IN CAVE OXIDATION OF ORGANIC CARBON AND THE OCCURENCE OF RAINWATER INFLOW CAVE SYSTEMS IN THE SEASONALLY ARID LOWLAND TROPICS.

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Abstract

Recent studies have shown that in cave oxidation of organic carbon can play a significient role in cave initiation and development. The production and flux of organic carbon in different seasonally arid tropical karsts and in perpetually humid tropical karst is described, with particular consideration of the role of large particle size organic carbon. The model developed is used to explain the extent of rainwater inflow cave development and the apparent scarcity of such forms in the perpetually humid tropics plus arrested development in the seasonally arid sub-tropics.

INTRODUCTION

Woods (1986) has invoked a model of in cave generation of carbon dioxide by the oxidation of transported organic carbon to explain corrosional enlargement of joints from the bottom up. He described organic carbon sources as being of three types; particulate organic carbon (POC), dissolved organic carbon (DOC), and organic carbon sorbed on mobilised inorganic material (eg. clay particles (SOC). In the tropics greater temperatures would result in greater microbial activity resulting in greater carbon dioxide preduction which in turn would result in a greater rate of corrosion, provided water was not limiting.

Woods' theory very adequately explains cave initiation in both tropical and temperate karsts. Further cavern enlargement and further influx of organic carbon (see James, 1981) is consequent upon fluvial or runnel invasion of the enlarged vadose fissures and phreatic tubes. This invasion is the result of headward growth of, and competitive piracy by, the most efficient anastomosing tube, forming a pressure tube from the spring which drains the vadose fissures and progressively captures surface streams (Ewers 1978). How can such models be applied to the pinnacled, seasonally arid, tropical karsts of northern Australia which in some ways seem to have remained at a very early stage of fluvial capture?

Shannon (1970) in describing the genesis of caves in the Mount Etna/Limestone Ridge karst, recognised rainwater inflow caves as a distinct cave type (autogenic, grike runnel runoff derived, solution pits and crevices); which he contrasted with river (or fluvial) caves. Shannon stated:

"The cave water generally deposits lime except where it is soaking through organic fill; the acid sponge effect is the main agent of solution. The cave floor is attacked. The acid is supplied by decaying vegetable matter in place."

Shannon considered that tree roots were probably the main source of acid (presumably carbonic acid directly by the root's metabolism or indirectly by decay). Particulate organic carbon POC, mainly tree roots, is probably of greater importance. Shannon divided the caves of Mount Etna/Limestone Ridge into three types: rainwater inflow caves, ramifying csves, and master caves. I would prefer to consider these as zones of the underground karst hydrological system, as some caves show combinations of two or three of these zones in the same area. The rainwater inflow cave, ramifying cave and master cave are equivalent to the vadose zone, the nothephreatic/epiphreatic zone and the shallow active phreatic zone, respectively.

SEASONALLY ARID TROPICAL KARST (MOUNT ETNA/LIMESTONE RIDGE, CHILLAGOE)

On limestones of low primary permeability in the seasonally arid tropics, large outcrops are intensively and extensively pinnacled, with joints enlarged into grikes between the pinnacles. The grikes often open out below into cave systems producing flask or bottle like cross sections eg, Figure 1, Mt. Etna.

The surface of limestone outcrops at Mt. Etna/Limestone Ridge and Chillagoe is covered with karstified bare rock interspersed with patches of clay soil and associated vine scrub. Soil is either residual or derived from interbedded volcanics, stratigraphically and topographically overlying mudstones and/or pediment derived, possibly multiply reworked cave fills exposed to the surface by karst denudation. The main form of particulate organic carbon is tree leaves. The pinnacled and griked karst pavement provides a fire refuge for vine scrub communities in a seasonally arid climate

