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Karst geomorphology of the White Limestone Group

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The karst geomorphology of the White Limestone Group of Jamaica is reviewed. The lithological and structural characteristics of the White Limestone Group are examined in relation to its karstification, specifically material properties such as purity, petrology, porosity and mechanical strength, which have been regarded as important in the development of karst landforms. The structural setting and palaeogeography during the deposition of the White Limestone, together with subsequent block faulting, are considered in relation to the origin and evolution of the karst topography. The phenomenon of case-hardening is examined as are the dissolution processes and influences related to the presence of a soil cover. The karst features on the White Limestone Group are considered in two categories; small-scale dissolution sculpturing phenomena, collectively termed karren, and larger scale landforms. The latter can be further divided into karst landform assemblages comprising doline, cockpit and tower karst. Cockpit karst is the most common landform unit on the White Limestone Group, and occurs on the harder crystalline limestones, dolostones and where case-hardening is important. Tower karst occurs on similar lithologies, but has a more restricted distribution. Doline karst is largely restricted to the chalky Montpelier Formation. The geomorphological characteristics of each landform type are described and their origin discussed. Other karst landforms include poljes, ridge karst, glades and a range of fluviokarst, each of which are described. The cave systems and underground rivers are also considered. Karst morphometric studies and theories of landform evolution are reviewed.

KEY WORDS: White Limestone Group, Jamaica, karst terrain, geomorphology.

Introduction

The White Limestone Group is geographically the most widespread lithostratigraphic unit in Jamaica and crops out over 60-65% of the island. Much of the outcrop is karstified, forming a range of karst landforms across the island (e.g., Sweeting, 1958; Versey, 1972). Indeed, The Cockpit Country (Figure 1) in northern Jamaica is famous worldwide for its spectacular karst topography, it being the type area for a tropical limestone terrain termed cockpit karst (kegelkarst). Cockpit karst is the most widespread landform type and occupies about 60% of all karst in Jamaica (Day, 1979). It comprises steep-sided, enclosed depressions with convex side-slopes, forming depressions which are star-shaped or polygonal in plan. Other common karst landform assemblages are doline karst, where the landscape is dominated by oval- or circular-shaped depressions; tower karst, forming isolated residual hills rising above an alluvial plain, planed limestone or non-karstic rocks; and poljes, which are large, structurally controlled depressions surrounded by a steep rim of limestone or, at least in part, non-carbonate rocks. There is also a wide range of fluviokarst features associated with the White Limestones.

The White Limestone Group is more extensively karstified than the underlying Yellow Limestone because of its purity and as a result of the extensive development of a secondary permeability along lines of structural weakness, leading to directed dissolution of the limestones. Dissolution of the limestones along lines of weakness has formed a classic karst landscape.

The palaeogeography and depositional setting of the White Limestone Group is examined by Mitchell (2004) and is considered to represent a tectonically quiet phase in Jamaica's geological history. Essentially, the carbonates were laid down on a block and belt structure defined by two major fault systems, an east-west set and a northwest-southeast set (Draper, 1987). The rapid subsidence of the troughs led to deposition of the Yellow Limestone Group and, in the Middle Eocene, the deep-water chalks of the White Limestones, while eventual subsidence and submergence of the blocks initiated shallow-water pure-carbonate sedimentation. The karstification of the White Limestone Group began in the Miocene when renewed deformation uplifted the limestones. Surface erosion and continued incision de-roofed the siliciclastics of the Yellow Limestones and the older Cretaceous rocks, to form a series of inliers, producing surface streams which provided large volumes of water to the White Limestones via river sinks and which greatly modified the karst from an essen-

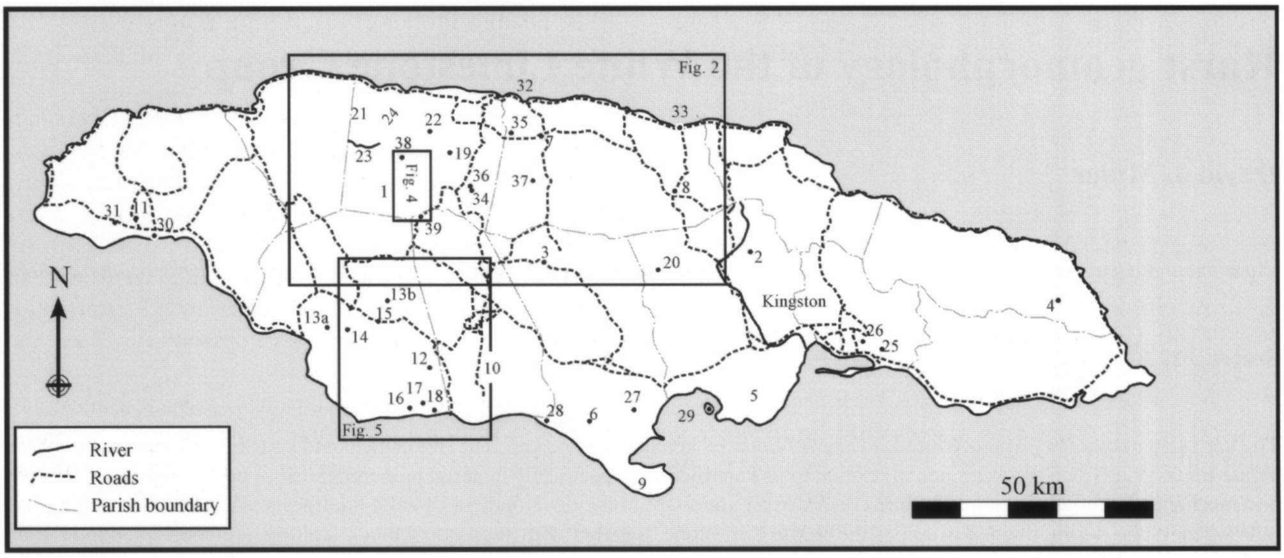

Figure 1. Locality map. Key: 1 = Cockpit Country; 2 = Natural Bridge, Riversdale; 3 = Central Inlier; 4 = John Crow Mountains; 5 = Hellshire Hills; 6 = Kemps Hill; 7 = Brown's Town; 8 = Moneague; 9 = Portland Ridge; 10 = South Manchester plateau; 11 = Cabarita River; 12 = Nain; 13a = Lower Black River Morass; 13b = Upper Black River Morass; 14 = Burnt Savannah; 15 = Santa Cruz; 16 = Top Hill; 17 = Ballards Valley; 18 = Bull Savannah; 19 = Barbecue Bottom; 20 = Lluidas Vale; 21 = Queen of Spain's Valley; 22 = Duanvale Fault Zone; 23 = Roaring River; 24 = Martha Brae River; 25 = Dallas Mountain; 26 = Long Mountain; 27 = Brazilletto Mountains; 28 = Round Hill; 29 = Great Goat Island; 30 = Savannah La Mar; 31 = Little London; 32 = Discovery Bay; 33 = St Ann's Bay; 34 = Quashies River Cave; 35 = Dornock Head; 36 = Bristol Cave; 37 = Dry Harbour Mountains; 38 = Windsor; 39 = Troy.

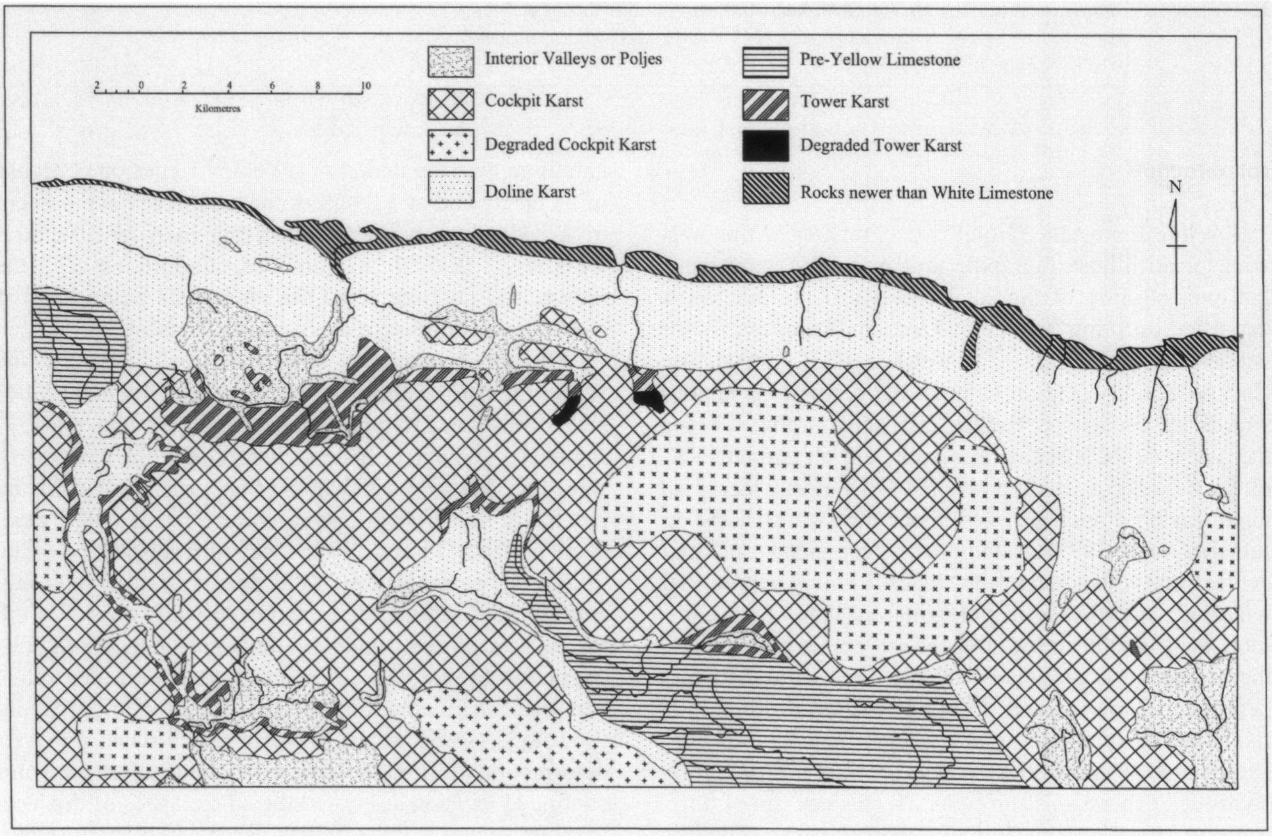

Figure 2. General geomorphological map of north-central Jamaica, showing the main karst landform assemblages (based on Sweeting, 1958).

tially autogenic to a mixed allogenic-autogenic karst system, particularly on the northern side of the island. Karstification of the limestones has continued through the later Tertiary and into the Quaternary.

Historical review

Some of the earliest descriptions of the karst in Jamaica were related to early cave explorations, summarised in Fincham (1997). The earliest descriptions of caves in detail were those by Edward Long (1774), who published a three-volume history of Jamaica, which contains descriptions of three caves. In his remarks on the geology of Jamaica, De la Beche (1827) described the Natural Bridge at Riversdale, which was the first surface karst feature to be documented (Miller & Donovan, 1999). Sawkins (1869) provided a detailed account of the geology and hydrology of the island. The Cockpit Country was mentioned in this volume for the first time, where the cockpits, dolines and lightholes were described and attributed to collapse of the limestones into pre-existing caverns. Some thirty years after the publication of the memoir, a reassessment of the geology of Jamaica was produced by Hill (1899) and, although there was little consideration of the karst, he attributed the origin of the cockpits to solution, not collapse. A few years later, Dane (1909, 1914) described the cockpits and other karst features, and also favoured solution, predominantly along joints and fissures, for the formation of the cockpits. His principal contribution to the development of karst studies was to add detailed observations of tropical karst in Jamaica to European investigations which had hitherto been the basis for karst evolution theories (Fincham, 1997). Lehmann (1954) examined the karst in northern Jamaica and also suggested a solutional origin to the development of cockpits.

In 1955, Marjorie Sweeting, a karst geomorphologist from the University of Oxford, conducted a two-month programme of hydrological studies in Jamaica in association with the Geological Survey Division. These studies led to three publications on the hydrogeology and karst geomorphology of the limestones of the island, but specifically the White Limestone areas (Sweeting, 1956, 1957, 1958). Her 1958 publication was to become the seminal work on the karstlands of Jamaica, and the first major review of the limestone geomorphology and hydrology of the island, including the first general karst geomorphological map of the northern part of Jamaica (Figure 2). This stimulated a wider interest in Jamaican karst and established The Cockpit Country as a geomorphological tropical terrain-type. She published later reviews and descriptions of Jamaican karst in her 1972 book, *Karst Landforms*, where she also documented previously unpublished work by other authors, notably Conrad Aub. Other general descriptions of the karst of the island were published in the 1950s by Doerr & Hoy (1957) and Urquhart (1958). In the 1960s, a number of German geomorphologists, notably Pfeffer (1967, 1969), also worked on the karst of the White Limestones, specifically in the north of the island and across southern St Elizabeth.

Versey (1972) also reviewed the karst geomorphology of the island from a geological perspective. Gardner *et al.* (1987) published a summary of Jamaican karst, chiefly from the earlier reviews of Sweeting and Versey, and a more recent summary review was presented by Draper & Fincham (1997). Other investigations are related to karst landform evolution (*e.g.*, Landmann, 1990; Pfeffer, 1986, 1997) and to karst landform development (*e.g.*, Smith *et al.*, 1972).

Karst morphometric studies on the White Limestones have, to date, been restricted to relatively small, localised areas of Jamaica. These studies include the work of Day (1976, 1978a) and Brook & Hanson (1986, 1991).

Geological background

The karst of Jamaica provides a good example of both lithological and structural controls on its development (Gardner *et al.*, 1987), while the case-hardening of many of the White Limestones has also had a significance influence on the development of karst landforms.

Lithological and material properties

There is a strong control on karst landform development related to lithology and specifically to certain material properties of the limestones. Sweeting (1958) noted that vertical relief development in the form of both cockpit and tower karst is confined to the areas of hard crystalline White Limestone, as well as to areas of high rainfall totals. In areas where the White Limestone is more marly, or where the rainfall amounts are relatively low, the landscape is dominated by doline karst. Sweeting further indicated a link between lateral relief development and lithology, as poljes are normally associated with the marly limestones, which promote extensive flooding and lateral planation. Urquhart (1958) also indicated that 'cockpit karst' is developed on the pure, hard and fissile limestones, while 'doline karst' is present on those which are marly or impure. White & Dunn (1962) also suggested the solubility, massiveness and well-developed joints of the White Limestone have been major factors in the development of karst topography in Jamaica.

Versey (1972) suggested that, in terms of the importance of lithological properties to karst hydrology, three broad lithological divisions can be identified, each with differing hydrological regimes. The first group are the Montpelier chalks which, according to Versey, are characterised by a primary, rather than diagenetic, porosity. This, together with the paucity of fractures, leads to a well-developed primary permeability, such that groundwater movements occur through the body of the rock rather than via conduits (Versey, 1972; Gardner *et al.*, 1987). Versey's second rock division based on hydrological characteristics is the recrystallized limestones and dolostones, representing the oldest formations within the White Limestone Group. These rocks are characterised by no primary permeability and groundwater movements are entirely along fissures. Definite lines of groundwater flow have developed only along the largest fractures (Gardner *et al.*, 1987). Enlargement of joints and other lines of weakness is the result of directed dissolution and the development of secondary permeability. Versey (1972) characterised the rest of the White Limestone Group as a 'rubbly limestone', having a widespread nodular texture, with occasional hard bands. The variable lithologies within Versey's 'rubbly limestones' range from soft powdery textures which are nearly impermeable, to limestone conglomerates which are highly permeable.

