

CAVES AND GROUNDWATER PATTERNS IN A TROPICAL KARST ENVIRONMENT: JAMAICA, WEST INDIES

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ABSTRACT. Karst landforms are well developed in tropical areas, and a recent expedition to Jamaica mapped over 30,000 m of cave passages in four different areas and traced three sinking rivers to their eventual springs by using dyed *lycopodium* spores. Within regions, cave patterns are similar, but different regions display patterns conditioned by differing lithologies; structures, such as faulting; and seasonal rainfall variations. Cave patterns can be used by the geohydrologist to gain insight into groundwater flow patterns. In Jamaica, groundwater moves through karst terrains quickly and in large, discrete conduits. These will not provide effective filtration of, for example, typhoid bacilli.

INTRODUCTION

Karst landforms, which are produced by groundwater solution of bedrock, usually limestone, present unique hydrologic and geomorphic problems. The absence of surface drainage networks leads to lack of information about the destination of sinking water, and catchment areas of springs cannot be readily delimited. Although "fossil" groundwater conduits may exist as caves, and evidence may be deduced from these about present-day flow patterns, well-developed or holokarst areas present a chaotic surface geomorphology. In the humid tropics where the total effective solution rates are high because of concentrated and large amounts of rainfall, high temperatures, and high soil CO₂ concentrations, holokarst landforms are found to be further developed than elsewhere in the world. In these areas, lack of surface water inhibits agriculture, absence of drainage networks on the surface often makes transportation extremely difficult, and ignorance of both the destination of sinking rivers and the sources of spring water, coupled with inefficient filtering of groundwater in limestone (for example, Atkinson, 1971), may lead to serious pollution problems.

In 1966 the British Karst Hydrology Expedition to Jamaica discovered and mapped over 30,000 m of cave passages and traced three sinking rivers to their springs (Livesey, 1966). This paper summarizes the scientific findings of the Expedition.

KARST OF JAMAICA

A recent excellent review of the karst of Jamaica (Versey, 1972) is the latest of many studies of the karst of the Island (for example, Sweeting, 1958; Zans, 1958; Smith, 1969; White and Dunn, 1962; Smith, Drew, and Atkinson, 1972). Figure 1 presents a simplified geology of Jamaica: limestone of Eocene age is exposed over two-thirds of the island. It overlies the Central Inlier, a crystalline and non-karst core which is exposed in the center of Jamaica. The White and Yellow Limestones dip gently north and south from the Inlier. Normal rivers collect on the Central Inlier and sink underground at the contact with the White Limestone. Karst dis-