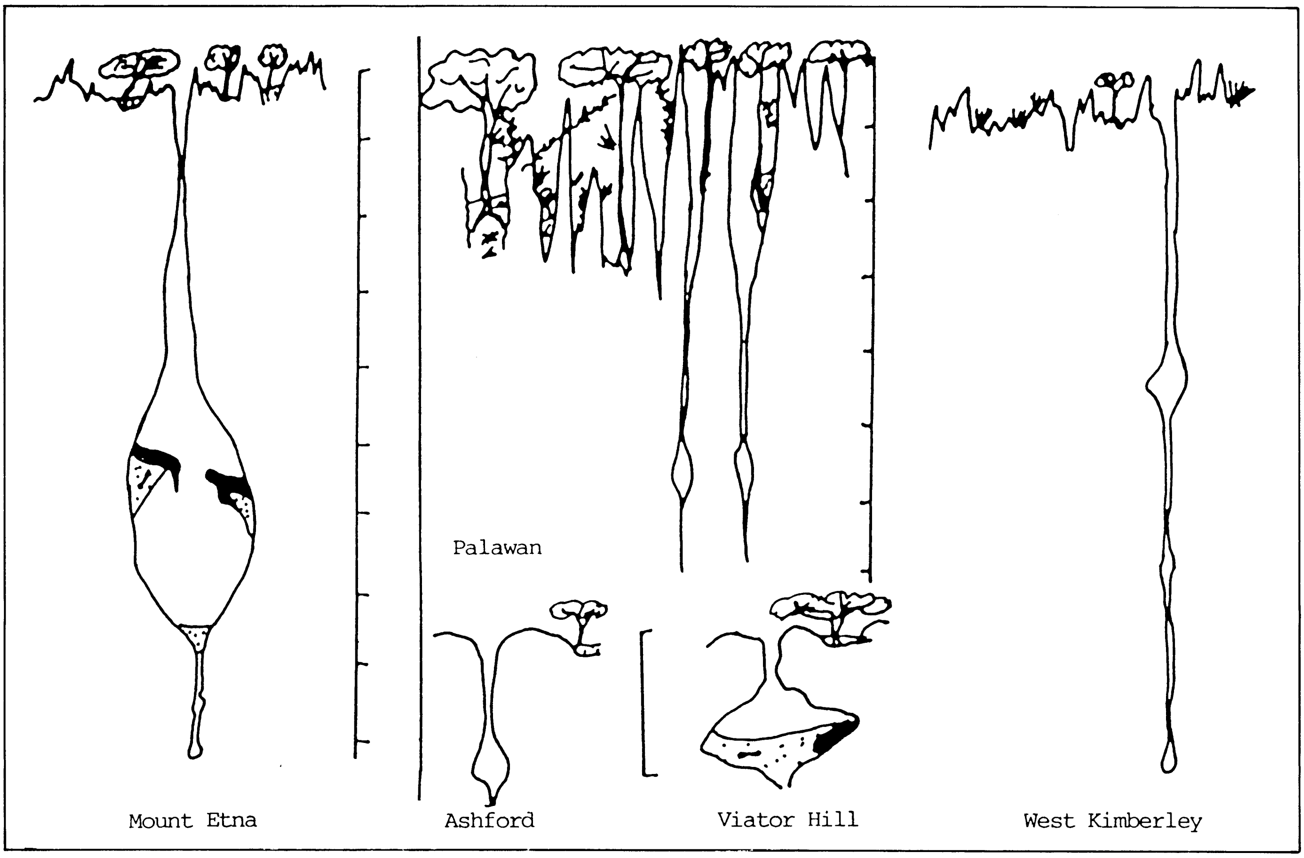

Figure 1 RAINWATER INFLOW CAVE SYSTEMS
SCHEMATIC TRANVERSE SECTIONS

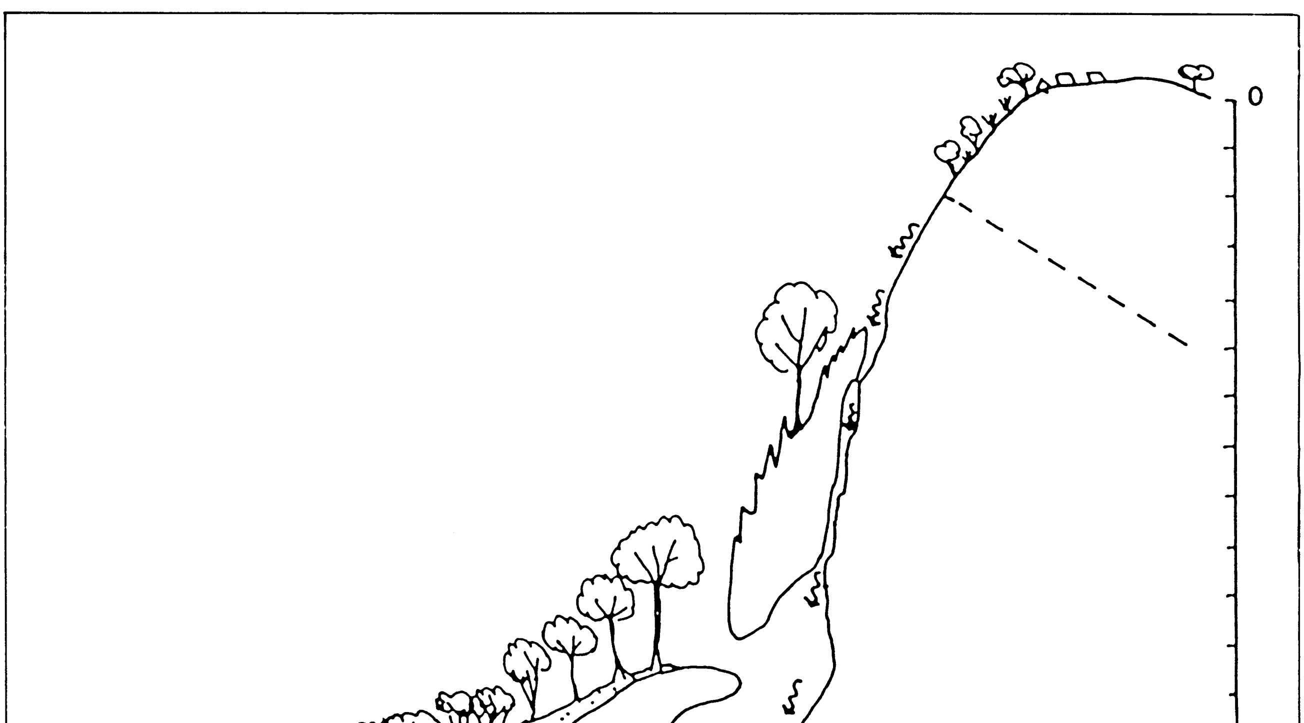

Figure 2. MOUNT ETNA RAINWATER INFLOW CAVE SYSTEM
SCHEMATIC LONG SECTION

(Webb and Tracey 1970). Many of the tree species in this community are dry season deciduous, depositing a covering of dead leaves on the limestone surface during the dry season.

The surface karst consists of joint or fault orientated grikes separated by pinnacle ridges with rillenkarren down their sides. Any leaves falling on such a surface will be washed down toward the grike floor where their decomposition will assist joint enlargement in depth and width. Joints enlarged to 10-20 cm are found at the base of larger grikes. Smaller particulate organic material formed from the decomposition and invertebrate digestion of these leaves will travel by sheet and then gratify assisted capillary flow to base level where it will assist the enlargement upward of the joint in the vadose zone as postulated by Woods (1985). Solution pans are less common surface karst forms; they may form at the base of a grike, and then coalesce to form a stepped runnel. Grikes developed on down slope orientated joints will form long runnels (rundkarren). Runnels 0.5-1 m across occur on Mount Etna above Huntsman Cave and stepped forms occur on Limestone Ridge above the Johannessens Quarry. Any leaves washed or dropped into such runnels will be washed down the runnel to where the underlying joint is sufficiently enlarged to take the entire flow.