The White Limestone Group formations are, for the most part, extremely pure carbonates. Versey (1972) noted that the non-carbonate fraction seldom exceeds 2% and is generally less than 0.5%. Comer (1974) (Table 1) found the Middle Eocene to Lower Miocene White Limestone Group to be on average 99.87 % pure calcium carbonate and that the source of the insoluble residue could have been contamination of the samples by bauxite or terra rosa soil. Comer also examined the Middle and Upper Miocene carbonates of the Montpelier Formation (Table 2), which contain several thin bentonitic interbeds and disseminated clays. These limestones were found to contain on average 6.17% insoluble residue, chiefly oxides of Si, Al and Fe, in the form of bentonitic and montmorillonite clays.

Day (1976) reported the results of acetic acid insoluble residue experiments on the limestones which indicate that the Browns Town, Walderston (both now referred to the

% Insoluble Residue	% Fe_2O_3	% SiO_2	% Al_2O_3	% P_2O_5	% TiO_2	% CaO	% CO_2
0.1275	0.0017	0.0275	0.0060	0.2072	0.0005	55.94	43.93

Table 1. Summary chemical composition of Middle Eocene to Lower Miocene limestones of Jamaica (from Comer, 1974).

% Insoluble Residue	% Fe_2O_3	% SiO_2	% Al_2O_3	% P_2O_5	% TiO_2	% CaO	% CO_2
6.1715	0.47	3.179	0.975	0.069	0.0048	52.69	41.28

Table 2. Summary chemical composition of Middle and Upper Miocene limestones of Jamaica (from Comer, 1974).

Formation	% Insoluble Residue Content	Dominant Specification	Texture	% Sparry Calcite	% Estimated Porosity	Schmidt Hammer Hardness Test
Montpelier	0.23	Fossiliferous Micrite	Fine	<10	<5	32.6
Bonnygate (herein, Montpelier)	-	Foraminiferal Micrite	Fine	<10	<10	30.4
Walderston (herein, Moneague)	0.16	Biomicrite	Fine-Medium	20-30	10-15	29.7
Brown's Town (herein,Moneague)	0.12	Biomicrite	Fine-Medium	30-40	10-15	32.1
Somerset	0.08	Biosparite	Medium	40-50	<10	33.1
Swanswick	0.09	Biosparite	Fine-Medium	30-40	10-15	36.3
Claremont (herein, Troy)	0.03	-	-	-	-	-
Troy	-	Dolomitic Limestone	Medium	10	<10	42.3

Table 3. Summary material properties of formations of the White Limestone Group of Jamaica (from Day, 1976, 1979, 1982).

Moneague Formation; Mitchell, 2004), Somerset and Claremont (now part of the Troy Formation) formations all contain considerably less than one per cent by weight insoluble residue (Table 3). Day (1982) further examined the role of material properties in the development of karst terrain in a number of localities within the Caribbean and central America, on the basis of the purity, petrography and mechanical hardness of the limestones in relation to the karst landform type developed (Table 3). He also described the White Limestone as extremely pure; of the samples tested, the Somerset Formation was found to be the most pure, with only 0.08% insoluble residue. Day examined the petrographic nature of the limestones and the samples he analysed are mostly biomicrites or micrites (Table 3), with a relatively low percentage of sparry calcite, though his samples of Swanswick and Somerset limestones were classified as biosparites. The Troy Formation was classified as a dolomitic limestone and displayed extensive recrystallisation. Texturally the rocks were found to be fine- to medium-grained, which is reflected in the low estimated porosities of <15%. Day also provided a summary of results obtained from *in situ* Schmidt Hammer testing and found the White Limestones vary from moderately hard to very hard, with the dolomitic limestone of the Troy Formation being the hardest, recrystallisation having destroyed the original limestone texture and resulted in increased cementation strength.

Day (1982) attempted to correlate purity, petrographic characteristics and mechanical strength with terrain type, and found that the most striking correlation is between terrain type and hardness of the rock types as demonstrated by the Schmidt Hammer, where 'tower karst' tends to develop on the hardest rocks, and 'doline karst' on the softest. Day concluded that the role of lithological variation, and particularly hardness, as a measure of mechanical strength is deserving of greater attention. The correlation between purity, petrography and terrain type was less striking for the White Limestone samples, but this is due to the fact that all are extremely pure and mostly micritic, and is also a reflection of the small sample size. More recently, however, Pfeffer (1986) indicated that cockpit karst occurs only on the 'pure' limestones and that the cockpit hills are steeper on the purest limestones. Limestones with marl layers tend to form less steep residual hills and dolines, while the impure limestones support doline karst only.

The relatively low porosity of the limestones is important, as directed, rather than diffuse, dissolution occurs along lines of weakness to develop a secondary permeability along joints and fissures, leading to the development of karst terrain through enhanced rates of dissolution where joints are more common.

Geological structure

The overall tectonic evolution of the island and the resulting geological structures have imparted significant control on the development of karst landforms within the White Limestone Group, not least, the block faulting and extensive east-west trending fault systems, the anticlinal folding of the platform carbonates and the erosional breaching of this structure, together with subsequent deroofing to form the Central Inlier. A detailed discussion of the structural geology and tectonic evolution of Jamaica is beyond the scope of this paper and the reader is directed to recent reviews of the block and belt structures by Draper (1987, 1998), Lewis & Draper (1990) and Robinson (1994). Essentially, Jamaica consists of three main structural blocks, separated by two northwest-trending graben structures (e.g., Draper, 1998). The blocks are composed of Cretaceous volcanics, siliciclastic sedimentary rocks with minor limestones, and granitoid intrusive rocks, capped by Tertiary limestones, and comprise, from east to west, the Blue Mountain Block, the Clarendon Block and the Hanover Block (Draper, 1998; Robinson, 1994). The belts separating the blocks are fault bounded and Tertiary in age. They consist of the Wagwater belt of siliciclastic sedimentary rocks, the Montpelier-Newmarket belt comprising Tertiary limestones and the North Coast belt, which abuts the northern margin of the Clarendon Block and consists of deeper water limestones.

The Lower Cretaceous to Palaeogene rocks, exposed in several inliers, represent parts of an island arc system (Draper, 1998). In the Palaeocene Jamaica rifted along major northwest-southeast-trending faults, when the present block and graben structure of the island was formed (Draper, 1998) producing blocks of different height. After cessation of the arc system, from the late Early Eocene to the Late Miocene, differential subsidence occurred and transgression led to the accumulation of shallow water carbonate sediments on the main structural blocks, although the Montpelier-Newmarket and North Coast belts underwent greater subsidence, allowing for deeper water carbonate sedimentation (Draper, 1998). As well as controlling the lithology of the limestones, the tectonic activity uplifted and exposed the island during the later Cainozoic. The uplift from the Late Miocene is most likely the result of northeast-southwest shortening which accompanied east-west, left-lateral transcurrent motions, which can be seen as three large, east-west trending fault systems that cut through the island (Lewis & Draper, 1990; Draper, 1998). In terms of the structural influence on karst topography, the Duanvale and the South Coast fault systems are the most important, and the Plantain Garden-Rio Minho system is less so.

On the Clarendon Block, the structural response to the northeast shortening accompanying the transcurrent tectonics was the large scale anticlinal folding of the platform carbonates (Draper, 1998) to form a major westnorthwest-eastsoutheast-trending anticline. The tilting of the limbs of the anticline also provided the hydraulic gradient necessary for much of the horizontal cave development in the centre of the island (Draper, 1998). Development of the anticline was followed by a general southward tilting of the block. The erosional breaching of the anticline and subsequent de-roofing, to expose the Cretaceous rocks of the Central Inlier, began about 9 Myr ago in the Late Miocene (Draper, 1998). According to Draper, at the margins of the Clarendon Block, the early Tertiary northwest-southeast-trending faults were reactivated as thrust faults.

In the east of the island, most of the northeast shortening has been accommodated by thrusting along a northwest-southeast directed axis in the Wagwater and Yallahs fault systems, which resulted in spectacular uplift (Draper, 1998). This has resulted in the erosion of the overlying White Limestone and the only remnants are the northeast dipping beds of the John Crow Mountains (Draper, 1998). These limestones form a pronounced escarpment on the eastern slopes of the upper Rio Grande Valley.

The renewed uplift in the Miocene exposed the carbonate platforms on the blocks to karstification and erosion. As far as the karst is concerned, the most important block is the Clarendon Block where two series of faults each have strong topographic expression (Versey, 1972). The east-west faults occur at the northern margin of the block and especially form the Duanvale fault system, which exerts strong geomorphological and hydrological controls on karst development. Similar east-west trending faults to the south of the block, near to the coast, also have a profound effect on karst landforms. Across the Clarendon Block, the faults are more or less perpendicular to those along its margins, and trend between northeast-southwest and northwest-southeast. Most of the major faults have clear topographic expression across the White Limestones. According to Versey (1972), to the north of the Clarendon Block, in the North Coast belt, faulting gives way to folding in the deeper water carbonates of the Montpelier chalks, which display clear dips, and faults lose their clear topographic expression. The general absence of faults in the Montpelier Formation leads to low secondary permeability, which in effect acts as a barrier to the northerly groundwater flow. It is also possible that impedance of drainage is caused by a reversal of the dip or by the upfaulting of the karst base (Gardner *et al.*, 1987). The other facies of the White Limestones rarely display clear dips and when they do the angle of inclination is generally small (15°), steeper dips indicating nearby faulting (Versey, 1972). The faulting had the effect of generally increasing the permeability of the limestones, though where the limestones were 'initially so incoherent', the faulting decreases the permeability as evidenced by the occurrence of fault-line ridges which have resisted dissolution (Versey, 1972).

Within the fault blocks of the Clarendon Block, the north-south trending faults are roughly perpendicular to groundwater flow and do not affect it significantly. However, where the regional groundwater flow is north or south through the limestones, the north-south faults are parallel to flow direction and they tend to impart a strong control, acting as lines of preferential groundwater movement (Versey, 1972). The Miocene to recent tectonic activity also produced many faults, which form numerous scarps, seen as strong lineaments on satellite imagery and aerial photographs (Draper, 1998).

The origin of the karst landforms in the White Limestone Group are closely related to the character and attitude of the limestones and their tectonic evolution (Versey, 1972; Gardner *et al.*, 1987). One of the main controls on the overall physiography of the limestones is their block-faulted structure. This episode of block faulting occurred in the late Tertiary, and is more pronounced and younger in the south than it is in the north. Basically, the karst features are superimposed on the block-faulted structural elements. According to Versey (1972) and Gardner *et al.* (1987), karst erosional processes have accentuated the structures in some areas. In other situations much of the original structure has been masked by deposition of alluvium, particularly in the interior valleys and poljes, which have been structurally depressed, rather than being the result of erosion.

Hydrologically, the faulting has generated drainage barriers and created distinct catchments within the karst. Some of the streams have eroded to base level and this has resulted in a major modification of earlier flow which was entirely subterranean (Versey, 1972; Gardner *et al.*, 1987). A major event was the erosional breaching and subsequent de-roofing of the anticlinal structure which now is exposed in the Central Inlier, which fundamentally altered the hydrological regime of the karst on the Clarendon Block. Surface drainage from the Cretaceous rocks was directed onto and beneath the karst plateaus surrounding them. Therefore, the karst was modified from an essentially autogenic system, where karstification was dominated by diffuse autogenic recharge by vertical percolation of rainwater through the limestones, to a mixed autogenic-allogenic system, where additional large volumes of water passed through the limestones as concentrated allogenic recharge, especially from the Cental Inlier. Versey (1972) suggested that the sediments contained within this allogenic water would also have abraded the limestones before being deposited in interior valleys or carried to the sea.

At the more detailed scale, Wadge & Draper (1977a, b) investigated the tectonic control on cave development in the limestones. Brook & Hanson (1991), in a quantitative analysis of cockpit and doline karst near Brown's Town, parish of St Ann, showed that northwest- and northeast-trending fractures exert a major influence on topographic development in the cockpit terrains and that east-west-trending fractures are relatively more important in the doline areas.

Case hardening

Calcareous weathering crusts commonly occur on residual limestone hills and outcrops in tropical environments. Their significance for karst was first appreciated in the Caribbean region, where the phenomena is known as case hardening (Ford & Williams, 1989). Most of the work on case hardening in the Caribbean comes from Puerto Rico (Monroe, 1966, 1968; Ireland, 1979) and Cuba (Panos & Stelcl, 1968). Both Monroe (1966) and Sweeting (1972) interpreted the hard caprock to be due to secondary deposition of calcium carbonate resulting from evaporation soon after torrential rain showers dissolve small amounts of limestone. Monroe (1966) considered case hardened surfaces to be thicker on exposed windward slopes, due to more pronounced wetting and drying, though Ireland (1979) indicated that it is much more uniform, with the zone of induration closely following topography. Commonly, case hardening in Puerto Rico is 1 to 2 m thick, but it may be at least 5 m in extent (Ireland, 1979). Ivanovich & Ireland (1984) considered that, for limestones consisting of more than 50% fossils, the dominant case hardening process is precipitation into solution cavities. In rocks with less than 20% fossils, the main process is aggrading neomorphism, a recrystallisation process resulting in the progressive increase of microspar. In both processes, the precipitation is caused by carbon dioxide degassing and it leads to a significant reduction in porosity of the limestones.

Although there has been no systematic work completed on case hardening in Jamaica, it is common. Pfeffer (1969) reported three distinct variations of cockpit karst in one small area in southwest Jamaica in relation to the presence of surface crusts. One type of conical hill is completely formed in firm limestone, a second type is encrusted with external stalactites and travertine covering the rock surface and on overhangs, while a third type is covered with weathering residuals and a limestone crust overlying decomposed limestone particles. The limestone crusts, travertine and stalactites reported by Pfeffer (1969) were taken to represent reprecipitated calcium carbonate, which at least in part forms a case-hardened caprock on some of the residual hills. On a smaller scale, McFarlane (1980) reported the occurrence of razor-sharp, case-hardened karren features on the karst landforms of the Newport Formation (now referred to the Moneague Formation; Mitchell, 2004) in the Hellshire Hills (Figure 1). As indicated by Ford & Williams (1989), case hardening is especially important in the development of karst on porous, mechanically weak and diagenetically young limestones, where it gives the rock more resistance to erosion, and reduces its porosity and permeability.

The case-hardening effect is normal throughout the White Limestone Group, but it is especially noticeable on those units, such as the Moneague Formation, which are soft, chalky to granular micrites when fresh. Thus, it would seem that case hardening may be more important in the development of karst topography on the rubbly and chalky limestone formations, rather than the older recrystallised limestones, some of which have been dolomitised. A 2 m thick caprock has been observed on some quarry faces in Moneague Formation tower karst at Kemps Hill, southern Clarendon, but more work needs to be done on the importance of case hardening in karst development in Jamaica.

Dissolution processes and controls

No systematic work has been done on dissolution processes and controls on limestone dissolution in Jamaica. Two groups of controls on limestone weathering can be generally identified, these being environmental and geological controls. In terms of lithology and structure, the main controls have already been discussed and occur at a variety of spatial scales. Environmental controls fall into four broad categories, related to soil conditions, hydrology, topography and climate. A major control on limestone weathering and dissolution in general is the presence or absence of a soil cover and the nature of the soil, especially as it relates to acidity, soil carbon dioxide production and content, and organic content. Sweeting (1958) indicated that, under tropical rainforest conditions, it would be expected that soils would have a high production and concentration of carbon dioxide. Accordingly, dissolution of the limestones would be rapid, which helps to explain the intense development of karst landforms and may also account, in part, for the occurrence of widespread *terra rosa* soils and bauxite deposits, which are commonly associated with the White Limestone (Zans, 1951a; Sweeting, 1958).