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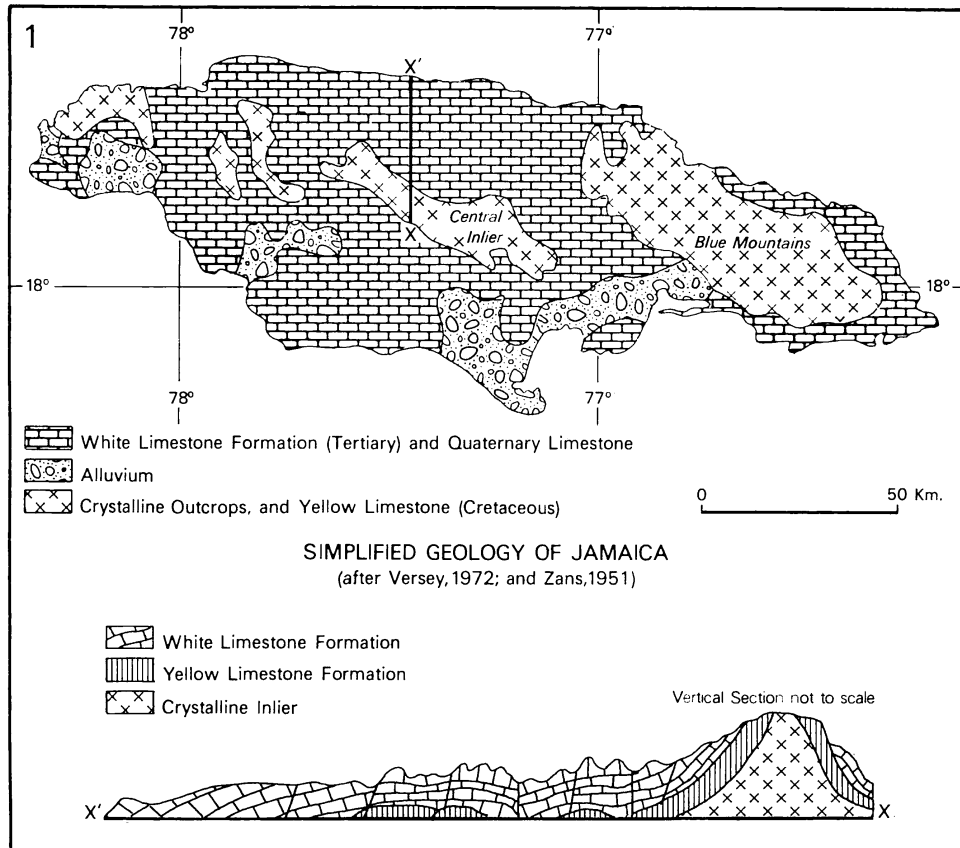


Fig. 1. Simplified geology of Jamaica.

section of the White Limestone outcrop north of the Inlier is very intense, creating the famous sinkhole region known as the Cockpit Country. There are many springs, at about 170 m above sealevel, along the northern edge of the Cockpit Country; they are 10 to 30 km distant from the sinks in the Inlier and 350 to 500 m lower in elevation. The region receives approximately 220 cm of rain per year, most of it during the wet season from April to October. Before 1966 several attempts to trace the destinations of the sinking rivers had failed despite the use of as much as 9 kg of the dye fluorescein (Ashton and Fincham, 1967).

GROUNDWATER TRACER TESTS

Three groundwater tracing methods were used in 1966: direct physical exploration and mapping of caves, injection into sinking rivers of the dyes fluorescein and rhodamine B, and injection into sinking rivers of dyed spores of the club moss, *lycopodium* (Maurin and Zotl, 1959) (fig. 2).

The conventional tracers fluorescein and rhodamine B did not succeed in tracing rivers (with one exception) despite use of activated charcoal for collection and later fluorometric analysis of the ellutant of the charcoal (White, 1967). The exception was the Hector River-Coffee

