HYDROCHEMISTRY, HYDROLOGY, AND MORPHOLOGY OF THE CAVES BRANCH KARST, BELIZE

by

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ABSTRACT

An extensive karst developed on Cretaceous limestones in Belize, Central America, was the site of a hydrochemical, hydrologic, and morphologic study. This thesis describes the results of analysis of several hundred water samples from this humid tropical environment (mean annual rainfall - 2376 mm; temperature - 24.5°C). An unusual positively correlated discharge/total hardness loading curve in a major cavern conduit is explained as due to a two-component mixing model. Hydrologic modelling, soil CO_2 sampling, and discriminant analysis were used to infer the interior structure of a karst aquifer. Minimum effective porosity was determined to be 0.7%. Mean areal hardness of 187 mg/L (as $CaCO_3$) was found for springs draining the aquifer, indicating a denudation rate of about 90 m^3/Km^2/year. Aqueous P_{CO_2} of these springs was 1.1%, significantly higher than the 0.7% of mean karst soil CO_2 levels. This implies open system calcite solution evolution and/or internal CO_2 production within the aquifer.

Various morphologic analyses suggest the cockpit-type surfaces of numerous karsts in the tropics may be significantly due to disaggregation of existing topographic lows originally formed by creation of a fluvial topography. These fluvial valleys acted as favorable sites for concentration of aggressive water and consequent cockpit formation.

Over 40 km of cavern passage were explored in the Caves Branch, including one of the largest tropical cavern systems known. Cavern development appeared to have been chiefly influenced by regional fracture patterns and topographic dip. The present development was completed by at least 140,000-215,000 years B.P., according to results of speleothems dated by the uranium/thorium disequilibrium method.

ACKNOWLEDGEMENTS

The opportunity to research in Belize was a rare and precious experience -- my thanks go to Carol Jo Rushin and Barbara MacLeod for first introducing me to the fabulous caves of the area. I am also grateful to my field assistants and caving companions of the summers, especially Logan McNatt and Jerry Davis, and Mike Shawcross, John Wyeth, Mark Gutchen, Peter Ireland, Harold Barba, and Ira Star.

The traces of past explorers and lost civilizations immeasurably added to the aura of wandering amid the holy places of the Maya. I thank Jaime Awe, Liz Graham, Harriot Topsey, and Joe Palacio of the Belizean Archaeology Department for granting permission to work in the area, and who with Dorie Reents, Logan, and Barb, provided some understanding of the grandeur of the Meso-American past.

Academia necessarily intervened -- I owe a debt (not fiscal) to my supervisor Derek Ford, who funded these adventures from a seemingly bottomless cornucopia of research funds of unknown (to me) provenance; and to my committee members Henry Schwarcz and John Drake, especially the latter for critically reviewing portions of the manuscript.

My time here was considerably shortened by Chris Malham, who typed the thesis. A host of others helped, by dating stalagmites (á la Mel Gascoyne and Alf Latham), or added to the quality of university life through caving, a wide range of discussions, etc. The Ontario government helped me cope by constant reminders of how well visa students were regarded here, and Pierre Trudeau was always good for a few belly laughs.

Lastly, if this were to be dedicated to any one person, it would be to Maryjka, who put up with me during all this time.

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CHAPTER 1

INTRODUCTION

The Caves Branch karst was chosen to document hydrochemical and hydrological processes of solution in a cockpit karst, and to investigate their interaction with its surface and subsurface morphology. Initial goals were 1) to outline the seasonal characteristics of the water chemistry, flow routes, and discharge, 2) to survey the morphology of the surface and subsurface features to determine their genetic sequences, and 3) to increase the data foundation of karst studies in tropical environments. As research progressed, additional objectives were formulated. These included developing an explanation for the solutional behavior of the largest spring in the area, and application of the large amount of hydrochemical data obtained to problems of karstic and/or carbonate erosion in general.

I. Physical Description

A. Location and Topography

1. Regional Belize (known as British Honduras until 1973) is a former colony of the United Kingdom on the southeastern flank of the Yucatán peninsula (Figure 1.1). Although quite varied physically, it is small in both area (ca. 28,000 km^2) and population (ca. 150,000). Simply, Belize consists of the ancient, escarpment-bounded Maya Mountains (rising

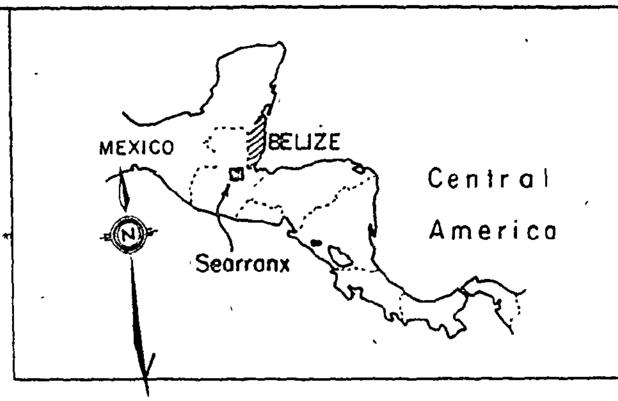
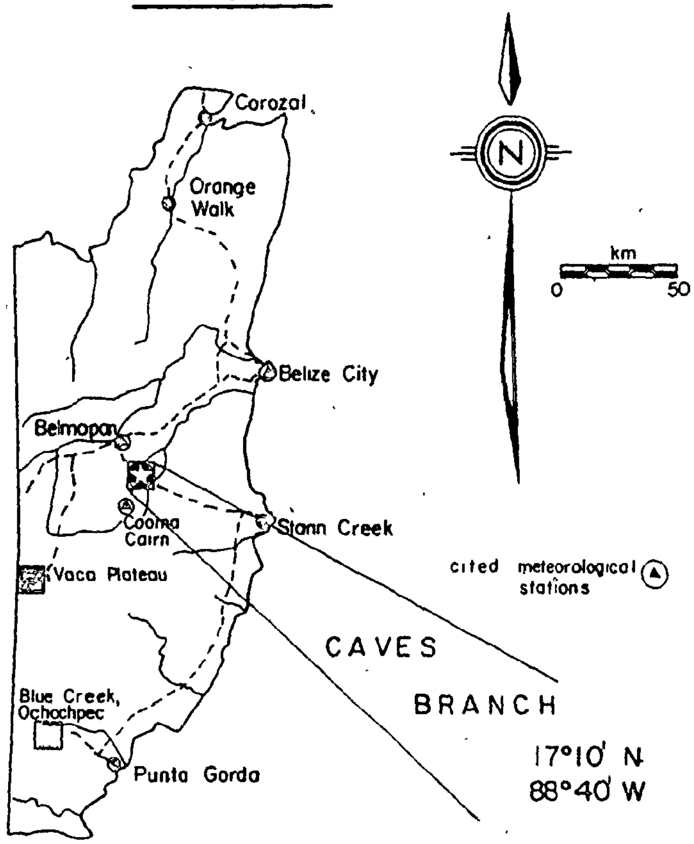


figure 1.1

BELIZE

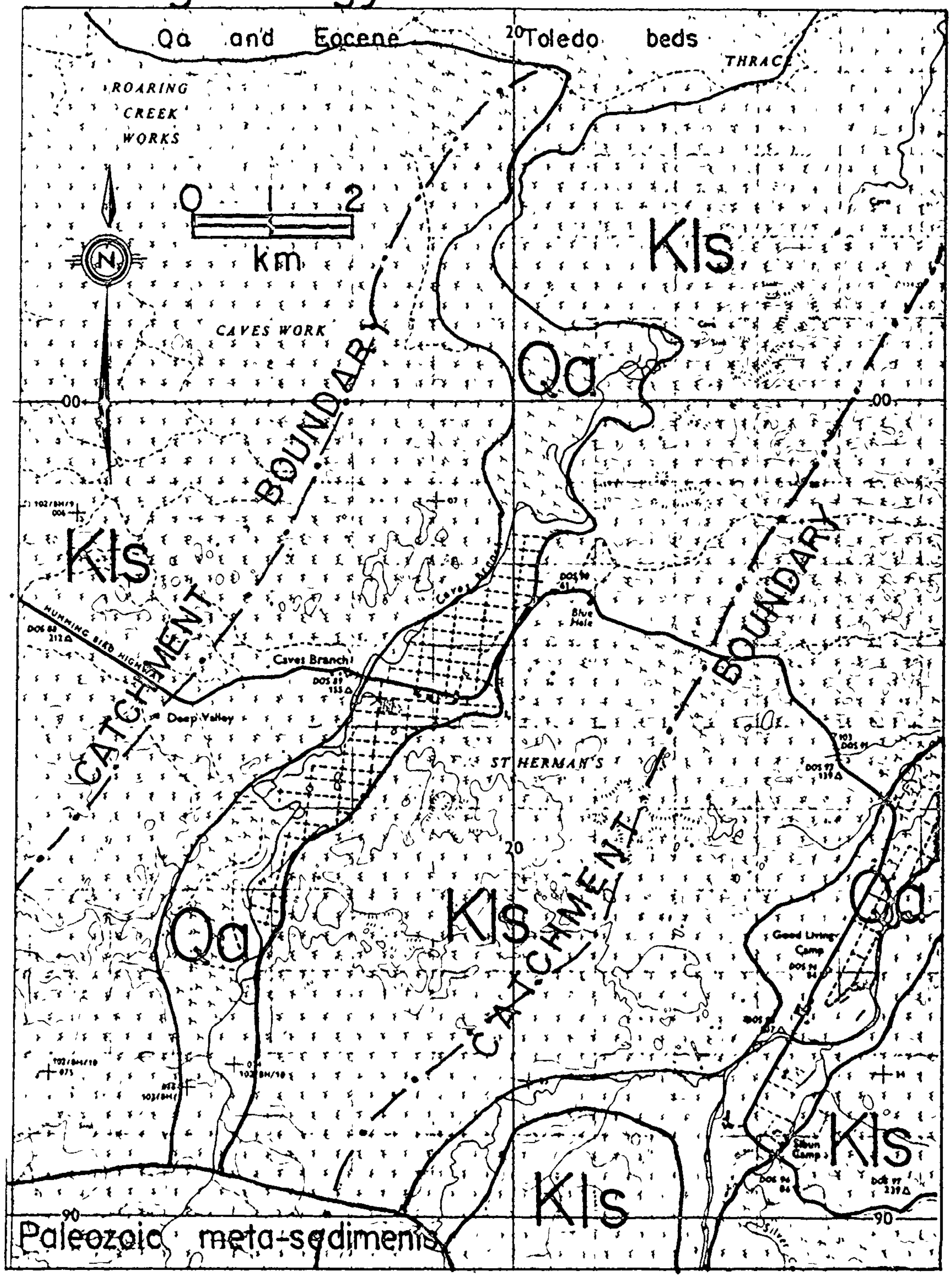


to 1100 meters), which are enclosed by younger (chiefly carbonate) sediments. Of primary importance is the broad belt of Cretaceous, karst-forming limestones and dolomites, which routes all but the largest highland streams underground. Most of the remainder of Belize is a seasonally swampy plain (0-100 m elevation) of soft Tertiary and Quaternary carbonates. The coastline is fronted by a 250 km-long barrier reef.

2. Local The Caves Branch river basin lies roughly in the center of Belize, covering an area of about 200-235 km^2. For this thesis it is defined as the hydrologic catchment contributing to the discharge of the Caves Branch River at its confluence with the Sibun River (Figure 1.2). Physiographically, it transects all the major provinces of Belize, extending northward from the Pine Ridge of the Maya Mountains through the karst fringe, and into Eocene carbonate plains. The Caves Branch River heads in the escarpment of the non-carbonate highlands, having a catchment area of 64 km^2. There are two other allogenic (or non-karst) sources of input; these are the resurgences of two major caves, Actun Chek and Actun Lubul: both feed runoff from the Pine Ridge through the karst to the Caves Branch, and have respective catchments of 20.3 and 3.3 km^2 respectively. The remaining area (of the actual karst catchment) can be only vaguely defined because nearly all of its drainage is internal. It is a frequent occurrence in karst regions that apparent surface drainage divides and actual karst routes do not coincide.

The karst is quite sharply delineated: it is bounded on the south at 200-300 m elevation by the Northern Boundary Fault (an escarpment 700-800 m high), and to the north by the abrupt end of the Cretaceous

figure 1.2 Caves Branch geology and catchment



=approximate catchment boundary

Kls = Cretaceous limestone

limestone in hills 30 m or more in height at an elevation of 40 a.s.l. A few isolated towers extend into the alluvium-covered plains. The Caves Branch itself disappears into the limestone at a large ponor (site of capture of a surface stream) after flowing more than ten kilometers through a prominent polje (a major alluviated depression in the karst). (Plate 1.1). The combined allogenic and authigenic (karstic) recharge of the area resurges five kilometers to the northeast at the termination of the karst. From here the Caves Branch meanders for ten kilometers through low plains, adding only minor streams. Eventually it joins the Sibun River, a through-flowing stream from the highlands.

B. Geology

1. Regional Although some preliminary geologic work was undertaken in Belize near the turn of the century, the first major studies were by Ower (1928). These were followed by Flores (1952), and numerous reports beginning in the late 1960's. Much of this work has little value to karst investigations, however. The economic potential of the Maya Mountains and ecological interest of the coast (Belize has the world's second longest barrier reef) have drawn most of the geologic attention, and even basic stratigraphic knowledge of the Cretaceous limestones has scarcely advanced beyond Ower's fossil-collecting (Figures 1.3 and 1.4)

Although early Paleozoic or even older basement rocks are believed to underlie northern Guatemala and Belize (Dillon and Vedder, 1973), the oldest exposures stem from sediments deposited in a mio-geosyncline south of the Yucatán (Dengo and Bohnenberger, 1969). A late Paleozoic or early

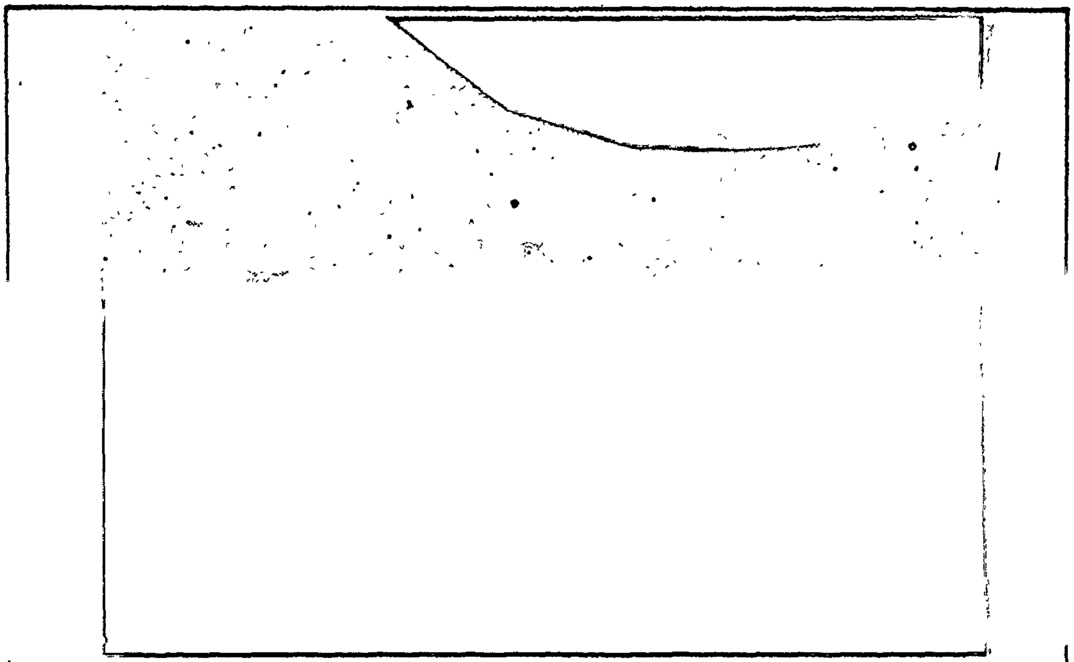


Plate 1.1 Caves Branch Polje looking N.E.

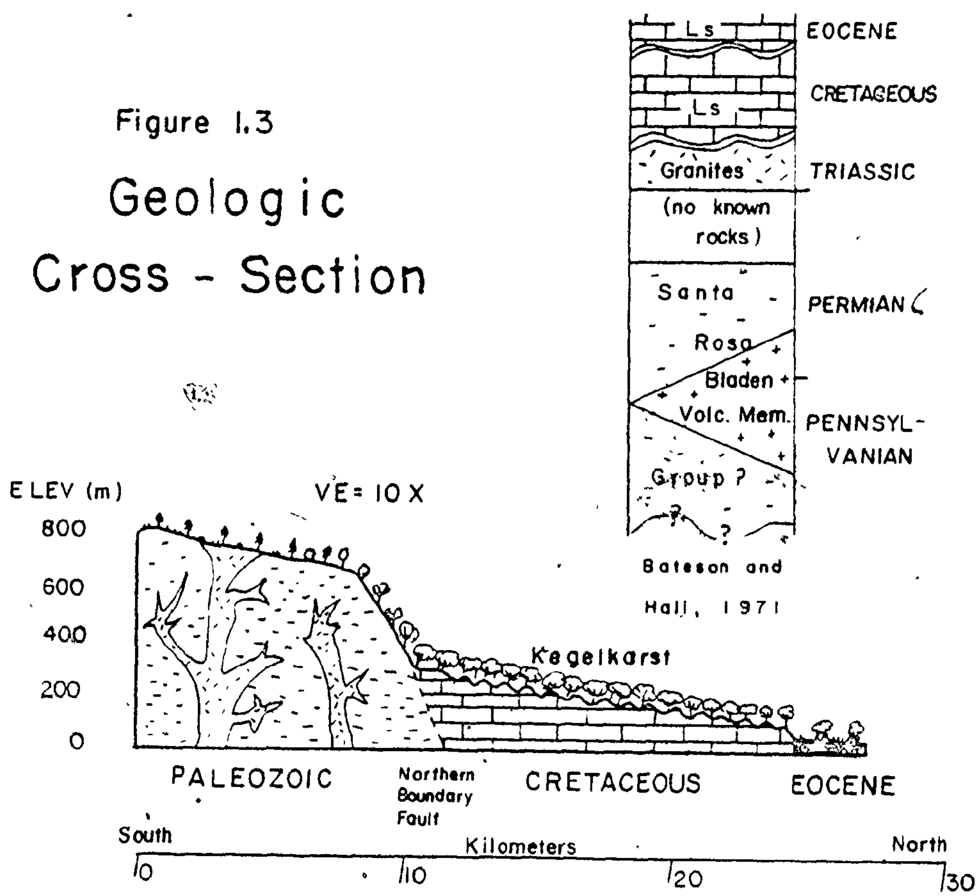


Figure 1.3

Geologic Cross - Section

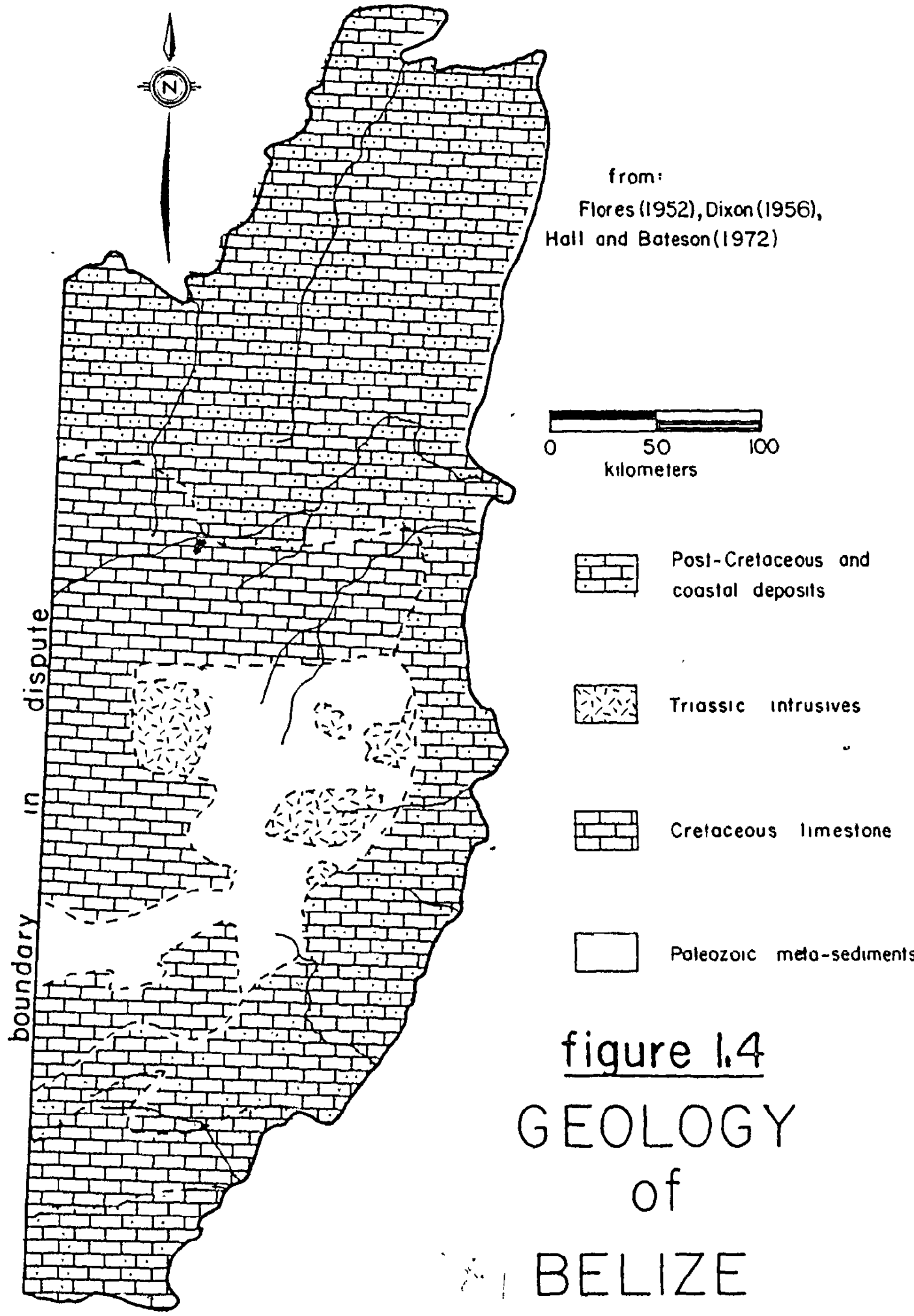


figure 1.4

GEOLOGY of BELIZE

Mesozoic orogenic phase uplifted these primarily clastic sediments to form the Maya Mountains, a "Paleozoic massif at the juncture of the stable Yucatán platform ... and unstable Antillean mountain systems to the south," (Hall and Bateson, 1972, Pusey, 1975). Some vulcanism and basalt outflow was associated with the orogeny, as well as the initiation of block faulting which left a marked NNE-SSW lineation of the rivers and lagoons as well as the submarine escarpments which form the east rim of the Belize shelf (op. cit.). Bateson (1972) believes the general uplift responsible for the lack of Triassic and Jurassic sediments and describes "the overall structure of the area [as] ... that of a synclinorium closing eastward and plunging 10° toward the west-southwest."

Continued diastrophism in the Mesozoic intensely deformed, metamorphosed, and intruded the Paleozoic rocks (Dengo and Bohnenberger, 1969). Beginning in Pennsylvania/Permian time, these rocks were covered with a clastic sediment wedge similar to the Santa Rosa series of Guatemala and others in southeast Mexico (Bateson and Hall, 1971, Dengo and Bohnenberger, op. cit; Viniegra, O., 1971). Continued sedimentation through the Permian was controlled by an island formed by contemporary acid vulcanism to the south and an east-west coastline trough on the north (Hall and Bateson, op. cit.). Following on the heels of the Permian deposition, north-south compression regionally deformed, uplifted, and forcefully intruded granites. This episode lasted until the late Triassic (Dillon and Veddar, op. cit.).

Although some scanty Jurassic sedimentation occurred, the next major event began with massive deposition of Cretaceous evaporites and marine carbonates throughout the Caribbean. These grade upward into reef facies in Guatemala and Belize that surrounded the then-extant islands of the Maya Mountains (Dillon and Veddar, op. cit.). A measure of the Cretaceous deposition can be obtained by noting that these are up to 1,000-2,000 meters thickness away from the Maya Mountains, yet thin to only 900 meters at the mountain fringes (Viniegra, O., op. cit.). At the end of the Cretaceous the west end of the Mayas was submerged and limestone and dolomite deposited there (Bateson, op. cit.). Although intense folding and thrusting occurred in Guatemala and Mexico during the late Cretaceous, only minor Tertiary activity affected Belize, and indeed some shales, siltstone and limestones were deposited over much of the area (Dillon and Veddar, op. cit.).

Since then, northern Belize has been characterized by slow subsidence and attendant carbonate deposition through most of the Tertiary, with the primary episode in the late Paleocene to Eocene (Pusey, op. cit. Dillon and Veddar, op. cit.). Quaternary sediments have filled in an arm of the ocean that persisted until late in central Belize. Tilted stalactites in the Blue Hole (a drowned doline or collapsed cave on the barrier reef) may indicate relatively recent and continued activity.

2. Local The two major elements of the Caves Branch, then, are primarily the result of massive Cretaceous carbonate deposition surrounding an ancient Paleozoic island of metasediments. The non-carbonates are separated from the low relief karst downstream by the imposing 700-800 meter Northern Boundary Fault escarpment (Figures 1.2 and 1.3).

The limestone of the Caves Branch has the restricted fauna typical of lagoonal to back-reef deposition (Flores, 1952). In the thesis area, the majority of exposures are small gray or cream-colored limestone breccias cemented in a red calcite matrix. Bedding is rarely encountered, and then only in relatively limited extent (a few scores of meters). The rock is well-fractured, and slickensides are evidence of some faulting. The latter, however, is frequently difficult to observe because the brecciation makes it difficult to observe relative movement, or amount of displacement. D.C. Ford (personal communication) states that the limestone is unusual in his experience for breadth and extent of brecciation, and the degree of clast fragmentation. Such bedding as is evident invariably has a gentle dip of 5° or less, frequently to the northeast.

Four rock samples from the Cretaceous limestone were analyzed at McMaster University. Two were of micritic clasts in the breccia (which resemble that exposed in bedded areas); one was a mixture of clast and matrix; the other was taken from a limestone tower in the Sibun area (Table 1.1). All are very pure calcitic rock.

TABLE 1.1

Rock Analyses (%)

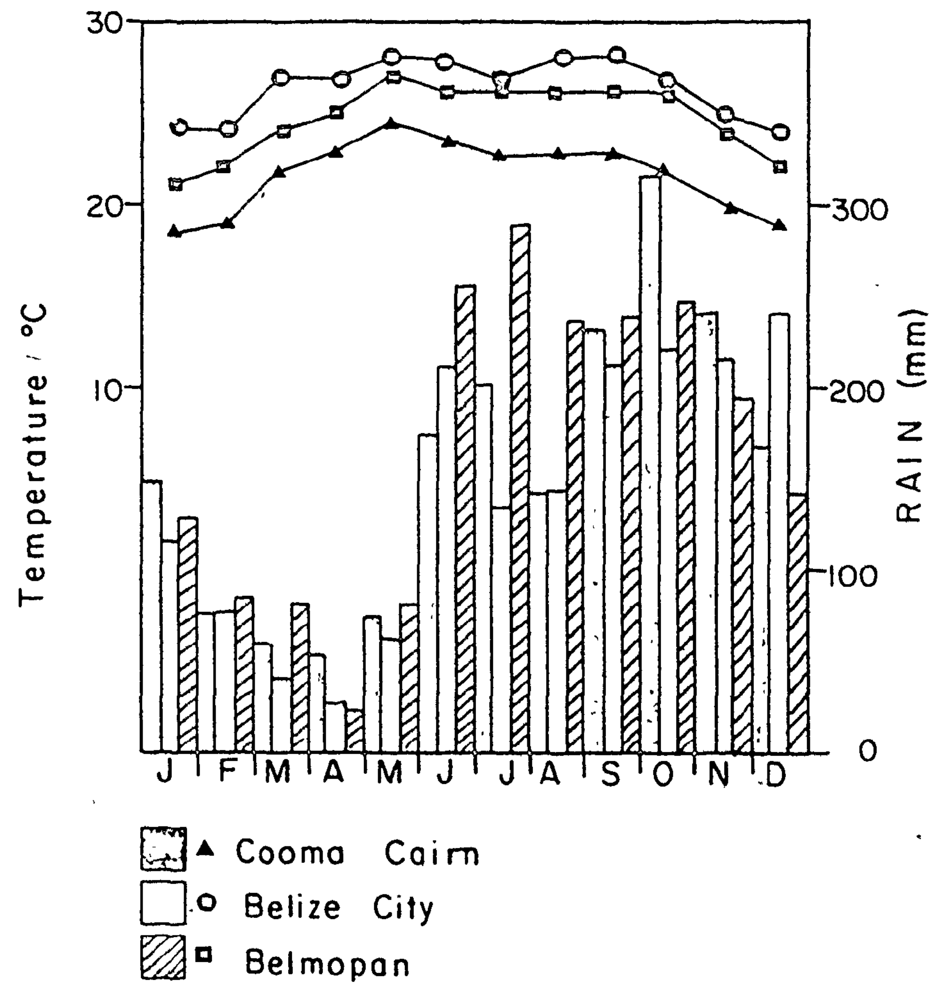
Site	CO_2	MgO	CaO
Micritic Clast	41.70	0.24	57.32
Micritic Clast	43.16	0.36	58.09
Breccia	41.80	0.92	57.08
Sibun	43.60	0.14	55.64

C. Climatological Setting

Belize is split into two sub-zones of tropical climates (Trewartha, 1968). The northern half of the country lies in a savanna-like region very similar to that of the Mexican Yucatán. The southern half, though also seasonal, is humid for all but two or three months of the year. The tropical humid climates of Central America and the Caribbean all show certain similarities, the most obvious and impressive being relatively constant weather types throughout due to the great width of the tropical zone. Day lengths vary only slightly (from eleven to thirteen hours), leading to situations where the diurnal temperature range is greater than the annual. The daily variations are due primarily to changes in cloud cover. The annual migration of the Intertropical Convergence Zone generally halts just south of Belize, such that the prevailing winds are easterly.

According to Portig (1976) the most dramatic meteorological event is rainfall. Density fronts, common in temperate latitudes, are rare in the tropics due to the uniform temperatures. Thunderstorms, and random convergence of similar, high-temperature saturated air masses, are the primary causes of precipitation. In Belize, rainfall rises with increased elevation and increased southerly latitude. Estimations of mean annual rainfall as high as 500 cm have been made for the areas northwest of Punta Gorda (Figure 1.1). Figure 1.5 shows monthly temperature and rainfall for three sites in Central Belize that range from sea level to 560 m elevation: all have annual precipitation greater than 1000 mm and mean temperatures above 20°C. At all three sites it can be observed that March and April are the driest months, with May being the

Figure 1.5



	Elevation(m)	Mean Annual Rain(mm)
Cooma Cairn	560	1877
Belize City	0	1690
Belmopan	60	1990

CLIMATE DATA, BELIZE

Selected sites

month during which the rainfall pattern is most variable.

Two other effects should be noted: occasional "northers", or outbreaks of polar air, lower temperatures to less than 10°C during the winter months. More importantly, it should be noted that only 63% of the possible solar insolation is received at the ground due to cloud interception, a major inhibitor of high temperatures.

Most of the vegetation of the area is broadleaf deciduous flora characteristic of the climate (palms, mahogany, cedar, sapote, sapodilla, bamboo, etc.). The thick dense growths are important controls on the evapo-transpiration occurring. Historical and economic causes have led to widespread logging in much of Belize since the 17th century, but high growth rates and the ruggedness of the cockpit terrain have combined to maintain large areas in proto-virgin condition. The most obvious impact upon the natural forest in the study area has been the development and maintenance of a cacao plantation in the polje of the Caves Branch River. Approximately half of this valley is under cultivation, and the remainder has been logged.

II. Research Goals

A. Past Research

The first half of the 1970's effectively marked the beginning of the application of principles of chemical equilibria to the field study of solution processes in karst terrain. The approach had been previously explored, although in a chiefly theoretical manner (Holland, et al., 1964, Roberson, 1964; Thrailkill, 1968). Regional and local studies such as those of Back and Hanshaw (1970), Langmuir (1971), and Ford (1971a), followed the suggestions of Garrels and Christ (1965) in attempting to quantify the magnitude and location of solutional erosion in carbonate terrains. Previous studies of process had employed the curves of Trombe (Ford, 1964; Drew, 1970) and other less precise methods (Stenner, 1969) to express the solution potential of various waters, or had simply used solute concentration for the same purpose (e.g. Pitty, 1966). The success and evident usefulness of the equilibria approach encouraged its application to the hydrologic problems of discriminating between different types of aquifer flow (Shuster and White, 1971; Jacobson and Langmuir, 1974) and water classes (Newson, 1972; Ede, 1972; Wigley et al., 1973; Drake and Harmon, 1973). The equilibria approach also offered an improved means of quantitatively assessing the influence of dissolved CO_2. Biogenically-produced CO_2 had long been acknowledged important in solution of carbonates, but few long-term studies of soil CO_2 in karst areas had been made (Miotke, 1974). Even fewer had been combined with hydrologic and hydrochemical samplings of the underlying aquifers (Miotke, 1973; Brook, 1976). Although Harmon et al. (1975), Drake and Wigley (1975), and Trainer and Heath (1976), had published papers suggesting regional, climatic-related variations in solutional erosion, few in-depth studies of hydrochemistry in tropical karst areas existed: Back and Hanshaw (1970), and Fish (1978, at that time in progress). Previous hypotheses of climatic solutional influences had been developed by Corbel (1954) on the basis of limited sampling of a number of karst areas. Data collected elsewhere in the tropics (e.g. Livesey, 1966; Brown and Ford, 1973) was also limited, or not yet published by the mid 1970's.

By contrast, published papers on karst morphology were in abundance from the early 1900's onward, even dealing with karst in the tropics (see Sweeting, 1972, ch. 15). Of these latter, however, nearly all were in the realm of speculation and theorizing concerning the development of karst morphology in the tropical regions, chiefly the areas known as kegelkarst (or cockpit karst) and tower karst. The major controvery centered around whether or not climate, age of development, or geologic structure, played the primary role in the development of these areas (Panoš and Štelcl, 1968; Jennings, 1971). Some more recent quantitative analysis had been applied to depressions elsewhere (Ford, 1964; La Valle, 1965; McConnell and Horn, 1972), but in the tropics was limited to Williams' work in New Guinea (1972). Although some papers (e.g. Palmer, 1975) suggested that the processes of cave formation in detail were still not completely understood, Ford (1971b) could state just four years before that no fundamental differences existed between caves in different climates. This statement could perhaps be made because so few accounts existed of tropical cave morphology, and all were descriptive (e.g. Young, 1961; Livesey, 1966).

In brief, then, some authors had suggested (but with conflicting hypotheses and data, little of which was from the humid tropics) that regional influences on hydrochemistry existed. Published results of surface morphology studies using quantitative data were quite limited in the tropics (save for Williams), and any sort of tropical cave morphology research practically nil. Publication since 1975-1976 of studies in progress at that time have partially rectified this problem -- notably Fish, 1978; Giusti, 1978; and Crowther, 1979; and to some extent McDonald

(1976) and Day (1978). To provide a better data base to address some of these problems, the initial objectives of this thesis research were to define the seasonal and areal locations of solution in a humid tropical regime, relate them to fluxes in the soil CO_2 production and concentration, and if possible to surface and sub-surface morphologic development.

The Caves Branch of Belize was selected as the site of research because of the familiarity of the author with the area. Earlier karst investigations had been made in Belize (Sweeting, 1968), or were in progress (McDonald, 1976; Day, 1978), but were mostly of a short term, exploratory nature.

B. Research Program

Field data collection occurred during 1976-79, consisting of two full seasons in the summers of 1976 and 1977, and one follow-up period in May and June of 1979. In addition, two weeks were spent in 1978 collecting water samples in the winter months of February-March. The initial field season was spent in collection and analysis of water samples, and outlining the physical framework of the local geomorphology and hydrology. Most of the data was obtained in the second season, 1977, with the installation of a stream stage recorder, tipping bucket rain gauge, and a hygrothermograph for temperature and humidity. Simultaneously, a bi-weekly program of sampling soil CO_2 concentration, and analysis of the chemical quality of a major cavern conduit was initiated. The hydrochemical variables measured were pH, calcium, magnesium and total hardness, alkalinity, specific conductivity (SPC), and temperature. Areally extensive random samples of soil and atmospheric (surface and cavern) CO_2 and water, were collected in addition to the continuous sampling program.

The final short season of 1979 was used primarily to substantiate earlier findings, concentrating on one section of the cavern system. Except for a greatly reduced number of soil CO_2 samples, however, the program was much as before, and in fact relatively more hydrological and hydrochemical data were collected. The latter sampling procedure concentrated primarily on total hardness, SPC, and pH, but added additional analysis for sulphate ions.

In all three summers there was physical surveying of both the extent and the morphologic characteristics of many individual caverns. Aerial photos were also used to outline visible lineations, cockpits, swallets and paleo-fluvial catchments. Measurements were then made of the surficial elements of two other karst areas in Central America for purposes of comparison.

The resultant data were compiled, catalogued and analyzed with the assistance of various computer programs and interpreted with respect to these present, and to previous, findings.

C. Thesis Design

The thesis is organized into three sections. The first describes the surface (Chapter II) and subsurface (Chapter III) morphology, and gives the results of analyses intended to research the history of any developmental sequence. This section is also intended to explain the framework of the physical setting and its influence both upon the general aspects of the hydrology and hydrochemistry (Chapter IV), and the interior of the aquifer (Chapter V). These latter form the second section. The final part (Chapter VI) compares the information obtained concerning carbonate solution in the Caves Branch with that of other areas, to suggest a possible synthesis of the morphology and hydrochemistry.

Chapter VII contains a summary of the thesis and suggestions for further research. It is followed by various appendices, and the reference bibliography.

CHAPTER II

THE KARST SURFACE

This chapter is concerned primarily with possible explanations for development of the surface morphology of the Caves Branch. Pertinent past research as well as work conducted during the course of this study will be cited.

I. Description of Surface

A. Highland Non-carbonates

The karst of the Caves Branch is part of a much larger area fringing the central physiographic core of Belize -- the Maya Mountains. The Pine Ridge of the mountains lies to the south of the Caves Branch, with a relatively level summit area at 900-1,000 m elevation. As described in the first chapter, it is part of a massif of metamorphosed shales, sandstones and other sediments, intruded by granites. An abrupt escarpment, the Northern Boundary Fault, separates the Cretaceous limestone from the highlands. It begins at about 200-300 meters elevation, continuing upwards to the Pine Ridge summit. Purdy (1974) quotes Dixon (1956) as saying the throw of the fault is at least 900 m.

Three separate catchments of 88 km^2 total contribute runoff from rain to the polje of the Caves Branch below. The upper slopes are covered chiefly with pines and some grass, giving way to tropical broadleaf deciduous flora below. The soil is generally thin, rarely more than a few tens of centimeters.

B. Cretaceous Carbonates

1. The Caves Branch and Actun Chek Poljes

These two relatively flat-floored valleys are extensions of the highlands' hydrological system into the body of the karst. Although underlain by the carbonates, their floors are a veneer of allogenic, relatively insoluble cobbles, gravels, and sands. They are abruptly bordered by limestone escarpments into which they have entrenched to as much as 200 meters. Across these armored beds, the invading highland waters meander for distances of up to ten kilometers before sinking into ponors in the limestone. Normal fluvial elements such as point bars, abandoned meanders, etc., are present at all points in the valleys. At places in the Caves Branch valley the river has cut trenches to ten meters depth, exposing thick accumulations of cemented cobbles. No bedrock is exposed in the valley floor, and the total fill depth is unknown. Because the river is rarely observed to attain bankfull stage (according to local knowledge), the entrenchments may indicate that the present period is one of net downcutting.

Although the present course of the Caves Branch River takes it underground, a wide, alluviated, flat-floored valley extends north from the present terminal sinkpoint to debouch on the broad plain north of the karst (Figure 2.1). Aerial photos show bordering limestone escarpments on either side which are not found in the main body of the karst. These are typical of polje and river margins in Belize and are likely indications that the valley represents a former through-flowing course of the Caves Branch River.

The opinion of most authors on the subject of origin of poljes and

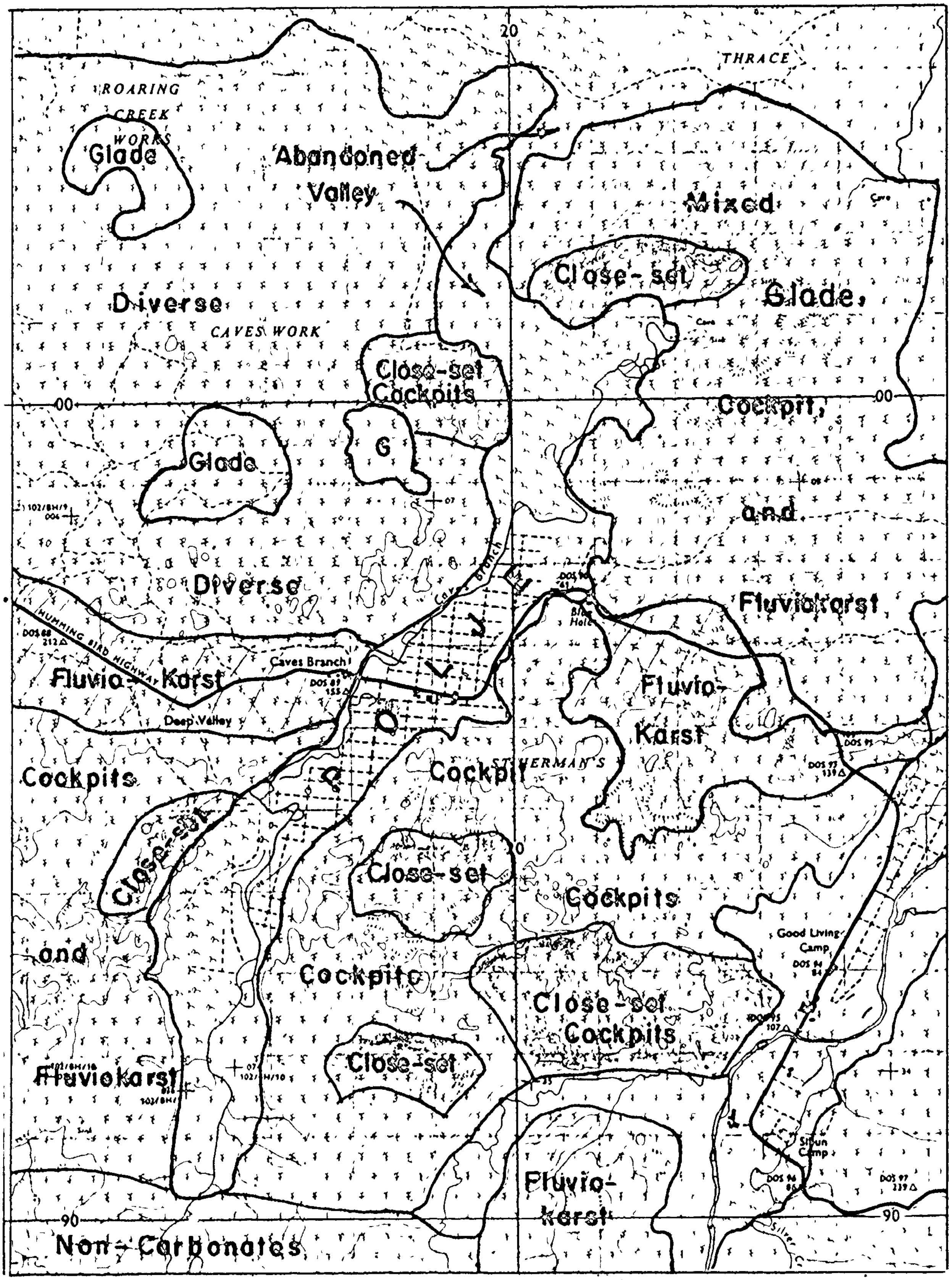


Figure 2.1 Surface Elements of the Karst

open poljes (i.e. throughflowing alluviated valleys in karsts) is that they are due to lateral corrosion by aggressive waters prevented by insoluble alluvium from downward solution (see Jennings, 1971; Sweetings, 1972). No studies have yet proved this completely. Examination of the Caves Branch field evidence shows intense corrosion and large scale pitting wherever allogenic water encounters bedrock limestone. Dissolution of the bedrock to such a degree is rarely encountered in the body of the karst and indicates that the explanation of growth by lateral attack may indeed be the most likely.

Poljes and open poljes are common in the Cretaceous karst surrounding the central highlands. Whether the polje remains throughflowing or sinks into a ponor appears to be a function chiefly of catchment size (and therefore runoff) and time (Table 2.1). Small streams from the highlands always sink, and show no traces of past surface throughflow. The Actun Lubul Ha source stream has a catchment of several km^2, which may be the minimum size (in conjunction with topographic variables such as dip) to at least temporarily maintain surface throughflow. The very largest streams such as the Caves Branch and the Sibun can armor their beds sufficiently to incise valleys completely across the limestone. In the Caves Branch case, however, its catchment was unable to maintain permanent flow, and it, too was ultimately pirated underground, leaving an abandoned surface valley.

TABLE 2.1

Areas and Penetration Distances of Some Allogenic Catchments

Basin	Area	Karst Penetration Distance
Lubul Ha	3.3 km^2	0.5 km
Chek	20.3	2.0
Caves Branch (+ above two)	87.7	9.2 (formerly throughflowing)
Sibun	249.5	throughflowing

2. The Karst

The karst of the Caves Branch is only a small part of a considerably more extensive karst belt that extends eastward to the Caribbean and westward into Guatemala. This entire karst region forms a relatively homogeneous geologic entity, with no abrupt morphologic boundaries. Description of this smaller area is thus a comment on the whole.

It is important to emphasize that the Caves Branch karst contains numerous fluvial elements, but these are, almost without exception, ephemeral. They are generally in use only during or immediately after intense rainfall. This essentially limits their periods of function to the wet season. Figure 2.1 shows known occurrences of fluvial portions of the karst.

Most surface flow in the karst is as relatively local (200 m length or less) stream channels leading to swallets in the bases of cockpits. Thick clay accumulation (at least two meters in some sites) effectively armors the sloping cockpit sides and allows runoff in discernible gullies. In very intense rainstorms, almost any soil accumulation can retard infiltration to the point that localized flow can occur. Longer stream channels have been noted even on possible bedrock, but bedrock that has been coated and armored by precipitation of calcium-carbonate in the streambed. Flow rarely persists for more than three or four hours.

In addition, there are segments of the surface karst visible on air photos that in topographic and apparent network form (i.e. dendritic) appear to be well-developed, graded fluvial catchments. Ground visits have shown only rare, incomplete localized channel elements, if any.

In other areas there are long, meandering valleys leading to the polje edge that are now segmented by dolines and perched tens of meters above the polje floor. These will be discussed in a later section.

The majority of the Caves Branch surface area consists of hundreds, if not thousands, of dolines of all shapes and sizes. This is an assemblage that in other areas of the world has been described as kegel karst, mogote karst, etc. Day (1978) attempted to quantify various karst landscapes topographically through dimensional measurement of height, width, depth, etc., and ratio combinations of these variables. He identified three types on this basis, noting that gradation between them is often present. The Caves Branch karst would be classified as Type II in his scheme because negative and positive topographic elements are equally represented in this terrain of moderately steep slopes. In the present thesis, the designation "cockpit" will be used for the major dolines of the karst. Because they appear to be the dynamic centres of erosion (Williams, 1972), the area will by extension be termed a cockpit karst. The latter is here defined as a karst assemblage dominated by macro-depressions of at least 30 meters relief and separated by residual hills.

An aerial view of the cockpits gives the appearance of smooth domed hills surrounding the dolines. The lobate hillsides often bulge inwards, and combined with the corridors that connect adjacent depressions, gives an overall star-shaped appearance. Beneath the forest cover, however, is an extremely rough topography (Figure 2.2). The hilltops are nearly completely bare rock, deeply fissured (often to several meters depth) along joints. The cockpit slopes and hilltops are frequently a stepped series of short vertical cliffs, also heavily fissured. Soil cover is thin or non-existent on upper slopes and summits except in bedrock crevices. Other

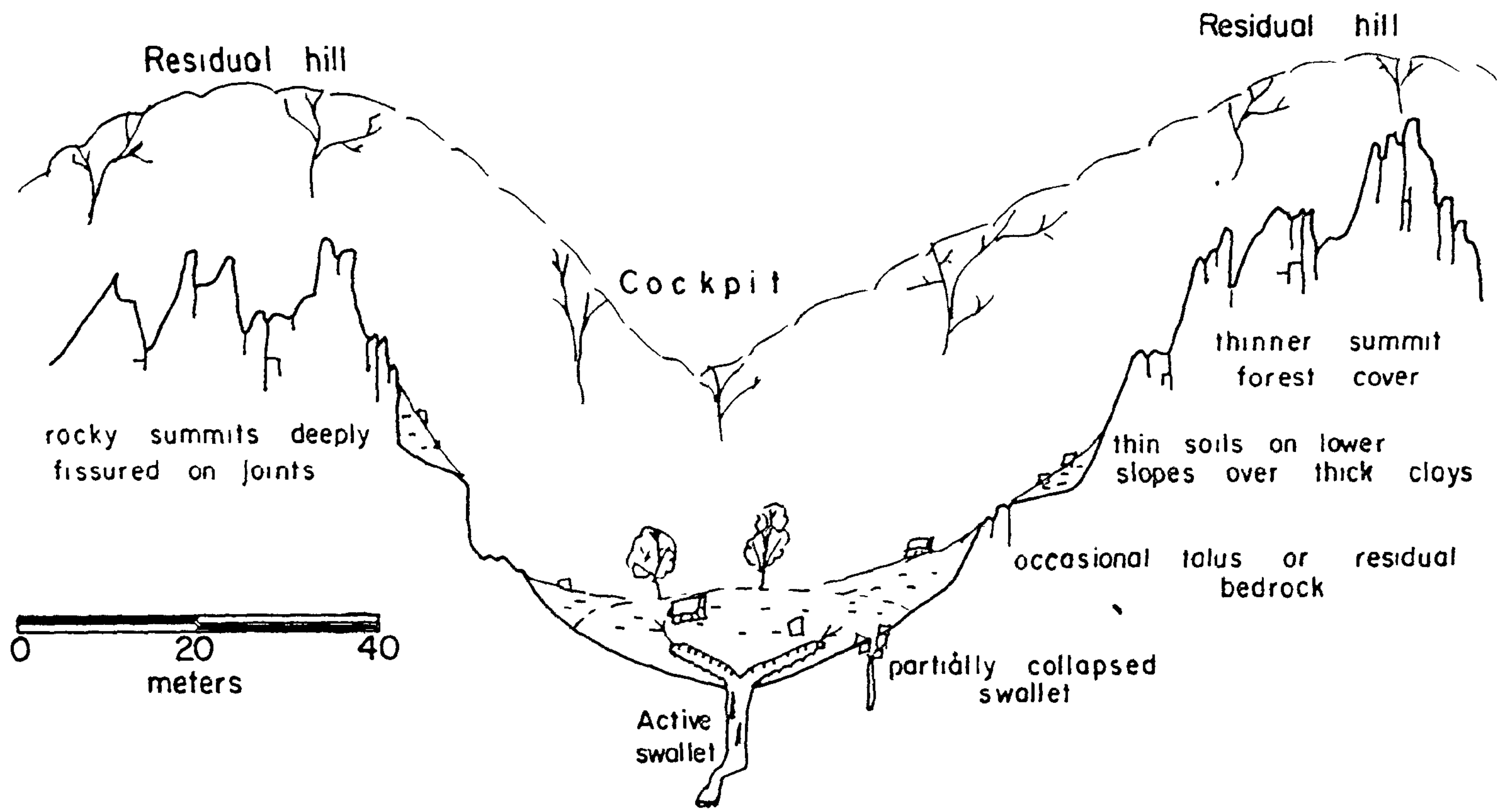


Figure 2.2 GENERAL COCKPIT ELEMENTS

authors, notably in Puerto Rico (Monroe, 1968), have described the phenomenon of induration or case-hardening of the limestone surface by solution and re-precipitation. Monroe has suggested that this process may actually protect the rock from solution. Although a very thin patina of weathered material (1-2 mm) may cover the bedrock in certain areas in the Caves Branch, the hard rock of the study area (as opposed to the frequently soft, porous rock of Puerto Rico) does not appear to lend itself to formation of the thick (to 10 m or more) crusts reported by Monroe.

Only the cockpit bottoms and corridors have appreciable soil, usually a few tens of centimeters covering relatively thick clay. Because of this alluviation, these are areas of relatively gentle topography except where detrital blocks have rolled into the depressions from above.

As mentioned previously, swallets are present in some cockpits. These are discussed in greater detail in Chapter III (see also Fig. 3.7). Not every cockpit contains a swallet, some have more than one. Not all swallets are fed runoff by a distinct gully, and not all are necessarily located at the lowest point of the depression, although all are close to it. These findings are similar to those of nearly all researchers in cockpit-like karst (Aub, 1969 a,b; Williams 1972 a; Gunn, 1977 a,b; Day, 1979).

A number of the cockpits are floored with jagged pinnacles of fluted limestone, corroded along joints, with no soil present. Any rainfall disappears immediately into the numerous open crevices. Occasional joint-aligned trenches or corridors are known, being similar to the zanjones of Puerto Rico (Monroe, 1969)

A fairly common occurrence is the nesting of smaller dolines within the larger cockpits. There are also visible textural differences apparent -- aggregations of similar-sized cockpits occur in some areas. These may occur as numerous small dolines densely packed, or as an areally large collection of very big dolines having similar sizes. Lithologic controls may be responsible.

Some alignment of cockpits is also obvious in some areas. Rather than a linear orientation of dolines of random floor and corridor elevations, there is usually a graded decline of elevation from corridor to corridor between these cockpits.

The connecting passes or corridors are smaller than those leading to other neighboring dolines, which may also show independent alignment.

Where depressions at low elevations occur only slightly above water surfaces in neighboring trunk caverns, flat alluviated floors are common. Ponors are sited at the alluvium/limestone contact. Limestone bedrock masses at these low elevations have been separated by alluvium from the main karst body. They have a steepness of slope comparable to the polje margins, and steeper than that in the karst interior. These have been termed towers in Belize (McDonald, 1976) and elsewhere.

Two final observations concern collapse features and depth of cockpit alluvium. A number of massive sinkholes are visible on aerial photos, the best known being that of the main entrance to Petroglyph Cave (Chapter III), which has a vertical extent of at least 150 meters. Although impressive, bedrock swallet caves and traverses of the karst surface show that they are of limited areal importance in surface development.

Swallet caves in cockpits are also useful sites to establish the relatively thin depth or cover of alluvium. Gullies leading to these never cut to depths of greater than four meters without encountering bedrock. Aub's (1969a) Jamaican research is pertinent in this context: he made 216 boreholes in cockpits, finding alluvial depths of only 1 1/2 to 5 meters, suggesting close correlation between the soil surface and bedrock. He believed this showed the results of soil retention rather than infilling.

In introduction then, the karst surface is affected by collapse to a small degree , by surface fluvial action to a larger degree, and most of it by some unspecified form of surface solutional activity (whether fluvial or holokarstic).

II. Analysis of Surface Patterns

Numerous origins -- collapse, surface solution, fluvial dissection, etc. -- have been proposed to explain the noted characteristics of cockpit-like terrains, indicating that there is a problem of broad scope. In addition to the Caves Branch, several other areas were studied for this thesis in the hope that they could contribute to understanding the genesis of this local area.

The general difficulties of physically traversing cockpit karst are obvious. There is extreme topographic ruggedness, thick foliage obscures vision, there are no paths, etc. Maps or aerial photos are the main interpretative aids. Problems of comparability need to be considered when map quality differs widely, or when air photos are not available with the maps.

Several types of analysis were used here, singly or in conjunction. These included measurement and comparison of swallet/cockpit dimensions, re-construction of paleo-fluvial networks, and mapping of photo-linears to compare them with distribution of the first two.

A. Cockpit/Swallet Dimensions

Williams (1971, 1972a, 1972b) investigated eight karst areas in New Guinea comprising a total of 1228 depressions. All data was obtained from aerial photos. These were measured for area, symmetry, distance and orientation to nearest neighbor, and long axis orientation. The centripetally-draining channels were ranked and ordered as per Horton/Strahler. For further comparison, the tectonic and topographic variables of dip, strike, general regional slope, and master joints were measured. The aggregate collection of variables was analyzed for nearest neighbor dispersion, and statistical comparison of the depression attributes with each other and the geologic variables. An attempt was then made to define similarities and differences between the various areas. Important to this was the application of dispersion analysis of doline nearest neighbor distances (Clark and Evans, 1954).

The nearest neighbor analysis gave results which differed significantly from that of a random orientation when tested against the standard variate of the normal curve. Nearest neighbor vectors and long axis orientations were found to be significantly related to topographic slope, master joints, and tectonic strike (in that order). Area and the internal fluvial (Horton/Strahler) ordering were positively correlated, while doline length/width ratios remained relatively constant, with respect to the fluvial ordering.

To Williams, the doline/geologic relationships, their departure from a random orientation, and the doline area/order association (reproducing Schumm's law of drainage areas), were evidence that these karsts are all to some extent aligned, even if they have no visible orientation. Thus, they are spatially organized small river basins of a special kind, attributable to surface solution rather than to collapse. Williams differentiated three distinct terrain types in these New Guinea karsts on the basis of certain similarities, all three being subsets of the cockpit karst category.

Williams' model postulated an initial horizontal or gently sloping surface with a simple master jointing system. As chemical weathering progresses, secondary porosity becomes increasingly important, concentrating the initially diffuse runoff more and more into the developing stream sinks forming at favorable sites of maximum joint inter-section. A second generation of ponors forms at less favorable sites, and like the first, are auto-catalytic: runoff begetting growth begetting more runoff. Eventually, depression pitting is complete, with boundaries established by mutual competition in a dynamic equilibrium. Local effects of lithology, topographic dip, etc., prevent the attainment of an ideal, maximum-density, hexagonal network. Williams' plot of length/width ratios versus increasing order were believed to show that internal asymmetry may increase as the ponor drainage matures, but no fundamental change in morphometry was expected without a major environmental change (e.g. the water table reached, the predominance of lateral solution, and the formation of residual hills -- tower karst). Williams notes the overall similarity of this scheme with that proposed by Grund, (Jennings, 1971) though the latter "takes no cognizance of climatic control of morphology".

Williams' work is worth reviewing in such detail because it is the most cogent cockpit development model to date that relies on actual data. Because of this, it has had influence on later authors dealing with the subject (Sweeting, 1972; Day, 1978). It was also a starting point for consideration of surface characteristics in this thesis.

1. <u>Methods</u> Two areas in Belize and one in Guatemala were chosen for similar analysis (Figure. 1.1). All three are covered by 1:50,000 topographic maps, but the Caves Branch contour interval is 40 meters, versus 20 meters for the Vaca Plateau, Belize, (Figure 2.3) and Searranx, Guatemala (Figure 2.4). It was possible to obtain photos for the Caves Branch at 1:25,000 scale, and these were used in conjunction with the map -- cockpit data was marked directly onto clear plastic overlays on the photos, then transferred to the map to eliminate photo edge distortion.

The climate of all three areas is similarly hot and humid, with mean annual temperatures above 22°C and at least 2000 mm of rain yearly. The Caves Branch and Vaca Plateau limestones are from the same Cretaceous formation; the Searranx rocks are Permian or Cretaceous, probably the latter. No prior cover is known to exist for any of the three -- it is very unlikely for the two Belizean karsts. All three have apparently been exposed for millions of years. Walper (1960) says the Searranx karst was exposed by the Pliocene; the other two were exposed no later than the Eocene, and probably before. The three have all been tectonically deformed to some extent by uplift. The Vaca Plateau and Searranx examples have similar elevations of 400-700 m, while the Caves Branch is the lowest.

Cockpits were defined as the areas of depressions individually separable by hill summits and intervening ridges. The cockpit nodes were

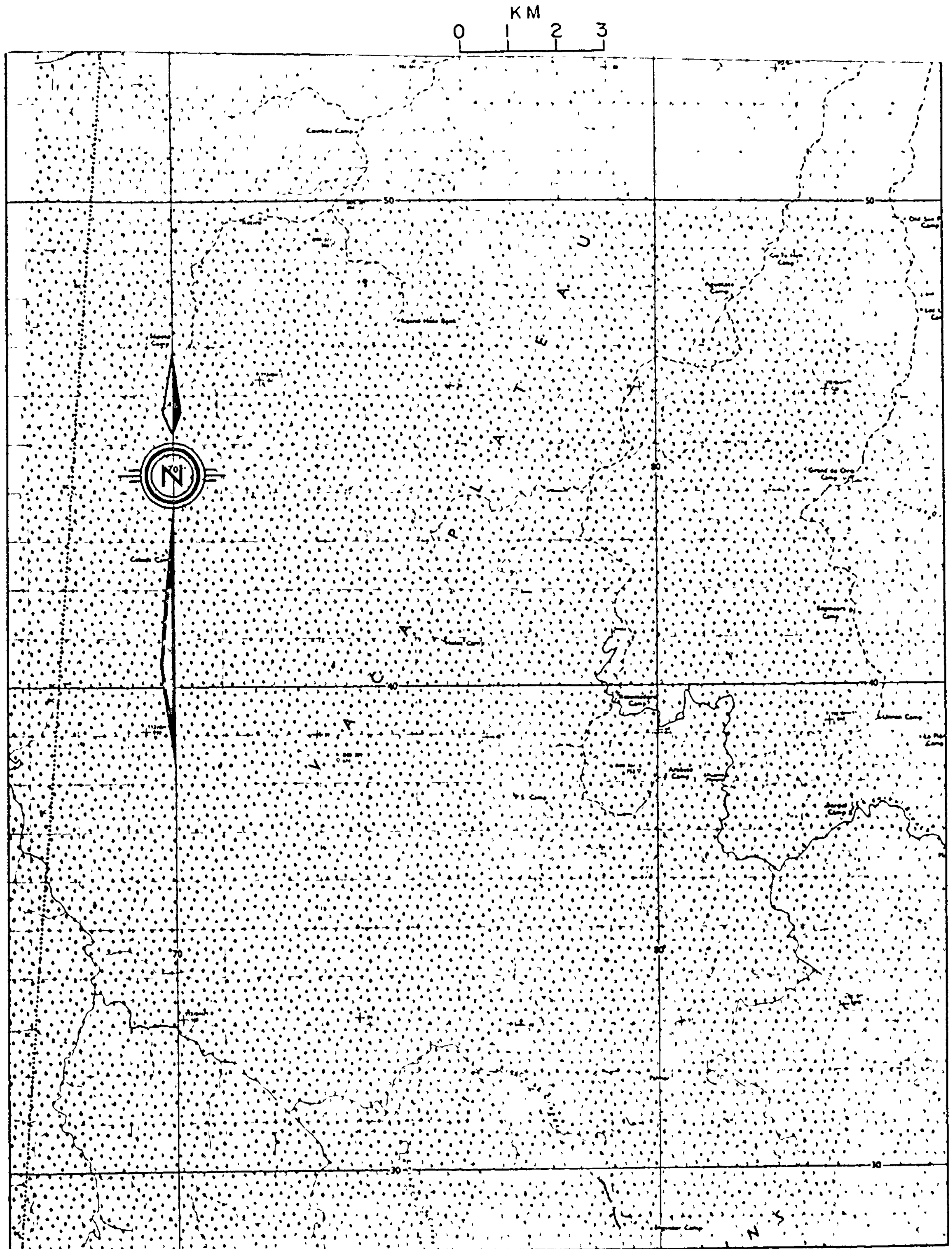


Figure 2.3 Vaca Plateau

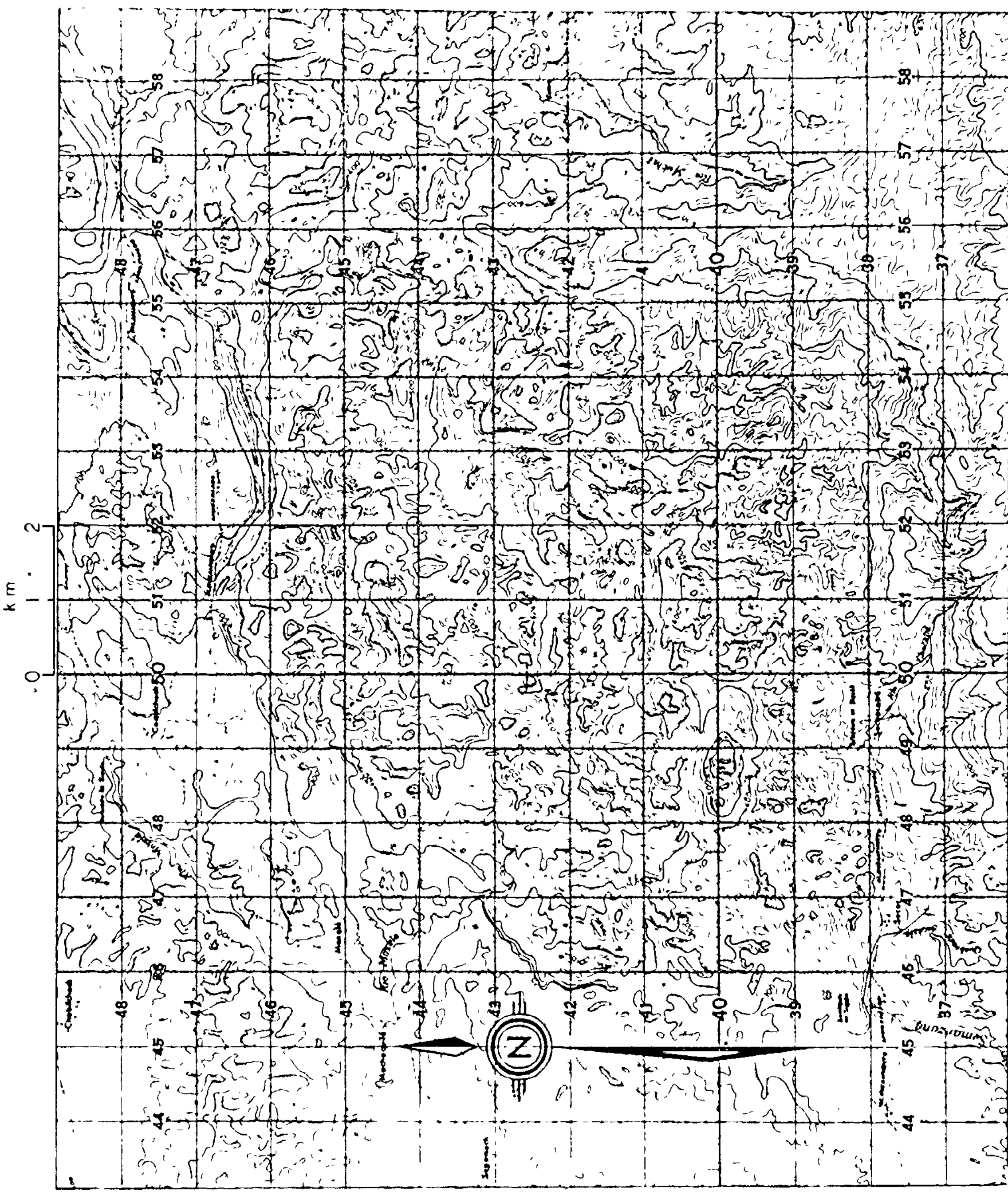


Figure 2.4 Searranx, Guatemala

defined as the lowest points of the depressions (Williams referred to these nodes as swallets). In Searranx and the Caves Branch, stream channel networks (as deduced from contours and cockpit shape) were outlined and ordered following Williams' procedure (Figures 2.5 and 2.6). Distance and azimuth between nearest neighbor cockpits were measured at all three study sites. Area was measured only in Searranx and the Caves Branch.