Measurements of the levels of soil carbon dioxide were made by the University of Bristol Karst Hydrology Expedition to Jamaica in 1967 (Smith, 1968, 1969a) and reported by Nicholson & Nicholson (1969). Carbon dioxide levels in soils over limestone varied from 0.6 to 1.9% with the highest concentrations occurring in soils under natural woodland with a high clay and humus content (Nicholson & Nicholson, 1969). It was found that the lowest concentrations occur under bare, cultivated soil with low humus content in the surface horizon, but the carbon dioxide content was generally higher than for soils in temperate regions as a result of the greater levels of biological activity in higher temperatures (Nicholson & Nicholson, 1969). Day (1976) analysed the soil carbon dioxide content in slightly to moderately acidic, red-brown bauxitic loams associated with doline-type depressions in the Brown's Town area and also found that levels were generally higher than those associated with temperate conditions. Soil carbon dioxide content was higher when the soil was approaching saturation (Day, 1976). This would be due to the fact that soil carbon dioxide diffusion to the surface is considerably reduced with increasing soil moisture content. Day (1976) also found that carbon dioxide levels increased in the base of the depressions and with increasing depth, though he concluded that the importance of a soil cover in facilitating limestone dissolution, as it relates to carbon dioxide content, in Jamaica requires further investigation.

Trudgill (1977) investigated the role of a soil cover in limestone weathering in a small study in the Troy area on the southern boundary of Cockpit Country. Rates of weathering were obtained by placing pre-weighed limestone tablets within both red and organic soils, which are moderately acidic and with low carbonate content, and at the soil to bedrock interface. Soil carbon dioxide content was also measured at the two White Limestone localities and was found to be lower in the organic soils, especially at the soil-rock interface, resulting from rapid diffusion to the surface in the open leaf litter organic soil compared to the more compact mineral soil (Trudgill, 1977). Measured erosion rates under both soil types were greater than where soil cover was absent, and this is related to leaching and the acid nature of the soils, rather than soil carbon dioxide content (Trudgill, 1977). Trudgill also surmised that the presence of a soil cover could markedly affect the development of dissected terrain on the White Limestone, as erosion rates would be greatest where pockets of red and organic soils occur, leading to differential rates of dissolution.

Based on a consideration of effective runoff figures and the values obtained for the hardness of springs resurging from the White Limestones (Smith, 1969b), Smith *et al.* (1972) suggested that the overall erosion rate of the White Limestone area lies between 40 mm and 70 mm per 1,000 years. According to Smith (1970), this variation is almost entirely due to spatial variation in effective runoff, which is controlled largely by variation in rainfall amounts.

Geomorphology

The karst geomorphology of the White Limestone Group can be examined at several spatial scales. On the small-scale, there is a range of fine solution sculpturing present on many limestones surfaces, which is the product of dissolution of the limestones by slightly acidified rainwater, and subsequent surface vertical trickle and flow under the influence of gravity. Collectively, these small-scale features are referred to as karren and a wide variety of such features are present, though to date very little systematic work has been undertaken on the phenomena. Work completed to date on karren features is summarised below. At the larger scale, there is a wide range of karst features, from cockpit and doline karst, both largely the product of vertically-directed dissolution, and tower karst, which is mainly related to laterally-directed dissolution, to ridge karst and poljes, which have a strong structural control. Poljes also induce horizontal water movements at or near to the regional groundwater table. There is also a range of fluviokarst, including dry and blind valleys, ephemeral limestone gullies and valleys with relict alluvial fans, steepheads and natural bridges. The formation and development of the surface karst phenomena is closely associated with the hydrogeology of the White Limestone Group, and cave systems and underground rivers are important karst phenomena across the island. Karst speleogenesis and the history of speleological work on the island is summarised in Fincham (1997); herein, research on the cave systems and underground rivers is reviewed as it relates to the development of the karst as a whole. Localities referred to in the text appear in Figure 1.

Dissolution sculpturing

No systematic work has been undertaken on the small-scale solution sculpturing of the limestones of the White Limestone Group. White & Dunn (1962) noted that the major karst landforms are covered with extensive karren, and classified the solution sculpturing on cockpit hills and towers as a type of spitzkarren. McFarlane (1980) reported a small descriptive study of karren morphology at three localities within the White Limestone Group at Troy (Troy Formation), Portland Ridge and Hellshire Hills (Moneague Formation). The features are predominantly of a linear nature in the Troy area, which contrasts markedly with the more sub-circular forms within the Portland Ridge and Hellshire Hills. It was further suggested that the karren features in the Troy area are better developed and have a wider range of morphologies. McFarlane (1980) postulated that the differences may be dependant on climatological and, more particularly, lithological factors.

More recently, Draper & Fincham (1997) noted the presence of several types of karren, especially solution pits, micro-pits and Hortonian runnels, which are widespread on exposed surfaces on many different kinds of limestone across the island. Other runnel or rill-like features in the form of rinnenkarren and fluted scallops are also present (Draper & Fincham, 1997). Draper and Fincham further indicated the occurrence of spitzkarren and cleft-like grikes on the thicker bedded and well-jointed limestones of the Troy/Claremont Formation, while honey-comb weathering features and littoral karren forms occur on the White Limestone exposed near to the coast.

The most common solution sculpturing features identified on the south coast limestones, specifically the Moneague Formation, appear to be honey-comb weathering phenomena (Figure 3) and rain pits. Although spitzkarren is present, hydrodynamically controlled linear sculpturing tend to be less common. The author agrees with the earlier observations of McFarlane (1980) that rillenkarren may be more prevalent on the older Troy Formation, but more systematic work needs to be completed in this regard.

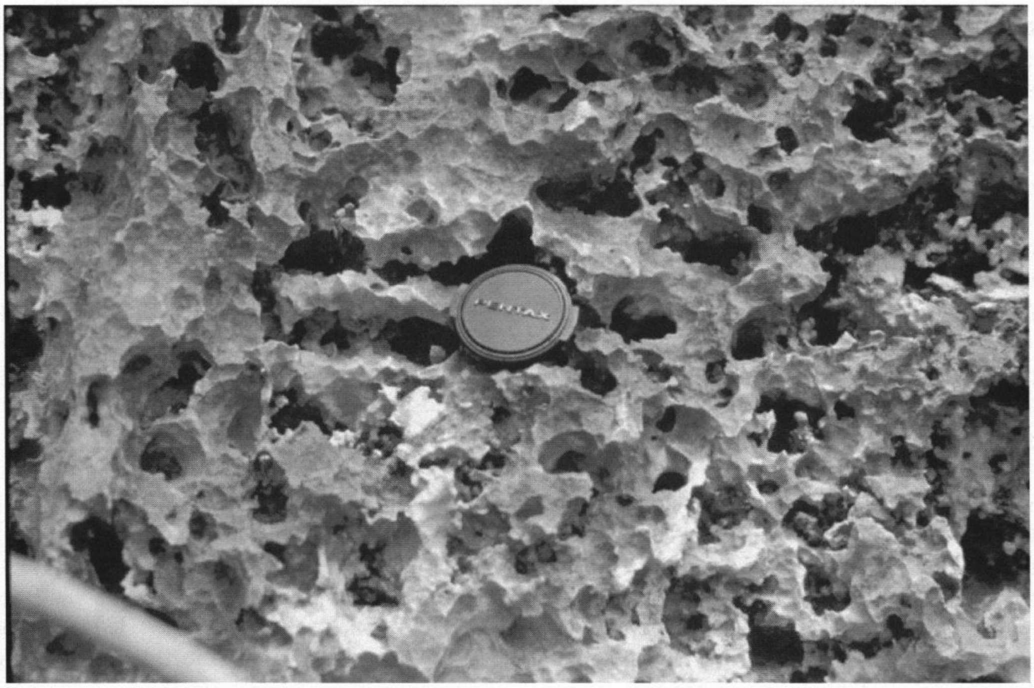

Figure 3. Honeycomb solution weathering on ridge karst in the Moneague Formation, southern parish of St Elizabeth.

Figure 4. Cockpit karst in northwest Cockpit Country, parish of Trelawny, showing well-developed preferred orientations due to faulting and joint-patterns (photograph courtesy of Mr Jack Tyndale-Biscoe).

Doline karst

Doline karst is an important landscape type on the Montpelier Formation and is also associated with areas of relatively low annual rainfall (Sweeting, 1958). The largest area of doline karst on the White Limestone Group occurs in the north central part of the island (Figure 2), a few kilometres inland from the coast, especially where it is underlain by the relatively soft, chalky Montpelier limestone (Draper & Fincham, 1997). Sweeting (1958) suggested that lithological and climatic conditions are responsible for the development of doline karst along the north coast, though she did indicate that dolines occur in the Moneague area, despite a fairly high annual rainfall. According to Sweeting, the dolines on the Montpelier Formation are usually shallow and have an open v- or funnel-shaped cross section. Similar shallow karst depressions occur in the area around Brown's Town, parish of St Ann in the north of the Dry Harbour Mountains (Day, 1976). Day carried out a morphometric and hydrological study of the enclosed depressions for which he was careful not to use the term doline, though he asserted that, 'Other workers might describe these simple depressions by the term doline or sink'. The depressions examined by Day are laterally extensive and shallow, and some individual depressions occur within larger, more complex depressions, though their complexity cannot be distinguished by size alone. The depressions range in diameter from <100 m to over 1 km, with a mean diameter of 219 m. Their depth range is also variable, with a mean depression depth of 18.4 m; although two of the largest depressions in the area of study are >30 m deep, many of the depressions are relatively shallow. Day found that the depressions are characterised by low angle slopes within a range of 2° to 12°. The depression density was found to be 12.5 per km^2. Day also found a strong correlation between depth and diameter, which was considered unlikely to have developed by chance and which must relate to the internal slope development of the depressions. Many of the depressions show a very strong tendency towards orientation in an east-west direction, with other weak orientations in an approximately northwest-southeast direction. Day (1976) interpreted the east-west direction as corresponding with the eastward extension of the Duanvale fault zone, which crosses the study area with an orientation of between 71° and 80°, while a secondary group of faults are orientated between 310° and 320°. Stream channel networks within the depressions were also analysed and the depressions ranked in relation to the network order. This was compared with depression size and it was found that depression area increases with increasing channel order. It was found that the channels, which are commonly up to 2 m deep and 4 m wide, contain surface runoff only at times of prolonged and/or intense rainfall. Day found that water flowing down the channels ponded in the lowest parts of the depressions, before being removed by subsurface drainage at an outlet. Some of the depressions were found to contain semi- permanent ponds which fluctuate according to supply of runoff.

Day (1976) dye-traced the water sinking from the enclosed depressions to the dry and ephemeral valley systems traversing the Montpelier Formation limestones to the north of the study area. The marked water commonly reappeared at altitudes of 250 m to 100 m, which gives a vertical height of underground flow in the order of 150 m. Lateral distances of flow ranged from 0.5 km to 5.0 km and Day estimated travel times of between 0.25 km to 0.5 km per day, which supports the idea that flow occurs through conduits rather than by diffuse percolation. In most cases, the water sinking from the depressions contributed to the flow in one valley only, but the main sources of flow to the valleys are not the depressions under study, but the karstified limestones of the plateau to the south of the study area (Day, 1976).

Day's study indicated that it is not possible to infer the dominant process in the formation and subsequent development of enclosed depressions. He suggested that small scale collapse may provide the initial form, which is subsequently modified by systematic solutional activity. The enclosed depressions generally show a regular distribution which could suggest solutional activity, as collapse events may produce a more random distribution pattern, while the control of structure on depression long axes orientation could also be suggestive of solution, though there is no reason why subsurface solution should not result in preferred orientation of collapse features (Day, 1976). In a later paper, Day (1984) attempted to predict the location of surface collapse within these karst depressions.

Draper & Fincham (1997) indicate that doline karst also occurs on the tilted plateau areas in the southwest part of the island which are underlain by the relatively soft, rubbly and mechanically weak Newport Formation (now referred to the Moneague Formation; Mitchell, 2004). According to Draper and Fincham, the lithology is too weak to support the steeper and more pronounced residual hills associated with cockpit karst. Dolines and sinkholes, circular to sub-circular in plan form and varying in diameter from a few metres to over 1 km, are common across the south Manchester plateau and westwards into southern St. Elizabeth. There is a wide spectrum of forms, ranging from saucer-shaped hollows to funnels, cones and cylindrical pits, and they may occur as isolated depressions or pock-mark the terrain in clusters. Within this area, a threefold subdivision of doline karst can be related to the characteristics of their associated positive relief features.

The first doline karst category is typified by circular to sub-circular depressions, ranging from 100 m to 400 m in diameter, but more commonly around 150 m to 250 m, which are conical to bowl-shaped, up to 30 m to 40 m deep, though usually shallower at around 20 m to 25 m, with depth to width ratios of <1.0. The intervening residual hills form small cones, <25 m high, with similar diameters to the depressions and occasionally occurring in beaded arrangements.

The second type of doline karst is common across the southern Manchester plateau and consists of enclosed depressions associated with elongated hills. The dimensions of the relief elements are similar to the doline karst described previously, but the hills are up to 300 m long, and commonly orientated northwest-southeast and north-south, probably in response to major joints and other structural controls.

A third type of doline landscape is characterised by enclosed depressions with subdued hills, generally <10 m to 15 m high, where the sinkholes dominate the landscape. Generally the depressions occur in clusters. Elsewhere across southern Manchester and southern St Elizabeth, isolated dolines can be identified. Some are large, shallow features, 1 km to 2 km in diameter, while others are narrow and deep, with a depth to width ratio of 1.2 to 2.0, commensurate with a collapse origin and possibly linked to well developed cave systems.

It is likely that a number of processes are responsible for the formation of the dolines across the south Manchester Plateau and southern St. Elizabeth. The morphology of the shallower, clustered, cone- and bowl-shaped dolines suggests a solutional origin, where solution is focussed along lines of weakness and where the vertical permeability of the limestones is spatially variable. The steeper-sided, more isolated dolines are probably the result of collapse, though many of the depressions are likely to be of a compound origin.

Cockpit karst

Cockpit karst (Figure 4) consists of a succession of cone-like hills and intervening enclosed depressions (Sweeting, 1958). Cockpit karst in Jamaica has also been termed kegelkarst, gerichteter karst (directed karst) (e.g., Lehmann, 1954) and cone karst (Sweeting, 1958, 1972). Versey (1972) considered the term kegelkarst as inappropriate due to the fact that the Jamaican cockpits are modified by an over-deepening of the depressions. Cockpit karst is restricted to the hard, fissured and recrystallized White Limestone and, as previously indicated, it does not appear on the chalky Montpelier limestones, nor does it occur on White Limestones which are associated with bauxite deposits, as on the Manchester plateau (e.g., Sweeting, 1958, 1972). The overall landscape is a highly irregular combination of positive and negative relief elements of roughly equal prominence (Chenoweth & Day, 2001; Day, 1979, 1982). This type of karst landscape is the most widespread in Jamaica (Sweeting, 1958), covering some 60% of all karst terrain (Day, 1979), Cockpit Country being the type locality for cockpit karst (e.g., Sweeting, 1958, 1972; Versey, 1972) (Figure 2).

