Origin and development of *Karstinselberge*, with particular reference to some South East Asian evidence

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Abstract: Some *Karstinselberge* are initiated by descending meteoric or vadose waters which weather the rock exposed in steeply dipping fractures just below the land surface. Others originate as domical or conical projections at the deep weathering front as a result of differential weathering by phreatic waters. The residuals are developed on compartments of rock that are massive, by contrast with well-jointed surrounding areas. These etch types are exposed in stages, and are converted to steep-sided towers by undercutting of the basal slope, commonly as a result of scarp-foot weathering, and consequent collapse of the slopes above. Reinforcement effects operate, with the exposed rock weathered less rapidly than the still-covered. Karst towers can be regarded as part-covered forms for they evolve partly before, partly after, exposure.

INTRODUCTION

Inselberg landscapes display spectacular and intriguing contrasts, with steep-sided hills rising abruptly from the plains. Whether developed in granitic rocks, sandstone or limestone, such terrains have stimulated great interest. Karst residuals are notably well represented in the humid tropics, including East and South East Asia, and are also recognised in the stratigraphic column (e.g. Gilewska, 1964; Silar, 1965; Jennings, 1982; Hocking *et al*., 1987; James & Choquette, 1988; Yuan, 1991).

Karst inselbergs are of several morphological types, some being turreted, others domical, some conical, others ensate, and yet others pinnacled (e.g. Wilford & Wall, 1965; Sweeting, 1973, p. 270 *et seq*.; Jennings, 1985, p. 201 *et seq*.; Fig. 1). Towerkarst or *Turmkarst* (*karst à tourelles, fenglin)* and *Kegelkarst* are prominent karst residual forms. They are spatially coincident, and indeed, elements of the contrasted convex and cliffed slope facets are commonly found on the same residual (Figs. 1c and 2). Towers commonly stand several scores or even a few hundreds of metres above the adjacent plains.

Most conekarst displays a lower relief amplitude. *Kegelkarst* is the *fengcong* of China (Yuan, 1991, pp. 57-61), the cockpit karst of the Antilles (Sweeting, 1958) and the *sewu* karst of southern Java (Lehmann, 1936; Flathe & Pfeiffer, 1965; Day, 1978). The term ‘conekarst’ is frequently applied to closely textured limestone uplands but, as Jennings (1985, p. 204) pointed out, this is in many instances a misnomer, for the slopes of the residuals are commonly not rectilinear but convex-outwards (e.g. Wilford & Wall, 1965, plates 1 and 4). For this reason such forms are referred to here as cupola- or domical karst.

Whatever their precise morphology, karst residuals pose several problems. Why are they upstanding? How have they evolved? What factors have determined the contrasted shapes of cones, domes and towers? Do any aspects of their genesis carry implications for general theory? Some of these problems have been considered in scholarly and penetrating reviews (e.g. Sweeting, 1973, p. 270 *et seq*.; Jennings, 1985, p. 201 *et seq*.; Ford & Williams, 1992) but other aspects have not been broached, and local evidence has been neglected.

FORMATION – HISTORICAL PERSPECTIVE

In a review of the problems posed by the survival of Malaysian karst towers, Paton (1964) referred to ideas developed by his colleagues in the then Geological Survey of Malaya. He recorded that one (unnamed) had interpreted them as plastic plugs thrust through granite during orogenesis, but no theoretical or field evidence was cited in support of the suggestion.

The earliest cogent explanation is due to Scrivenor (1913, p. 14) who suggested that the towers of the Kinta Valley of Perak “owe their origin primarily to faulting” with an implied throw of some 450 m and are horst blocks. Subsequent detailed mapping, however, has revealed no such regional assemblage of faults in the Kinta Valley. In Perlis, some towers are developed in faulted strata (Jones, 1978; see Figs. 3a and 3b) but that is incidental to their existence. Some are fracture-defined, but even these, such as Bukit Wang Pisang, are not horsts, for the bounding faults throw in the same sense, with an upthrown block to one side of the residual and a downthrown on the other (Figs. 3c and 4). Scrivenor’s tectonic interpretation was rejected by Jones (1916), but he maintained his position for several years (Scrivenor, 1923), citing in support of his argument a personal communication from W.C. Klein concerning faulted karst hills in northern Sumatra, and limestone residuals in Sarawak which Geikie (1905-6, pp. 65-66) attributed to the joggling and vertical displacement of blocks defined by an orthogonal fault system.

By 1931, however, Scrivenor had abandoned the tectonic hypothesis so far as the Kinta Valley residuals were concerned. Instead he suggested that the towers, rising sheer from the sea or the plains, may have been “carved