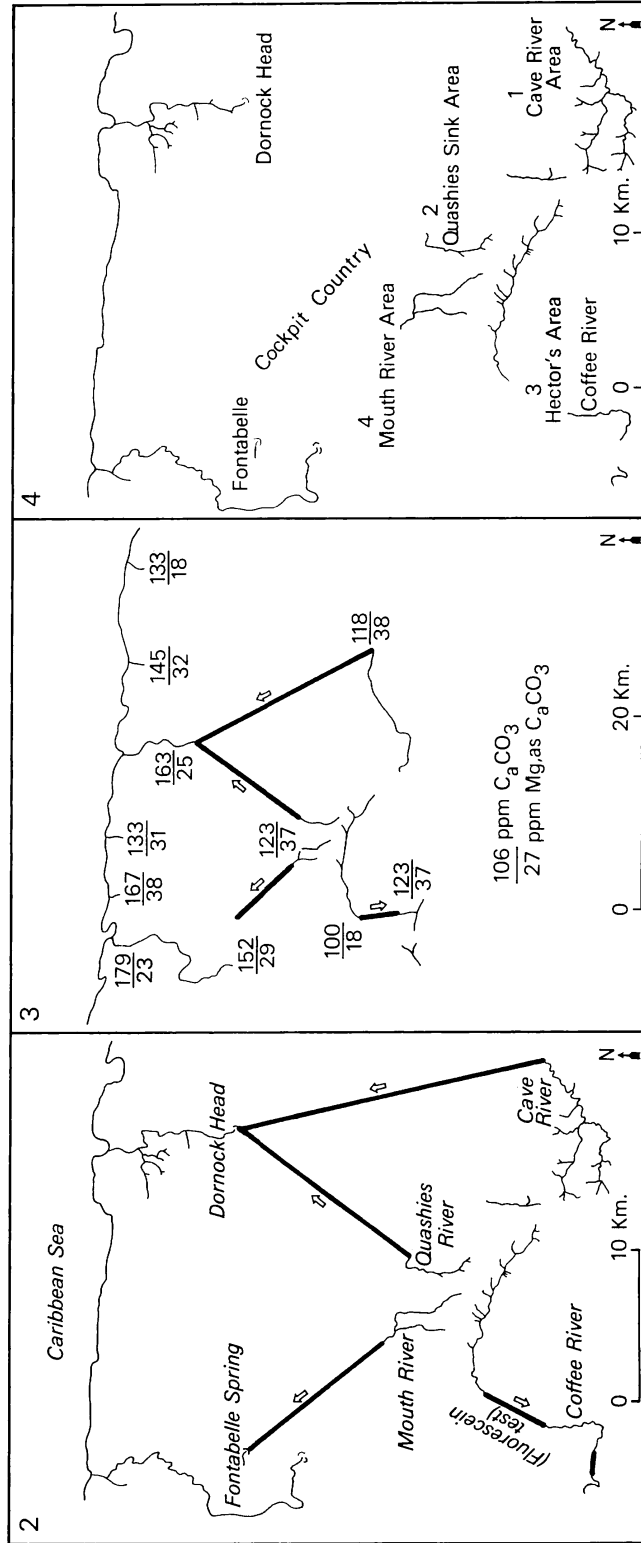


Fig. 2. Groundwater tracing results.

Fig. 3. Groundwater solute concentrations.

Fig. 4. Four principal areas of cave exploration.

River test, which showed a flow-through time of about 48 hours for 4.1 km with a discharge of 1.3m³/sec. The failure of the dyes on the other tests, over routes later established by *lycopodium* spores (fig. 2), may be attributable to disintegration of fluorescein by sunlight and adsorption of rhodamine B by clay particles suspended in the underground waters (Scott, Norman, and Fields, 1969). These effects appear to be particularly strong in the humid tropical environment.

The major advantages of *lycopodium* spores as a tracer are that with the use of spores dyed different colors, simultaneous tests can be run upon different sinkpoints in an area, and there is no possibility of background interference with results because there are no naturally occurring colored *lycopodium* spores. Disadvantages include ease of contamination, possibility of filtering by sand, time of preparation, and sample analysis. Spore diameters are typically 30 microns. Spores were collected with large plankton nets placed in the suspected risings. The results are shown in table 1 and figure 2.

The long underground connections thus established not only prove the reliability of this tracer but support the earlier contentions of Zans (1958) concerning the flow patterns. While future testing of smaller sinks may be expected to show some criss-crossing of groundwater channels, it appears that the catchment hydrology of this area is relatively simple. Assuming straight line distances between sinks and risings, the flow rates are 1.5 to 3.0 km per day during the dry season. Known cave channels are sinuous, and these rates should probably be doubled. But even the straight-line rates are sufficiently high to leave little doubt that the groundwater moves by flow along discrete conduits of large size rather than by widespread drift through an anastomosed zone of the limestone. Thus the underground hydraulic pattern is much more akin to that of a dendritic surface channel net than it is to groundwater drift in a granular aquifer.