The cockpit depressions are deep according to Sweeting, with an average depth of 90-120 m, though they may extend to over 150 m deep and have a diameter of upwards of 1 km. The associated residual hills are broadly conical in shape, though some are elongated, 30-130 m high and up to 1 km in diameter. In the larger cockpits, there is a marked break of slope at the base of the hillslope, while in the smaller depressions the floor and sides grade into one another (Sweeting, 1972). Although distinguishing between the depressions and hills of cockpit karst is essentially meaningless, since they are not separate landforms, but integral components of the surface pitting, individual cockpits are described as being surrounded by three or more residual hills of a similar elevation to the depths of the depressions. When the depressions are delimited on the basis of their topographic divides, the surrounding residual hills and ridges connecting the depressions constitute a cellular network (Day, 1979) termed polygonal karst (after Williams, 1971, 1972a). The depression side-slopes are convex, which gives the overall landscape a star-shaped or polygonal plan, though Chenoweth & Day (2001) suggested that there is a range of cockpit morphologies from complex star-shaped patterns to simple circular forms. The cockpits are contiguous with a clearly identifiable col or divide between each depression (Barker & Miller, 1995; Miller, 1998), forming corridors and passages between hills that connect adjacent cockpits, though other divides form saddles, which are less pronounced notches between adjacent hills (Chenoweth & Day, 2001). Canter (1987) estimated a frequency of 15 cockpits per km^2 in the area around Quickstep, with an estimated 20 cockpits per km^2 in the centre of Cockpit Country, totalling about 4,000-4,500 depressions.

The bounding slopes of the cockpit depressions are extremely irregular, although Sweeting (1958) indicated they average about 30°-40°, consisting of chemically weathered and honeycombed blocks and scree. Where bedrock is exposed the sides are steeper and form cliffs and precipices (Sweeting, 1972). Aub (1964a, b, 1974a, b) examined in detail the array of different slope elements associated with the cockpits and recognised six types of hillslope (Figure 5). These were defined by Aub (1964a *in* Sweeting, 1972) as; staircase slopes, comprising small ledges and vertical steps, the latter being up to 2-3 m high and where bedding planes are conspicuous; broken cliffs, consisting of higher steps and less uniform ledges, where the steps are intersected by widened joints; steep even slopes of honeycombed limestone covered with loose talus and blocks; major cliffs, of varying height, but undercut by horizontal notches to depths of 2-3 m and often associated with springs; cliffs of similar height but without undercutting; and scree slopes covered with small limestone fragments.

Chenoweth and Day (2001) identified two major slope types according to their cover, talus and soil covered slopes. The former are the more common and it was suggested that tree-tipping and bedrock disruption as a result of windthrow may play an important role in the development and maintenance of the talus slopes.

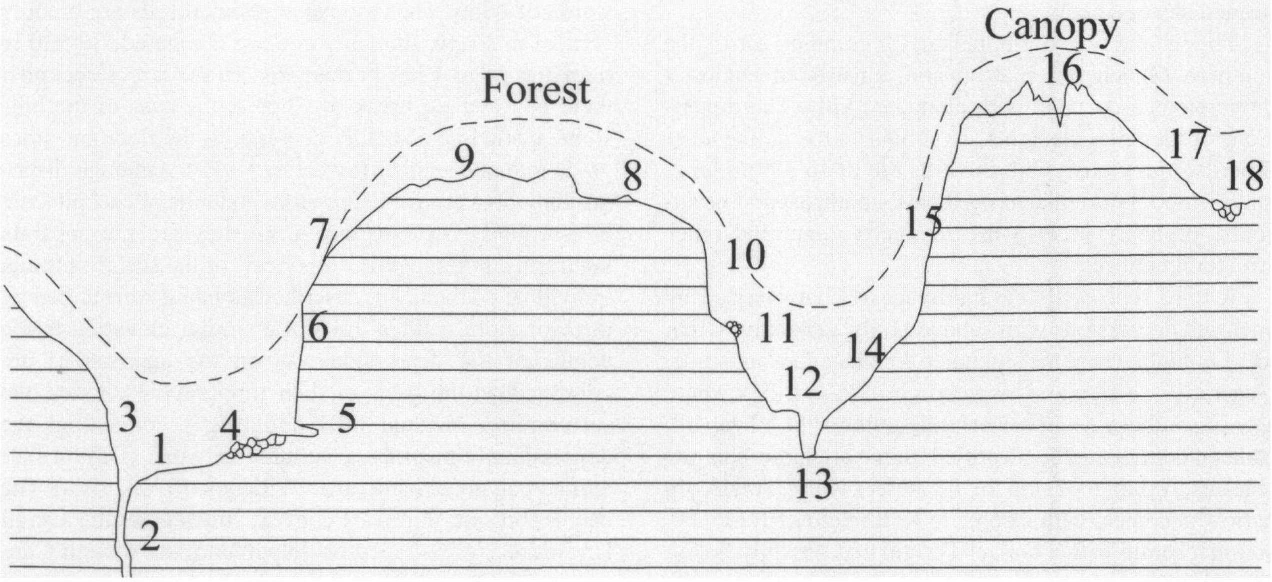

Figure 5. Stylised cross-section of cockpit karst, showing the main elements of relief (from Aub, 1964a *in* Sweeting, 1972). Key: 1 = glade floor, with soil and projecting rock; 2 = vertical shaft, joint-guided sinkhole; 3 = cliff over sinkhole, with gentle solution scallops and other karren phenomena; 4 = scree slope; 5 = undercut notch at base of major cliff and associated with softer limestones; 6 = high cliff with undercut base, with scalloped or pitted surface, often with a case-hardened surface; 7 = steep even slope; 8 = hill summit with projecting rock and loose fragments, some summits are planar, others more conical; 9 = pinnacles summit surface, dissected into pinnacle and cleft 'castles' (may be isolated or in groups and up to 10 m high); 10 = cliff without undercut base, rising from a bench in solid limestone; 11 = staircase slope, consisting of steps up to 3 m high and ledges up to 5 m wide; many of the ledges are undercut and the slopes covered with large limestone blocks; 12 = cockpit floor, covered with soil and boulders; 13 = sinkhole, vertical shaft with rubble floor and solid limestone walls, indicating the cockpit is not a collapse feature; 14 = cockpit floor, with some joint solution and abundant rubble; 15 = broken cliffs, with honeycombed walls, narrow bedding plane ledges and solution-controlled joint plane openings; 16 = pinnacle-and cleft topography, with large boulders; 17 = small cockpit, with soil covered slopes and surface drainage channels; 18 = sinkhole, impenetrable sink among boulders at the lowest end of the drainage channels.

Chenoweth and Day also identified two basic hilltop morphologies in the cockpit karst in the area around Windsor; some are dome shaped and rocky, while other hill summits are flatter in plan view.

Normally, the cockpit depressions and conical hills are more or less symmetrical, but some asymmetry occurs. Two explanations have been presented to account for the asymmetry. The first is related to the dip of the limestones, that is, when it exceeds more than a few degrees, the cockpits become steeper on the up-dip side. The second is differential dissolution rates in response to exposure to the oncoming trade winds, as occurs near the north coast where north facing slopes are less steep (Sweeting, 1958). Similar explanations have been presented for mogote asymmetry in Puerto Rico (e.g., Day, 1978b; Monroe, 1968) and a more thorough discussion of residual hill asymmetry is presented in the section on tower karst. The cockpits and residual hills are often arranged in lines following faults or jointing (Sweeting, 1958) (Figure 4) and the cockpit karst often occurs in the form of winding sinuous chains or ridges separated by glades (Sweeting, 1972) (Figure 6), though elsewhere no structural guide can be identified (Wadge & Draper, 1977b). Aub (1964a) also indicated the cockpits he studied show no apparent fault or joint guide and that the morphology of the slopes and cones is variable.

Smith *et al.* (1972) also stressed that the cockpit areas show considerable variation in morphology and display irregular slope forms, though they have a mean slope angle of about 30°. According to Sweeting (1958), the summits of the hills tend to reach an even level, which she interpreted as a structural surface, or part of a more extensive peneplain surface, dissected by cockpits of variable depth, representing one-cycle and multi-cycle landforms. However, Smith *et al.* (1972) concluded there is no correlation in the elevation of hill summits or depression floors except where the depressions have eroded down to the underlying Yellow Limestone.

Most of the depressions 'drain' towards a deep vertical shaft in their lowest part eroded in solid limestone. In some areas the shafts may have a number of narrow entrances which unite at a relatively shallow depth (Smith *et al.*, 1972). Smith *et al.* indicated that it is possible to gain entry to some of the shafts, though others are blocked by debris or too narrow for exploration, contending that it is rare for the shafts to be explored beyond 30 m depth.

Figure 6. Cockpit karst in the north of Cockpit Country, parish of Trelawny, showing development of dissolution widened glades and pocket valleys (photograph courtesy of Mr Jack Tyndale-Biscoe).

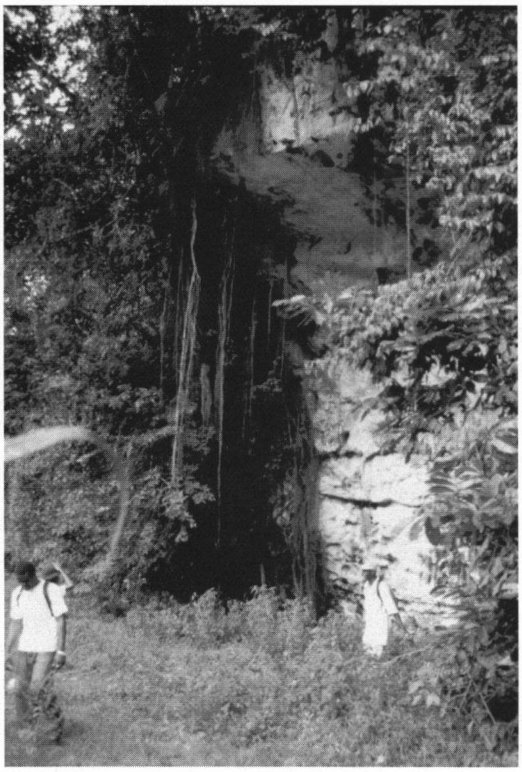

Figure 7. Tower in Troy Formation showing basal undermining, west of Lluidas Vale, parish of St Catherine.

Versey (1972) indicated that many cockpits are floored with boulders, while others have solid floors with vertical sinkholes that connect with deeper horizontal caves. However, Baker *et al.* (1986) explored several of these to depths of 80 m, without intersecting the water table, and Canter (1987), in an attempt to estimate the frequency of pits, indicated they reach up to 70-80 m deep, but without significant lateral passage development with most shafts bottoming out in narrow joints or debris chokes.

Sweeting (1956, 1958) further delimited cockpit karst into two variants which she termed 'true cockpit' and 'degraded cockpit'. According to Sweeting, cockpits become degraded when deepening ceases due to a 'slackening' of solution processes. Degraded cockpits are shallower with slumped and gentle side slopes, the overall relief of the landscape becomes more 'subdued and rolling', and there is a greater dissociation between surface and groundwater circulation (Sweeting, 1958). The basic morphological difference between the two relates to the accumulation of debris within the depression. The bases of 'cockpits' contain little superficial material (Figure 7) and a near vertical shaft is evident, whereas in the 'degraded' form the bases of the depressions are occupied by bauxitic material, commonly up to 10 m deep (Day, 1979). Degraded cockpit karst exhibits a wide variety of forms, in relation to the degree of accumulation of 'soil', from a nearly flat bauxitic plain with occasional protuberances of limestone, through a vermiform pattern of limestone ridges separated by bauxite infills, to cockpits where only the central portions of the depressions are filled with bauxite (Smith *et al.*, 1972).

Versey (1972), as indicated earlier, questioned the use of the term kegelkarst to describe cockpit karst and considered the term to be more aptly applied to depressions which have not undergone 'overdeepening', where the side-slopes are relatively gentle and where the depressions are filled with bauxite. Versey proposed two main terrain types of the karst uplands, cockpit karst and kegelkarst. He considered that 'degraded cockpit karst' represents a cockpit karst which has suffered either uplift or freeing of its drainage.

A number of contrasting observations have been made about the hydrological characteristics of the cockpit karst. Zans (1951b) noted instances in which the depressions are partially flooded following heavy rainfall and similar observations have been made by Sweeting (1958), who noted temporary ponded water, though frequent flooding of cockpits only occurs when they extend near to a level close to underground water circulation. Versey (1962) described the flooding of cockpits after heavy rainfall, where water issues from basal sinks which at other times drain the cockpits, and Aub (1974a, b) noted the presence of small channels leading to a central depression with temporary surface drainage after heavy rainfall. Aub (1964b) found the depressions receive 13-15% more precipitation than the hill summits and suggested that vegetation rafting of rain water into the cockpits by throughfall led to dissolution being greater there. Smith *et al.* (1972) noted that the presence of near-vertical shafts in the bottom of cockpits would suggest surface runoff, but they found no evidence of recent flow in the shafts and no surface runoff, other than in a few locations where a thin soil cover is present, when small channels develop and become locally active. They also found no well developed channels in the degraded cockpits and no evidence of flooding. In contrast, Day (1977, 1979) noted occasional basal ponds in 'degraded cockpits' and small channels cut into the superficial bauxite cover, but not extending onto limestone bedrock, where water disappears by vertical infiltration. Similarly, in the 'cockpits', slow vertical percolation is the dominant hydrological process, no surface flow occurred, either dispersed or in surface channels, the shafts are inactive and essentially relict (Day, 1979).

Surface drainage channels similar to those in New Guinea cockpits (Williams, 1971, 1972a, b) are virtually absent in the Jamaican cockpits and are confined to the superficial cover in the 'degraded' forms. According to Day (1979), the shafts once acted as drains at the foci of surface channels under conditions of either lower secondary permeability and/or a wetter climatic regime. It is highly likely that the vertical shafts developed due to surface drainage and, according to Gardner *et al.* (1987), the vertical shafts in Jamaica may have developed because of the greater relief available, due to more recent tectonics, or because the limestones are more dense than in Puerto Rico, where shafts are seldom found. It could also be the case that shafts in Puerto Rico are obscured by debris.

The hydrology of the cockpits is now dominated by slow and diffuse percolation, which is the only contemporary connection between the cockpit depressions and underground drainage. Day also concluded that the degraded cockpit forms are currently experiencing the greater solutional attenuation as dissolution is focussed beneath the superficial deposits. However, Aub, in a personal communication to Versey (1972), considered that an important difference between cockpit karst and karst areas elsewhere on the island was that there has never been a bauxite cover in the former and dissolution has a more powerful effect than in areas where the depressions are infilled with bauxite, thus inhibiting dissolution and impeding deepening. It is clear that more work needs to be done on the relationship between the bauxite cover and karstification of the limestones, but, as indicated in an earlier section, work subsequent to that of Aub has shown that in most cases the presence of a soil cover enhances dissolution (Trudgill, 1977).

A number of explanations have been given for the origin of the cockpits, but they basically fall into either solution-related or collapse-related categories. The original collapse explanation for the cockpits was presented by Sawkins (1869), where in the first detailed descriptions of The Cockpit Country, the depressions were ascribed to the sinking of water through the cavernous structure of the limestones, which forced its way through and subsequently removed underlying beds of shale and sand of the 'Trappean Series'. The cavities formed were unsupported and collapsed to form the cockpit depression. Some thirty years later, a lengthy reassessment of the geology of Jamaica was published by Hill (1899), who, although there was little descriptive interest in the karst, ascribed the origin of cockpit depressions to dissolution rather than collapse. Daneš (1909, 1914) was the first worker to widely adopt the theory that the cockpit depressions originated predominantly by dissolution of the limestones along fissures and other lines of weakness, though he did concede that they may be further deepened by localised collapse of caves which would help to further enlarge them. Using evidence such as the regular distribution and linear arrangement of the cockpits, together with their dissociation from subsurface groundwater circulation, Sweeting (1958) also concluded that the cockpits are formed by dissolution with subsequent enlargement by collapse along fissures. Versey (1962) suggested that the physiography of The Cockpit Country is closely related to the hydraulic and abrasive action of floodwaters in underground drainage systems, and that solutional and mechanical action of confined floodwaters was responsible for the enlargement of cockpits, along with collapse. Versey also noted that the deepest cockpits occur where underground water movement is close to the surface, and he further refined this theory by suggesting that a rise in water levels during rainfall brings groundwater circulation close to the bottom of the cockpits, eroding them, and that subsequent collapse then deepens the depressions and removes the soil cover (Versey, 1972). According to Versey, if the cockpits have developed over a long period of time, then the rate of erosion has matched the rate of uplift. In areas where uplift has been more rapid, water circulation becomes too deep to be effective, then dissolution takes over as the main erosive process and a soil cover develops in the depressions leading to the development of 'degraded cockpit karst'.