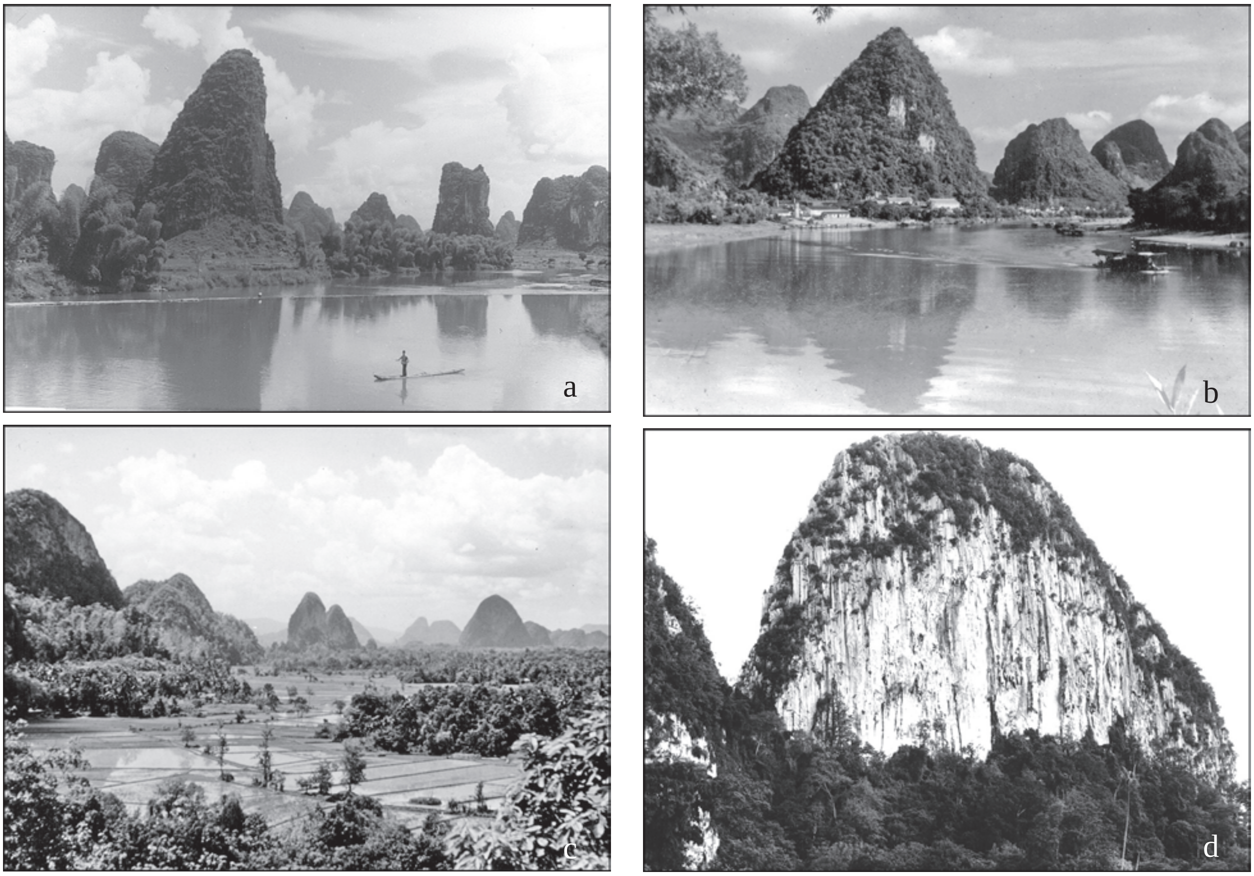

Figure 1. (a) Towerkarst, and (b) conekarst, Li River valley, Guilin, central China (I.R. Stehbens). (c) Karst towers of the Kinta Valley developed in Late Palaeozoic limestone. Some show the effects of undermining and steepening, thus converting convex slopes to cliffs, and domes to towers. The hills rise some 360 m above the plains (J.N. Jennings). (d) Karst tower near Ipoh, Perak, with undermined and collapsed slope on one aspect. Note debris or scree slope at extreme right.

out by marine denudation" (Scrivenor, 1931, p. 123) though he allowed that some, both at higher levels and in earlier times, may be due to the action of subaerial processes; but as with his 'marine denudation', he did not go into details.

Cameron (1924) suggested that the limestone towers, which occur mainly on the western side of the Kinta Valley (Morgan, 1886; Ingham & Bradford, 1960), had been translated laterally on a thrust plane. Though the limestone strata are folded and the tower sediments in places rest on granite or other older 'basement' rocks (Ingham & Bradford, 1960; see also Jennings, 1985, p. 211), as they do also in northern Kelantan and Trengganu (MacDonald, 1967), detailed mapping has produced no evidence of thrust planes between the basement and overlying sedimentary rocks (Senathi, 1979).

Later, Cameron (1925) argued that in the Kinta Valley the limestone hills are developed on essentially flat-lying limestone, which rests unconformably on more resistant, contorted older limestone, granite and metamorphics in which the plains are developed. That the latter are weathered to depths of 30 m or more appears to contradict this suggestion, as does the persistence of remnants of the supposedly weaker younger limestone. Rastall (1927) invoked relatively simple folding and faulting in explanation of the Kinta Valley towerkarst but in reality the structure is complex (Ingham and Bradford, 1960). Reed (1949) echoed Cameron (1924) and considered the limestone residuals to be remnants of a nappe structure.

Several early workers attributed towerkarst to the "denudation of a strongly-jointed limestone" (Jones, 1916, p. 171), that is, the preferential weathering and erosion of steeply inclined fractures. Richardson (1947, 1950) discussing the towerkarst of western Pahang considered that surface evolution began in the Cretaceous following the uplift of the region and concluded that the limestone towers are due to the exploitation of steeply inclined fractures by descending meteoric waters. They are aligned in meridional ranges underlain by east-dipping (typically about 70º) strata, and stand on the divides between major rivers. As in other karst areas, fractures also determined the pattern of cave systems and streams. Thus, steeply dipping fractures were identified as the key to tower development and in his review Paton (1964; see also Senathi, 1979) concurred, concluding that most Malaysian towers are of this origin.