SOLUTE CONCENTRATIONS

A large number of dry-season water samples from both sinks and risings were analyzed by EDTA titration (Schwarzenbach, 1957) for Ca and Mg concentrations. The mean results (fig. 3) show that the rivers

TABLE 1
Groundwater tracing (*Lycopodium* spores) data

Test	Quantity of spores (dyed wt)	Spores detected at	Duration in days and no. of spores recovered		
			0-7	7-14	14-28
A. Sink of Mouth River	33 lbs (green)	Fontabelle Spring (only)	0	25 green	100 green
B. Sink of Quashies River	30 lbs (red)	Dornock Head Spring (only)	0	200 red	20 red
C. Sink of Cave River	78 lbs (blue)	Dornock Head Spring (only)	0	*N.A.	200 blue

* N.A. = data not available

when sinking have already picked up 75 percent of the Ca^{++} which they contain at their risings. In three of the sink-to-spring courses, the rivers appear to lose Mg^{++} . This is probably accounted for by the addition of diluting water from the intervening sinks of the Cockpit Country. This suggests that much of the small Ca^{++} increase at the springs may result from addition of Ca^{++} rich waters from the cockpits. Independent analyses in the area by Smith (1969) confirm the concentrations indicated in figure 3. Miotke (1972) has measured similar values in Puerto Rico.

CAVES AND REGIONAL GEOMORPHOLOGY

Geomorphologically, there is a gradation from the "normal" landscape on the crystalline Inlier to the holokarst Cockpit Country. The rivers carve their way through elongated valleys and eventually sink. Near the edges of the Cockpit Country elongation of the valleys is more pronounced than in the interior. This may represent former stream courses, but Smith, Drew, and Atkinson (1972) have presented strong arguments that no such relics exist, and that the drainage of the whole area has been underground since emergence of the White Limestone in late Miocene time. Elongation of depressions deep in the Cockpit Country, which are locally called "glades" or "bottoms," is probably related to fault or joint patterns. For a discussion of the quantitative nature of linearity in tropical holokarsts and an outstanding review of the relation between form and process in such areas, see Williams (1972). The depth of alluvium on the floors of the depression seems to decrease with distance from the edge of the Cockpit Country but is still 2 m deep at 2 km from the Inlier.

Caves were discovered and explored systematically in four areas (fig. 4). In each area the pattern of development was different. Thus the areas will be described separately, with common features then summarized.

In the Cave River area (fig. 5), the groundwater occupies one major route and flows more or less in a straight line toward its eventual rising. The cave appears to be an example of lithological perching of drainage. It is contained within the lowest member of the White Limestone, (the Troy member), which rests directly upon the less soluble Yellow Limestone. Passages are large enough to contain all but the most severe floods, and gradients are low. The linearity of this system and of cockpits in general led Zans (1958) to postulate the effects of many faults. But these are probably small fractures, or even joints, because evidence of faulting is rarely observed underground. In the Cave River system, there is little evidence of early cave development at higher levels, although the resolution of massive secondary calcite deposits which is presently taking place is evidence of phase variation. Surface lowering of the karst is proceeding faster than vertical cave development, as evidenced by the large number of collapses from overlying cockpits which intersect the system. This arrest in cave development can be attributed to the perching effect, mentioned above.