This sinking runnel water will invade the upwardly enlarged joint and enlarge it further usually into a circular shaft or a vadose canyon with a waterfall at its head. This water fall or cascade to vase level or an intermediate structure ledge, where its organic sediment load will be dropped with the sudden drop in energy, producing a sediment filled sump. Such a sump, 30 m below a runnel fed sink in Helms Deep Cave, Mount Etna, looks a poor site for carbonate dissolution as the surface is covered by caloareous land snail shells and phosphetic bones. At 10 cm depth the sediment is dark, high in organic carbon and low in snail shells and bones - presumably due to acid dissolution.

The small size of the active phreatic conduits draining the final earth sump, means that the sudden influx of storm waters from a number of runnel fed sinks is drained away slowly, and ponds at base level. This increased residence time (see Wilson 1975) of the ponded water, plus the added aggressiveness due to the concentration of POC at base level by sediment load dropping, and coupled with the fast rate of decay in the warm moist sumps, results in the corrosion of large nothephreatic chambers - often showing spongework and roof pendants over a considerable depth.

With lowering of base level, the zone of maximum corrosion or cave enlargement will move downward, enlarging and obliterating small bore active phreatic donduits, and phreatic rifts. Short remmants of active phreatic conduits may be left between nothephreatic chambers eg. the Test Tube passage in Main Cave, Mount Etna. At the same time, especially where runnels run along downslope oriented joints, slope retreat will result in sinks and runnels occurring further back into the mountain and in runnels further down the mountain intersecting nothephreatic chambers through karst windows further down the neck of the flask. Hence the tight upper level inflow entrances and larger lower level karst window entrances on Mount Etna. Vadose forms will be superimposed upon the sides of nothephreatic chambers - the corkscrew meander channels found in the sides of outer Johannessens Cave, Limestone Ridge; or else the lower level karst window inflow will be in the center of a chamber and will plunge free to the nothephreatic epiphreas with no vadose interaction.

The water chemistry of the spring north of Mount Etna suggests that the water has travelled some distance in small, completely water filled, passages and is in carbon dioxide equilibrium at a level typical of soil or organic sump fine sediment (Dunkerley, 1981). The flow rate is a few tens of litres per minute; the water is warm and very hard (650ppm dissolved carbonate) and the theoretical pCO_2 at 8.3 per cent. This, according to Dunkerley is consistent with "movement of water through an environment enriched in carbon dioxide by organic processes and probably as suggested by the warmth of the water at relatively shallow depth". To reach the exsurgence front the inflow points on the slopes of Mount Etna, the karst water must flow 1-1.5 km. under a gently sloping pediment hence the shallow depth. At the exsurgence end of the active phreas, the conduits are continually water filled and must be too small for human entry to be active phreatic at such a low flow rate. At the other end of the active phreatic zone, where it drains the nothephreatic chambers, pressure tubes up to a metre in diameter are round. Lowering of base level may result in phreatic canyons or rifts, or these forms may be produced by clay deposition causing floor filling and protection, coupled with roof corrosion (eg. Mikes Delirium in Johannesens Cave, Limestone Ridge). Such pressure tubes may connect downstream to further nothephreatic chambers, where further ponding occurs. Successively smaller poressure tubes corresponding to successively lower flow rates will connect each downstream ponding area. In Mela Grotto, Limestone Ridge, a perennial underground stream flows through such a system and has deposited banks of organic mud and silt (A. Robson, pers. comm.). Further into the active phreatic zone sorbed organic carbon may play a greater role in increased aggressiveness.

In the middle section of Limestone Ridge a near horizontal andesite dyke (Shannon 1970) presented a impermeable barrier resulting in extensive ponding above base level which led to the formation of large flat floored and roofed, nothephreatic chambers until chemical weathering and clay mobilisation breached the barrier and a new series of runnels and sinks occurred in the floor of the underground chamber, sinking to the new base level below. The upper levels of caves in this region have large, flat, nothephreatic chambers developed along the dyke while the lower levels have the typical flask shaped cross section nothephreatic chambers developed along vertical joints or faults.