Where the fractures are far apart the resultant blocks are of considerable diameter. In addition, massifs or complex compartments of limestone comprise numerous individual cupolas or towers. The Gunung Rapat and the

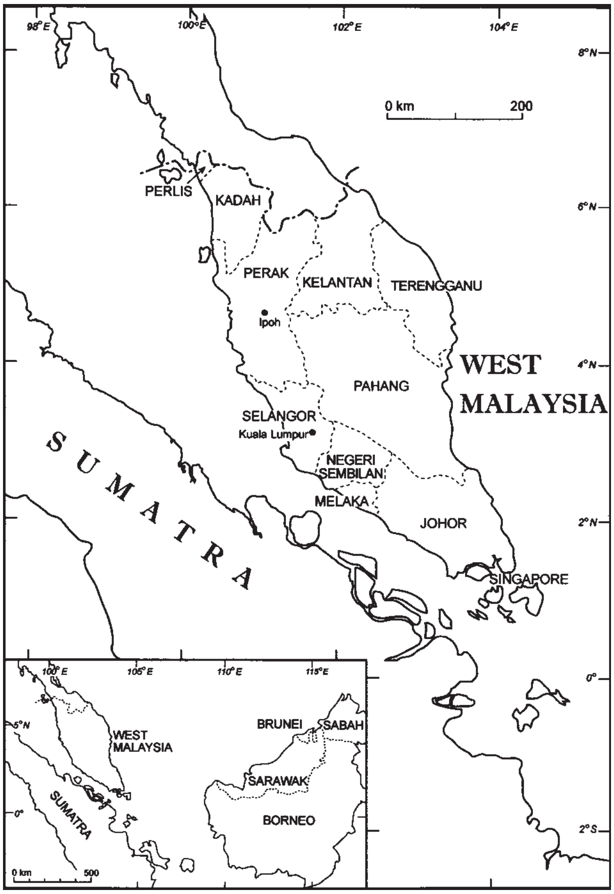

Figure 2. Location map.

adjacent Gunung Terendum of the Kinta Valley provide an example (Ingham & Bradford, 1960, plate III). Slopes are modified according to the relative rates of down- and back-wearing (Tjia, 1969; see also Tricart, 1957).

But there are complications. Drogue and Bidaux (1992), for example, illustrated towers near Guilin, in southern China, the plan form of some of which is defined by fractures. Some, however, are transected rather than delimited by fractures: in some instances the topographic boundary of the residual does not coincide with structure. Some of these cross-cutting fractures may have been cemented by secondary calcite (*q.v.*) and so rendered ineffective as avenues of weathering. Such anomalous partings also can be explained by the changes in location and geometry of fractures with depth. Drogue and Bidaux (1992) suggest deep weathering beneath a planation surface. Unless the significant fractures were vertical, the plan locations of the fractures that determined the initial weathering pattern must have changed, for a deviation of 10º from the vertical, for instance, implies a lateral shift of almost 2 m every 10 m in depth. Thus, a fracture which determined the boundary between much weathered and virtually fresh rock at one level may, after the lowering of the land surface, appear within the residual the plan shape of which has been maintained, presumably by positive feedback mechanisms (*q.v.*;Twidale, 1972; Twidale *et al.*, 1974).

ORIGIN OF KARSTINSELBERGE: EPIGENE OR ETCH?

Even within the same terrain, karst inselbergs are developed in various stratigraphic and structural contexts, in places on flat-lying sequences, elsewhere in steeply dipping strata, here rising from plains underlain by limestone, but elsewhere standing on a non-carbonate base. Thus, in Perlis, karst residuals are developed on gently folded and on faulted strata, in areas entirely occupied by limestone and at sites where the carbonate rests unconformably on granite or some older rock. Karst towers are developed in the gently folded and locally faulted Permian-Triassic Chuping Limestone (Jones, 1978), whereas those of the Kinta Valley are shaped in steeply dipping Late Palaeozoic rocks (Ingham and Bradford, 1960). Wilford and Wall (1965) describe *Karstinselberg*e of various types, including spectacular pinnacles (Gunong Api) and cupolakarst (Bukit Krian) developed in complex geological settings. Yuan (1991) records towers in China formed in various structural contexts - flat-lying and folded, faulted and undisturbed. Similarly, karst inselberg terrains are recorded from contrasted structural settings in the Antilles, and in Indonesia, New Guinea and northern Australia (e.g. Lehmann, 1936, 1954; Jennings & Bik, 1962; Jennings & Sweeting, 1963; Monroe, 1968; Panos & Stelcl, 1968; Willmott & Trezise, 1989).

The essential requirements for the formation of karst domes and towers appear to be, first, the presence of a massive crystalline limestone and, second, the development of a system of open, steeply dipping joints, which have been exploited by meteoric and shallow groundwaters associated either with present or with past climatic regimes. Thus Cameron (1925, p. 26) describing the Kinta Valley residuals of Perak, referred to strongly jointed limestone and MacDonald (1967, p. 18) described the karst hills in northern Kelantan and Trengganu, as developed on outliers of limestone which is "…typically compact, often well bedded, and massively jointed". The structure and stratigraphic setting of the country rock are irrelevant so long as the two basic requirements are met.

The exploitation of fairly closely spaced, steeply dipping fractures (e.g. Richardson, 1947; Sunartadirdja & Lehmann, 1960; Jennings & Sweeting, 1963; Drogue & Bidaux, 1992) has produced towers with only minimal rounding of corners and edges. Brook and Ford (1976, 1978) and Twidale and Centeno (1993) have described towers shaped by weathering along steeply inclined joints apparently just below the land surface (Figure 5). Elsewhere, however, weathering has been achieved by circulating deep phreatic waters retained in a regolith. For instance, in the Kuala Lumpur area some karst towers have been shaped at the weathering front some 70-130 m beneath the surface and below a regolith consisting of alluvium overlying weathered bedrock (Ho, 1993). The limestone surface has a relief amplitude of 50-60 m and includes domical hills. There is no suggestion of epigene shaping followed by burial. The weathered bedrock is *in situ*. The bedrock residuals were formed at the weathering front (Fig. 6). The rounding of the bedrock projections is due to the preferential weathering of the corners and edges.