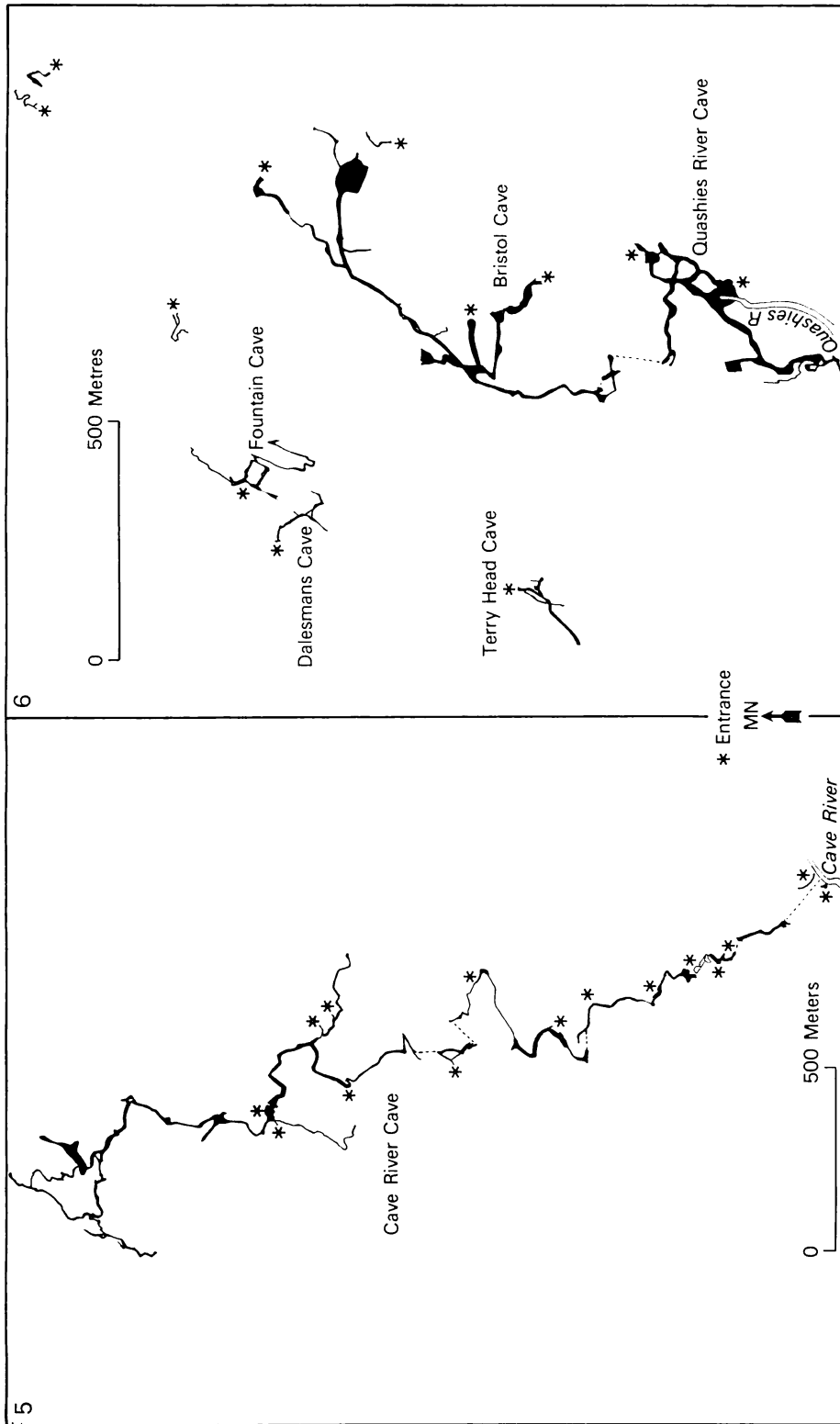


Fig. 5. Cave River area.

Fig. 6. Quashies Cave area.

The second area is that of Quashies Cave (fig. 6). This cave has a steep initial descent, the river plunging over a series of waterfalls to a depth of 170 m. The inlet area is a complex of abandoned routes. Fault control is not evident inside the cave, but its surface valley is in the major Barbeque Bottom Fault Zone. The steepness of the cave gradient could well be explained by faulting. The cave is terminated by a large siphon. Other small caves in the area are minor, abandoned, high level tributaries feeding from adjacent hills. Their patterns indicate strong joint control.

The third area studied was that of the Hectors Coffee River systems (fig. 7). The connection between these was established by the positive fluorescein test. As at Cave River, the cave development is at much the same level, and massive stalagmites are being dissolved by water in the modern phase. However, maze caves as well as linear systems can be found, there are distinct long dry valleys rather than cockpit karst, and the hydrology of this area is complex.