Other workers have suggested that dissolution alone is responsible for cockpit formation. Aub (1964b) suggested there is very little evidence of any widespread collapse or mechanical action, and that there is no correlation of cockpit shape or size with height above the underground drainage. Aub further indicated that the depressions receive more throughfall than the hill summits and suggests that solution could be greater in the depressions which makes them self-perpetuating features. Aub also attempted to link the development of 'degraded cockpits' and the occurrence of bauxite, where he considered that the shallower cockpits are the result of greater sediment deposition within them, and they are associated with parts of the Central Inlier that were breached first. He further suggested that if this were the case then the 'degraded cockpits' may not be a development from 'normal' cockpits, but have a different history. Smith *et al.* (1972) and Day (1979) also supported a dissolution origin for the development of cockpit karst.

Two geomorphological aspects of the cockpits which have been largely overlooked are the importance of mechanical breakdown to their development and modification, and possible fluvial inheritance. Many of the cockpit slopes are strewn with angular, block- and boulder-sized talus and scree which cannot be explained by simple dissolution processes, and the importance of mechanical breakdown actively modifying the landscape has been understated. These talus-strewn slopes may be the result of bedrock disruption by the windthrow of trees (Chenoweth & Day, 2001), while dissolution along joints and bedding planes could increase the susceptibility of the cockpit slopes to rockfall. Some of the cockpit depressions have a beaded arrangement, others are linear in nature, while the cockpit karst landscape often occurs as winding chains or ridges separated by sinuous channels and glades, particularly at the margins of The Cockpit Country. The geomorphology suggests a possible fluvial inheritance to the cockpit landscape, at least in some parts. Aub's (1964b) suggestion that 'true' and 'degraded' cockpits have a different evolutionary history also requires further investigation.

From the foregoing, it is clear that cockpit karst has a wide variety of form and several interchangeable terms have been used to describe the landscape, including 'cockpits', 'kegelkarst' and 'cone karst', while 'true' cockpit karst and 'degraded' cockpit karst were additionally introduced to differentiate between cockpit depressions devoid of, or with a soil and debris cover. Pfeffer (1969, 1984) identified distinct variants of cockpit (Kegelkarst) in southwest Jamaica and, more recently, Miller (1998) mapped three principal classes of cockpit karst in The Cockpit Country between Windsor and Troy, based on the size and shape of the intervening residual hills (Figure 8). The three types are: cockpits with conical hills; cockpit depressions with small elongate hills up to 50 m high, aligned in a general north-south direction, probably along faults and major joints; and depressions with larger elongate hills in a beaded arrangement, grading into ridges. A recent survey of 'cockpit karst' terrain in the south of the island, in parts of Westmoreland, southern St Elizabeth and Manchester (Sir William Halcrow & Partners, 1998), classified the cockpit landscape based on the presence or absence of an integrated surface drainage pattern across the terrain, on the size and shape of the intervening hills and on the extent of the enclosed depressions, especially whether or not they contain a residual soil infill. In this study, an area of cockpit karst to the east of the Cabarita River, parish of Westmoreland, is associated with ephemeral drainage lines, comprising gullied slopes and dry, short valley systems, often draining to larger interior valleys and poljes. Most of these drainage lines are probably inactive and the landscape is partly relict terrain.

Versey (1972), as indicated earlier, suggested that the term 'kegelkarst' is an inappropriate term for the over-deepened cockpits within The Cockpit Country heartland, and that it is more appropriate to use the term for the 'degraded' cockpits around its margins. It is evident that the terminology used needs to be cleared up, and to help overcome terminological confusion some workers have turned to morphometric analysis to develop a more objective classification of the terrain (e.g., Day, 1979, 1982). This and other morphometric approaches to the study of cockpit and other karst terrain types in Jamaica will be discussed in a later section.

Tower karst

Lehmann (1954) described the geomorphology of tower karst (Turm karst or Mogote karst) in Jamaica, which comprises a landscape of residual hills scattered across a relatively flat plain (Figures 9, 10). Some of the residual towers are isolated and others occur in groups. They occur on the crystalline White Limestones, but tower karst is much less widespread than cockpit karst (Sweeting, 1958) (Figure 2). According to Sweeting (1958), towers are steep-sided hills which slope up to 60°-90°, rising up to 100-150 m above a flat alluvial plain. The towers are subconical, though many have flattened tops and appear tabular in profile. The tower slopes are frequently broken and devoid of a soil cover, except for isolated pockets. Many tower bases are undermined and display undercut notches associated with well-developed foot-caves and springs (Figure 7). A well-developed ring of sinkholes, which often become flooded in the wet season, commonly occurs around the base of the undermined and over-steepened towers. Indeed, some of the towers are situated in small enclosed depressions, similar to those described on alluvial plains in Belize (McDonald 1975, 1976).

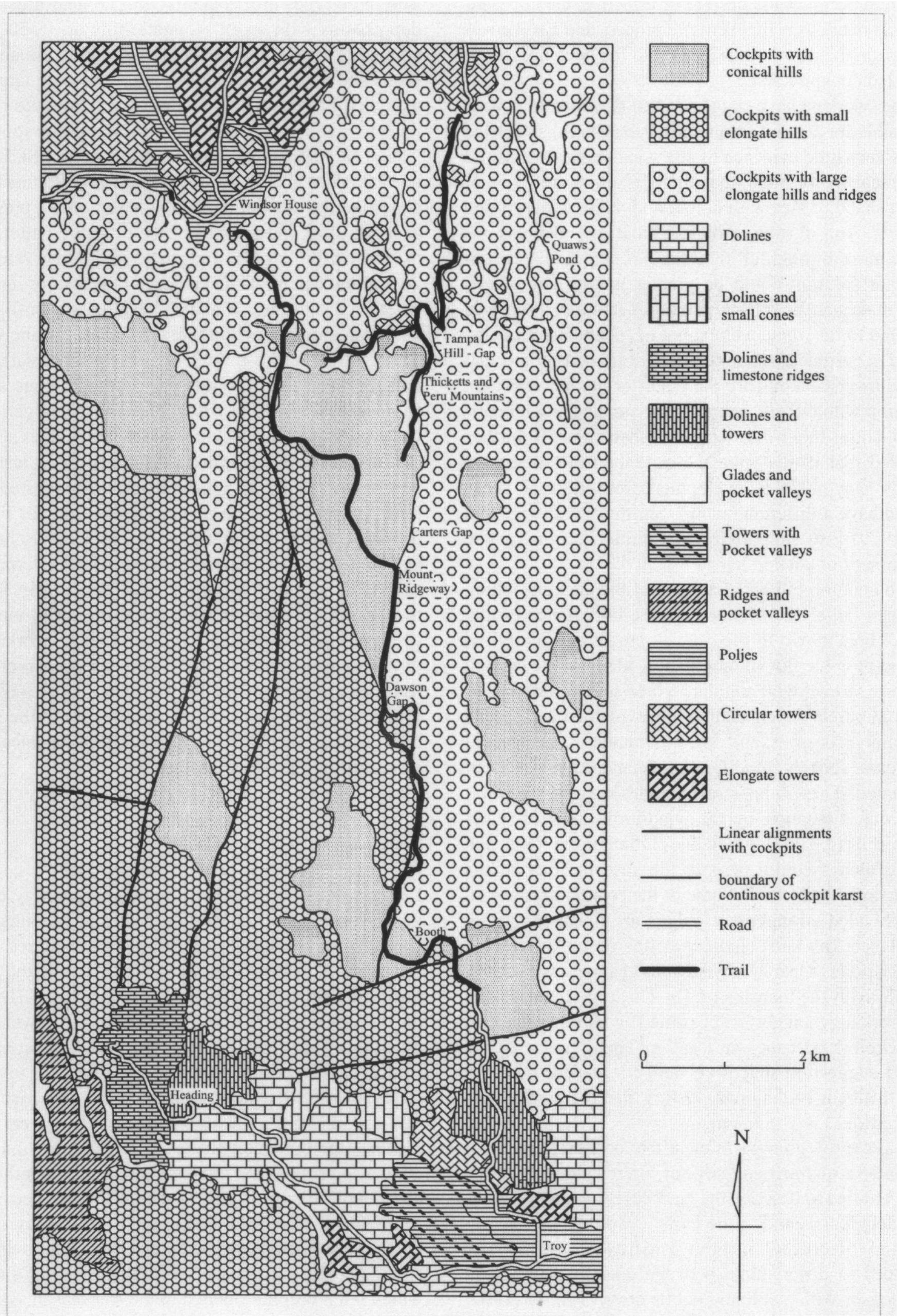

Figure 8. Geomorphological map of the area of Cockpit Country between Windsor and Troy, parish of Trelawny.

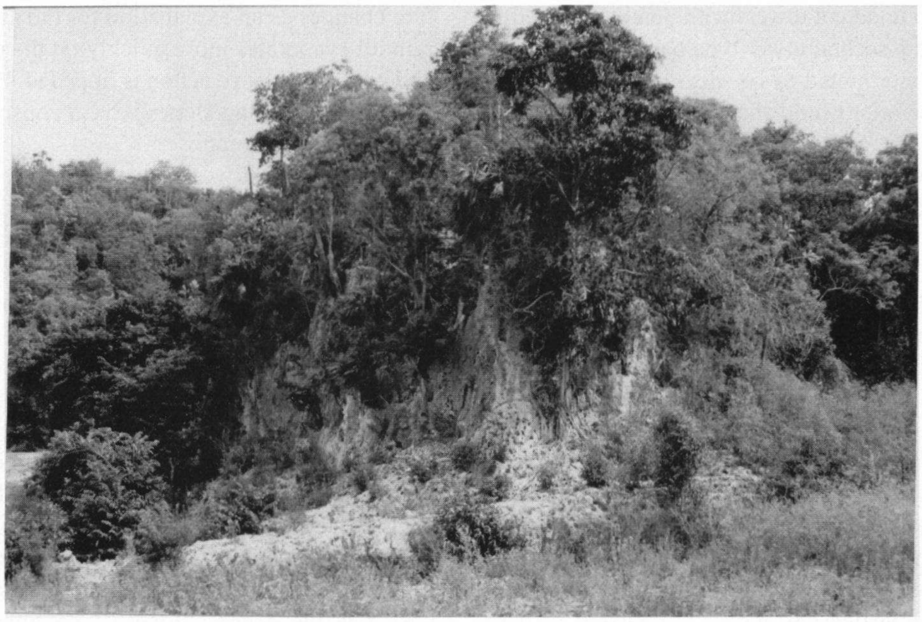

Figure 9. Tower karst in Moneague Formation with basal pedestal in plane limestone, south Manchester Plateau, parish of Manchester.

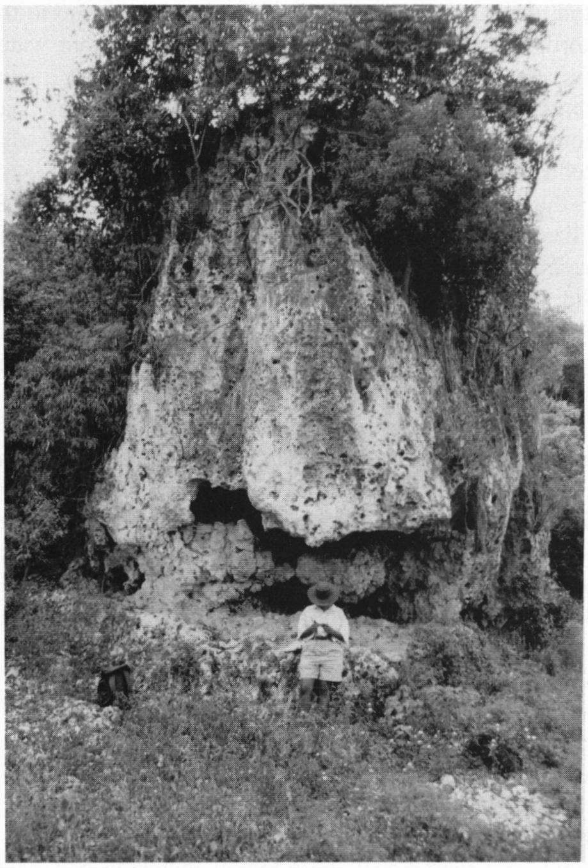

Figure 10. Case hardened tower karst in Moneague Formation, south Manchester Plateau, parish of Manchester.

According to Sweeting (1958), two particular geological conditions favour tower karst development. They occur near to the base of the White Limestone at the junction of the Yellow Limestone and within the crystalline facies of the White Limestone Group in close association with the marly Montpelier Formation. They are also associated with rapid spring-head recession, which gives rise to the flat-floored, steep-sided and steep-headed 'pocket valleys' which accompany tower karst on the northern margins of Cockpit Country (Sweeting, 1958). Sweeting (1972) further identified two main types of tower karst, which both occur within the White Limestone Group. One type of tower occurs as a visible remnant of limestone surrounded by alluvium, beneath which is a planed limestone. The other tower type is developed on a plain of non-limestone rocks, as occurs where towers within the White Limestone form outliers on the much less pure Yellow Limestone, though they may also occur where the White Limestone is in faulted contact with older Cretaceous rocks, especially in the Central Inlier. Draper & Fincham (1997) indicated that isolated towers of White Limestone formed by erosion down to the less soluble Yellow Limestone or older Cretaceous rocks are best developed around Maroon Town, on the western edge of The Cockpit Country, while the other tower type, with residual hills protruding through an alluvial blanket in a glade, polje or plain is well developed in the Cave Valley area and on the western edge of Lluidas Vale. Draper & Fincham (1997) have observed many examples of shelter caves at the base of the towers, with solutional pockets and anastomoses, suggesting solutional undercutting at the base of the towers.

In addition to undercut towers with notches, Sweeting (1958) identified a second tower type based on morphology, which she interpreted to be 'degraded tower karst' (Figure 2). These are towers where the lower slopes display slumped sides, and the sharp break of slope at the undercut between the tower base and alluvial floor disappears, resulting from a decrease in limestone dissolution at the foot of the tower due to a cessation of flooding of the alluvial area.

Some towers show little evidence of undermining, and contain colluviated footslopes or aprons of blocky limestone talus and scree, sloping upwards of 25°-30°. These are seen on the western edge of Lluidas Vale at higher altitudes than the current level of alluvial cover within the vale. They may be similar to towers at interfluve locations in Belize, where McDonald (1979) showed that the morphogenesis of towers located on interfluvial plains is controlled by the progressive lowering of the alluvial surface by erosion due to overland flow, and the tower-base landforms revealed are gentle, colluviated or bare bedrock footslopes. As the interfluve plains are eroded and lowered, bedrock slopes are formed around the towers with a slope angle approaching 20°-60°, which rise to meet the base of cliffs about 10-50 m above the surrounding plain. The towers on the interfluve plains are therefore not the result of tower undermining and lateral planation, but are formed by the vertical dissection of the plain sediments.