Topographic irregularities were also demonstrated by seismic profiling in the Batu Caves area, near Kuala Lumpur (Ho *et al*., 2000). Oleh and Wan (1993) carried out a geophysical survey in a limestone area south of Kuala Lumpur in connection with the routing of a major road, and detected dolines and an irregular bedrock topography at the weathering front, beneath 10-15 m of regolith.

Monroe (1969, 1976) has suggested a similar origin for spectacular karst towers (*mogotes*) up to 50 m high in Puerto Rico. However, instead of a weathered mantle increasing in depth with time as limestone is altered and consumed at its base, as in Malaysia, the Antillean forms develop in the subsurface as a result of attack by moisture held in a blanket of detrital quartz sand of shallow-water marine origin, and of probable Pliocene or Pleistocene age. Monroe argued that the interface between sand and limestone has been lowered as much as 70 m by this process. The mogotes were formed by differential weathering and lowering of the limestone surface beneath a sand cover. Simultaneous weathering, shaping and lowering of the bedrock-regolith interface is envisaged.

It may be noted that a similar mechanism, albeit on a small scale, was earlier suggested by Speak (1905-6). He disputed Geikie's (1905-6) assertion that in the gold fields of Upper Sarawak, basins were formed in the limestone prior to the deposition in them of auriferous ores, instead arguing that sulphide-bearing shale overlying the limestone had attacked and weathered the carbonate, forming a "gigantic pot-hole into which the ore-bearing shales subsided" (Speak, 1905-6, p. 85).

Thus some karst towers originate in the shallow subsurface as a result of the exploitation of major steeply inclined joints by meteoric waters. Others are initiated at depth at the weathering front and when exposed are basically etch or two-stage forms (Hassenfratz, 1791; Falconer, 1911), though they have suffered critical modifications since exposure. In karst terminology they are half-covered (see Eckert, 1902; Lindner, 1930; Zwittkovits, 1966; Jennings, 1985, p. 5), for though the gross morphology originated at the weathering front, the undermining and steepening of the bounding slopes has taken place since exposure.

PROTECTION AND SURVIVAL

Why some compartments have survived weathering and erosion when all around has been eliminated remains unanswered, but differential weathering and erosion has been crucial. Where limestone towers rest on a granite or metamorphic basement, the distribution of the limestone remnants indicates that there was formerly a continuous sheet of carbonate most of which has been destroyed.

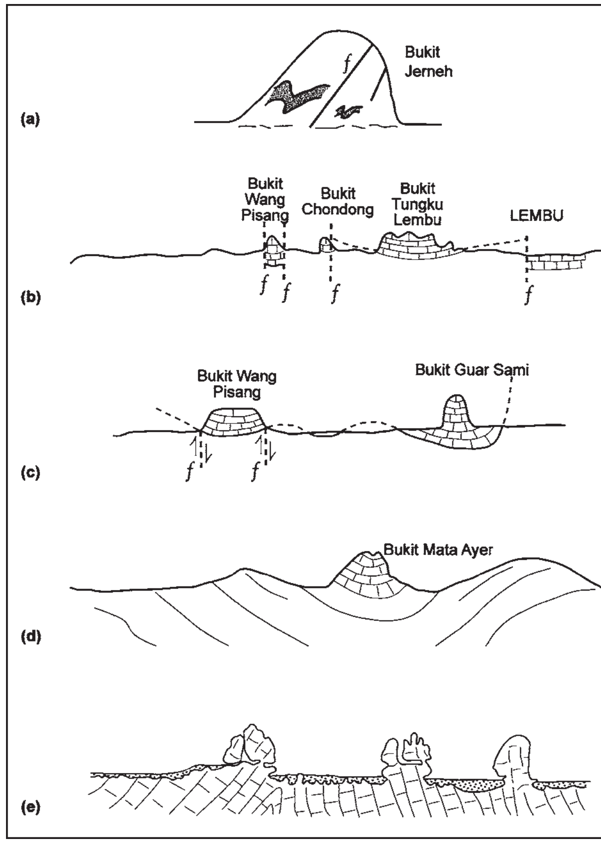

Figure 3. (a) Cliff face of Bukit Jerneh, Perlis, showing domical hill eroded in steeply dipping (80°) and faulted limestone (after C.R. Jones, 1978, p. 100). (b) Section (B-B[1] in Figure 4) showing towers in limestone affected by faults and the synclinal Bukit Tungku Lembu (after C.R. Jones, 1978, p. 93). (c) Towers preserved on synclinal troughs (after C.R. Jones, 1978, p. 93). Section A-A[1] in Figure 4. (d) Synclinal Bukit Mata Ayer (after C.R. Jones, 1978, p. 75). (e) Diagrammatic section through towerkarst in the Kinta Valley (partly after Jennings, 1985, p. 207).

Similarly, many limestone towers rise from plains underlain by limestone, and again differential weathering and erosion are implied. Jones (1978) pointed to geophysical and borelog evidence in Perlis and northern Kedah that the alluvial plains adjacent to limestone towers are underlain at depth (14-33 m) by limestone. Again, in the Kinta Valley, Ingham and Bradford (1960) recorded evidence from valley-floor excavations of at least 30 m of regolith overlying an intricately sculpted limestone surface.

The appeal to fracture-controlled weathering and erosion satisfactorily explains those towers developed in the shallow subsurface on simple fracture-defined blocks (see below) but like other accounts it does not explain why some masses of rock have been eliminated while others have survived.