Underground karst processes at Chillagoe are essentially similar to those at Mount Etna Limestone Ridge (Ford 1978, Wilson 1975, Marker 1977, Jennings 1982). These two areas represent the fullest development in Australia of rainwater runnel inflow caves below a pinnacle/grike surface, with pediment exsurgences below the towers.

Chillagoe	803 mm.
Mount Etna/Limestone Ridge	852 mm.
Old Napier Downs (West Kimberley)	691 mm.
Mulu	6,000 mm.
Texas (South-east Queensland)	644 mm.

Based on Graham (1970), Grimes (1978), Jennings and Sweeting (1966), Marker (1976), Robinson (1982) and Waltham and Brooks (1980).

TABLE I - AVERAGE YEARLY RAINFALL VARIOUS KARST AREAS.

Chillagoe has a significantly lower rainfall than Mount Etna (Table I) and being further north has higher evaporation. As a result of this, vine scrub is virtually absent from exposed surfaces but occurs in sun sheltered tower feet and karst corridor bases, unlike Mount Etna where vine scrub occurs on the limestone slopes wherever soil patches occur. A Chillagoe the vegetation distribution may have concentrated inflow to the karst corridors and tower cliff bases, on pediment steps and ramps.

At inflow points along enlarged grikes water cascades to partially fill networks of nothephreatic passages showing structural control. This water backs up at earth sumps which contain organic muds and silts. The sumps presumably drain into the phreatic tubes, up to 3 m in diameter, described by Smith (1985)) as often providing connections between caves. A number of writers (Jennings 1982, Wilson 1975, Robinson 1978 and Pearson 1982) have stressed the importance of phreatic solution forms (i.e. roof pendants and spongework) in the caves of Chillagoe and how much of the solution occurs above the level of permanent water (i.e. the nothephreatic epiphreas), during the flooding associated with exceptional wet seasons.

THE WEST KIMBERLEY RANGES - A LESS VEGETATED SEASONALLY ARID KARST

On the northern edge of the Canning Basin or the southern edge of the Kimberley Block lies an extensive range of pinnacled and griked Devonian limestones which have been subject to little if any tilting and still reflect the bedding angles and morphology of a barrier reef (Playford and Lowry 1966). The surface karst is as well developed as that at Chillagoe and giant grikelands occur in places (Jennings and Sweeting 1963). However, sizeable rainwater inflow cave systems of the type found at Mt. Etna/Limestone Ridge have not been found. Sizeable perennial (usually cliff foot) springs do occur, presumably representing integrated flow. The few large cave systems described in the literature are derived from superimposed allogenic drainage - Tunnel Creek and the Cave Spring System (Jennings and Sweeting, 1963); Lowry, 1967) or essentially allogenic drainage from the sediments of a Tertiary erosion surface developed on the limestone, (Jennings and Sweety, 1966).

Bases of enlarged joints in the cliffs of Windjan Gorge are 0.5-2 m in width. Small increases in width occur above present base level (e.g. Pigeon Cave), may be indicating a past less arid time. The vegetation of the West Kimberley limestone is predominantly spinifex (Triodea) with a few shrubs and stunted boabs, and rare vine scrub in very sun-sheltered spots. Jennings and Sweeting (1963) describe the soil and vegetation of the dissected part of the Napier Range as minimal, reducing the biological carbon dioxide so necessary for cave development. The spinifex and scattered shrubs would not produce the readily decomposable leaf mat POC such as is supplied by deciduous vine scrub. Spinifex leaves stay on the plant even in drought; spinifex organic carbon is removed by fire rather than decomposition. Thus less POC is avoidable from the grike fields to fuel base level corrosion and extensive nothephreatic epiphreatic chambers are absent.