The fourth major area explored was the Mouth River Sink district (fig. 8). As at Cave River, the Mouth systems are at the karst margins, and there is development in the Upper Yellow Limestones as well as the White Limestone. Mouth River itself is inaccessible after a very short cave and is not seen again in the area. However, a large and well developed system of flood routes leads from this sink to the north. This maze of passages receives large amounts of water annually, as evidenced by fresh mud, lack of formations on the floor, and crayfish in standing pools. The flood passages show rectilinear joint control and have a geometry that indicates their formation under water-filled conditions. There are higher, abandoned systems (Harties and Printed Circuit) which are older flood water conduits 15 to 30 m above the present development levels. These caves have extensive calcite deposits and show a complex sequence of phases in their development. The large dimensions of passages in Harties Cave suggests that it once took the main flow of the river. This has now shifted to the east and been lowered to the impermeable clays in the Yellow Limestone. Printed Circuit, on the other hand, has always fed local drainage into the main system.

Plate I shows caves of the Mouth River of the Mouth River sink area superimposed upon a vertical air photograph. The main flood route can be traced through three separate cockpit floors, where it consists of gullies cut into alluvium. It should be noted that the cockpits do not have extensive flat floors, and that most of the shadowed areas on the air photograph are hillsides. Although it appears that the caves are only found under the hills and not under the cockpits, it must be pointed out that these are all accessible (that is, not water-filled) caves. It seems that, although there is a genetic relationship between cave conduits and cockpits, the present drainage does not strictly follow the cockpit pattern. But because it is a combination of this drainage and intercockpit drainage that must determine the position and pattern of the cockpits, it is reasonable to infer that the development of the cockpits may be very dynamic over