For nearest neighbor analysis, Clark and Evans' (1954) 'R' was used as a measure of spatial dispersion, where

$$R = \bar{r}_A / \bar{r}_E \qquad (2.1)$$

$\bar{r}_A$ = the mean of a series of distances to nearest neighbors,

and

$\bar{r}_E$ = the mean distance to nearest neighbor expected in an infinitely large, random distribution of a given density ρ.

Possible values of R range from 0.0 to 2.14 -- values less than 0.5 demonstrate clustering; above 1.57 an arrangement shows uniformity; 1.0 is random.

2. Results Table 2.2 shows a summary of results from the sites of this study; Table 2.3 shows those of Williams (1972b) in New Guinea. Figure 2.7 shows graphs from the Caves Branch and Searranx. As all cockpits in the Caves Branch have boundaries that run from summit to summit, the number of neighbors per cockpit was substituted for summits per cockpit.

The tables and graphs demonstrate the general similarities found in all eleven karst areas (8 in New Guinea, 3 in Central America) examined in this manner. In spite of differences in density of dolines between them,

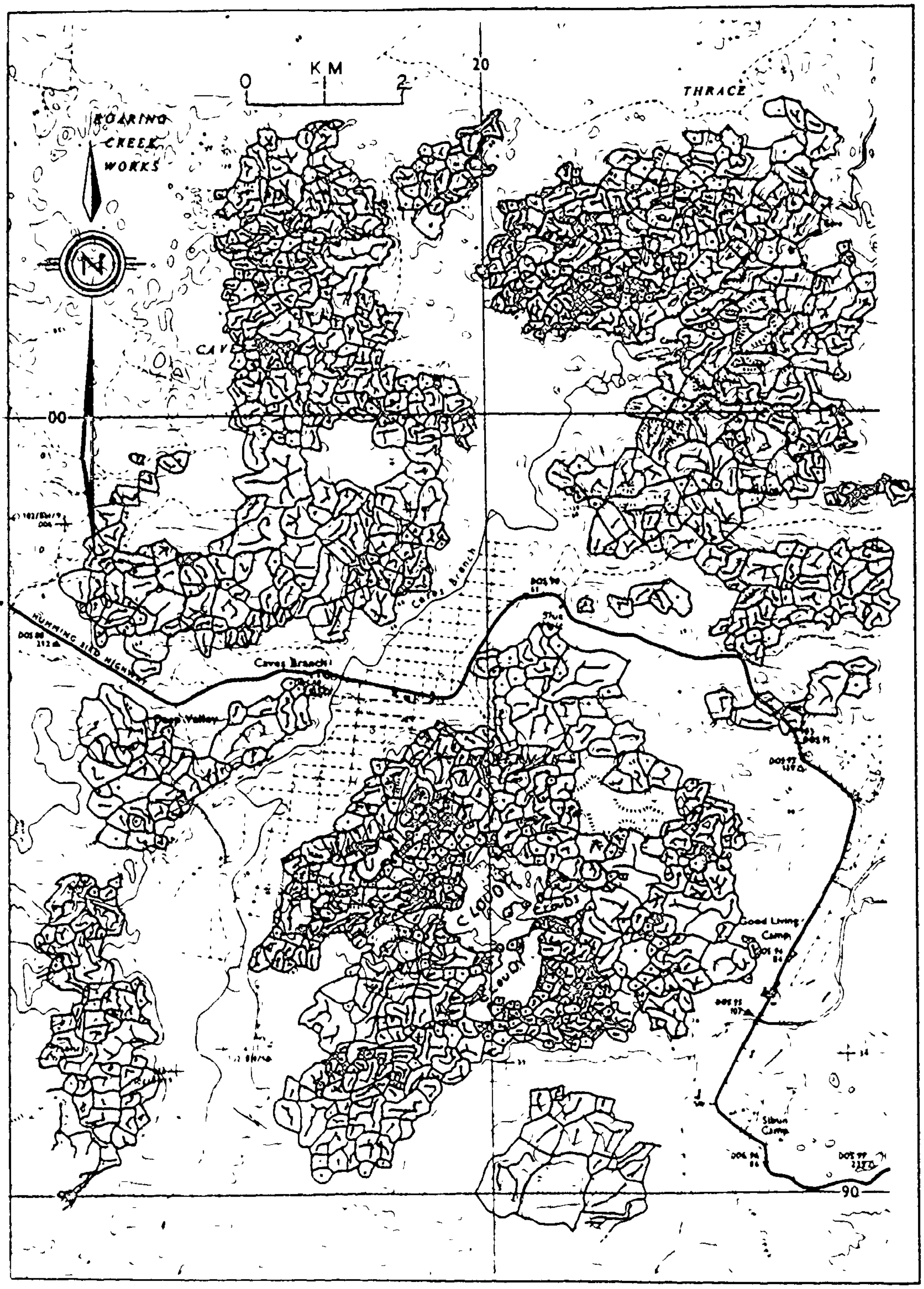


Figure 2.5 Cockpit Catchments, Caves Branch

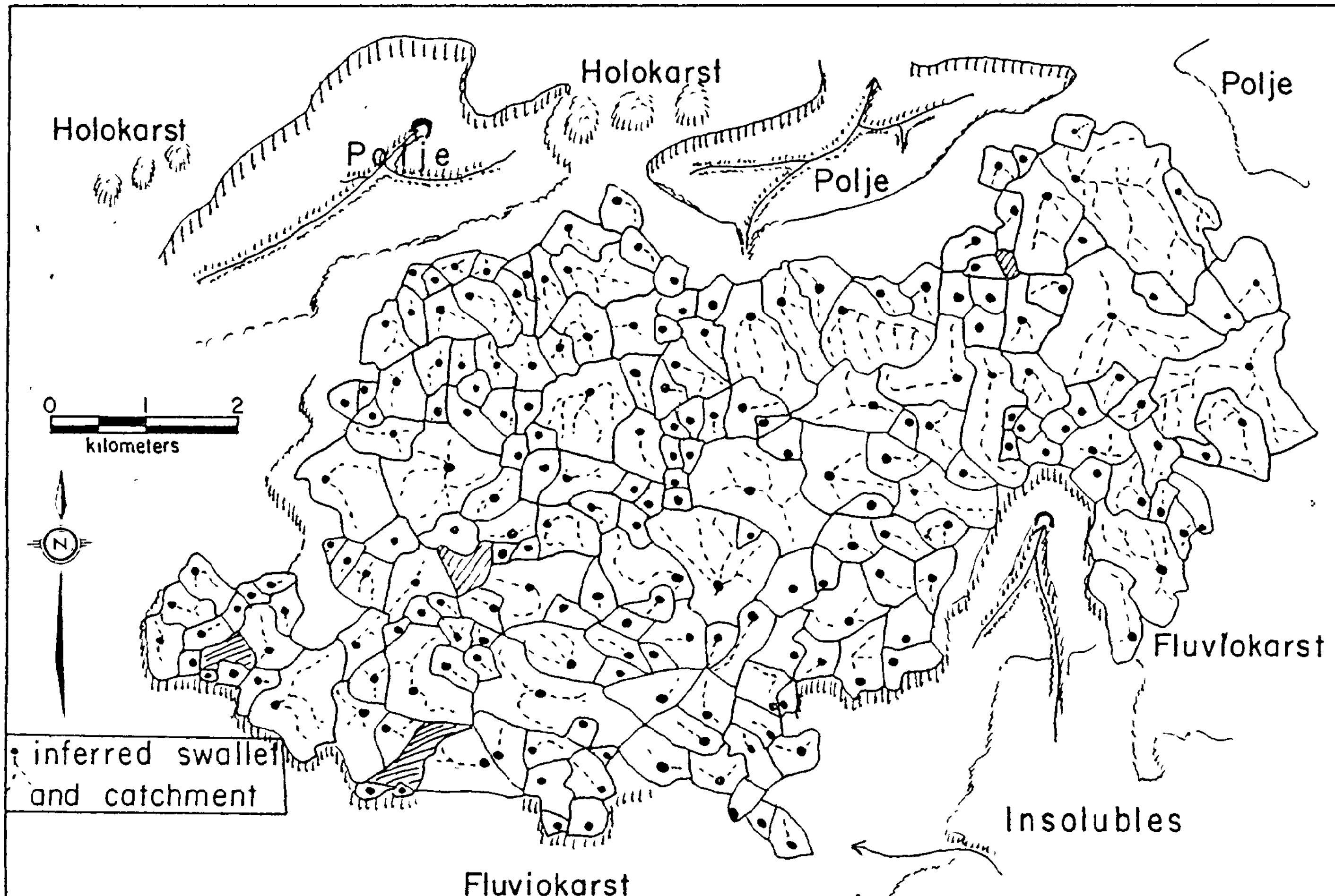


figure 2.6

The Searranx Cockpit Karst

TABLE 2.2

Cockpit Morphometry of Searranx, Caves Branch and Vaca Plateau

	Searranx	Caves Branch	Vaca Plateau
Number of Dolines	210	853	166
Area	57 km^2	43.6 km^2	76.6 km^2
Doline Density	3.7/km^2	19.6/km^2	2.2/km^2
$\bar{r}_A$	390 m	157 m	407 m
$\bar{r}_E$	260 m	113 m	340 m
R	1.507	1.39	1.20
C	14.07	144.3	42.7

Note: values as in (2.1) and $C = \frac{\bar{r}_A - \bar{r}_E}{\sigma \bar{r}_E}$ = the standard variate of the normal curve.

Searranx

Order	Number	% of Total	Mean Area	Mean Depth	Symmetry*
0	68	32	0.064 km^2	21 m	1.4
1	102	49	o.137	28	1.3
2	37	17	0.28	40	≃ 1.4
3	8	1	0.79	90	≃ 2.0

Caves Branch

Order	Number	% of Total	Mean Area	Mean Channel Length	Symmetry
0	433	51 %	0.022 km^2	0	1.66
1	320	38	0.062	164	1.84
2	98	11	0.138	482	1.92
3	2	0.2	0.247	913	1.97

* Symmetry = length of longest axis/the longest perpendicular axis

TABLE 2.3

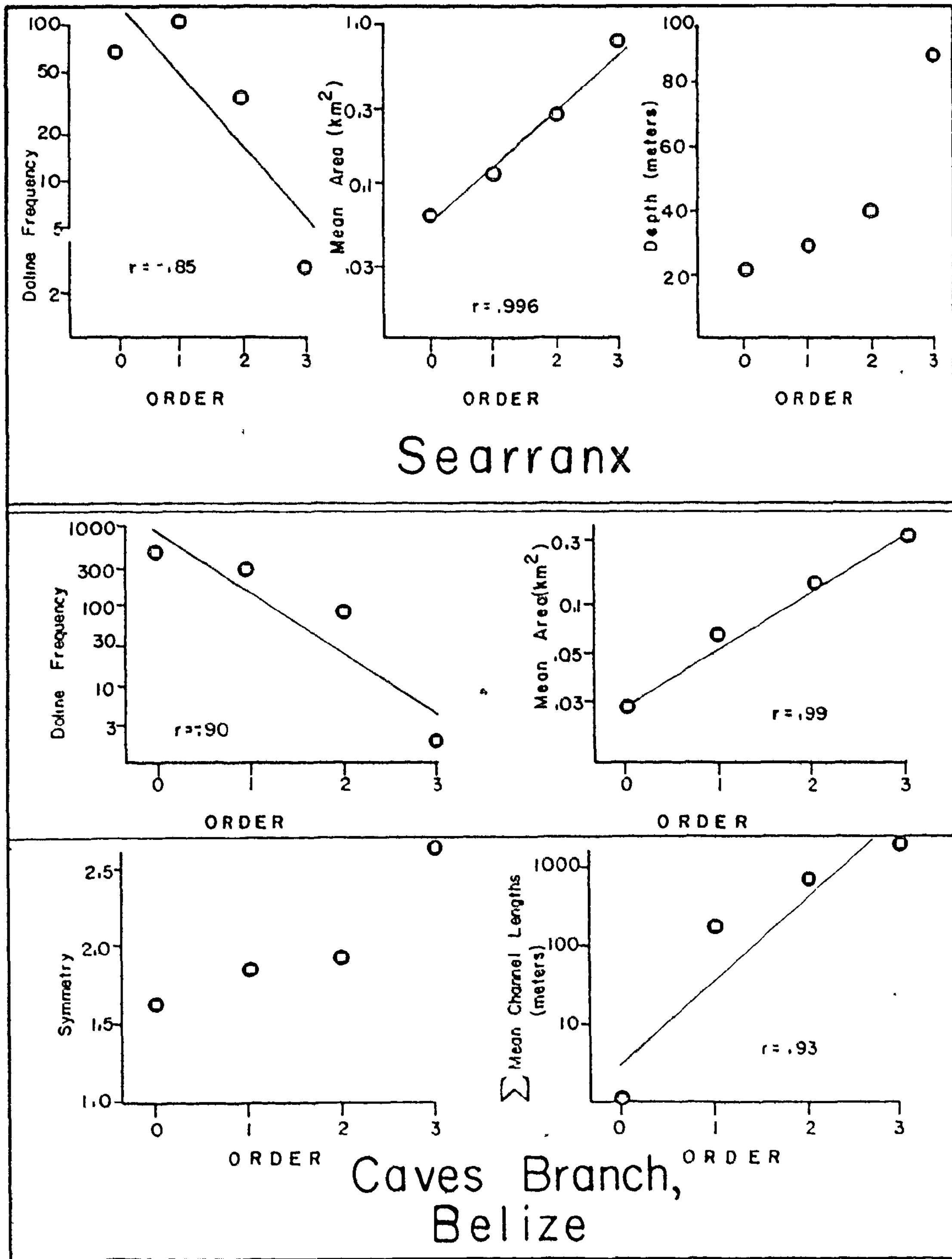
Summary of nearest-neighbour analysis, New Guinea Karsts

Locality name Abbreviation	Number of Depressions	D (per km^2)	$\bar{r}_A$ (km)	$\bar{r}_E$ (km)	R
KAP	148	20.8	0.120	0.110	1.091*
KH	172	13.1	0.154	0.138	1.116*
ET	93	17.7	0.134	0.119	1.126*
DF	185	10.5	0.193	0.154	1.253*
DD1	130	18.5	0.154	0.116	1.328*
DD2	130	22.1	0.130	0.106	1.226*
DH	188	13.5	0.191	0.136	1.404*
DR	182	18.3	0.156	0.117	1.333*

* Significantly different from random (R = 1) at the 0.05 level.

Taken from Williams (1972b)

D = dolines, other values as in (2.1)



DOLINE MORPHOMETRY
of
TWO COCKPIT KARSTS

figure 2.7

all show a positive area/order relation, and differ significantly from a purely random organization with the trend being towards uniformity.

3. Discussion Much of this type of analysis is open to criticism, particularly the basic assumptions of swallet and swallet ordering importance. As noted in the surface description of the Caves Branch, not all cockpits have swallets. This is also remarked upon by Day (1978) and Aub (1969a) in Jamaica, Gunn (1977b) in New Zealand, and even Williams in New Guinea. Swallet positions are assumed to exist, then these sites are interpreted from the air photos. Not only is the actual presence of the sink points uncertain, but their importance is unknown -- all of the above authors cite the rarity of observance of flow in such channels as do exist; as Day notes, the presence of a channel does not necessarily indicate that this is the original formative mechanism of the depression, even though the present morphology may be affected by it.

Secondly, the validity of drawing conclusions from results based on ranking and ordering the cockpits is questioned. Larger areas should correlate with larger ranking order because the likelihood of forming these orders will increase with size as greater numbers of channels will be included. Linear relationships between order and frequency, order and area, etc. have been demonstrated in network simulation to be expected even from random aggregation of "channels", given the same pre-conditions of joining and ranking set down for natural streams (Sprunt, 1972; Smart, 1978). In addition there is the problem introduced by the use of different scales of air photos, or of maps, when outlining cockpit boundaries. A "badlands" effect is produced when ordering channels on exposed bare rock:

because they are highly visible, and densely textured (as in the pinnacle karsts of New Guinea), the result is that small outcrops can be assigned a high number in the drainage order scheme. Another effect is simply the result of the resolution at which depressions of a given size can be recognized; as previously noted, smaller dolines frequently nest within larger cockpits and it is possible, for example, for the nested depressions to be identified at 1:24000 scale, and not at 1:48000. The two karsts examined from relatively close-contoured 1:50000 maps (Searranx and the Vaca Plateau) have a significantly lower density of dolines that the areas studied from aerial photos. This could affect the results of an interpretation of the dispersion pattern if two population sizes of cockpits were present, each the result of a differing process or group of processes of formation. In this context is noted Day's work in Barbados, where using air photos and field checking he found higher doline densities than an earlier study using 1:10000 scale topographic maps. However, Day noted that the relative proportions of frequencies for the given classes remained the same in spite of the increase in total numbers.

Other possible faults lie in overemphasizing certain sites out of proportion to their areal extent. Two New Guinea locations -- the Kaijende "Arête and Pinnacle", and Kaijende "Honeycomb" karsts -- are represented essentially in their entirety, a few square kilometers, when Williams' other examples are merely small samples of areas encompassing 100's of square kilometers. These two karsts are also the most indicative of operation of a random process according to the results of the dispersion analysis.

Day (1978) lists several criteria for the most effective use of the nearest neighbor statistics 1) the number of points should be large, 20 or more; 2) the area sampled should lie within the total area covered by the entire population; 3) they should be interpreted as a measure of inter-point distance, rather than of pattern; 4) "the technique should only be used to test the null hypothesis that the distance between adjacent points is that which would be expected to result from a random process; it should not be used to infer the cause of this dispersion, neither should the term 'random' be ascribed to this distribution, being reserved solely as indicative of the nature of the process responsible for its production."

The main use of this type of spatial examination appears to be that it strongly indicates that there is order in the pattern of cockpits developed in widespread areas of the tropics, and that this is caused by the influence of a non-random process. Whether this justifies the labor needed to arrive at this conclusion is a matter of opinion. Williams, as noted earlier, believed topographic and geologic influences to play a part in the network structure of these karsts. Possible structural influences in the Caves Branch will beconsidered in a later section.

B. Fluvial Network Reconstruction

The three karsts examined in Central America all appear at first glance to be either chaotic doline assemblages, or at best partially aligned. However, the last section has shown that some non-random process(es) to have operated in producing the pattern of all three. Fluvial elements are noted on both the Vaca Plateau surface and in the Caves Branch. Closer examination indicates the seeming presence of a dissected stream network of considerable extent at all three sites.

1. Methods Simply stated, dolines and cockpits on the topographic maps or aerial photos are ignored -- the landscape is treated as though the enclosed

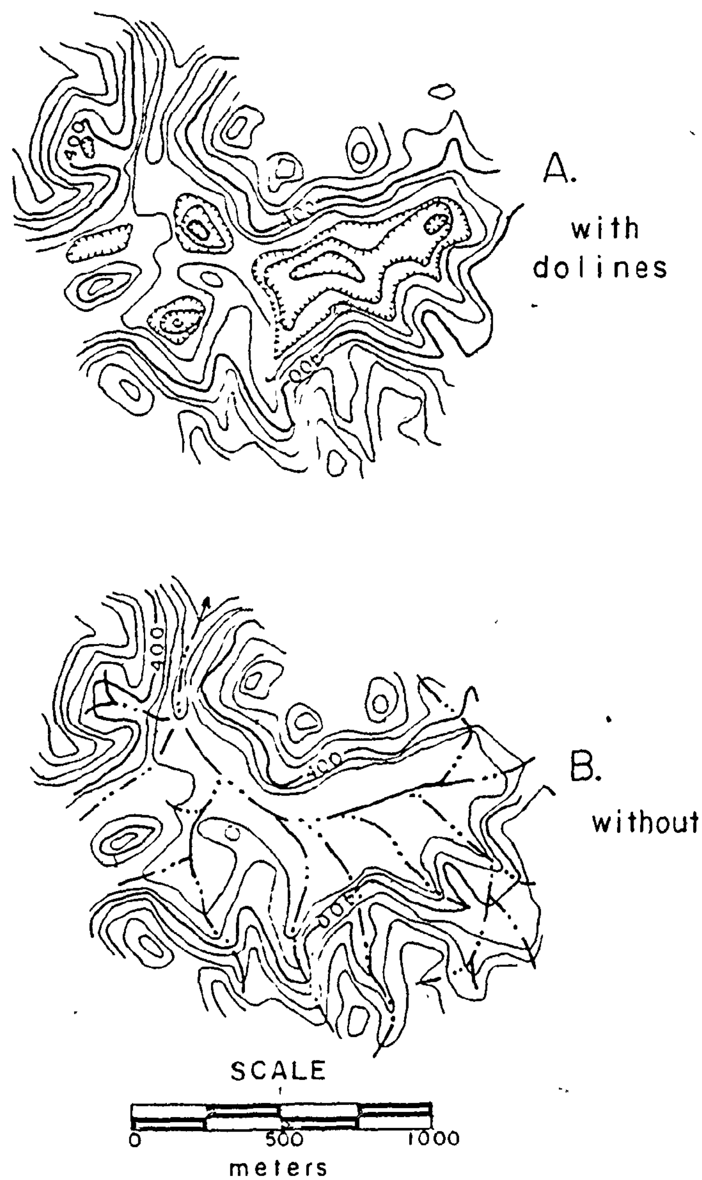
depressions were "filled in" to the level of the surrounding topography. Figure 2.8 shows an example of how this was done for Searranx. The result is that the Vaca Plateau and Searranx are readily seen to have valleys with a dendritic pattern and topographically graded profiles. Stereo-photographs were used in the Caves Branch due to the contour interval of the map available, with somewhat similar results.

Inferred paleo-stream channels were superimposed on the topography with the results shown in Figures 2.9, 2.10, and 2.11. In the Caves Branch, clear overlays were placed on the photos, and the assumed thalwegs were marked according to the topographic trend of the small ridges separating individual cockpits; this overlay data was then transferred to the map.

2. Results and Discussion Searranx and the Vaca Plateau have fairly obvious fluvial patterns. Major extended topographic lows (the valleys) are separated by topographic ridges of far greater amplitude than the minor interfluves occuring between the depressions in the valleys. These cockpit or depression interfluves descend "downstream" in a topographically graded manner, in spite of the variations in size and depth of the cockpits between them. "Tributary" valleys to the main trends are also graded in a similar fashion, and form dendritic networks. That these apparent thalwegs are not simply the result of influence of exploitation of rock partings on a general dip slope is shown by 1) the often multi-directional meandering of the valley courses, and 2) the maintenance of the remnant hill summits and valley side ridges at relatively constant elevations while the valley floor (i.e. the cockpit interfluves) descends. In addition, the chances of a group of cockpits aligning themselves randomly in such a topographic descent decreases rapidly with the number of networks involved and the

Reconstruction of
Relict Drainage

Figure 2.8



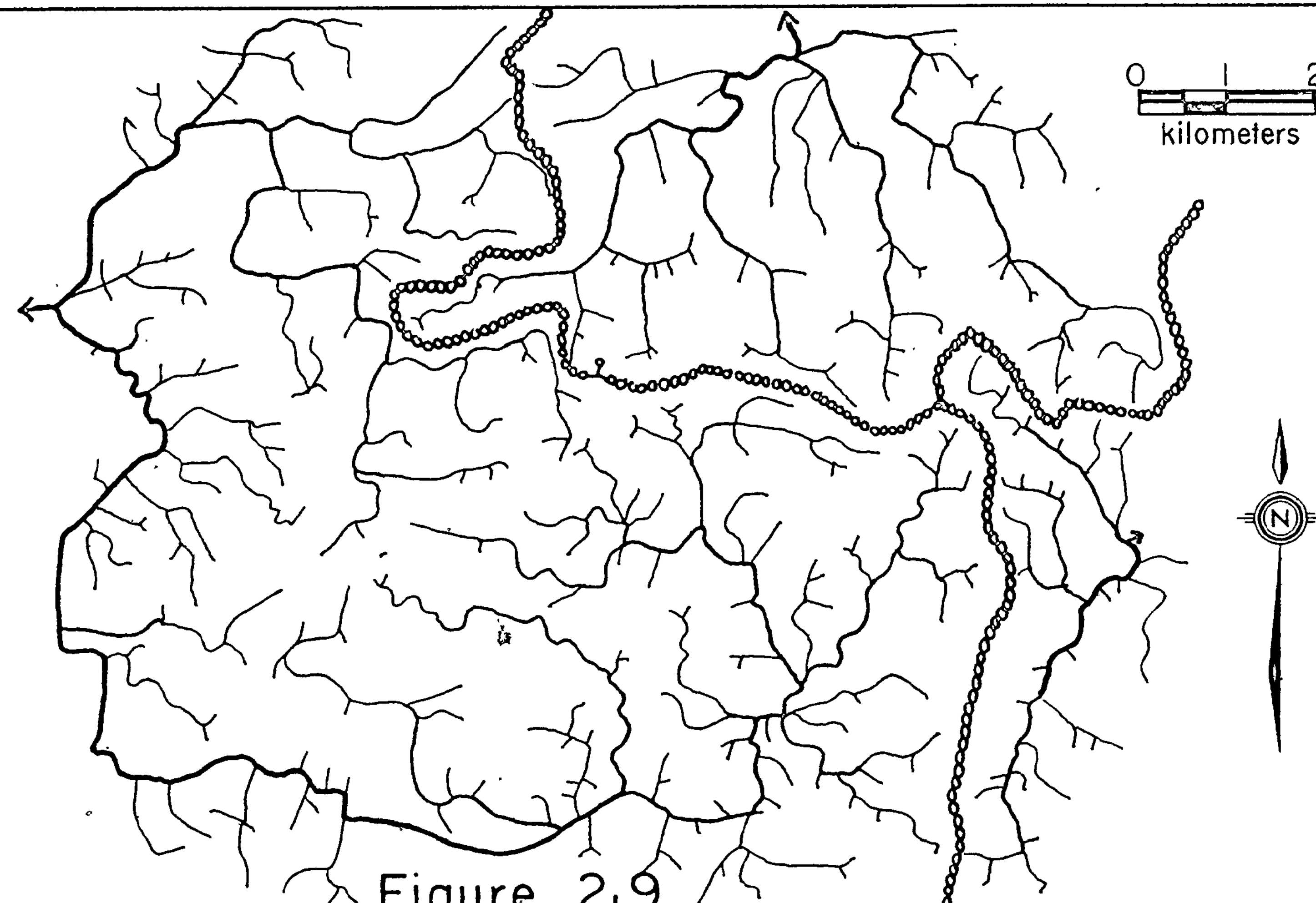
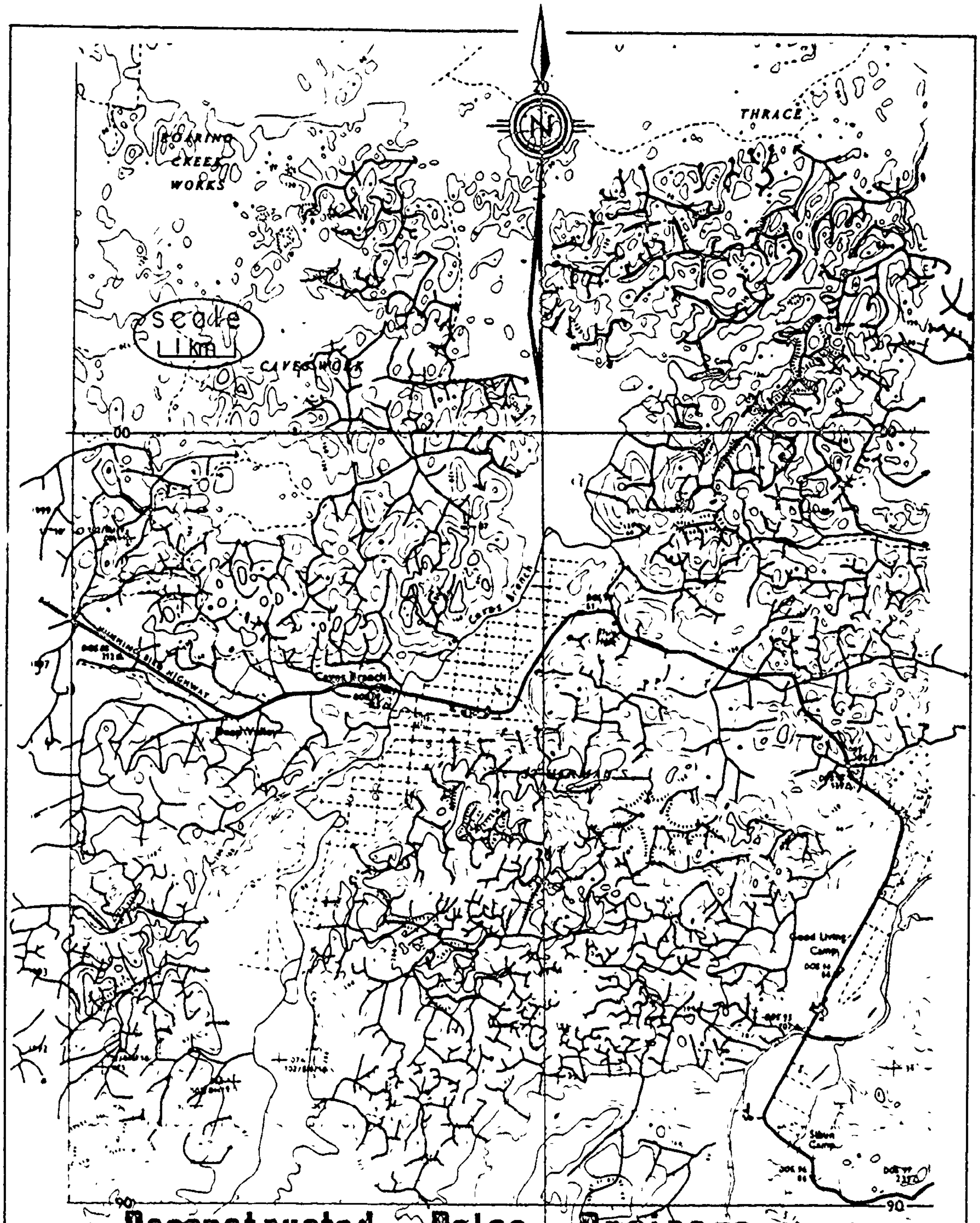
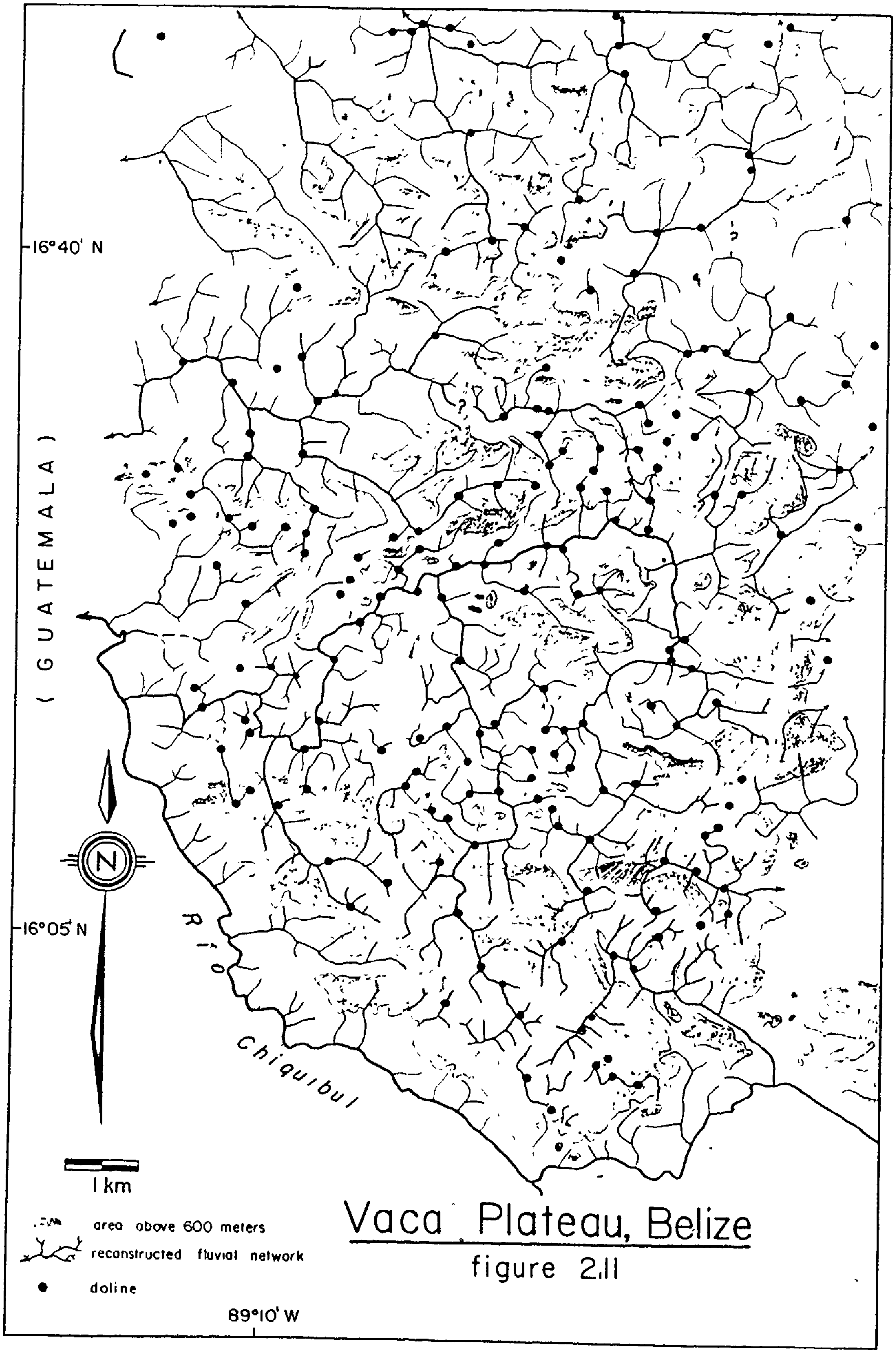


Figure 2.9
Reconstruction of Searranx Drainage



Reconstructed Paleo- Drainage

figure 2.10



Vaca Plateau, Belize

figure 2.11

number of cockpits per network. The topological theory necessary to deal with estimation of the probabilities of random alignments is not yet fully developed.

(2.1) omitted

In all three areas there are sites where "hanging" valleys debouch at considerable heights above polje floors. These appear to represent the stabilization of valley entrenchment in the past, perhaps signalling the transition to subsurface channeling of drainage. Meanwhile, the poljes were able to maintain downcutting to the present time.

In a few places in these karsts are sites where two conflicting "spillover points", or possible channel routes exist. Invariably, these divergent routes rejoin in short distances. At other sites, particularly in the Caves Branch, there are areas that show no preferred topographic alignment of cockpits along valleys. These are always located near the head of relief valley systems, or at likely interfluves. These two characteristics are probably demonstrative of disaggregation occurring since abandonment of the valleys, and also suggest the possibility that surface stream networks may not have covered 100% of the entire karst areas.

Conclusive evidence (e.g. stream sediments) has not been found in the Caves Branch, and the Vaca Plateau and Searranx have not been physically visited. Small rounded pebbles found in swallet caves in the Caves Branch could easily be due to fluvial action within the host cockpit. With the exception of clays, fluvial sediments could be expected to be limited in an authigenic stream system developed on the pure limestones of the area. Almost no clastic material is found in the authigenic inlets and spring caves draining the karst. If the entrenchment of the Caves Branch River fifty meters below the hanging valleys is an indication of the great age of a disaggregated stream network, such sediments may possibly not have survived.

Of the three examples, the Caves Branch karst network is most problematic. As mentioned earlier, the hypsometric detail of the topographic maps is rather coarse (40 m contour interval) and merely hints at networks of the scale so readily visible in the Vaca Plateau and Searranx. The most obvious valleys of topographically descending doline networks are also quite linear and could conceivably be simply macro-exploited joint or fault alignments. The network shown in Figure 2.10, then, conforms to the "laws of fluvial morphometry" (i.e. the frequency of examples of a particular stream order within a catchment, the areas drained, the mean channel length of individual segments, and the cumulative mean channel length, all increase linearly with increasing order) and is a collection of topographically aligned dolines where the probabilities of such alignment being obtained from random origins is slight. However, the internal relief is such that only rarely do obvious valley walls parallel the alignments, and the gaps between the "connected" dolines are nearly as prominent as the passes to dolines assigned to other networks. Although fluvial remnants are apparent in the non-cockpit areas, the network outlined in the cockpit sections is unsatisfactory and inconclusive compared to the Searranx and Vaca Plateau karsts.

C. Photo Lineations and Topographic Alignments

The influence of rock partings -- joints, faults, bedding planes, etc. -- upon the development of secondary porosity and permeability has long been noted in carbonate terranes, as well as other areas. Recent research has indicated some correspondence between photo-lineations and fault/joint sets of the host rock. An area of the Caves Branch was chosen to test possible correlations between cockpit distribution and fault/joint sets assumed to be expressed as photo-lineations.

There are varied opinions concerning the significance of lineations. The majority of investigators believe there is a relation between them and joint and fault patterns, but this view is not shared by all. Boyer and McQueen (1964) found a "clear relationship" between linear fractures and mapped bedrock joint patterns in rocks of less than 5° dip, while Lattman and Matzke (1961) noted no correlation in strongly folded areas. Of relevance to karst studies are Lattman and Parizek's (1964) findings that wells located on "fracture traces" in dolomite or limestone gave higher yields and had more cavernous openings than wells elsewhere in the same rock. Further statistical study (Parizek, 1976) of 37 wells demonstrated that lineament wells were more productive and less variable than others in the same setting. His measured lineaments were from 3 to 33 m in width.

On the other hand, Brown (1961) found that the distribution and orientation of airphoto linears does not always agree with structural features. Faults were accurately depicted by linears, as well as joint sets, but not always consistently for the latter. Finally, Meisler (1963) and Ogden (1976) found no correlation between lineaments and well yields in West Virginia and Pennsylvania.

Several studies have noted relation of caves to lineations. Wermund and Cepeda (1977) found that fractures apparently controlled cave formation in the Edwards limestone aquifer of Texas, and that these fractures showed good agreement with field and office (air photo) measurements. Kastning (1981), in the same general area, noted that distributions of linear cave passage segments, and structural lineaments mapped from aerial photos, agreed in orientation, although differing locally in frequency and extent. Kastning and Kastning (1981) investigated an area in western Kentucky and noted that some lineaments and distinct doline alignments corresponded to known subsurface water courses and cave passages.

Lattman (1958), and Wermund and Cepeda (op. cit.) have noted the effect that viewing time, alluviation, man-made features, and observer biases can have upon the number and location of lineations mapped. However, the former observed that acceptable precision and accuracy was obtained by different observers in the same area, after sufficient practice elsewhere.

1. Methods El-Etr's (1974) proposed terminology will be followed, where "lineation" is defined as a "natural linear feature of any length within or on a rock exposed or partly covered by surficial material", and "linear" is "any lineation ... less than ten kilometers long". Both terms are descriptive and non-genetic, and will be used interchangeably in this section.

In the Caves Branch, 275 photo lineations were identified and measured for length and azimuthal orientation (Figure 2.12). The lineations were identified on the basis of differences in tone, vegetation growth and tone, and obvious alignment of natural features (ridge tops, dolines, vegetation, etc.). It is emphasized that most lineations were a composite of these elements, and extended across ridges, valleys and other doline

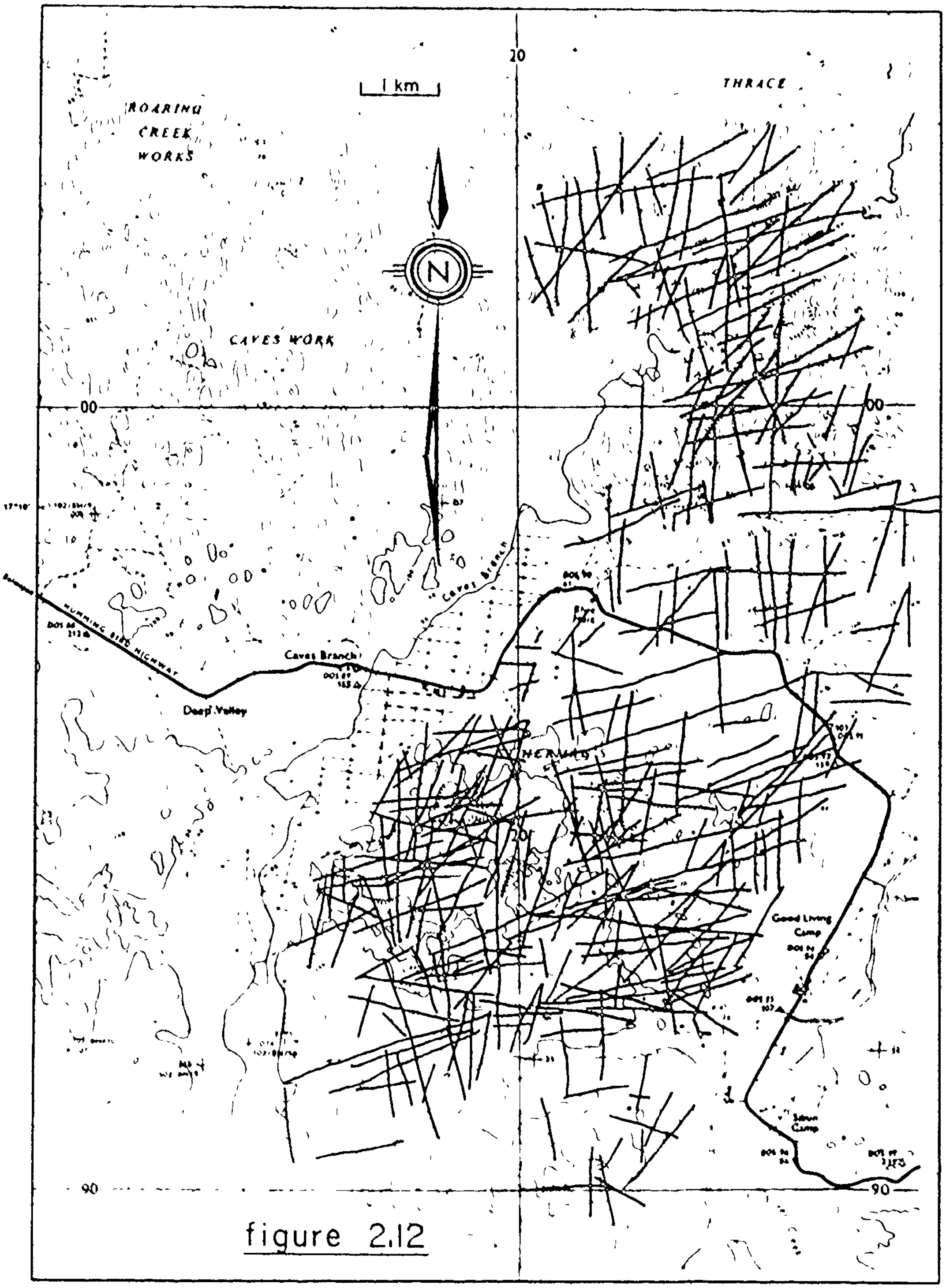


figure 2.12

Photo Lineations, Belize

alignments. They were only rarely an expression simply of depression alignments. No man-made interferences were present.

Interference from alluviation, vegetation, and occasional cloud cover are responsible for most of the interruptions in what is probably one sustained lineation. Lineations were copied onto transparent overlays, then transferred to the topographic map of the area.

2. Results and Discussion The pattern of the observed photo-lineations is shown in Figure 2.13. Total measured length was 335.6 km, giving a mean of 1220 m/lineation, and a density of 7.70 km/km^2. Frequencies of orientations are graphed in Figure 2.13, with use of a one-tailed chi-square test of uniformity of dispersion to examine for significant orientations:

$$X^2 = \sum_{i=1}^{k} \frac{(o_i - e_i)^2}{e_i} , \qquad (2.3)$$

where o_i = observed frequency for the i^{th} cell

e_i = expected

k = the number of cells

x^2 = the chosen chi-square value for a given probability

The critical value for the rejection of the null hypothesis that none of the orientation groupings are significantly aligned (to 0.05 probability) is 4.74% for each of the 36 10° cells of the lineations. A marked peak of 60-80° and lesser peaks at 350°-5° and 15-20° appear similar to regional fault trends and cave passage orientations.

As an apparent correlation between photo-lineations and cockpit nodes was observed, distances between the nodes and the nearest portion

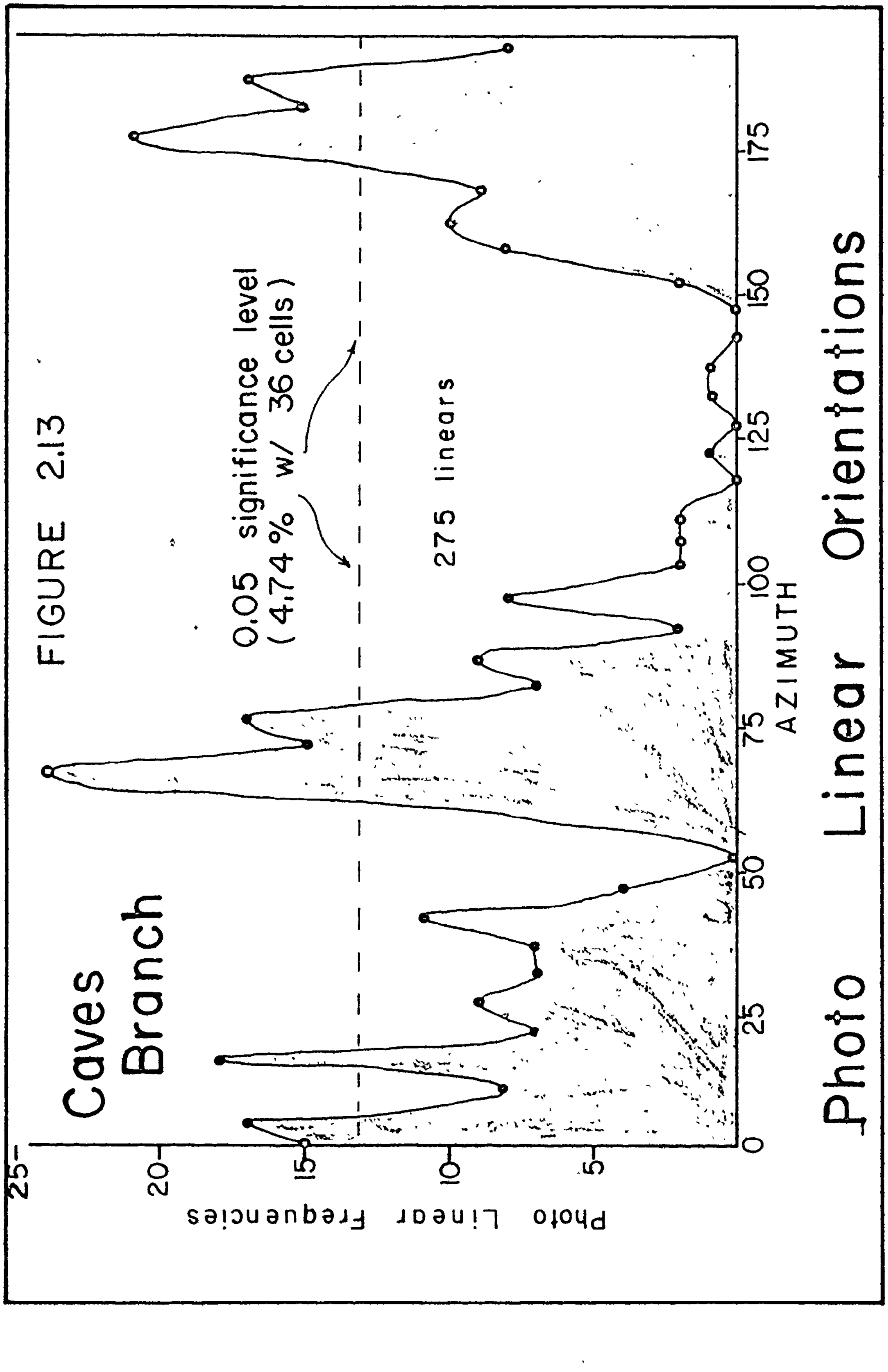


FIGURE 2.13
Caves Branch
0.05 significance level
(4.74 % w/ 36 cells)
275 linears
Photo Linear Frequencies
0
25
50
75
100
125
150
175
AZIMUTH
5
10
15
20
25
Photo Linear Orientations

of a lineation were measured. It is noted again that as linear alignments of cockpits in valleys were used to identify some parts of some lineations, correlation to a certain degree in these cases is expected, but nearly all lineations were composites of other features of the terrain as well. The portion of karst used in this analysis and outlined in Figure 2.12, has an area of 17.9 km^2, 75.4 km of lineations, and 255 cockpits and depressions.

The number of swallets (or cockpit nodes) within a given distance of the lineations was measured. This total was then compared with the number expected from a random distribution of swallets for the total area covered by lineations of that width. The arbitrary widths chosen were 12.5 and 25 meters, similar to Parizek's (op. cit.) findings that lineation widths varied from 3 to 33 m. The numbers expected for a completely random distribution were 13-14 for 12.5 m width, and 27 for 25 m. The actual values of 44 and 65, respectively, were far in excess of the 0.001 probability exceedance values of 26.7 and 45.2.

It is highly unlikely that the observed association of photo-lineations and cockpits is due to chance. Given the similarity between regional fault trends and significant alignments of photo-lineations, it is logical to assume the latter represent expressions of the major fracture systems of the area; the lineation/cockpit node associations then, appear to be due to localization and enhancement of solution along the fracture patterns presumably represented by the lineations.

Summary

The major karst areas of Belize are formed on Cretaceous limestones. These karst are all invaded by allogenic streams from the non-carbonate Maya Mountains.. These streams penetrate the karsts to appreciable distances in poljes or wide valleys armored by alluvium of unknown depth. The penetration distance is generally a function of catchment area and discharge, but whether or not piracy of allogenic water to within the karst occurs, these allogenic streams form the basic skeletons of integrated drainage in the karst. Authigenic discharge enters these drainage systems in numerous low discharge inputs.

The Caves Branch River is the major stream in the study area, collecting two smaller allogenic sources routed through the karst via large trunk caverns. Presently, all flow enters cavern systems, but the Caves Branch River at one time appears to have been throughflowing.

Surrounding the polje is the karst, most of which is covered by hundreds of dolines and/or cockpits up to 60 m in depth. Large collapse features exist, but appear to be of minor significance compared to the cockpits and apparent paleo-fluvial elements forming the remainder of the surface. The vegetated karst surface is deceptively smooth. In actuality, it is very rugged, with rocky hill summits, and steep rocky slopes surrounding depressions containing thin clay and soil deposits. Many of the cockpits contain primitive drainage systems in operation only during intense rainstorms. Those with such networks drain to swallets in the cockpit bases, but swallets are not universal cockpit features, and do not always possess drainage.

Two additional Central American karsts (Searranx, Guatemala and the Vaca Plateau, Belize) were analyzed with the Caves Branch in a manner similar to Williams' (op. cit.) work in New Guinea. Williams' conclusions that cockpits are due to operation of solutional surface drainage networks is not necessarily valid as discussed in this chapter. Searranx and the

Caves Branch all showed similarities to the New Guinea karsts studied in the type of Horton/Strahler analysis employed by Williams. All three Central American karsts shared the common findings of the New Guinea dispersion analysis investigation in that all showed significant evidence of operation of a non-random process tending towards uniformity. It was found that the karsts demonstrating the greatest trend towards a uniform dispersion were generally areas with pronounced evidence of past fluvial dissection.

Karsts showing evidence of paleo-fluvial activity are widespread in the tropics, with examples cited by Williams in New Guinea; Day (1978) and this thesis in Guatemala; Lasserre (1954) in Guadeloupe; Monroe (1973) in Puerto Rico; and this thesis, in Belize. Nearly all of these are karsts with evidence suggesting millions of years of exposure and denudation. The importance of past fluviality in forming karst landscapes and positioning depressions has probably not been fully appreciated in development of cockpit landscapes. This is probably in some measure due to lack of adequate hypsometric data in the form of good topographic maps. The major reason, however, may be simply failure to search for these fluvial remnants, as most recent hypotheses of formation have tended to ignore or disregard their presence.

The Caves Branch contains certain paleo-fluvial karst features, but it cannot be conclusively demonstrated that these processes were predominant in creating the present landscape. Mapped photo lineations showed preferred orientations similar to regional fault trends, and in one area they were found to be significantly associated with cockpit occurrences. It is suggested that the present karst surface of the Caves Branch is primarily influenced by solutional exploitation of intersecting joint sets, as suggested by Williams' New Guinea work. Collapse of underground cavities plays a minor role, and fluvial action an unknown amount. It would be logically expected that any past fluvial courses would also be positioned with reference to exploitable jointing systems. The separation of the Caves Branch karst into areas of primarily paleo-fluvial form, and areas of primarily cockpit occurrence (as well the further separation of the cockpit areas into regions of different cockpit densities or textures) is either due to the great age of the Caves Branch having destroyed fluvial relicts, or lithologic bedrock differences, or some combination of both.

CHAPTER III

CAVERN MORPHOLOGY

All discharge of the Caves Branch area ultimately undergoes transport through the cave systems. Development of the cave network has undoubtedly influenced its hydrology and geomorphic history, and its measurable hydrochemistry. The latter can be more easily understood in the context of the channeling cave systems.

Historically and popularly, a cave or cavern may be defined as a "natural roofed cavity in rock which may be penetrated for an appreciable distance", (Bretz, in Sweeting, 1972, p. 130). Genetically, a cavern can be said to exist when primary rock openings attain widths of approximately four to five millimeters, the threshold of turbulent phreatic flow. At this size hydrologic conduits function similarly in both hydraulics and solution kinetics, and differ fundamentally from smaller openings. The former definition will be used in this chapter because it will deal with features of explorable dimension, as discussed in Chapters IV and V.

I. Classification

Extent

Several score caves were examined in the Caves Branch, (Figure 3.1) and another dozen visited elsewhere in Belize. In the Caves Branch, some 40 kilometers of cave have been explored, of which 33 km have been

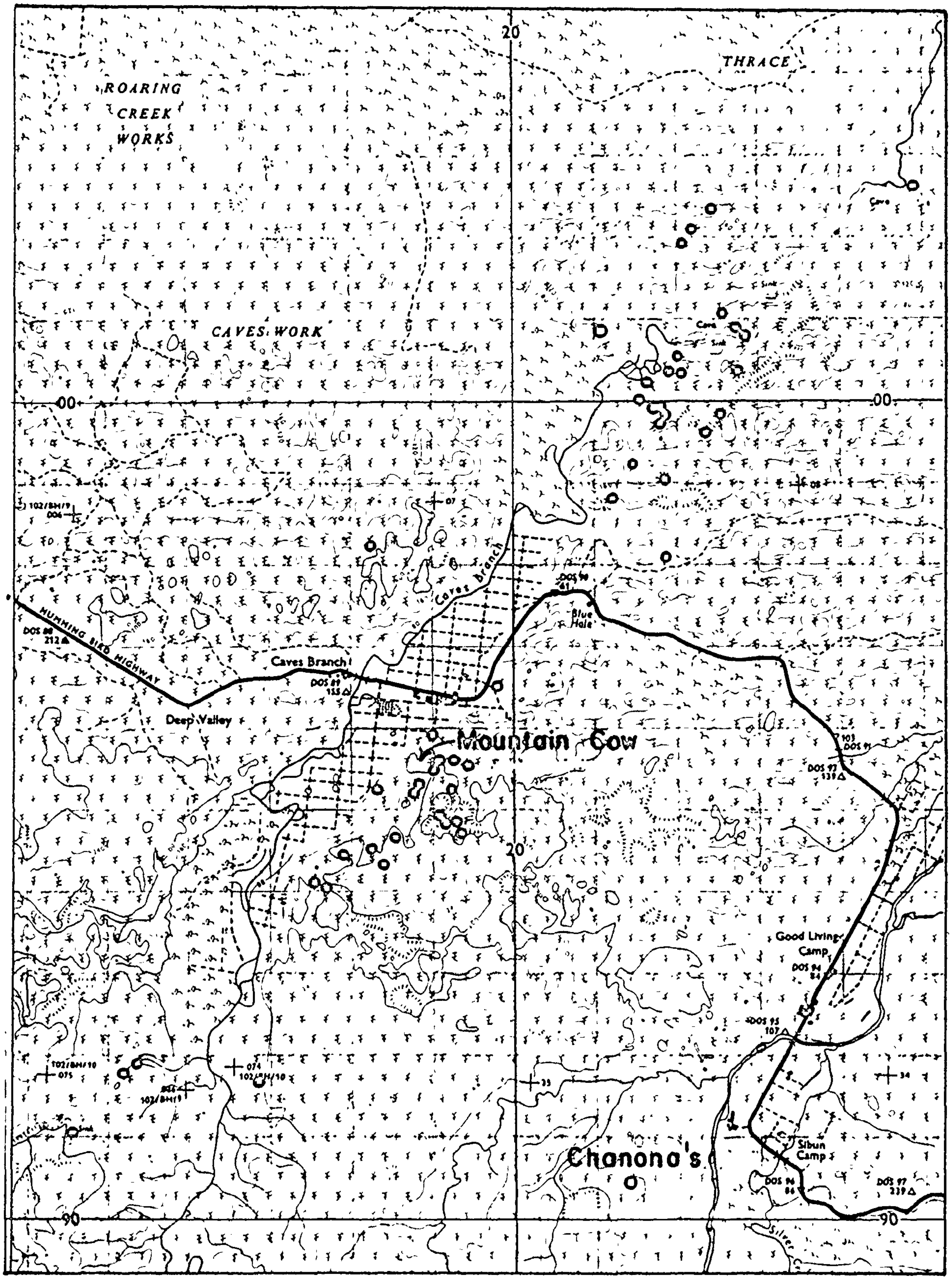


Figure 3.1 Non-conduit Caves, Caves Branch

mapped. Cave populations present unique problems in that their total numbers, or even size of known caverns, can rarely be known with certainty. If the densities already encountered are typical of the unvisited portions of the Caves Branch catchment, there are hundreds, if not thousands, in the immediate area. Because of the relative ease of finding master trunk conduits, they are presently represented out of proportion to their number: these trunk conduits account for perhaps 90% of the presently known total cave length and probably distort perceptions and conclusions concerning their overall importance (Figure 3.2).

There are two basic elements to the location pattern of the conduits. These consist of 1) the connecting trunks draining two smaller allogenic catchments from the western, updip side to the Caves Branch polje (Actun Lubul Ha and Actun Chek); and 2) the extensive Chac Be Haabil system that drains the polje under all conditions of flow. The latter can be subdivided into a) the Nab Nohol Branch, a continuous, active trunk b) Nohoch Tata, an abandoned, intermittently used conduit that formerly channeled the entire flow of the polje; and c) Caves Branch River Cave, the present final ponor and active through-conduit of the Caves Branch River to the Sibun River valley. Except where noted in the following section, the non-conduit caves are apparently randomly located.

Cavern Types

Morphologic and hydrologic criteria were used to establish cavern categories in the Caves Branch. The more relevant characteristics are outlined for each cave and respective group in Table 3.1. Hydrochemical

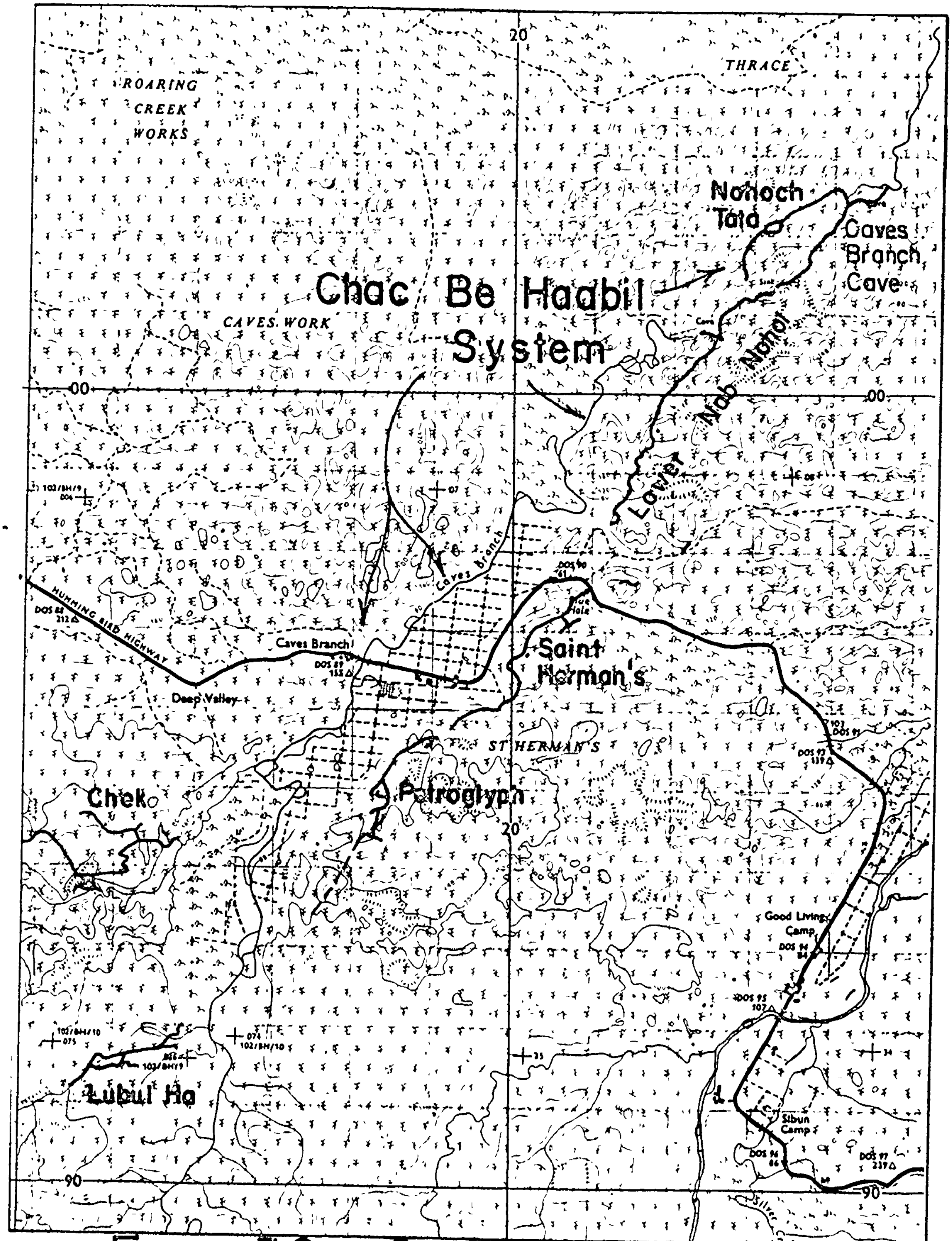


Figure 3.2 Conduit Caves

TABLE 3.1

Some Type Examples of Cavern Morphologic Classes, Caves Branch

Class	Name	ID	UTM Location	1 Phreatic	2 Vadose	3 Plan Type	4 Size	5 Col-lapse	6 Speleothem Development	7 Sedi-ments
Zuhuyha	Toh	Z-4	997218	Cs	s	H	60			
"	5% Solution	Z-7	971187	C	?	?	?			
"	Crooked Bend	Z-31	943184	Cs		2	150+			au
Isolated Phreatic	Swiss Cheese	0-3	004227	Cf		3	200?			
	Candlestick	0-12	947193	If		3	1-200	M1	M3	
	Cave-Around-The-Bend	0-17	912146	If		3	150?	M1	M2	
Swallet	-	S-1	997225		s	V	20			
	Swallowet Hole	S-4	955194		s	V	40			au
	VICEG	S-5	956191		s	V	100?			
Pirate	Thunder Road	P-4	007221	Cs	s	2	200+			al
	Buccaneer Alley	P-5	004218	Cs	s	2	500			al
	Zephyr Zig-Zag	P-8	956185	Cf,s(?)	f,s(?)	2	300			al
Margin Swallet	-	M-2	001217	Cs	?	?	?			
	-	M-7	965197		s	V?	?			
	-	M-11		f?		2	40		M1	
Trunk Conduit	Tuxmanu Yocmac, Chek		940152	Cs	s	2	1100		M2	al
	High Levels, Lubul Ha		915150	Cf	f	2	300	M1		al
	Petroglyph			C	P	2	3000+	M1	M2	al
Collapse Chamber	Cantzicnal Caan, Lubul Ha		918157	If		2	200	M3	M3	
	Burial Chamber, Petroglyph		983175	If		2	300	M3	M2	
	Mtn. Cow		958188	If		2	1000	M3	M3	

1 Phreatic — C - conduit; I - isolated; f - fossil, s - seasonally active
2 Vadose — P - permanent stream; s - seasonally active, f - fossil
3 Plan Type — H - linear horizontal; V - linear vertical; 2 - two dimensional (horizontal) 3 - three dimensional
4 Size — (known passage length, in meters)
5 Collapse — M - 3,2,1 major, moderate, minor
6 Speleothem Development — M - 3,2,1 major, moderate, minor a - active f - fossil
7 Sediments — Co - cobble fill; D - dirt; al - allogenic source, au - authigenic

and hydrologic differences are discussed in Chapter IV. Because the master trunks conduits are so extensive, they often contact other cave types, forming aggregates or systems. In Table 3.1 these intersecting cave passages have been treated as separate caves.