The most common tower karst in the White Limestones involves residual hills protruding from either a planed carbonate surface veneered by alluvium or from an alluviated surface burying a pinnacled limestone. Many of the towers have been case-hardened and two morphological types of tower associated with an alluvial infill from allogenic streams can be recognised, namely circular and elongate (asymmetric) towers. Both types of tower are formed by laterally directed solution at or near to the water table, coupled with aggressive floodwaters from allogenic rivers. Symmetrical (circular) towers are commonly up to 100 m elevation and 1 km in diameter with steep, almost vertical slopes and with associated sinks and depressions around their bases. They may occur singly or in small clusters. Asymmetrical or elongate towers tend to be larger and can be over 1 km long with a length to width ratio in excess of 2.0. Asymmetric towers occur where one slope facet exceeds the opposite aspect by more than 20°. There is no general trend in terms of the orientation of elongate towers, but where they occur in clusters across the south of the island, their broad arrangement is northwest-southeast and north-south. Elongate towers occur on the slopes to the west and north of Alligator Pond and around Bull Savannah, with an east-west asymmetry, where the west-facing slope is steeper than the slope on the eastern side. These tower-like hills were described by Pfeffer (1967) as being only about 10-12 m high, with striking east-west asymmetry, where the west facing slope (60°) is about 25° steeper. Pfeffer suggested aspect related moisture changes as an explanation for the asymmetry, where rainfall evaporates more quickly on the east-facing slope and with it corrosive action is impeded. Pfeffer also noted that the west-facing slopes have a conspicuously thicker case-hardened caprock.

Similarly, east-west tower karst asymmetry in Puerto Rico has been linked to the dominant wind direction and resultant differential dissolution and reprecipitation of calcium carbonate. Gentler slopes on the eastern sides of towers have been related to the increased exposure to rainfall and dissolution (Thorp, 1934), while the asymmetry has also been linked to variation in the extent of case-hardening (Monroe, 1966, 1968). In this case, the rim of indurated caprock is thicker on the eastern side and the thin case-hardened surface on the opposing slope tends to spall-off the slope, leaving a vertical cliff and overhanging slopes. Day (1978b), in a study of the mogotes on the Aymamon Limestone in northern Puerto Rico, showed that tower asymmetry is not as simple as previously suggested, as the steepest slopes do not always occur on the western side of the towers, but are found at different locations around the towers, including many towers that displayed a north-south asymmetry. Day linked the asymmetry to concentrations of sinks in particular locations where tower slopes became undermined by both corrosion and mechanical action. The geological dip is also to the north in this area and it might be expected that water movement would be in that direction, leading to a concentration of sinks on the steeper southern slopes. Day considered that the general dip of the strata may also contribute to the asymmetry, though this is generally <5°. In the case of the towers near Bull Savannah, parish of St Elizabeth, Jamaica, the present author considers the asymmetry is related to the dip of the limestones, which dip about 10°-15° to the east and southeast. Thus, the steeper slope facet is on the up-dip side of the tower and suggests a strong structural control in the morphogenesis of the towers.

Small towers, from 5 to 20 m high and 100 m or less in diameter, together with asymmetric and elongate forms similar to the Pepino hills of Puerto Rico, are common on the plateau surfaces and slopes of southern Manchester and southern St Elizabeth, developed chiefly on case hardened Moneague Formation limestones. They were described by Pfeffer (1967), where small isolated towers are associated with corrosion surfaces and what he termed Kuppenruinen (which literally means ruined hilltops), which are basically small towers up to 8 m high and <100 m in diameter (Figure 11). The towers in this area are unusual in that they are not associated with low-lying alluvial plains close to base level. Pfeffer (1975, 1997), through relief analysis near Mandeville and Alligator Pond, considered that the karst in that area had been uplifted during the Quaternary, when they were lifted well above the regional groundwater table. The mode of formation of these towers is still uncertain, as some are oversteepened with footcaves, indicating active or relatively recent undermining, whereas other towers, in the same area, rise above small limestone pedestals (Figures 9, 10). The towers are probably the product of vertically directed dissolution processes rather than corrosional planation at or near the water table. They are therefore similar in origin to towers in northern Puerto Rico, where there is a concentration of water within the coversands at the base of the towers and vertically directed solution controlled by the presence of depressions and sinkholes, concentrating erosion at the tower base (Miotke, 1973).

Some of the towers on the plateau surfaces and slopes above local base level in southern St Elizabeth seem to be aligned and are separated by corridors where the topography is less marked. The tower alignments correspond to major joint directions. They may have evolved in a similar fashion to the giant grikeland or labyrinth karst in the Nahanni region of northern Canada (Brook & Ford, 1978), where joint controlled grikes are opened up by dissolution to form enclosed depressions with steep, residual towers up to 50 m high, emerging from a developing, uneven karst plain. The corridors between the aligned towers may be similar morphogenetically to the zanjones of Puerto Rico (Monroe, 1968).

Ridge karst

A number of limestone ridges have been recently reported across southern St Elizabeth and to a lesser extent on the Manchester plateau, in the Moneague Formation limestones (Sir William Halcrow & Partners, 1998). They were initially described by Pfeffer (1967), who noted a range of narrow ridge-like horsts and what he termed Kalkrippen (limestone ribs), commonly associated with karst corrosion surfaces, to the south of Nain, southern St Elizabeth (Figure 11). Versey (1972) also noted the occurrence of 'fault-line ridges' associated with low-permeability faults that have resisted erosion, though he did not indicate their precise location. The karst limestone ridges in the parish of St Elizabeth are up to 4 km long, but more commonly 0.5 to 2 km, and from <50 to 300 m wide, with heights ranging from <5 to 40 m. Some are topped by limestone exposures in the form of rock walls. They occur across a variety of geomorphic settings on plateau surfaces, slopes, broad depressions and on valley floors. They particularly occur in topographically low-lying settings to the south of Burnt Savannah, parish of St Elizabeth and to the east of Santa Cruz, where they disappear northwards beneath the swamps of the upper Black River morass. They are also associated with a range of other karst landforms, including dolines, elongate hills, large uvala-like enclosed depressions, dry valleys and tower karst.

Many of the ridges are broadly symmetrical, though others are asymmetrical across their axes. Most are aligned roughly along northwest-southeast and northeast-southwest axes, probably in response to major joint and fault trends. A second set of predominantly east-west trending ridges displaces the north-south ones, in the area between Top Hill, Ballards Valley and Bull Savannah, parish of St Elizabeth. The development of the limestone ridges appears to be related to the prominent faults, where the faulting leads to a marked resistance of the limestone around the fault to weathering. The exact mechanism of their formation requires more detailed investigation, although Versey (1972) attributed this resistance to dissolution as a result of reduced permeability around the fault.

Glades

Glades were first described by Sweeting (1958) as elongated and enlarged cockpit depressions, similar to uvalas, where individual cockpits extend by growth along lines of jointing and faulting, and coalesce to form more complex forms along a well-defined tectonic line. Glades and cockpits tend to merge into one another (Sweeting, 1972). Sweeting indicated that Barbecue Bottom (Figure 12), in the northeastern part of Cockpit Country, is a typical glade formed in such a way along a northnortheast-southsouthwest-trending fault line. According to Sweeting (1972), glades are sinuous depressions with concave and angular contours, and are steep sided. The floors of glades also tend to consist of a series of shallow basins being separated by low divides which are much shallower than the passes leading out of the glades. Sweeting also indicated the contrasting drainage of cockpit depressions and glades, in that drainage of cockpits tends to be toward the centre, whereas drainage in channels on the floor of the glade often disappears into caves and sinkholes at the margin of the glade. Glades have also been described as broad areas between residual hills that can individually be classified as either compound depressions, such as uvalas, or as dry and underdrained valleys (Chenoweth & Day, 2001). Accordingly, their cross-profile may be flat, convex, concave or undulating, and in plan view their shapes are either linear or sinuous. According to Chenoweth and Day, many glades have thick soils and when left undisturbed they support large trees and dense vegetation.

Poljes

Poljes are large, flat-floored, enclosed depressions in karst terrain, commonly with ephemeral or perennial streams flowing across their surface (Ford & Williams, 1989). Poljes have three diagnostic criteria (Gams, 1978): a flat floor in solid rock or unconsolidated sediments such as alluvium; a closed basin bordered by a rim of steep marginal slopes, though the steep slope may be restricted to one side of the polje, with an abrupt break of slope between the floor and sides; and karstic drainage with stream sinks, especially at the margins of the polje.

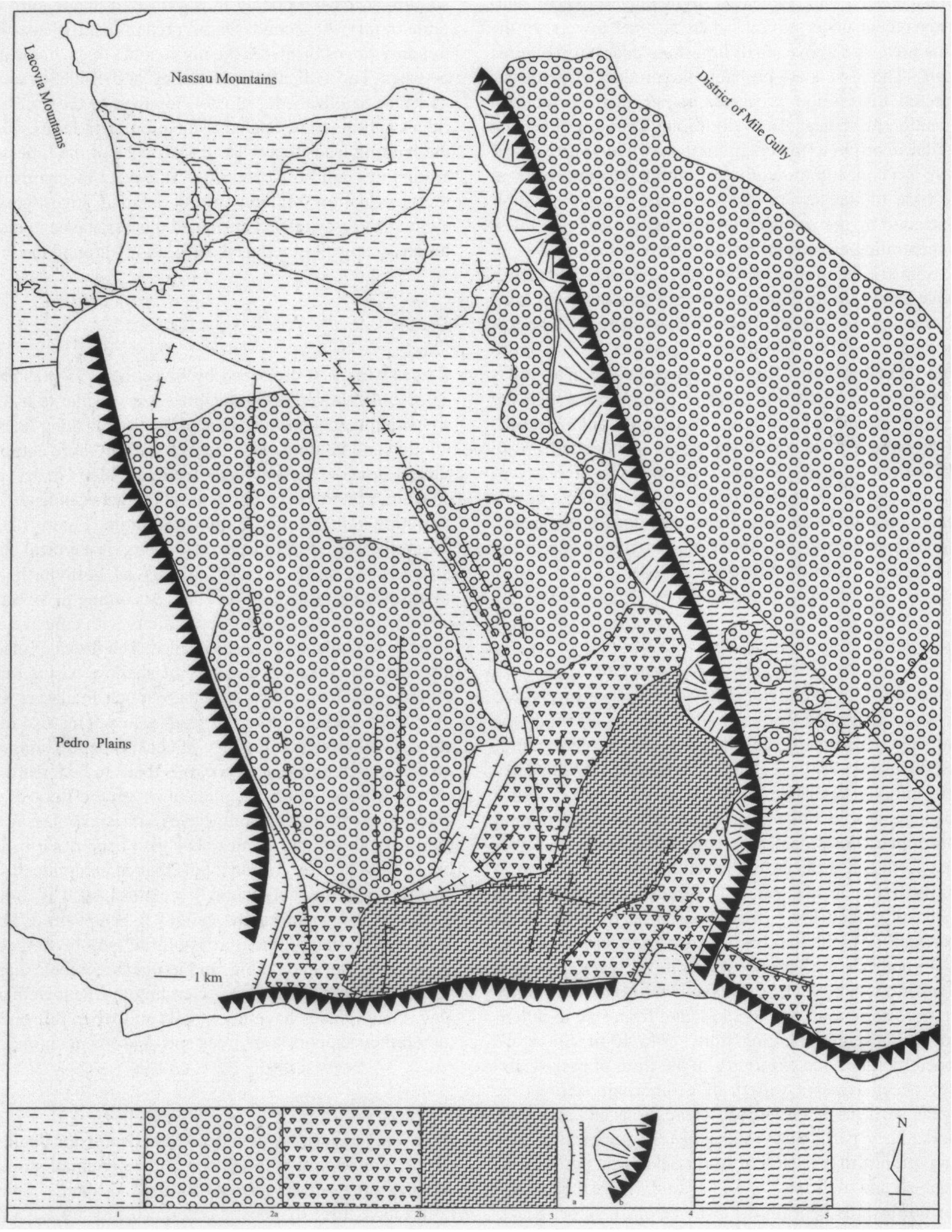

Figure 11. General geomorphological map of southwest Manchester and southeast St Elizabeth (redrawn from Pfeffer, 1967). Key: 1 = karst marginal plain - alluviated karst plain (Karstrandebene); 2 = cone karst (Kegelkarst): (a) residual hills up to 30-50 m elevation, high relief on gentle slopes; (b) tower-like residual hills, up to 8-12 m elevation; 3 = corrosion surface (Korrosionsfläche); 4 = (a) small steps, narrow ridge-like horsts and limestone ribs (Kalkrippen); (b) escarpments and landslides; 5 = karst plateau (Karstebene).

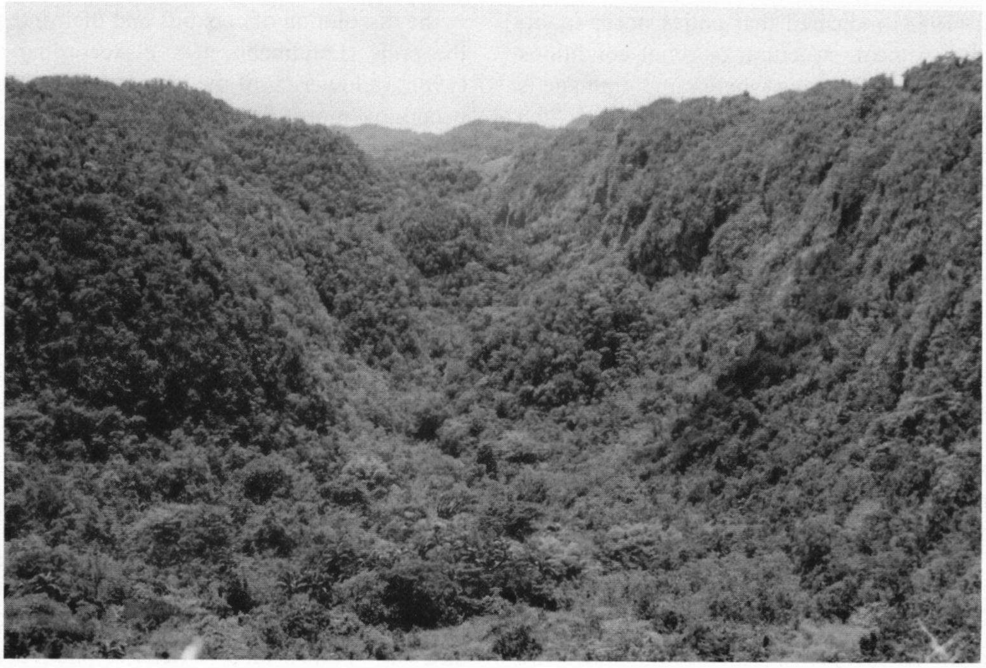

Figure 12. Glade at Barbecue Bottom, northern Cockpit Country, parish of Trelawny.