Why such a dramatic absence of vine thicket should occur in the West Kimberley is puzzling as Napier Downs has a rainfall only marginally less than Chillagoe (Table I) and lies at similar latitude. The pediment tower interface at the West Kimberley is abrupt with the pediment steps and ramp found at Chillagoe (Jennings 1982). At Chillagoe this area provides a sun shelter and fire shelter. In the West Kimberley karst, fire-adapted savanna grassland comes right up to the tower base. In 1981 a fire came off the tertiary erosion surface and burnt out almost all the spinifex in the Old Napier Downs Polje except for a small area of vine scrub in sheltered location near the fluvial inflows (Williamson

1981). Lamotte (1985) recorded 40 per cent of organic carbon being removed by fire in moist savanna - the percentage in dry savanna would be even greater.

KARSTS OF THE SEASONALLY ARID SUBTROPICAL ZONE

Very small rainwater inflow caves have been reported from areas south of 30'S at Texas, Ashford, Wellington and Timor (Shannon 1970). Large pinnacles and runnels are absent in these areas due to the reduction in both overall precipitation and torrential summer rain, and an increase in more diffuse winter rain. Rillenkarren and grikes are present but soil cover varies between areas reflecting local differences in lithology and stratigraphy. Vegetation includes some vine scrub but tends toward fire resistant sclerophyll woodland (Archer 1978). The larger rainwater inflow cave systems show nothephreatic features e.g. Russenden (Grimes 1978). Grimes reported acid cave earths from Main Cave on Viator Hill. Water is channeled underground by sheet flow down the sides of grikes; and at grike intersections by more concentrated flow (Grimes 1978). No pressure tubes are reported. Cavern dimensions are much smaller reflecting reduced POC input due to lower temperatures and rainfall, plus the removal by fire of surface organic material and also the lack of runnels to mobilise the leaf-size POC. Due to the more even precipitation and lack of runnels seasonal fluctuations of water table within the caves behind back up points are of much smaller amplitude than seen in the Mount Etna nothephreatic epiphreas. At Texas Caves, notch marks on the wall reflect phases of downcutting by Pike Creek (Grimes 1978).

PINNACLED AND GRIKED KARSTS OF THE PERPETUALLY HUMID TROPICS

In the perpetually humid lowland tropical karsts large (30 m) pinnacles and grikes have been reported under lowland rainforest (e.g. Mulu - Osmaston, 1980; Palawan - Longman and Brownlee, 1980, and the Darrai Hills, New Guinea - Williams, 1972). There are no reports of rainwater inflow cave systems of the extent found in the Australian seasonally arid karsts. In the profusely vegetated lowland tropics soil covered polygonal and doline karst forms become more significant even on the tops of towers. With perpetual moisture and high temperature little accumulation of leaves occurs in a lowland tropical forest as leaves decompose quickly after falling. Whitmore (1984) reports highly acid organic soils from the top of karst towers in Malaya. Much less organic matter is washed deep into pits as most decomposition occurs on the limestone surface causing pitting, or in soil and vegetation further up the grike. This produces the greatest development of surface pinnacle and grike karst at the expense of a well developed rainwater/POC fed cavernous nothephreatic/epiphreas. Williams (1972) reported small phreatic mazes developed below crevice karst in New Guinea.

The paucity of reports of rainwater inflow cave systems from the lowland moist tropics may be a byproduct of the greater areal significience of soil cover karst forms in many areas, or simply that the rugged topography of lowland tropical pinnacle/grike karst has caused exploration to concentrate on the more accessible and locatable fluvial systems, especially those formed from large allogenic streams.