The most broad morphologic division is separation into phreatic (water-filled) and vadose (free-surface) form. These distinctions can blur in actuality, especially for vadose conditions. Frequent, major floodings associated with heavy rainfall can create seasonal separation, in that epi-phreatic (both vadose and phreatic) conditions occur. Additionally, it is not unusual for different hydraulic states to co-exist in separate sections of the same channel.

A. Phreatic Caves

Four groups of chiefly phreatic origin can be distinguished; two are inactive or fossil, the other two are only seasonally active but owe most of their features to solution under phreatic conditions.

1. Isolated This group is composed of fossil chambers scattered at moderate to high elevations. They are generally of complex plan (three dimensional) and consist primarily of rooms rather than passages. No scalloping or fluvial sediments are present to identify localized conduit flow, and the solutional pocketing, discordant elevations, and non-graded floors all indicate an isolated, non-integrated phreatic origin. Joint control appears predominant with only minor bedding effects. Collapse and/or sedimentation present is invariably due to breaching and invasion related to surface erosion, rather than to phases of cavern formation. Speleothem development is variable in extent and activity, though generally

common (Figure 3.3).

2. Chamber Stratum A large number of massive collapse areas exist underground that are similar in their morphological and topographical positioning relative to the trunk conduits. In most instances they consist of rubble-floored chambers with extensive active and inactive speleothems. With rare exception, ceilings occur at elevations of 50 meters or less above neighboring master conduits. For obvious reasons, it is not possible to determine the elevations of the bottoms of the collapses, but they appear to be no lower than, and sometimes above, the floors of the master conduits. Nearly all these rooms are parts of cave systems that include master trunk conduits. Sizes of the chambers range up to 300 meters in length with ceiling heights of 20 meters not uncommon (Figures 3.4 and 3.5). Bedrock, undisturbed sections, are almost lacking due to the collapse. Higher portions sometimes show undisturbed phreatic tubes and chambers with little or no evidence (e.g. scalloping) of localized conduit flow. The collapse material nearly always lacks markings from any solutional activity subsequent to collapse. Clastic sediment accumulations are absent except where bordered by a trunk channel.

3. Zuhuyha* (diffuse-flow, percolation) These active conduits of authigenic flow generally are found at the lowest levels of the explorable karst. Most debouch into the trunk conduits, but several emerge as surface springs. No clastic sediments of obvious allogenic origin

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* pronounced zū hö´ē hä. Literally, "virgin water" collected from underground springs for use in Maya religious ceremonies (Thompson, 1970).

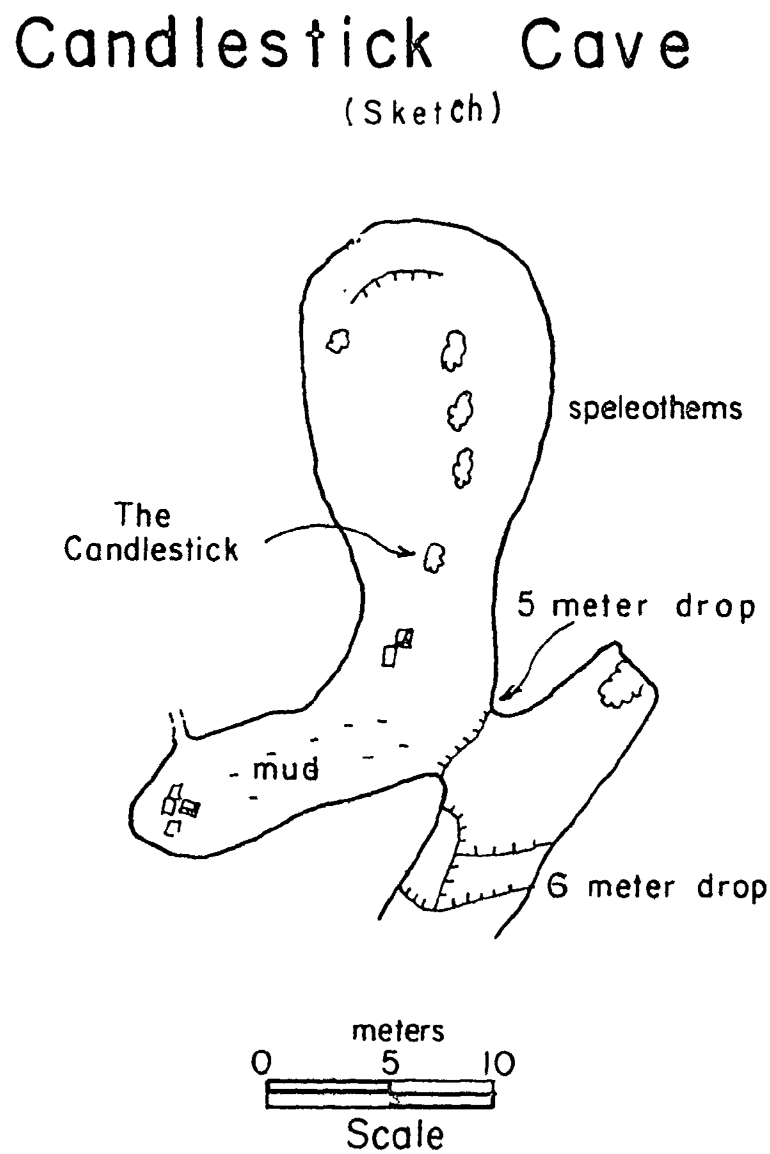

Candlestick Cave
(Sketch)
speleothems
The Candlestick
5 meter drop
mud
6 meter drop
meters
0 5 10
Scale

FIGURE 3.3

Figure 3.4

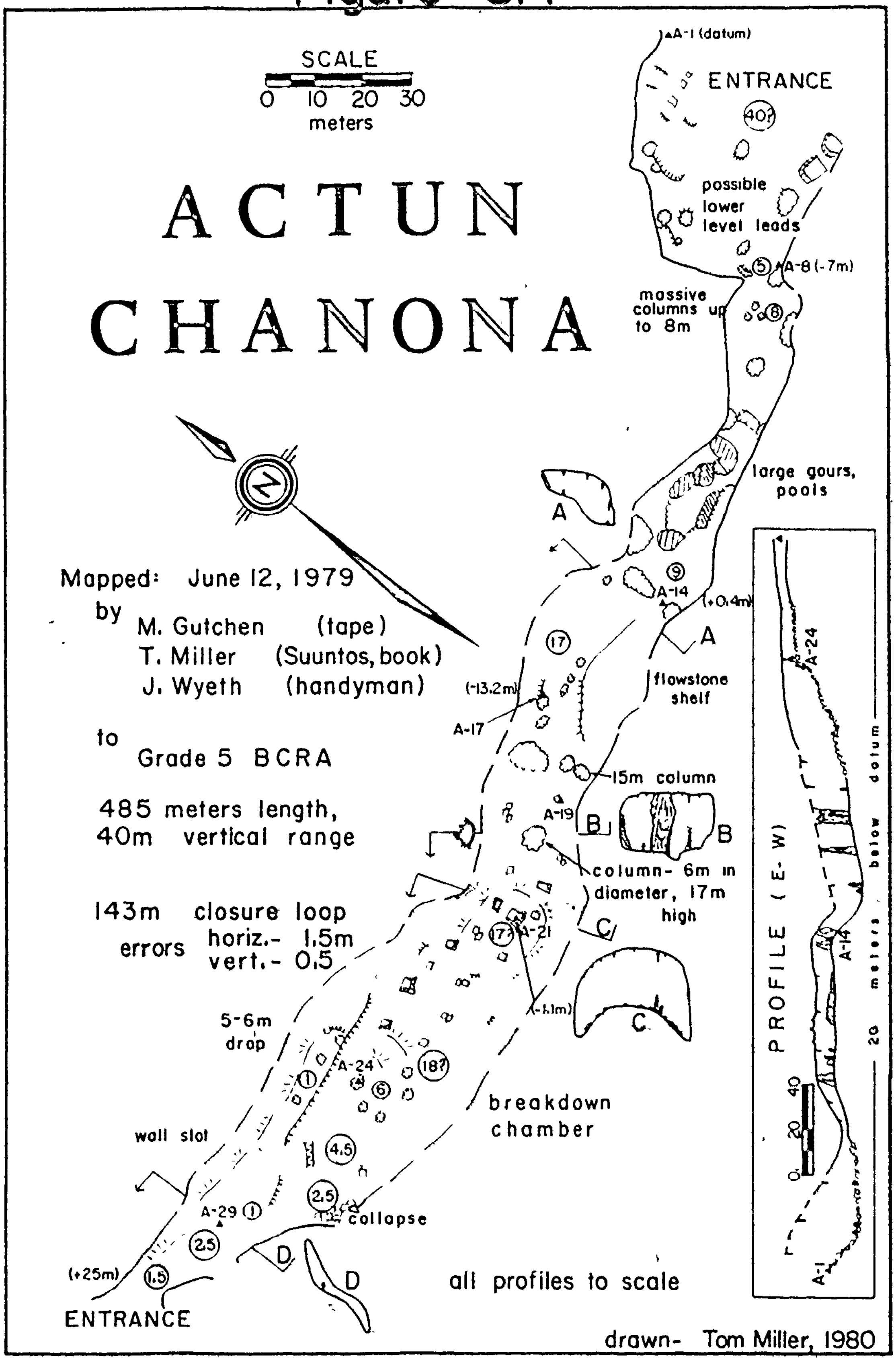
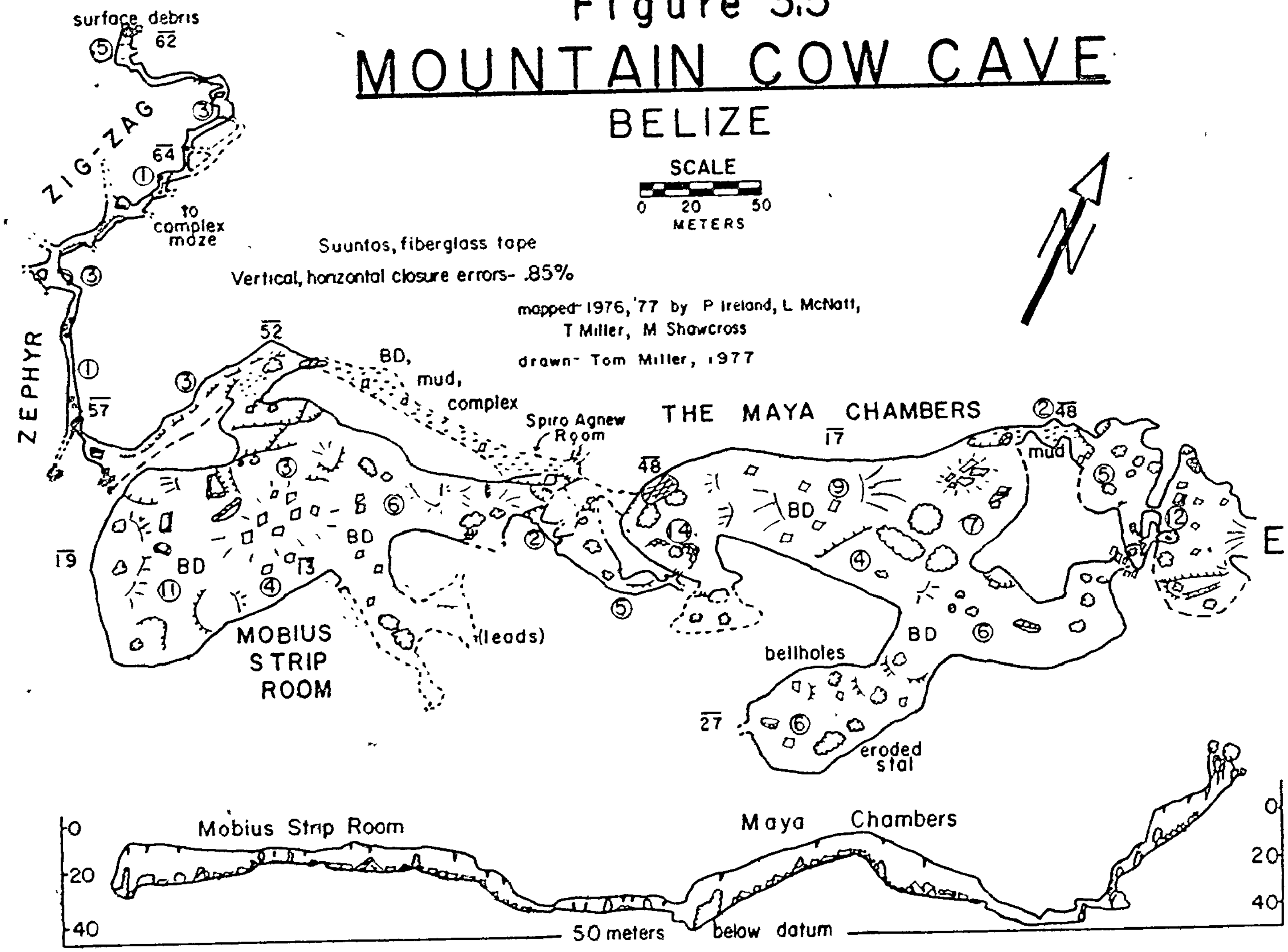

SCALE
0 10 20 30
meters
ACTUN
CHANONA
Mapped: June 12, 1979
by
M. Gutchen (tape)
T. Miller (Suuntos, book)
J. Wyeth (handyman)
to
Grade 5 BCRA
485 meters length,
40m vertical range
143m closure loop
errors horiz.- 1.5m
vert.- 0.5
A-1 (datum)
ENTRANCE
possible lower level leads
A-8 (-7m)
massive columns up to 8m
large gours, pools
A-14
(+0.4m)
flowstone shelf
(-13.2m)
A-17
15m column
A-19
column- 6m in diameter, 17m high
A-21
(-1.1m)
5-6m drop
A-24
breakdown chamber
wall slot
A-29
collapse
(+25m)
ENTRANCE
all profiles to scale
PROFILE (E-W)
20 meters below datum
drawn- Tom Miller, 1980

Figure 3.5

MOUNTAIN COW CAVE

BELIZE



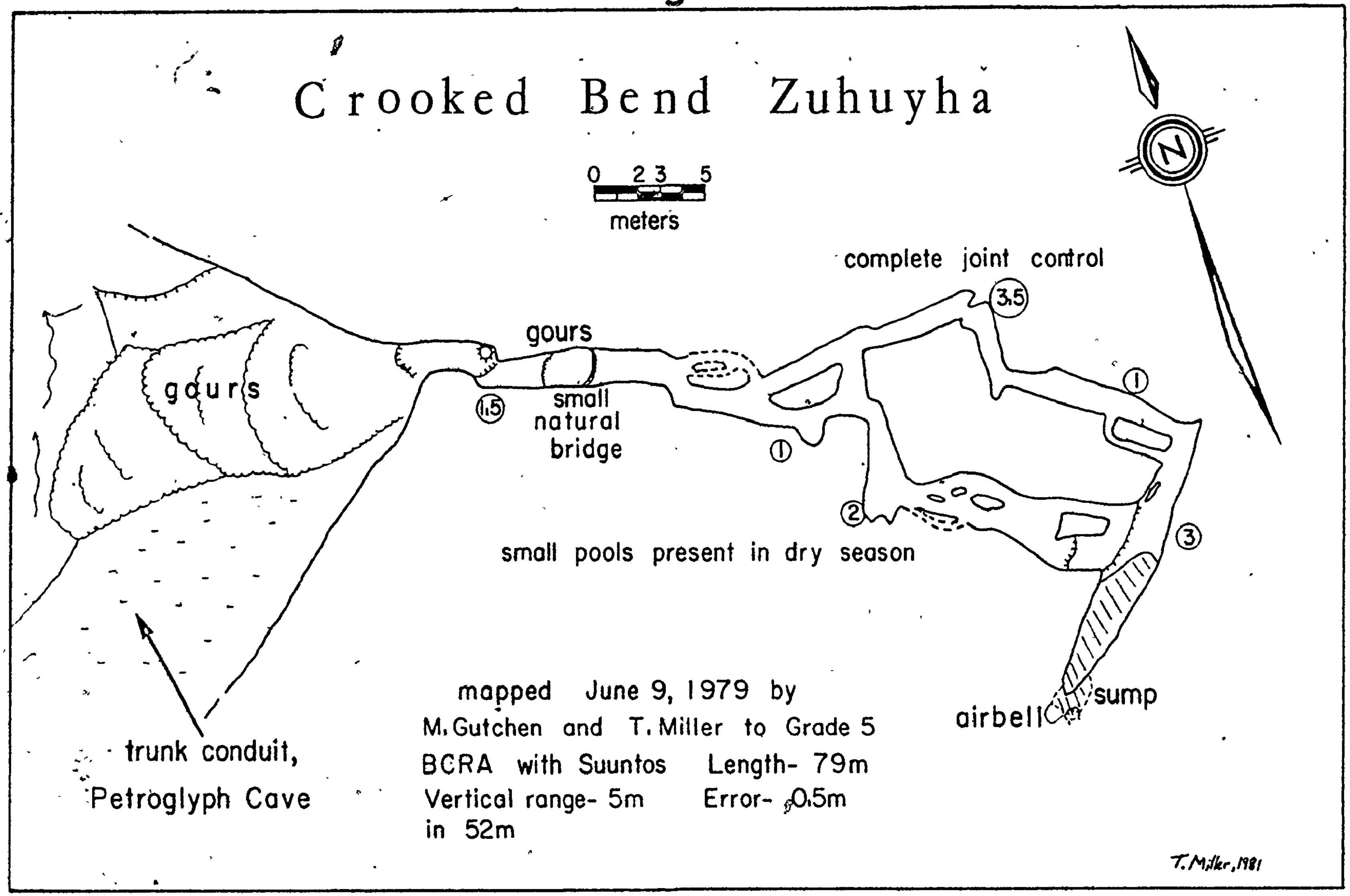
are ever present, and inferential hydrochemical evidence (Chapter IV and V) identifies them as probable dendritic collectors of long residence karst water, subject to pulse transmission and expulsion during the wet season. In other words, they are diffuse flow springs having the morphological character of conduits in their downstream ends. They are presently undergoing seasonal to continuous modification, and, when active, consist of flooded segments (sumps) with intervening air-filled sections except in highest flow. Passages are occasionally anastomosing, frequently tubular in form, scalloped, irregularly pocketed, joint-guided, and lack a graded profile (Figure 3.6). It is expected that the headwater sections are dendritic, collecting input from different areas of the karst surface above, but at present only one zuhuyha has been penetrated to these predicted inner regions (Figure 3.7). Most are penetrable to at best 50 to 100 meters. Speleothem development is rare, as is calcite deposition except at debouchment.

4. Karst Margin Swallets These caves are found at or near local base-levels and function as intake conduits for solutionally aggressive run-off from valley clays and clastics into the limestone. They are commonly phreatic and anastomotic in plan, and rapidly lead to sumps which fluctuate seasonally in level. Their further courses will be discussed later.

B. Epiphreatic/Vadose Channels

1. Master Trunk Conduits The bulk of the known Caves Branch caverns belong to this category. The trunks are the counterpart of the zuhuyhas, functioning to transport allogenic water from the highlands

Figure 3.6


Crooked Bend Zuhuyha
0 2 3 5
meters
complete joint control
3.5
1
gours
gours
1.5
small
natural
bridge
1
2
3
small pools present in dry season
sump
airbell
mapped June 9, 1979 by
M. Gutchen and T. Miller to Grade 5
BCRA with Suuntos Length- 79m
Vertical range- 5m Error- 0.5m
in 52m
trunk conduit,
Petroglyph Cave
T. Miller, 1981

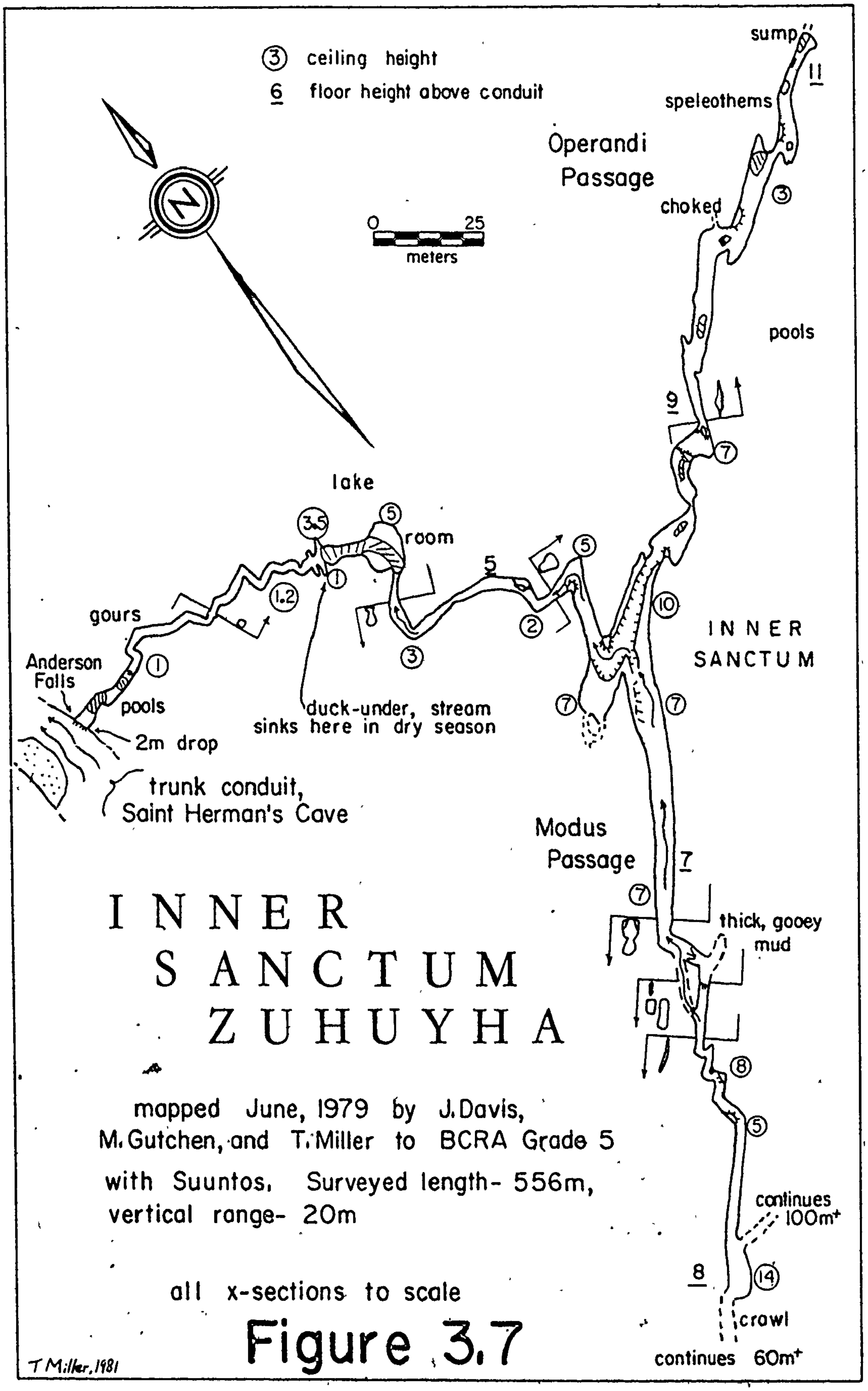

③ ceiling height
6 floor height above conduit
0 25
meters
sump
11
speleothems
Operandi
Passage
choked
③
pools
9
⑦
lake
3.5
⑤
room
5
⑤
①
1.2
gours
Anderson
Falls
①
pools
2m drop
③
②
⑩
INNER
SANCTUM
duck-under, stream
sinks here in dry season
⑦
⑦
trunk conduit,
Saint Herman's Cave
Modus
Passage
7
⑦
thick, gooey
mud
INNER
SANCTUM
ZUHUYHA
⑧
⑤
mapped June, 1979 by J. Davis,
M. Gutchen, and T. Miller to BCRA Grade 5
with Suuntos. Surveyed length- 556m,
vertical range- 20m
continues
100m+
8
⑭
all x-sections to scale
crawl
T Miller, 1981
continues 60m+

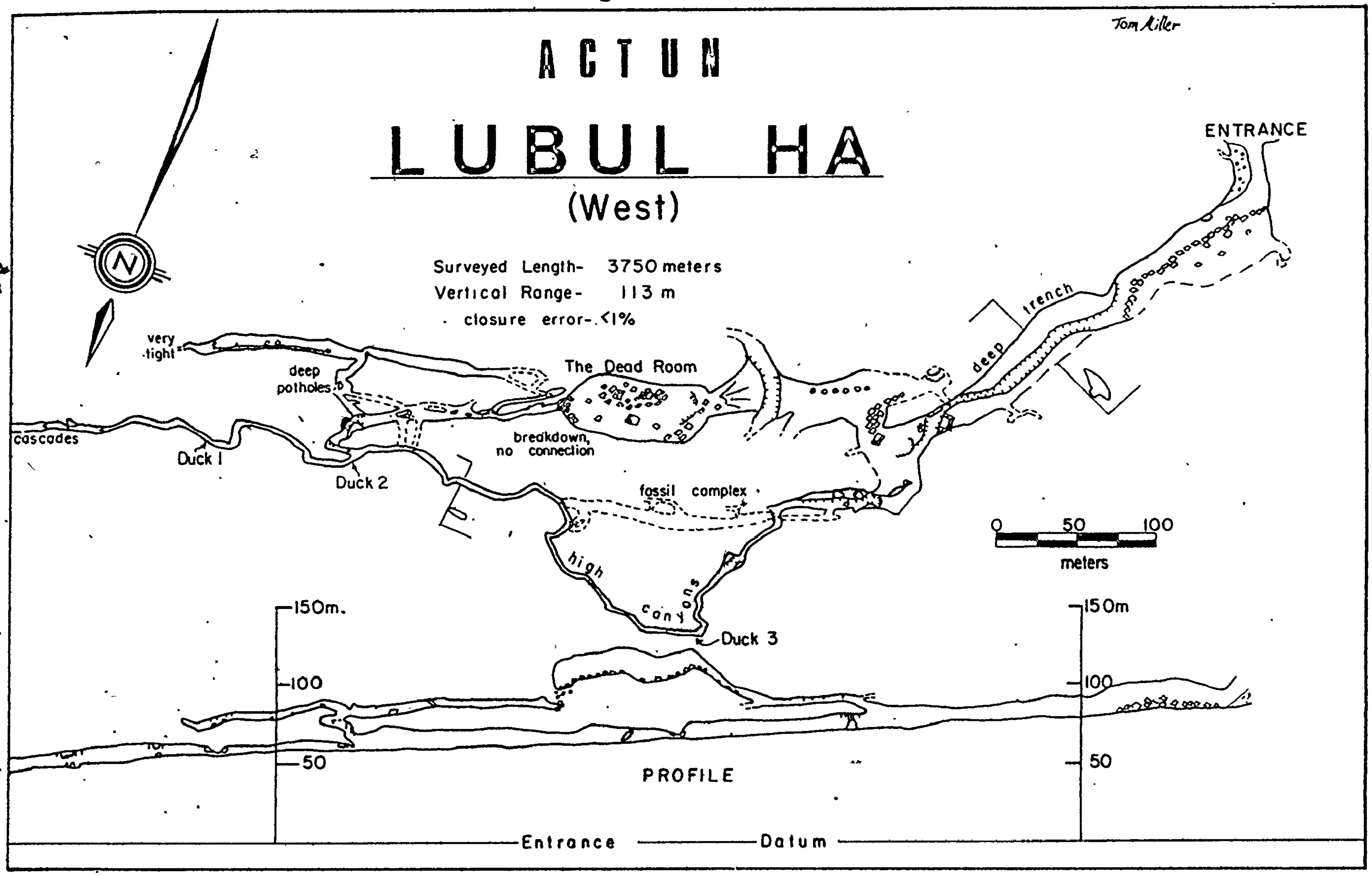
Figure 3.7

through the karst. Because of the large areal coverage provided by the lengthy conduit networks, much authigenic water also empties directly into them.

The most striking feature of the trunk channels is their size. Accessible lengths range from two to six kilometers, and cross sections average at least ten meters in height and 15-20 meters in width. All carry considerable quantities of highland-derived clastics, ranging from clay to large cobbles. Phreatic morphology is always present either as tubular configurations in the upper levels of the passages, or sumps. Abandoned loops, levels and trunk segments are ubiquitous, as is the occurrence of very large collapse rooms along the underground courses. Corrosion niche levels and wall undercuttings are present in all of the conduits (as many as five in some channels), and one is so persistent and widespread it is simply called "The Niche". Some sort of infill phase is common to all the trunk channels. Usually there is an accumulation of cemented cobbles, and frequently a clay phase as well. Channel gradients are extremely gentle (with one prominent exception), averaging only two to four meters per kilometer. Geologic controls appear to be mostly joints or faults, as bedding is almost non-existent.

Figures 3.8 and 3.9 show several thousand meters of two trunk conduit caves. The first figure shows the active and abandoned passages of the uppermost section of Lubul Ha, the single steep gradient cave. The second figure is of a portion of Actun Chek, a "typical" trunk with very low gradient; a fossil channel is shown reconnecting with the active portion. Two other master conduits are shown in Figures 5.6 and 5.7 of Chapter V.

figure 3.8


ACTUN
LUBUL HA
(West)
Surveyed Length- 3750 meters
Vertical Range- 113 m
closure error- <1%
Tom Miller
ENTRANCE
deep trench
The Dead Room
very tight
deep potholes
cascades
Duck 1
Duck 2
breakdown, no connection
fossil complex
high canyons
Duck 3
0 50 100
meters
150m.
100
50
150m
PROFILE
Entrance Datum

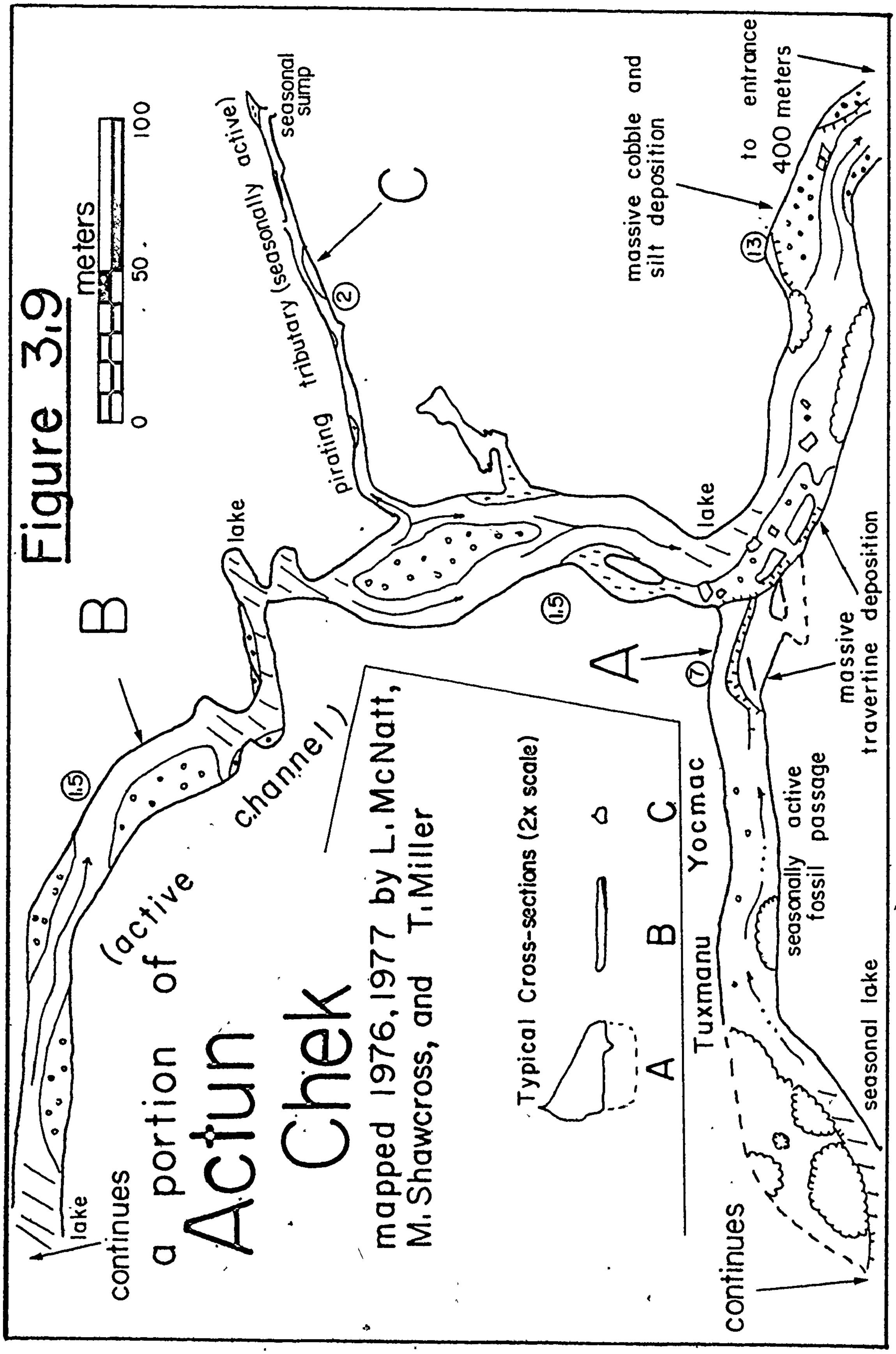

a portion of
Actun
Chek
(active channel)
mapped 1976, 1977 by L. McNatt, M. Shawcross, and T. Miller
meters
0
50
100
Typical Cross-sections (2x scale)
A
B
C
continues
lake
continues
B
1.5
lake
pirating tributary (seasonally active)
C
2
seasonal sump
1.5
lake
A
7
Tuxmanu
Yocmac
massive cobble and silt deposition
13
to entrance 400 meters
massive travertine deposition
seasonally active fossil passage
seasonal lake

Figure 3.9

2. Piratic Sub-Conduits Pirate channels are differentiated from the master conduits chiefly by smaller size, location, relative age, and the transport of "pure" allogenic water (Figure 3.10). They exist only where the Caves Branch River parallels a major conduit, and feed extracted river water to the neighboring master trunk. Although no pirate conduit has been physically followed for its entire length, the details of the configuration seem reasonably complete. All have joint-controlled courses and sizes averaging 2-3 meters high, and 1-2 meters wide. They are always located on the polje-ward side of the conduit that they empty into, have sediments of Pine Ridge origin, low solute loads (less than 100 ppm total hardness), and comparatively high water temperatures (25.0°C). These last four characteristics are diametrically opposite those of the zuhuyhas of the same trunk channel. Finally, the mean solute content of each pirate conduit increases with distance downstream in the polje and mimics that of the nearby river. The present evidence indicates the origin of the entire Nab Nohol Branch is as a pirate channel of the Caves Branch River.

Except for short sump sections, all are presently in states of active vadose entrenchment and all but one enter flush with the master conduit floor.

The furthest downstream of the channels has been successfully dye-traced* to its outlet in a trunk conduit. The courses of the other have been inferred from location and orientation of known pirate passage and their respective source ponors in the river bed (Figure 4.1).

3. Swallets These shaft caves function as transport channels for run-

* (With an optical brightening agent as described in Glover, 1972)

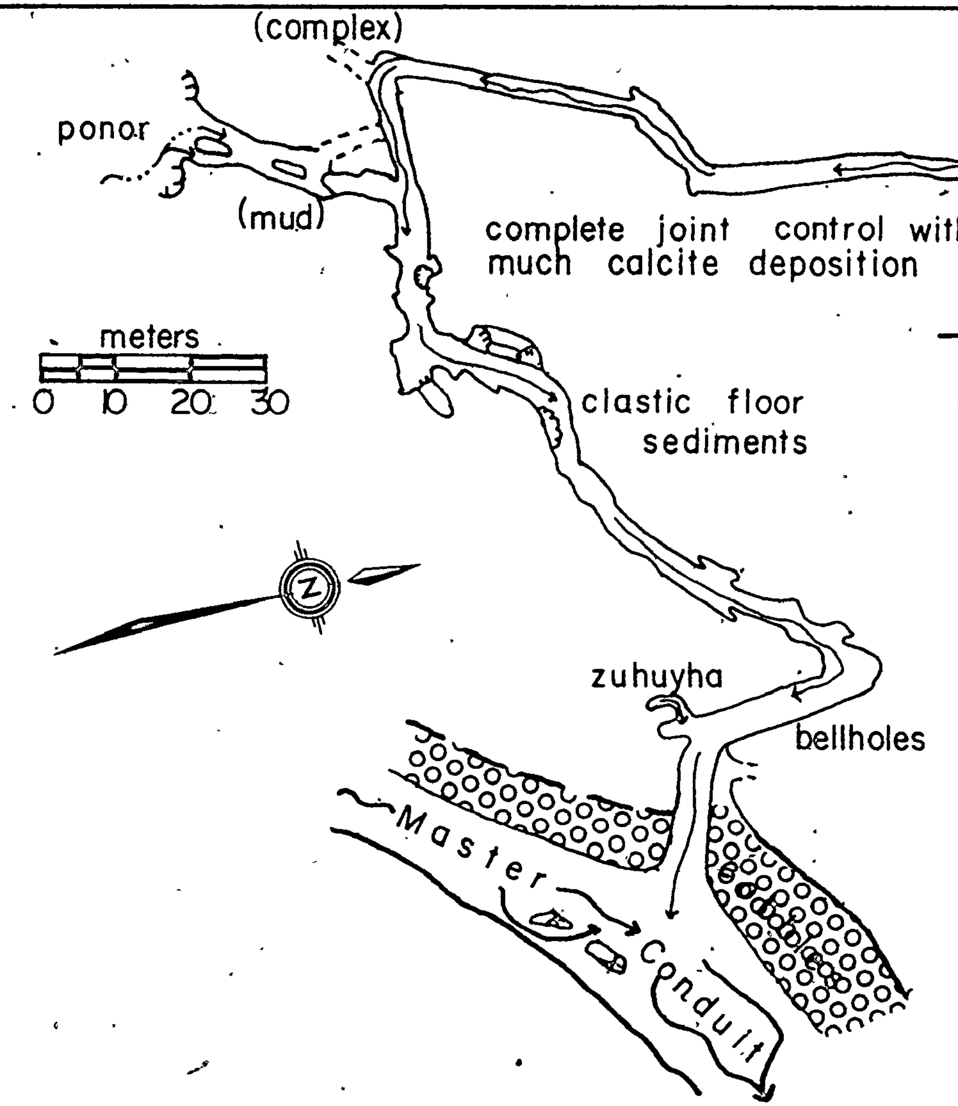


figure 3.10
Thunder Road

a pirating sub-
conduit mapped
June 9, 1977 by
T. Miller and L.
McNatt

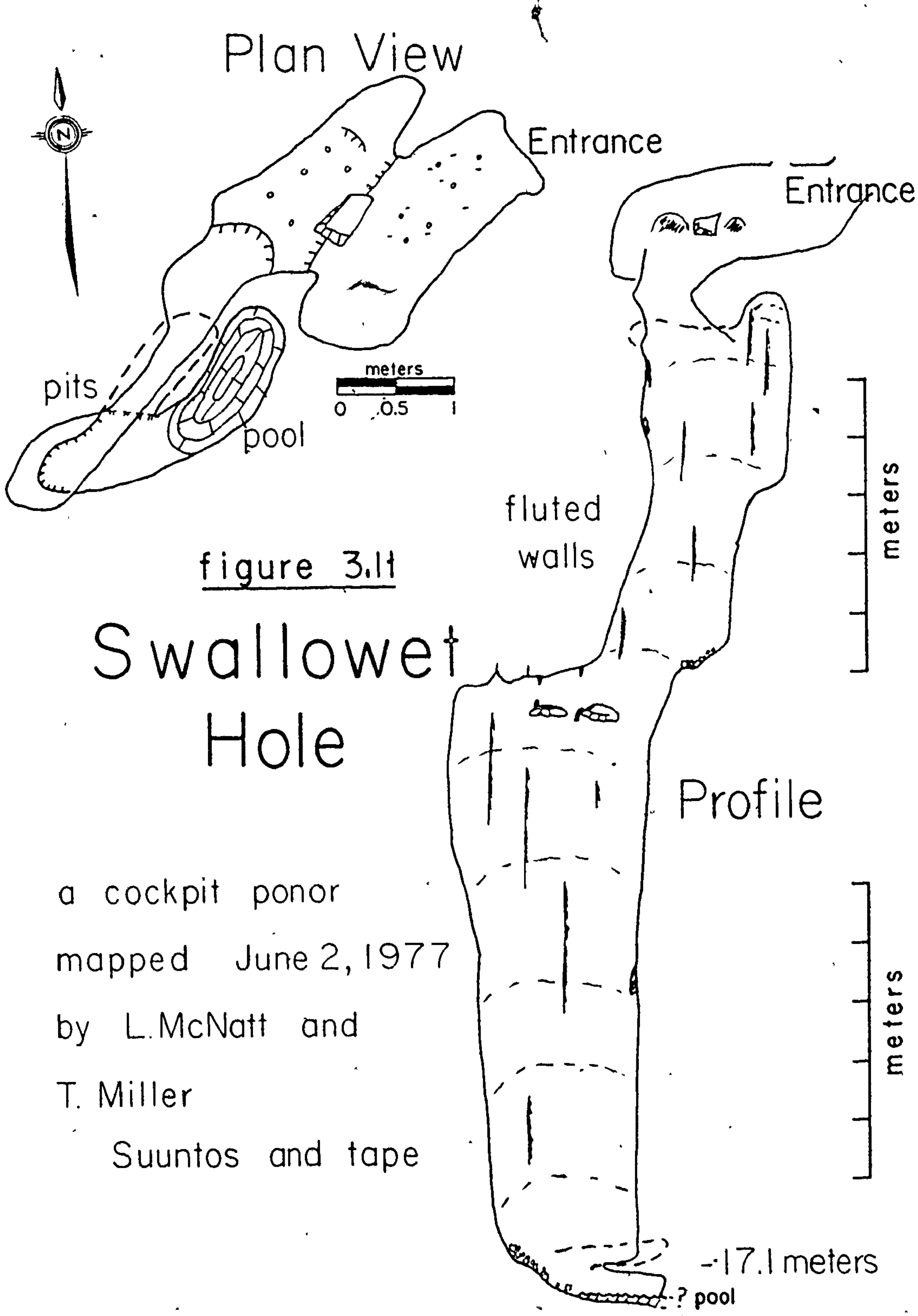
length- 283 m
(Suuntos, tape)

off from the karst surface to the karst interior. They are almost exclusively vadose in morphology, with vertical, fluted walls and minor clastic deposits. Those presently known are located at or near cockpit bottoms, frequently at the end of a gully cut into the floor. These gullies appear to function only during prolonged or very intense rainfall. Passage orientation in the swallets is exclusively by joint control, in bedrock. Collapse occurs as solutionally "rotted" limestone, but is not common. In contrast to the other cave types, swallets diminish in size along their courses. They end either in sediment chokes,or impassably narrow fissures. Those known are all less than 30 meters deep (Figure 3.11).

C. Miscellaneous -- Bell Holes

A discussion of the caves would be incomplete without mention of these common features. They are known also from Jamaica, Puerto Rico, Indonesia, etc., and previous writers have attributed them to solutional flow. In the Caves Branch they are found in active vadose and epi-phreatic stream areas, but are also found above relatively recent collapse in old phreatic chambers, where it is obvious they postdate the phreatic activity.

In form, bell-holes are cylindrical, symmetrical cavities in cavern roofs. They extend vertically from one-half to two meters in depth. Those in the Caves Branch appear to be randomly located without regard to joints or other lithologic controls. In some areas, depressions are found directly beneath the bell-holes, perhaps indicating an origin by films of aggressive water as suggested by the re-solution of some nearby stalagmites. Many of these floor depressions also contain bat guano, and no group of bell-holes has been located without the presence of bats.


Plan View
N
Entrance
pits
pool
meters
0
0.5
1
figure 3.11
Swallowet Hole
a cockpit ponor
mapped June 2, 1977
by L. McNatt and
T. Miller
Suuntos and tape
Entrance
fluted walls
meters
Profile
meters
-17.1 meters
? pool

It is possible that bats play an important, if little understood, role in bell-hole formation, perhaps through the action of their urine upon the limestone. Further study may also indicate the influence of some other, and as yet unknown, process.

II. Morphologic History and Discussion

Caves are often very much individual examples of a particular history of formation, even within a small region. Because only an unknown fraction is usually available for study, they are best treated as clues to the course of development of an entire general sequence of events.

Reconstruction of a morphologic sequence is often intuitive: e.g. a passage plugged with cobbles must have existed prior to the infilling event. Caves in most tropical areas have an abundance of speleothems that can be used to obtain absolute dates, but as this procedure is expensive and subject to its own limitations (Gascoyne, 1979), most morphologic sequences are derived from a comparison of relative ages of individual events. The time intervals between important events are therefore not always even of the same order of magnitude, and relating development phases from cave to cave can be difficult.

From the preceding classification of caverns in the area, several broad general phases of development can be distinguished. These phases are separated chiefly by altitudinal differences, on the assumption that the highest are the oldest. The high-lying phreatic caves appear to belong to two ancient phases, 1) an initial diffuse phreatic period, and 2) a possible phreatic conduit period. The third phase is that of the period in which integration of the areal allogenic and authigenic flows into the present phreatic/vadose conduit networks occurred. Being more recent and more accessible, greater detail is preserved of this last development period.

A. Phreatic Cavern Development

1. Diffuse Phreas Because no definite conduits have been found in any of the isolated high-lying phreatic caves, the indication is that they represent the result of slow diffuse groundwater movement in perhaps the initial stages of bedrock penetration. All groundwater flow was primarily, perhaps exclusively, joint-controlled, a situation which would presumably tend to enhance vertical movement. However, even the largest of these caves has a vertical range of no more than 30 meters. Such a limited range under supposedly optimal conditions tends to indicate formation at relatively shallow depth. It is a matter of conjecture whether any set or group of these caves developed simultaneously. A number of relatively stationary groundwater "stillstands" may have developed in response to entrenchment of local through-flowing rivers, but the small sample size of these caves and their lack of adequate hysometric data discourage any attempt to treat them as anything other than isolated, individual phenomena.

2. Chamber Stratum The nature of this group of subterranean cavities causes interpretation problems. Widespread collapse on a massive scale has obscured bedrock clues concerning its development. Two possible origins are suggested by the limited evidence: a) development basically

the same as for the higher, isolated phreatic caves, and b) for one set of these chambers, an origin possibly as an extensive, integrated phreatic conduit aligned along a fault. Evidence for the latter consists of the similar size, elevation, and linear trend of a series of collapse chambers paralleling hundreds of meters of the Nab Nohol Branch. Slickensides occur in the collapse in this area in several places.

a) The primary differences between the large collapse rooms and the isolated high level caves are the far greater volume of the former, and their limited elevation range. Any of the major collapse chambers far exceeds the total volume of all the known isolated phreatic caves. All collapse chambers range in elevation from slightly above neighboring trunk conduit floors to at most 70 meters above them. Generally, they clearly predate the trunk channels. The modern river conduit at the Petroglyph Cave entrance runs at one point in a symmetrical tunnel 15-20 meters diameter with a roof composed of breakdown blocks in the sink above, and a floor cut in bedrock. In most other chamber/conduit intersections the conduit has cut into bedrock slightly below the apparent base of the collapse. The channel obviously skirts the edge of the chamber, with no evidence that suggests any post-formative diversion of the conduit. Rarely, an entirely bedrock channel passes completely beneath collapse blocks.

Some examples of collapse after conduit formation exist. In the Dead Room of Lubul Ha (Figure 3.8), collapse has filled a passage and presumably forced its abandonment as an active channel: streams cut smaller channels on both sides of the blockage upstream, but failed to link up again with the former downstream segment. In St. Herman's Cave, a higher level bedrock conduit was filled with debris from a neighboring collapse chamber, apparently after abandonment. The active stream below is still experiencing occasional fresh collapse, but not at a rate exceeding its ability to maintain its channel. It has, however, been forced further away from the collapse area. A few other sites are experiencing similar recent collapse. In nearly all collapse chambers no clastic sediments or remnants (buried by collapse or otherwise) have been found in any part except directly alongside active conduits. Huge speleothems are additional evidence of the great age and relative stability of most collapse chambers.

b) Collapse chambers in the Nab Nohol Branch form a linear NE-SW trending series of rooms extending nearly two kilometers. Surface valleys appear to separate the Petroglyph/Mtn. Cow segment from that in the Edinboro Entrance of St. Herman's Cave, and the latter from the downstream section in the same cave. Widths of collapse sections vary from 50 to 100 meters. They are at an average of 20-30 meters above the trunk conduits, with a range of perhaps 5-70 meters above them. Obvious controls (e.g. major joints or faults) are absent except in the downstream section of St. Herman's Cave, where some slickensided surfaces have been found. Two stalagmites from a room in Mtn. Cow Cave were radiometrically dated by A.G. Latham (McMaster University). The base of the oldest gave a date of 176 ($^{+49}_{-36}$) ky B.P., which would be a minimum for the age of this level.

B. Conduit Integration

Three types of conduit have developed in the Caves Branch: master trunks, zuhuyhas, and pirates. Figure 3.12 shows an idealized assemblage.

1) Trunk conduits appear to have formed from initial phreatic tubes of 1-2 m diameter. Occasional isolated examples or half-tubes can be

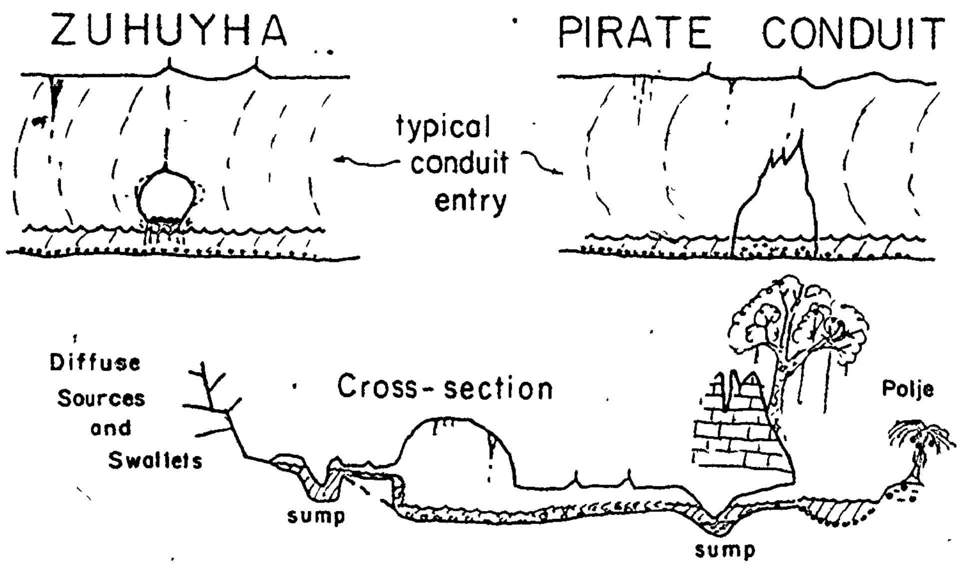
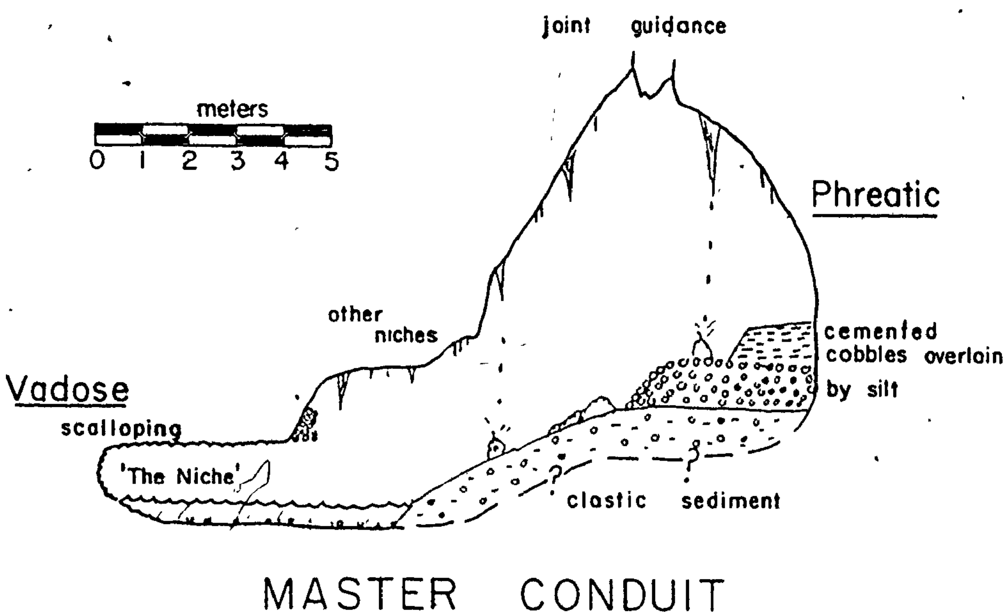


Figure 3.12
Karst Drainage Pathways



located at roof level. These tubes then grew to the order of ten meters or more in diameter, consequently attaining vadose conditions. Entrenchment followed in most instances, or the development of new independent routes. Abandoned passages and superposed tubes above the present vadose channels remain as evidence of the first major phase. Prior to the second, at least two major cobble infillings occurred. The larger attained a depth of eight meters in Actun Chek. As entrenchment progressed in the vadose phase, widths remained relatively constant, while floors were lowered 5-10 meters. Another infilling episode then appears to have nearly completely filled the lower reaches of the Caves Branch System and the Nab Nohol Branch. St. Herman's Cave in the latter is the lowest point at which bedrock is exposed in the floor. Fill of 3-4 meters depth occurs further downstream in St. Herman's, eventually increasing to at least 7 meters in deep impounded lakes near the final resurgence of the Caves Branch River. Actun Chek has no known exposures of bedrock in its active section, with lakes at least 5-6 meters in depth. A stalagmite growing on cemented cobbles two meters above the present floor of Actun Chek was radiometrically dated to 72.5 $\binom{+12.9}{-11.6}$ ky B.P. Another from Lubul Ha (that had been overturned and then covered by fill) gave a date of 102 $\binom{+3.9}{-3.8}$ ky B.P. If the same fill episode is being dated, this event occurred between 60-100 ky B.P. There is no assurance however, that the two fills are related, coming as they do from two quite different caves.

At the upper limits of this widespread fill is an incised bedrock niche common to all conduits of the area. It displays a constant height of about 1.5 meters graded to the elevation of the fill. The niche cuts across both phreatic and vadose inlet channel elements and represents the most recent solution phase rather than an old "water-table" level. As such, it is paragenetic -- sedimentation has raised conduit flow to a higher level and carved out the present niche. Many, if not all, of the present conduit sumps are possibly due not to failure to reach an "ideal water-table" state, but to flooding caused by a change in base level. Because the cemented cobbles from Chek are higher than the infilled conduit floor and The Niche, the stalagmite date does put an upper age on these events.

Every master conduit in Belize known to date is associated with the sinking of invading aggressive allogenic water. This is apparently essential for the solution of the large channel volumes. Jointing and topographic dip appear to be the major controls as defined bedding is rare. Although many sections are obviously controlled by a joint visible in the roof, in most instances the initial joint or joints responsible for alignment have been obscured by the size to which the passage has developed. The Caves Branch Cave System has an overriding NE-SW alignment, paralleling regional fault trends. Direct fault-induced orientation is difficult to prove because the amount of brecciation in the limestone bedrock masks evidence of fault displacement.

2) Pirating sub-conduits of the Nab Nohol Branch enter flush with the conduit floors. They have ceilings perhaps 1-2 meters higher, and floors aggraded with sediment. Correspondence of many passage sections with The Niche, and the sediment infilling, demonstrate an integration with the conduits that preceded the base level rise. The low elevation of the piratic conduit ceilings relative to those of the trunk conduits, however, do imply that the main channel had achieved its present dimensions long

before link-up.

These pirating channels may be common features of poljes elsewhere. Legrand and Stringfield (1963) have noted that the lower course of the Río Cobres, in Jamaica, lies on alluvium higher than the neighboring water table in the limestone. Brown and Ford (1973), also in Jamaica, and McDonald (1975, 1976, 1976b) in Belize and Indonesia, have noted the apparent affinity of many polje and open polje streams for residual limestone masses. McDonald postulates that "the limestone is highly soluble and has developed much secondary porosity, which allows for freer movement of runoff to the watertables than the relatively insoluble and impermeable alluvium".

The active pirating channels are found only where the river channel passes close to the escarpment bedrock. What appears to be a fossil pirate channel is the Zephyr Zig-zag (Figure 3.5) of Mountain Cow Cave. It contains clastic Pine Ridge sediments, and has the other morphologic characteristics of the pirate channels. It is inactive, however, apparently related to its distance from the river channel which is presently located on the far side of the valley from it.

Karst margin swallets have been previously noted as occurring at the contact of limestone bedrock and alluviated level surfaces (either the river polje or small low-lying dolines). Aggressive runoff is the probable reason for their positioning. Their seasonally fluctuating interior water levels imply connection with a base level conduit system. The margin swallets would have been likely sites to exploit in the creation of the pirate sub-conduits when river flow was available.

3) Zuhuyhas enter most frequently 2-3 meters above the present

floors of active conduits, although several pour in from the ceilings. Some of the larger examples end in sumps with floors at or below the present water surface of the neighboring conduit. Tuxmanu Yocmac and Nohoch Tata, both semi-abandoned higher level trunks, contain zuhuyhas that do enter at floor level. It appears that integration of the authigenic karst discharge, then, did not occur until the master conduits were already fully functional, but had been nearly completed before the vadose entrenchment phase that preceded the major infilling and the Niche. The lack of zuhuyhas with graded floors extending back into the karst is probably due to the relative slowness with which the saturated waters are able to remove hydraulic obstructions. Although ungraded, few of those known have particularly steep overall gradients in spite of the considerable depths of limestone they underlie. When considered with the direct, vertical penetration of the swallet caves, a maturely evolved karst is indicated, with integration achieved at a near-horizontal base level in the karst interior.

C. Network Evolution in the Caves Branch

Ford (1971), Ewers (1978), and Ford and Ewers (1978), have attempted to model initiation of conduit routes in limestone aquifers. Ewers (1978, 1981) has used salt blocks, gypsum blocks, and electrical analogues in the laboratory to model solutional networks in varying conditions of dipping strata. These were then compared with actual networks observed in caves, and certain similarities noted. Ford (1968, 1971b) has proposed the idea of increasing fissure frequency, and fissure expansion, to explain changes in cavern morphology as multiple levels develop over time.

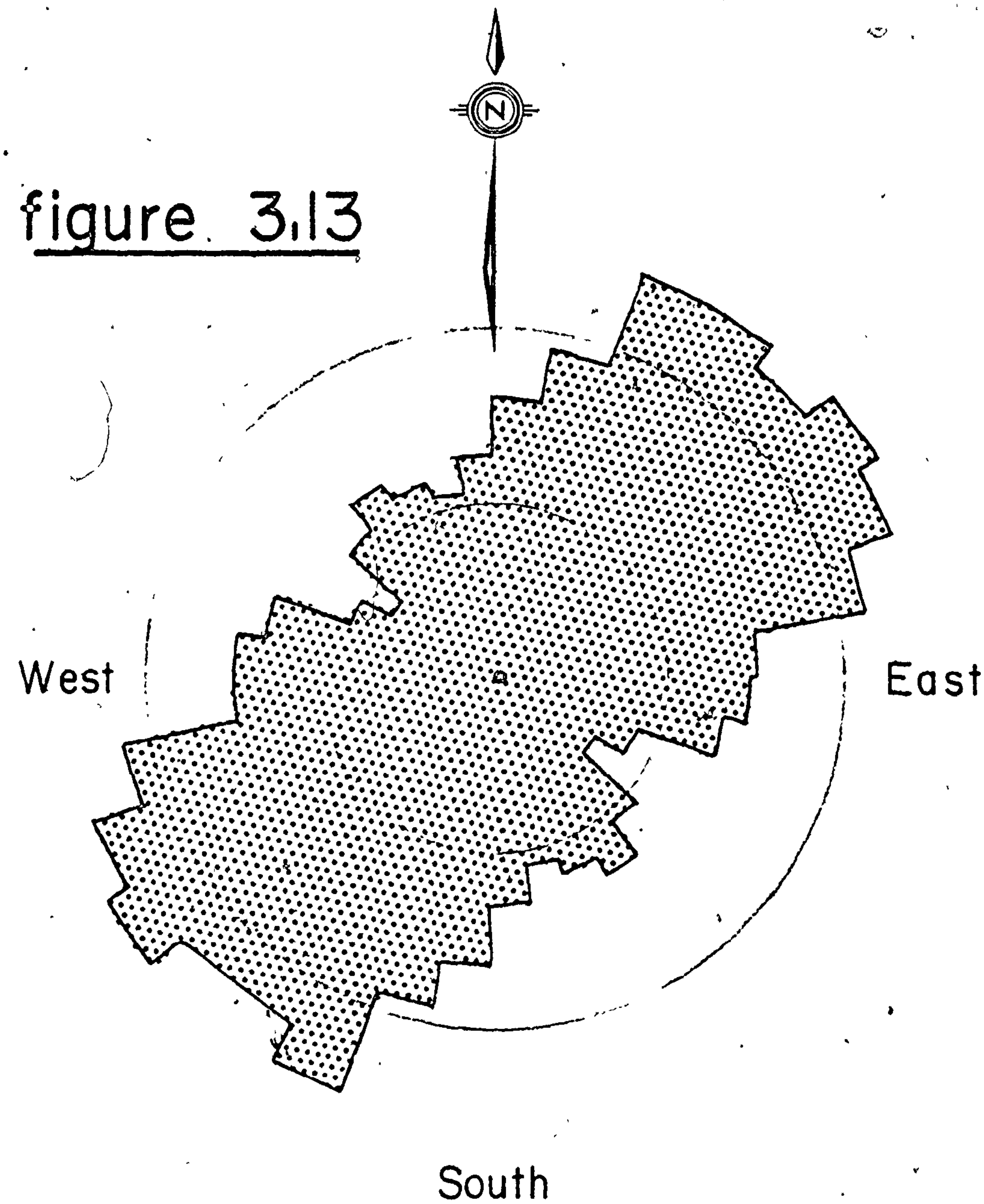
His work in the Mendips has used this idea to produce a model of cave systems evolving toward progressively more integrated, lower gradient states, with elimination or modification of phreatic flow amplitudes.

Ford and Ewers suggest that cave patterns will develop in response to lithologic, structural, topographical, and hydrological variables, and cite some cave examples of the various influences. Their major generalizations are that caves will initially propagate from the input, yet integrate headward, and that with the increased solution of the host bedrock the channels will progressively approximate more closely the piezometric surface of the aquifer. Ford and Ewers also believe that competition between flow routes should create an inverse relation between frequency of springs and their flow magnitude -- large integrated springs should be few, less important springs more numerous.

As discussed earlier in the chapter, the documented high-level caves show no signs of having been a part of any integrated network, and appear to be examples of isolated cavernous development. Networks and conduits are known only from the lower twenty meters of the limestone. Previous sections demonstrated the apparent greater age of the allogenic trunk conduits relative to both the zuhuyhas and the pirating sub-conduits. Length-weighted orientations of trunk conduit passages are shown in Figure 3.13. These can be compared with photo-lineation orientations of Figure 2.13, and it is obvious that the major significant trends in both instances are identical, and similar to the regional fault trends. The cave passages, photo-lineations, and fault trends also parallel the local topographic dip, which is generally to the northeast.