One possible explanation for the persistence of some of the masses of limestone that form residuals was noted by Jones (1978) who remarked that some of the limestone towers of Perlis and the Langkawi Islands, residuals such as Bukit Mata Ayer and Bukit Tungku Lembu, are preserved in synclinal troughs developed in the Chuping

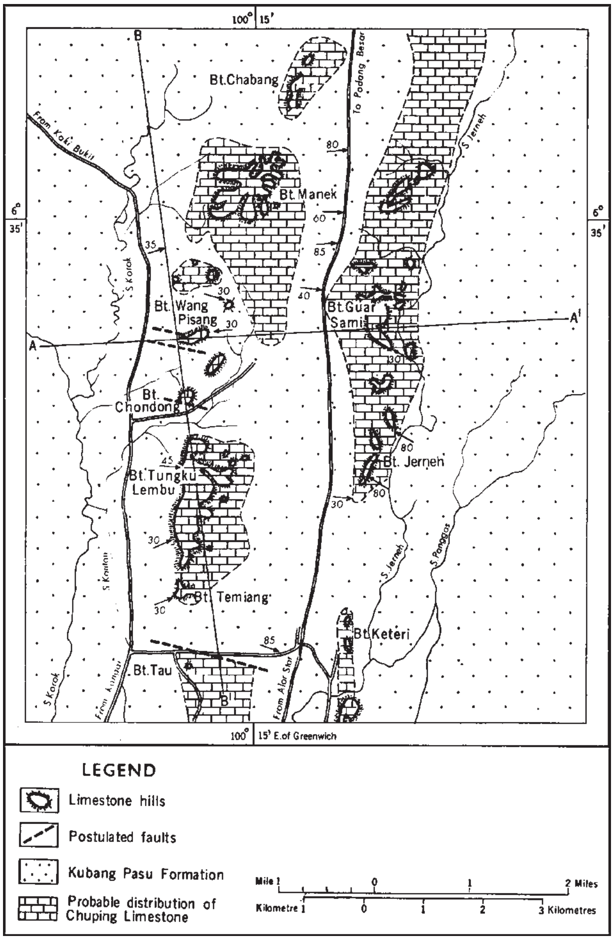

Figure 4. Photocopy of C.R. Jones' (1978, p. 93) map of part of the karst terrain of central Perlis. A-A[1] is here Figure 3c and B-B[1], Figure 3b. Bukit Jerneh (Figure 3a) is also indicated.

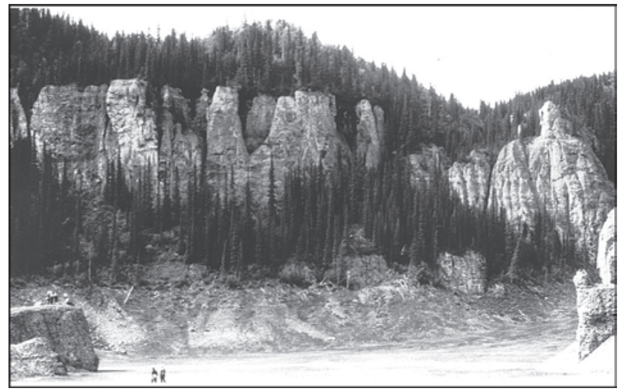

Figure 5. Towers due to weathering of steeply dipping joints in Devonian limestone, Nahanni region of the Yukon, northwestern Canada (D.C. Ford).

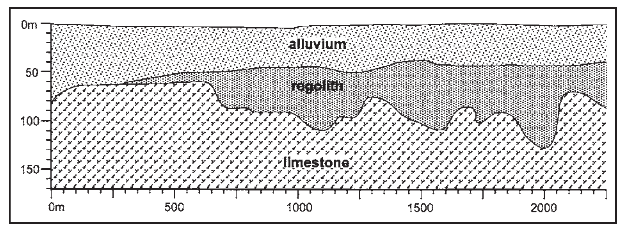

Figure 6. Seismic reflection profile of Sepang area, Selangor (after Ho, 1993).

Limestone (Figures 3b-d). The evident resistance of the limestone in which the residuals are shaped can be attributed to their being effectively massive, for they are located in the compressed cores of synclines and basins.

In the Kinta Valley, however, Ingham and Bradford (1960) depict Gunong Marawan and Gunung Kuang located not in the cores but on the flanks of folds, and Yuan (1991, p. 67) identified an anticlinal karst massif on a horst block (see also Jennings (1985, p. 207; Figure 3e). It can, however, be suggested that the strata involved in the anticlines originated deep in the compressive cores of the structures. Alternatively, shearing may have introduced compressive as well as tensional stresses (e.g. Weissenberg, 1947).

As suggested also by Drogue and Bidaux (1992), the solution to the problem may be found in contrasted fracture densities. The geometry of the fracture patterns exploited by weathering is probably due to tectonics. Recurrent shearing of a brittle rock like crystalline limestone creates a system of orthogonal fractures such as those that have been exploited to produce cave systems, as well as fracture propagation resulting in compartments with fractured marginal zones around compact cores (Gifkins, 1965).