Crowther (1982) reported conduits within West Malasian karst towers contributing water to the abandoned fluvial systems below. Waltham and Brook (1980) report side streams entering the large allogenic streams under the towers of Mulu. These must drain either doline or grike/pinnacle karst. Similar side streams enter the main streamway in St. Pauls River Cave, Palawan. In humid tropical lowland alluvial plain tower karst e.g. Mulu, Mt. St. Pauls, underground corrosion by rainwater inflow could be just as great as in the seasonally arid tropics but will pale into insignificience compared to the rate and extent of lateral corrosion by allogenic fluvial processes at past and present tower base level.

CONCLUSIONS

The hydrology of caves occurring below the pinnacled and griked seasonally arid karsts of central and north-eastern Queensland is unique in that inflow water is derived from rapid rainwater runoff from steep bare rock surfaces, with little surface ponding or soil leaching. The water carries its POC load with it to earth sumps where soil-like microbial processes occur below ground, and extensive underground corrosion occurs in the nothephreatic epiphreas. Steeply dropping, often freefall, vadose passage fed by runnel sinks lead to large nothephreatic epiphreatic chambers where the sediment load is dropped and water backs up behind active phreatic conduits which slowly drain the flood waters, maybe by more nothephreatic backup areas, to pediment springs. This hydrologic system is best termed a rainwater inflow cave system to distinguish it from allogenic fluvial systems and from autogenic gully fluvial systems of polygonal doline and honeycomb karst with soil and interstitial flow (Williams 1972). Rainwater inflow cave systems remain at an earlier stage of fluvial capture as the initial seeps and eventual sinks are from runnel/grike floors rather than from stream floors. This results in more, but smaller, inflows per unit area. Surface integration of flow is prevented by pinnacle karren divides, though some degree of underground integration of flow may occur.

Cave systems can be classified in terms of degree of integration of surface flow before inflow, ie. order of stream, as follows:

1. interstitial flow in rocks of high intergranular porosity e.g. Augusta and Roe Plain.

2. rill and sheet flow with the start of runnel flow at joint intersections - rainwater inflow grikes, solution pits and nothephreatic allogenic karst of the seasonally arid subtropics e.g. Viator Hill.

3. runnel flow down grikes to rainwater inflow cave systems e.g. Mt. Etna, Chillagoe.

4. gully flow between hills - polygonal karst forms e.g. Darrai Hills, Waitomo.

5. streamsinks - fluviokarsts, usually allogenic e.g. Camooweal, Yarrangobilly.

Some humid tropical karsts (e.g. Mulu) are a large scale mosaic of types 3, 4 and 5.

In seasonally arid tropical karsts lacking a vine scrub community, particulate organic carbon is limiting and consequently extensive development of rainwater inflow caves does not occur. In the perpetually humid topics no dry season accumulation of leaves occurs and soil processes and carbonate corrosion is concentrated more on the surface leading to limited nothephreatic development in the rainwater inflow cave system. In reviewing tropical karst processes Sweeting (1972) concluded that most corrosion occurs near the surface due to rapid solution and evaporation. Hence caves are generally small except when formed by through-flowing (allogenic) rivers. "Solution is controlled by bacteria and other micro-organisms and tends to take place in swamps, lakes and the bases of cockpits", ie. is predominately lateral. The seasonally arid tropical pinnacled and griked karsts of Queensland differ in that, while fast solution and eveporation occur on the limestone surface and there is microbial activity and lateral corrosion in the soils of the tower base pediments, the microbial activity in the shallow soil patches and leaf mats on the towers is limited by the even higher rates of evaporation in the seasonally arid tropics. This preserves particulate organic carbon and allows it to be transported down to the earth sumps of the cave system's epiphreatic zone, where the enclosed cave environment protects the soil microbial processes from the inhibiting effects of dessication (except in severe drought or in areas of through draft). Thus substantial in-cave microbial assisted corrosion occurs in the epiphreatic zone of seasonally arid lowland tropical rainwater inflow caves, forming large cave systems where surface vegetative production is both sufficient and in a suitable form. In the seasonally arid subtropics the nothephreatic development in rainwater inflow cave systems is restricted for other reasons which relate ultimately to lower temperature and the quantity and type of precipitation.

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