There appear to be three major geomorphic elements of the trunk

figure 3.13



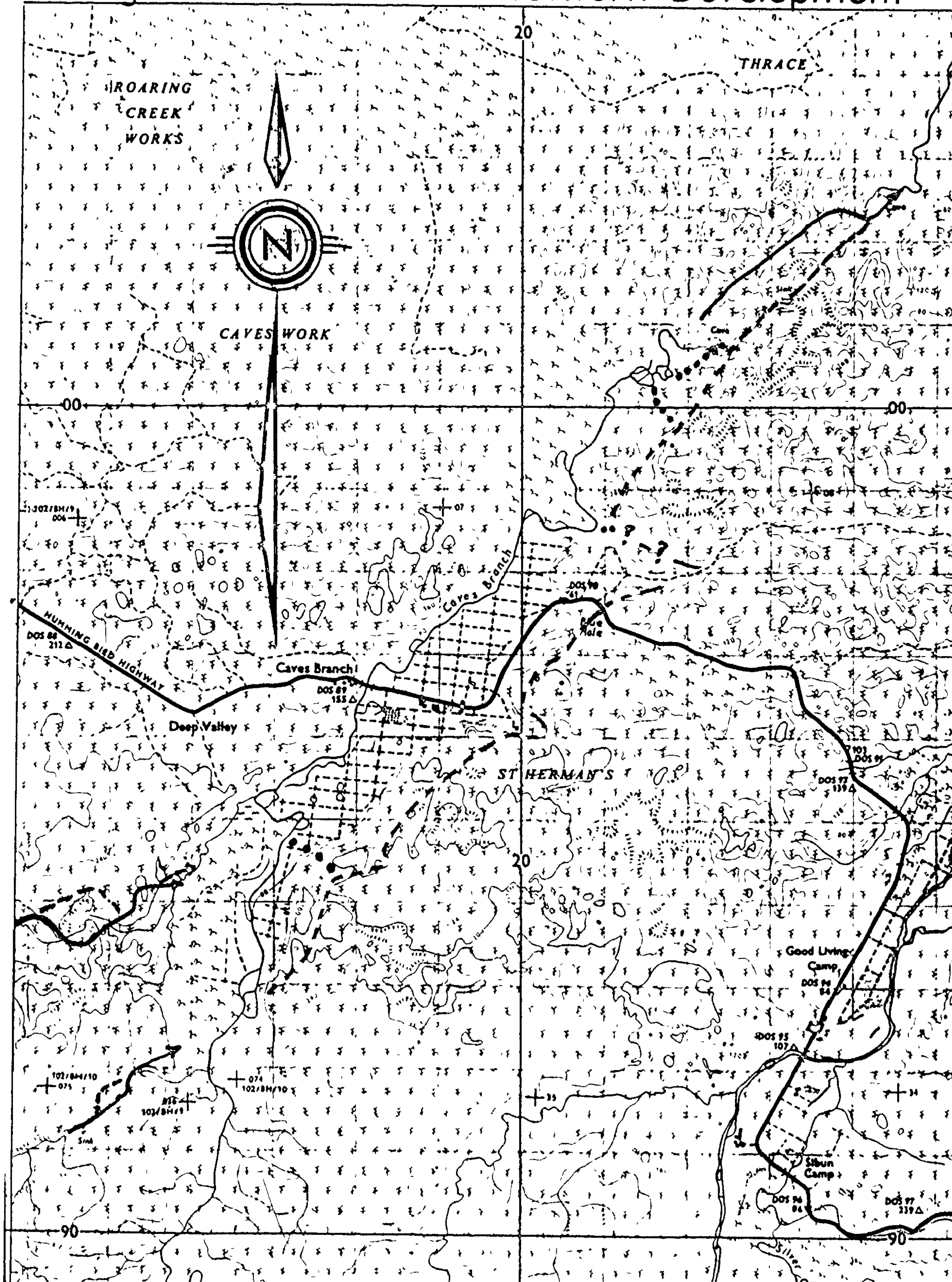
Length-Weighted
Cave Passage Orientations
Caves Branch

conduit system; 1) Actun Lubul Ha and Actun Chek 2) Actun Nohoch Tata, and 3) the Nab Nohol Branch (Figure 3.2). The last is distinct from the others in being the largest, the most simple in plan, and in paralleling a large surface stream rather than crossing beneath a thick section of limestone. The conduit complex of Nab Nohol maintains relatively constant dimensions throughout, suggesting an early complete integration -- no evidence exists to suggest a stepwise accretion of initially independent hydrologic routes. All presently known inputs (piratic or zuhuyha) are relatively late-joined elements. The major change occurring at present in the Nab Nohol complex is the growing complexity of the network through growth of feeding piratic channels. The main trunk is laterally offset and topographically lower than the surface river channel that it parallels, giving it a hydraulically advantageous position relative to the independent surface stream. This same situation is repeated further downstream where Nohoch Tata united with the Nab Nohol trunk -- Nohoch Tata is analogous to the surface river in this respect.

Actun Chek and Actun Lubul Ha have examples of offset multi-level development, as apposed to the entrenchment that occurred in the Nab Nohol trunk. In both caves, the fossil channels lie up-dip and topographically higher than the present active channels (as Lubul Ha lies higher, and is closer to the mountain/limestone contact than Chek, the topographic dip is somewhat more northerly at that point).

Figure 3.14 shows the labeled stages of cavern network development in the Caves Branch as determined from the geomorphic evidence: surface river flow was followed by 1) development of large phreatic conduits; 2) zuhuyha integration with the main channels, 3) vadose entrenchment and/or development of lateral cut-offs, and 4) formation and integration

Figure 3.14 Cavern Network Development



STAGE 1
2 (downdip piracies)
3 (pirate, zuhuyha integration)

of pirate sub-conduits in the Nab Nohol Branch.

Almost none of the conduit levels (fossil or active) in the Caves Branch (represented as either a separate channel, or high remnant in an entrenched passage) differ substantially along their length from that expected of a well-integrated, low-gradient channel. There are no known examples of phreatic circulation of loops greater than the ten meters or so amplitude of the present-day sumps. As previously noted, most of the sumps would probably not exist today were it not for major infilling of the lower sections of the cave systems. This suggests long-term, relatively stable water base levels or piezometric surfaces. The geologic and lithologic constraints of the host rock are such that major avenues of water penetration are almost entirely vertical joints and faults in a massive, relatively homogeneous breccia. There are no natural horizontal constraints of shale/chert aquicludes. Where bedding planes are present, some tubes have developed on the partings, but these are of limited extent. In this area of apparently relatively stable base levels and well-jointed rock, three major elements of network drainage are dominant: 1) where the major regional fracture trend and the topographic dip coincide, a relatively undeviating entrenched conduit develops because base level did not drop too fast for conduit solution to keep pace (Nab Nohol type); 2) where independent allogenic streams link up with other streams across the topographic dip, declining base levels encourage lateral off-set of developing conduits in hydraulically advantaged down-dip positions (Actuns Chek and Lubul Ha) and 3) where paralleling streams aligned along the fracture/topographical dip axis are sufficiently close and of sufficent elevation difference, piracy from higher to lower will occur (Caves

Branch polje to Nab Nohol; Nohoch Tata to Nab Nohol). Initial impetus for the latter can be where polje sediments armor the underlying limestone, giving an erosional advantage to cave passages in neighboring limestone.

From the foregoing, it can be seen that the trunk cave network of the Caves Branch does not readily fit into a model of the Ford/Ewers type -- there is no apparent evidence of headward integration of the various components, and certainly no known remains of gradual evolvement of the aquifer to the present low-gradient state. The high caves are isolated, and unintegrated in the top 70-150 m of the hostrock, then suddenly replaced in the bottom 20-30 by the well-integrated present network.

A variety of reasons could explain the discrepancy. Firstly, the basic conditions differ from the assumptions of Ford and Ewers, where many smaller inputs integrate in an environment of strong constraints on vertical water movement. There are no aquitards (and/or aquicludes) and bedding planes to encourage lateral motion and truncate vertical joints and crevices. In the Caves Branch, the most significant elements of the fluvial network have probably always been the joining of the independent allogenic basin flows. These are already large, integrated networks of solutionally aggressive water before they encounter a limestone where the near-absence of bedding planes provides little resistance to vertical flow in the well-jointed rock. These allogenic penetrations along the NE-aligned fracture sets were as much as 12 km in a straight line for the Nab Nohol Branch, and at least several km for each of the others. They apparently were targeted primarily on the final outlet rather than on intervening existing zuhuyha networks because the geomorphic evidence indicates the zuhuyhas did not integrate with the trunks until after the latter had achieved sizes comparable to the present. Present phreatic amplitudes appear to result from a major alluviation phase which may also have initiated pirate sub-conduit development by plugging the ponor at the upper end of the Nab Nohol Branch and enabling the valley floor to aggrade. This created the necessary hydraulic head gradient between the polje and cave for the pirates to form.

The second cause of disparity could be inadequacies in the speleogenetic model chosen. Salt and gypsum are dissolved in a one step temperature-dependent process; carbonate solution is primarily the result of the second of two-steps -- the diffusion of CO_2 into the water, a process inversely dependent upon temperature. Not only could kinetic/dynamic effects of initial solutional enlargement of fractures differ between sulphate and carbonate rocks, but the carbonate solutional process is also affected by seasonal and locational constraints on the availability of water. Questions of scale in the Ewers experiments also arise -- actual caves are usually considerably longer in horizontal dimension than in vertical dimension. The Caves Branch aquifer is many kilometers long, yet averages only 100-150 meters deep. The study area's caves, then, differ considerably in both total and relative dimensions from the laboratory salt and gypsum blocks. Networks in the latter may possibly have no physical relevance to the networks of the Caves Branch.

Thirdly, the possibility that undiscovered fossil routes may exist cannot be ignored. As stated in the opening of the chapter, it is difficult to determine the total extent of cave populations, and further discoveries would probably require modification of the developmental sequence already outlined. At present, the old watertable development hypothesis Swinnerton (1932) appears to most accurately represent the Caves Branch situation.

In spite of the apparent relation of both trunk conduit passages, and surface depressions (Chapter II) to the NE-SW trending fracture system as determined from photo-lineations and regional geologic work, there appears to be little correlation between surface and subsurface features. Observed photo-lineations are only rarely found to guide cave passages (as in the downstream linear end to Petroglyph Cave, Figure 5.6). Other photo-lineations (such as that crossing at the seasonal sump in the Inner Sanctum, Figure 3.7) seem to inhibit passage development, occurring at narrowings of the passage diameter.

Except where massive collapse occurs to the surface (which is uncommon), breakdown chambers in the caves have no surface expression. Dolines, previously demonstrated to have a significantly greater occurrence near photo-lineations than elsewhere, are presumably located at favorable sites for the movement and penetration of groundwater. Some of the zuhuyhas did demonstrate a tendency to occur at sites where a large doline was located near a conduit, but the trunk conduits themselves rarely passed beneath surface dolines, and never followed surface valleys. Most of the course of the Nab Nohol correlated very strongly with surface ridges, in spite of the limestone thickness of close to 100m. Brown and Ford (1973) observed a similar situation in Jamaica where conduits tended to locate beneath hills rather than depressions. They thought this suggested lateral migration of cockpit bases as they eroded downward. This is probably unlikely as vertical development would presumably continue to be guided by the initiating fracture intersections, and the survival of paleo-fluvial channels in Searranx, Vaca Plateau, and possibly the Caves Branch, also argues against this. At present, there seems to be no logical explanation for the affinity of the obviously joint-guided cave passages with surface ridges, rather than beneath the dolines which are demonstrably favorable locations for water movement.

As emphasized earlier in the chapter, individual caves have individual histories. Actun Lubul Ha is the best example of this. It has the steepest overall grade of any trunk conduit in the area (35m/km including a section of waterfalls), and a considerable segment of entrenched vadose canyon below phreatic form levels. These phreatic levels show evolution to vadose conditions, and appear to demonstrate growth under low gradient conditions; except for the underlying active vadose canyons, they generally conform to the morphology of the lower part of Lubul Ha (below the falls). Both Actun Chek and Lubul Ha show more faulting than other area trunks, presumably because they are closer to the major Northern Boundary Fault which has upthrown the Mayas. The receding niche of the waterfall section of Lubul Ha and the vadose canyon upstream of it may well be due to a major fault which has uplifted the region of the cave nearest the mountains. Additional work is necessary to confirm such speculation -- the point is that regional cave histories require considerable effort to explain more than the major general development phases.

III. Regional Relations

Cretaceous carbonates exposed in Belize are cavernous throughout their range of elevation, from below sea level to over 600 meters altitude. Those exposed in the coastal areas (from the base of the Maya Mountains to the sea) share common altitudes and similar morphologic characteristics. They spread over a north-south extent of 150 km, at elevations 40-100 m above sea level. As at Caves Branch, all trunk conduits known elsewhere have formed by allogenic stream invasion (Figures 3.15 and 3.16). Those caves closest to the mountains, or furthest removed from the sea, have slightly higher elevations than others, but nearly all have outlets at 30-60 meters elevation. Each also has either an abandoned, well-developed upper level situated 15-25 meters above the present active conduit, or has superposed passages of 20+ meters height caused by vadose entrenchment. It seems logical that these widespread similarities represent adjustment to a regional base level over a 20 meter range. A combination of tectonic disturbance related to the Maya Mtns., and/or sea level fluctuations may be responsible.

Little is known of the other two primary Belizean karst areas (Figure 1.1). Caves occur beneath the offshore cayes of the Belizean barrier reef which Purdy (1974) has described as essentially a drowned karst of considerable relief. The offshore Blue Hole, for example is a sinkhole at least 100 m deep. In the Vaca Plateau area of western Belize is another well developed karst, a portion of an extensive area extending into Guatemala and Mexico. The highest limestones there are at elevations of just over 700 m. Maps and aerial photos show numerous sinking allogenic streams of Maya Mountains origin, few as yet described.

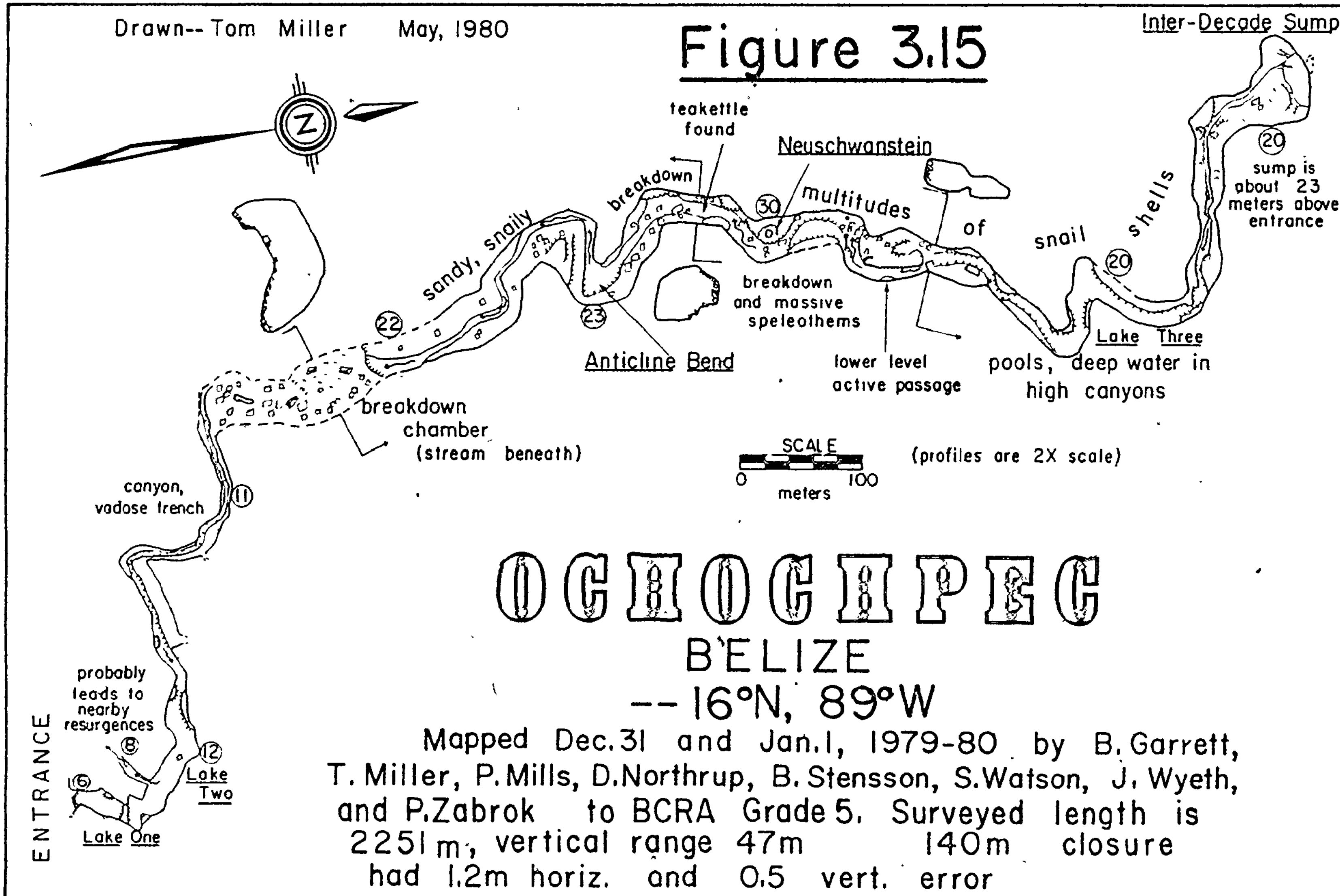
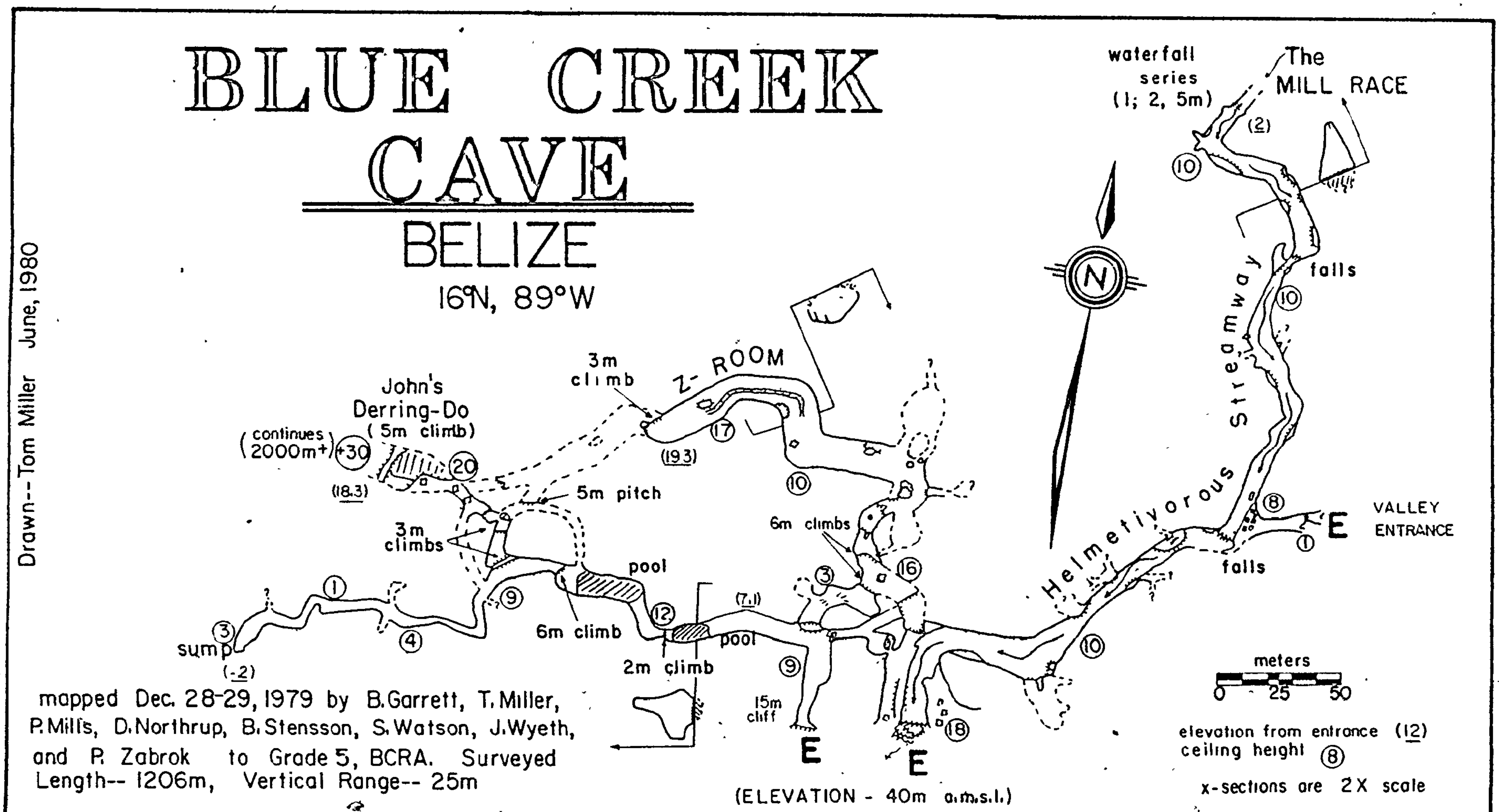

Drawn-- Tom Miller May, 1980
Inter-Decade Sump
teakettle found
Neuschwanstein
breakdown
multitudes of snail shells
sandy, snaily
sump is about 23 meters above entrance
breakdown and massive speleothems
Anticline Bend
lower level active passage
pools, deep water in high canyons
Lake Three
breakdown chamber (stream beneath)
SCALE
0 100
meters
(profiles are 2X scale)
canyon, vadose trench
probably leads to nearby resurgences
Lake Two
Lake One
ENTRANCE
OCHOCHPEC
B'ELIZE
-- 16°N, 89°W
Mapped Dec.31 and Jan.1, 1979-80 by B. Garrett, T. Miller, P. Mills, D. Northrup, B. Stensson, S. Watson, J. Wyeth, and P. Zabrok to BCRA Grade 5. Surveyed length is 2251 m, vertical range 47m 140m closure had 1.2m horiz. and 0.5 vert. error

Figure 3.15

Figure 3.16


BLUE CREEK
CAVE
BELIZE
16°N, 89°W
waterfall series (1; 2, 5m)
The MILL RACE
falls
Streamway
Helmetivorous
VALLEY ENTRANCE
E
falls
Z- ROOM
3m climb
John's Derring-Do (5m climb)
(continues 2000m+)
5m pitch
3m climbs
6m climbs
pool
6m climb
2m climb
pool
15m cliff
sump
meters
0 25 50
elevation from entrance (12)
ceiling height (8)
x-sections are 2X scale
(ELEVATION - 40m a.m.s.l.)
mapped Dec. 28-29, 1979 by B. Garrett, T. Miller, P. Mills, D. Northrup, B. Stensson, S. Watson, J. Wyeth, and P. Zabrok to Grade 5, BCRA. Surveyed Length-- 1206m, Vertical Range-- 25m
Drawn--Tom Miller June, 1980

Archaeological reports (Pendergast 1969, 1970, 1971) and maps indicate that the caves so far visited are usually of simple, horizontal, apparently phreatic, development.

Summary

Cavern development in the Caves Branch shows a diversity of morphologic types that apparently only formed integral networks at a quite recent stage in evolution. Fossil remnants demonstrate that caverns were initially relatively small, simple, and independent, with signs of integration appearing only in caverns at the base of the aquifer. Nearly all presently active stream inlets are found in the bottom 15-20 m of the accessible karst. The lack of fossil zuhuyhas or pirates, and the restriction of active inlets of these classes to the lower of the two major master conduit phases shows relatively late integration of all three. Several phases are recognizeable in the trunk conduits: an initial phreatic phase, development of lower vadose levels, and then an infilling phase. It is emphasized that conduit histories are often singular and unique to a particular system beyond a general regional pattern. Presently known caves may not be representative of the areal population as a whole and considerable information about growth and development may have been lost through erosion. This would be particularly true of piratic networks, which would be easily truncated or destroyed by any lateral polje growth.

The major caves of the area are impressively allogenic in origin and occupy by far the largest fraction of total known cavern volume. They have developed independently of the caves formed by authigenic water, although both combine into unified hydrologic networks. Both trunk conduits and authigenic inlets appear to function primarily as transporters of runoff, rather than to concentrate solution. Zuhuyhas discharge predominantly saturated water, and conduit traverses in low flow (see Chapter IV) show little rise in hardness directly attributable to aggressive solution. Solute concentration rises in the wet season more in response to increased zuhuyha discharge than to direct erosion. Unfortunately, traverses during periods of highest flow have not been possible, when exposure of bedrock to aggressive water would be at maximum.

Pirating tributaries are important elements of the hydrology of the Nab Nohol complex, and may possibly be effecting a progressively headward abandonment of the polje. Their chief role of transporting surface allogenic water to paralleling conduits does not seem important in extending the polje margins.

Radiometric dating has shown that major cavernous development in the bottom 30 meters of the Caves Branch karst was well advanced by 140-215 ky B.P. Filling episodes of unknown regional significance occurred between 60-105 ky B.P. in very large, mature trunk conduits of certainly much greater age. These networks were apparently influenced in location primarily by regional fracture patterns and relative topographic dip in a massive well-jointed/faulted limestone. Local relative base levels targeted by these caves appear to be gently declining overall in the recent geologic past.

CHAPTER IV

GENERAL HYDROLOGY AND HYDROCHEMISTRY OF THE CAVES BRANCH

The emphasis of this chapter will be on solutional erosion in the study area. The first part will deal with the basic controls on solution; the second part will describe variations in solute concentrations that occur with season and site changes.

Controls of Solution in the Caves Branch

I. Local Climatology

A. Historical

The Caves Branch lies within the tropical humid region of Central America, and has a mean annual temperature of about 24°C (as indicated by air and water temperatures in local cave interiors). The nearest permanent weather station, 15 km to the NW at Belmopan, has an annual temperature of 24.6°C. No temperature data is known to have been collected at Caves Branch itself prior to the initiation of field research in 1976.

Daily rainfall records were kept at the plantation headquarters (Fig. 4.1) from 1956-1965, discontinued for several years, then resumed from 1969-1975. Four of these seventeen years are incomplete. The instrument was apparently a manually-read gauge set in the open. Mean annual rainfall for these two periods as calculated from the data was 2376 mm (Table 4.1).

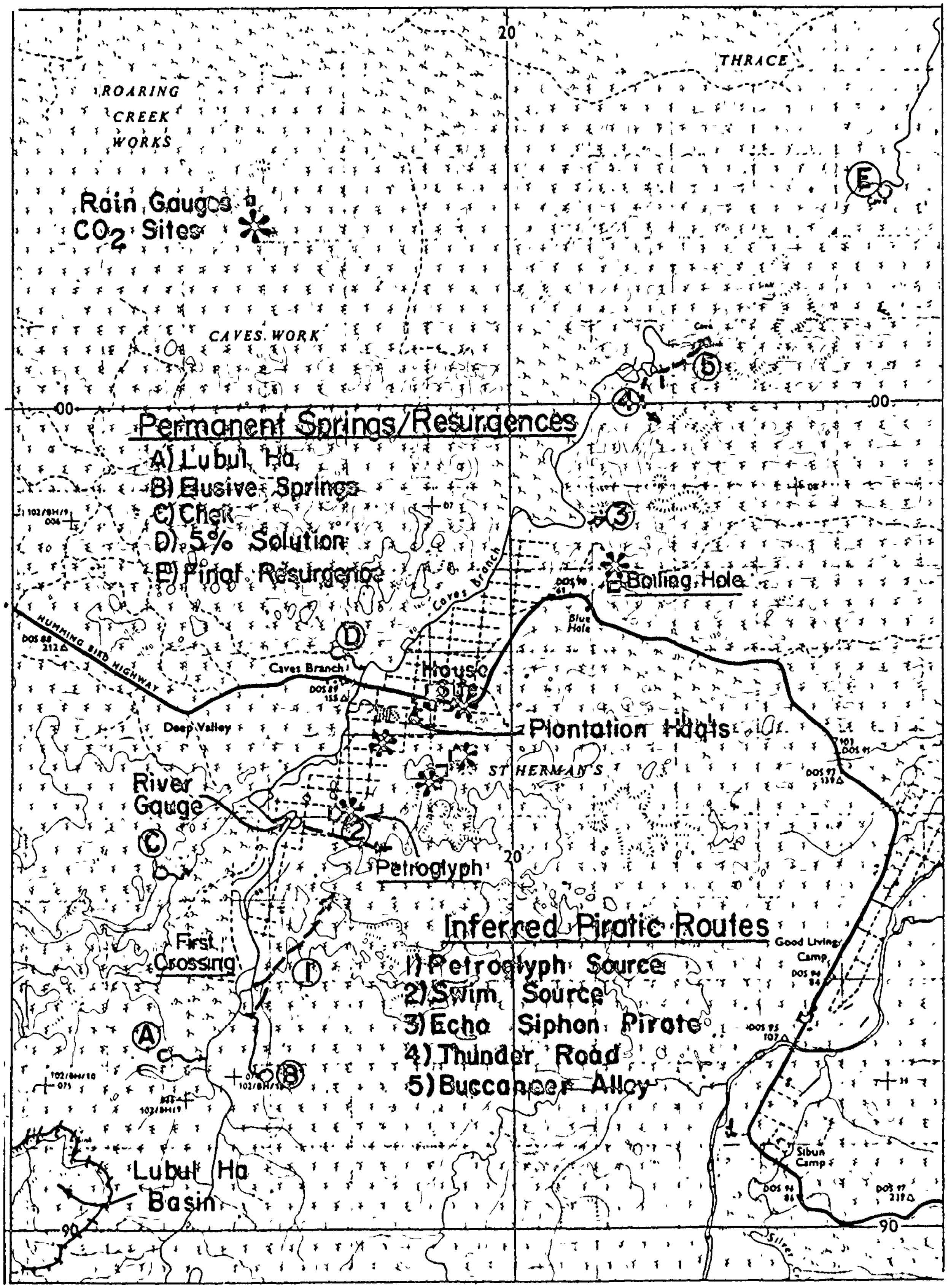


Figure 4.1 Hydrologic Sites

TABLE 4.1

Rainfall in the Caves Branch Region

Caves Branch Yearly Totals

Year	Amount
1956	inc.
1957	2213 mm
1958	2146
1959	2067
1960	2419
1961	2732
1962	2434
1963	2235
1964	2393
1965	inc.
1966	-
1967	-
1968	-
1969	inc.
1970	2593
1971	2234
1972	2995
1973	2086
1974	2151
1975	inc.

Mean Monthly Rainfall, Caves Branch

Month	Amount
Jan.	156 mm
Feb.	87
Mar.	63
April	70
May	109
June	294
July	434
Aug.	245
Sept.	257
Oct.	254
Nov.	231
Dec.	177
	2376

Site	Mean Annual Rain*	σ
Caves Branch	2361 mm	264
Roaring River	2076	125
Hummingbird Sibun	2644	255

*based on complete-year totals

Two nearby areas owned by the same company also recorded rainfall: Hummingbird Sibun (1968-1975) and Roaring River Estate (1952-1965). The former is located 6 km to the SE, the latter 9 km to the NW (Figure 1.1). The Table 4.1 data show the individual differences. These are best explained by the strong orographic effects on rainfall of southern Belize, and the relative positioning of Roaring River at a greater distance from the Maya Mountains.

The rainfall data show that monthly and daily variations were more extreme than between-year differences at Caves Branch. Annual complete-year totals ranged from 2067 to 2995 mm, while monthly totals were more erratic: June, for example, recorded a range of 61 mm (1975) to 580 mm (1962). Individual 24-hour maxima reached a recorded high of 232 mm on July 24, 1972, during a 6-day storm that totaled 570 mm. This was a convectional frontal disturbance, not a hurricane. As noted in Chapter I, nearly all precipitation is related to convection fronts and has an easterly (oceanic) source; this latter has minor implications for the local solute chemistry.

Table 4.1 also shows the yearly rainfall cycle: a wet period from June through October that corresponds to maximum summer insolation; and a gradual decline to the dry months of February, March, and April. In some years, these months are indeed dry, in others, considerable rain may fall. In all years, May is the transition month before major rain storms begin in June. For the data recorded, June has always had a higher recorded precipitation than May.

B. Field Seasons: 1976, 1977, and 1979

No local climatological data was obtained in 1976, and the measurements from the Belmopan weather station were used. This was decided to be of insufficient accuracy and local instrumentation was added in the subsequent field seasons. In 1977, this comprised one tipping-bucket rain recorder and three manual rain gauges. The automatic rain recorder and a hygrothermograph were placed at the Boiling Hole (Fig. 4.1). During 1979 a second tipping-bucket recorder was added. Three different manual gauges were used in 1979, and were also relocated. As each automatic rain recorder had a backup manual gauge, this left two independent manual gauges in 1977 and one in 1979. Figure 4.2 shows 1977 climatological data; 1979 is shown on Figure 4.3.

Temperature/Relative Humidity

During both field seasons there were higher temperatures and lower humidities in the comparatively rainless periods marking the end of the dry season. High temperatures ranged from 30°C to 36.5°C, and lows from 13.5-19°C. With the wet season, high temperatures dropped markedly, rarely exceeding 30°C in either year. Mean temperatures, however, showed a smaller decrease because daily minima became more stable and reached higher values (17°-19°).

Relative humidities were higher during the wet season, as expected. Ranges of daily maxima were 34-99% during the two field seasons, with the lower values in the dry season. Maxima approached or reached 100% every night, with morning dew a daily occurrence in both seasons.

In both 1977 and 1979 an inverse relationship between relative humidity and daily temperature maxima was noted, both years having correlations of r=-.89. Temporary instrument malfunctions in 1977 made use of this relation to calculate missing maximum temperature values.

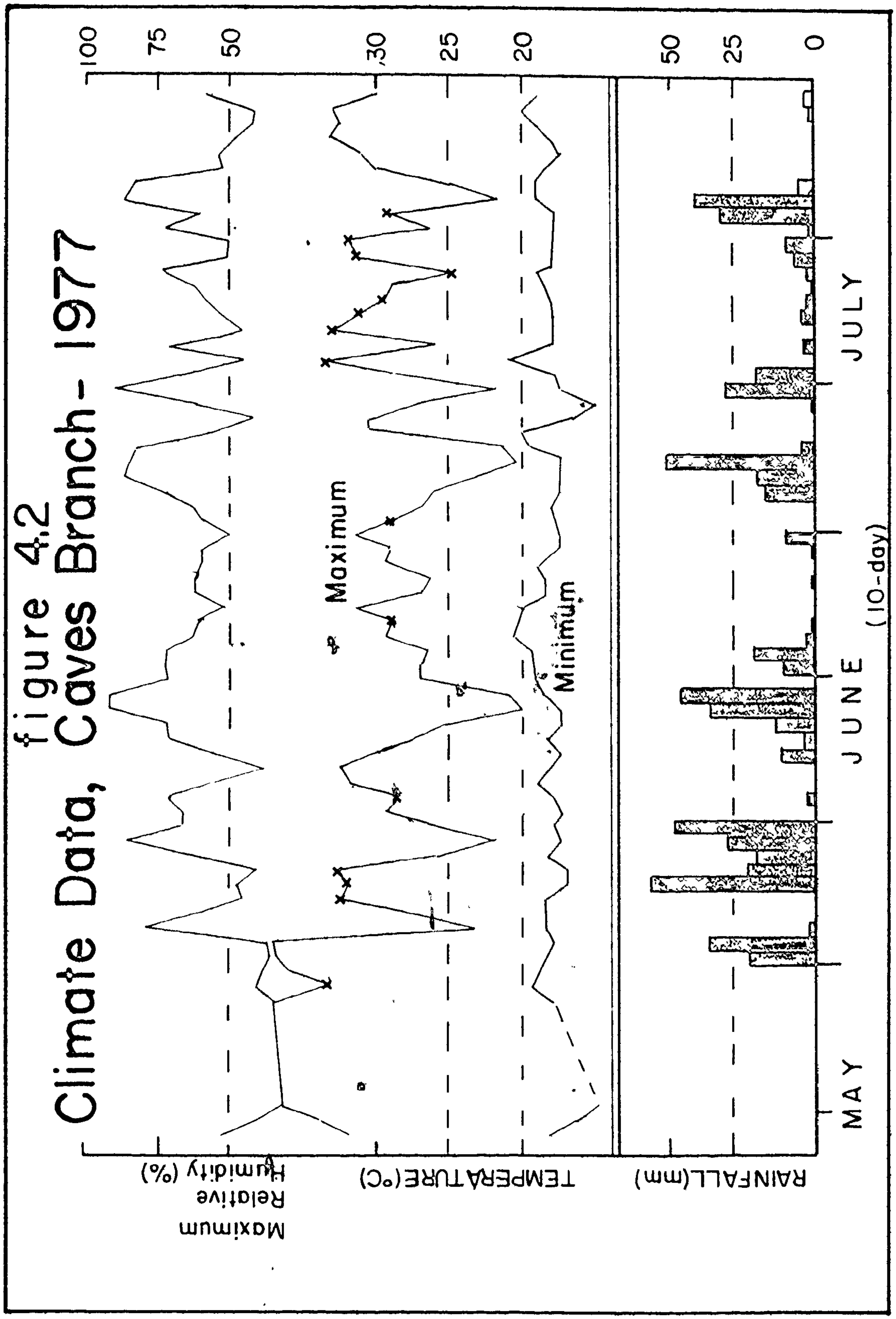


figure 4.2
Climate Data, Caves Branch - 1977
Maximum Relative Humidity (%)
100
75
50
TEMPERATURE (°C)
30
25
20
Maximum
Minimum
RAINFALL (mm)
50
25
0
MAY
JUNE
JULY
(10-day)

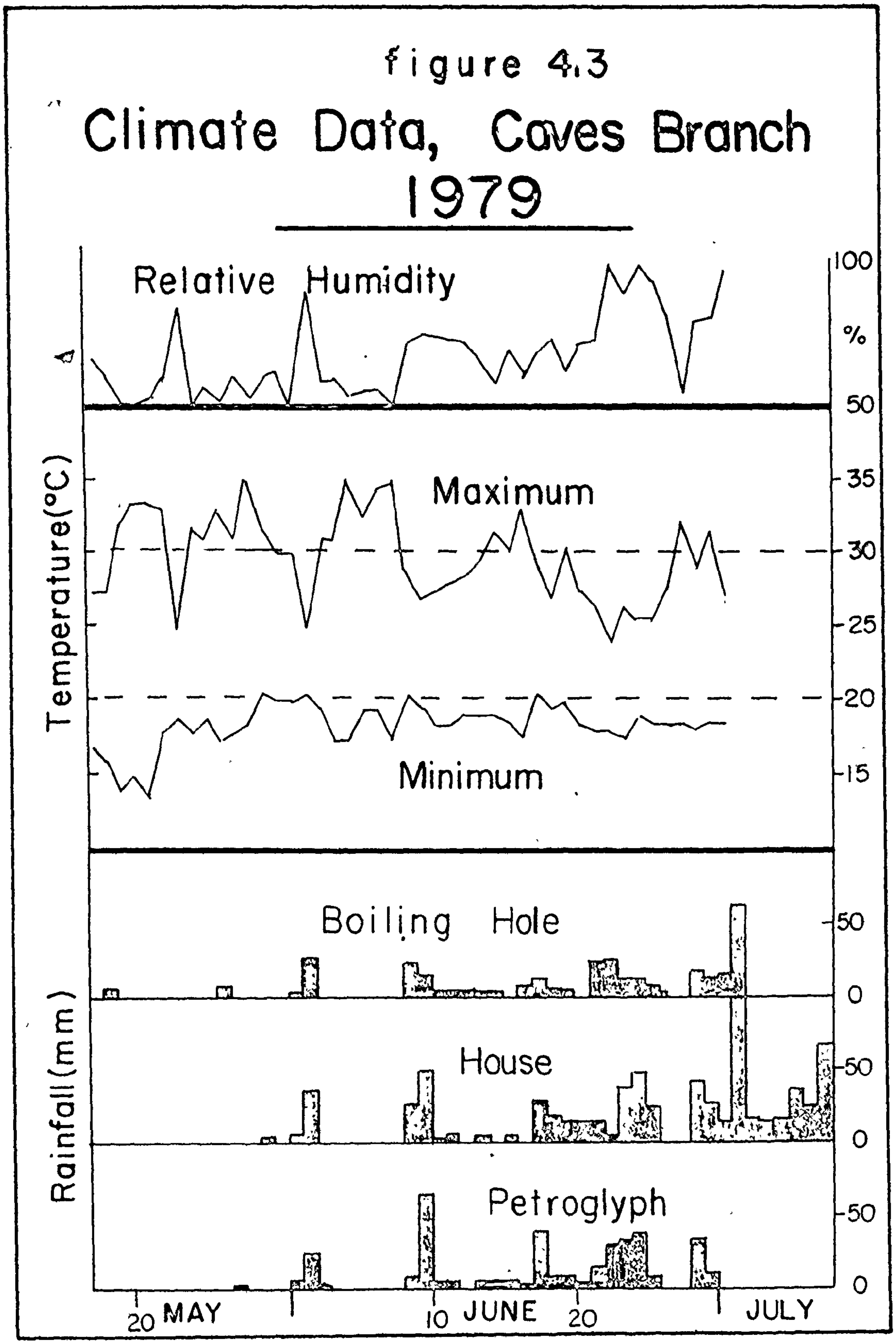


figure 4.3
Climate Data, Caves Branch
1979
Relative Humidity
100
%
50
Temperature(°C)
Maximum
35
30
25
20
15
Minimum
Rainfall(mm)
Boiling Hole
50
0
House
50
0
Petroglyph
50
0
20 MAY
10 JUNE 20
JULY

These are marked with an asterisk on Figure 4.2. Little error appears to be introduced as the standard error of estimate of the regression was 0.2°C. Missing minimum values (all in the wet season) were assumed to equal 18°C, the mean minimum temperature (σ=1°C).

Regression analysis was performed on measured 1979 temperature data to compare the Caves Branch and Belmopan. Maximum, minimum, and mean daily temperatures had correlation R^2 values of 0.49, 0.85, and 0.35 respectively. Combined with the Belmopan-Caves Branch rain regressions cited below, they indicate that the Belmopan data were collected at a point too distant to have sufficient short-term relevancy to the study area.

Precipitation

As emphasized in Chapter 1, rainfall is a much more variable meteorological event than either temperature or relative humidity. Daily rainfall in 1977 ranged from 0-60 mm, and in 1979 from 0-97 mm.

Only isolated, limited, rainfall occurred in each of the three field season dry periods. In the first week of June the wet season began, with a very marked change in precipitation amount and frequency. Most came in storms of several days' duration, separated by drier periods. The total rainfall amounts were large: 709 mm for the 77 days of 1977, and 618 mm for 52 days in 1979. This latter figure was calculated from all three gauges in the Caves Branch using the Thiessen polygon method.

An analysis of the 1977 rainfall shows that it was quite concentrated. Only 250 of the recorded 1537 hours showed precipitation, and in half of these hours less than one millimeter fell. Most precipitation fell in the remaining period at intensities of from 6-50 mm per hour. To emphasize, 370 mm fell in 32 hours, 2% of the 1977 field season duration. Late morning and early afternoon were the most common times for showers.

The manual backup gauges used in 1979 consisted of funnels and jars. They were calibrated by regression with either the Boiling Hole or Petroglyph tipping bucket recorders by which they were located. The Boiling Hole and Petroglyph automatic and manual gauges had R^2 correlations of 0.93 and 0.95 respectively. The regression equation of the latter was applied to the data from the isolated manual gauge at the House Site as it was felt the more open conditions at the Petroglyph Site were better representative than those at the Boiling Hole. The data from the backup gauges did not need to be used in 1977 or 1979 as no mechanical failures occurred.

As only 4.5 km separated the two most distant gauges, there was some intercorrelation between the three sites. Values of R^2 for daily rain totals ranged from 0.48-0.73 with standard errors of 8-10 mm. Between Belmopan and the two tipping buckets at the Caves Branch, there was less relation, as could be expected. The regressions explained only 16-19% of the total variation, with standard errors of 10-13 mm.

Evapotranspiration

For the hydrologic balance calculations of Chapter V, some knowledge of evapotranspiration (ET) is needed. This was desired to a minimum resolution of at least a week, the scale of most major stormflow events in the area. Because no wind data was obtainable either for the Caves Branch or Belmopan, the available methods of calculation were limited to those empirical formulae using temperature and relative humidity. A variety of methods using only temperature data are known, but the most commonly used and studied in a variety of environments is that of Thornthwaite (Wilson, 1974). Two other methods (Blaney and Morin, 1942; and Fitzpatrick, 1963) combine temperature and humidity but have rarely been applied outside of their initial areas of development. As the available method most studied in the widest variety of environments, Thornthwaite was chosen for the Caves Branch.

A number of criticisms of the assumptions inherent in the Thornthwaite method have been made. Pelton et. al. (1960) state that although a number of studies have found satisfactory correlations of Thornthwaite's potential evapotranspiration (PET_{TH}) with actual ET, this is not unexpected as both relate to periodic phenomena with the same period, having maximum/minimum values approximately in phase. A more acute problem is that of accuracy. For short-term calculation (e.g. daily) there can be significant deviation from actual ET, and even well correlated PET_{TH}/ET data may have coefficient slopes that vary considerably from 1. This latter introduces the necessity of initial calibration. On the other hand, there has been considerable support for the Thornthwaite method, especially if allowances for declining available moisture are incorporated. Many of the criticisms are directed at the initial version of the model, particularly because of the results obtained in situations where declining soil water levels cause actual ET to fall below potential. In these instances Thornthwaite tends to overestimate ET. Yet even those generally critical of the method agree that it gives reasonably accurate and comparable results to other methods when moisture is plentiful, e.g. Smith (1964) in a study of 26 years of evaporation data from an English catchment, and Pegg and Ward (1972), also in Britain.

In instances of application to arid low latitiude areas, the unmodified method is found least reliable in the dry season (Stern and Fitzpatrick, 1965) and can underestimate ET by 10-40% in the rainy season (Brutsaert, 1965).

With modification to take into account the lesser ET when available moisture is restricted, the Thornthwaite model is considerably more accurate. Smith (1959) in Trinidad found it to be as good as more complex methods in weekly resolution, with a ratio of ET/PET of close to one. In 1972, Hann applied the revised model to 7 basins in the central U.S. (one of them in karst) and found adequate prediction of runoff (r=0.93-0.97) on a monthly basis using daily totals.

The general consensus appears to be that the method is reasonably reliable provided 1) it is to be used chiefly in instances where PET and ET are comparable (e.g. a tropical rainforest in the wet season), especially at the initial start of a humid period; and 2) provision is made to minimize PET when moisture availability is not at optimum.

The first restriction is applicable to the Caves Branch. The second was incorporated into the Thornthwaite model used. Thornthwaite's modification employed the assumption that a linear relation existed between evaporation rates and soil moisture deficit (Smith, 1959). Staple and Lehane (1944) quote data indicating a more logical exponential decrease and this was the assumption used in the equation in the Caves Branch.

The pertinent equations for the study area were:

$$E_j = a\text{-}b\ (D_j) \text{ and} \tag{4.1}$$

$$D_j = D_{j-1} + E_{j-1} - P_{j-1} \tag{4.2}$$

where E_j = evapotranspiration for a given day, j

D = soil moisture deficit (SMD), initially set at 0

P = precipitation

$j-1$ = the previous day

a = daily Thornthwaite PET as calculated from the monthly and/or dry season value

b = dimensionless exponential constant for SMD increase, associated with a

[all values except b in mm]

If the daily Thornthwaite PET was not satisfied by precipitation, the SMD was increased by an amount proportional to that in storage. Rainfall excesses were subtracted from the SMD. Soil moisture and ET, therefore, were assumed to decline exponentially from a maximum at ground saturation to a minimum fixed percentage of total soil moisture based on the wilting point.

The values relevant to the above equations were empirical data obtained from other studies, or observation in the Caves Branch. Assumptions involved figures for field moisture capacity, wilting percentage, and time-to-wilting for soils similar in physical properties to those in the Caves Branch. Field moisture capacity (Steila, 1976) was taken to be 25%; a wilting percentage of 10% estimated from Buckman and Brady (1969); and amount of time necessary for unreplenished soil moisture to decline to wilting levels determined to be two weeks (Hendrickson and Veihmeyer 1945; Slatyer, 1967). Mean soil depth was calculated from readings associated with soil CO_2 in the cockpits (Tables 4.3 and 4.4). The karst in the study area was split into sections comprising either the cockpits or the hill summits, and aerial photos showed them to be approximately equal in area. Ground observation estimated soil cover on the rocky hill summits to be one-fifth as extensive as those of the cockpits.

Calculated ET for the Caves Branch was 220 mm in 1977, and 151 mm in 1979. These values were 31% and 24% respectively of the measured rainfall in those seasons. The soil moisture refinement was of value chiefly for calculation of moisture deficit at the end of the dry season, because near-constant humid conditions prevailed in the rainy season.

Table 4.2 shows comparison of unmodified Thornthwaite PET with pan evaporation data from Belmopan. In no month did the two vary by as much as 20%, as calculated on the larger figure, and the mean difference was 10%. This demonstrates the general validity of the Thornthwaite formula in the local region, as pan evaporation and actual evaporation are nearly equivalent at times of unlimited moisture supply.

The Table also shows the difference between the modified and original Thornthwaite models in the dry season periods for the Caves Branch. The former is almost certainly more representative as the Caves Branch rainforest was definitely in a wilting condition (leaf-shedding) at the end of each dry season during field observation, and ET would be expected to be very slight.

CO_2 of the Soil and Atmosphere

Numerous studies in a variety of locations (Ford, 1971; Woo and Marsh, 1977; Crowther, 1979 Jennings, 1978; and others) have demonstrated

TABLE 4.2

Comparison of Methods for Evapotranspiration Calculation, Caves Branch and Belmopan

	1976					1977			1979			
	A	M	J	J	A	M	J	J	A	M	J	J
Belmopan, PE		157	158	163	150	-	137	137	165	157	122	181
Belmopan, PET		170	144	149	143	-	155	150	153	173	150	154
Caves Branch PET		-	-	-	-	87*	109	113	-	66*	109	29*
Caves Branch MET		-	-	-	-	19*	99	102	-	19*	103	29*

all values in mm

where PE = actual pan evaporation

PET = Thornthwaite potential evapotranspiration

MET = model-derived PET for the Caves Branch

* These are figures derived only for the active portion of the field season

Note: Belmopan PE values are calculated on the basis of those days for which measurements were taken. All months were to some extent incomplete.

the importance of biogenic CO_2 in soil in determining pH and solute concentration of groundwaters. For the Caves Branch study, seven permanent monitoring sites for measuring soil CO_2 concentration were established in 1977, and read bi-weekly for most of the season. Many other spot samples of soil and atmospheric CO_2 (both above and below ground) were taken throughout the area. In 1979, samples were taken primarily as checks on the previous CO_2 readings, but only two sites were monitored.

The sampling instrument consisted of two nested metal rods which were forced into the soil layer to its bottom. The air was then extracted by a Draëger hand bellows and analyzed for CO_2 concentration as it was drawn through a Draëger tube. Procedure andinstrument description is amplified in Appendix A.

Results

1. Soil Samples

Figure 4.4 and 4.5 show the behavior of the monitored sites during the field seasons. There is a sharp rise in concentration following the beginning of the wet season in both 1977 and 1979. Table 4.5 also shows a similar effect for the random samples taken in the area. Other effects are the generally higher values associated with greater depth (Table 4.4), and a rise in concentration of CO_2 following the larger rainfall events.

The range of CO_2 concentration was considerable, from as low as 0.20% in the dry season, to 6.7% in the wet season. The usual range was about 0.5% to 2.5%; and is comparable to other tropical soil values (Miotke, 1973; Smith and Atkinson, 1976). Nearly all the readings were taken at relatively shallow depths. Thin soils typically develop in many tropical karst areas. Soils in the cockpit karst were markedly shallower than those in the polje

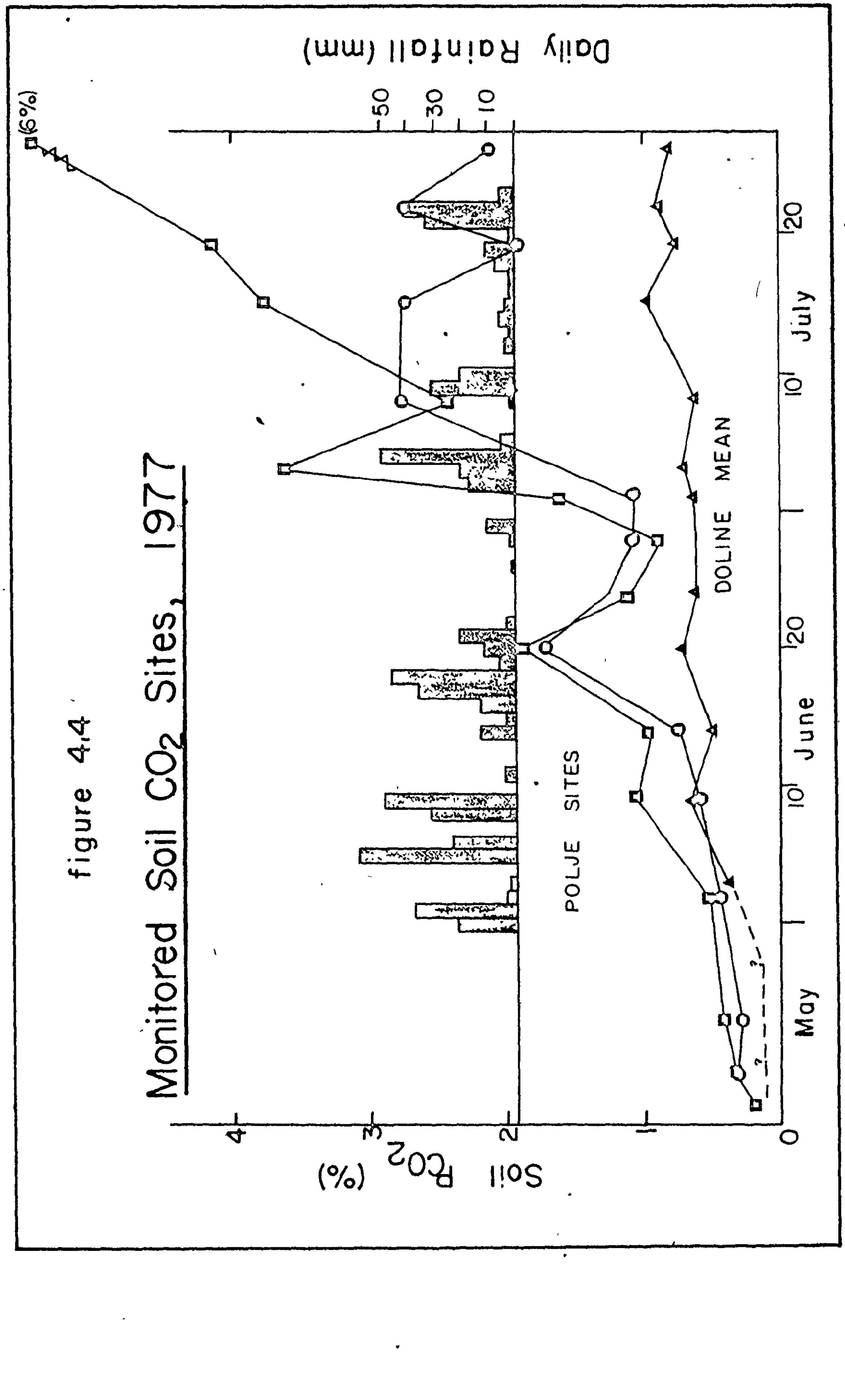


figure 4.4

Monitored Soil CO_2 Sites, 1977

figure 4.5

Monitored Soil CO_2 Sites, 1979

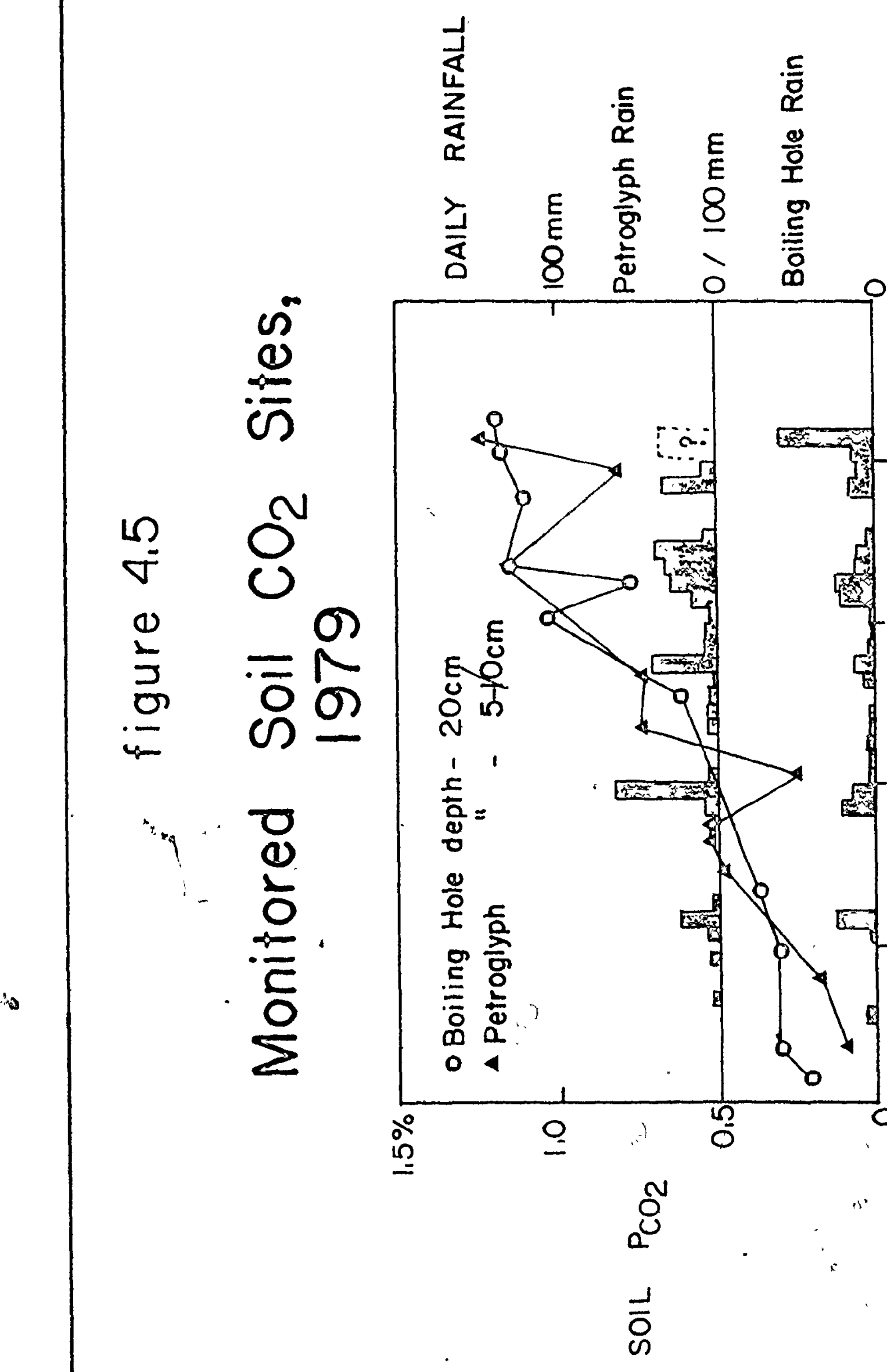


TABLE 4.3

Monitored Soil CO_2 Sites, Caves Branch, 1977

Date	Site 1	Site 2	B.H. Res.	Doline Ia	Ib	Ic	Doline II	Doline $\bar{x}$[1]	Previous Day's Precipitation
5/18	0.20%	0.22%	0.76%						
20	.33	.32							
24	.42	.30							
6/1	.52	.46							
2				0.30%	0.60%	0.36%	0.29%		
8	1.05	.60		.96	.80	.62	.31	0.67%	20. mm
14	.99	.75	1.33	.46	.72	.40	.41	.50	-
20	1.90	1.75	.80	.72	.75	.74	.61	.71	6.
24	1.10	1.25	3.30	.54	.80	.56	.56	.62	1.8
28	.87	≈1.08	1.30	.41	.77	.85	.42	.61	.3
7/1	1.65	1.10[2]	.51	.62	1.00	.50	.49	.65	.8
3	3.65	.50[2]	.65	.80	.70	.69	.70	.72	17.8
8	2.4	1.8		.56	.80	.47	.41	.56	-
15	3.8	2.8	(discontinued)	.51	1.40	.95	1.1	.99	4.8
19	4.2	1.9		.80	1.25	.50	.62	.79	7.
22	.8*	2.8		1.0	1.0	.6	1.0	.90	46.
26	6.0	2.15		.63	1.35	.60	.66	.81	-

(Wet Season)

Locale	$\bar{x}$	σ
Site 1	2.51%	1.60%
2	1.54	.76
Doline Ia	.67	.18
b	.95	.24
c	.62	.15
Doline II	.61	.23
Doline $\bar{x}$	.71	.14

[1] Doline $\bar{x}$ = mean % of all four doline sites

[2] Possible error

TABLE 4.4

Soil CO_2 Spot Samples; Caves Branch 1977

Polje and Glade Samples

Date	%	Depth
5-15	.40%	77 cm
	.20	10
	.20	10
	1.20	46
	.34	9
	.30	15
6-14	1.50	20
6-22	2.80	20
6-24	1.40	10
	1.05	28
6-28	1.75	15
6-30	.77	30
"	.77	13
7-7	.75	10
	.70	12
7-11	1.52	21
	2.5	10
	1.3	5
	6.7	45
	1.3	10
7-18	1.4	20
	1.0	18

Cockpit Samples

Date	%	Depth
6-14	.46%	11 cm
	.71	20
	.98	13
6-22	.70	9
	.95	15
6-24	.80	10
	.45	32
6-28	.75	10
6-30	.55	20
7-18	.42	20
	.56	10

Mountain Pine Ridge

Date	%	Depth
6-26	.48-.75	10 cm
"	.22	12
	.50	5

Atmospheric Samples

Date	%	Type
5-15	.038	Surface (cacao plantation)
5-27	.42*	Petroglyph Cave
5-29	.48	Actun Chek
	.75	"
	.06	" (near entrance)
6-1	.038	Mountain Cow Cave
6-16	.042	Actun Lubul Ha
	.06	"
	.07	
	.055	
	.04	
6-22	.09	(rainforest)
7-7	.07	Actun Lubul Ha
	.12	"
	.15	
7-10	.10	(rainforest)
7-11	.064	Actun Nohoch Tata
7-11	.06	(rainforest)
7-16	.08	Petroglyph Cave
7-17	.06	Petroglyph Cave

All samples taken with Draeger hand pump, 100 cc capacity.

* possible error

and low-lying alluviated areas. The well-documented effect of increased aeration may well account for the much lower values obtained in the cockpits. This differentiation of polje versus cockpit soils has been noticed in most other karst areas in the tropics as well (Smith and Atkinson, op. cit.; McDonald, 1976). The monitored and random (or spot site) groups for the alluviated valleys had mean values of approximately 2.0% and 1.6% respectively. This was higher than for either cockpit category - both the four monitored sites and those measured at random had values of about 0.7%. Thick clays are found to considerable depths beneath the active soil layer, but only rarely could any readings be obtained from them. CO_2 concentrations in the clays are apparently nil or are unable to migrate through the impermeable material.

It should be emphasized that these readings established only the relative contribution of CO_2 to the soil atmosphere, not the absolute amount. When considerable rain fell, the ground became saturated and forced the CO_2 closer to the surface. This resulted in relatively high concentrations, yet because the available air space was considerably reduced, the total amount of CO_2 may have been less than at other times.

2. Atmospheric readings

Table 4.4 shows the twenty samples taken at the surface and in several caverns. The global mean atmospheric value is a nearly constant 0.03%, but can be affected by cold temperatures, high altitude, lack of ventilation, or other factors (Miotke, 1974). All of the surface readings were above this figure, and occasionally ranged as high as 0.09% in dense forest. A typical finding in most caves is that atmospheric concentrations are even higher, apparently due to diffusion of CO_2 from high P_{CO_2} streams and drips.

In the Caves Branch, values ranged from just over the global mean (0.038% in Mountain Cow, a dry, well-aired cave) to as high as 0.75% in Actun Chek, in a poorly ventilated cul-de-sac passage. The entrance of Actun Chek gave a reading of only 0.06%.

There is also an apparent rise in cavern air CO_2 following an increase in discharge, perhaps due to increased diffusion from turbulent water, or the increased contribution of very high P_{CO_2} karst inlets, or both. These values can be compared with Ek (1969), Atkinson (1975), or Fish (1978) who quoted roughly comparable figures.

Discussion

As Miotke (1974) points out, a variety of factors affect soil CO_2 concentration at any particular time: soil thickness, soil saturation (or dryness), soil type, time available for soil air/water equilibration, etc. The overriding variable is that of seasonality, as expressed in temperature and precipitation. Boynton (1944) early showed the relation of CO_2 concentration with seasonal temperature and water supply, while de Jong (1974) demonstrated the especial effect of temperature in the range 5°-15°C. It is of importance to note that de Jong found that the temperature effect diminished above 15°C, with implications for tropical areas because of the overriding effect of rain above this thermal limit upon biogenic production. The work of Zonn and Chen-Kuei (1960) produced similar results; in the forest zone of the tropics in China they found that soil moisture controls CO_2 because of the uniform temperatures. In cooler areas with greater temperature range, the latter is more important.

The other major considerations when using measured soil CO_2 concentrations is applicability of the values obtained. As already mentioned these are relative values, not absolute concentrations, and may also not be representative of all the soil air contained in the soil profile; some soil atmosphere elements may be more difficult to draw out with suction, biasing the results. These same soil elements (e.g. soil "crumbs" vs. looser material) may be involved in greater or lesser degree with the actual process of equilibration of percolating water with the CO_2 in the soil atmosphere. Combined with the problems of adequately measuring a highly spatially, temporally, and seasonally variable gas, these factors make "effective" CO_2 concentration inputs difficult to determine.

To determine the effect of climatologic variables upon soil CO_2 production, tests were made of the correlation of temperature and rain with the mean values recorded at the four monitored doline sites (Table 4.4). To allow for possible delay between a climatologic input and resultant biogenic output, the previous day's rainfall and temperature were also tested for correlation. Table 4.5 shows that temperature was not significant either alone, or in conjunction with rainfall. The $\log_{10}$ of the rainfall of the day preceding the CO_2 measurement was found significant at the 0.01 significance level, giving a modest R^2 of 0.17. Rainfall of the same day was not found to be significant.

It was expected that the influence of rainfall could be refined if evapotranspiration were included. The calculated soil moisture deficits (SMD) (of section I.2, Chapter IV) of both the day of soil CO_2 measurement, and of the day preceding it, were used to test this. The SMD of the previous day gave a marginally better correlation (R^2=0.27) at the same 0.01 significance level. As the difference between the SMD and the rainfall is entirely the result of inclusion of temperature data, it is implied

TABLE 4.5

Soil CO_2 and Climatic Variables, 1977

Equation	t_1**	t_2	t_3	Se	*R^2
Soil CO_2 (%) = $.389 + .0063\ X_1$	3.41	2.93		.11	40.8%
$.669 + .119\ X_5$	14.6	1.62		.13	13.0
$.786 + .0208\ X_8$	15.3	-2.06		.12	22.7
$.780 + .0445\ X_{10}$	14.8	1.84		.13	17.8
$.469 + .0061\ X_1 - .0201\ X_8$	5.34	3.90	3.09	.08	68.0
$.425 + .0067\ X_1 - .0151\ X_9$	3.86	3.29	-1.52	.10	47.7
$.0416\ X_2 - .223\ X_5$		2.52	3.09	.11	43.3
$.451 + .0065\ X_1 - .0471\ X_{10}$	5.30	4.17	3.16	.08	69.0

X_1 = days from season start
X_2 = previous day's temperature
X_3 = temperature of reading day
X_4 = rainfall on reading day
X_5 = previous days' rainfall
X_6 = runoff, day of reading
X_7 = runoff, preceding day
X_8 = soil moisture deficit, day of reading
X_9 = soil moisture deficit, preceding day
X_{10} = $\log_{10} X_5$

Note: Soil CO_2 is the mean of the four monitored dolines for 12 wet season readings;

.01 significance level, t = 3.17
.02 = 2.76
.05 = 2.23
.10 = 1.81
.20 = 1.37

other variable regressions and combinations were not significant at these levels.