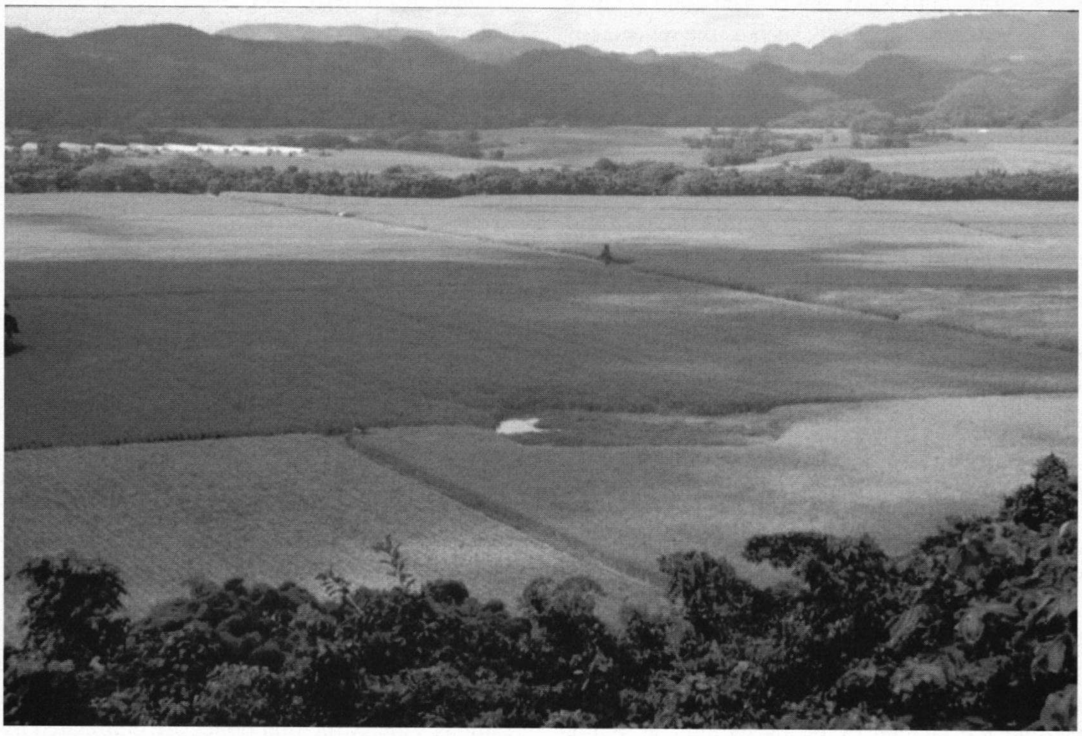

Figure 13. Polje at Lluidas Vale, parish of St Catherine, displaying gently undulating floor with subsidence doline and steep-sided rim in part due to faulting.

The poljes or 'interior valleys' of the island have been described in general by Sweeting (1958) and Versey (1972). Specific poljes have also been studied in more detail, especially The Queen of Spain's Valley (Pfeffer,

1986) and Lluidas Vale (Landmann, 1985, 1990) (Figure 13). Sweeting (1958) indicated that poljes occur in Jamaica where lithological, structural or relief conditions permit flood water to collect and where rapid drainage is impeded. Accordingly, they are conspicuous along the northern margin of Cockpit Country, where lateral water movement is promoted by the Montpelier Formation chalks, and on the northern side of the Duanvale fault zone (Sweeting, 1958). Sweeting (1958) also noted poljes to be common where the White Limestone Group comes into contact with the older Yellow Limestone Group, where flood water can be ponded due to poor drainage through the older rocks. Sweeting (1958) further suggested that, as the poljes across the island occur at a range of elevations, local water table fluctuations were more important to their development than regional variations. She also noted the occurrence of drained poljes where flooding is absent or occurs infrequently due to changing hydrological conditions and marginal poljes (border poljes) where they are not completely surrounded by White Limestone.

According to Versey (1972), all of the poljes are structurally controlled in their entirety and there is no evidence to suggest an erosional origin. They are downfaulted on at least one side and the character of the faulting tends to impede drainage, which forces groundwater to the surface during high water stages. The drainage may be impeded by a structural control, such as the reversal of dip, by the upfaulting of the karst base (Gardner *et al.*, 1987), or by an abrupt decrease in limestone permeability (Versey, 1972). Some poljes are prone to alluviation during flood events, especially in low-lying areas, while in others the alluvium is being dissected. In some poljes, the up-slope part of the valley is periodically flooded and subject to deposition of alluvium, while the down-slope area carrying floodwaters to sinkholes is being dissected (Versey, 1972). The poljes are generally linear, with the long axes perpendicular to overall direction of groundwater flow (Gardner *et al.*, 1987). Versey (1972) described some of the best known poljes on the island including the Nassau Valley and the interior valleys of northern Trelawny. He considered that faulting and folding within the Nassau Valley forms a barrier to drainage and forces groundwater to the surface, which causes periodic flooding and leads to the deposition of alluvium. In describing the valleys of northern Trelawny, Versey (1972) indicated that the structural barrier which impedes the northerly flow of groundwater, leading to a series of springs, is a combination of an upfaulted block of Yellow Limestone beneath the valleys and the change of facies within the White Limestone from the crystalline and rubbly limestone to the Montpelier Formation chalks.

According to Landmann (1985), lateral planation was responsible for the development of the polje at Lluidas Vale. The process takes place at the border of alluvial fans on the floor of the depression and in small areas in a neighbouring cone karst area to the southwest of the Vale. Lateral planation at the margins of the polje has resulted in the dissolution of cockpits and their integration within the polje (Landmann, 1985). According to Landmann (1985), a lowering of the base level has lead to the polje becoming more dissected, forming channels and sinkholes. At present the permanent water table is at some depth beneath the polje surface and it is more likely that local perched water tables within the alluvium account for lateral planation after heavy rainfall. Landmann (1990) further developed his theory of polje formation at Lluidas Vale in relation to changing climatic regimes. He attributed the landforms around Lluidas Vale to different climatic regimes, in that intensive weathering conditions in the 'Neogene' formed etch-plains and cone karst surrounding much of the Vale, while alluvial fans and dolines in the Vale represent drier climatic conditions and a lower intensity of weathering in the Quaternary. According to Landmann (1990), the polje is the result of lateral expansion of the limestone at or near the water table and began as 'the meandering canyon of a river'.

Pfeffer (1986) described the Queen of Spain's Valley as a large polje with an extensive plain, about 90-100 m elevation, surrounded by higher relief. To the south, the valley is bordered by steep limestone hills which rise abruptly to form cockpit karst; to the north, east and west, the polje gives way to limestone hills and dolines. According to Pfeffer (1986), the polje floor is dissected by dolines, which may contain shallow ponds, and many karst springs rise on the polje floor near to the southern border to flow northwards as the Roaring River and Martha Brae River systems. Pfeffer (1986) interpreted the landforms of the Queen of Spain's Valley and the surrounding karst landscapes as the result of different relief generations, possibly influenced by tectonic uplift and climate change. He considered that the polje and the surrounding cockpit karst are Tertiary landforms, and that subsequent Quaternary uplift and climate change led to the development of the dolines, dry valleys and subdued limestone hills forming the northern border of the polje, a similar interpretation to that of the evolution of Lluidas Vale given by Landmann (1990).

In Jamaica, the three basic types of polje outlined by Ford & Williams (1989) can be identified, these being border, structural and base-level poljes. Border poljes receive allogenic drainage from a non-carbonate area and are therefore not bordered on all sides by limestone. The valley floor contains a number of allogenic streams which bring alluvium onto the polje and eventually disappear at stream sinks (ponors). A typical border polje occurs at Lluidas Vale. Structural poljes are dominated by geological control and associated with graben or fault angle depressions formed by block faulting. Structural poljes are common across the White Limestone. Base-level poljes are common to the north of Cockpit Country, though here they are also associated with faulting. Base-level poljes are water table dominated where the regional epiphreatic zone reaches the surface. They are typically located on the outflow side of the karst drainage, which partly explains their occurrence to the north of Cockpit Country.

Incipient (weakly developed) karst terrain

There are a number of upstanding massifs within the White Limestone Group, mostly across the southern sections of Jamaica, where karstification is restricted to small-scale dissolution sculpturing, about 1 to 2 m deep, extending to a maximum of about 5 m, accompanied by the development of a case-hardened surface. They are also often covered by limestone talus and scree, and may have limestone debris fans on their lower slopes associated with dry valley systems and gullies. Uncommon sinkholes, collapsed dolines and ephemeral surface drainage lines are associated with the incipient karst surfaces of these limestone massifs. Typical locations include the Dallas Mountain, Long Mountain, Hellshire Hills, Brazilletto Mountains, Portland Ridge, Kemps Hill, Round Hill and Great Goat Island. Although they have poorly developed surface karst, some of the massifs have well developed cave systems, such as the Jackson's Bay Great Cave on Portland Ridge (e.g., Fincham, 1997). The poor surface karst development on these massifs could be a factor of the duration that they have been exposed to sub-aerial weathering processes, with most having been uplifted in relatively recent geological time.

Karst surfaces of low relief (buried karst)

Both buried and exposed karst surfaces of low relief are extensive in the upper and lower morasses of the Black River. This area was described by Pfeffer (1967) as a karst marginal plain (Karststrandebene) (5), which is basically an alluviated karst plain. Karst surfaces are also exposed above the blanket of alluvium in the Cabarita River immediately west of Savannah-la-Mar, where the north-south alignment of the exposed surfaces may be a response to a structural control. Karst surfaces of low relief also occur around Little London, parish of Westmoreland, where they are associated with a thin alluvial cover and numerous enclosed water-filled depressions.

Many of the karst surfaces may be a legacy of a former polje surface, now covered by alluvium and wetlands, such as the lower morass of the Black River (Grontmij, 1964; Pfeffer, 1967). An alternative explanation is that they represent partially buried base level corrosion plains, while allogenic rivers flowing across the former polje aided in the planation process by periodically introducing large volumes of aggressive floodwaters. Corrosional planation may have also been encouraged by the sandy bedload of the rivers. In addition, overbank deposition would stimulate biochemical activity on the floodplain and, through the production of soil carbon dioxide, would enhance soil water impacts. Many of the karstic surfaces are associated with residual tower karst emerging above the alluvial cover.

Limestone valley systems and other fluvio-karst

Dry and ephemeral limestone valley systems and limestone gullies are quite common across the White Limestone Group outcrops over the island, but very few have been described in detail. Allogenic streams, blind valleys, steepheads and pocket valleys also occur, the latter having been described by Sweeting (1958) from around the margins of northern Cockpit Country and were further briefly examined by Miller (1998). Gullies and gorges are common on the limestone outcrops to the south of the island, and are an expression of ephemeral drainage or may in some cases be relicts of wetter periods in the recent geological past. Gullies drain the southern part of the south Manchester plateau, especially in the Robert's Run-Sixteen Mile Gully area. Some of the gullies on the southern end of the Manchester plateau are associated with alluvial fans that have been slightly displaced by faulting, suggesting that the faulting is a relatively recent occurrence, though no detailed work has been undertaken to date.

Day (1985) examined the limestone valley systems along the north coast, particularly where they are well developed between Discovery Bay and St Ann's Bay where seventeen major valley systems extend up to 7.5 km inland. Streams in these valleys range from permanent to mostly dry, except at times of intense or prolonged rainfall, while others show alternate wet and dry reaches. The headwaters of the most extensive valley systems are located in the so-called Browns Town-Walderston formations (now the Moneague Formation; Mitchell, 2004), though much of their valley length is across the Montpelier Limestone, and they are associated with a series of gravel fans of Quaternary age near to the coast. Day investigated the geomorphology of the valleys and examined their morphometric properties, including drainage density, valley order and orientation. Two distinct valley orientation concentrations were shown, one virtually normal to the present coastline (north-south), and a second which parallels the coast (east-west). Day compared the valley systems with similar dry valleys developed on the raised reefs in Barbados (Fermor, 1972) where the drainage pattern was attributed in part to the effect of raised reef morphology on drainage extension across the reef during surface runoff under wetter conditions than present. Day indicated that the Barbados model can only be invoked for the valley sections across the raised reefs and that the east-west valley orientations are structurally controlled due to east-west faulting in the Duanvale Fault Zone. Control on the north-south valley trends is less clearly explained, but Day considered that they may either be joint controlled in a similar way to zanjones in Puerto Rico or be related to north-south faults.

Smith & Atkinson (1976) described the landscape developed on the Montpelier Limestone as a fossil fluviokarst with a well-integrated dry valley network. Day (1985) considered the valley systems to be fossil in that certain of their components may be attributed to past conditions and that they are undergoing little or no development under most present conditions, though during prolonged or intense rainfall they are fully active, so it would be incorrect to describe them as totally fossil. The extensive gravel fans on their lower reaches were also taken to indicate greater transport ability in the past. Day (1985) examined the sources of runoff within the valleys, which comprise two components, surface runoff after rainfall and water supplied by underground drainage sources, the latter providing the baseflow for the permanent streams. Some of the baseflow is supplied from adjacent enclosed depressions and sinkholes via springs within the valley courses (Day, 1976, 1978a, 1984), though much is derived from the limestone and non-carbonate areas to the south of the valleys. The dominant formative mechanism for the valley systems was thought to be fluvial erosion rather than karst solution (Day, 1985).

Miller & Donovan (1999) examined the Natural Bridge at Riversdale, parish of St Catherine, which occurs in a small gorge cut into limestones of the Somerset and Troy formations. The bridge spans a 20 to 22 m section of the Rio Doro channel and is 17 m high with a distinct limestone bed forming the roof span. The natural bridge was inferred to be the result of partial roof collapse of an underground river system, while river capture may also have contributed to its formation through the work of a more aggressive lower base-level capturing stream. Miller & Donovan further suggested that initial collapse probably formed karst windows that were subsequently connected by more complete collapse to form the gorge.

Cave systems and underground rivers

A summary of cave exploration and the development of speleological studies within Jamaica was presented by Fincham (1997). The first detailed speleological studies of cave systems within the White Limestone Group were published in the 1950s (*e.g.*, Zans, 1951b, 1953, 1954a, b, 1958a, b, 1959). White & Dunn (1962) indicated that the largest caves appear to be single cave passages with little or no branching. Brown & Ford (1973) investigated the caves and associated groundwater patterns in northern Jamaica, and the hydrological link between the Quashies River sink and the Dornock Head rising.

Sweeting (1958) suggested that most known caves in the White Limestone Group are located in two main stratigraphic locations: first at the contact between the lower formations of the crystalline White Limestones and the top beds of the older Yellow Limestones (Troy Formation/Chapelton Formation); and, secondly, at the zone of contact between the Montpelier Beds (Montpelier Formation) and the crystalline White Limestones. Sweeting (1958) further indicated that most cave passages are fairly long, with tunnel-like cross-sections and undulating floors due to the common occurrence of roof-fall debris (breakdown), though for the most part gently inclined passages predominate similar to the generally shallow gradients of underground water flow.

According to Draper & Wadge (1997), most of the explorable caves occur in the shallow water limestones which are commonly crystallised to at least 40% sparite. There is also evidence to suggest that the sparite-rich limestones are more resistant to solution than the micritic limestones with low sparite content and tend to produce cave passages that are taller than they are wide and are more strongly joint controlled (Wadge & Draper, 1977a).

Wadge & Draper (1977a) investigated the size and shape of cave passage cross-sections in several formations of the White Limestone Group. They found that most caves of great length occur in the oldest Troy Formation (and in the Chapelton Formation of the Yellow Limestone Group), associated with allogenic rivers flowing off the Cretaceous inliers to form stream sinks. Thus, the large cave passage lengths encountered in these formations may be under stratigraphic rather than lithologic control, related to water flow routes. Wadge & Draper (1977a) further indicated that cave passage cross-sections within the Troy Formation are typically rectangular in shape, indicating a strong bedding-plane and joint control. The biggest cave passages occur in the Swanswick Formation, typified by huge, single-passage dip-tubes formed along major phreatic routes, possibly related to the massive bedding and lack of jointing within this formation (Wadge & Draper, 1977a).

The tectonic control on cave development was also investigated by Wadge & Draper (1977b) who found little evidence of caves along major fault planes, though some caves may be along small subsidiary faults. A few river caves of steep gradient do occur alongside major fault systems (e.g., the Bristol Cave-Quashies River Cave system) (Waltham & Smart, 1975). Major faults tend to produce large collapse features especially where they intersect cave passages at high angles, while strike-passages and dip-tubes tend to develop where drainage is parallel to strike (Wadge & Draper, 1977b). The most important cave type is the fairly straight, large river passage, simple in plan and flowing down dip. According to Wadge & Draper (1977b), although phreatic 'lift' passages would be expected to occur in caves where the hydraulic gradient is less than the dip of the beds, only a few exist, as they may have become fragmented and disconnected by rapid surface lowering, such that remaining passages only occur within inter-depression hills. Although some horizontal passages occur in areas of cockpit topography, these are essentially fossil features, cut by later erosion of the karst surface (Draper & Wadge, 1997).