If such fracture propagation has caused variations in fracture density, it ought to be demonstrable in the field. Though arguing that towers represent massive compartments of rock, Drogue and Bidaux (1992) offered no evidence of spatial variations in fracture density either in their account of the Guilin karst of southern China or elsewhere; and for good reason, for the bedrock is most commonly covered by a substantial regolith. Nevertheless, the limestone exposed in towers and other residuals, though fractured includes few open joints, for some fractures are sealed by the precipitation of secondary calcite (Cameron, 1925; Monroe, 1966). To the contrary, artificial exposures in the Kinta Valley indicate that some, at least, of the limestone beneath the plains is closely jointed. Much of the area is covered by alluvium of various types and ages but the so-called older alluvium is fluvial and stanniferous (e.g. Newell, 1971; Senathi, 1979). It has been extensively quarried, revealing closely fractured limestone and a highly irregular topography with pinnacles, mushroom rocks and rounded projections common (Figure 7). The spacing of the residuals – a few metres high in some instances - described in Scrivenor (1928, p. 83, 1931, p. 142), Ingham and Bradford (plate VII, facing p. 30), Paton (1964, plates 1 and 2), Sunderam (1970), Ayob (1970), and Gobbett and Hutchison (1973, p. 164) implies joints only a metre or two apart, for the separation of the closely-packed spikes of rock is due to solution along steeply dipping fractures. Such close jointing is typical of several contemporary quarry exposures, and stands in marked contrast with the effectively massive bedrock evident in cupolas and towers.

Though this evidence is strongly suggestive, it might be argued that comparison with present piedmont and valley floor exposures is irrelevant, and what is significant is the contrast between the hill and the rock that was adjacent to the now upstanding residual but which has been eroded. Statistical analyses of fracture spacing at depth and at the surface suggest (Blès, 1986) that the latter indicates conditions in the former. It has been argued that if that is so, joint spacing at the surface provides a pointer to fracture density in the eroded compartment above (Twidale, 1987a). Thus towers are associated with massive compartments of rock.

Topographic highs formed at the weathering front shed water both when beneath the surface and after exposure. Once formed, but particularly after exposure, the inselbergs are relatively 'dry' sites. Not only are they weathered more slowly than adjacent areas, but the latter receive an excess of water. Thus, the amplitude of relief on the bedrock surface tends to increase. A reinforcement or positive feedback mechanism operates.

Protection is also afforded by surficial mineral concentrates. The base of the regolith in granite is in many places characterised by small but distinct concentrations of iron oxides (mainly haematite and goethite). Similar encrustations are found on exposed weathering fronts in limestone. Scrivenor (1931, p. 141) states that coatings of iron oxides and siderite are common in the Kinta Valley exposures. Pyrolusite occurs occasionally, both as veneers and 'nests' or discrete masses. Ingham and Bradford (1960, p. 30) record skins of siderite and of haematite developed on the limestone surface in contact with alluvium. They are due to "…the action of ferruginous solutions on the limestone". Jones (1978, pp. 97 and 195) noted discrete masses of iron-enriched limestone.

However, although superficial secondary carbonate indurations contribute to the preservation as well as the shaping of some limestone residuals, the persistence of karst towers mainly reflects positive feedback acting on compartments that are massive and thus inherently durable.

CUPOLA- AND TOWERKARST

How many towers are of shallow etch derivation and how many originated at a deeper weathering front is not known, but there is general agreement that cupolas or domical residuals are converted to towers as a result of basal notches undermining and inducing the collapse of the slopes above. Field observations show that not only do conical and turreted forms coexist but the basic elements of both cupola- and towerkarst, namely convex-outwards and steep cliffed slopes, are present on many individual residuals (Figures 1c and 1d). How are the two forms related?

Morphological variation: theoretical considerations

Flathe and Pfeiffer (1965) attributed the contrast between towerkarst and conekarst (or sinoid karst) to the depth of the water table. The former develops in response to a deep water table and strong through-drainage, the latter to shallow groundwaters. This is compatible with the contrasted characteristic height range of the two residual forms (but see below). Yuan (1991, pp. 57 and 61) interpreted the contrast between closely spaced conical karst and towerkarst as tectonic, with the *fengcong* developed on slightly higher areas. He also construed the morphological variations as stages in a karst cycle, with cupola forms developing early, towers late (Yuan, 1991, p. 61). Regardless of causation, however, the topographic separation of types of limestone residual is in accord with Verstappen's (1960) crucial observation that in Sumatra, for example, towers are developed on lower areas, typically *padi* fields, whereas cupolakarst is found on higher ground, where there is no standing water.

Basal notches and the conversion of cupola- to towerkarst

Many residuals are shaped like half-oranges set down on the cut or flat side. Some with rounded or flat crests display steeply convex flanks, but in some these slopes have been replaced in whole or in part by vertical cliffs resulting from the development of cliff-foot caves or swamp slots (Jennings, 1976) and undercutting and collapse of the slopes above (Fig. 8a). This has led to the undermining and eventual collapse of the slopes above, resulting in bare rock faces that stand in marked contrast to the densely vegetated, slightly less steep slopes of the original domical hill (Twidale, 1987b). For instance, numerous lower slope scars of bare rock are visible in aerial views of the Gunung Rapat near Ipoh, both on slopes facing the adjacent plains and in valleys within the upland (Ingham & Bradford, 1960).

At some sites notches can be attributed to the exploitation of bedding, but elsewhere the indents cut across such sedimentary structures (e.g. Paton, 1964). Basal notches are spectacularly displayed within the present tidal range on limestone islands and stacks, for example off the coasts of Thailand, Vietnam and northwest Malaysia. There can be no doubt of their marine origin, but the process or processes mainly responsible is matter of debate. Wave abrasion is favoured by some (Tjia, 1985), chemical and biotic action by others (Hills, 1949; Hodgkin, 1970; Stevenson & Kirk, 2000).

Some notches preserved on inland towers have been interpreted as abandoned marine forms related to Pleistocene interglacial high sea levels to an elevation of at least 70 m above sea level (e.g. Walker, 1953, cited *in* Ingham and Bradford, 1960, pp. 88-94, and *in* C.R. Jones, 1978, pp. 90 and 146). Such a vertical range includes all of the Kinta Valley and as well as the Perlis lowlands. If related to sea level, and in any significant degree to wave abrasion, notches ought to show a preferred orientation toward the open sea, as they do in places (Tjia, 1985), but they also occur all around the bases of some residuals.