* adjusted for degrees-of-freedom
** test of degree to which value differs significantly from 0

that temperature does have a very minor effect upon CO_2 in this climate but only through the evaporation process.

Regardless of the short term effects of the climatologic variables there was a constant rise of CO_2 with time. Combined with the SMD it accounted for 68% of the variation with soil CO_2 at the 0.01 significance level. This relationship continued at least through the duration of the field season. It suggests that given a minimum maintained level of soil moisture, biological growth and production will increase to some unknown maximum in the wet season.

It was suspected that the association of increased soil CO_2 with increased rainfall might lead to significant differences between the P_{CO_2} of actual recharge water to the aquifer, and that of the mean season P_{CO_2}. Using the time-rain-CO_2 regression of Table 4.5, the calculated seasonal mean CO_2 was weighted on the basis of runoff as determined from rain-ET differences. Surprisingly, no significant difference was found. Irrespective of possible ET errors from daily calculation, this result may be explained by both the lag between rain and CO_2 production, and the small contribution of rain compared to the time influence. There is such slight daily autocorrelation of rainfall (r=.21) that periods of minor runoff following major storms may actually have the highest mean P_{CO_2} values.

II. Hydrology and Hydrochemistry

It is difficult to separate these as reference to one generally implies reference to the other. Their general features will be discussed separately, but both will be cited together during interpretation of the solutional aspects of water in the Caves Branch.

A. Local Hydrology

1. Historical

No stream gaging records were ever made at the Caves Branch, although notice was taken of severe or exceptional flooding. On at least two occasions in the early 1970's large areas of the polje valley were inundated to depths of a meter or more in the vicinity of the highway bridge, and to greater depths downstream (B. MacLeod, personal communication). Various debris of natural and human origin (large logs, oil drums, etc.) has been observed lodged in trees and other sites up to 10 meters above stable low water levels, and far higher than anything observed during the months of record.

2. General Hydrology

Seasonal effects are the most fundamental in determining flow in the Caves Branch -- pronounced differences in volume and occurrence of flow exist between the dry season end, in May, and the start of the rains. There are also obvious differences in type of flow occurring in the karst and allogenic segments of the catchment, with surface flow predominating in the latter, and subsurface flow in the former areas. Dry season flow in the karst is mostly confined to cavern trunk conduits. The three streams originating in the highlands (Caves Branch, Lubul Ha, and Chek) all sink and ultimately contribute to the maintenance of the year-round cavern conduit flow. Unlike the other two, the Caves Branch River sinks in its bed long before reaching any open ponors, then resurges and sinks several more times within a short distance before disappearing completely. Lubul Ha and Chek convey their highland streams completely through the karst, resurge into the polje valley, then sink again in the Caves Branch river channel.

Authigenic contributions to dry season flow are minimal. There are some tiny drips from stalactites, a few inputs from zuhuyhas, but there is no flow at all anywhere on the karst surface.

In brief, then, nearly all dry season karst streamflow occurs in cavern conduits, and is maintained largely by invading, sinking allogenic water.

Changes at the onset of the wet season are abrupt and profound. Within an interval of a few days, the Caves Branch flow exceeds the infiltration capacity of its bed and of the pirating conduits, and extends throughout the polje to sink at the downstream ponor. After especially heavy rainfall, ephemeral streams occur in channels on the karst surface. Underground, previously dry inlets (channels feeding water to the trunk conduits) now begin to flow, and the perennial inlets increase discharge by an order of magnitude or more. Perhaps the most impressive qualitative change is that of the discharge from thousands of stalactites that were dry only days before.

In spite of the greatly increased volumes of water, actual flooding occurs during only a small proportion of the wet season. The chief differences from the dry season are not only the greater flow, but the more widespread occurrence of flow.

3. Instrumentation

Discharge volumes were chiefly measured with a Gurley-type velocity meter, although weirs, volumetric cylinders, and surface floats were also used. Subjective estimations were occasionally made where necessary (e.g. very small flows; physically awkward situations). When such estimations could be compared with flows that were subsequently measured, they indicated the subjective estimates to be with 20% of the true values.

Few measurements were made in 1976 due to early failure of the meter, but in the succeeding field seasons stage recorders were set up to monitor the Nab Nohol Branch of the Caves Branch Cave System at the site named the Boiling Hole Resurgence. In the 1977 season, a second stage recorder briefly recorded the Caves Branch River in mid-polje, but the stilling well was torn away by a flood after several weeks. In 1979, this stage recorder was installed further up the Nab Nohol Branch cave conduit to supplement the Boiling Hole data. Figure 4.1 shows these locations. These hydrographs are presented in Chapter V, as Figures 5.8 and 5.11.

Intermittent measurements were taken of the flow of surface and subsurface springs, other cave conduits, etc. Where possible, the Gurley meter was used, but frequently access and size difficulties made the other methods necessary.

Results of the discharge samplings are discussed with their hydrochemistry in the following section.

B. Local Hydrochemistry

General Two primary hydrochemical sources of flow exist in the Caves Branch -- 1) allogenic, waters invading the karst with a source in the non-carbonate rocks of the Maya Mountains and 2) authigenic, flows originating from direct rainfall on, and runoff from, the limestone. Both ultimately combine to create hybrid waters which have characteristics midway between these two basic types.

1. Sampling Design In all three field seasons a monitoring program was maintained to some extent at karst windows on the Nab Nohol Branch of the Caves Branch Cave System. Frequency of observations increased with each successive season, and in 1979 two flood pulses were sampled at hourly intervals across the flow peaks. Other sites were checked at less regular time intervals, and many samples were taken of less accessible, or "interesting", sites on a random basis. Depending on the season, and the desirability of information for a particular sample, total or partial analyses were made which included noting date, location, discharge, and measuring temperature, pH, specific conductivity, and analyzing for calcium, magnesium and bicarbonate ion concentrations. These sample data were later used to compute calcite and dolomite saturation indices, and carbon dioxide partial pressures.

Further details on procedure and calculation are contained in Appendix B.

The data are presented in Tables 4.6a-4.6j. There are individual gaps from instrument failure, as well as general gaps in entire variables due to design. The 1977 data indicated that certain features of the hydrochemistry could be more profitably investigated with fewer variables. In 1979, Ca^{2+}, Mg^{2+}, and HCO_3^- (except for occasional checks), were largely dropped in favor of specific conductivity (SPC) and total hardness (TH) measurements. Check analysis for SO_4^{2-} was also added in 1979.

It is emphasized that the basic focus of the research was upon the solutional destruction of one primary rock -- limestone. Because of this simplification of chemical considerations, and because of prior convention

Table 4.6 Caves Branch Hydrochemistry

Table 4.6a Allogenic

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
	UPPER CAVES BRANCH RIVER(POLJE)										
7 2 76	318	24.6			16	10	6	14			
7 6 76	322				11	7	4	11			
8 7 76	335				33	26	7	30			
811 76	338				33	22	11	29			
518 77	302	28.3	6.65		22	15	7	21	-2.49	-2.54	.62
520 77	303	29.1	7.10		26	19	7	25	-1.86	-1.96	.26
6 3 77	304■	30.3	7.62		35	27	8	35	-1.03	-1.17	.11
6 7 77	305■	26.9	7.85		22	16	6	26	-1.19	-1.30	.05
611 77	306■	26.1	6.80		10	7	3	9	-3.05	-3.14	.18
616 77	310	25.9	7.30		34	27	7	30	-1.48	-1.67	.19
630 77	319	27.0▲	7.35		19	13	6	18	-1.94	-2.00	.10
630 77	320	27.0▲	7.20		12	8	4	11	-2.50	-2.54	.09
715 77	324	26.4	7.05		33	27	6	31	-1.71	-1.93	.35
3 4 78	301	24.6		67	31						
3 5 78	304	22.2		41	18						
520 79 I	307	27.5	6.30	102	40		8	41▼	-2.25	-2.45	2.66
520 79 I	308	28.0		56	25		7	28			
520 79 I	309	29.5		76	35		8	37			
520 79 I	310	28.0		69	32		7	34			
520 79 I	311	31.0		76	35		8	37			
520 79 I	312	31.0		73	34		7	36			
520 79 I	313	31.5		78	36		8	38			
622 79 I	337	27.7			22		6	24			
	Other Allogenic Sources										
6 4 79 I	321■	28.5	6.15	46	9	4	5	11▼	-3.79	-3.64	1.07
6 4 79 I	325	30.5		48	21	16	6	24			
6 4 79 I	326	31.0	7.15	78	25	19	6	27▼	-1.76	-1.86	.26
621 79 I	336■	26.6	8.50	57	17	11	6	19	-.82	-.87	.01
811 76	440				28	18	10	24			
7 6 76	321				14	10	4	17			
626 76	603	26.0			38	26	12	22			
616 77	418	24.0▲	7.10		20	13	7	20	-2.18	-2.23	.20
625 77	314■	24.6	7.10		14	13	1	22	-2.13	-2.60	.22
629 77	315■	23.9	6.45		7	5	2	12	-3.45	-3.56	.54
626 77	316	26.2	7.15		27	19	8	25	-1.85	-1.94	.23
630 77	321	25.0▲	6.55		29	23	6	27	-2.35	-2.55	.96
78	306	24.0		45	20						

Table 4.6b Authigenic Surface Flow

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
	WET SEASON STREAMS										
630 76	605	24.6			186	153	33	180			
723 77	607	28.5	7.56		240	176	64	238	.41	.31	.81
613 77	608	27.9	7.89		215	199	16	211	.75	.31	.34
630 77	516	24.0▲	7.55		256	185	71	250	.38	.26	.83
724 77	534	23.2	7.54		195	171	24	199	.25	-.10	.67
310 78	525	17.0		228	125						
6 4 79 I	322	28.5	8.22	295	152	133	19	149▼	.79	.44	.11
6 4 79 I	324	29.5		595	294	261	33	286			
	EPHEMERAL(COCKPIT)										
619 76	601	24.3			15	9	6	19			
716 76	607				53	43	10	50			
6 5 77	601■	24.4	6.98		40	34	6	33	-1.69	-1.97	.43
6 9 77	603■	24.3	6.88		51	47	4	45	-1.52	-1.97	.73
617 77	604		7.05		106	103	3	100	-1.05	-1.88	.82
620 77	605	25.1	7.05		50	46	4	47	-1.33	-1.77	.52
7 5 77	606■	23.5	6.35		30	26	4	26	-2.54	-2.86	1.43
7 2 79 I	340	24.0▲	7.10		29	22	7	31	-1.78	-1.95	.30
7 2 79 I	341	24.0▲	7.30		26	19	7	29	1.41	2.58	2.07
625 79 I	339	20.0▲	6.65		29	22	7	31	-2.29	-2.48	.82

Table 4.6c Misc. Surface Karst Water

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
6 5 76	301	29.6			74	62	12	74			
6 7 76	303				43	30	13	25			
613 77	308	28.8	7.58		105	84	21	87	-.26	-.44	.29
310 78	302	27.5		180	87						
612 79 I	333	27.0	8.93	58	34	27	7	36	.23	.06	.01
610 79 I	329	23.0▲	8.00	190	90	77	13	89	.06	-.25	.11
7 3 77	322	27.0	7.81		271	226	45	155			.29
615 79 I	335	29.5	8.00	570	281	250	32	274			.34
6 4 79 I	323	26.5		143	69	58	11	69			
610 79 I	330	26.0▲	7.95	182	88	76	13	88	.04	-.25	.12
610 79 I	331	24.0▲	7.95	182	88	75	13	88	.01	-.29	.12
610 79 I	332	25.0▲	8.00	181	88	75	13	88	.07	-.22	.11
724 77	326	24.8	7.45		88	78	10	92	-.45	-.80	.40

Note- ion values in mg/L $CaCO_3$,

temp. in °C,

P_{CO_2} in %

■=ion balance error >5%

▲=interpreted temperature

1979 Ca, Mg, and HCO_3 are estimated from TH correlations. These are marked with a bar (I)

Table 4.6d Monitored Zuhuyha/Spring Waters

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
PETROGLYPH CAVE											
SATIRE ZUHUYHA TAO											
228 78	508	24.2		298	157						
630 79	544	24.5	7.90		166	153	13	163	.50	.05	.25
CROOKED BEND											
619 76	506	23.7	*		190	190	20	163			
527 77	504	23.7	7.75		190	177	13	195	.48	-.00	.42
717 77	570	24.0	7.36		186	157	29	190	.02	-.25	.99
227 78	506	23.3		345	178	0	0	0			
519 79	507	24.5	7.25	379	190	172	18	186	-.15	-.45	1.25
617 79	520	24.5	7.30	392	211	189	22	206	.08	-.29	1.23
624 79	532	23.8	7.38		202	182	20	197	.12	-.27	.97
630 79	552	24.5	7.40		177	162	15	173	.05	-.38	.82
7 1 79	550	24.5	7.50		142	135	8	140	-.01	-.54	.53
7 3 79	546	24.5	7.50		125	121	4	124	-.10	-.74	.47
7 7 79	551	24.5	7.40		146	138	8	143	-.09	-.61	.69
SWIM ZUHUYHA											
527 77	501	23.6	7.00		192	162	30	204	-.30	-.58	2.40
717 77	532	23.3	7.28		180	173	7	193	-.04	-.65	1.13
227 78	507	23.6		340	175						
524 79	505	23.8	7.15	420	207	186	21	202	-.10	-.44	1.69
529 79	506	23.6	7.10	393	195	176	19	191	-.19	-.59	1.79
617 79	521	24.5	7.29		204	183	21	199	.04	-.34	1.22
624 79	531	23.7	7.53		206	185	21	201	.28	-.11	.70
630 79	542	24.5	7.40		176	161	15	172	.04	-.33	.82
WHITE GOURS											
630 79	541	24.3	7.60		186	169	17	182	.28	-.12	.55
7 4 79	549	24.5	7.55		187	170	17	183	.24	-.17	.62
NATURAL BRIDGE GOURS											
624 79	530	23.4	7.47		166	153	13	163	.06	-.40	.65
630 79	539	24.5	7.40		172	158	14	168	.03	-.41	.80
7 4 79	547	24.5	7.43		191	173	18	187	.10	-.30	.89
NEW SPRING, PETROGLPH ENTRANCE											
630 79	540	24.5	7.45		187	170	17	183	.14	-.27	.77
7 4 79	548	24.5	7.40		184	168	16	180	.08	-.34	.96
SAINT HERMAN'S CAVE											
EDINBORO TRIBUTARY											
6 5 76	501				150	135	15	142			
6 4 76	502	24.7			150	130	20	141			
6 1 77	506	24.7▲	7.40		149	137	12	148	-.08	-.51	.71
618 79	522	24.5	7.50	302	150	141	9	147	.03	-.47	.56
GOOD NEIGHBOR TRIBUTARY											
321 79	531	25.0		322	167						
614 79	518	24.5		319	154	145	10	152			
PICTURE SPRING											
319 78	528	23.5		620	301						
[illegible] 79	502	24.0	7.37	635	314	270	44	305	.43	.17	1.51
[illegible] 79	557	24.5	7.55	635	294	254	40	296	.57	.26	.94
614 79	515	24.5		600	296	257	40	299			
[illegible] 79	525	24.5	7.70	619	304	262	42	296	.75	.44	.69
627 79	534	24.5	7.50		297	257	40	289	.53	.22	1.07
PICTURE SPRING TWIN											
319 78	529	24.2		325	169						
[illegible] 79	501	24.0	7.30	352	178	163	15	174	-.06	-.49	1.04
[illegible] 79	555	24.5	7.15	348	171	158	14	168▼	-.23	-.66	1.42
614 79	516	24.5		329	161	150	12	158			
618 79	525	24.5	7.41	335	164	152	12	161	.01	-.45	.75
FALLEN STAL INLET											
310 78	510	24.5		320	166						
[illegible] 79	503	24.5	7.23	352	173	159	14	169▼	-.14	-.57	1.19
[illegible] 79	555	24.5	7.25	357	175	161	15	172	-.11	-.53	1.16
614 79	517	24.5		319	154	145	10	152			
627 79	535	24.5	7.35		151	142	10	149	-.11	-.61	.80
BARBA'S STAL DRIP											
310 78	527	23.5		323	168						
614 79	514	24.5		400	197	178	19	133			
[illegible] 79	523	24.5	7.63	448	221	197	24	216	.41	.05	.64
[illegible] 79	524	24.5	7.35	420	210	188	22	209	.12	-.25	1.09
PRENANCI											
522 79	504	24.5	7.15	653	312	269	43	303▼	.21	-.09	1.51
[illegible] 79	554	24.5	7.35	545	287	249	38	280	.35	.04	1.47
FOUNTAIN ZUHUYHA											
[illegible] 76	503	23.8			165	160	5	145			
6 4 76	505	24.0			177	170	7	163			
627 79	533	24.5	7.60		179	164	15	175	.26	-.10	.53
7 1 79	545	24.5	7.45		180	164	16	175	.11	-.31	.75
ANDERSON FALLS											
[illegible] 76	513				234	183	71	274			
627 79	536	24.5			272	237	35	265			
TINKLE TUNNEL											
[illegible] 78	513	24.5		423	213						
6 4 79	513	24.5		365	179	134	16	176			
[illegible] 79	537	24.5	7.25		214	[illegible]	[illegible]	233	.04	-.37	[illegible]

see note for legend

4.6d (cont.) Other Monitored Zuhuyha/Springs

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
CATFISH CREEK											
728 76	516				165	143	22	168			
712 77	527	24.5	7.16		175	159	16	173	-.20	-.61	1.43
3 8 78	523~	24.0		300	157						
SHELTER BREAKOUT ZUHUYHA											
727 76	514				163	137	26	140			
711 77	524	24.5	7.25		170	151	19	169	-.14	-.50	1.14
3 9 78	505	24.0		313	163						
YOL HA											
3 3 78	517	23.8		400	202						
616 77	508	23.6	7.25		213	179	34	209	-.01	-.28	1.38
7 7 77	517	23.0	7.58		223	195	28	223	.38	.04	.68
5 PERCENT SOLUTION											
620 77	511	24.3	6.85		292	247	45	286	-.15	-.42	4.73
624 77	512	24.3	6.88		292	265	27	296	-.37	-.47	4.56
6 3 79 ▮	512	24.8	7.05	600	296	257	40	289	.08	-.23	3.02
BAT INFLUENT											
628 77	514	23.8▲	7.22		270	266	4	282	.25	-.57	1.98
3 8 78	524	24.0		590	288						
531 79 ▮	511	24.5		578	262	230	33	256			
ELUSIVE SPRING											
630 77	515	24.0▲	7.65		126	93	33	119	-.09	-.22	.32
520 79 ▮	314	26.5	7.95	221	108	93	15	107▼	.21	-.09	.15
FISSURE PASSAGE											
529 77	505■	23.9	7.52		209	175	34	233	.31	.04	.83
620 79 ▮	529	23.8	7.70	378	202	182	20	198	.44	.05	.47
NOHOCH TATA TRIBUTARY											
812 76	504	24.4			228	195	33	222			
727 76	515				209	199	10	235			
3 3 78	504	24.0		405	205						

Table 4.6e Miscellaneous Cave Waters

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
ZUHUYHAS AND SPRINGS											
623 76	507	23.7			161	138	23	153			
7 8 76	510				120	115	5	112			
7 8 76	511				167	160	7	159			
716 76	512				195	176	19	191			
8 5 76	517				142	140	2	134			
8 5 76	518				174	169	5	181			
8 7 76	519				203	193	10	195			
716 77	529	23.8	7.45		189	184	5	231	.20	-.49	.84
228 78	509	24.0		283	150						
3 3 78	512	21.3		324	[illegible]						
310 78	534	23.5		610	297						
531 79 ▮	508	25.9	7.22	266	133	127	6	131	-.32	-.89	.97
531 79 ▮	509	25.9	7.30	226	130	125	5	123	-.26	-.85	.79
531 79 ▮	510	24.1	7.25	478	254	223	31	247	.16	-.18	1.63
6 2 79 ▮	553	24.5	7.05	690	341	292	50	332	.18	-.11	3.44
620 79 ▮	527	23.7	7.50	310	152	143	10	150	.03	-.47	.56
620 79 ▮	529	23.3	7.60	365	200	181	20	196	.33	-.06	.59
630 79 ▮	543	24.5	7.60		180	164	16	175	.25	-.16	.53
POOLS											
7 3 76	509				129	125	4	125			
3 2 78	601	24.0		145	70						
228 78	603	24.0		182	88						
3 3 78	605	22.0		209	102						
3 3 78	606	22.8		228	[illegible]						
3 3 78	607	24.0		372	183						
3 3 78	608	23.0		324	159						
310 78	609	23.4		354	174						
310 78	610	23.7		450	222						
310 78	526	22.8		268	143						
LOW-SOLUTE INLETS											
BICENTENNIAL TRIBUTARY											
616 77	509	23.1	7.15		58	48	10	56	-1.17	-1.43	.48
3 3 78	514	21.8		124	78						
SNAIL TRIBUTARY											
7 7 77	522	23.5	7.65		92	74	18	91	-.29	-.51	.25
3 3 78	516	21.4		115	74						
CAPUT ZIHIL HA											
618 77	510	24.0	7.79		66	61	5	63	-.37	-.83	.13
CRAWL INLET.LUBULHA											
3 3 78	513	23.0		145	88						
STALACTITE DRIPS											
628 77	513	23.8▲	7.70		221	175	46	206	.43	.23	.48
7 7 77	514	23.8▲	7.59		206	177	29	205	.33	.02	.62
7 7 77	519	23.5	7.24		211	199	12	210	.03	-.49	1.42
7 7 77	520	23.4	7.63		195	190	5	188	.36	-.34	.52
7 7 77	521	23.8▲	7.45		233	202	31	227	.29	-.04	.95
710 77	523■	23.9▲	7.33		205	194	11	222	.14	-.39	1.22
712 77	525■	23.8▲	7.38		156	117	39	194	-.07	-.22	.96
712 77	526	23.8▲	7.58		177	171	6	170	.23	-.41	.53
717 77	531	23.9▲	7.49		162	159	3	160	.39	-.08	.62
717 77	533	23.9▲	7.62		132	131	1	136	.08	-.89	.39

see notes for legend

Table 4.6f Pirating Sub-conduits

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
UPSTREAM LIMIT, PETROGLYPH CAVE											
716 77	429	25.0	8.05		43	37	6	43	-.46	-.76	.05
PETROGLYPH SUMP(UPSTREAM), WITHOUT WET SEASON FLOW											
527 77	413	24.5	7.35		44	38	6	43	-1.16	-1.47	.24
524 79	403	25.0	7.43	107	51	42	9	52	-.96	-1.20	.25
529 79	405	25.1	7.52	103	44	36	6	45	-.99	-1.21	.17
624 79	419	24.5	7.83		76	65	11	75	-.25	-.54	.15
7 2 79	421	24.5	7.55		133	116	17	131	-.05	-.37	.45
PETROGLYPH SUMP TRIBUTARY											
527 77	502	24.5	7.90		44	36	8	44	-.62	-.86	.07
716 77	528	24.5	7.64		85	79	6	84	-.29	-.76	.24
228 78	702	24.0		86	40						
524 79	702	25.0	7.30	107	51	42	9	52	-1.08	-1.32	.33
526 79	705	25.1	7.43	102	44	36	8	45	-1.08	-1.30	.21
529 79	706	25.0	7.60	105	50	41	9	51	-.79	-1.03	.16
624 79	709	24.6	7.60		104	90	14	103	-.20	-.51	.32
630 79	711	24.5	7.55		146	128	18	143	.03	-.30	.49
7 4 79	713	24.5	7.55		122	106	16	120	-.12	-.44	.41
7 7 79	715	24.5	7.50		125	109	16	124	-.15	-.47	.47
SKIM PIRATE											
527 77	503	24.0	7.20		56	49	7	55	-1.09	-1.42	.44
228 78	701	24.0		109	51	0	0	0			
524 79	701	24.5	7.55	150	77	66	12	78	-.49	-.77	.27
529 79	704	24.8	7.60	138	66	56	11	67	-.56	-.83	.21
617 79	708	24.5	8.13	131	59	49	10	60	-.14	-.40	.05
624 79	710	25.3	8.03		56	47	9	57	-.27	-.52	.07
630 79	712	24.5	7.65		77	65	12	77	-.40	-.68	.21
7 4 79	714	24.5	7.60		105	91	14	104	-.19	-.50	.32
ECHO SIPHON											
531 79	707	25.2▲	7.15	263	123	107	16	121	-.50	-.82	1.05
629 77	218	26.4▲	7.35		117	94	23	102	-.41	-.61	.67
THUNDER ROAD											
6 9 77	307	24.9	7.37		92	80	12	89	-.53	-.85	.47
622 77	311	25.4	7.25		95	85	10	92	-.60	-.97	.64
628 77	317	25.4	7.37		92	80	12	88	-.53	-.84	.47
626 79	703	24.3	7.35	265	126	110	16	124	-.30	-.62	.67
BUCCANEER BRANCH											
630 76	315	26.4			96	77	19	93			
711 76	323				99	87	12	94			
711 76	324				98	88	10	94			
727 76	330				90	75	15	87			
622 77	312	25.6	7.08		84	75	9	80	-.88	-1.24	.82

Table 4.6g Trunk Conduits

UPPER-/DRY SEASON-CONDUIT FLOW

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
LUBUL HA											
811 76	439				37	20	17	34			
516 77	419	23.2	7.55		39	30	9	36	-1.15	-1.33	.16
516 77	420	23.1	7.75		58	44	14	56	-.61	-.78	.12
517 77	421	23.1	7.70		77	62	15	71	-.42	-.65	.17
ACTUN CHEK											
529 77	413	24.4	7.32		80	66	14	80	-.71	-.95	.47
530 77	414	24.4	7.25		118	99	19	114	-.47	-.74	.78
PETROGLYPH CAVE											
618 76	413	24.4			63	51	12	59			
8 5 76	437				61	53	8	59			
227 78	401	23.4		95	45						
227 78	407	23.2		92	43						
227 78	408	23.6		92	43						
228 78	409	22.9		93	44						
228 78	411	23.3		93	44						
228 78	412	24.0		83	39						
529 79	406	24.9	7.55	111	53	44	9	54	-.80	-1.04	.19
6 5 79	409	24.5	7.65	113	54	45	9	55	-.69	-.94	.15
6 9 79	410	24.5	7.80	120	57	48	10	58	-.48	-.74	.11
SAINT HERMAN'S CAVE											
6 5 76	401	24.6			71	53	18	73			
6 9 76	404	24.4			116	87	29	99			
614 76	409	24.5			95	83	12	89			
616 76	411	24.4			92	80	12	85			
618 76	412	24.4			90	75	15	83			
614 77	401	24.3	7.27		80	69	11	77	-.76	-1.07	.51
615 77	402	24.4	7.35		81	69	12	79	-.66	-.95	.43
616 77	403	24.5	7.20		82	69	13	79	-.81	-1.08	[illegible]
617 77	404	24.3	7.05		82	66	16	79	-.99	-1.20	.86
618 77	405	24.4	7.35		80	67	13	76	-.69	-.96	.42
620 77	407	24.5	7.48		82	71	11	80	-.52	-.83	.32
7 1 77	415	24.4	7.85		70	59	11	66	-.30	-.58	.11
720 77	429	24.4▲	7.59		102	87	15	98	-.24	-.53	.31
BLUE HOLE											
812 78	102	24.5		212	105						
BOILING HOLE											
8 7 78	101	24.8		223	110						
LOWER NAE NOHOL											
522 77	410	24.4	7.25		103	88	15	100	-.57	-.86	.68
526 79	404	24.8	7.25	241	110	95	15	109	-.50	-.81	.74
531 79	408	24.7	7.28	208	110	95	15	109	-.47	-.78	.69
531 79	407	24.8	7.15	214	120	104	16	118	-.53	-.84	1.02

see notes for legend

Table 4.6g (cont.)

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
WET SEASON CONDUIT FLOW											
LUBUL HA											
710 76	426				81	63	18	78			
710 76	422				103	80	23	95			
7 7 77	425	23.5	7.59		115	97	18	110	-.17	-.45	.34
3 2 78	413	21.8		127	61						
3 3 78	414	21.9		128	61						
3 3 78	415	21.9		119	56						
3 3 78	416	22.2		133	64						
3 3 78	417	21.9		120	57						
3 3 78	418	21.5		118	56						
3 3 78	419	21.8		114	54						
3 3 78	420	21.8		113	54						
3 3 78	421	21.4		111	53						
3 3 78	422	21.6		114	54						
3 3 78	423	21.8		93	44						
3 3 78	424	22.2		133	64						
3 4 78	426	22.0		133	64						
ACTUN CHEK											
7 6 76	421			0	130	114	16	126			
716 76	425			0	146	124	22	142			
716 76	427			0	145	127	18	143			
722 76	431			0	141	121	20	137			
3 7 76	438			0	119	103	16	113			
3 4 78	427	23.0		198	96						
3 4 78	428	23.5		197	96						
3 4 78	429	23.3		197	96						
3 4 78	430	23.3		198	96						
3 4 78	431	22.7		145	70						
3 4 78	432	24.0		133	64						
3 4 78	433	24.0		101	48						
3 4 78	434	24.0		99	47						
3 5 78	402	22.7		95	45						
620 79	417	24.8	7.70		140	122	18	138	.15	-.18	.33
PETROGLYPH CAVE											
618 77	422	23.8	7.45		138	137	1	138	-.07	-1.05	.59
229 79	410	24.0		128	61						
623 79	420	24.7	7.72		156	137	19	153	.25	-.08	.35
630 79	422	24.5	7.60		149	130	19	146	.09	-.24	.44
7 2 79	425	24.5	7.50		93	80	13	92	-.39	-.69	.36
7 4 79	426	24.5	7.60		119	104	16	119	-.09	-.40	.36
7 7 79	427	24.5	7.60		118	102	16	116	-.10	-.41	.35
7 7 79	428	24.5	7.57		127	111	16	125	-.07	-.39	.41
7 7 79	429	24.5	7.57		120	105	16	119	-.11	-.43	.39
SAINT HERMAN"S CAVE											
6 7 76	402	24.4			142	120	22	134			
6 8 76	403	24.3			131	110	21	124			
619 76	414	23.8			154	142	12	141			
619 76	415				150	135	15	136			
620 76	416	23.9			166	151	15	152			
620 76	417	24.0			164	151	13	150			
623 76	418	23.9			135	125	10	126			
624 76	419				150	132	18	143			
720 76	428				107	99	8	103			
720 76	429				102	95	7	105			
720 76	430				107	94	13	113			
311 78	444	23.0		163	79						
311 78	445	23.5		168	91						
311 78	446	23.7		175	85						
311 78	447	23.6		193	94						
311 78	448	23.5		205	100						
312 78	449	23.5		172	83						
522 79	402	24.5		160	70	59	11	70▼			
614 79	411	24.5		161	78	66	12	79			
614 79	412	24.5		161	78	66	12	78			
614 79	413	24.5		161	78	66	12	79			
614 79	414	24.5		158	81	70	12	81			
618 79	416	24.5	7.93	170	82	71	12	82	-.09	-.38	.13
7 1 79	424	24.5	7.70		142	125	18	140	.16	-.17	.34
LOWER NAB NOHOL											
6 9 76	405	24.4			137	115	22	131			
630 76	420	24.1			146	123	23	141			
714 76	423	24.5			132	114	18	129			
728 76	434				95	80	15	100			
728 76	436				117	95	22	113			
3 7 78	436	23.6		226	110						
3 7 79	437	24.4		215	105						
6 9 77	416	24.3	7.40		151	139	12	144	-.09	-.53	.69
622 77	423	24.4	7.35		143	137	6	137	-.16	-.75	.74
628 77	424▲	24.4	7.39		126	110	16	124	-.24	-.57	.63
710 77	426	24.0	7.48		139	124	15	138	-.08	-.45	.55
630 79	423	24.5	7.60		140	122	18	138	.04	-.29	.42

see notes for legend

Table 4.6h Caves Branch River

CAVES BRANCH RIVER AT THE BRIDGE

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
6 5 76	302				34	21	13	31			
614 76	308	28.4			112	96	16	101			
616 76	309	29.1			111	93	19	105			
618 76	310	27.7			107	81	26	100			
727 76	331				88	73	15	88			
8 3 76	332				90	75	15	84			
9 5 76	333				88	74	14	85			
9 7 76	334				78	64	14	71			
9 9 76	336				88	72	16	80			
911 76	337				89	74	15	83			
515 77	201	26.6	7.45		77	65	12	75	-.59	-.84	.33
516 77	202	27.2	7.50		80	69	11	76	-.49	-.79	.30
517 77	203	26.9	7.35		82	71	11	81	-.61	-.91	.46
614 77	206	26.1	7.45		74	63	11	71	-.62	-.90	.32
624 77	209■	25.7	7.45		70	60	10	63	-.70	-.99	.29
628 77	210	26.3	7.90		76	67	9	71	-.14	-.48	.11
7 1 77	211	26.5	7.65		77	66	11	72	-.39	-.69	.20
7 8 77	213	25.9	7.58		98	89	9	95	-.23	-.63	.31
715 77	214	25.1	7.37		95	90	5	94	-.45	-.99	.49
726 77	217	29.5	7.79		94	82	12	93	-.04	-.34	.20
728 77	218	26.7	7.40		94	86	8	90	-.44	-.85	.45
517 79	301	26.9	7.30	170	78	66	12	78▼	-.70	-.97	.49
519 79	302	26.5	7.50	169	85	73	12	85▼	-.44	-.72	.34
518 79	303	27.2		164	79	68	12	73			
520 79	304	27.5		170	82	71	12	82			
522 79	305	27.0		180	87	75	13	87			
5[illegible] 79	306	26.5	7.58	220	97	83	14	96▼	-.25	-.54	.32
5[illegible] 79	315	31.0	7.13	175	78	66	12	73	-.81	-1.06	.76
5[illegible] 79	316	30.0	7.21	175	85	73	12	85	-.67	-.94	.68
530 79	319	29.9		228	111	97	15	110			
6 7 79	327	29.0	7.58	175	85	73	12	85	-.32	-.59	.29

CAVES BRANCH RIVER IN THE LOWER POLJE

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
6 7 76	304	25.0			131	113	18	120			
6 [illegible] 76	307	28.4			77	63	14	71			
6 [illegible] 76	406	24.4			119	100	19	114			
630 76	316	25.4			96	83	13	93			
7 4 76	327	[illegible]			119	99	20	115			
713 76	325				85	75	10	80			
7[illegible] 76	326				79	68	11	75			
727 76	329				104	87	17	100			
522 77	409	24.5	7.20		86	74	12	84	-.76	-1.06	.65
6 2 77	313	27.2	7.45		52	41	11	44	-.39	-1.16	.20
710 77	323	26.9	7.53		87	76	11	87	-.37	-.68	.32
8 7 78	435	25.5		170	82						
522 79	317	30.5	7.10	188	91	79	13	91	-.72	-.98	.94
526 79	318	26.0	7.00	190	92	80	13	92	-.87	-1.16	1.14

CAVES BRANCH RIVER AFTER SINKING

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
7[illegible] 76	435				111	92	19	109			
714 76	424	24.9			122	104	18	118			
727 76	433				11[illegible]	94	17	106			
6[illegible] 76	407	24.9			114	97	17	114			
7[illegible] 76	432				122	103	19	122			
6[illegible] 76	4[illegible]8	[illegible]			123	105	18	104			
7[illegible] 77	427	25.[illegible]	7.60		133	123	10	123	.03	-.42	.30
3 7 78	438	23.3		200	97						
3 8 78	439	24.3		208	101						
3 [illegible] 78	440	24.1		205	100						
3 [illegible] 78	441	23.[illegible]		208	101						
310 78	442	23.[illegible]		207	101						
3[illegible] 78	443	23.8		231	113						
[illegible] 78	305	23.3		235	115						
[illegible] 78	[illegible]	3[illegible].0		239	117						
310 78	337	24.3		245	120						
320 78	303	24.3		248	121						
3 4 78	403	22.7		232	113						

Table 4.6i Miscellaneous

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
626 76	504				176	166	10	168			
7 [illegible] 76	926				156	138	18	146			
6[illegible] 76	5[illegible]8	24.1			180	169	11	177			
[illegible] 77	5[illegible]	23.8	7.40		155	151	4	150	-.05	-.75	.71
6 [illegible] 77	5[illegible]2	24.4	7.99		86	65	21	77	-.06	-.3[illegible]	.10
[illegible] 78	334	[illegible]▲	8.10	203	99	85	14	89	.28	-.01	.19
[illegible] 78	404	24.0		407	200						
[illegible] 78	405	[illegible]		150	7[illegible]						
6[illegible] 79	110	24.5		240	117	10[illegible]	[illegible]	11[illegible]			
6[illegible]4 79	122	24.5		210	1[illegible]	99	14	102			
6[illegible] 79	125	24.5		200	97	84	14	97			

Table 4.6j Actun Chek Surface Flow

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
[illegible] 77	406	25.6	8.15		1[illegible]5	95	20	104	.43	.13	.10
[illegible] 77	4[illegible]3	25.3	8.2[illegible]		114	101	13	113	.53	[illegible]	.13
[illegible] 77	411	27.1	8.25		117	102	15	11[illegible]	.30	.08	.13
[illegible] 77	417	24.4	7.55		127	115	12	12[illegible]	-.18	-.4[illegible]	.4[illegible]
[illegible] 79	401	27.5	8.10	232	108	93	15	107▼	.38	.0[illegible]	.11
[illegible] 7[illegible]	413	25.3			10[illegible]	9[illegible]	14	101			

see notes for legend

for this particular rock, further reference to ionic constituents (except where explicitly stated otherwise) will be expressed in terms of mg/L as $CaCO_3$. The specific ion concentrations 20 mg/L Ca^{2+}, 12 mg/L Mg^{2+} and 122 mg/L HCO_3^- will then be represented as 50 mg/L Ca^{2+}, 50 mg/L Mg^{2+}, and 100 mg/L HCO_3^-, respectively, of $CaCO_3$.

The saturation index for calcite (SIc) or dolomite (SId) is as used in Drake (1974) and Fish (1978):

$$SI_m = \log_{10} \left({}^{IAP}/_{Km}\right), \qquad (4.1)$$

where SI_m = the saturation index of a given mineral 'm'

IAP = the ion activity product of the ions in solution

and Km = the equilibrium constant for 'm' at a given temperature

2. Behaviour of Measured and Calculated Variables In this section, brief discussions of variable relations are made. Table 4.7 shows the matrix of correlation, indicating its frequent occurrence at a significant level. Except for specific conductivity (SPC), these values are based on the relatively complete analyses of 1977. For this sample size of 145, a correlation can be considered significant at the .05 level if r is $>\pm$ 0.163.

a) Temperature Except as discussed in the following chapter on the Boiling Hole, temperature bears only moderate relation to most of the other variables. Temperatures easily fall into two groups, those of the cave conduit inlets, and those samples collected on the surface. Water entering the subsurface environment quickly assumes the temperature of the bedrock, reflected in the small (23° - 25°C) range of values recorded. Because most samples were collected during the daytime, surface water values were

TABLE 4.7

Correlation of Measured and Calculated Hydrochemical Variables, 1977

	Temp	pH	Ca^{2+}	Mg^{2+}	HCO_3^-	SI_c	SI_d	P_{CO_2}	Log P_{CO_2}	Tot. Hard.
pH	.168									
Calcium	-.181	.188								
Magnesium	.041	.176	.494							
HCO_3	-.173	.176	.977	.584						
SI_c	-.050	.678	.782	.451	.769					
SI_d	.042	.715	.721	.571	.729	.976				
P_{CO_2}	-.188	-.473	.567	.317	.592	.131	.095			
Log P_{CO_2}	-.291	-.600	.605	.282	.619	.179	.108			
Tot. Hard.	-.156	.200	.989	.618	.984	.784	.749	.567	.596	
SPC	-.319	.324	.980	.776	.997	.786	.805	.312	.246	.995

1977, 145 samples

.05 level of significance (145 samples) = ± 0.163

.01 " ± 0.138

Note: all SPC correlations are significant at the .01 level except P_{CO_2} and log P_{CO_2}.

There were 27-44 SPC samples

higher. This is due simply to higher air temperatures for the most part, although direct insolation of exposed streams may also play a role. In a few instances, it was not possible to measure water temperatures. Where they were necessary for calculation of SI_c's, etc., cave samples were given the value of 24.5°C, and surface samples the value of the corresponding air temperature. These sample temperatures are marked with an triangle in Tables 4.6.

Although temperature explains little of the variation between variables, a statistically significant relation is often evident: In Table 4.7, hardness, and variables expressing solute concentration are negatively correlated with temperature, while pH shows positive correlation. Reference to Table 4.6 indicates that this closely approximates division into cavern-collected, and surface-collected, samples. The surface samples, as noted, are nearly always warmer and with much les opportunity to achieve saturation -- hence the correlations. Log P_{CO_2} is also negatively correlated with temperature; this will be discussed when more data are presented in a later section.

b) pH All waters sampled were well within the normal pH range for natural limestone waters. Extreme values were 6.35-8.22, with the great majority falling in the 7-8 interval. Swallet and allogenic waters had the lowest pH's (occasionally below 7), but karst inlets and springs were also low, reflecting their high P_{CO_2} concentrations. The highest pH's were those of conduit waters, affected apparently both by degassing and decrease in aggressivity with solution of limestone.

As demonstrated in Table 4.7, pH was significantly correlated with the other measured variables. The P_{CO_2} and saturation index variables are of obvious relation. The lower correlations for the other variables result from the higher pH's generally associated with more saturated, higher solute waters of the Caves Branch.

c) Hardness As noted in the analyses of Table 1.1, the bedrock of the Caves Branch karst appears to be composed nearly entirely of calcite, with little dolomite present. As such, it is not surprising that total hardness, calcium, and bicarbonate, show such close correlation. What is unexpected is the amount of magnesium present in the analyses, considering its apparent near-absence in the host rock. Two possible explanations are 1) the limited number of rock samples analyzed is quite probably not representative of the bedrock geology as a whole, and 2) the magnesium may occur in a more readily soluble form, although this is not generally the case in most studies. Introduction of exotic magnesium ions from outside the area is rejected because karst inlet waters collected above the level of the allogenic trunk conduits have the highest total concentrations of the ion.

The higher hardness expected of more saturated waters is reflected in the high positive correlations of these variables. As examined later in this section, higher partial pressures of carbon dioxide are found in the inlets to the conduits, which are also those sources of highest hardness. This is further reinforcement to the other expected positive correlation of P_{CO_2} and carbonate solute concentration.

Because of the very high correlations of TH with the calcium and HCO_3^- variables, these two elements of the hydrochemistry were estimated from TH in 1979. Both had R^2 values of 0.97 or higher with TH. The TH/Mg^{2+} correlation was also quite significant, but had a much lower

R^2 of 0.38. The applicability of this method will be discussed in more detail in the sub-section on SI_c, SI_d, and P_{CO_2}.

TH ranged from as low as 7 mg/L for allogenic waters, to 314 mg/L for karst inlets flowing into trunk conduits. Calcium ion content was almost always at least 90% of the TH, but had a generally smaller proportion in waters of allogenic origin. Mg^{2+} values from the 1976 and 1977 titrations were rarely greater than 30 mg/L, usually averaging between 5-10% of the total hardness. The highest value recorded -- 71 mg/L -- was from a zuhuyha source, but as this was one of the few titrations done only once, it may represent an error.

d) Alkalinity Unless pH rises to 8.3 or higher, CO_3^{2-} does not contribute significantly to ionic strength (Hem, 1970) such that in the waters of the Caves Branch pH range, alkalinity and bicarbonate ion (HCO_3^-) can be safely considered equivalent*. As mentioned previously, the host rock and contributing ions are overwhelmingly of carbonate origin. Alkalinity and the several hardness constituents, then, have predictably high correlations, with the TH/HCO_3^- regression explaining 97% of the total variation between these two.

Ion balance errors (IBE) were calculated for the 1977 samples. These were defined as the difference between the measured anions and cations, divided by their sum. Units were equivalents-per-million: epm. Mean of the IBE's was +1.4% with a 95% confidence interval of +0.65 - 2.15%. This is well within the generally accepted confidence range of ±5% IBE. The IBE mean quoted above does differ significantly from 0. (at greater

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* Hem (1970 p. 152) states that "alkalinity is defined as the capacity of the solution to neutralize acid...Several different species contribute to the alkalinity...as defined...In most natural water, the alkalinity is practically all produced by dissolved carbonate and bicarbonate ions."

than 0.01 significance, t = 3.696), probably indicating the presence of minor concentrations of other anions, that were not analyzed.

Range and water class differences were essentially a copy of the total hardness distribution.

e) Other Ions As noted above, the generally positive ion balance errors possibly indicate that an anion of minor concentration is not being analyzed for. In 1976, several samples were brought back from the Caves Branch and analyzed at the McMaster University Geology Department. In Table 4.8, these samples can be seen to have small amounts of SO_4^{2-} and Cl^-, but none in sufficient quantity to significantly affect calculation of ionic strength, saturation indices, or P_{CO_2}. In 1979, use of a LaMotte Sulphate Testing Kit on a number of samples of all types of water classes found no SO_4^{2-} concentrations that exceeded the 10-12 mg/L detection limit of the kit.

TABLE 4.8

Analysis for Minor Ions

	Date	Ca^{2+}	Mg^{2+}	HCO_3^-	SO_4^{2-}	Cl^-
Caves Branch R. (upper polje)	8/10	21.5	11	28.5	3.63	2.5
Footprint Cave (entrance)	8/6	102.5	16.5	113.0	.25	6.3
Blue Hole	7/8	87.	18.	93.5	1.4	6

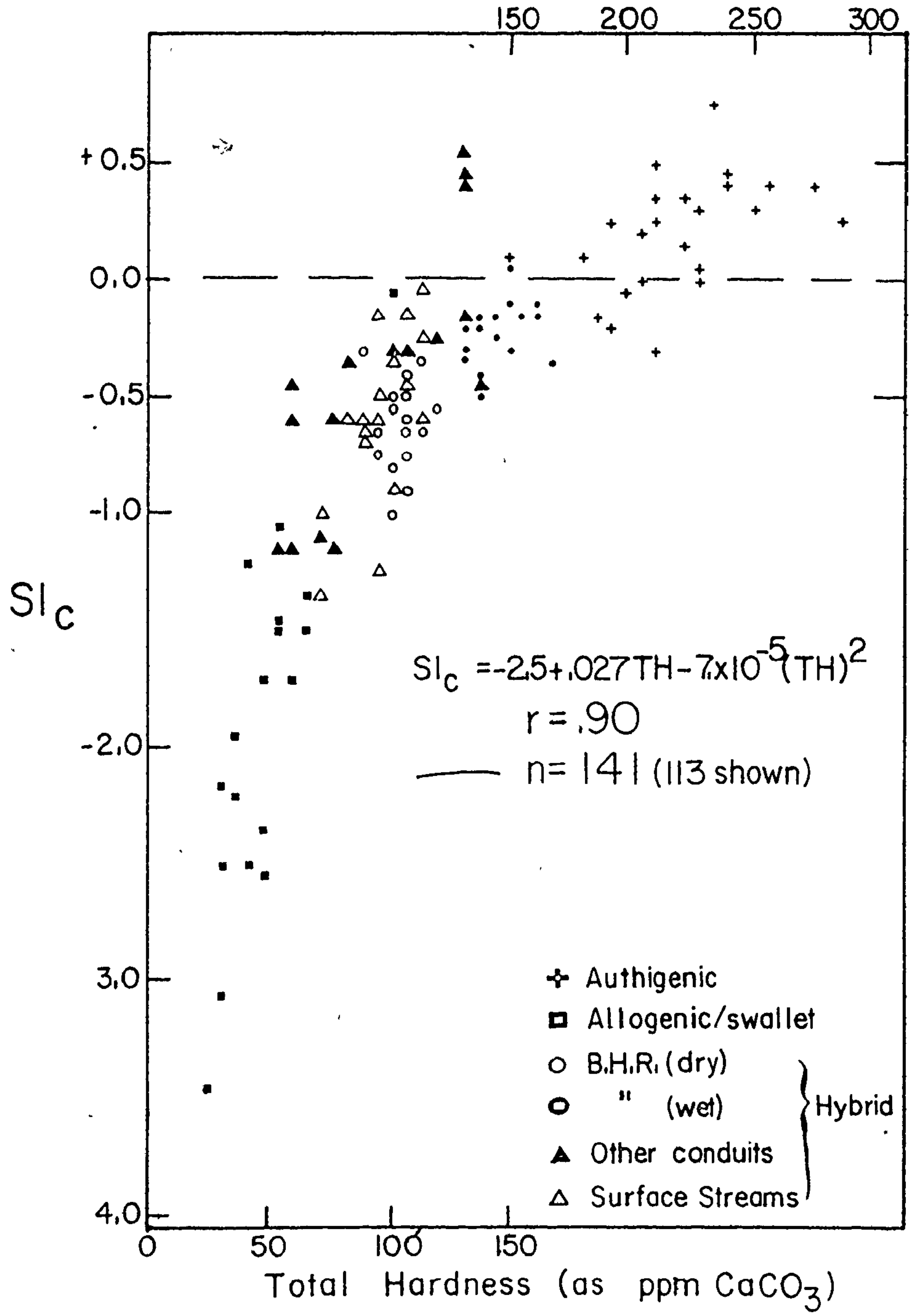
Remarks: no pH values for these 1976 samples
Ca^{2+}, Mg^{2+}, HCO_3^- expressed as mg/L $CaCO_3$
SO_4^{2-}, Cl^- as mg/L, respective ions

For the three samples shown, SO_4^{2-} shows smaller values for waters from the two conduit caves than from the allogenic source stream, while Cl^- shows an increase. This would be expected if the sulphate had an external source in the highland rocks and was progressively diluted, and if the Cl^- was brought from the Caribbean by the predominantly easterly winds. Addition of oceanic-derived Cl^- also implies some Na^+ content. A further test of the completeness of the analysis is done in the section on specific conductivity.

f) Saturation Indices of Calcite and Dolomite Except for zuhuyha waters, most samples in the Caves Branch were undersaturated wrt both calcite and dolomite. The allogenic and swallet waters often had values of less than -2.00 SI_c and SI_d. Karst inlet waters were nearly always saturated, often supersaturated. Drake (1974) quotes Plummer (1972) that calcite precipitation can be expected to occur at SI_c values of +0.30 in supersaturated solutions. That an upper limit of +0.30 to +0.40 exists in the Caves Branch suggests that the data are an accurate reflection of the natural conditions of the environment.

SI_c and SI_d showed close correspondence, but in all cases the samples were more saturated wrt calcite than dolomite. This would be expected from the high calcite content of the host rock. Water from sources with less bedrock contact (e.g. allogenic or surface karst) had smaller Ca/Mg ratios, and SI_c/SI_d ratios much closer to unity. SI_c and TH are related as shown in Fig. 4.6 with waters reaching the saturation region at about 155 Mg/L. Further increases in TH are achieved with only slight increases in SI_c.

As mentioned earlier, the excellent regressions of TH with Ca^{2+} and HCO_3 were used to estimate these latter in 1979, which saved considerable time and effort. To determine the amount of error introduced, the 145 complete sample SI_c's of 1977 were compared with SI_c's that would be calculated from the TH/Ca^{2+}, TH/Mg^{2+}, and TH/HCO_3^- relations for the same samples. Significant at the .01 level of confidence, the regression equation R^2 was 0.99, with a standard error of estimate (Se) of ±.068 SI_c



Hydrochemical Classes,
Caves Branch
(1977 data)

figure 4.6

units. Individual errors were also ±.068 SI_c units at this sample size.

g) Carbon Dioxide Partial Pressure (P_{CO_2}) Nearly all water samples in the Caves Branch were in equilibrium with at least ten times the atmospheric concentration of CO_2. One particular spring in the karst gave consistenly high readings, one of which (4.73%) was the maximum for all samples in the area. Two main groupings were present, again those of the allogenic and karst waters. Zuhuyhas and other internal karst sources had values ranging from 0.34% upwards, while allogenic samples had lower P_{CO_2}'s of 0.05 to 0.96%.

The TH/HCO_3^- correlation for SI_c determination was used to calculate P_{CO_2} for the 1979 samples. Regression of TH-calculated P_{CO_2}'s on full analysis P_{CO_2}'s resulted in an R^2 of .99 and a standard error of estimate of ±.057% P_{CO_2}. Individual error was no larger.

Most of the relations of P_{CO_2} with other variables has been discussed in those relevant sections. It is worth noting in passing that although direct P_{CO_2} may be easier to comprehend, log-transformed P_{CO_2} is equal to, or superior to, P_{CO_2} in correlation with every other variable (Table 4.7).

h) Specific Conductivity (SPC) Measurements of SPC were taken in 1977, 1978, and 1979. They were intended primarily for use where titration was not possible, chiefly when a large number of water samples were collected over a short period of time. With suitable initial calibration and sufficiently high inter-variable correlations, SPC can be used to estimate concentrations of other chemical variables (Hem, 1970, p. 96).

Charged ionic species in solution create an electrical conductivity which increases with increases in both temperature and ionic concentration of the solution.

SPC is related to concentration by

$$\Lambda N = k \qquad (4.2)$$

where Λ = equivalent conductance (cm^2/ohm^{-1} equivalent)

N = normality of the solution

k = specific conductivity ($ohm^{-1}\ cm^{-1}$)

The equivalent conductance of a weak electrolyte is determined by assumption that the equivalent conductance at infinite dilution (Λ_0) represents the sum of the equivalent conductances of the constituent ions at infinite dilution (Mortimer, 1975). This is a reasonable step given the concentrations found in most karst waters. Comparison of measured SPC with that calculated from known concentrations of ions in a solution can thereby provide an indication of the extent to which an analysis is chemically complete. Twenty-seven samples analyzed for Ca^{2+}, Mg^{2+}, and HCO_3^- in 1977 were used in such a regression. The R^2 was 0.99, with a standard error of 9.2 micro-siemens (μS). [Values of individual ion equivalent conductance were taken from Robinson and Stokes, (1959)].

Specific conductances ranged from 45-645 μS, yielding the correlations with other variables shown in Table 4.7. As noted in the table, the number of samples upon which the correlations were based varies, particularly as regards SPC/TH.

In the introduction to this section, the basic purpose of measuring SPC was described as being a tool to expand the number of hydrochemical analyses where complete analysis was not desired or possible. In 1979, some of the samples taken were simply pH and SPC, from which SI_c and P_{CO_2} were calculated. Because of the early failure of the SPC meter in 1977, there are many fewer samples available where HCO_3^- and Mg^{2+} were taken concurrently with SPC, than where TH and SPC are available together. Because of this, HCO_3^- and Mg^{2+} were estimated indirectly by first calculating TH from the SPC/TH regression equation, then using the TH/HCO_3^- and TH/Mg^{2+} regressions for these latter variables. The error involved was estimated in several stages. Firstly, the ±.95 confidence interval values for the TH/SPC regression was determined. Secondly, these extreme values were combined with all of the measured TH values of 1977 to give the ±.95 value range for TH. Thirdly, HCO_3^- and Mg^{2+} were estimated from their respective TH regressions and ± SI_c and ± P_{CO_2} values for each of the samples was calculated. When the complete-sample SI_c's and P_{CO_2}'s were compared with ± ranges, R^2 was $^{+.98}_{-.96}$ for SI_c with an Se of $^{+.08}_{-.17}$, and R^2 was $^{+.95}_{-.91}$ for P_{CO_2} with an Se of $^{+.15}_{-.17}$%. Although SI_c values were not significantly affected, it is obvious that P_{CO_2} calculated by this method is less trustworthy. This is the result of the greater influence of the HCO_3^- estimations upon P_{CO_2} than upon SI_c. Although trends may be satisfactorily indicated by this method, individual P_{CO_2} are somewhat suspect. However, for the great majority of cases in 1979 where pH was measured, TH was also, such that few SI_c and P_{CO_2} values listed in Tables 4.6 were from pH and SPC alone. In 1979, only 4 of 68 samples from the Boiling Hole were of this type, and 31 of the other 116 general samples.

In the Caves Branch, SPC data proved useful for estimation of most measured variables after initial calibration. The labor saved from laboratory analysis was considerable. As shown above, it provided accurate estimates of variable values for SI_c in spite of the additional TH calculation step. More reasonable P_{CO_2} values could be expected with direct use of SPC/HCO_3^- regression equations.

It was found that individual water classes had slightly different TH/SPC regressions, and these were used for the determination of TH for the individual class samples where this was necessary. Each class regression had a correlation coefficient greater than 0.93. The overall TH/SPC relation can be compared with similar regressions derived from other karst areas (Table 4.9). In general, for most karst waters of normal hardness, the relations provide similar values. Much of the variance is caused by differences in the proportion of Ca^{2+} to Mg^{2+}, TH to non-carbonate ions (such as SO_4^{2-}, Cl^-), etc. The high correlations given for three of these areas demonstrates that with suitable regional calibration, it is a tool with widespread usefulness.

TABLE 4.9

TH/SPC Regressions from Several Karst Areas

Source		Area	Regression	n	r	Se
Hess and White	(1973)	Kentucky	Ca= 0.51 SPC-7	-	-	-
Bray	(1976)	Wales	TH= 0.60 SPC-11	97	.996	3.3
Allbutt	(1977)	Great Britain, Wales	TH= 0.63 SPC-20	160	>.9	20.
This study		Belize	TH= 0.50 SPC-2	126	.99	8.4

Where Ca = mg/L Ca^{2+} (as $CaCO_3$)
TH = mg/L Total Hardness (as $CaCO_3$)

C. Identification and Separation of Water Types in the Caves Branch

In this section, an attempt is made to identify separate classes of water in the study area. The initial method of separation was on the basis of physical situation and morphology. The seasonal hydrological and hydrochemical characteristics of the physically identified classes will be described, then the results of a statistical discrimination to test this initial classification will be examined. The statistical test was based on the hydrochemical behavior of the sampled classes. The ultimate objective of this section is to provide a basis for inferential interpretation of the karst interior environment, which will be made in the following chapter.

1. Description of Water Classes

a) Allogenic As already noted, most dry season flow in the Caves Branch is of water from the Maya Mountains that has been pirated into cavern conduits within the karst. The three known sources of allogenic water are the Caves Branch River, the Actun Chek catchment, and the Actun Lubul Ha Basin (Figure 4.1). The dry season hydrology of the Caves Branch polje can be divided into two parts: 1) in the upper part of the valley the Caves Branch River accepts minor contributions from Lubul Ha and a small karst spring to the east (Figure 4.1), then sinks in its bed a short distance after first contacting limestone bedrock. Small amounts feed pools that appear at intervals further down the river bed 2) water from Actun Chek resurges (after undergound passage from the highlands) onto the polje and flows two kilometers to its confluence with the dry bed of the Caves Branch River. Here, it mixes with the small flow feeding the pools in the bed, and flows a further 3 or 4 kilometers before it, too, sinks in the bed of the river. Some pools extend down the bed, (apparently fed by seepage as they remain fresh) to the locality where bedrock is again encountered on the downdip side of the polje. Few pools appear past this point and all are stagnant. This two-fold hydrologic distinction was encountered in all three field seasons and is shown in Figure 4.1.

Because the small karst stream that joins the Caves Branch River above its first bedrock contact parallels the limestone escarpment for a kilometer with no loss of flow, it demonstrates that no piracy occurs from the river itself upstream of the first measuring point. At this site, discharge of the river in the dry season is measured at about 0.5 cumecs. With sufficient rain and highland runoff, the front of the free-flowing river migrates downstream as fast as its permeable bed can be saturated. During 1976 it was observed at one point to advance at approximately fifty meters/hour following an estimated 100-150 mm of rain during the previous day.

The impermeable rock base, thin soil, relatively light vegetation, and steep slopes are responsible for the rapid and large magnitude response to precipitation. The maximum measured flood during the field seasons was 20 cumecs, but much larger flows occurred that were not possible to measure properly. They are estimated to have attained 50 or more cumecs; this is a combination of both the Caves Branch and Actun Chek discharge. Use of the "rational equation", and Lacey's formula (Church and Kellerhals, 1970, p. 5), for determination of maximum expected discharges gives estimates of 144 and 79 cumecs respectively for the maximum combined flow. Although rough approximations, they indicate the potential of allogenic influxes.

All water samples were aggressive (Table 4.6a) with respect to calcite, having SIc's of -1.0 to -3.0. Total hardness were low, 10-40 mg/L, with the lower values tending to occur at the highest flows. P_{CO_2} was also low, with most samples in 0.05-.35% range. The two high readings of Table 4.7a were waters from pools fed by undergound seepage. These latter two are probably due to subsurface enrichment, with the generally low readings of the others most likely the result of de-gassing during extensive surface travel.

A number of other streams were sampled in the highlands themselves, or on the periphery before contact with carbonate rocks. They are essentially the same in hydrochemistry as the Caves Branch River -- aggressive, low hardness, and low P_{CO_2} (Table 4.6a).

b) Authigenic In contrast to the relative homogeneity of allogenic water, several different flow types of authigenic source can be identified. These develop because of the diverse paths that flow can take after falling as rain on the karst. The primary difference is the substantial alteration caused by passage through the karst interior.

i) Ephemeral Surface Karst Flow No flow occurs on the karst surface by the end of the dry season, and there are no known pools. When the rainy season starts, substantial rainfall must occur to initiate flow in any of the channels in the cockpits (Chapter 2). In the Caves Branch, flow was observed only 6 times, after amounts of 12 mm or more. Streams rarely persist more than an hour or two after cessation of rainfall. The largest are estimated to discharge less than 100 L/sec.

In Table 4.6b are listed various surface authigenic water samples. It can be seen that they bear similarities to allogenic waters -- their TH's are low (15-53 mg/L), and they are aggressive (-1.33 to -2.54 SI_c). One important difference is their P_{CO_2}: the lowest is 0.30%, the highest is 0.82%. Both mean and range are considerably higher than for allogenic water. This is due in some degree simply to greater continual contact with soil atmosphere and lack of opportunity to degas, but may also reflect higher soil CO_2 in the alluviated cockpits than in the mountain soils.

Most rainfall does not collect into discernible flow. Either the rainfall intensity is insufficient, or the rain falls on the heavily fissured summits and immediately disappears.

ii) Wet Season Surface Streams In the surface area of the Caves Branch extraneous to the cockpits (i.e. poljes, glades, flat areas within the karst), some wet season flow does occur on a more or less permanent basis (Table 4.6b). In one case, flow is maintained over a bed armored by considerable travertine deposition. None of these flows have known sources, but are probably more likely to be from resurgent springs rather than from collection of small surface flows. Both origins will be considered later. They have high TH's (up to 294 mg/L), moderate P_{CO_2}'s of 0.11 - .81%, and all those sampled are greatly supersaturated (SI_c > 0.25).

iii) Springs, Zuhuyhas, and Stalactites Seasonal changes are as pronounced for these waters as those on the surface: drips from stalactites are rarely encountered in the dry season, and less than half of the springs have discharge then. The largest known authigenic springs (including the small number of known surface outlets) have flows of at most 100-200 L/sec in the dry season. With the wet season, the majority of the springs and zuhuyhas begin to flow, and thousands of stalactites come to life. Several of the largest zuhuyhas (including the biggest) in the wet season are those that had no flow at all only weeks before. The Crooked Bend zuhuyha of Petroglyph Cave (Figure 5) had a maximum recorded flow of greater than 2 cumecs following a major rain storm.

The differences in hydrochemistry between the authigenic and allogenic waters are striking. Temperature of the karst waters is nearly constant at 23-24°C and all other chemical variables measured were higher than for the allogenic flows. Most pH's were in the range 7.3 - 7.7, with one spring as low as 6.85. Total hardnesses were far higher, never lower than 120 mg/L (except in several cases discussed later), and ranging to excess of 300 mg/L. Ca^{2+} and Mg^{2+} were also higher as could be expected, but the releative proportion of Mg^{2+} declined. Alkalinity distribution was no different from the TH. Most waters were in the saturation range, from -0.2 to +0.2 SI_c, but a moderate number showed supersaturation of greater than +0.3 SI_c. No sample had an SI_c lower than -.32. The mean P_{CO_2} of the samples collected was greater than 1%, ranging generally from 0.6 - 1.5%. Extreme values were 0.15 and 4.73%.

Hardness of the stalactite drips is slightly lower than for the zuhuyhas, but in approximately the same range (130 to more than 200 mg/L total hardness) and with similar P_{CO_2} (0.64%). They have the same saturation characteristics as the larger outlets. Although impressive number of stalactites are present in various sites of the Caves Branch conduits, their actual discharge contribution is minimal simply because of their low flow rates compared to the zuhuyhas.

Pools account for only minor amounts of total water volume, and are all but absent in the dry season, probably as they are fed chiefly by stalactites subject to the same controls. Calcite precipitation at nearly all pool boundaries indicates that most are at or above saturation. Average total hardnesses were about 140 mg/L, which would be expected from waters equilibrating to slightly enriched cave atmospheres; this is similar to Ford's (1971) findings in the Canadian Rockies.

In spite of the fact that significant increases in flow occur with the advent of the wet season, chemical properties change little. Table 4.6d lists 24 springs and zuhuyhas in the Caves Branch that have been sampled more than once, most of them at least 3-4 times. With one exception (discussed later) all have coefficients of variation (CV) of total hardness that are less than 10.3%. SI_c's change slightly more, perhaps 0.2-0.3 units, and occasional P_{CO_2} values may differ by a factor of two.

In two studies in Pennsylvania, Shuster and White (1971), and Jacobson and Langmuir (1974) compared the hydrochemistry of springs draining aquifers where conduit flow would be expected, with aquifers where diffuse drainage would most likely occur. They found that for saturated waters, the CV of TH was the most useful distinguishing variable, with 10% CV found to be the upper threshold for waters of diffuse aquifer origin.