In terms of vertical cave development, a large number of 'cockpit' shafts are known within the White Limestone Group, and many have been explored, described and surveyed (Fincham, 1997). Most cockpit shafts are regarded to be solutional in origin, though block- and boulder-chokes within many shafts may indicate some collapse. There are also a significant number of caves with both vertical and sub-horizontal passages, which seem to be concentrated in specific areas of steep hydraulic gradients and where faulting is prevalent (Wadge & Draper, 1977b). Many caves are abandoned vadose systems descending in a series of shafts. Wadge & Draper (1977b) suggested that the development of these steep vadose systems may have been related to the presence of thin, impermeable bentonite clay layers near the top of the White Limestone Group, which would have provided sufficient concentration of surface drainage to account for the steep vadose cave development. Elsewhere, many dip-tube phreatic systems are now being modified under vadose conditions.

Karst morphometry

There are many quantitative morphometric techniques available for karst terrain research, but only a few have been used in research on the karst phenomena of the White Limestone Group. The first published work using morphometric analysis on the karst of Jamaica was that by Day (1976), who considered that such an approach provided the basis for a more objective classification of karst terrain, while the correlation between form and process, and the controls on karst development, are also greatly aided by a morphometric approach. Specific morphometric analysis of karst terrain on the White Limestones includes that of Day (1976), Brook & Hanson (1986, 1991), Hanson (1985) and Draper *et al.* (1998), while a review of morphometric techniques used in karst studies, with examples of work from the Caribbean as a whole, was presented by MacGillivray (1997). Morphometric analysis of karst on the White Limestones has also been incorporated into Caribbean-wide research, specifically in the classification of karst terrain types (e.g., Day 1979, 1982).

In a morphometric study of depressions in the Browns Town area of St Ann, Day (1976) used randomly located profiles to measure depth, diameter and internal slope angles of the features, from which a number of morphometric ratios were developed. The analysis facilitated a correlation between shape and distribution of the depressions with factors influencing their morphology. It was thought that the analysis, by quantifying the spatial distribution of dolines, would allow for a preliminary inference as to their formation, as collapse might be expected to be more randomly distributed than solution dolines. However, Day concluded that it was impossible to infer from morphometric data alone whether collapse or surface solution was the dominant process in depression formation and considered a compound origin was likely.

Day (1979) used vector analysis to examine the distribution and orientation of planar surfaces within several sampling areas across the Caribbean, including localities on the White Limestone, to develop a surface roughness index in order to classify landforms on a more objective basis. Day calculated the surface roughness values of the ten sites to develop a threefold classification of the landscape, the three types being roughly equated with doline (type I), cockpit (type II) and tower (type III) morphologies. Day (1982) developed an additional general classification index from Caribbean-wide karst terrain, which analysed different degrees of theoretical roughness and simulated overall karst landscapes. The negative and positive relief elements of the landscape were analysed to develop a ratio of vertical to horizontal components. On the basis of the ratio of their vertical component compared with their horizontal component, twelve types of landform unit could be recognised within the three classification types, giving 36 possible landform unit combinations. The scheme provides an index of terrain type upon which comparisons can be made (Day, 1978), and was correlated against bedrock properties, such as purity, porosity, petrology and mechanical strength, in order to ascertain the most influential properties on karst terrain type.

Brook & Hanson (1986, 1991) used morphometric analysis to assess how successfully karst terrain could be modelled, to reveal organised patterns in the terrain and to assess the potential of morphometry in distinguishing karst types. They used double Fourier series analysis to uncover significant patterns in the spatial variability of doline and cockpit karst in northern Jamaica, and provided correlation data between landform type, and bedrock structure and lithology. Brook and Hanson measured fracture trace, depression lengths and orientations in the Brown's Town area, parish of St Ann. The data were grouped into ten degree orientation classes and the length weighted values were converted to percentages. The dominant directions concurred with the directions of the more important frequency pairs of the Fourier analysis, while the wavelengths of the frequency pairs coincided with the fracture and depression densities analysed from aerial photographs. They concluded that local structures had a strong influence on the formation of depressions in the area, there was also a significant difference in the density of depressions related to two bedrock types, which was a function of folding and faulting. However, the results could not be used to determine the reason for variance in depression depth in similar bedrock.

Draper *et al.* (1998) applied a nearest neighbour analysis method, used in structural geology to measure strain, to the distributions of sinks and summits of polygonal karst in Cockpit Country. Results showed the distribution of sinks is essentially random, while that of the summits is more uniform with nearest neighbour spacings of 125-250 m, with the longer nearest neighbour distributions generally trending to the northeast. Draper *et al.*

suggested that the polygonal karst develops from originally randomly distributed sinks, and that depression growth ultimately produces uniformly distributed summits.

Landform evolution

Early publications on the karst of the White Limestones interpreted the development of landforms in relation to the petrographic differences between the pure, hard crystalline limestones and the less pure, marly varieties, in that cockpits and towers tend to occur on the pure limestones and dolines on the less pure limestones (e.g., Sweeting 1958, 1972). More recent studies by German geomorphologists have suggested that palaeoclimatic change may have had an important influence on the development of karst landforms in Jamaica (Pfeffer, 1986, 1997; Landmann, 1990). Pfeffer (1997) agreed with many of the early observations of Sweeting, in that areas dominated by impure or thinly-bedded limestones with interbedded marly layers always develop doline karst, and that the purer, more massive limestones underlie areas of residual hills with cockpits. However, some areas have dolines developed in bedrock which would otherwise show cockpits and, according to Pfeffer, cannot be explained by Sweeting's (1958) interpretation.

Pfeffer (1997) argued that the original relief was a peneplain, the main line of evidence for this being the similar elevation of the residual limestone hills, and that this can be dated from the Oligocene-Miocene. The karstification of the peneplain in the Miocene-Pliocene led to the development of cockpit karst with poljes, and that karstification may have been triggered by sea-level fall or local uplift. According to Pfeffer (1969), analysis of relief in southwest Jamaica shows that Tertiary cockpit karst was uplifted during the Quaternary. Pfeffer (1969, 1997) also argued that the bauxites found in the large cockpits are the weathering residue of Tertiary relief formation, and have a higher rate of quartz dissolution and desilicification than the red-earth and red loams associated with the residual hills, which are considered to be the result of present soil formation and younger karstification. Pfeffer (1997) suggested this as evidence for higher weathering intensities and different morphodynamic processes during the Miocene-Pliocene which formed cockpit karst, compared to the Quaternary karstification, which led to a new 'relief generation' as a result of a change in palaeoecological conditions.

Similar interpretations of the landform evolution of Lluidas Vale were made by Landmann (1990), who considered the oldest relief unit in the Lluidas Vale area is an etch-plain which was formed by intense weathering conditions in the Neogene. The etch-plain was subject to intense karstification during the late Miocene to late Pliocene, which led to the development of cockpit karst and a strongly-weathered residual bauxitic soil. Dolines, which occur in the southern part of the vale in the same White Limestone facies as the surrounding cockpit karst, developed on an etch-plain which was uplifted at the end of the Pliocene or the beginning of the Quaternary during a drier climate, as the residual soils associated with the dolines are not as intensely weathered. The alluvial fans and gravel terraces seen on the floor of the vale are similarly the product of a drier climate in the Quaternary, though Landmann (1990) suggested that several phases of alluvial fan formation occurred as a result of humid and dry cycles, which were repeated at least eight times during the Quaternary.

Thus, according to the German school of geomorphologists working in Jamaica and the wider Caribbean, the evolution of limestone landforms can be explained not only by geological controls, but also by contrasts in the intensity of karstification during the Tertiary and Quaternary as a result of palaeoclimatic and palaeoecologic changes. Some of their interpretations are highly contentious and speculative, as both the depressions and residual hills, and the weathering products and soils they contain, cannot be treated as separate landforms; they are both an integral part of the overall pitting of the surface. Their interpretations also rely strongly on the premise that the bauxites are residues of the karstification. It is likely that geological controls combined with climatic change and climate variations have both had a profound influence on the development of karst landforms on the White Limestone Group. Of equal importance to karst evolution would have been the erosional breaching of the anticlinal structure and subsequent de-roofing to form the Central Inlier. This exposed non-carbonate rocks and led to the development of surface streams which carried large volumes of water to the limestones. Subsequent sinking and subterranean flow through the White Limestones modified their hydrological characteristics from essentially autogenic systems dominated by vertical percolation routes through the limestone, to a mixed allogenic- autogenic system with not only vertical percolation, but also horizontal water movement, forming fairly rapid flow paths.

An earlier theory on the evolution of karst landforms on the White Limestones also stressed this link to the bauxite deposits, where Smith *et al.* (1972) suggested that, 'the origin of the karst landforms is intimately connected with that of the bauxite deposits'. Smith *et al.* considered that the bauxite originated by the weathering of limestones in the cockpits, from which the weathering residue was transported via underground drainage to the 'degraded' cockpit, where it was deposited by floodwaters, a process which is no longer active. A mathematical model was constructed in which they suggested that the White Limestone was first exposed to erosion by uplift in Late Miocene times and the development of karst landforms began with an undulating surface with shallow depressions. In the model, an incomplete soil cover then developed in the depressions leading to differential rates of dissolution, the latter being concentrated beneath the soil cover. Smith *et* *al.* then contended that more significant slopes develop due to preferential dissolution, and as they become steeper their soil cover is lost by mechanical erosion. Thereafter, the slopes cease to become steeper, as the erosion rate is constant over the entire length of the slope. Smith *et al.* assumed in their model that this 'equilibrium time' is reached when the slope angle is 30°, after which time the slope will retain its form.

Smith *et al.* also incorporated into the mathematical model the development of the cockpit shafts, by supposing that while the slope remains soil covered, all the drainage leaves at its base, through fissures in the limestone, leading to the formation of a shaft. The depths of the shafts are also controlled by the presence of a soil cover and, once this is removed, the shaft and slope erode at the same rate, due to the fact that drainage is no longer concentrated down the shafts, but seeps directly into joints and fissures in the bare limestone. This, according to Smith *et al.*, accounts for the fact that shafts are rarely greater than 60 m deep and the final depth of the shaft will be reached when the surrounding slopes reach an angle of 30°. Based on their mathematical model, Smith *et al.* maintain that a shaft of some kind will form at the base of the slope as a natural consequence of the presence of a cockpit. They also modelled final depths and radii of shafts, and 'equilibrium times' in relation to cockpit development. The development of degraded karst in relation to bauxite deposits was also modelled by Smith *et al.* (1972) and a true 'equilibrium landform' towards which all slopes in degraded cockpit will tend was equated.

Smith *et al.* (1972) attempted to show that their mathematical model of landform development produced landform shapes which are not dissimilar to real karst landforms on the White Limestone. Based on their model of landform evolution, Smith *et al.* contended that the equilibrium time for the production of cockpits is about 0.6 million years, while the total time required to produce an equilibrium bauxite deposit, or fully degraded karst, is 0.6 million years plus 2.7 million years, or 3.3 million years for an average economic deposit and 3.7 million years for a non-economic deposit, similar to the 3.5 million years that Smith (1970) estimated as the time required to produce the total known bauxite reserves.

The times presented by Smith *et al.* (1972) for the evolution of both the cockpit landforms are constrained by assumptions in the model, not least the generation of mean erosion rates, which were constructed using water hardness values and runoff rates using present day data. The model also presupposes that the bauxite deposits originated as the insoluble residue of limestone from the cockpit areas, which is transported through the subterranean drainage system and deposited by floodwaters to form areas of degraded karst. In addition to Smith *et al.* (1972), other workers who favoured a residual origin for the bauxites include Ahmad *et al.* (1966), Hose (1963), Clarke (1966) and Sinclair (1966, 1967, 1976). The Newport Formation (now referred to the Moneague Formation; Mitchell, 2004) is the host of the most extensive bauxite deposits, while the Browns Town-Walderston Formation (also Moneague Formation) is the principal host of bauxite in the north coast belt, with important reserves on the Troy Formation (Lyew-Ayee & Stewart, 1982). The residual theory of the origin of bauxite has been questioned and, although the deposits are mainly confined to areas underlain by the shallow water carbonate units of the White Limestone Group (Robinson, 1994), the relationship of these deposits to the bedrock has been the subject of numerous papers (e.g., Wright, 1977; Lyew-Ayee, 1982).

Zans (1958c; see also Chubb, 1963) proposed an alternative alluvial theory for the origin of bauxites which is closely associated with the groundwater hydrogeology of the White Limestone. Zans theorised that alumina-rich argillaceous debris was eroded from Cretaceous tuffs in the Central Inlier and fluvially transported by surface streams which sink when flowing onto the White Limestone. The fine debris continued to be transported by underground drainage, and was carried to the surface and deposited by karst waters over the floors of karst depressions of various sizes. According to Zans' theory, the first of these muddy sediments were laid down while the island was still being uplifted and continued uplift elevated the alluvial deposits high above the water table, where laterisation converted them to bauxite. In the alluvial theory, uplift accounts for the occurrence of bauxites on the limestone plateau surfaces high above the water table.

It has also been proposed that much, if not most, of the superficial cover of bauxite is derived from the weathering of ashfall deposits produced by volcanic activity in the region surrounding Jamaica, especially in the late Cenozoic, some of which are still preserved as ash beds in the deep water limestones of the Montpelier Formation (Comer, 1974, 1976; Comer *et al.*, 1980; Comer & Jackson, 2004). The ash-fall theory is also supported by other workers (e.g., Lyew-Ayee *et al.*, 1989). Comer (1974) indicated that the relatively high percentage of bentonitic clay within the Montpelier chalks, the chemical composition of the clay (including the high alumina and low silica contents), and the stratigraphic position above the host limestone all suggest that these rocks are the more likely source of material for the bauxites than the parent rocks proposed in the residual theory. According to Comer, the timing of volcanic ash deposition coincided with the emergence of the island, and so much of the ash was deposited subaerially and concentrated in pre-existing karst depressions. Subsequent elevation of the ash deposits and intense leaching of ash and ash-bearing carbonates eventually caused the formation of bauxite. Comer concluded that the exclusive association of bauxite with karstified limestone was related to both the drainage and the dissected nature of the limestones. According to Comer, the effect of karst development was to trap the parent ash-fall material in karst depressions which prevented erosion, while the high relief topography of the pre-existing karst resulted in well-drained slopes where vertical drainage through the limestones provided the optimum conditions for the subaerial leaching processes required for bauxite formation.

Conclusions

This study has attempted to review our current understanding of the karst geomorphology of the White Limestone Group and to provide a summary of the work completed to date. It has also attempted to identify the gaps in our knowledge and to indicate areas of future research. A detailed description of each of the main karst landforms occurring on the White Limestone Group has been presented. The most extensive karst landform type is cockpit karst, followed by doline and tower karst. Poljes are also important landform elements and most have a strong structural control, being closely related to block faulting. Both lithological and structural controls are important in the development of karst landforms within the White Limestone Group, and the de-roofing of the Central inlier fundamentally altered the karst hydrology of the limestones and greatly modified the overall karst landscape. Climatic change may also have had a profound influence on karst development of the White Limestone Group, as it may be argued that some karst phenomena are essentially hydrologically relic and represent karstification during wetter periods than experienced at present, specifically the vertical shafts associated with cockpit karst.

Detailed geomorphological mapping of the karst has been restricted to a few small localities and more systematic mapping of the karst of the White Limestone Group needs to be undertaken. In addition, only a few morphometric studies of the karst have been undertaken in Jamaica, and these have been limited to small isolated areas of karst for quantitative analysis and classification of the landforms. A combination of geomorphological mapping and a more systematic morphometric analysis of the karst would greatly increase our knowledge base and understanding of the karst landscapes on the White Limestone Group.

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