Many towers with basal notches, however, are located at such elevations as to be out of reach of even the highest stands of Pleistocene seas (e.g. Roe, 1951; MacDonald, 1967; Yuan, 1991). Some investigators have attributed such basal notches to lateral stream erosion by rivers in flood (e.g. MacDonald, 1979). Scrivenor (1931, p. 123) noted an occurrence at the base of Gunong Pempurong, more than 75 m above sea level in such a situation that stream erosion was the only possible causative agency.

However, the distribution of notches both in plan and depth argues against river planation as a general explanation. First, regardless of their elevation above sea level, many towers are irregular in plan shape and an abrupt hill-plain junction is found on most if not all aspects, including some not bordered by active stream channels. Second, channel forms migrate downstream so that cuts due to meanders ought to be confined to a particular elevation, whereas notches extend through several metres of vertical range both above and below present plain level. Swamp slots (Fig. 8b) are deceptive for, though they extend many metres into the hill base and appear shallow, excavations have shown that at some sites they extend some 5 m beneath the surface of the present plain.

The notches found around the bases of towers in various parts of Malaysia evidently were attributed by one geologist to sand-blasting under desert conditions (Paton, 1964), but Peel (1941) noted that basal sapping of sandstone bluffs in the Libyan desert was due to water seepage. Paton (1964) sensibly concluded that the rainforest notches are 'subaerial' and have been formed by acid waters of streams and swamps (also Lehmann, 1954; Corbel, 1959; Gerstenhauer, 1960). In this he concurred with a suggestion due to J.F Newsom (*pers. comm*., cited *in* Scrivenor, 1928, p. 189, 1931, p. 123) that the notches or slots are due to attack by swamp waters which stand at the same level for long periods and, if extended to include very shallow groundwaters, can account for the etching of the cliff bases around even the most intricate plan outlines of the towers.

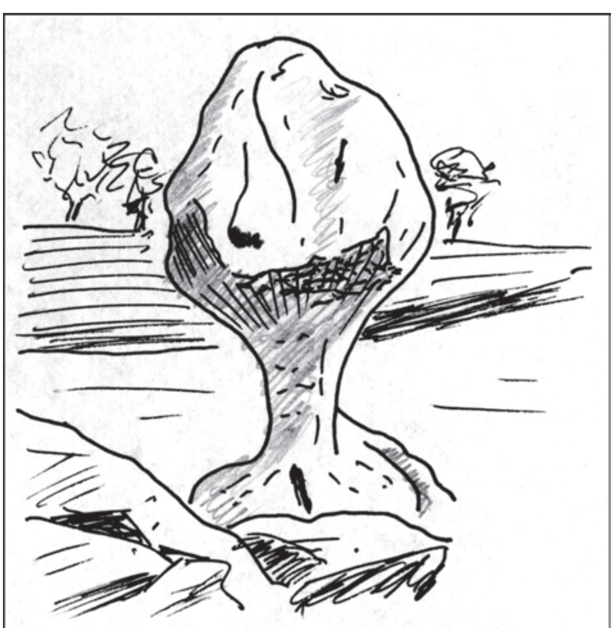

Figure 7. Mushroom rock exposed in quarry floor, Kinta Valley, Perak (drawn from photograph in Ingham and Bradford, 1960).

Paton (1964) recorded that stream water with a pH of more than 6.6. had been sampled in Malaysia but stated that in low-lying areas streams and swamp waters commonly have a pH as low as 3.5. Douglas (1977, p. 31) records the pH of Singapore and Malaysian streams in the range 4.7-7.2. Such acidity of streams draining limestone terrains is presumably due to decaying vegetation and photosynthesis by plants (e.g. Kaye, 1957, pp. 41-42; Monroe, 1968, p. 80; see also Verstappen, 1960).

The plan distribution of slots, their depth beneath the surface and sapping at various heights above plain level at the cliff–debris slope junction according to the elevation of the debris slope-cliff face junction, sustain Jennings' (1976, p. 92) conclusion that "subsoil solution is mainly responsible for the formation of such" [*cliff-foot*] "caves". Three comments are, however, in order.

First, though many notches are due to scarp-foot weathering not all notches develop precisely at plain level. Scree slopes are found in karst terrains in the humid tropics (e.g. Wilford & Wall, 1965; Drogue & Bidaux, 1992) and excavations elsewhere demonstrate that alcoves due to spring sapping develop at the bedrock-debris slope junction (Twidale, 1964; 2000).

Second, some slots are straight, narrow and horizontal, and resemble saw cuts (e.g. Paton, 1964). They transect structure. Their morphology also stands in marked contrast