It is tempting to compare the results from Belize with those of Pennsylvania, but there are significant differences in how the surveys were conducted. The Pennsylvania data was collected at least once per month (over a period of two years in the case of the Shuster and White study). As such, it has a considerably greater statistical validity for expression and interpretation of hydrochemical seasonality. Conversely, although the Caves Branch springs could not be sampled to the same statistically rigorous standards, they do represent waters sampled across the time interval of greatest seasonal change -- dry to wet season. Additionally, 14 of the 24 sites include samples collected in winter (February/March, 1978). There was no difference between these data and those from the three-year span of the summer field seasons. In summary, there is certainly a strong indication that these waters, collected over three summers, across the interval of greatest seasonal variation, many of them with some winter sampling, and all having hydrochemical variation to the same minimal degree as those of the Pennsylvania diffuse springs, represent discharge of diffuse flow aquifer source.

iv) Low-hardness Springs Four springs sampled (of the 57 stalactites, zuhuyhas, and springs) had TH's of less than 95 mg/L (Table 4.6e). Those with pH data were also found to be undersaturated, and low in P_{CO_2}. Their physical siting (high above the trunk conduits, or in Actun Lubul Ha) was such that they could not be of allogenic source, yet there were no morphologic differences between them and the other springs. Two sites that were sampled twice did show somewhat greater variation in total hardness. Their possible origin will be considered in the next chapter.

Of passing interest is the Caput Zihil Ha spring in Petroglyph Cave which continually fills and drains a small phreatic tube. Its periodicity is approximately 10-15 minutes. Such springs are quite rare (25(?) described worldwide) and a prevailing theory (Bögli, 1980) is that they represent the activity of an intermittently operating siphon.

c) Hybrid Waters Because mixing of flows is inevitable in the Caves Branch, hybrid waters with characteristics intermediate between authigenic and allogenic sources are common. All trunk conduit flow (and that of the Caves Branch River after only a short distance into the polje) belongs to this category.

i) Piratic Flow The morphology of the conduits carrying this water has been discussed in Chapter III. They represent the other main source of flow input to the Nab Nohol Branch, and function as channels extracting surface river water and conveying it to the trunk conduits. Table 4.6f shows analyses of the five known or surmised pirates. The two lower examples (Thunder Road and Buccaneer Alley) do not carry discharge in the dry season because the Caves Branch River sinks well before their ponors. The hydrochemical characteristics of the pirates vary according to geographical location and season. Basically, the solute concentration increases with downstream position relative to the surface river and the trunk conduit because the respective source sites in the river bed increase their hardness. At the pirate outlets, the chemistry parallels very closely that section of the Caves Branch River which is nearest. Additionally, an increase in hardness occurs in the pirated water between the river and the trunk conduit because of solution of the limestone with which the water is in contact. At times of stable (non-storm) dry or wet season flow, all piratic discharge is aggressive (approx. SI_c -.50 to -1.0), with moderate P_{CO_2} of .3 - .6%. Temperatures measured are always higher than either trunk conduit water or authigenic water, being generally about 25°C.

Figure 4.1 shows the inferred flow routes of the allogenic Caves Branch River through the piratic sub-conduits. The physical evidence for these was discussed in Chapter Three. In Table 4.10 are listed some discharge and chemical data for the upper polje and various flow routes. Most of the measurements are from the dry season.

Discharge measurements of the Caves Branch River were made prior to losses to the stream bed, and indicate that approximately 0.5 cumecs of allogenic baseflow enters the polje at the end of the dry season.

TABLE 4.10

Discharges of Upper Polje Flows

Date	Site	Q (cumecs)	SPC	TH
5/15/77	1st Crossing (River)	.50	55	21.5
5/20	1st Crossing	.52	67	25.5
6/3	"	.45		34.5
5/18	pools in riverbed	?	59	21.5
5/18	Chek Stream	.33	225	114.5
5/15	Bridge	.5	160	77.
5/17	Bridge	-	170	82.5
5/20/79	C.B. River (upper polje)	.52	78	36.
"	riverbed pools	?	56-76	25-35.
"	Chek	.24	232	108.
5/18	Bridge	.13	164	79.
5/20	"	.25	170	82.

Swim Piracy, Petroglyph Cave

Date	Q (cumecs)	SPC	TH
5/24/79	.05	160	77
6/24	.02-.03		56
6/30	.15		77
7/04	.21		105

As mentioned previously, some is lost as pirated flow to Petroglyph Cave, while the rest continues a further 2 km to mix with hybrid flow from Actun Chek. The mixing occurs as a series of small seeps and springs and cannot be gauged in total. The discharges at the bridge cannot be used to estimate this contribution because some subsurface flow occurs there. However, assuming complete mixing of the Chek and river water in the two km traveled, and knowing the concentrations of the individual and mixed waters, it is possible to solve the relevant equation to determine the amount of river flow to this point:

$$Q_B C_B = Q_R C_R + Q_C C_C \qquad (4.3)$$

where $Q_{B,R,C}$ = discharge of the Bridge, River, and Chek waters (cumecs)

$C_{B,R,C}$ = the conductivity (μS)

and $Q_B = Q_R + Q_C$

Solving, for 1977 and 1979, the river discharge is .187 cumecs and .190 cumecs.

ii) Caves Branch River As noted, the allogenic source waters of the Caves Branch River sink into the bed within a few kilometers of entering the polje in the dry season. Some underflow does maintain a number of pools scattered down the thalweg until junction with the perennial Chek stream. At this point the two flows mix and maintain a relatively stable hardness of 70-85 mg/L in the dry season where measured slightly further downstream at the highway bridge (Table 4.6h). Surprisingly, this hardness is not greatly affected by the shift to wet season conditions, when the Caves Branch flows throughout the length of the polje. Calcite undersaturation (about -.35 to -.70), and moderate P_{CO_2} of about .2 - .4%

are typical of both seasons. Short-term fluctuations do occur when floodwaters from the mountains initially reach the bridge, and values as low as 34 mg/L have been recorded then. After such allogenic pulses pass, lagged discharge from Actun Chek may then raise TH's above normal, but these effects are transitory. Without major rains, discharge is usually 1-2 cumecs.

Downstream hardnesses are slightly higher before the river sinks into the ponor at the end of the polje. This is because of both slight solution by the aggressive waters, and the admixture of hard authigenic water from the surrounding karst. Typical TH's are 95-100 mg/L.

iii) Trunk Conduits Table 4.6g shows conduit water samples split into two categories: 1) dry season flow/upper conduit reaches, and 2) wet season flow. The most apparent difference between the two is the greater stability (or lack of variation) in solute concentration in the dry season for the various conduits. The other common conduit trait is demonstrated by the three traverses listed in Tables 4.6g and 4.6h. The increase in solute concentration in all three is easily understood as the simple enrichment of water of initial allogenic character by the constant addition of high hardness flow from within the karst aquifer.

The wet season hydrochemical response is less easily understood. Except for a common grouping of all waters of this category about saturation with respect to calcite ($SI_c = 0.0$), no clear pattern for total hardness and P_{CO_2} emerges initially. When the Nab Nohol group is considered separately from the Caves Branch, Lubul Ha, and Chek conduits, some order is apparent. Although all four conduits have much more variable hardnesses in the wet season than in the dry season, only the Nab Nohol shows a consistently higher solute level in the wet season. Table 4.6g shows the analysis of six samples taken during a flood event in Actun Chek; a dilution effect is noted as the allogenic flood pulse from heavy rain seven hours before passes through the cave. A drop in hardness with rise in discharge has been observed also at Lubul Ha and the Caves Branch Cave conduit, but conversely, higher solute concentration has also been found at other times when discharge is much higher. The lack of consistent pattern could be expected of wet season behavior: hardess dilution because of allogenic storm influx would be followed by higher than normal solute concentration and discharges as karst water was released into the conduits. Essentially, the general rise in discharge would create greater potential for variability as either allogenic or authigenic water temporarily increased its relative share of the mixture. But no dramatic seasonal shift in hardness should be seen because the proportions of total authigenic and allogenic flow should remain relatively constant, even with some variation in effective runoff due to different evaporation and aquifer characteristics.

The Nab Nohol Branch differs from the others in that there is a definite rise in solute concentration with the season. The Boiling Hole, the monitored site midway along its length, in fact shows a strongly positive correlation of discharge with hardness. The behavior of this conduit will be discussed in the following chapter.

Conduits, then, have hydrochemical characteristics midway between authigenic and allogenic waters. They have moderate hardnesses (30-100 mg/L), moderate aggressivity (-.10 to -1.00 SI_c), and moderate

P_{CO_2} (.20 - .90%).

2. Discriminant Analysis of Water Classes

Many waters in the Caves Branch have sources that are physically inaccessible or are inconvenient to follow to inception. If viable means of classifying waters on the basis of their chemical properties can be achieved, then waters of unknown origin can be assigned to reasonable classes, increasing knowledge of the aquifer's interior. Particularly useful variables can also be focused upon in future research, eliminating unnecessary data collection. Wigley et. al. (1973), Drake and Harmon (1973), Cowell and Ford (1980), and Mills (1981) have applied stepwise linear discriminant function (SLDF) analysis in such a context to carbonate waters.

In the Caves Branch, SLDF analysis was performed on six water classes initially identified solely on the basis of their physical characteristics. The physical locations of the six classes below were described in Chapters Two and Three, and their chemical characteristics in the preceding section of this chapter. They are:

1) allogenic water of the Caves Branch River
2) zuhuyhas and springs (those sampled at least twice)
3) swallet (ephemeral karst surface flow)
4) karst flow (intermittent surface karst streams)
5) stalactite drips
6) piratic sub-conduits

Eleven other categories were established, but were used only in the classification portion of the analysis, and will be discussed separately in Chapter IV. They include non-Caves Branch River allogenic water, those zuhuyhas and springs for which only one chemical measurement was available, several conduit water categories, and miscellaneous river waters.

An initial analysis was run to determine which of the variables and/or their logarithmic transformations were most useful. Measured and calculated variables were run within their separate groupings. The variables listed in Table 4.7, with the exception of temperature, SPC, and the addition of the Ca^{2+}/Mg^{2+} ratio (Ca/Mg), were those used. Only 1977 and 1979 data was used as other data sets did not have pH measurements. The program used was of the SPSS set (Klecka, 1975), with the selection criterion of choosing at each step the variable which maximizes the overall multivariate F-ratio among the group centroids.

In the initial run, the measured variables were entered in the order: log HCO_3^-, TH, pH, Ca/Mg, and Mg^{2+}. Ca^{2+} was not entered. The calculated variables were entered as SI_c, log P_{CO_2}, SI_d. P_{CO_2} was not entered. It is obviously inappropriate to repeatedly enter highly correlated variables into the analysis. With reference to Table 4.7, Ca^{2+} and TH were deleted as log HCO_3^- adequately explained their contribution. For these same reasons SI_d and P_{CO_2} were not used in the calculated variables run. Because the 1979 data involved estimation of Mg^{2+} from TH, it too, was deleted although it demonstrated some promise as part of the Ca/Mg ratio. Because the remaining variables were not well correlated within the pooled variable sets (pH/log HCO_3^- $r = -.21$; SI_c, log P_{CO_2} $r = -.32$) they were not subjected to a principal components analysis prior to SLDF analysis.

Table 4.11 shows the results of the secondary analysis. Stalactites were the only group where there was major difficulty of separation from others, and there appears to be no statistical reason to consider them as

TABLE 4.11

Discrimination Matrix

Variable entry order:	SI_c, $\log P_{CO_2}$						$\log HCO_3^-$, pH				
	1	2	3	4	5		1	2	3	4	5
2	1	-				2	1	-			
3	2	1	-			3	1	1	-		
4	1	.1	1	-		4	1	.2	1	-	
5	1	(.41)	1	(.14)	-	5	1	(.41)	1	(.13)	-
6	1	1	1	1	1	6	1	1	1	1	1

(#)= step at which groups are separable at the .01 level

(#)= confidence level of separation after two steps

Classification Matrix

			SI_c, $\log P_{CO_2}$ (predicted group)							$\log HCO_3^-$, pH						
			1	2	3	4	5	6	no. Misclass	1	2	3	4	5	6	no. Misclass
1	allogenic	10	7	-	2	-	-	1	3	7	-	2	-	-	1	3
2	zuhuyhas/spring	50	-	29	-	8	13	-	21	-	31	-	9	10	-	19
3	swallet	6	1	-	5	-	-	-	1	1	-	5	-	-	-	1
4	karstflow	5	-	-	-	2	3	-	3	-	-	-	4	1	-	1
5	stalactite	10	-	4	-	2	4	-	6	-	4	-	1	5	-	5
6	pirates	24	-	1	1	-	2	20	4	-	2	1	-	1	20	4

% correctly identified = 63.8(62.3)* 68.6(71.3)*

(*)mean of equally-weighted groups

	Function 1	Function 2		Function 1	Function 2
Canonical Correlation	.95	.47		.95	.47
Standardized Canonical Coefficients					
SI_c	1.01	-.30	pH	.33	.97
$\log P_{CO_2}$	.60	.86	$\log HCO_3^-$	-1.02	-.11
Function/Variable Correlations					
SI_c	.81	-.57	$\log HCO_3^-$	.95	-.32
$\log P_{CO_2}$	.29	.95	pH	.11	.99

a class distinct from the zuhuyha/springs. They are also quite similar to the karst flow waters, even though these latter form a class separable from the zuhuyha/springs.

Although the majority of the water classes are satisfactorily distinguishable to an arbitrary statistical degreee, a large degree of misclassification results if the SLDF results are reapplied to the original samples. However, if stalactite and zuhuyha waters are considered as part of the same class, the classification success rate is improved to about 80%.

There were 218 other samples belonging to the 11 uncertain water groups. The second half of the SLDF analysis classified them according to their relationship to the group centroids of the initial discriminating categories. The results are discussed in the next chapter, which concerns inference of the karst interior.

In both discriminatory power and subsequent classification ability, the measured variables appear to have a slight edge: they separate the same number of groups at the .01 confidence with each step, but correctly classify 5 more of the 105 samples. It is important to note that these two variable sets are in a sense non-orthogonal transformations of each other, obvious from examination of an evolutionary calcite solution diagram (Langmuir, 1971). The two variables entered on the first step (SI_C, log HCO_3^-) are significantly correlated (r = .77) as are the two variables of the second step (r = .60). From Table 4.11 it can be seen that SI_C and log HCO_3^- are chiefly associated with, and of primary magnitude in, the first SLDF function of their respective analyses (function/variable r = .81 and .95 respectively). Conversely, the pH and log P_{CO_2} are most important in the loading of the second function. The canonical correlations demonstrate that the first SLDF function is highly associated with the variables, more so than the second function. Because the loadings demonstrate the non-orthogonality of the variables, conclusive interpretations of the importance of a single variable cannot be validly made. However, there is enough difference in the variable loadings, and high enough function/variable association to state that the first function is predominantly that of either SI_c or log HCO_3^-, the second function is chiefly that of pH and P_{CO_2}. The first two variables (best seen if HCO_3^- is polynomially transformed) are essentially an indication of the degree of saturation of a sample -- and are correlated with the function best associated with all the variables. The second two variables are an indication of the solution potential, and are most correlated with the second, somewhat less useful function. It can be strongly inferred then, that in this area, variables measuring degree of saturation are statistically more important in differentiating water classes, than those indicating solution potential.

In other carbonate terranes where SLDF analysis has been performed, few common variables have appeared. This appears to be due chiefly to the relative proportion of the various minerals in the host rock -- Wigley et. al. (1973) found Ca^{2+}, temperature, and SI_g (g=gypsum) most useful in the Canadian Rockies in an area where gypsum outcrops were present; Cowell and Ford (1980) used temperature, Mg^{2+}, and P_{CO_2} in a dolomite area of Ontario; and Drake and Harmon (1973) found SI_c and log P_{CO_2} best in a Pennsylvania karst. The Pennsylvania results were most similar to those of the Caves Branch, not surprising as the general set-up of water groups was similar and the host rock was also limestone. Another similarity was that Drake and Harmon found pH and HCO_3^- (not log HCO_3^-) to be the most useful measured variables, as they provided identical separation quality relative to the calculated variables.

Although temperature has been noted to be of value in the mid-high latitudes discussed above (Drake and Harmon found it to be the third most useful measured variable in their area), it was not used in the Caves Branch SLDF analysis. The major reason was that the low temperature variability in the tropics made measurements to 0.1°C necessary, beyond the resolution of the thermistor on the SPC meter (≈0.5°C). When such data is collected to the required precision it has been demonstrated that piratic sub-conduits and zuhuyhas are separable, and zuhuyhas and trunk conduits in some areas. The great seasonal temperature difference of more northerly latitudes makes this variable of more use there, although presumably best when samples of the same collection season are compared.

For the Caves Branch, when only two variables are used, the use of log HCO_3^- and pH is advocated. The reasons are three-fold 1) the loadings on the standardized canonical coefficients are such that this pair is more orthogonal than SI_c/log P_{CO_2} and can be interpreted with respect to individual variables more validly 2) with the previous point in mind, interpretation of the variables as presented on a calcite evolutionary path diagram is not only more valid statistically, but can also easily incorporate the SI_c and P_{CO_2} information, and 3) log HCO_3^- and pH provide marginally better discriminatory power.

Summary

Seasonal and locational variations of CO_2 concentration are present in the Caves Branch. These are controlled by climate factors which influence the rainfall pattern, and by the depth of soil available for biogenic activity. Rainfall is at a minimum and temperature is highest in the dry season, creating conditions of soil moisture depletion and consequent low production of soil CO_2. In the wet season, large, intense rainfalls occur, and CO_2 production increases dramatically. There is a lagged correlation of CO_2 with the rainfall of the preceding day, and also a general rise with time. In spite of the correlation with daily rainfall, there would not appear to be significantly greater P_{CO_2} in storm waters entering the aquifer during the wet season, as opposed to the calculated mean for that season. Temperature apparently has little effect on CO_2 production, probably because of its minimal range, and perhaps also due to an upward limit on its influence as postulated by DeJong (1974) and Zonn and Chen Kuei (1960). Aquifer recharge, then, is composed of wet season runoff of relatively high CO_2 content, to the virtual exclusion of any low P_{CO_2} input from the dry season.

The wet season rainfall increases solution potential not only through the rise in soil CO_2, but in the massive influx of discharge into the karst. Allogenic flow entering the polje via the Caves Branch River is about 0.5 cumecs at the end of the dry season, but increases to maximums of 20-50 cumecs during the wet season.

The Caves Branch area has a hydrochemistry almost exclusively bicarbonate. Some sulphate appears to be introduced from the Maya Mtns., and minor chloride concentration is readily explained by the oceanic

source of the prevailing winds. The hydrologic network gradually mixes the two radically opposite source waters -- allogenic and authigenic -- producing a variety of hybrid types. Six of these major water classes are amenable to statistical discrimination. The most valuable variables in this type of analysis appear to be those related to degree of saturation, and initial solution potential.

Rainfall directly on the karst is dramatically altered within the karst aquifer. Swallet waters are aggressive, with low solute content on the surface. Their presumed resurgence at numerous springs is as water at saturation and with greatly increased hardness. There is strong indication that these resurgent springs and zuhuyhas are diffuse flow, chemically stable water of the type described by Shuster and White (1971).

Because of the amount of correlation of solute variables, and their correlation with SPC, the latter demonstrated value for quick determination of bicarbonate ion concentrations. Combined with pH, and after initial SPC/ion calibration, it gave satisfactory results in estimation of SI_c and P_{CO_2}.

CHAPTER V

Internal Environment of the Karst

As emphasized in Chapter 3, the great majority of the karst interior is inaccessible for sampling and observation. Interpretation of the dynamics of the hydrology and hydrochemistry must therefore be derived from analysis of karst springs emptying into trunk conduits or rivers. Of the known trunk collectors of authigenic source flow in the area, the Nab Nohol Branch of the Caves Branch Cave System is the best known and most accessible, and the Boiling Hole karst window was chosen as the most favorable sampling site along its length. This chapter will first describe and analyze the hydrologic and hydrochemical response of the Boiling Hole to local weather behavior in the field seasons. Secondly, the behavior of other waters as discussed in the preceding chapter will be considered together with the Boiling Hole to arrive at conclusions concerning the evolution of water traversing the karst.

I. The Boiling Hole

The Boiling Hole location is shown in Figure 4.1. As noted, a small weather station was located there in 1977 and 1979, and a stream stage recorder was installed within 100 m. This recorder was maintained 50 meters downstream from the Boiling Hole spring, where the stream runs in a bedrock limestone trench. Some clay and sand alluvium is also present in the trench, but there is no substantial year-to-year modification of the channel morphology; this same channel section (free of rock obstructions) was used in both seasons to measure discharge for construction of a rating curve (Figure 5.1). There was no difference between the stage and discharge relationship of the two seasons. Appendix C describes the methods used.

A. Hydrological and Hydrochemical Behavior

In both field summers, the Boiling Hole stream regime in the dry season was that of a base flow in recession. Table 5.1 lists the hydrochemical values recorded, and Figures 5.2 and 5.3 graphs these, the discharge; and the precipitation, against time. Discharge was greater in the 1977 dry season, than in 1979. The range for 1979 was about 0.6-0.65 cumecs, and .75 - .9 cumecs for 1977. Both stage and velocity were lower in 1979 and corresponded to the overall rating curve such that this difference is likely to be real and not due to instrument or procedure error. Slight rises in flow occurred occasionally in both field seasons. Temperatures recorded were generally about 24.5 - 25.°C in the dry season, although two higher readings (to 26.4°C) have been recorded . Solute concentrations showed minor variation, ranging from 85-100 mg/L total hardness, with Mg^{2+} being about 16 mg/L of this. The Boiling Hole discharge was undersaturated with respect to both calcite and dolomite in this season (about -.3 to -.8 SI_c), and had moderate P_{CO_2} of 0.3 to 0.9% (mean = 0.4-0.5%). Essentially then, in the dry season the Boiling Hole shows a stable, declining baseflow, slightly aggressive, with low solute concentration and P_{CO_2}.

Profound changes occur in the wet season. Individual rain storms may cause discharge peaks of nearly 10 cumecs, and flow never declines to less than one cumec. The water flow is cooler, with minimum values to 23.5°C, and a considerably larger variance. The pH rise slightly, from

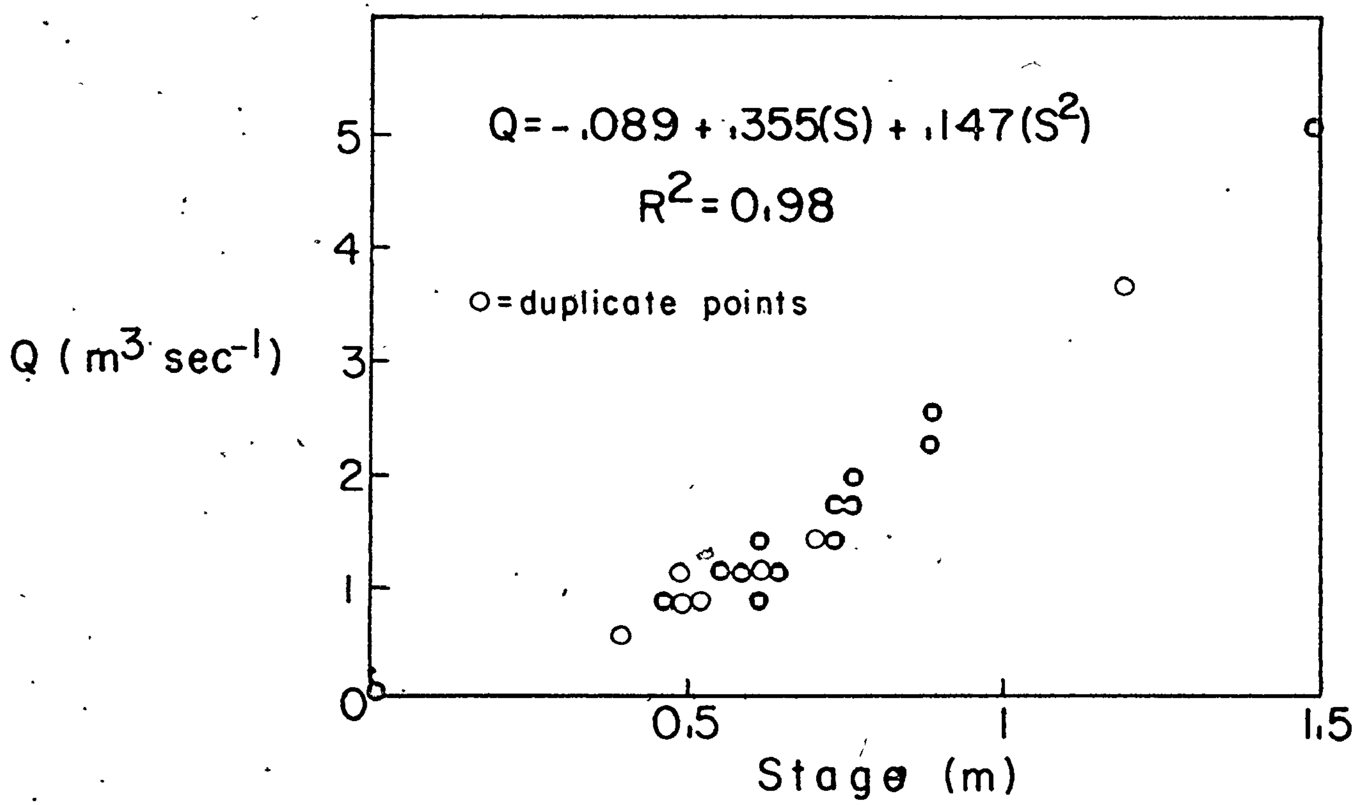


figure 5.1

Rating curve, Boiling Hole, 1977-9

Table 5.1 Boiling Hole Hydrochemistry

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
	BLUE HOLE,1976										
6 5 76	101	24.8			92	74	18	87			
6 7 76	102	24.4			130	111	19	124			
6 8 76	103	24.3			139	115	24	130			
6 9 76	104	24.4			116	93	23	107			
614 76	105	24.6			107	91	16	100			
614 76	410	24.5			114	100	14	105			
616 75	106	24.7			104	88	16	101			
618 76	107	24.4			106	92	14	97			
620 76	108				168	150	18	156			
623 76	109	23.9			144	131	13	136			
624 76	110				142	126	16	134			
626 76	111	24.2			138	125	13	129			
628 76	112	23.9			137	120	17	126			
630 76	113	24.0			143	118	25	133			
7 2 75	114	24.1			140	121	19	136			
7 5 76	115	24.2			134	120	14	130			
713 76	116				123	110	13	120			
716 76	117				124	114	10	129			
720 76	118	24.4			110	96	14	106			
722 76	119				118	105	13	114			
729 76	120				103	86	17	100			
8 3 76	121				101	87	14	97			
8 5 76	122				101	88	13	98			
8 7 76	123				100	85	15	93			
8 9 76	124				105	87	18	94			
811 76	125				100	84	16	92			
	BOILING HOLE,1977										
514 77	101	24.5	7.30		92	74	18	87	-.65	-.86	.53
515 77	102	24.5	7.35		91	75	16	87	-.59	-.84	.47
516 77	103	24.5	7.20		91	76	15	89	-.73	-.99	.69
517 77	104	24.4	7.05		93	77	16	87	-.88	-1.13	.95
518 77	105	24.4	7.55		91	75	16	87	-.39	-.64	.30
520 77	106	24.4	7.45		91	77	14	86	-.49	-.77	.37
524 77	107	24.4	7.24		94	81	13	92	-.55	-.95	.64
531 77	108	24.4	7.55		98	81	17	93	-.33	-.58	.32
6 3 77	109	24.4	7.45		86	72	14	82	-.53	-.80	.36
6 6 77	110	24.4	7.40		113	98	15	111	-.33	-.65	.54
6 7 77	111	24.4	7.55		117	97	20	114	-.18	-.43	.39
6 9 77	112	24.3	7.41		149	134	15	147	-.09	-.47	.69
6 9 77	113	24.3	7.15		153	136	17	147	-.34	-.70	1.25
611 77	114	24.2	7.40		139	123	16	134	-.17	-.52	.64
614 77	115	24.4	7.30		116	101	15	113	-.42	-.74	.69
617 77	116	24.2	7.45		127	118	9	122	-.17	-.64	.52
620 77	117	24.0	7.39		147	137	10	142	-.11	-.59	.69
624 77	118	24.4	7.28		128	121	7	126	-.32	-.84	.80
625 77	119	24.4	7.32		124	111	13	122	-.33	-.70	.71
628 77	120	24.4	7.17		121	106	15	116	-.52	-.85	.95
7 1 77	121	24.4	7.45		114	101	13	109	-.28	-.63	.47
7 5 77	122	23.9	7.40		159	146	13	154	-.05	-.49	.73
7 6 77	123	23.6	7.38		153	144	9	151	-.09	-.60	.75
7 8 77	124	24.4	7.48		139	129	10	134	-.07	-.53	.53
710 77	125	24.4	7.48		137	120	17	134	-.10	-.43	.53
715 77	126	24.5	7.29		132	116	16	132	-.31	-.64	.82
719 77	127	24.4	7.52		121	111	10	119	-.13	-.57	.43
722 77	128	24.4	7.45		123	114	9	124	-.18	-.64	.53
723 77	131	24.3	7.45		139	129	10	139	-.08	-.55	.59
726 77	129	24.3	7.48		132	121	11	127	-.12	-.55	.51
728 77	130	23.6	7.30		119	110	9	116	-.38	-.84	.70

Table 5.1 (cont.)

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
	BOILING HOLE, 1979										
516 79	131	23.5	7.40	167	85	73	12	85	-.58	-.88	.41
517 79	132	25.0		170	82	71	12	82			
517 79	103	24.5		185	90	77	13	90			
518 79	104	24.7			93	80	13	92			
519 79	105	24.7	7.35		94	81	13	93	-.53	-.83	.51
522 79	106	24.8	7.35	192	99	85	14	98	-.48	-.79	.54
522 79	107	25.0		178	86	74	12	85			
524 79	108	24.5	7.10	208	101	88	14	101	-.72	-1.03	.97
529 79	109	24.5	7.15	186	90	78	13	90	-.76	-1.06	.78
530 79	110	24.8	7.48	200	94	81	13	93	-.40	-.70	.38
6 4 79	112	24.8	7.35	135	90	77	13	90	-.56	-.86	.49
6 4 79	111	25.3		165	80	68	12	80			
6 7 79	113	24.8	7.50	223	98	84	14	97	-.34	-.65	.38
6 8 79	114	24.8	7.40	218	104	90	14	103	-.39	-.70	.50
610 79	115	23.0	7.70		91	78	13	90	-.23	-.54	.22
611 79	116	24.5	7.65	229	110	95	15	109	-.10	-.42	.30
611 79	117	24.5	7.73	232	114	99	15	113	-.02	-.34	.27
611 79	118	24.7	7.70	218	120	104	16	118	.02	-.30	.29
613 79	120	24.5	7.59	175	85	73	12	85	-.37	-.67	.27
614 79	121	24.9		196	95	82	13	95			
615 79	123	24.9	7.65		90	77	13	89	-.26	-.56	.25
616 79	124	24.5		180	87	75	13	87			
616 79	125	25.0		211	97	83	14	96			
618 79	127	24.5		179	87	75	13	87			
619 79	128	25.0		201	98	84	14	97			
620 79	129	24.5		211	106	92	14	105			
620 79	130	24.5	8.00	204	107	93	14	106	.23	-.09	.13
621 79	132	24.5	7.40	204	106	92	14	105	-.38	-.69	.51
622 79	134	24.9			110	95	15	109			
623 79	135	24.9		234	114	99	15	113			
623 79	137	24.9			110	95	15	109			
623 79	139	24.5		208	101	88	14	101			
623 79	138	24.5	7.50		118	102	16	116	-.20	-.51	.45
623 79	136	24.5		225	110	95	15	109			
624 79	142	24.8		273	128	111	17	126			
624 79	143	24.5		294	144	126	18	142			
624 79	144	24.5		295	156	137	19	153			
624 79	145	24.4		236	145	127	18	143			
624 79	146	24.7		293	156	137	19	153			
624 79	147	24.3		308	151	133	19	149			
624 79	148	24.4		305	157	138	19	154			
624 79	149	24.7			153	134	19	150			
624 79	150	24.5		310	154	135	19	151			
624 79	151	24.9		322	158	139	20	155			
624 79	152	24.9		321	157	138	19	155			
624 79	153	24.3		310	153	134	19	150			
624 79	154	24.7		320	157	138	19	154			
624 79	155	24.5		320	157	133	19	154			
624 79	156	24.4	7.35	318	165	145	20	162	-.08	-.41	.86
624 79	157	24.7		322	158	139	20	155			
624 79	158	24.4		317	155	137	19	153			
624 79	159	24.7		316	155	136	19	152			
624 79	160	24.4		316	158	139	19	155			
625 79	161	24.5		318	156	137	19	153			
625 79	162	24.7		318	156	137	19	153			
625 79	163	24.8		340	167	147	20	164			
625 79	164	25.2		345	169	149	21	166			
625 79	165	24.8		333	166	146	20	163			
625 79	166	24.9		340	167	147	20	164			
625 79	167	25.1	7.45	335	159	139	20	157	.03	-.33	.67
625 79	168	25.0		340	167	147	20	164			
625 79	169	25.0		333	166	146	20	163			
625 79	170	25.0		333	166	146	20	163			
625 79	171	24.9	7.90	340	155	136	19	152	.43	.10	.23
625 79	172	24.8		340	167	147	20	164			
625 79	173	24.5		365	179	158	22	176			
625 79	174	24.5	7.50		157	138	19	154	.04	-.30	.58
625 79	175	24.5		380	187	165	22	183			
626 79	933	24.7	7.35		159	139	20	156	-.10	-.44	.84
626 79	934	24.5	7.73		156	137	19	153	.23	-.10	.37
626 79	935	24.5	7.60		155	136	19	152	.12	-.21	.46
626 79	937	24.5	7.30		150	131	19	147	-.20	-.53	.89
626 79	938	24.5	7.40		147	129	18	144	-.12	-.45	.69

post 6-26 temp's are all set equal to 24.5°C

Table 5.1 (cont.)

DATE	ID	TEMP	PH	SPC	TH	CA	MG	HCO3	SIC	SID	PCO2
	BOILING HOLE, 1979 (CONT.)										
627 79	176	24.5	7.70		146	128	18	143	.18	-.15	.34
627 79	177	24.5	7.60		129	113	17	127	-.02	-.34	.39
628 79	178	24.5	7.75		137	120	17	135	.18	-.15	.29
629 79	179	24.5	7.55		129	113	17	127	-.07	-.39	.43
630 79	181	24.5	7.60	317	152	133	19	149	.11	-.22	.45
630 79	182	24.5	7.60	313	151	133	19	149	.11	-.23	.45
630 79	183	24.5	7.60	319	153	134	19	151	.12	-.22	.45
630 79	184	24.5	7.55	318	149	131	19	147	.05	-.29	.50
630 79	185	24.5	7.60	322	151	132	19	148	.10	-.23	.45
630 79	186	24.5	7.60	328	157	138	19	154	.14	-.20	.47
630 79	187	24.5	7.60	334	157	138	19	154	.14	-.20	.47
630 79	188	24.5	7.65	340	150	132	19	148	.15	-.18	.40
630 79	189	24.5	7.60	345	164	144	20	161	.17	-.16	.49
630 79	190	24.5	7.60	347	166	146	20	163	.18	-.16	.49
630 79	191	24.5		348	171	150	21	169			
630 79	192	24.5	7.60	347	165	145	20	162	.18	-.16	.49
630 79	193	24.5		348	171	150	21	168			
630 79	194	24.5	7.65	347	163	143	20	160	.22	-.12	.43
630 79	195	24.5		346	170	150	21	167			
630 79	196	24.5	7.60	344	166	146	20	163	.18	-.15	.49
630 79	197	24.5		343	168	148	21	165			
630 79	198	24.5	7.60	341	165	145	20	162	.18	-.16	.49
630 79	199	24.5		340	167	147	20	164			
630 79	900	24.5	7.60	339	163	143	20	160	.17	-.17	.48
630 79	901	24.5	7.65	339	159	139	20	156	.20	-.14	.42
630 79	902	24.5		335	164	145	20	161			
630 79	903	24.5	7.65	330	161	141	20	159	.21	-.13	.42
630 79	904	24.5		329	161	142	20	159			
630 79	905	24.5	7.55	327	159	139	19	155	.09	-.24	.52
630 79	906	24.5		326	160	141	20	157			
630 79	907	24.5	7.60	323	157	138	19	154	.14	-.20	.46
630 79	908	24.5		323	158	139	20	156			
630 79	909	24.5	7.60	321	155	136	19	152	.12	-.21	.46
630 79	910	24.5		320	157	138	19	154			
630 79	911	24.5	7.60	320	154	135	19	152	.12	-.21	.46
630 79	912	24.5		320	157	138	19	154			
630 79	913	24.5	7.65	320	154	135	19	152	.17	-.16	.41
7 1 79	914	24.5	7.65	318	151	132	19	149	.15	-.18	.40
7 1 79	915	24.5		317	155	137	19	153			
7 1 79	916	24.5	7.65	316	143	125	18	141	.11	-.22	.38
7 1 79	917	24.5		316	155	136	19	152			
7 1 79	918	24.5	7.65	313	141	123	18	139	.10	-.23	.37
7 1 79	919	24.5	7.60	313	140	122	18	138	.04	-.29	.42
7 1 79	920	24.5	7.65	318	145	127	18	143	.12	-.21	.39
7 1 79	921	24.5		323	150	132	19	148			
7 2 79	922	24.5	7.55		157	138	19	154	.09	-.25	.52
7 2 79	923	24.5	7.50		142	124	18	140	-.05	-.37	.53
7 3 79	924	24.5	7.50		137	120	17	135	-.07	-.40	.52
7 3 79	925	24.5	7.50		138	120	18	136	-.07	-.40	.52
7 3 79	926	24.5	7.50		139	122	18	137	-.06	-.39	.52
7 4 79	927	24.5	7.50		142	124	18	140	-.05	-.37	.53
7 4 79	928	24.5	7.60		139	122	18	137	.04	-.29	.42
7 5 79	929	24.5	7.60		141	123	18	139	.05	-.28	.42
7 6 79	930	24.5	7.60		145	127	18	143	.07	-.26	.43
7 6 79	931	24.5	7.60		146	128	18	144	.08	-.25	.44
7 7 79	932	24.5	7.55		148	129	19	145	.04	-.29	.49

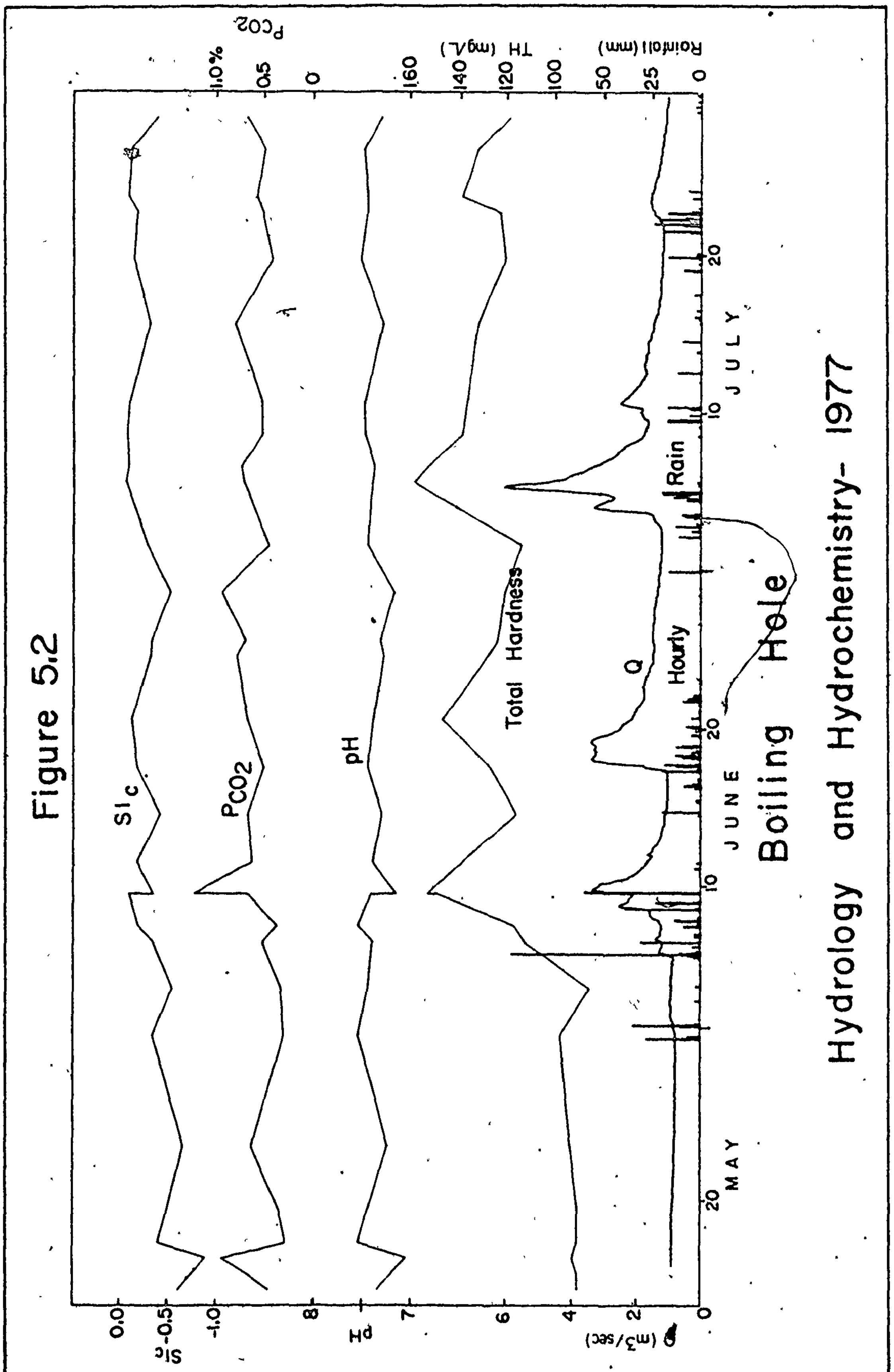


Figure 5.2

Boiling Hole

Hydrology and Hydrochemistry- 1977

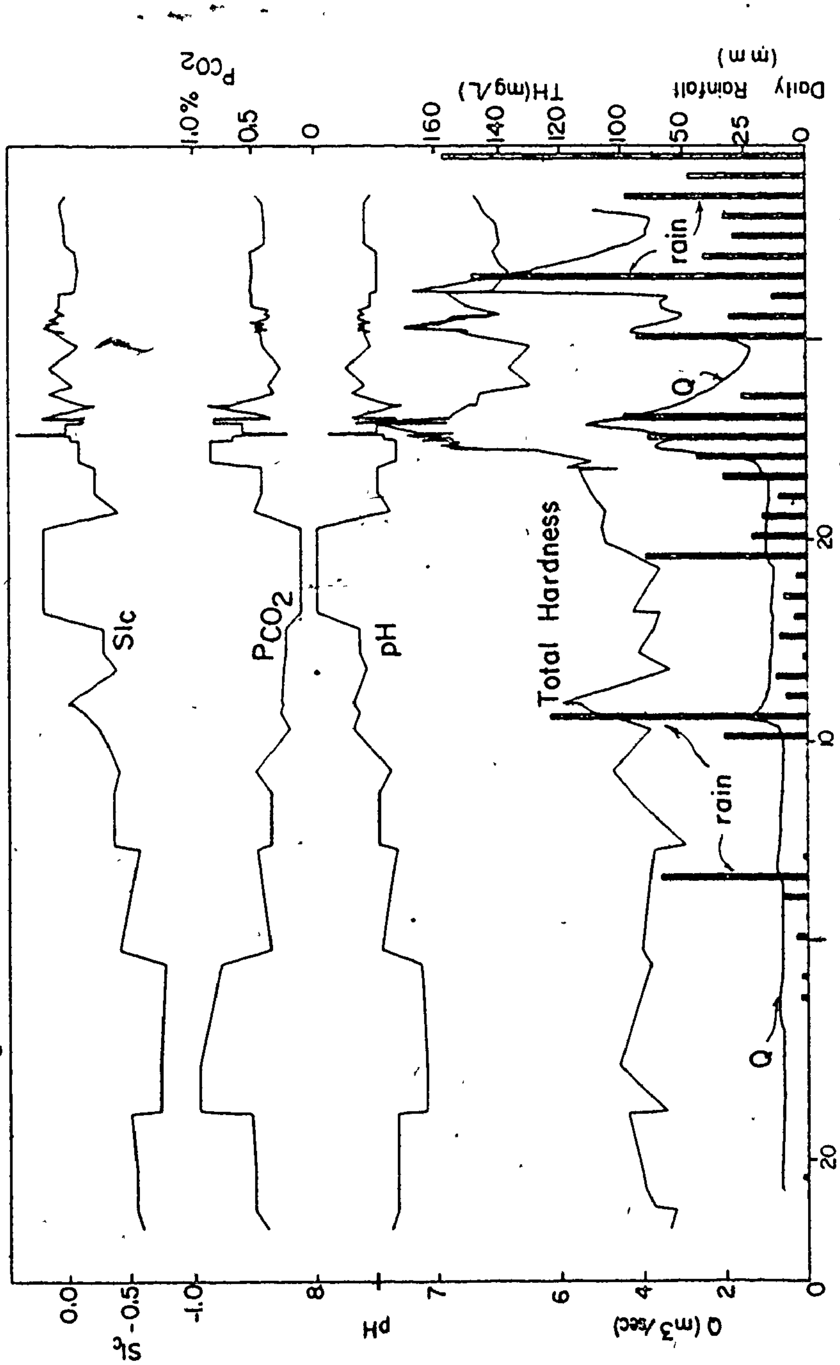


Figure 5.3 BOILING HOLE, 1979

about 7.4 to 7.6, but the most dramatic effects are shown in the hydrochemistry. The minimum wet season values of TH, SI_c and P_{CO_2} are generally all higher than their respective maximum values of the dry season; they correspond strongly with discharge. TH was found to vary from 100 to nearly 170 mg/L, and P_{CO_2} averaged about 0.5 to 0.7%. Most of the wet season flow was saturated (or nearly so) with respect to calcite. Total hardness was found to be directly correlated with discharge (Figure 5.4), and rose and fell predictably with the various storm flows. This is in contrast to its dry season behavior, when it showed an inverse correlation. Figure 5.4 also shows that for the extreme high flows (above 5 cumecs, and all from 1979) there was an apparent drop in TH. TH also demonstrated an inverse relation to temperature: in 1976 when the best temperature data was obtained, the correlation coefficient was -.88. Temperatures in 1977 and 1979 were sometimes taken with thermometers of less resolution. (e.g. that on the SPC meter) -- the trend, however, was the same.

An important point is that at the start of all three wet seasons a noticeable lag existed between the advent of major rains, and significant response at the Boiling Hole, This transition period may last only a few days if heavy rains continue (1977), or as much as two weeks if precipitation is less intense (1979). During this transition the dry season inverse TH/Q relation shifts to the direct relation found throughout the wet season. In Chapter IV, a maximum soil moisture deficit of 13.5 mm was calculated for the end of the dry season. This alone cannot account for the transition delay because 270 mm of rain fell in 1977 before significant response, and 248 mm in 1979. Evapotranspiration would have amounted to less than 80 mm at maximum.

As a final note, some estimations of discharge (based on timed floats, stages, and some measured flows) are available for 1976. These

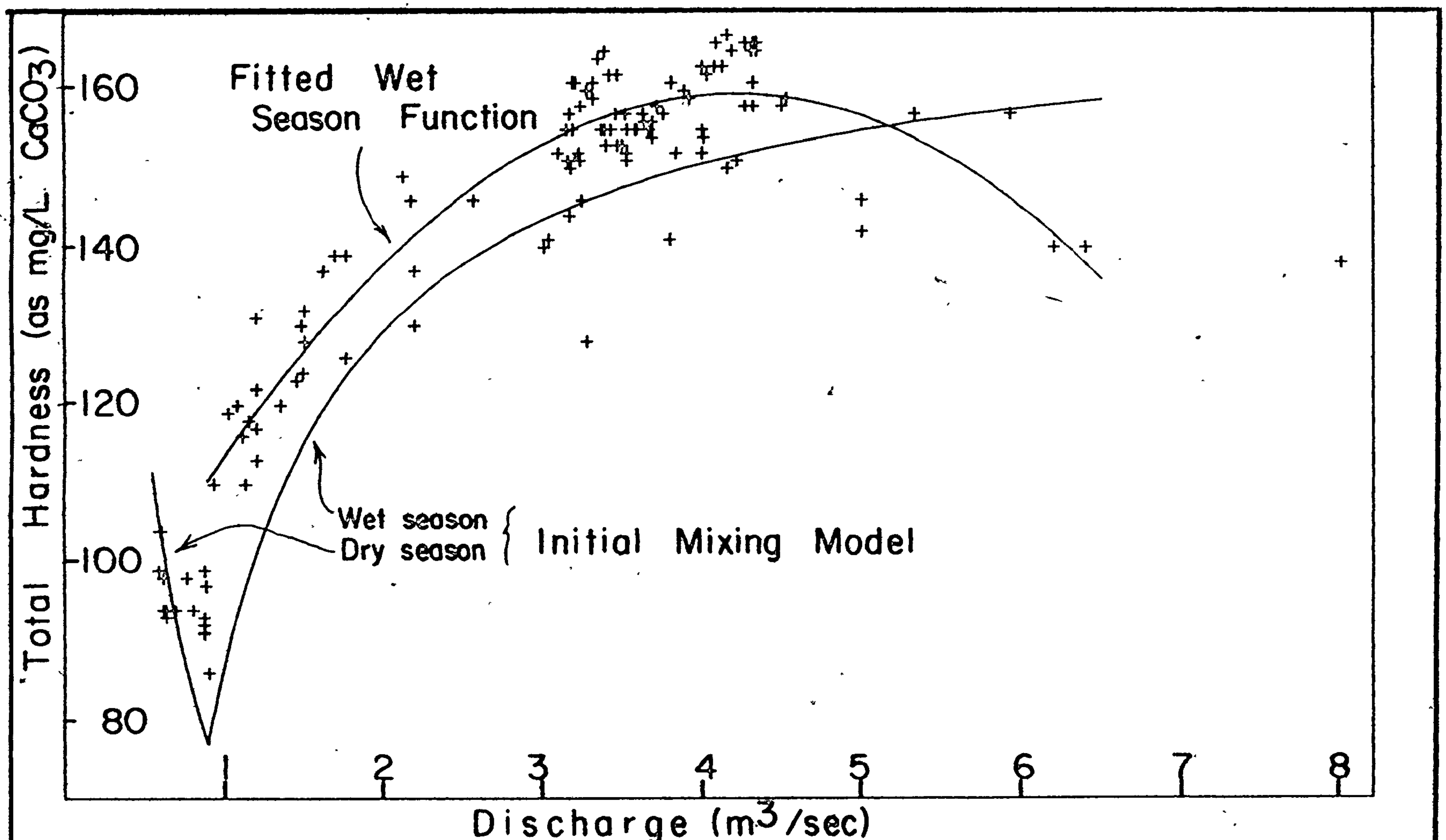


Figure 5.4 Boiling Hole hardness-discharge

data, with 1976 Belmopan precipitation, are shown in Figure 5.5 and Table 5.2. Although of lower quality, they definitely show the same response as that of the 1977, 1979 seasons.

This wet season response is unusual. The great majority of investigators worldwide have cited the general dilution effect of discharge upon solute content. Where a rise is evident, it is nearly always temporary, and attributed to flushing (the rapid removal of static, high hardness water by storm flow following dry conditions). Yet this phenomenon is insufficient to explain the repeated, prolonged events of the Boiling Hole.

B. Initial Model of Boiling Hole Behavior

In Chapter III, the physical elements of the cave systems of the Caves Branch were outlined. Because of its size, morphology distinct from the zuhuyhas, and Pine Ridge sediments, the Nab Nohol Branch was considered to be almost certainly a conduit of allogenic origin or modification. It differs from the other conduits in not having a known upstream entry for allogenic water, and in having a number of sub-conduits that pirate Caves Branch River flow from the surface into the trunk conduit. These pirating channels either begin at small ponors or have no known source at all. In the latter case they are surmised to be hidden under alluvium and so at least partially plugged. In the preceding section of this chapter, Boiling Hole discharge was noted to become cooler in the wet season, more saturated, and higher in hardness and P_{CO_2}; it becomes more like authigenic flows in these characteristics. When initial classes of allogenic and authigenic water were established for a discriminant analysis, then used to classify samples from the Boiling Hole, all dry season samples (on this basis) were identified as allogenic, and all wet season waters as

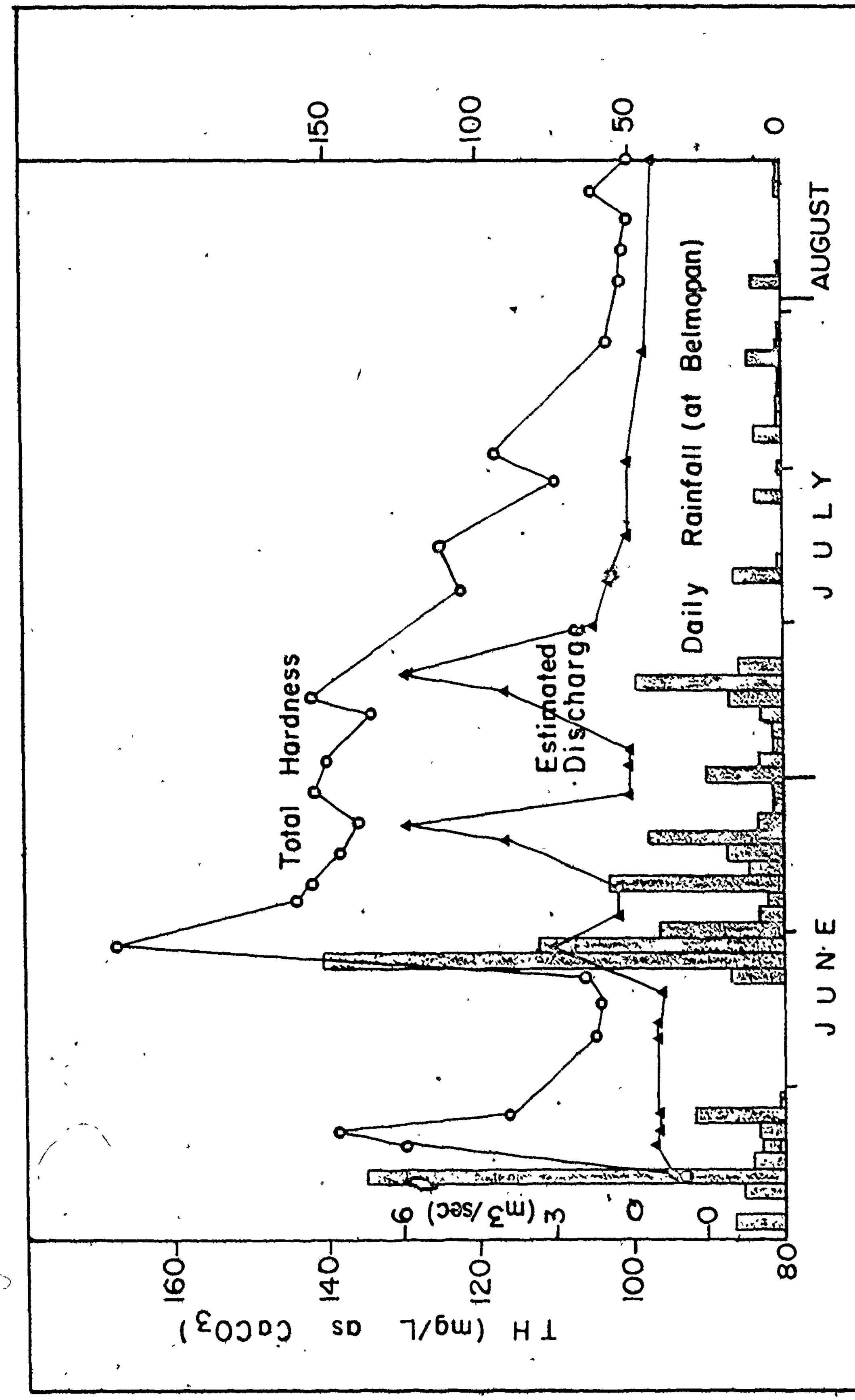


Figure 5.5 Blue Hole, 1976

TABLE 5.2

Measured Flows, Caves Branch, 1976

Blue Hole	6/7/76	0.43*	
	6/8	.81	
	6/9	.99	
	6/14	1.29	
	6/16	1.28	
St. Herman's Cave (entrance)	6/8	0.61	
	6/9	.99	
	6/14	.99	* (5 readings)
	6/16	.76	* (2 readings)
	6/19	2.10	
Caves Branch River (at bridge)	6/7	5.90	
	6/9	3.53	
	6/14	.79	
	6/16	.61	
Caves Branch River (after resurgence)	6/12	3.87	
Caves Branch River (before resurgence)	6/12	3.35	

* based on one velocity reading only

authigenic.

The wet season behavior of the Boiling Hole, then, can be best explained as due to an increased proportion of authigenic flow. A total seasonal increase in flow would cause the overall trend, while individual high discharge events would account for the short term effects. Because the total influx of the Caves Branch River is pirated underground prior to reaching the end of the polje in the dry season, but not in the wet season, there are obviously hydraulic restrictions present on the capacity of the pirating channels. The small ponor openings and probable sediment infills noted before would explain this. The Boiling Hole wet season response must also be due then to inhibition of the allogenic component which would increase the relative share of authigenic flow.

Dry season hydrochemistry behaves oppositely. Karst aquifer baseflow is presumably more stable than allogenic flow, and insulated from minor rain events. It also has no response to distant precipitation in the wetter May Mountains that could conceivably increase allogenic flow. A dilution effect dependent primarily upon changes in allogenic flow contribution could cause the TH/Q effect noted.

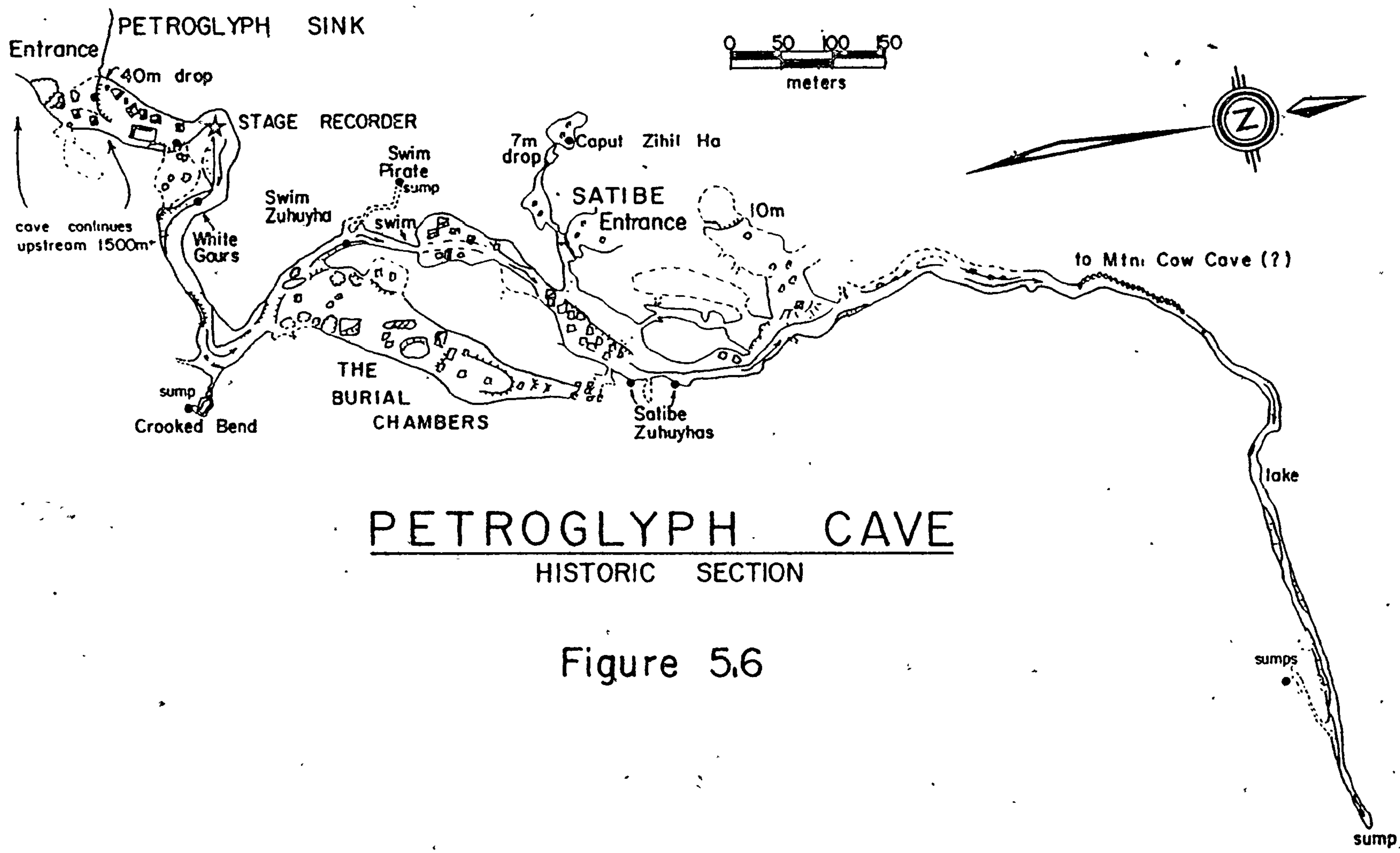
For the Boiling Hole, a mixing model is proposed to account for its observed hydrologic and hydrochemical behavior. The two components -- authigenic water of high hardness and allogenic flow of low solute concentration -- are assumed to mix in a dynamic response to seasonal flow influences. The following section will attempt to test the validity of the hypothesis. In this context, it is noted that the few other researchers mentioning similar positive TH/Q effects in streams all presume a similar mixing control (Douglas, 1968; Edwards, 1973; Jacobson and

and Langmuir, 1974; and Burt, 1979).

C. Investigation and Test of Model

In 1979, considerably more effort was concentrated on sampling within the trunk conduits upstream of the Boiling Hole. The two known caves feeding the monitored site are Petroglyph and Saint Herman's (Figures 5.6 and 5.7). Petroglyph Cave is not only the uppermost, and closest to the presumed piratic source, but has the largest number of inlets in which discharge can be measured. In contrast to 1977, when few samples (and only one discharge) were taken because of the difficulty of access, 18 discharges were measured just of the major inlets, and a stage recorder was installed. Table 5.3 shows the data collected for the upper Nab Nohol Branch, with the corresponding values for the Boiling Hole. Figure 5.8 shows the super-imposed hydrographs of Petroglyph and the Boiling Hole.