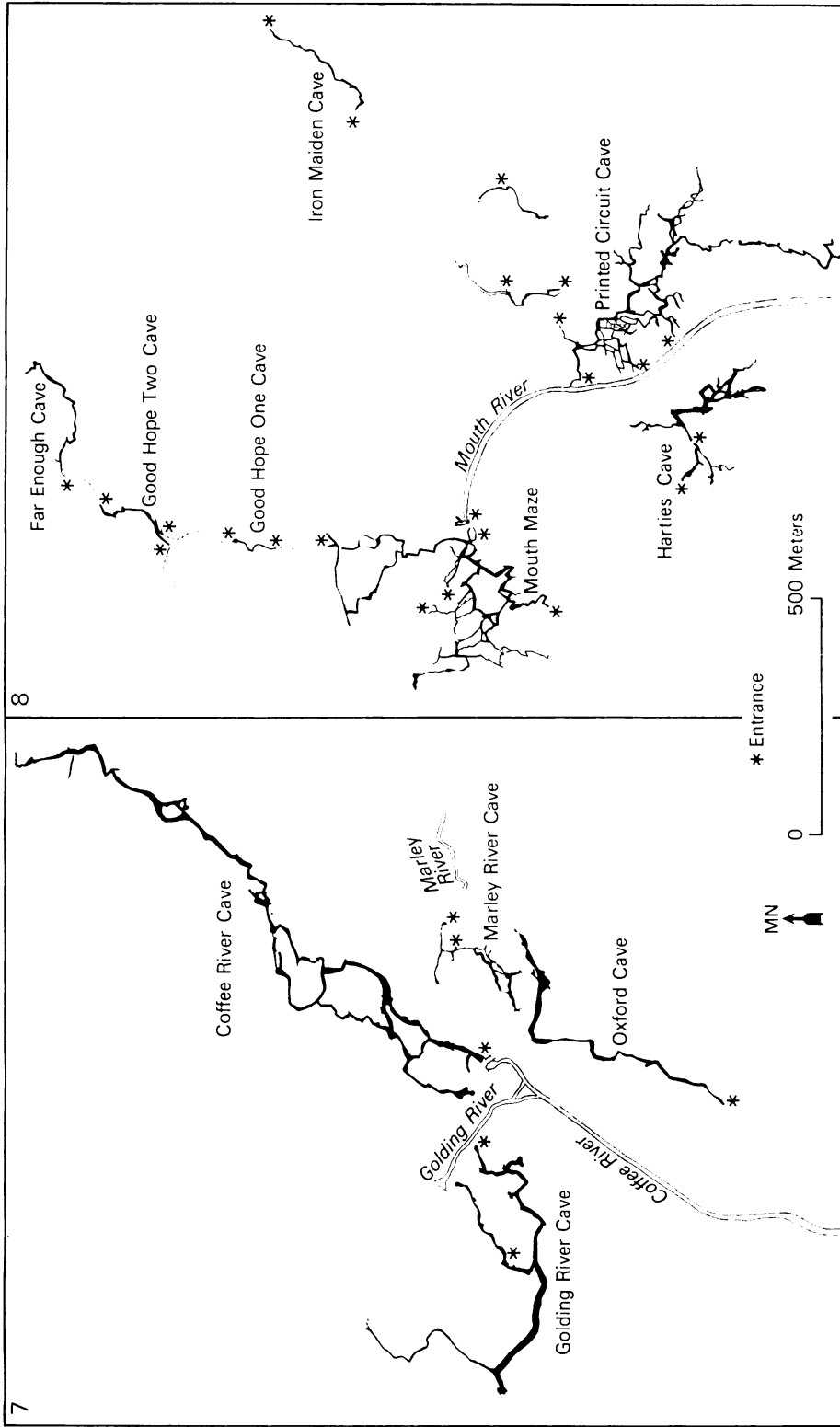


Fig. 8. Mouth River area.

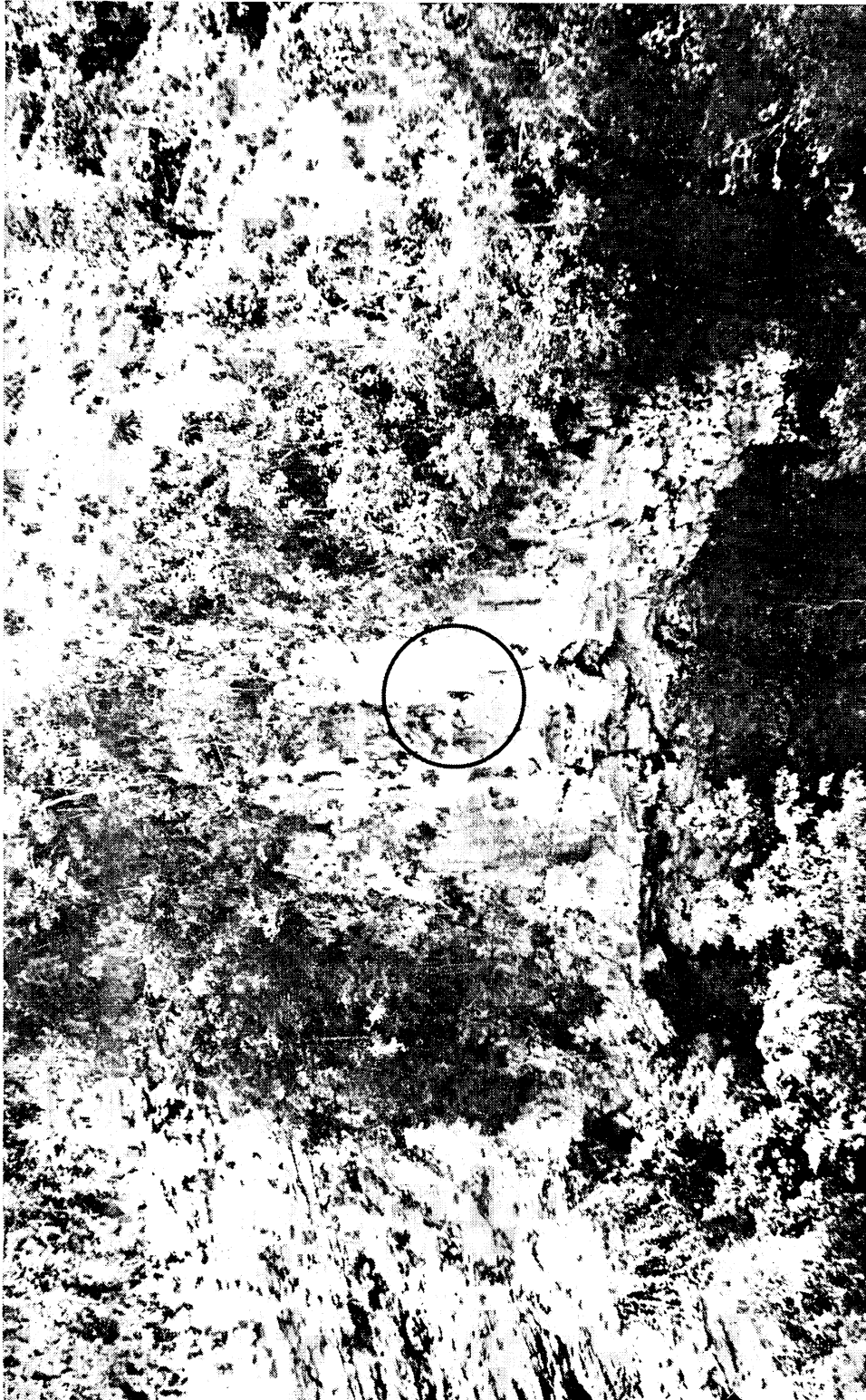
Fig. 7. Coffee River area.

