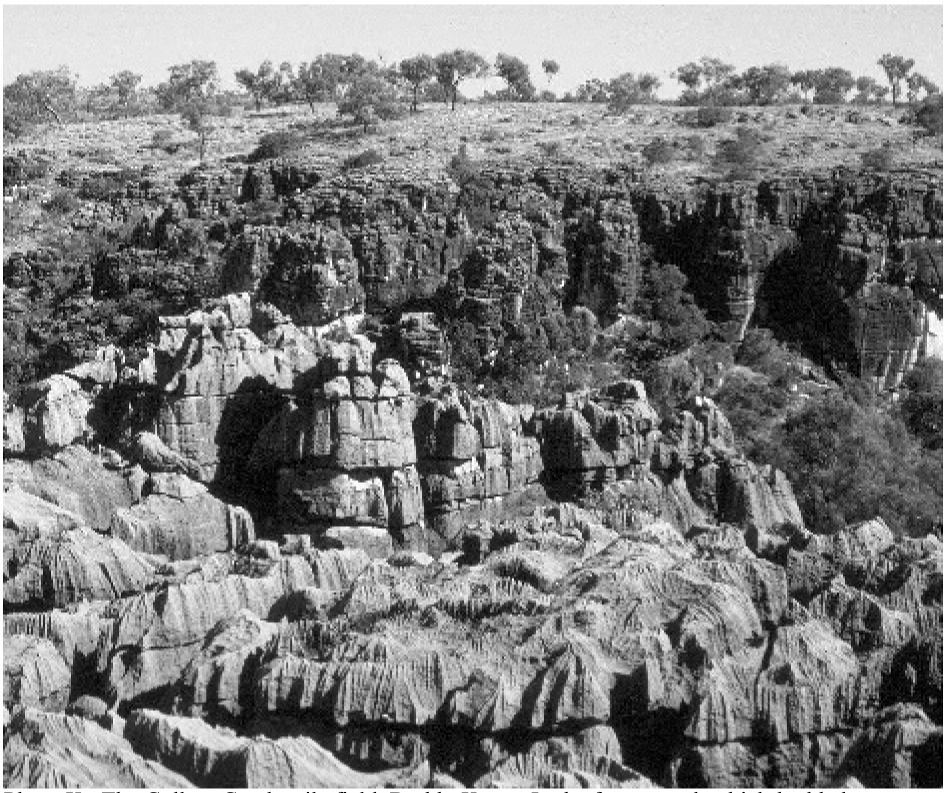

Photo K: The Colless Creek grikefield, Barkly Karst. In the foreground a thick-bedded limestone is dissected into deep grikes and spitzkarren. Beyond the gorge of Colless Creek is a plateau developed on a less pure and thinner bedded limestone. This photo is typical of many outcrops of flat-lying thick-bedded limestones in tropical Australia.

Figure L: Fine etching of cacks in dolomite at Camooweal, Barkly Karst. Pen is about 15 cm long.

Figure M2: Decantation micro-rills on side of a limestone cobble in the arid Boulia area. Scale in mm.