Between these sites and the Boiling Hole, the water travels over 5000 meters, doubles its hardness, yet becomes scarcely more saturated. This is because the P_{CO_2} has increased substantially in spite of the distance traveled in well-aerated conduits (note Table 4.4, in which only one atmospheric CO_2 reading, taken in a cul-de-sac fossil passage, has been recorded as high as the P_{CO_2} to which the Boiling Hole appears equilibrated). The total discharge of the conduit has doubled, and now has a hydrochemistry midway in characteristics between the allogenic surface flow and that of zuhuyhas and springs. Because no other piratic conduits are found between the Swim Pirate and the Boiling Hole, and the surface river has shifted to the farther side of the polje (Figure 4.1) the likelihood is quite high that simple addition of authigenic water to the



PETROGLYPH CAVE

HISTORIC SECTION

Figure 5.6

Figure 5.7
Saint Herman's Cave
South

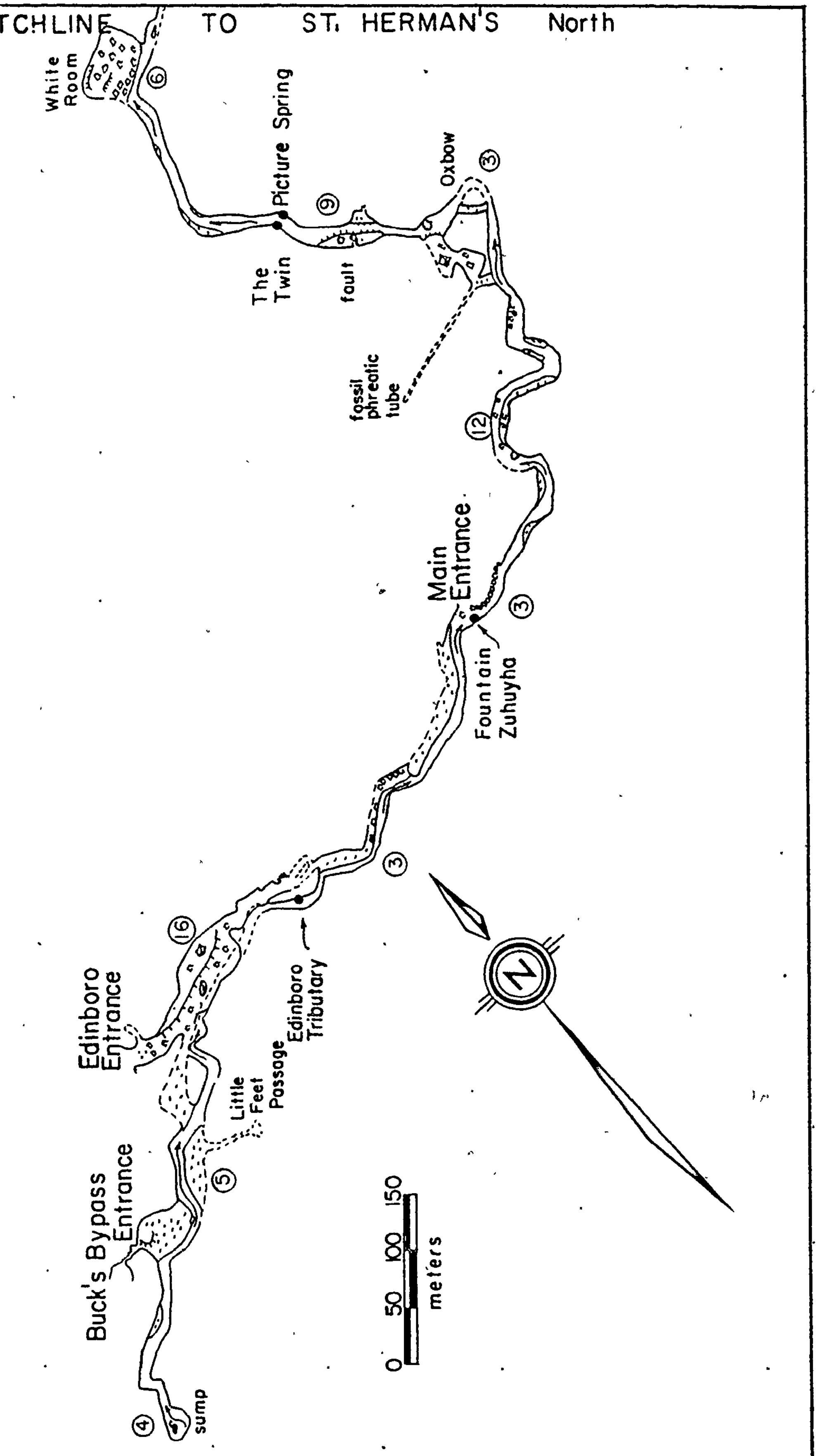


Figure 5.7

Saint Herman's Cave

North

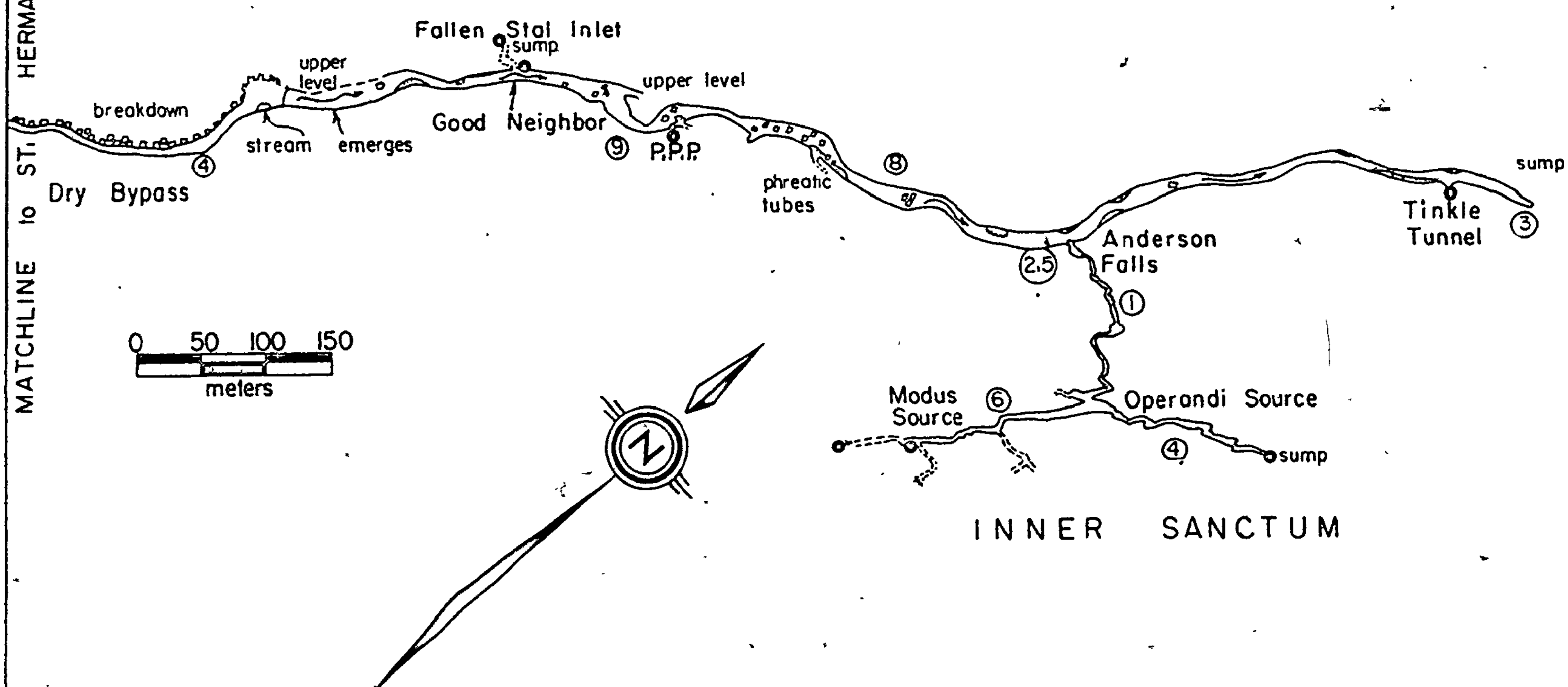


TABLE 5.3

Upper Nab Nohol Chemistry, Discharge

1979

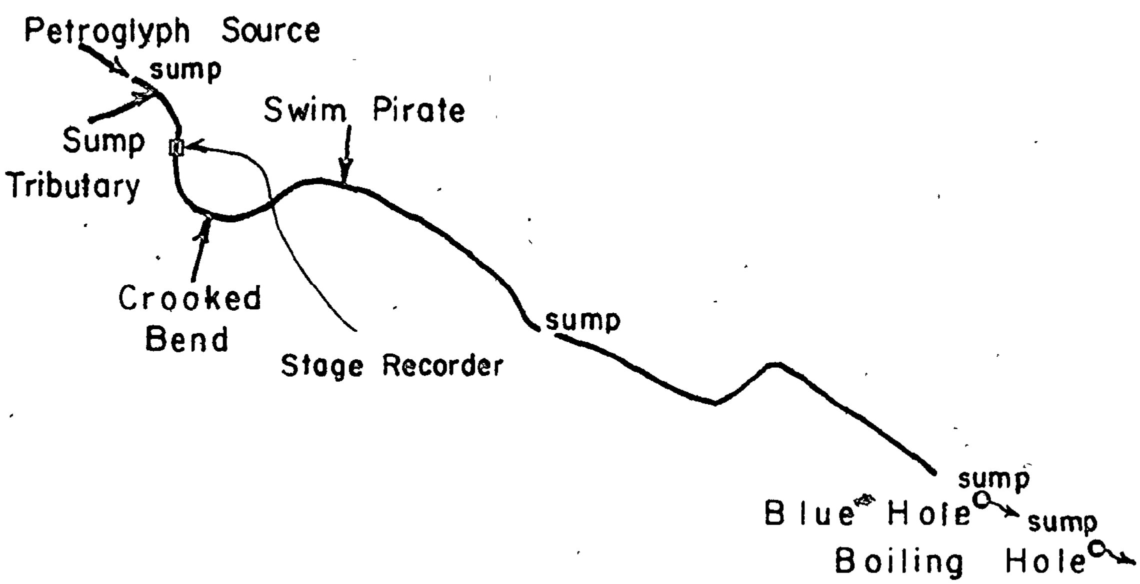
	Date	Q	TH	SPC	SI_c	P_{CO_2}
Sump Tributary	5-24	.19	51	107	-1.08	.33
	29	-	44		-1.08	.21
	6-24	.31	104		- .20	.32
	6-30	.39	146		+ .03	.49
	7-4	.38	122		- .12	.41
	7-7		126		- .15	.47
Petro Sump (Upper)	5-24	.1(?)	51	107	- .96	.25
	29		44		- .99	.17
	6-24	1.7(?)	76		- .25	.15
	30	1.57	133		- .05	.45
	7-4	1.4	120		- .09	.36
	7-7		118		- .10	.35
Petro Stage	5-24	.33				
	29	.3	53	111	- .80	.19
	6-5	.3	54	113	- .69	.15
	9	.15	57	120	- .48	.11
	17	.5				
	24	2.				
	30	2.				
	7-2	3(?)	93		- .39	.36
	7-4	2-2½				
	7-7		121		- .11	.39
Crooked Bend	6-17	.002,3	211		.08	1.23
	24	1.7	202		.12	.97
	30	1.47	177		- .01	.53
	7-2	>3	126		- .10	.47
	7-4	2.21	143			
	7-7	>3	146		- .09	.69
Swim Pirate	5-24	.05		160	- .49	.27
	29			138	- .56	.21
	6-17		59	131	- .14	.05
	6-24	.02-.03	56		- .27	.07
	30	.15	77		- .40	.27
	7-4	.21	105		- .19	.32

TABLE 5.3 (Continued)

Upper Nab Nohol Chemistry, Discharge

	Date	Q	TH	SPC	SI_c	P_{CO_2}
Saint Herman's Cave	5-22		70			
	6-14		(78)	161		
	18		(82)	170	-.09	.13
	7-1		142		.16	.34
Boiling Hole	5-24	.6	101	208	-.72	.97
Blue Hole	29	.62	≈90	≈186	-.76	.78
Boiling Hole	6-5	.68	90	≈200	-.56	.49
	10	.61	91		.23	.22
	17	.86	≈97	≈211		
	24	3.61	156	318	-.08	.86
	30	4.2	152	317	.11	.45
	7-2	8+	≈140		-.05	.53
	7-4	6.4	140		.04	.42
	7-7	5+	148		.04	.49

5-27-77	Satibe	.62 cumecs	43.5 mg/L
	Boiling Hole	.78	96
	Sump Trib.		56



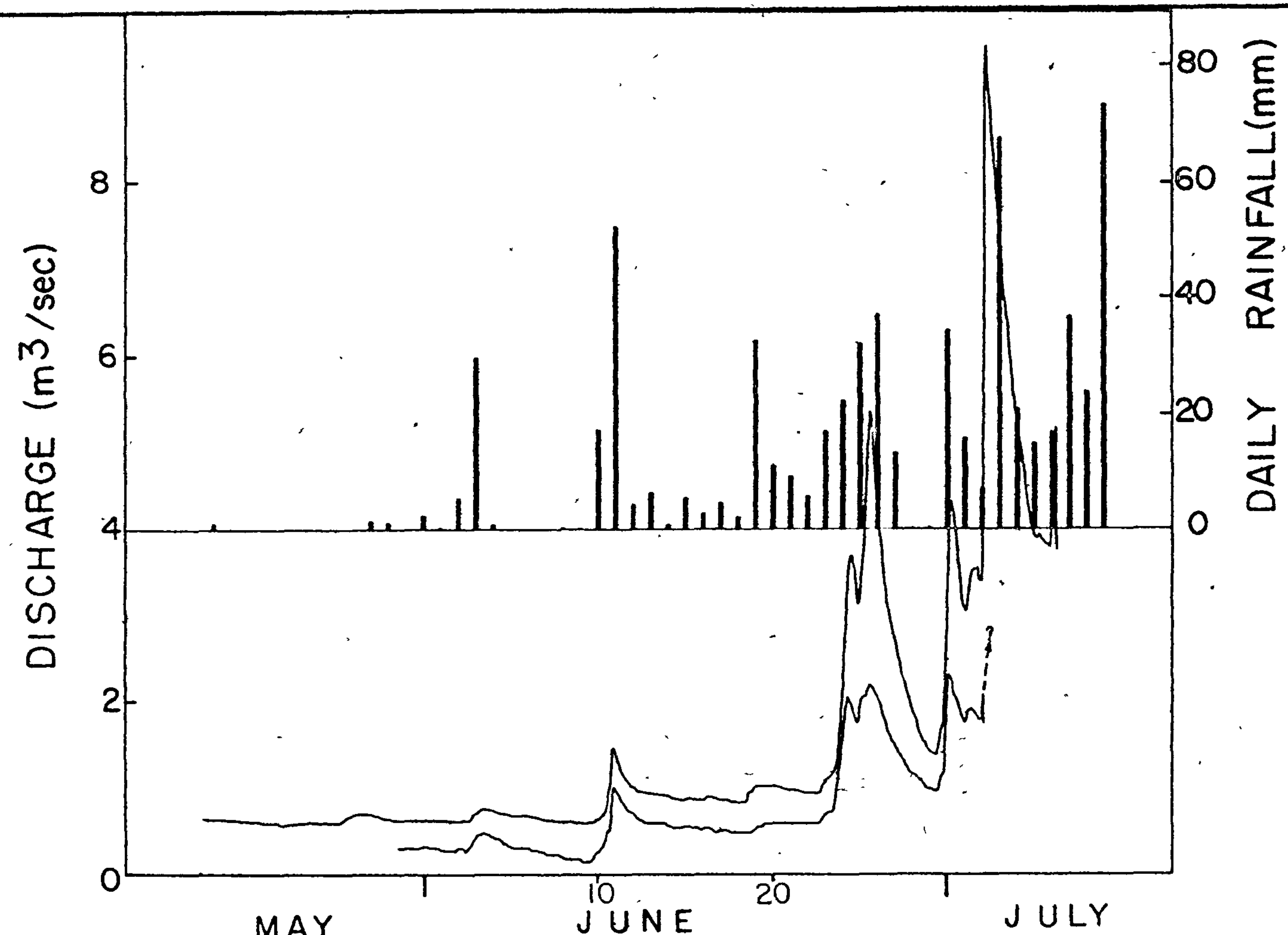


Figure 5.8
Petroglyph and Boiling Hole Hydrographs

river has primarily caused the rise in hardness, rather than solution by the aggressive water found at the upstream Petroglyph sump.

In Chapter IV (II.C.1., Table 4.9), it was noted that losses to the Petroglyph Cave area of the polje appeared to be at least 0.3 cumecs in both 1977 and 1979. This is almost exactly the same as the discharge measured at the upper end of Petroglyph Cave. The water at this point in the cave is slightly richer in P_{CO_2}, with a higher hardness and saturation. These increases would be consistent with minor mixing occurring with authigenic influxes upstream.

With the available evidence appearing to support the hypothesis, the pertinent equation for testing is that of Chapter IV (II.C.1);

$$Q_B C_B = Q_A C_A + Q_K C_K \qquad (4.3)$$

where $Q_B = Q_A + Q_K$

Q_i = discharge (cumecs) for the Boiling Hole (B), allogenic (A), and karst (K) components,

and C_i = hardness (mg/L as $CaCO_3$) for the above

In 1977 and 1979, 122 simultaneous Q_B and C_B readings were taken at the Boiling Hole. Using the data of Table 5.3, the relative proportions of the allogenic and karst discharge (Q_A and Q_K) contributing to Q_B could be approximated. The hardnesses of the Q_A and Q_K components were estimated as outlined below. Using this estimated C_A and C_K, and combined with the estimated relative proportions of Q_A and Q_K, the predicted hardness (C_B) for a given Q_B could be compared with that actually recorded.

As discussed in the previous chapter, authigenic springs and zuhuyhas in the Caves Branch all had highly stable concentrations during the periods in which they were measured. Using the flow of each zuhuyha, and its stable TH, a mean areal hardness (C_K) was estimated from this discharge-weighted concentration of all the springs in the Caves Branch. This gave a value of 187 mg/L. The allogenic samples were weighted equally to calculate C_A, giving a mean of 24.5 mg/L. It was observed that TH of the upper Caves Branch River was generally inversely proportional to discharge, with the lowest values occurring in the highest floods (e.g. that for 6-11-77, 10 mg/L). Unfortunately, since discharge could not be measured for some of these larger flows, which form the majority of discharge, a loading curve could not be properly calculated. Because the higher flows also occurred under conditions when access was most difficult, the sample mean hardness was felt to be biased toward lower, higher hardness flows. As a partial solution, it was decided to use for the mean hardness the lowest value which did not differ significantly from the sample mean at the .05 level of significance. This value was 22 mg/L, and used for C_A.

The 1977 Boiling Hole dry season discharge was higher, yet with slightly lower hardness than 1979, and both showed an inverse correlation of Q/TH. Because of this, relative authigenic/allogenic dry season flows were assumed to be a function solely of variations in allogenic flow. Authigenic contributions in 1979 between the Swim Piracy and Boiling Hole were a steady 0.3 cumecs. On May 27, 1977, discharge half a kilometer downstream of the 1979 Petroglyph stage setting was about 0.6 cumecs, while Boiling Hole flow was about 0.8 cumecs. As some additional authigenic input would have occurred by then, total influx from karst springs would also have been approximately 0.3 cumecs in 1977 as well.

The dry season flow component of the model, then, would be

$$Q_A = Q_B - 0.3 \text{ cumecs} \qquad (5.1)$$

where $Q_K = 0.3$ cumecs

and $Q_B \leq 0.9$ cumecs

In the wet season, authigenic inflow should be an unrestrained function of surface precipitation while the allogenic flow proportion should decline because of the restrictions on piracy of the river water caused by narrow, or partially infilled ponors. In the 1979 dry season, about one-sixth of the allogenic flow (0.05 cumecs) entered through the swim piracy. Allogenic contributions at higher flow can be roughly estimated if this ratio is assumed to stay constant at higher discharges (e.g. for the 0.15 cumec swim piracy flow of June 30, total allogenic input would be 0.9 cumecs of a total Boiling Hole flow of 4.2 cumecs). If a linear relationship is assumed between these points and the upper end of the dry season function (where from Equation 5.1, allogenic contribution is calculated as 0.6 cumecs of a total 0.9 cumecs), the wet season portion of the model would be represented by

$$Q_A = .518 + (.091)\, Q_B \text{ cumecs} \qquad (5.2)$$

where $Q_K = Q_B - Q_A$

and $Q_B > 0.9$ cumecs

Using the above discharge equations and the mean allogenic/authigenic concentration values, the model curve of Figure 5.4 was derived. Hardnesses calculated from the model for the 122 discharges recorded at the Boiling Hole in 1977 and 1979, were compared with the hardnesses actually recorded for those discharges. This latter function is shown in Figure 5.9. The intercept coefficient for this linear function was

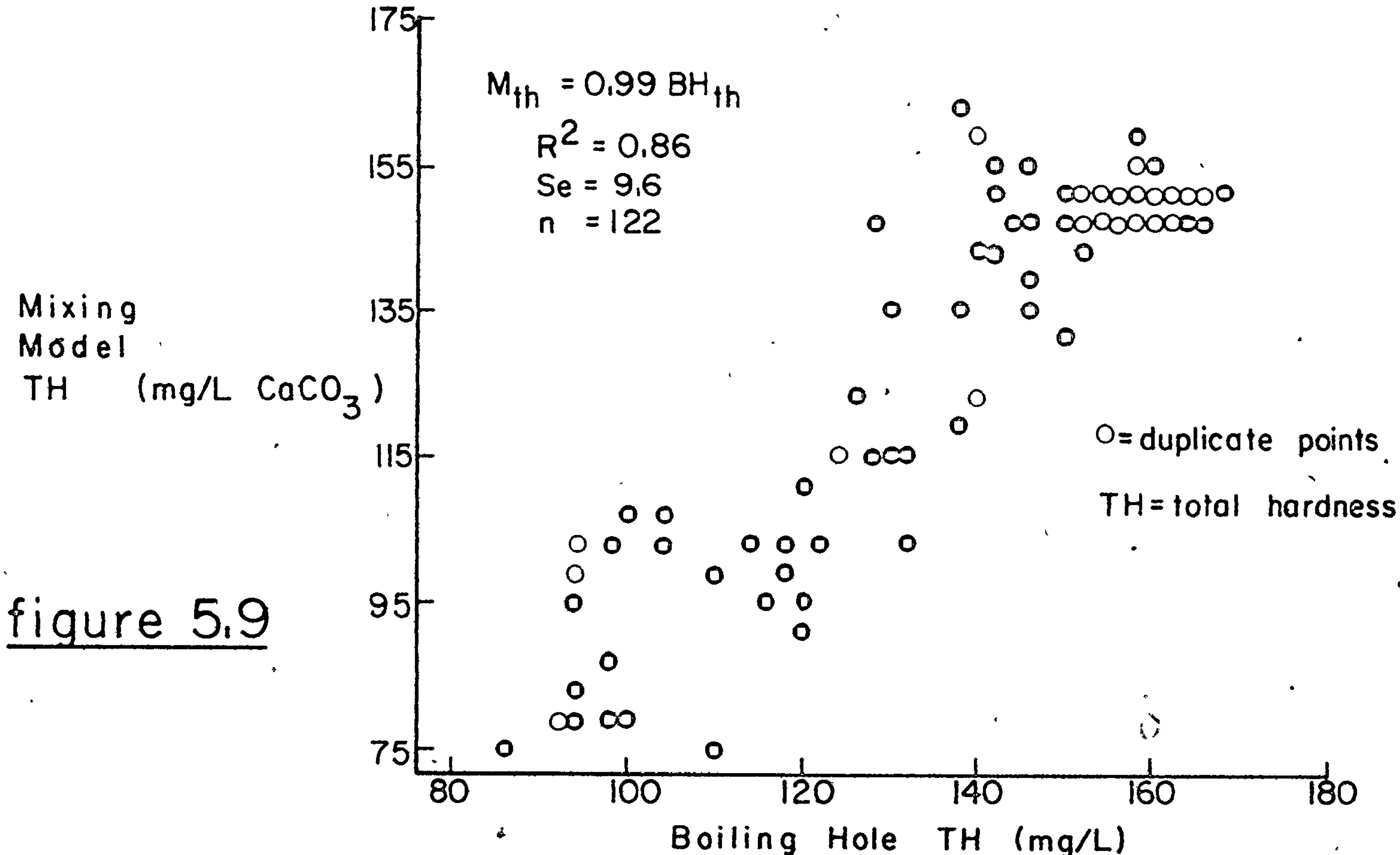


figure 5.9

Comparison of mixing-model/actual TH

not found to differ significantly from 0 at the .05 significance level, (t = -1.23), nor was the slope coefficient found to differ significantly from 1.0 at this level (t = -0.31). Both results indicated that the model gave a satisfactory representation of the actual Boiling Hole TH's at this level of significance. The R^2 for the regression itself was 0.86 at the .01 level of significance.

Referring to Figures 5.4 and 5.9, it can be seen that the model corresponds well with actual recorded flows for all ranges except the extreme high flows of 1979. This variance will be discussed in the following section. Overall, the seasonal hardness concentration behavior of the Boiling Hole is well accounted for by the model, which assumes mean areal hardness concentrations for the allogenic and authigenic components, a dry season flow dominated by influxes of pirated river water, and a wet season regime in which the hydraulically restricted pirate influx is overcome by periodic storm and storage outflow of authigenic water.

Some explanations for the variation of the model from the observed behavior are discussed in the following sections.

II. Hydrologic Mass Balance of the Aquifer

The previous section demonstrated that a two-component mixing model assuming restriction of allogenic flow at higher discharges could adequately explain the discharge/hardness regime of the Boiling Hole.

Season	R.E.	C.C.	S.L.	
1977 (dry)	TH = 151-68.4Q	-.89	.05	(5.3)
1979 (dry)	TH = 150-85Q	-.54	.10	(5.4)
1977, 1979 (wet)	$TH = 78.5 + 34.6Q - 3.65Q^2$	+.95	.01	(5.5)

[where TH = total hardness in mg/L; and Q = discharge (cumecs)]

R.E. = Regression Equation
C.C. = Correlation Coefficient
S.L. = Significance Level

All 3 correlations were significant at the noted level of confidence. The individual wet season equations were so similar (and covered the same discharge ranges) that they were combined. The wet season relation fitted was that of a 2nd order polynomial because of the previously noted drop in hardness with extreme discharges.

A. Systematic Hydrologic Effects

In addition to random deviations of the total hardness about a given discharge, there are systematic effects:

1. Crooked Bend Contribution It was noted earlier that TH at the Boiling Hole in 1979 was lower for the extreme high discharges than expected from behavior at lower flows. It is further noted that these deviant flows were all from the same storm event, the last monitored during that summer. Two other storms, one in 1977 (July 2), and the other in 1979 (June 20-24) also had flows above 5 cumecs but did not demonstrate a Q/TH response any different from that expected.

It is apparent from Table 5.3, that the most obvious single change in the flows of the final two weeks of 1979 is the massive increase in discharge from the Crooked Bend Zuhuyha (Figure 5.6). It increases from no flow in the early part of the wet season to 2-3 L/sec on June 17, and following the major rainfall of June 23, to 1.7 cumecs. By the last two weeks it appears to account for one-third to one-half of the total flow recorded at the Boiling Hole. Until that period, the difference in discharge between the Boiling Hole and the Petroglyph gauge was minimal, about 0.3-0.5 cumecs (Figure 5.8). Afterwards, a much larger 2-4 cumec disparity appeared, most of it readily accounted for by the increased

Crooked Bend Flow.

From Table 4.6d, it can be seen that Crooked Bend at all other times of sampling demonstrated the same stability of hardness typical of diffuse flow springs. It also has the morphologic characteristics and siting of zuhuyhas and springs. During the final extreme 1979 floods hardness, saturation index, and P_{CO_2} dropped markedly at the Crooked Bend, then began to recover after the major storm peak had passed. Discussion of the behavior of this authigenic spring will occur later -- for now, it is enough to note that its flow increase (to >2 cumecs) and drop in solute concentration (to 126 mg/L) readily explains the simultaneous occurrences at the Boiling Hole.

2. Extreme High Flow Backflooding

Stage increased to a depth of at least seven meters at the Boiling Hole in the last recorded flood of 1979. This was 5 meters above the highest previously recorded for the two seasons of record, and from the rating curve should have corresponded to a dishcarge of about 25 cumecs. There are a number of reasons, however, for believing this stage rise is due primarily to backflooding rather than to a tremendous rise in discharge: 1) velocity of flow decreased markedly (although at that depth it could not be measured accurately); 2) previously, Boiling Hole flood rises and peaks always lagged behind those of the Petroglyph stage by 1-5 hours; on July 2 the Boiling Hole storm rise preceded that at Petroglyph; 3) discharge at the Petroglyph recorder was about 2.5 cumecs at a stage of 24 cm (the previous record high was 25 cm) at 0730 on July 2 -- in the following 20 minutes it rose at least a meter, peaking later at about 5.3 meters. In spite of this, when the flood receded, the unsecured recorder was found still in place -- any normal velocity expected from these stages should have swept it away; 4) finally, a similar 5 meter rise at the Blue Hole in 1976 was associated with pronounced flooding of about 1 km^2 of the lower river polje to a depth of at least 4 meters (as evidenced by muddy waterlines in the trees). Bedrock scallops averaging one cm in diameter on the ceiling of the ponor entrance of the Caves Branch River indicate formation at velocities of about 1.8 m/sec (Curl, 1964; Goodchild, 1971) -- at river flows greater than 50 cumecs the 30 m^2 cross-section is unable to accept all of the available river discharge. Inside, the trunk conduit would be completely filled with fast-moving water -- at the confluence with the Nab Nohol Branch the much smaller influx coming from Boiling Hole, Petroglyph, etc. would be effectively dammed. Until the flooding of the surface river subsides, flow from the Nab Nohol appears to back up in the entire trunk conduit, to depths of at least 5 m in Petroglyph Caves nearly nine kilometers upstream of its union with the Caves Branch River.

3. Cyclical Variation Deviation of total hardness about a given discharge occurs. Two large storm flows in 1979 were sampled across flood peaks on an hourly to half-hourly basis. Figure 5.10 shows sequential migration of the TH/Q relation for the storm of June 30 - July 1. The hysteresis effect is obvious: solute concentration is higher at the same discharge on the falling limb of the hydrograph. The basic positive relation is seen as a composite of an inital slow TH rise with discharge, followed by an abrupt surge in TH while flow rises comparatively little. The TH/Q relation following the storm peak passage differs from that preceding

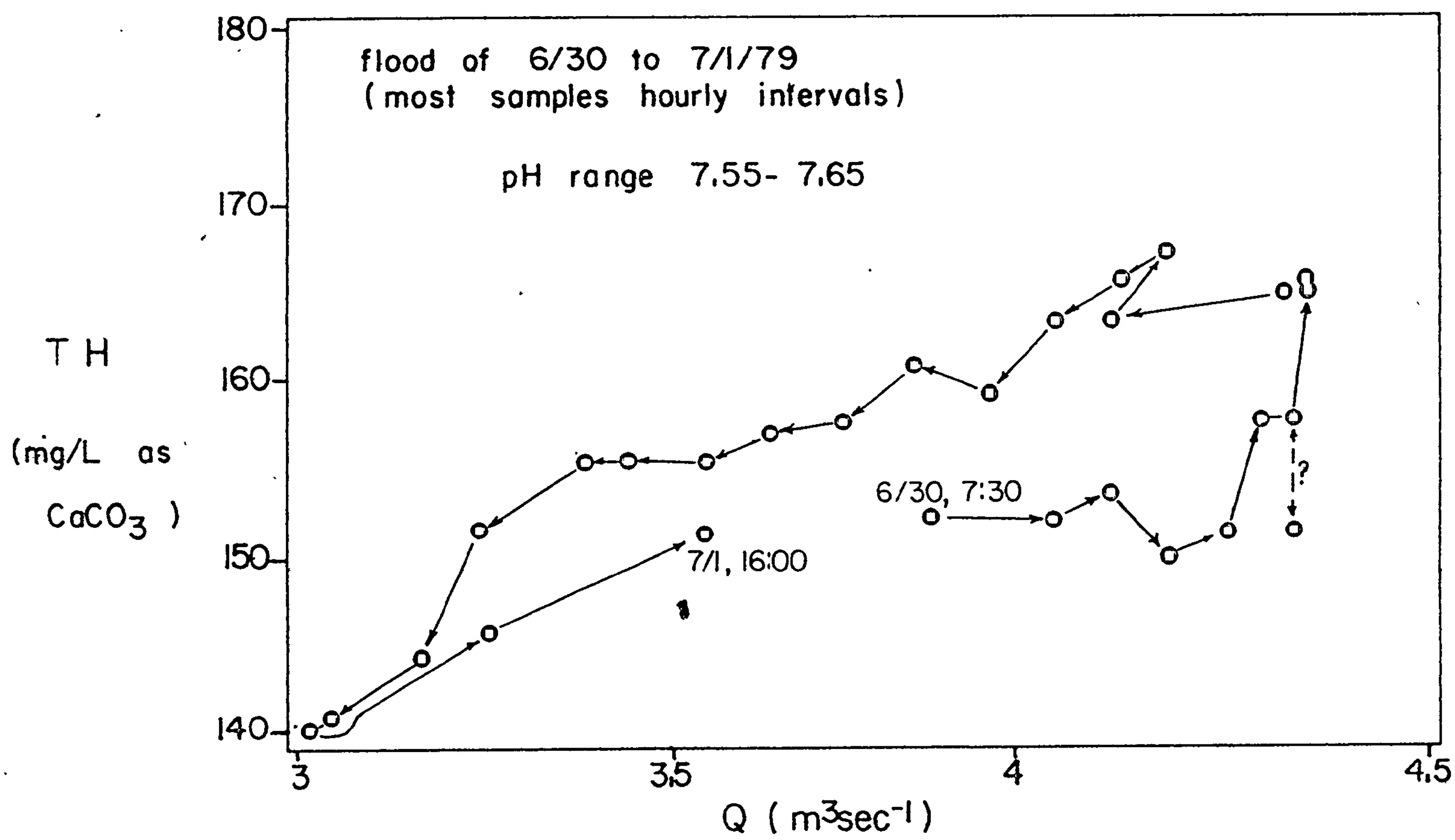


Figure 5.10 HYSTERESIS, Boiling Hole

it. Closely following the passage of the first peak is the rise to the second, which mimics that of the first storm pulse. This cyclical rotation is consistent with an early allogenic contribution being followed by the main lagged karst runoff. In this storm, differences of about 10 mg/L occurred for similar discharges depending on whether they were on the rising or falling limb: much of the variation in the overall TH/Q relation is explained by this. Hysteretic effects of similar type were observed during other storms as well.

B. Aquifer Recharge and Storage

It has been mentioned previously that a considerable delay exists between the start of the wet season rains, and comparable response at the Boiling Hole. In 1977 and 1979, the amount of rain that fell prior to response at the spring was 270 and 243 mm, respectively. In 1976, 206 mm were recorded at Belmopan during this interval. Figure 5.11 shows the 1977 hydrograph of the stage recorder that was placed in the upper half of the Caves Branch polje (prior to the confluence of the Chek and Caves Branch River streams). Although much of the recorded flow is due to rainfall on the Maya Mountains rather than in the immediate Caves Branch polje area, there is sufficient correlation of rainfall between the areas to be able to remark upon the swift reaction of the allogenic flow to the initial wet season rains. This reaction is much slower for the chiefly authigenic flow of the Nab Nohol trunk conduit (Figures 5.2 and 5.3).

In Chapter IV, the soil moisture deficit (SMD) of the Caves Branch karst is estimated to be approximately 13.5 mm at the end of the dry season. Evapotranspiration (ET) during the interval of little or no discharge

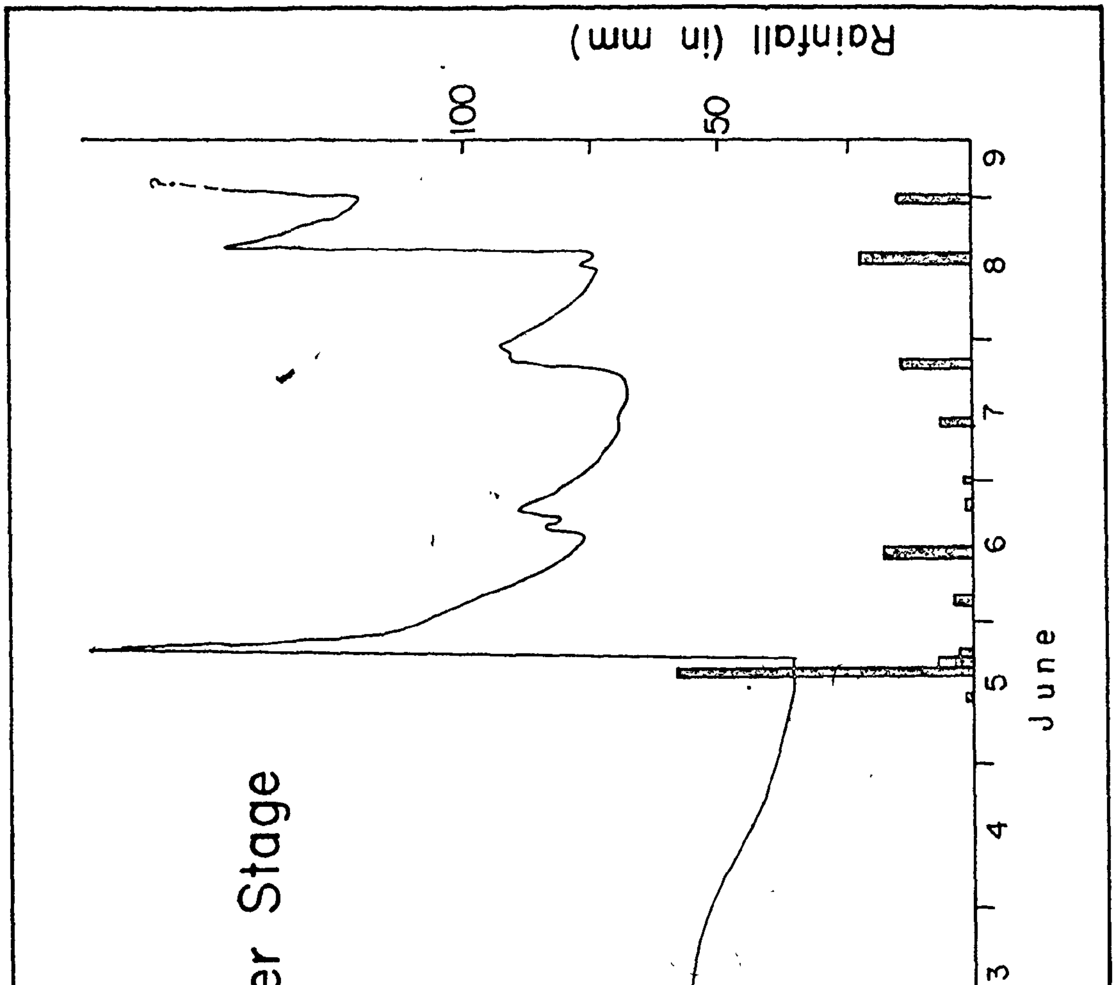


figure 5.11
Caves Branch River Stage
1977

of rain for 1977 and 1979 was calculated to be 24 and 79 mm respectively. The SMD and ET together are obviously insufficient to account for the delay in discharge response.

Influx of allogenic base flow into the Caves Branch polje from the Maya Mountains has been measured at about 0.5 cumecs in the 1977 and 1979 dry seasons. For the known catchment of 64.1 km^2, this is an instantaneous discharge per area of 7.8 X 10^{-3} cumecs/km^2. The external source area of an inaccessible aquifer such as that of the karst feeding the Boiling Hole is obviously difficult to define; with allowance made for known peripheral springs and streams in the region, the most likely size and shape is shown in Figure 5.12. This latter catchment area is 22.3 km^2, giving an instantaneous discharge per area of 13.5 X 10^{-3} cumecs/km^2 for the approximate 0.3 cumec authigenic component of Boiling Hole discharge. The greater flow of the karst catchment per unit area is apparent, and is presumably due to a greater storage capacity.

It is logical to assume that the relatively rainless period preceding the wet season is an interval of more or less continual water storage decline for the karst aquifer. Table 4.1 lists mean Caves Branch precipitation as being less than 110 mm for each of the four dry season months of February, March, April, and May. During these more cloud-free months, temperatures and PET are slightly higher than for the wet season summer months (Figure 1.5). With monthly PET equal to 140-150 mm, it is apparent that there can be very little, if any, recharge to the aquifer at this time. This section will attempt to correlate this dry season storage loss with the delayed response of the Boiling Hole to the start of the wet season. This will be done by 1) computing the loss from storage to base flow during the dry seasons; 2) calculating the storm runoff of the field

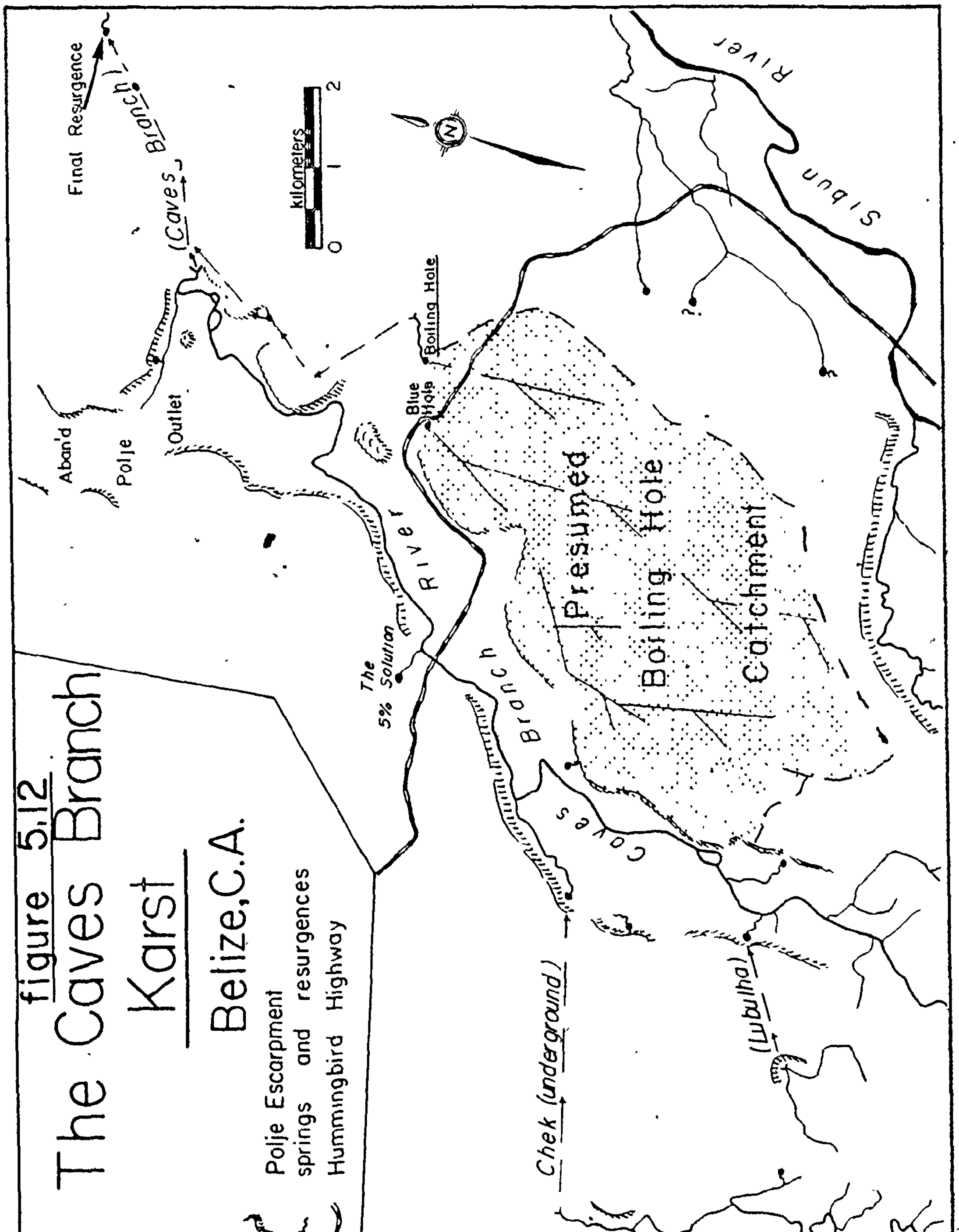


figure 5.12
The Caves Branch Karst
Belize, C.A.

seasons using the Boiling Hole mixing model, and comparing this to the amounts of runoff expected on the basis of area and excess rainfall; and 3) attempting to correlate the differences between expected runoff and that recorded at the Boiling Hole, with the anticipated seasonal base flow loss of the aquifer storage.

1. Separation of Karst Flow from Total Discharge With the mixing model shown to adequately represent the Boiling Hole behavior, it can justifiably be used to separate the authigenic and allogenic discharge components.

As before,

$$Q_B C_B = Q_A C_A + Q_K C_K \qquad (4.3)$$

where $Q_B = Q_A + Q_K$

Using the constant hardness values as calculated (authigenic, or C_K = 187 mg/L; allogenic, or C_A = 22 mg/L) and substituting,

$$Q_B C_B = 22Q_A + 187Q_K.$$

Recombining, $Q_K = (Q_B C_B - 22Q_A) \div 187 \qquad (5.6)$

(and $Q_A = Q_B - Q_K$)

For a given Q_B, the actual Q/TH regression relations are used for more accurate TH estimation:

C_B (1977 dry season) is obtained from 5.3

C_B (1979 dry season) is obtained from 5.4

At flows in excess of 4.5 cumecs, when the Boiling Hole concentration lowered in response to Crooked Bend declines, allogenic discharge was held constant so that the calculated authigenic flows would not show a false drop. The remaining wet season values were fitted to a new regression for the wet season Boiling Hole hardness (C_V, wet season),

$$TH = 80.0 + 37.9Q - 4.51Q^2 \quad [0.9 - 4.5 \text{ cumecs}] \qquad (5.7)$$

with values as before, and R^2 of 0.90, significant at the .01 level. Using the above equations, the amount of authigenic flow (Q_K) was calculated for the 1977 and 1979 seasons.

2. Karst Baseflow Storages The form of a hydrograph in base flow is that of an exponential decay function, representative of withdrawal from a storage reservoir:

$$Q_t = Q_0 e^{-kt} \qquad \text{(5.8, from Burden and Papakis, p. 148, 1963)}$$

where Q_t = instantaneous discharge at elapsed time, t

Q_0 = instantaneous discharge at time t=0

k = recession constant (or slope)

e = base of natural logarithms

Gray (1970, p. 7.7) states "The shape of the curve is independent of variations in rainfall or infiltration, and is essentially dependent upon the physical features of the channel alone." The equation has value in determination of discharges, or time intervals and moments of discharge, if the recession continues uninterrupted by further precipitation. When logarithmically transformed, recession discharges should form a straight line when plotted against time. Linear regression was used on the 1977, 1979 Q_K discharge values of the dry season to calculate the recession slopes (K). The R^2 for each baseflow regression was >0.92, and significant at the .01 confidence level. The calculated K-values for 1977 and 1979 were 4.25×10^{-8} and 9.17×10^{-8}/sec. These are comparable to those of the very large Dumanli Spring in Turkey, which has a baseflow K value of 3.01×10^{-8}/sec (Karanjac and Günay, 1980).

Integration of (5.8) yields the storages contributing to the recession flow:

$$S_t = Q_t/k \qquad (5.9)$$

where S_t = storage in m^3 (above the elevation of the aquifer outlet) at time t

Q_t = instantaneous discharge (cumecs)

k = recession constant (sec^{-1})

Using (5.9), storages at the end of the 1977 and 1979 dry seasons were calculated as 8.1×10^6 and $3.0 \times 10^6 m^3$ for the dry season karst flows of 0.31 cumecs (1977) and 0.29 cumecs (1979). Assuming continuous 4-month dry season recession decline, the initial discharges (Q_0) of Q_k at the end of the previous wet season could be calculated from (5.8), and their storages (S_0) from (5.9). The storages were $12.8 \times 10^6 m^3$ and $7.8 \times 10^6 m^3$ for 1977 and 1979, for initial Q_0 flows of 0.54 cumecs, and 0.72 cumecs. Dry season baseflow losses would be the differences between the storages at the start and end of each year's dry season. Because of the steeper recession curve for 1979, total losses to baseflow for both four month dry season periods were approximately the same -- 4.7-4.8 million m^3 (Table 5.4). If the delay in Boiling Hole response is due primarily to replenishment of aquifer storage losses, these figures should be similar to the difference between expected wet season karst discharge (as determined from area and excess rainfall), and that determined from separation of the authigenic component of recorded stormflow. The latter will be calculated in the following section.

3. <u>Karst Runoff of Indivdual Storms</u> Using (5.8), karst baseflow (recession discharge at the end of the dry season) was calculated and removed from the authigenic component (Q_k) of the Boiling Hole flow for 1977 and 1979. This left only seasonal karst stormflow for each of the wet seasons. The procedure is illustrated in Figure 5.13.

Individual storm-related discharge for each of the 1977 and 1979 wet season storms was determined in a similar fashion (Figure 5.13). For each storm, there were two regimes contributing to total storm flow 1) the rising limb (to peak) of flow beginning after a rainfall event, and ending at the start of recession flow; and 2) the recession flow, generally starting shortly after peak flow was reached -- some recession flow of each storm continued into the time interval of the following storm flows. Using (5.8) this long-term recession discharge of each storm was calculated and removed from the discharge of the following storms. The removal of long term flow was accomplished in a serial fashion -- recession flow of the first storm was removed from all subsequent flows, then recession flow from the second removed from subsequent flows, and so on. Each of the linear regressions used to calculate K from logarithmically-transformed Q_t had correlation coefficients generally in excess of 0.94. All were significant at the .01 significance level. The recessions ranged from 14 to 72 hours in length.

The total flow for each storm was the sum of that occurring in the two flow regimes of each storm. Equation 5.9 was used to determine the storage of the tail of each long-term storm recession, and this was

Separation of Flow Components

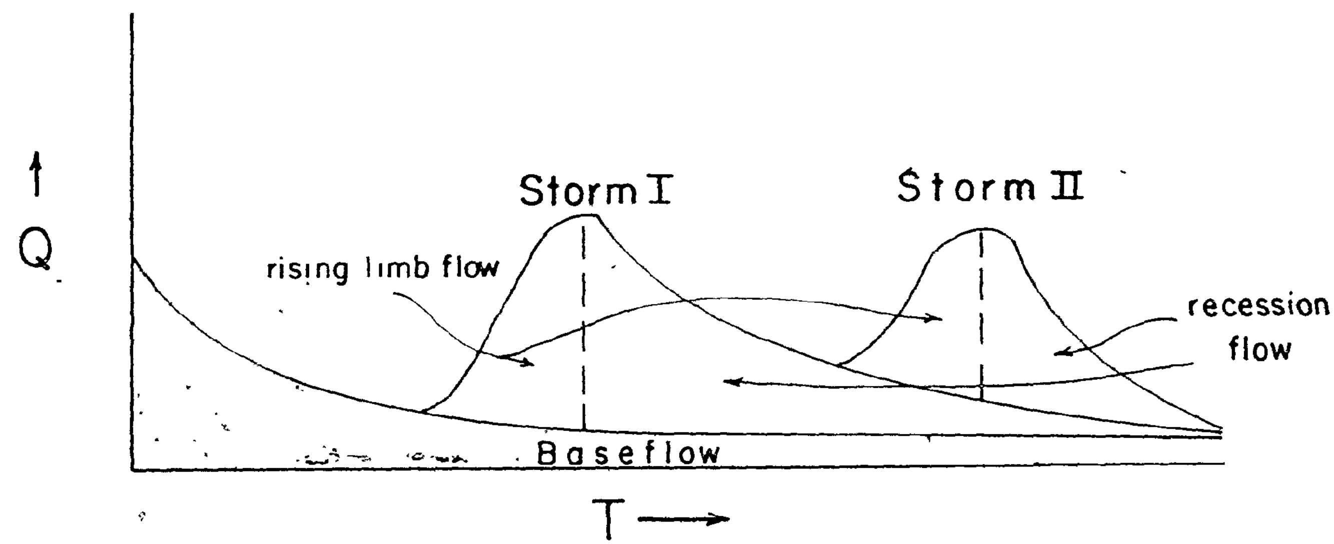


figure 5.13

added to the total storm flow. Total storm-induced flow related to these rain events is shown in Figure 5.14 as recorded runoff.

4. Predicted Storm Runoff

a. Storm Totals With the amount of authigenic flow per wet season storm known at the Boiling Hole, it can be compared with that expected from a consideration of area and excess rainfall. The area used is the 22.3 km^2 figure of Figure 5.12. The calculated soil moisture deficit (SMD) and evapotranspiration (ET) figures of Chapter IV (I.B.) can be subtracted from the measured areal rainfall to give excess rainfall for each of the major rainstorm events of 1977 and 1979. Because the rainfall occurred in discrete storm events of several days duration, inter-storm interference was minimal; daily ET variations were also smoothed out over the longer intervals. The total discharge expected from the rainfall excess is also shown in Figure 5.14, and is compared with that recorded.

Two features are apparent from Figure 5.14; 1) there is a noticeable disparity between the storm runoff totals of the two methods, and 2) this difference decreases rapidly as the season progresses. Excepting the final storm of 1977, the ratios of the methods eventually approach unity. This last storm of 1977 had a recorded runoff only 20% of that expected; it will be considered later.

This is the type of overall response expected as a partially drained storage is replenished during the wet season. Each succeeding storm will result in an outflow closer to that predicted on the basis of area and excess rainfall. Eventually, the two should become essentially equivalent when storage replenishment is completed.

figure 5.14

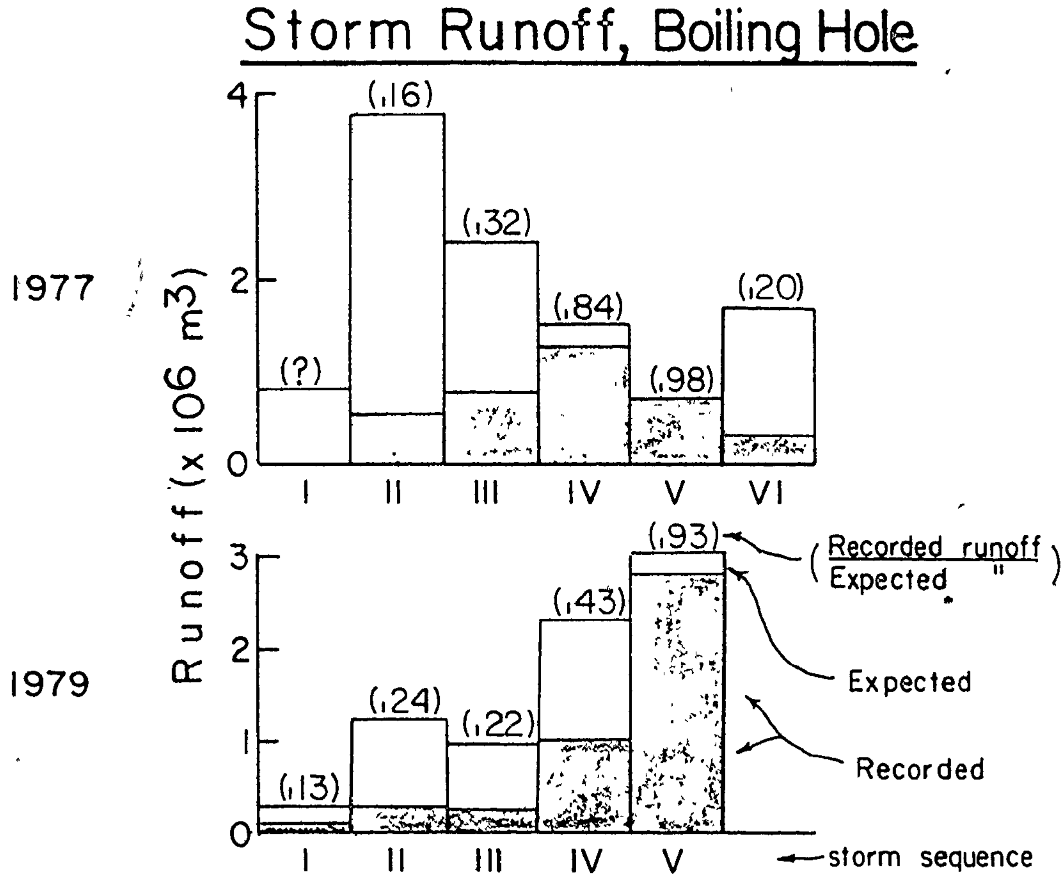


Table 5.4
Storm Runoff Totals

Year	RE	DSB	RR	ER
1977	486	4.7	3.63	10.8
*1977	413	4.7	3.31	9.2
1979	351	4.8	4.35	7.8

RE = rainfall excess (rain-(SMD+ET)), mm
DSB 4 month dry season baseflow (10^6 m^3)
RR recorded karst storm runoff (")
ER expected runoff (RE x area) (")

*without final storm

Of the 11 recorded storm periods of 1977 and 1979, all but the final storm of 1977 are part of this pattern. Because the single automatic rain recorder of 1977 was located at the Boiling Hole, its placement at the northern end of the catchment would not always be representative of precipitation over the entire karst area contributing to the Boiling Hole and flow. As discussed in Chapter IV (I.A.2), although a good relationship was found for daily rainfall totals between the 1979 tipping bucket recorders (R^2 = 0.48), the Se was 11 mm. On one occasion 65 mm of rain was recorded at the Petroglyph gauge and only 16 mm at the Boiling Hole. It is entirely possible that the final storm event of the 1977 field season was either a thunderstorm localized at the Boiling Hole, or the edge of a passing storm. If this one storm of the 11 recorded is eliminated, the expected discharges for both years (on the basis of excess rainfall and area) differ by only 15% from the sums of the calculated authigenic runoff and the four-month estimated aquifer storage loss (Table 5.4).

b. Predicted Hourly Discharge Figure 5.14 and Table 5.4 demonstrate the relation of the karst out-flow recorded at the Boiling Hole, to that expected from rainfall, on time scales equivalent to that of an entire storm interval. An attempt was made to compare the two on a finer-resolution scale of an hour.

Some of the recorded 1977 and 1979 storms displayed more than one recession regime during the periods following peak karst flow. Nineteen recession slopes (k-values) were derived for the 11 storms. These k-values appeared to be associated with a given range of flow: steeper slopes were associated with the highest recession discharges of the bigger storms, then shallower slopes when the discharge had declined to lower levels. The initial discharges of the recessions (Q_0) were correlated with the recession constants (k);

$$Q_0 = 345000k \qquad (5.10)$$

with R^2 of 0.68, and a significance level > .01

The reason for the flow range/recession slope relation is apparently due to inhomogeneities in permeability, size, and other physical characteristics within the aquifer: as runoff invades or abandons portions of the karst reservoir, its mean response alters.

With elimination of the two much larger baseflow storages, the remaining storm Q_0 and the associated S_0 (as calculated from 5.9) were also found to be correlated, with $R^2 = 0.45$, at the .01 significance level:

$$Q_0 = 6.93 \times 10^{-6} (S_0) \qquad (5.11)$$

Using 5.11, an hourly instantaneous flow could be calculated by assuming that surface runoff (rain - (ET + SMD)) passed immediately into the karst aquifer as storage. To allow for the travel time required between runoff into the aquifer and actual outlet at the Boiling Hole, a cross-correlation of bi-hourly rainfall and Boiling Hole discharge was done; statistically significant correlation between the two ($r > 0.17$) did not occur until 8 hours after the initiating precipitation. Accordingly, discharge was lagged by 8 hours,

$$Q_t = 6.93 \times 10^{-6} (S_{t-8}) \qquad (5.12)$$

The expected hourly streamflow resulting from the above method is compared with the actual karst outflow as calculated from the mixing model, in Figure 5.15. The 1977 field season was chosen because there are a number of storms scattered throughout the season, rather than the very large storms that are clustered at the end of the 1979 field season.

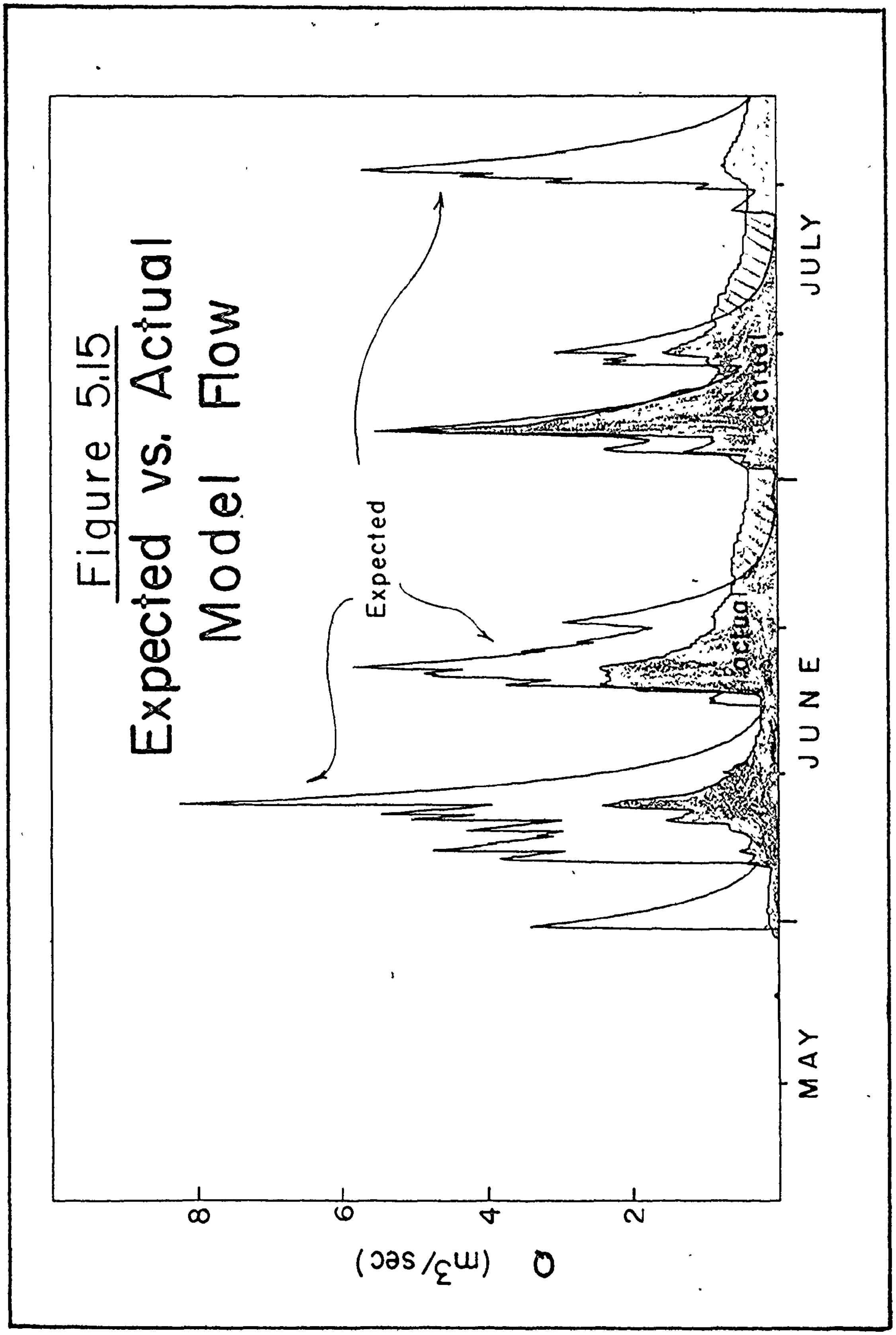


Figure 5.15
Expected vs. Actual Model Flow

Figure 5.15 shows essentially the same pattern as Figure 5.14. There is increasing similarity of response to the same rainfall events as the season progresses, with the exception of the final storm. Use of Equation 5.12 exaggerates the rapidity of decline of storm-induced runoff for the predicted flow (actual recession flow at the lower discharge ranges shows much shallower recession slopes than expected), and has the effect of overpredicting the magnitude of discharge during the immediate flood response period. Most of the individual rain events are indentifiable in the figure, but scaling effects make this difficult in many instances. These effects are presumably the result of the complex interferences between closely-occurring rain events within the body of the aquifer (e.g. some routes may be more efficient at runoff transport than others), as well as effects due to the inhomogeneities of storage replenishment. Figure 5.15 is not intended as proof of the storage replenishment hypothesis, but as an illustration of the preceding discussion in this chapter on a somewhat finer time scale.

5. Summary of Section B

The annual lag of Boiling Hole discharge response to the beginning of wet season rainfall (noted in all three field seasons) appears to be well explained by delay related to replenishment of a large storage aquifer depleted by dry season baseflow. This is supported by both hydrochemical and hydrological evidence. As demonstrated by the Boiling Hole mixing model earlier in the chapter, major discharges are due to influxes of high hardness authigenic flow into the conduit feeding the Boiling Hole Resurgence. These authigenic discharges occur only following periods of major rainfall on the karst surface near the Boiling Hole. The unitary baseflow discharge of the non-carbonate Caves Branch River catchment is only half that of the karst outflow that contributes to the Boiling Hole, in spite of the higher rainfall; the Caves Branch River also shows a nearly immediate response to wet season rainfall, with little or no lag. This is consistent with the much larger storage capacity that would presumably be present in the cavernous limestone.

Response at the Boiling Hole for a given amount of rainfall increases throughout the wet season, until recorded authigenic outflow is equivalent to the amount of runoff expected simply on the basis of area and rainfall excess; e.g. excess rainfall decreased from the 2nd to 4th rainstorms of 1977, but recorded karst runoff actually increased with each storm. The final storm of 1977 (of 11 total for both years) did not follow this pattern, but this can be logically explained by rainfall variability within the area. Disregarding this final storm, the sum of the recorded karst runoff and that expected to occur as baseflow recession during the dry season, approximate to within 15% the outflow expected from area and excess runoff. The lagged runoff of the aquifer, which becomes increasingly responsive as the wet season progresses, is presumably explained by progressive replenishment of storage lost during dry season outflow.

Although the aquifer replenishment hypothesis works well, some unexplained variation occurs: in 1977, recorded runoff (including dry season flow) was $10^6 m^3$ less than expected; in 1979 it was $10^6 m^3$ more than expected. The fact that the ratio of the recorded/expected outflows reaches unity is encouraging, but field season operations always had to be interrupted before the end of the wet season -- the ratio may eventually exceed unity if, for example, the actual karst catchment area is greater than anticipated, and the observations are allowed to run full course. More accurate prediction of runoff on shorter time scales (e.g. hourly or bi-hourly) would be possible with a greater number of rain gauges, more advantageously placed, as well as better evapotranspiration determination. It would then be possible to determine a "coefficient of effective runoff" -- numerous researchers (e.g. Jennings, 1971, p. 66-67; Fish, 1978) have reported a damping effect upon evaporation caused by runoff into shielded karst interiors: this would affect calculation of the actual karst catchment area. Finally, without longer-term data, estimates of dry season conditions are imprecise, and replenishment (if any) occurring during that season can only be guessed.

III. The Aquifer Interior

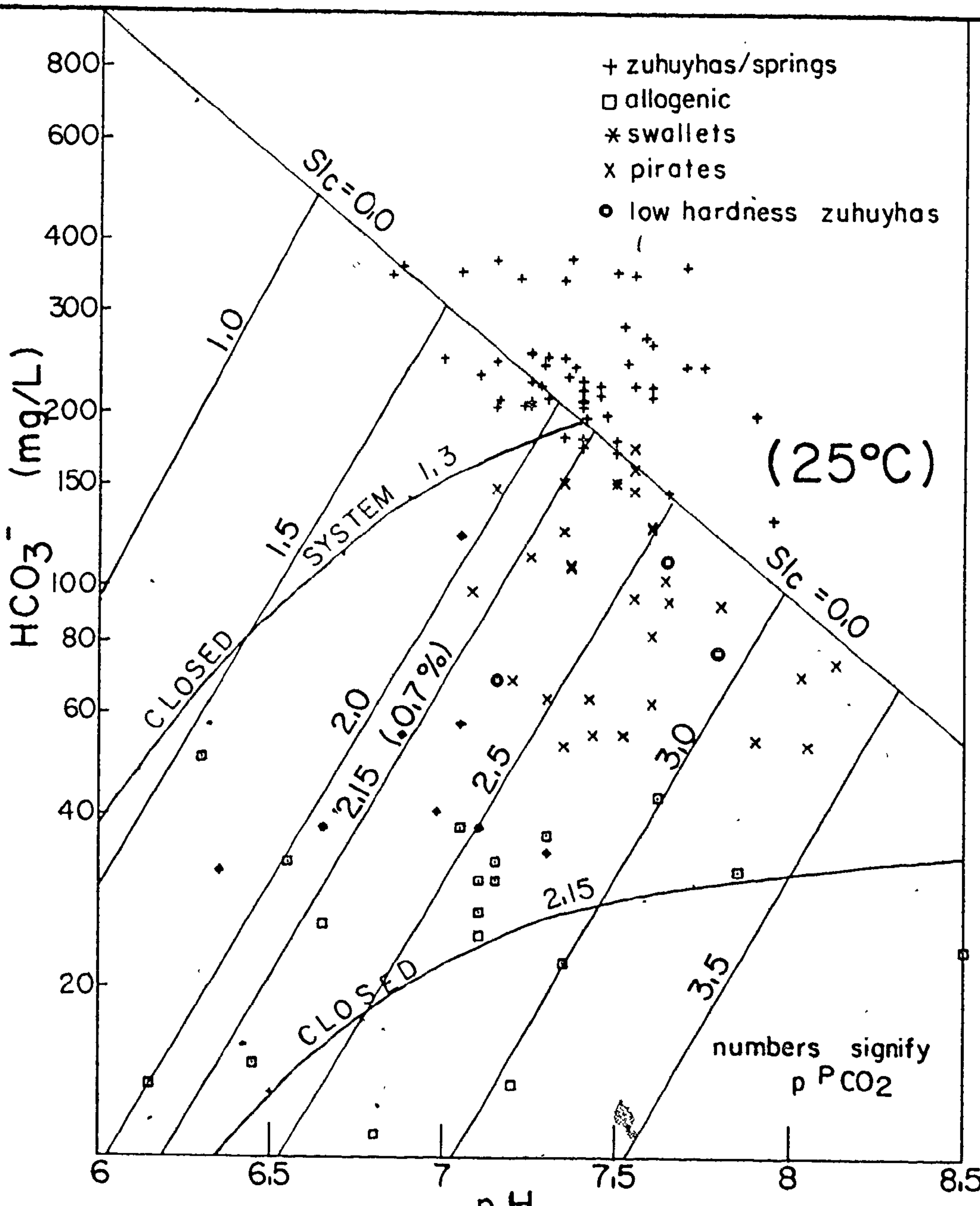
The previous chapter outlined general controls upon solution in the Caves Branch karst. Considered with study of the behavior of the Boiling Hole spring, they can provide some indication of the interior of the karst that is presently inaccessible.