PLATE 1



Mouth River area caves superimposed on vertical air photograph.

PLATE 2



Linton Park Light Hole, a surface collapse. Circled figure is man for scale.

short geological times. It is suspected that there is considerable lateral displacement of cockpit floors as they are eroded downward.

Plate 2 illustrates a feature not encountered in the four areas described above: the presence of large collapse sinkholes. These occur when a surface that is eroding downward breaches a cavern passage, and in the case of Linton Park Light Hole ($77^{\circ} 25' W$, $10^{\circ} 17' N$), the form of the cave roof indicates that the passage was formed under phreatic or water filled conditions. Although the cave accessible from this collapse sink is not explorable for more than 100 m in either direction, the size of the passage evident in plate 2 gives an indication that at least some of the main conduits draining the area are quite large.

CONCLUSIONS

In areas of karst hydrology, speleological explorations of caves can be of help to the hydrologist; in each of the four areas described the directions of underground water flow were not at all evident from surface drainage patterns.

Conventional tracer dyes may not be appropriate for hydrologic work in tropical areas; but the efficiency of dyed *lycopodium* spores is established. The flow rates established show that the groundwater moves in discrete large channels, and that earlier predictions of Zans (1958) concerning the regional hydrology are substantially correct.

Cave passages in this tropical karst are of diverse types but seem consistent within small areas. Passages are often joint oriented, while faulting leads to strong vertical development.

Superimposition of cave maps on air photographs shows caves under ridges and never under cockpits, but this is believed to be because caves under the cockpits are water filled. This indicates a strong possibility of rapid horizontal displacement of cockpits with vertical erosion.

It is significant that the *lycopodium* spores are ten times larger than typhoid bacilli and many other pathogenic germs. The Jamaican work supports Bauer and Zotl's (1972) findings in an Alpine karst of high relief: a karstified aquifer may not be an effective water purifier even where the groundwater flowline is as long as 20 km.

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