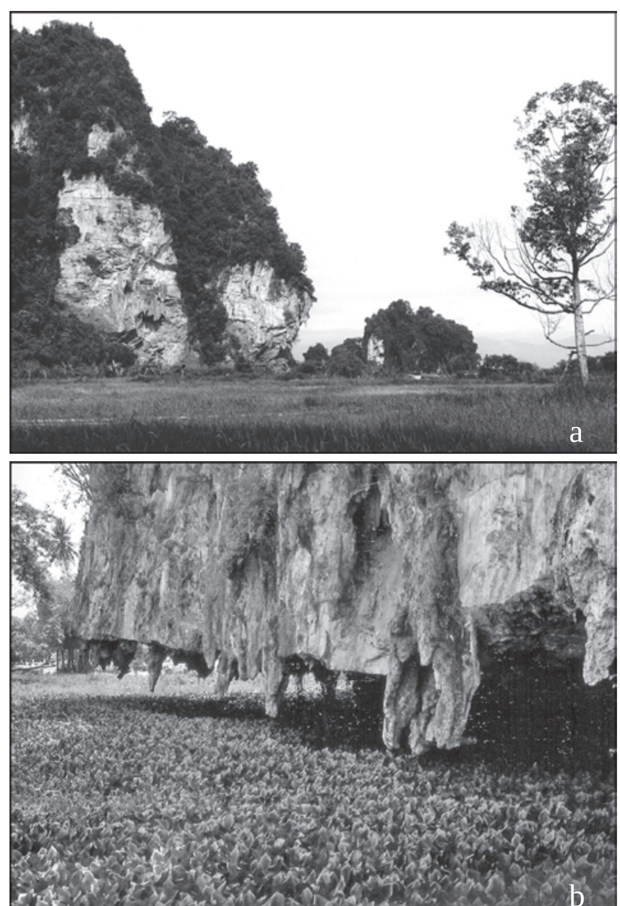

Figure 8. Ipoh region, Perak: (a) basally-steepened slope and notch, (b) swamp slot developed at base of limestone tower.

with the gaping rounded notches attributed to marine action and to the alcoves associated with soil and standing water. Their origin remains enigmatic.

Third, the deep zone of shallow groundwaters armed with chemicals and biota causes swamp slots to extend some metres below plain level, but in addition, some notches may be initiated at deeper levels, at the weathering front. The undercut pinnacles and mushroom rocks uncovered in alluvial tin operations at depths of up to 30 m in the Kinta Valley (Ingham & Bradford, 1960, plate VII, figure 2, facing p. 30; Fig. 8) attest such basal attack by groundwaters at and near the weathering front (Twidale, 1962; Twidale & Bourne, 1998).

SUBSURFACE DEVELOPMENT AND EPISODIC EXPOSURE

King (1966) pointed out that many bornhardts are higher than the thickest regolith known from the particular area He used this apparent anomaly as an argument against the two-stage or etch origin of bornhardts. Many inselbergs, however, have evidently been uncovered not in a single stage but in several. They have evolved through episodic exposure (Twidale & Bourne, 1975; Twidale, 1978, 1982; Bourne & Twidale, 2000).

Some karst towers pose similar problems in that many towers are an order of magnitude higher than local regoliths are thick, for whereas regoliths are some tens of metres deep, the hills are a few hundreds of metres high. Is there any evidence that, like bornhardts they may have been exposed episodically as a result not of recurrent faulting but to the episodic lowering of the adjacent regolith-veneered plains.

Many *Karstinselberge* display perched notches or slots and cave systems, both of which have been taken as indicators of former baselevels (e.g. Lehmann, 1954; Yuan, 1991, p. 60; Fig. 3e). and perched basal notches or slots occur on many karst residuals (e.g. Jones, 1978; Yuan, 1991). The great lateral extent of some cliff-foot caves and swamp slots suggests extended periods of weathering followed by relatively rapid lowering and exposure.

The origin of cave systems is controversial and prevents their use, in isolation, as evidence of episodic exposure. Debate has centred on the relative significance of chemical and mechanical erosion (corrosion or solution on the one hand, corrasion or abrasion on the other) and which parts of the karst hydrological cycle – vadose, water table, deep phreatic (Ford & Ewers, 1978) - are involved in the development of which caves (for review, see Jennings, 1985, p. 135 *et seq*.). Structure (*sensu lato*) plays a significant role in determining the pattern of cave systems. It has been argued that extensive systems developed in a limited vertical range are related to regional water tables and hence to baselevels (Sweeting, 1950; Jennings, 1963), but whereas some systems develop in relation to the water table, others are formed at the same time in the deeper phreatic zone (e.g. Bretz, 1953; Kaye, 1957). Such simultaneous development would seem to rule out caverns as indicators of past baselevels (e.g. Drogue & Bidaux, 1992) unless taken in conjunction with other evidence and, in particular, perched piedmont forms.

Thus, though the evidence for episodic exposure of karst tower differs from that preserved in granitic inselbergs – cliff-foot caves and swamp slots rather than flared slopes, tafoni and breaks of slope (Twidale & Bourne, 1975; Twidale, 1978) – a plausible argument can be made favouring the suggestion. Episodic exposure explains the disparity between the relief amplitude of the residuals developed at the weathering front, and the contrasted characteristic relief amplitudes noted in cone- or cupolakarst terrains, on the one hand, and towerkarst on the other. Not only is the latter derived from the former but relief amplitude has increased simultaneously with the steepening of marginal slopes.

CONCLUSIONS

Karst inselbergs are developed on compartments of limestone that are delimited by open, steeply dipping fractures. Fractures are exploited by moisture both just beneath the land surface and at depth. The bedrock is massive and thus relatively resistant to weathering and erosion. By contrast, the limestone that has been lowered to form the adjacent plains was well jointed and hence more susceptible to moisture attack.

Whatever their dimensions and origin, notches undercut and undermine the slope above. In this way conekarst and cupolakarst are converted to towerkarst. They have increased in relief amplitude through time. Karst residuals are basically structural in origin and as such, though well and widely developed in the humid tropics, are not exclusively of that provenance.

Whether due to fracture exploitation just below the land surface, or initiated at the deeper weathering front, *Kartsinselberge* are etch or two-stage forms, for they are due to weathering followed by the exposure of the weathering front so formed. As with all etch forms it is unwise (Twidale, 2002) unreservedly and without corroboratory evidence to accept karst towers, including those preserved in the stratigraphic record, as evidence of hot humid climates in past times (e.g. Silar, 1965).

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