Direct physical evidence is difficult to obtain. Only one zuhuyha (Figure 3.8) has been penetrated for any appreciable distance. It consisted of a collector network, integrating at least four discrete inputs to produce the single outflow debouching into the master conduit. This is the type of pattern expected if the numerous swallets and crevices of the surface produce the far fewer karst springs and zuhuyhas feeding the trunk caves.

A. Evolutionary Calcite Solution Paths

Internally, most of the resurging zuhuyha water appears to have evolved under predominately open system conditions. Figure 5.16 shows several water groups plotted on an evolutionary solution diagram. As previously discussed, soil CO_2 levels in the karst (as opposed to the polje soils) average 0.7%. The diagram shows both the "open" and "closed" evolution paths of a water in equilibrium with this given initial soil P_{CO_2}. It is obvious that the majority of zuhuyha (i.e. saturated, equilibrated) samples still lie left of this line, indicating equilibration with higher CO_2 pressures. Indeed, the mean P_{CO_2} of these waters is 1.1%, considerably higher. The method used in measuring the soil CO_2, gives values comparable to those measured in other areas, with varying climates. Readings in the karst soils can be taken to the bottom of the CO_2-producing layer because of the thin soils. These values are broadly correlable with the P_{CO_2} of surface water samples (Table 4.6c), indicating their relevancy. Soil profiles and occurrence of soil in the karst do not indicate any major areal variations in CO_2 production levels. Because the surface soil CO_2 and cavern spring P_{CO_2} differences cannot be explained by logical surface variations in CO_2 it appears likely that some significant production must occur within the aquifer itself. This is a conclusion shared by Atkinson (1975) in work in England, Fish (1978) in Mexico, and James (1977) in Australia. The latter author particularly has studied the problem of CO_2 in caves, concluding it is most likely in tropical caves, and that caves subject to periodic flooding followed by long low-water periods are most susceptible to high CO_2 levels. James quotes other research to the effect that multi-entrance cave systems below a plateau are ideal as well; the Caves Branch meets all of the above criteria.

Referring again to Figure 5.16, two evolutionary paths are



Evolutionary Calcite Solution Paths

Figure 5.16

apparent -- most allogenic waters, continuing to move in well-ventilated conduit environments after piracy, follow "closed system" paths apparently through de-gassing, while the slightly harder of these, more influenced by karst inputs, lie on the swallet to zuhuyha path, a route of increasing P_{CO_2}. Atkinson, Fish, and James, suggest decay of washed-in vegetal debris as a source for the presumed intra-aquifer CO_2 production, and certainly in the Caves Branch some accessible caves contain large quantities. A closed system evolution leading to a 1.1% P_{CO_2} at saturation must have an initial P_{CO_2} in excess of 4-5%. Because this is so much higher than recorded soil or cave atmospheric CO_2, it is probable that the Caves Branch karst waters undergo both open system evolution as well as internal CO_2 production.

The essential homogeneity of the aquifer is indicated by the relatively tight grouping of chemical properties of the zuhuyhas and the placement of nearly all sampled cavern inputs in the open system category. There are some minor exceptions indicating local differences. The low-hardness zuhuyhas appear to follow a closed evolution path through at least part of their course and possibly have a somewhat greater solute concentration variability than other springs. Such traits could be due to early union of swallet origin waters with the trunk conduits. Short residence times would inhibit equilibration with the CO_2 of the karst interior, and consequent low hardnesses would result. Stalactite drips also have a tendency to be lower in P_{CO_2} and hardness than zuhuyhas and springs. Coupled with their low flows, it probably indicates a general origin in less integrated, possibly non-swallet sites (e.g. hilltops), with slow vertical migration abruptly terminated by intersection with the cavern passages.

B. Network Independence

Although broadly homogeneous in porosity and other physical properties, the aquifer, as evidenced by the numerous zuhuyhas, is composed of many independently integrated flow networks, the largest being that of Crooked Bend. The responses of these separate drainages are surprisingly similar (Figure 5.8) -- although the Petroglyph conduit flow is doubled by addition of the Crooked Bend input, the union as expressed by the Boiling Hole hydrograph is essentially a carbon-copy of the Petroglyph hydrograph. Cross-correlation of the two hydrographs confirms this near-perfect agreement in timing.

The behavior of Crooked Bend Zuhuyha is anomalous. As noted earlier, during nearly all periods of sampling it exhibited the relatively stable characteristics of diffuse flow. In the final storms of the 1979 field season (which were the most severe of all three field seasons), total hardness dropped to a low of 125 mg/L from a previous high of 211 mg/L. The P_{CO_2} also dropped, to .47%, much lower than that of most zuhuyhas, and more similar to that of ephemeral surface flow. This drop in hardness and P_{CO_2} is only temporary; when the storm peaks have passed, the Crooked Bend flow begins to return to previous levels. The behavior probably indicates a relatively better developed integration with swallets than most other zuhuyhas. In times of excessively high rain input, concentrated low hardness swallet water overwhelms the diffuse flow component, and is able to pass through the aquifer quickly enough to avoid saturation.

C. Storage and Porosity

As estimated in the previous section, total storage of the Boiling Hole karst aquifer at the end of the wet season is on the order of

$8 - 11 \times 10^6 m^3$. When major rainstorms of 100 mm/day occur (as in 1979), and outflow at a daily maximum mean of 7-8 cumecs can only remove a third of the input total, short term storage additions of at least another 1.5 million m^3 can be expected. Topographic profiles of the area indicate a mean aquifer thickness of about 100 meters above the level of the Boiling Hole spring, or a rock volume of $2.2 \times 10^9 m^3$. Maximum storage estimates of $9.5 - 14.5 \times 10^6 m^3$ would give porosity estimates of 0.45-0.66%. These are minimum estimates as most of the karst remains air-filled, and there are perhaps water-filled reservoirs not integrated into any drainage system. Exploration in non-trunk conduit caves in the karst interior finds no evidence of flooding at elevations greater than 15-20 m above presumed base level. If it is logical to assume that the apparently rapid passage of storm runoff through the upper section of the karst indicates a greater porosity in that area, and that most of the storage porosity of the aquifer is concentrated near the bottom, actual porosity is probably at least 2-3%. Estimates made in other limestone areas are not common -- Atkinson (1977) quotes a figure of about 1% for a karst in England and Tobarov (1976) gives an example calculated at 1-1.5% and 3-3.5% for two segments of a Yugoslav karst. Permeability cannot at present be estimated for the internal karst as there is no piezometric well level data. The volume of the trunk conduits is unlikely to be characteristic of the remainder of the Boiling Hole aquifer, but indicates the potential volume of caverns in the area: with a measured length of at least 7 kilometers, and cross-sectional area of at least $150 m^2$, their volume alone would add an additional one million m^3 to the total.

The hydrologic evidence supporting the model of a relatively porous, integrated aquifer, essentially "conduit", is somewhat at variance with the chemical evidence of a diffuse flow, equilibrated system. This is apparently a result of the large storage capacity of the karst. Total outflow measured for the 1977, 1979 field seasons was 3.6 X 10^6 and 4.4 X 10^6 m^3 respectively, which is still considerably short of replacement of the estimated 10-13 million m^3 of storage. The flow recorded during storms, then, is runoff that has probably entered the aquifer perhaps 5-6 months previously (with the exception, apparently, of those quick flow-through swallet waters sampled at Crooked Bend in the height of severe flooding). The effluxes of the Caves Branch karst, are conduits which have all the chemical characteristics of diffuse flow -- the zuhuyhas. Excess rain runoff enters a queue of water slowly equilibrating over a period of some months under the open system conditions prevailing in the relatively porous aquifer. High flow conditions follow early wet season replenishment of the storage, when storm pulses force out the saturated interior waters.

IV. Conceptual Model of Water Evolution in the Caves Branch

In the preceding chapter, a discrimination analysis was performed on water samples that been assigned to six classes on the basis of morphologic characteristics. The analysis tested the validity of the priori classification, and classified over 200 additional samples on the basis of the initial assignment and discrimination. These latter water samples and their categorization will be discussed with reference to the other findings of this chapter.

Samples from eleven water types were assigned to one or more of the six original classes; this matrix is shown in Table 5.5. Generally, most

TABLE 5.5

Classification Matrix of Ungrouped Water Classes

Actual	Assigned 1	2	3	4	5	6	Total
7 Low Hardness Springs						3	3
8 Unmonitored Springs and Zuhuyhas		7			6		13
9 Lower Caves Branch River					1	6	7
10 Caves Branch R. at Bridge			3			23	26
11 Upper-and Dry Season Conduits			1			20	21
12 Wet Season Conduits		2		4	12	2	22
13 Other Maya Mtn. Source Waters	6		1	1			8
14 Miscellaneous Streams				2		7	9
15 Miscellaneous		1	2		3	4	10

1) allogenic
2) zuhuyha/spring
3) swallet
4) Karstflow
5) stalactite
6) pirate

Note: these classifications were made using HCO_3^- and pH as the discriminating variables. The six assignment classes are those of Table 4.11.

samples of the 11 types were assigned to only two of the six possible classes. The variables used for the discrimination and classification were log HCO_3^-(as mg/L $CaCO_3$) and pH. SI_c and log P_{CO_2} gave virtually the same results as these two variables.

From the table, it is apparent that Boiling Hole water samples are nearly all assigned to either the pirate or zuhuyha/spring classes. A time series plot would show that this two-fold classification is seasonal: dry season period samples are classed as pirate (when the proportions of allogenic and authigenic flow are mostly nearly equal), and wet season samples are classed as zuhuyha/spring flow. These results are expected from the research outlined earlier in this chapter.

A similar result is obtained from the classification of samples taken in the trunk conduits. These samples obtained in the upper sections of the conduits or in the dry season are almost exclusively classified as piratic; those collected in the wet season are closest in character to the authigenic waters, expected as karst efflux to the conduits reaches its peak in that season.

It is interesting to note that low-hardness zuhuyhas are classified as pirates, even though such an origin is excluded by the locations in which they are found. They are almost certainly of swallet origin, although lower in P_{CO_2} than most swallet or zuhuyha waters. They may represent swallet water of low soil CO_2 source that because of early union with conduits was unable to equilibrate with the normally high P_{CO_2} found within the aquifer.

Most of the other water groups are classified as expected. Samples taken of the Cayes Branch River, an allogenic stream progressively altered along its course by additions of authigenic water, are primarily classified as piratic; allogenic streams of the Maya Mountains are placed mostly in the same category as the allogenic water of the upper Caves Branch polje; and water from non-pirate cavern sources that were only sampled once, were classed as either zuhuyha/springs or stalactite drips.

The information obtained from the investigation into the aquifer feeding the Boiling Hole, as well as the results of the discrimination analysis and the classification of water samples are combined in Figure 5.17. This is a flowchart illustrating the hydrologic routes of the waters of the Caves Branch catchment, as well as the influences upon the hydrochemistry caused by the loss or addition of CO_2. The most basic factor in the chemical evolution of the local runoff is whether or not it passes into the karst aquifer storage. Such runoff is not only presumably protected against further ET loss, but receives both a boost in P_{CO_2} and a delay in flow that allows it to achieve saturation at high levels of dissolved mineral concentration. This storage influence is considered further in the following chapter.

IV. Summary

Solution of mixing model and mass balance equations appears to have been reasonably successful in interpreting the internal environment of a major, inaccessible portion of the Caves Branch karst. This has enabled explanation of the anomalous positive Q/TH behavior of a large trunk conduit spring in the local area, and is encouraging in its potential of usage in other karst areas.

The Boiling Hole resurgence spring shows distinct seasonal relationships. It is undersaturated with respect to calcite, has low P_{CO_2}, and low TH in the dry season; in the wet season its saturation, P_{CO_2}, and low

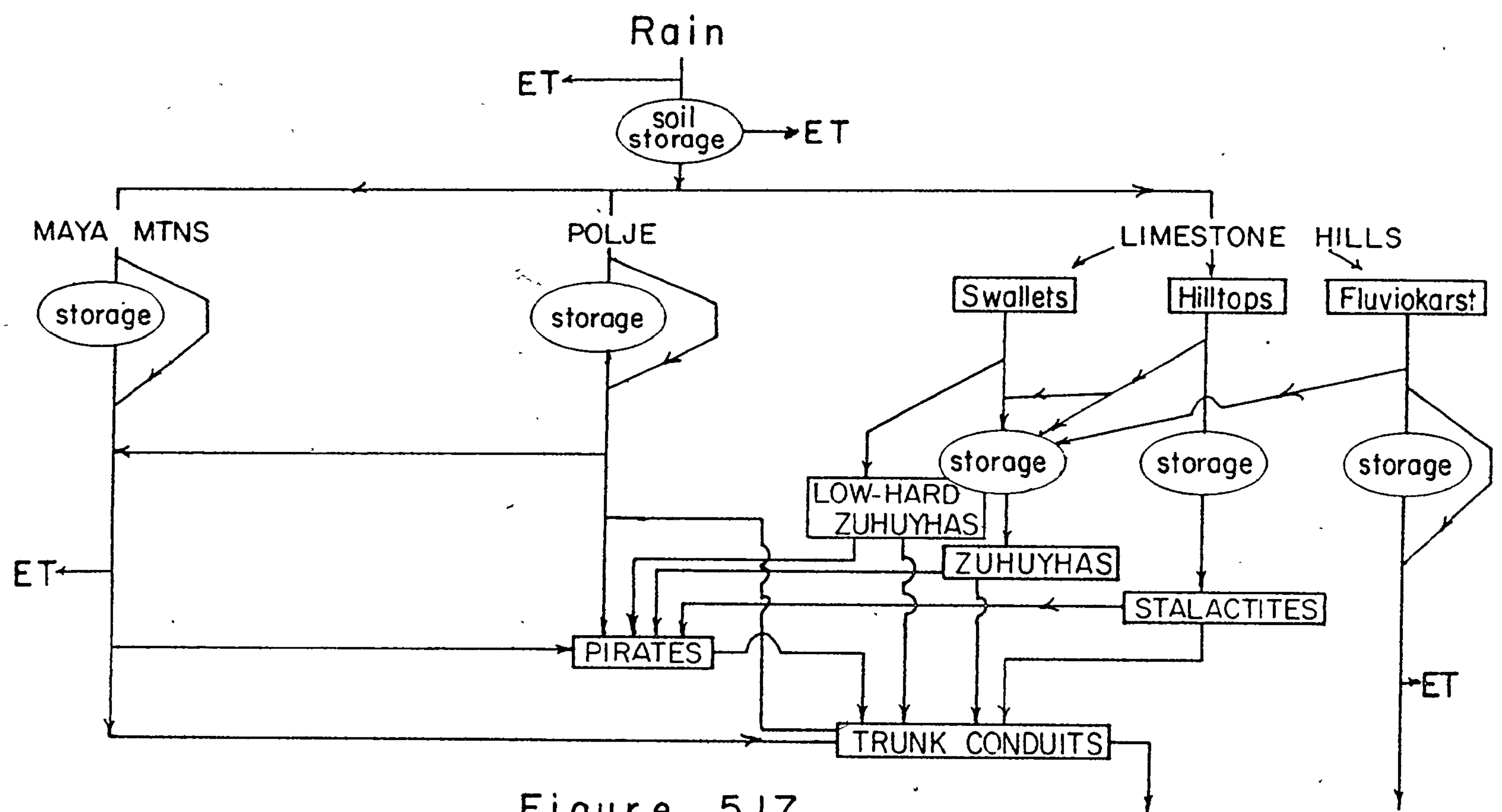


Figure 5.17

Hydrologic Routing, Caves Branch

TH increase dramatically, and in addition its temperature lowers and its chemical loading curve (TH/Q) switches from a normal inverse, to a rare positive correlation. These changes become more pronounced during the higher discharges associated with storms.

Physical investigation of inlet passages contributing discharge to the trunk conduit upstream of the Boiling Hole was made and numerous discharge data were collected from individual samples and two stage recorders. The hydrochemistry, hydrology, and physical morphology of two distinct types of trunk conduit inputs (zuhuyha/springs, and pirating channels), led to the conclusion that the Boiling Hole behavior could be best explained by a two-component mixing model where a hydraulically restricted allogenic (i.e. piratic) source combines with authigenic water responsive only to storm discharge influxes. The quantitative expression of the model was based on actual discharge and chemical sampling of the upstream sources of the Boiling Hole. The recorded TH for a given Q at the Boiling Hole was found to agree very well in both dry and wet seasons with that predicted from the model. Major variances between the mixing model and observed TH for a given Q were shown to caused largely by 1) a change in the flow regime of a major zuhuyha contributor, 2) backflooding during extreme discharge events and 3) intra-storm Q/TH hysteresis.

With the success of the model as justification, karst discharge of the aquifer (as calculated from the model) was compared with flow expected purely on hydrologic considerations of area, rainfall, evapotranspiration, and soil moisture deficit. Major disparities between the two were coincident with a noticeable delay between the onset of wet season rain storms, and the corresponding discharge and chemical response at the Boiling Hole. Amounts of rain occurring in this lag period were similar (240-270 mm) in both 1977 and 1979, and too large to be explained by SMD and ET. In both summers, each storm in this lag period also showed a progressively more positive response at the Boiling Hole. Expected and recorded outflow ratios ultimately approached unity. Most of these differences between expected and actual rainfall were readily explainable on the basis of expected aquifer storage losses to baseflow during the four month dry season, when recharge would be minimal. Total storage is indicated to be at least 9.5 - 14.5 X $10^6 m^3$.

The above investigations were used to estimate the porosity of the aquifer to be at minimum 0.5 - 0.7%, and probably at least 2 - 3%. This relatively large porosity is apparently corroborated by hydrochemical evidence that most of the water passing through the aquifer appears to have undergone evolution in open system conditions. A factor in this type of investigation (which uses calculation of expected open/closed calcite evolutionary paths) is that some considerable production of CO_2 appears to occur within the body of the aquifer, below the soil production zone. Resurging zuhuyha and spring waters have a mean P_{CO_2} of 1.1% (with extremes to 5%), higher than measured soil CO_2 in the overlying cockpits (0.7%), this CO_2 increase perhaps creates an impression of greater open system evolution than is the actual case.

The large storage capacity of the aquifer has a profound influence upon surface runoff entering the karst because it retards flow for perhaps several months. This delay allows equilibrating solutions to reach saturation or supersaturation with respect to calcite. The large storage and porosity also enhance solutional potential both by appearing to provide an optimal environment for decay of washed-in vegetal debris and consequent increase of P_{CO_2}, and by allowing solution of calcite along open system evolutionary paths.

CHAPTER VI

CARBONATE SOLUTION IN THE CAVES BRANCH

One of the chief results of the Caves Branch research lies in its contribution to the volume of data recently accumulating concerning solution in tropical karsts. The hydrochemical samples from the study area form one of the larger sets from a perennially warm climate. Using them, a variety of hypotheses concerning location and time constraints can be tested more confidently in climates differing from the temperate areas where they were constructed originally. Tropical areas may perhaps have the majority of known karst terranes, and as discussed in chapters two and three appear to possess some unique physical karst forms. It is an unfortunate oversight that so little quantitative process data has been collected there in the past.

I. Local and Regional Solution Controls

A. Solute Concentration An unsettled controversy in karst hydrochemistry concerns relative and total amounts of solution and denudation vís-a-vís climatic location. This is of importance primarily in its relation to discussion of landform development -- whether apparent differences in karst landforms (e.g. cockpit karst) between temperate and tropical areas can be attributed to fundamental differences in solution intensity, location, etc. A first approach was that of Corbel (1954, 1959) whose data suggested that the inverse temperature dependence of CO_2 solubility in water was responsible for a decrease in solute concentration from arctic/alpine areas through temperate to tropical. Later researchers acquired values suggesting doubt as to the reliability both of Corbel's data and his main tenet (Sweeting, 1964; Pulina, 1971 in Drake and Wigley, 1975). Harmon et al. (1975) collected North American samples suggesting a positive correlation between temperature (and by extension, climate) and solute concentrations. They explained this function for samples from Canada, the U.S., and Mexico as due to greater CO_2 production in progressively warmer soils; they then derived a supporting equation relating aqueous P_{CO_2} to regional climate (mean temperatures). Conversely, however, later researchers (Smith and Atkinson, 1976; and Drake, 1980) have cited data showing temperate, coolers regions to have generally higher TH/HCO_3^- concentrations than tropical, warmer, areas. Drake, and Drake and Wigley (1975) used the different approach of open/closed equilibrium system evolution to reconcile observed P_{CO_2} and solute variations. Drake and Wigley suggested that measured soil CO_2 flux and production, and Harmon et al.'s temperature/water P_{CO_2} relation, could be explained if closed system evolution was predominent in North American karst terrains. Drake (1980) has been the latest of a number of researchers (e.g. Williams, 1964; Trainer and Heath, 1976) to argue that the apparently higher solute concentrations in cooler (e.g. temperate areas) are the product of open system evolution encouraged by glacial replenishment of carbonate sources in surface tills. Drake explained exceptions as due to overriding local hydrogeologic conditions in individual small environments.

It is noted that most of those approaching the regional problem acknowledge the influence of factors other than climatic variables.

Trainer and Heath and Harmon et al. for example summarize these as 1) hydrogeologic effects and 2) short-term and seasonal variations in flow patterns, volumes, and external conditions (both stochastic and systematic). Some of the conflicting conclusions concerning solute concentrations and their explanations derive both from the use of different data sets and sources, and the assumptions made concerning their use. Harmon et al. (1975), Drake and Wigley (1975), and Drake (1980) all discuss the importance of eliminating kinetic/dynamic factors of carbonate solution in regional scale analysis by restricting consideration to saturated, diffuse-flow springs (as identified by Shuster and White, 1971) or to some other consistent hydrologic criteria. Fish (1978), however, has criticized the results of Harmon et al. because of errors in logic made in this type of segregation. Smith and Atkinson (1976) lumped their many worldwide samples of river and spring waters together: this would have the effect of obscuring regional differences because rivers within karst areas are frequently undersaturated and have solute values easily reached in most areas regardless of P_{CO_2} contribution available.

In spite of Harmon et al.'s (1975) findings for North America, the aggregate of recent data for karst areas generally supports a conclusion that somewhat higher solute concentrations are recorded from temperate, as opposed to tropical or arctic/alpine areas. As mentioned above, Fish (1978) attributes the temperature/solute relation to errors of inclusion of non-carbonate Mexican springs with high sulphate contents, and inclusion of Appalachian springs not necessarily of diffuse origin. The data cited by others (Brook, 1976; Trainer and Heath, 1976; Pitman, 1978; Fish, 1978; Giusti, 1978; Miller, 1979; Cowell and Ford, 1980; Drake, 1980), and this thesis, complement Smith and Atkinson's general conclusion that tropical and sub-tropical areas generally have lower mean hardnesses. This is with the exception of arctic/alpine areas which are explained as having inhibited solution from low CO_2 production due to thin soils, cold temperatures, and short growing seasons.

As noted, Drake and Wigley (1975), Drake (1980), and Drake and Ford (1980) use Harmon et al.'s data to argue that open/closed equilibrium system models can generally explain the regional/climatic solute differences. The foundations of the Drake/Wigley model (Drake, 1980) are 1) the acceptance of the temperature/P_{CO_2} relation of Harmon et al., and 2) the assumption that soil CO_2 production (and hence water-equilibrated P_{CO_2}) is markedly higher in tropical areas.

Cowell (1976), Brook (1976) and Fish (1978) have re-assessed the first assumption, and Figure 6.1 is thus a fourth-generation plot with more recent information added from South Dakota, Puerto Rico, New Guinea, and Belize. It is obvious that there is still a significant, positive relation between P_{CO_2} and temperature. However, the strength of the relationship is slightly less and the intercept and slope of the regression equation is changed. A higher P_{CO_2} is now expected for cooler areas, and lower for tropical areas. Because the slope is less, there is also a smaller difference between the expected end-members.

Smith and Atkinson (op. cit.) attempted to test the second assumption, that tropical soils have significantly higher CO_2 concentrations than temperate soils. They arrived at tentative values of 2% for the tropics and 1% for cooler areas. Because most data on soil CO_2 has in the past been collected in non-karst, non-limestone areas, their data has a serious bias. Karst soils are universally acknowledged to be generally thinner than other

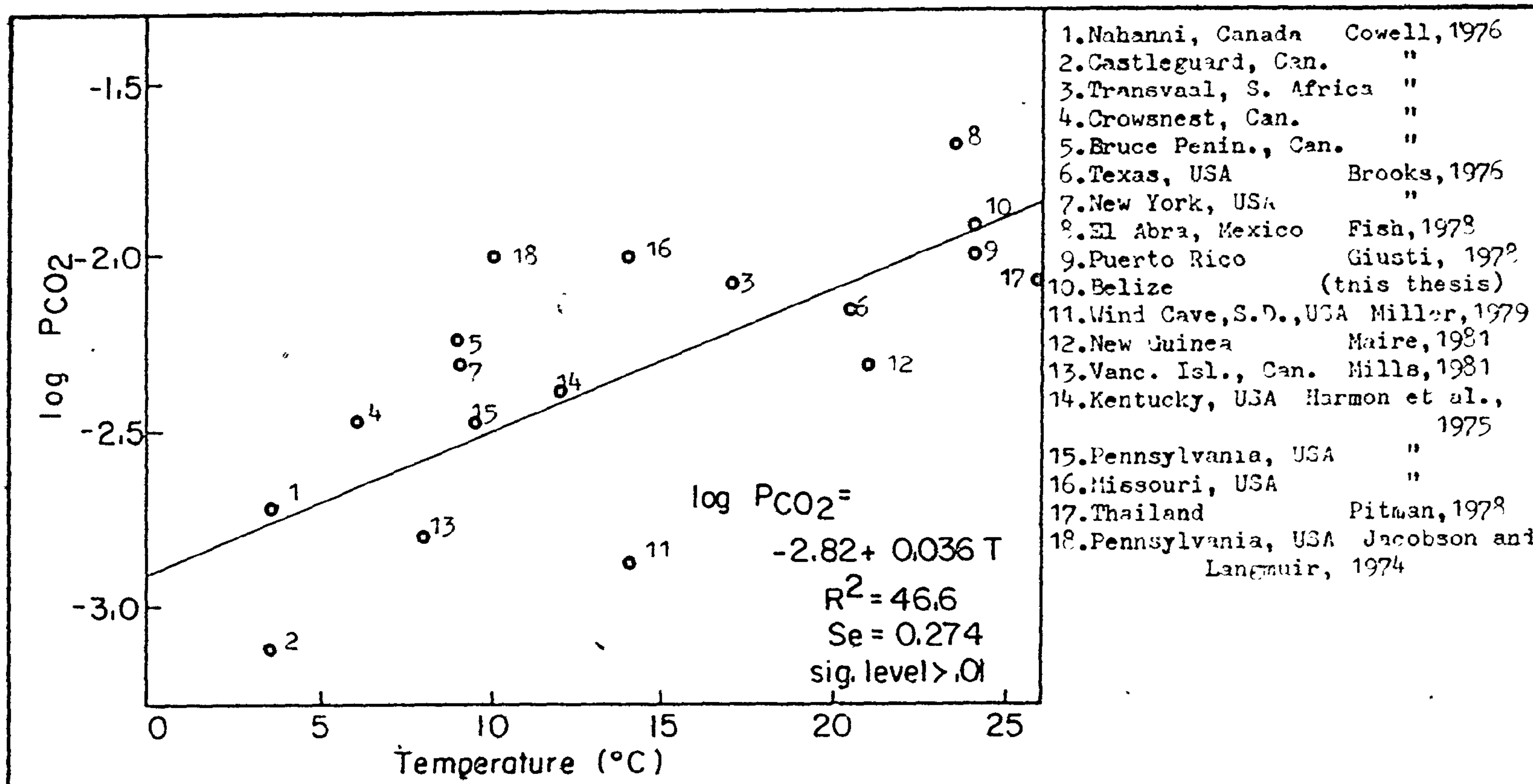


Figure 6.1

P_{CO_2}/Temperature Relations of Various Karst Areas soils, especially the economically interesting types of agricultural soils where CO_2 testing has been concentrated. Some of these quoted tropical readings, such as Vine and Hardy (1943) are from cacao plantations, for example, and in addition, these are cultivated soils where production would likely be artificially maintained at a maximum. Table 6.1 shows CO_2 concentrations measured in tropical, limestone soils, and compares these with readings quoted in the past, from non-limestone tropical soils. The readings from the limestone soils are not significantly different from the temperate mean found by Smith and Atkinson. It is obvious that the thin-soiled karsts of tropical, limestone soils are incapable, even in optimum wet season conditions, of producing the 6% P_{CO_2} predicted in the D-W model. As previously noted in Chapter 4, at higher temperatures, especially in the minimal ranges of the tropics, moisture and rainfall are more important than temperature in encouraging CO_2 production. If there is little or no change in the dependent function (CO_2) with change in temperature, this has implications for conclusions based upon the substitution of temperature for P_{CO_2} in situations where the actual pH measurement of a sample is lacking.

Drake and Ford (1980) have shown a good relationship between the type of equilbrium evolution system (open or closed) predicted on the basis of recent carbonate till replenishment, and that appearing to be demonstrated by consideration of total hardness/P_{CO_2} endpoints (where the latter has been calculated entirely from temperature using the D-W model). At least two tropical areas cited fitting the model, however, are apparently open systems. The Caves Branch is one. Table 6.1a shows soil CO_2 samples collected from the other at the southern end of the El Abra, Mexico, where

TABLE 6.1

P_{CO_2} of Some Tropical Limestone Soils

Location	Min (%)	Max (%)	Mean (%)	Reference	Remarks
Sulawesi	0.20	2.0	0.9	McDonald, 1976	hillslopes on limestone (ls)
"	2.6	6.0		"	soils in plains
Thailand	1.9	3.2		Pitman, 1978	limestone soils in plains
Jamaica	.6	3.6		Jennings, 1971	varied soil types
"	.3	3.0		Nicholson and Nicholson, 1969	ls soils
"	.05	1.2		Trudgill, 1976	ls soils, varied types
"	.04	5.4		Day, 1978	large depressions (slope < 20°)
"	.07	4.5		"	cockpits and depression slopes > 20°
Puerto Rico	.9	1.3		Miotke, 1974	mogote slopes
"	1.5	7.0		"	plains, glades
El Abra, Mexico	.2	.92	.64	see below	see below (soil pockets excluded)
Belize	.29	1.40	.70	this thesis	cockpit soils
"	.2	6.7	1.45	"	glades, polje soils
New Britain			.45	Maire, 1981	ls soils, 40 cm depth

TABLE 6.1a

Soil CO_2, El Abra Mexico (Feb. - Mar., 1981)

depth (cm)	% CO_2	remarks
18	0.5	Llano Trinidad
18	.84	"
10	.2	Llano Trinidad
18	.92	forest soil
22	.72	"
	.40	soil pocket
	.1	"
	.015	atmospheric

Fish (1978) quotes mean P_{CO_2} for resurging saturated springs as at least 2%. The soil samples, however, have a P_{CO_2} range of only 0.20-0.92% -- although for this latitude they would normally be in a dry season phase, they were collected from a perennially moist cloud-forest environment in the wettest portion of the El Abra, during a period of occasional rainfall. The El Abra would also appear likely to be a system of open system evolution. A third area, Puerto Rico (Giusti, 1978), has hardnesses for saturated springs usually in excess of 200 mg/L, with P_{CO_2} of 1% or greater. This is what would be expected for an open system equilibrated to the mogote soil CO_2 recorded by Miotke (1974) in Table 6.1. A fourth area in Thailand (Pitman, 1978) has been cited as an example of closed system evolution because of the lower P_{CO_2} in spring waters collected at the base of limestone towers compared to soil CO_2. The latter values, however, were not collected from the actual tower summits, with presumably thinner soils, but from soils in the flatlands surrounding them -- it is clear from Table 6.1 and other soil CO_2 data that the deeper soils surrounding limestone towers, buttes, and massifs have considerably higher P_{CO_2} than the actual catchment areas.

Although attractive, the carbonate till model of Drake, and Drake and Ford, cannot explain the lower solute values of the tropics. Primarily, the substitution of temperature for P_{CO_2} (or pH) in incomplete water samplings appears to be unsound. It leads to overprediction of initial soil P_{CO_2} for higher temperature areas, and results in the assignment of most tropical waters to closed system paths. Additionally, it would seem pertinent to consider aquifers from cooler areas that lack substantial amounts of carbonate till in the surface. Brook (1976, Ch. 5) describes several springs issuing from a limestone aquifer in northwestern Canada (mean summer water temperature = 4.3°C) which have mean hardnesses of 151 mg/L (TH). Even under the lower P_{CO_2} expected for these cold climates in the D-W model, this would be classified as a closed system environment. Yet Brook's data records similar P_{CO_2} for both initial soil values (originating on both limestone and shale) and their respective spring resurgences, indicating open system evolution. The Nahanni is an area that evidence appears to indicate has not been glaciated possibly for at least 250,000 years and remaining till cover is slight. It should therefore be akin to the tropical areas in the D-W model, (which supposedly lack available carbonate material in the soil), where soil waters are most likely to be in open system equilibration with the highest initial CO_2 atmospheres.

Smith and Atkinson (pp. 380-381, 1976) state "There is, therefore a broad agreement between actual hardness values in the temperate and tropical zones and the values and ranges predicted from available data on carbon dioxide levels." They go on to compare an area in Jamaica with one in England where measured soil CO_2 concentrations are similar and show that, save for the temperature-related CO_2 solubility, the amounts dissolved in the sampled waters are similar. For the Caves Branch and the El Abra, mean hardnesses of about 187 and 230 mg/L respectively would increase to 243 and 300 mg/L if a temperature adjustment were made. These are values comfortably within the higher range of sampled temperate waters. At present then, for temperate and tropical waters, Corbel's original hypothesis (that temperature-related CO_2 solubilities explain climatic solute concentration values) appears sufficient to account for most of the recorded differences in concentration values. The other component of total solutional erosion is that of the amount of total runoff, which is discussed in the following two sections.

B. Rainfall Intensity

A qualitative and quantitative difference exists between rainfall in the tropics and temperate latitudes. In the tropics, the uplift necessary to induce condensation is generally convective, rather than the frontal or cyclonic activity of temperate latitudes. Because of the convective rising, the upward air movements are often of higher speed, but shorter duration, and because warm air masses change their moisture-retention capacity faster than cooler ones, as well as having a larger capacity, tropical rainfall is frequently brief, localized, and very intense (Nieuwolt, 1977; Riehl, 1979).

These rainstorms are important because they contribute up to 90% of the total rainfall in many parts of the tropics, and much of this is concentrated in just a few of the rain days. In Tanzania, two-thirds of the rainfall originates from storms which last less than 15 minutes, and it has already been noted that nearly 55% of the total 1977 Caves Branch rainfall fell in less than 2% of the wet season. In spite of the popular image of a tropical humid climate, "it almost never rains in a cumulus regime, in contrast to the climates with stratus precipitation in higher latitudes!" (Riehl, 1979). Table 6.2 compares the high intensities prevailing in the tropics with those of some temperate regimes; because these figures are calculated for daily intervals, and tropical rainfall usually falls in much shorter intervals, the actual difference between temperate and tropical mean precipitation intensities is perhaps an order of magnitude or more.

TABLE 6.2

Annual mean rainfall per rain-day, in mm (rain-days with over 1 mm of rain)

Quito, Ecuador	8.5	Accra, Ghana	13.6
Georgetown, Guyana	13.3	Lagos, Nigeria	14.4
S. Salvador, El Salvador	16.1	Entebbe, Uganda	12.4
S. Juan, Puerto Rico	10.1	Bombay, India	22.4
Caves Branch (1965-1976)	14.1	Calcutta, India	15.5
London, England	5.5	Vienna, Austria	4.1

(from Nieuwolt, 1977, p. 122)

C. Denudation/Total Solutional Erosion

The concept of denudation rate must be used with reservations, as a number of assumptions are expressed in the following equation applicable to the Caves Branch:

$$E = Q_A H/d \qquad (6.1)$$

where E = erosion rate (solute load removed/given time interval, e.g. mm/Ky)

Q_A = mean surface discharge (mm) [precipitation-evapotranspiration]

d = density of rock (gcm^{-3}, here taken to be 2.5 gcm^{-3})

H = mean discharge hardness (mg/L $CaCO_3$)

Solutional erosion rates are obviously variable in terms of both time and space; intensity and total amounts of rain and evapotranspiration vary within, and between, individual storms, seasons and years. The CO_2 to which the solute equilibrates varies in the Caves Branch because of soil thickness, prior rainfall and soil moisture deficit, as well as the amount of time the wet season has progressed. Denudation rates are generally expressed in terms of uniform surface erosion, whereas considerable internal solution must occur within a karst aquifer, especially the Caves Branch, where P_{CO_2} appears to be boosted internally. A factor of unknown influence is the possible compensation for removal of rock material by a decrease in the bulk density of the remaining bedrock. Finally, any useful extrapolation of rates, even based on the mean of a few year's samplings, must ignore future or past changes of climate, vegetation, or land use.

Limestone solution in the study area has been previously demonstrated to proceed to equilibration over a time interval requiring perhaps months because of the large storage capacity of the aquifer. The approximation of long term rate would be the integration of the total amount of solution occurring between runoff and resurgence. This is best expressed as the mean concentration of zuhuyha/spring waters, derived earlier as 187 mg/L. From Table 4.1, mean rainfall in the months for which runoff could be expected (June to January) is 1970 mm. Assuming that potential evapotranspiration (with mean monthly temperatures of 24°C and calculated from Thornthwaite's method, Chapter IV) equals actual, runoff is estimated at 1190 mm/year, 50% of total precipitation. Using (6.1), the mean Caves Branch erosion rate is calculated at 90 mm/Ky, where use of the 1,000 year rate is simply for standardization with most previous workers (a number prefer to use $m^3/Km^2/y$). Ignoring seasonal variations of rainfall distribution within years, the maximum and minimum yearly recorded rainfall totals would give values of 55 and 110 mm/Ky, respectively.

These of course, represent the sum of numerous rainfall events, each of much higher individual rate. Ephemeral swallet waters in the area reach concentrations of 15 to 53 mg/L TH within an hour, representing rates of 2600 to 8000 mm/Ky (for hourly rainfall of 50 mm). Longer lasting surface flow reaches 130 mg/L in six hours, a rate of 3300 mm/Ky for a similar rainfall intensity. Even the yearly totals are actually the result of run-off that falls only in the 7 1/2 to 8 month wet season period, with two months (June and July) accounting for as much as 50% of the mean total runoff in some years.

TABLE 6.3

Erosion Rates from Limestone Areas in Different Climates

	n	$\bar{x}$	s.d.	
Arctic/alpine	24	62	38	(from Smith and Atkinson, 1976)
Temperate	87	57	43	
Tropical	18	46	34	

The figure of 90 mm/Ky for Belize can be compared with previous compilations of denudation rates (Smith and Atkinson, 1976, p. 385) in Table 6.3. It is apparent that the Caves Branch rate is quite high. Giusti (1978) calculated erosion rates for karst in Puerto Rico of 70 mm/Ky. Fish (1978) quotes data from Mexico where karst runoff is about 40% of precipitation of 2500 mm/year, lower than Caves Branch, but mean TH is higher. These values would give denudation rates comparable to those of the Belizean study area of 80-100 mm/Ky. The amount of thermal energy receivable at tropical latitudes places an upper limit of 1500-2000 mm/year on evapotranspiration, but rainfall may considerably exceed this. In New Guinea/New Britain, precipitation may be of the order of 5-10 m/y, and Maire (1981) has calculated erosion rates of 250-400 mm/Ky there. In two other humid tropical karsts recently studied, Day (1981) estimated erosion rates of 80-200 mm/Ky in Sarawak, and Zhang Zhiyi (1979) gives figures of 120-300 mm/Ky in Central Guangxi, China. All of these tropical areas have rates considerably higher than expected from previous tropical values, and are high even when compared to temperate karst areas.

D. Distribution of Solution

The location of solution within the vertical range of the aquifer is difficult to determine. The mean TH of swallet waters in the Caves Branch is 38 mg/L, only one-fifth of the mean areal authigenic TH of 187 mg/L. The previously noted effect of apparent internal CO_2 production is important; open-system saturation of water equilibrated to 0.7% P_{CO_2} in the Caves Branch would dissolve 153 mg/L, but a further internal boost to 1.1% would allow an additional 42 mg/L to be dissolved. It is not yet possible in the Caves Branch to determine where the other approximately 60% of solution occurs. The data of Smith and Atkinson (1976) and Williams and Dowling (1979) suggest that in a number of temperate karsts 50-80% of the total solution occurs within 10-30 m of the karst surface. At present there are no known studies using detailed hydrologic measurements that provide an adequate estimation for karsts in the tropics; Corbel and Muxart (1970) cite some estimates for a number of Caribbean karsts, but their data is seriously biased in that it uses river data rather than spring samples for calculation of total areal solute removal.

In this context, the behavior of the Crooked Bend zuhuyha (Chapter V) should be noted. It is the biggest authigenic spring known in the area, with sources presumably several kilometers distant, but during major floods (e.g. July 2, 1979) its resurging waters can still be aggressive. This indicates the potential for solution throughout the range of the karst.

As a final note, Sweeting (1972) has remarked upon the enormous quantities of calcite precipitated in tropical caves. She interprets this as evidence for higher surface solutional rates than indicated by measured water hardnesses. As the vast majority of travertine and flowstone is probably inaccessible, calculation of its volume is not possible. Relative to total cavern volumes, however, total calcite precipitation is minor, and yearly increments can also be expected to be only a tiny fraction of the total erosional load removed. Caverns of great age should have larger calcite precipitation deposits; age alone may be the major factor in tropical caves deposition.

E. <u>Age of the Caves Branch karst</u>

It is difficult to assign an age to the Caves Branch karst; it is obviously far in excess of 176,000 years, the oldest stalagmitic material dated so far. As discussed in Chapter I, there does not appear to be any conclusive evidence for the existence of any past surficial covering of the Cretaceous carbonates in the Maya Mountain area. Solutional erosion could have commenced immediately upon exposure, and tentative evidence suggests a number of emergences and submergences since the original deposition. Eocene carbonates exposed in the area (Flores, 1952) appear to be deposited only between ridges and uplands of Cretaceous rocks, and at low elevations, suggesting the latter were exposed at least briefly by Eocene time, 35-55 million years B.P.

A traditional method of estimation is to divide the difference between covered and eroded stratigraphic thicknesses by the mean denudation rate. This assumes previously similar thicknesses, and no significant change in rate. Similar Cretaceous carbonates in Belize and eastern Guatemala range from 1750-3200 m in thickness (Vinson, 1962; Vineagra O., 1971; Dillon and Veddar, 1973), and Vineagra O. reports the carbonate thickness at the fringe of the Mayas to be about 900 m. If this lesser figure is due to erosion (and not an initial difference of deposition) and a solutional erosion rate of 90 mm/1000 years is used, an age estimate of 9.5-27 million years would result.

Another method is to divide the total porosity (estimated in Chapter V to be at least 2-3%) by the yearly change in porosity (derived from the mean yearly erosional rate). Because porosity changes should have been considerably smaller in the early stages of karstification, the estimate can only set a lower limit, in this case an obviously low 22,000-33,000 years. To adjust for lower rates of porosity enlargement in early development, an assumption can be made that the ratio of yearly porosity change to total porosity remains constant. By backward calculation to a typical initial porosity of 0.01% (Smith, Atkinson, and Drew, 1976), an age of 190,000 years is calculated, still far too low. It is apparent that initial porosity increases are probably very slight for a long period of time, then rise rapidly.

It is generally conceded that karsts in the tropics have had greater lengths of time available for development than those in higher latitudes. The effects of glaciation and permafrost have been generally to slow and interrupt solutional processes, or even to destroy karst landforms. These drastic alterations are not believed to have occurred to the same degree, if at all significantly, in the tropical regions. No evidence of glaciation is known anywhere in the highlands of Belize, and considered with the geologic evidence indicates a solutional landscape than has developed more or less uninterruptedly for perhaps millions of years.

F. Discussion and Summary of Section I

A number of points have so far been made in this chapter comparing the solutional erosion of tropical and temperate areas, and indicate that various elements of the solution process do vary significantly between these climates. On the other hand, some previously postulated effects have been found to be of dubious importance.

Recent research in limestone areas in the tropics indicates that the high P_{CO_2} expected from measurements in cultivated areas, and predicted from temperature-related biotic reactions, does not occur. Tropical karst soil P_{CO_2} may still be higher than temperate soil P_{CO_2}, but not to the degree hitherto believed. Saturated spring waters from different sites tend to have P_{CO_2}'s roughly comparable to that of the overlying soil, with solute concentrations that imply evolution and equilibration under open system conditions. These saturated springs exhibit positive temperature/ P_{CO_2} relations in spite of the apparently higher TH's of temperate climate springs relative to those in warmer areas. This apparently anomalous situation can exist because of the inversely-temperature-dependent solubility of CO_2 in water; colder waters can have higher solute concentration than warmer waters in spite of considerably lower P_{CO_2}. The temperature/ aqueous P_{CO_2} relation is possibly due to a combination of somewhat higher soil CO_2 concentrations, intra-aquifer production of CO_2, and temporal differences in the recharge of P_{CO_2} to local aquifers: much of the recharge to temperate aquifers could be expected from snowmelt at a time when soil CO_2 is low, but tropical soil CO_2 production appears most strongly related to availability of moisture. Recharge and highest soil CO_2 concentrations should coincide in tropical areas.

Although solute concentration may be lower, recent data indicate that actual amount of total annual unit solute removal in the tropics is comparable to, and quite possibly exceeds, that of temperate areas. This is due to greater runoff in high precipitation humid tropical environments in spite of high evaporation rates.

Consideration of the rainfall regime emphasizes one of the most fundamental differences between temperate and humid tropical climates. Not only is the total rain greater in the tropics, but it occurs in short duration, high intensity events. This encourages a runoff pattern more strongly oriented towards flooding than temperate areas. This pattern is possibly encouraged in cockpit areas by higher amounts of throughfall (14% greater) into the cockpits than on the hilltops (Aub, 1969a); the phenomenon is explained as due to gravitational effects on stem and leaf flow in thick jungle foliage and would presumably be less pronounced in the deciduous areas of the temperate zone. A runoff regime strongly influenced by flooding will also be more likely to entrain debris, such as vegetal matter. The overall effect in cockpit areas is that of enhanced concentration of aggressive water combined with the avenues afforded to aquifer access by the frequent swallets in the bases of depressions.

Three other points are worth noting: 1) carbonate-rich till has been cited as responsible for the high solute concentration and open system evolution of temperate waters 2) the greater length of time of unhindered erosion of karsts in the tropics has allowed development of relatively high porosities and permeabilities, and 3) internal production of CO_2 should be greater in a tropical aquifer because of greater likelihood of washed-in vegetal matter in a flood-prone environment, and the increased effect of the higher temperatures on biogenic activity and production.

The combination of these effects is that solution where carbonate till is present is more likely to be concentrated in surficial areas, whereas large amounts of aggressive water in the tropics is channeled into conduits leading directly into the aquifers, where high porosity encourages open system evolution, and solution is further bolstered by addition of internally-produced CO_2. Greater internal penetration of aggressive water and a far higher proportion of internal solution should result. This would also be a self-reinforcing process -- concentration of aggressive waters at these "solutional hot-spots" would result in rapid growth of the transporting conduits, with consequent increase in capacity to channel still more aggressive runoff, and so on. Not only are there indications that total erosion rate may be higher in the tropics, but also that fundamental differences in location of the solutional attack may exist. If real, these distinctions could possibly explain much of the morphologic variation between temperate and tropical climates. In intervening areas, of non-glacial modification and non-tropical climate, a drop or saddle in solute concentration because of closed system evolution could be expected -- this has been tentatively observed by Trainer and Heath (1976) in the U.S.

II. A Model for the Caves Branch Development

Thus far in this study, the morphology and hydrology/hydrochemistry of the Caves Branch have been discussed separately. An attempt will now be made to consider if a synthesis into a united model is possible.

The salient features of the morphology are 1) a landscape that is at present completely drained internally. Its past development, considered with other major nearby karsts developed on essentially similar rock, suggests a fluvial phase of unknown areal coverage. This phase and the present location of major cockpits and depressions were to some extent controlled by regional and local fracture patterns; and 2) a cavern system indicating sudden development of conduit porosity and integration targeted upon a previously formed network of trunk conduits created by invading allogenic water. The local hydrology and hydrochemistry can be readily characterized by the evolution of runoff. Runoff from the karst surface, including infiltration, is concentrated into a relatively small fraction of the wet season time period both because of the intense nature of the rainfall, and the high evapotranspiration which effectively erases the contribution of the more frequent light rainfalls. This runoff enters the karst as solutionally aggressive flow, and resurges after passage through an aquifer dominated by open system conditions and internal production of CO_2. Most of this flow is at chemical equilibrium with the host rock, but in extreme flooding, aggressive discharge can penetrate completely through the aquifer.

Two other points concerning the morphology should be made:

1) the actual area of the enclosed depressions is only a fraction of the total karst area. Where hypsometric data is available (e.g. Searranx, Vaca Plateau, and to lesser extent the Caves Branch, Figures 2.1, 2.3, and 2.4) it can be seen that although cockpit "depths" are often quoted as 100 m or more, this includes ridge and hill heights; actual depths of the enclosed depressions are usually only a minor part of the total topographic relief. In short, valleys dominate the "negative relief"* of the topography, in spite of the greater visual impact of the cockpits.

2) Within the area occupied by the closed depressions (and including those portions of the hillsides which drain to the cockpits) the swallets and their drainages can perform a significant channeling function; in Chapter II it was noted that runoff in the channels was infrequently observed, but this can be expected from the intensity/frequency distribution of tropical rainfall.

As noted, runoff was observed following rainfall of 12 mm or more that occurred during time intervals of 2 hours or less. The hourly rainfall data of 1977 for the Caves Branch shows that nearly a quarter (23%) of the total observed precipitation fell during single hours when rainfall exceeded 12 mm. Further examination shows that the seventeen two-hour periods in which more than 12 mm of rain fell accounted for 332 mm, or nearly half of the total 709 mm rainfall for that period. Thus, the channels are rarely in operation, but still function during a large percentage of the total rainfall.

A possible sequence of development would then be:

1) an initial fluvial net developed on the dense, though fractured limestone, with valleys etched to 50-100 m. Fluviality would be encouraged by the large, concentrated runoff typical of the tropical rainfall regime.

2) gradual solution within the aquifer would enlarge fissures to the point that surface runoff and vegetal debris could be accepted. Solutionally aggressive waters would be channeled to swallets developed at favorable sites, chiefly in valleys where runoff concentration would be most effective. Given a greater concentration of solution in the aquifer interior than for temperate areas, and the presence of chiefly vertical joint/fracture control, integrated conduit systems would have developed so rapidly that no significant intervening cavern system would have formed prior to that of the essentially baselevel zuhuyhas known at present.

3) these authigenic conduits would join to trunk conduits already developed by aggressive allogenic water integrated into large flows prior to entering the limestone.

The result is a surface pitted by imposing sites of concentrated solution -- the cockpits -- which have, however, developed in a landscape of predominantly fluvial origin. A change of solutional erosion rates with time should also be expected from such a model of development: with development of a large-storage internal porosity, solution should be enhanced by increased rock contact and higher internal P_{CO_2}. This should increase to some maximum point, at which conduit enlargement ultimately allows interior flow to resurge before reaching equilibration in the interior. The Crooked Bend zuhuyha may be an example of an aquifer that has just reached this threshold. Further conduit growth would coincide with an actual decline in solute hardness.

CHAPTER VII

SUMMARY

I. General

The Caves Branch area is located in the center of Belize, Central America, at approximately 17°N. and 89°W. It was the site of three summers of research in 1976, 1977, and 1979, and one brief winter visit in 1978. The study area comprises slightly over 200 km^2, of which 80 km^2 lies on non-carbonate rocks in the Maya Mountains to the south, and the remainder on limestone. The limestones are of Cretaceous age, occurring at 40-320 m a.s.l. in the study area; the non-carbonates are chiefly Paleozoic meta-sediments of sandstone, shale, etc., with Triassic granitic intrusives. A major structural feature (the Northern Boundary Fault) separates the limestones from the highland rocks, which lie at elevations of 200-1000 m. The limestones are apparently of lagoonal or back reef origin, and in the study area have been massively brecciated, with the white to dark gray limestone now appearing mostly as angular clasts in a breccia cemented with a red matrix. Both infrequent bedded rock and breccia are hard and massive, with a $CaCO_3$ purity of >97%. Numerous small faults have been identified. There is no evidence to suggest the past existence of any sediment covering of the limestone; they have probably been exposed to denudation at least intermittently since deposition. Their original thickness may have been as much as 2 km.

Three individual hydrologic catchments on the highlands funnel allogenic runoff onto the limestone below. Nearly all Caves Branch discharge ultimately passes through cavern trunk conduits developed at the basal level of a mature karst that has formed on the limestone. The limestone has two fundamental hydrologic entities, 1) the Caves Branch polje and smaller flat, alluviated areas also at base level, and 2) a rugged karst surface composed of 1,000's of internally draining depressions, dolines, and cockpits.

II. Climate

The area lies within a region of humid tropical climate. The mean annual temperature (as determined from local caves) is about 24°C., and mean annual rainfall is 2376 mm with no month having mean precipitation below 60 mm. Rainfall on the highlands and mountain slopes may be somewhat higher, perhaps by 200-400 mm. The karst surface supports a luxuriant tropical rainforest biota, mostly natural, although some logging has occurred in the past. The Caves Branch polje is partially under cultivation and the remainder has been logged.

Rainfall is the most variable element of the climate. Mean monthly temperatures at lowland stations in Belize vary by only 7°C through the year, and extreme minima/maxima ranges rarely exceed 10-45°C. Rainfall, however, shows stronger seasonal aspects, having a pronounced dry season from February through May. During these months of relatively cloud-free weather, high temperatures and evapotranspiration (ET) create a moisture deficit broken finally by the beginning of the wet season (usually in June). As is typical in the tropics, the rain falls mostly in short intense storms, with 709 mm recorded in the 1977 field season and 618 mm in 1979.

In the former year, 55% of the total fell at intensities of 6-50 mm/hour, in only 32 recorded hours. A diurnal component was observed, with most rain occurring in late morning and early afternoon. The annual ET is estimated at 1190 mm, or about half of the total precipitation. The rainfall has an easterly, oceanic, source, believed responsible for minor influx of chloride ion (Cl^-) to the area.

III. Hydrology and Hydrochemistry

Numerous springs occur on the surface of the karst and within the trunk conduits of local cave systems. As discussed later, the largest have many of the hydrologic properties of conduits, but have the hydrochemistry of diffuse flow springs; they are termed "zuhuyhas". The lack of clay or clasts in great amount from these zuhuyhas and springs is indicative of both the purity of the host limestone, and of the overriding importance of solution as an erosional agent in the karst landscape. Modification and destruction of the limestone can be explained by the process of reaction of the rock with CO_2 dissolved in the rainfall run-off. The source of the CO_2 is biogenic material of the karst surface; the CO_2 is produced by either respiration of the growing plants, or oxidation by decay of dead plant matter. Plentiful moisture and high temperatures encourage soil CO_2 production, but because temperature is so stable, the availability of rainfall becomes the chief source of variation. This introduces a seasonal element related to the rainfall, and P_{CO_2} is considerably higher in the wet season, when soil moisture is relatively unlimited. The soil CO_2 shows a lagged correlation with the $\log_{10}$ of rainfall of the preceding day, but the best correlation (r^2 = 0.68 at the significance level) is that of soil CO_2 with both SMD (soil moisture deficit, (a function of rainfall and ET), and time since the start of the wet season. Thin soils (generally <30 cm) inhibit production of CO_2 within the dolines and cockpits, especially as compared to thicker alluvial soils in the polje. Very little soil exists on limestone hill summits except in pockets and fissures. Cockpit soils averaged 0.7% P_{CO_2} in the wet season, polje soils 1.6 - 20%. Maximum dry season values were usually below 0.3%. The highest soil CO_2 recorded was 6.7%.

Biogenic CO_2 is carried into the aquifer by runoff. This is a seasonal effect, being the result of the moisture surplus created by the greatly increased wet season rainfall. Runoff with maximum solutional aggressivity was produced by this correlation of high soil CO_2 with maximum excess of precipitation. This runoff appeared approximately equilibrated with soil P_{CO_2}, having aqueous P_{CO_2} of 0.3 - 0.8%. It was aggressive, with SI_c's of -2.54 to -1.33, and had dissolved less than 55 mg/L (total hardness as $CaCO_3$) at maximum.

Runoff into the karst occurs through either 1) infiltration into numerous small fissures, crevices, etc., or 2) integration within small drainage networks, developed on the doline and cockpit soils, that lead to swallet sites. These swallet drainages were not universal to all cockpits in the karst, and were observed to be active only following intense rainfall periods of at least 12 mm. Resurgence of this runoff is in the numerous zuhuyhas and springs. Although sampled over several years and seasons, 24 of these springs exhibited the same minimal hydrochemical variations in TH and other characteristics as did the diffuse flow springs of Shuster and White (1971) and Jacobson and Langmuir (1974). The mean, discharge-weighted-TH of these springs was 187 mg/L (as $CaCO_3$), with mean P_{CO_2} of 1.1%. Individual TH values ranged as high as 341 mg/L, and P_{CO_2} to 4.7%. Nearly without exception, all were saturated with respect to calcite. The large boost in P_{CO_2} subsequent to passage through the aquifer suggests both considerable internal production of CO_2, as well as a more or less open system evolution of calcite solution within. The internal production of CO_2 is probably due to oxidation of vegetal debris washed inside during heavy rains.

Monitoring and modelling of a site located on a major conduit indicated that there is large scale retention of rain runoff within the aquifer. This amounts to some 10 - 13 X $10^6 m^3$, for a minimum calculated porosity of about 0.7%. Water in storage is lost during the baseflow of the four month dry season, and is replaced by rainfall runoff early in the following wet season. This creates a typical lag in discharge response of the aquifer during the first 200-300 mm of wet season precipitation. Neither an SMD of 13 mm, or ET of between 30-80 mm in this interval observed during the field seasons is sufficient to explain it. Each storm in the wet season sequence displays a discharge outflow response progressively more similar to that expected from a consideration of area rainfall and ET. Both the large storage, and the need to replenish the dry season baseflow losses, retard flow through the karst to the extent that several months appear to be required for passage. This allows ample time for both oxidation of washed-in organic debris to boost internal P_{CO_2}, and for complete equilibration of the aggressive runoff with the host rock.

The other major hydrologic regime within the study area is that of the invading highland allogenic water. Although presumably having a lower initial P_{CO_2} than the authigenic waters due to thinner soil, and having lost CO_2 from de-gassing during overland travel, this water is still highly aggressive when it reaches the limestone (SI_c = -3.0 to -1.0, TH = 10-40 mg/L). Some minor sulphate concentrations appear to be introduced from the highlands. Total flow from the Mayas is about 0.5 cumecs in dry season baseflow, and up to 50-100 cumecs or more in extreme wet season floods. Carrying non-soluble sediment, and already being large, integrated flows, these streams are able to armor their beds and penetrate many kilometers into the body of the limestone. After they are finally pirated below ground, they flow in the largest conduits known in the karst, created both by their aggressively solutional concentrated flow, and some unknown amount of corrasion due to the insoluble alluvial load. This allogenic hydrologic regime is also seasonal, as expected. In the dry season, flow cannot be maintained throughout the Caves Branch polje because it is pirated via several routes into the passages of the Nab Nohol cave group, which parallels the polje on the eastern side. In the wet season, the combined flow of the Caves Branch, Chek, and Lubul Ha streams persists to a ponor sited at the downstream end of the polje. Because they are already fully integrated streams prior to entry into the karst, the allogenic surface courses and cavern conduits serve as collector systems for all of the authigenic discharge as well.

The hydrochemistry of the Caves Branch is almost exclusively bicarbonate, as indicated by low ion balance errors (IBE <5%) and the excellent correlation (R^2 = 0.99) of measured specific conductivity (SPC) with that calculated from the titration analyses. The mean IBE was 1.4%, differing significantly from 0, reflecting the introduction of exotic Cl^- and SO_4^{2-} ions. TH (Ca^{2+} and Mg^{2+}) and HCO_3^- concentrations showed excellent correlation, with a ratio near unity, as could be expected from the rock analyses. Mg^{2+}, however, was higher than expected, but almost never more than 10% of the TH; it probably is a reflection of minor inhomogeneities not detected in the limited rock analysis. The pH of water samples was slightly alkaline (range 6.35-8.22) and typical of that expected from natural limestone waters.

IV. The Aquifer Interior

Of interest is the explanation of the behavior of the hydrochemistry and hydrology of one of the large cavern conduits. At a monitored site, the Boiling Hole, the conduit demonstrated a stable, declining baseflow in the dry season (<0.9 cumecs), with slightly aggressive water having a low solute concentration (<95 mg/L as $CaCO_3$) and P_{CO_2}. In this season it demonstrated a linear inverse correlation of discharge and total hardness. In the wet season, baseflow increased to more than one cumec, and occasional flood peaks approached 10 cumecs. SI_c and P_{CO_2} assumed higher values in the wet season, and TH showed an especially strong (r=.95) and unusual positive correlation with discharge. Even though P_{CO_2} reached higher levels of 0.5 to 0.7%, the flow was more saturated with respect to calcite. Because of the Q/TH relation, actual solute load removal rates were 3-13 times as great. Maximum removal occurred during the highest floods, when TH reached as high as 170 mg/L.

Two distinct types of inlets convey flow into the trunk conduit leading to the Boiling Hole. These are the zuhuyha/springs, and the pirating sub-conduits. The pirate channels feed extracted water from the Caves Branch River to the neighboring trunk conduit of the Nab Nohol.

They are always located on the polje-ward side of the conduit they empty into, have sediments of allogenic origin, and dimensions of about 2 m diameter. Their water temperatures are higher than those of the zuhuyhas (about 25°C), and they are aggressive, with moderate P_{CO_2} of 0.3-0.6%. The mean solute content (50-95 mg/L) increases with distance downstream, mimicking that of the nearby river. Examination of the hydrology, hydrochemistry, and physical morphology of the two channel types led to the conclusion that the seasonal flow regime behavior could be best explained as due to dynamic mixing of 1) the hydraulically restricted, piratic, allogenic flow with 2) authigenic water responsive to the storm discharges of wet season rains. A quantitative two-component mixing model was formulated to explain the observed behavior, using actual discharge and chemical sampling of the upstream sources of the Boiling Hole. The dry season flow appeared to be dominated by influxes of pirated river water, and the wet season flow by periodic storm-caused outflow of authigenic water able to overcome the restricted piratic influx. Predicted TH of the mixing model was well correlated (R^2=0.86) with recorded TH for a given discharge at the Boiling Hole. The correlation slope of near-unity, and intercept near zero, made it capable of accurate prediction of Boiling Hole behavior. Differences between calculated and expected TH appeared to be chiefly due to several systematic hydrologic effects, 1) cyclical variation or hysteresis in TH with regard to discharge: TH is higher on the falling limb, 2) back-flooding (or ponding) during extreme high discharges, caused by inability of the trunk conduit downstream to accept the combined flow of both the Caves Branch River and the Nab Nohol stream, and 3) a drop in hardness during extreme floods for discharge contributed by a major spring (Crooked Bend) to Boiling Hole flow.

Five major water classes were identified in the Caves Branch that were separable statistically using a stepwise linear discriminant function (SLDF) analysis. The six original classes were the allogenic, zuhuyha/ spring, swallet, and pirate waters previously discussed, and two other types -- stalactite drips, and karst flow. The latter is surface flow of authigenic origin that occurs on a more less permanent basis in areas extraneous to the cockpits. The TH's are often high (up to 294 mg/L), with moderate P_{CO_2} (0.11 - 0.81%), and all are supersaturated (SI_c>0.25). The stalactite drip class was found to differ little from the zuhuyha/ springs so they were combined. A success rate of 80% was achieved when comparing the SLDF functions with the a priori identified groups. The most useful discriminating functions were found to be those associated with measuring degree of saturation, and solution potential, in that order. Two sets of discriminating variables were ultimately used: a measured set (log HCO_3^-, pH) and a calculated set (SI_c, P_{CO_2}). The measured variables appeared to be slightly more accurate when used in subsequent classification attempts.

V. The Karst Surface

The landscape upon which these solutional processes operate is of the type elsewhere described as a cockpit karst. It contains many depressions of varying size (up to 60 m in depth) which dominate the landscape. Many of these cockpits lie within apparent paleo-fluvial areas which form a significant share of the surface. Scores of photo-lineations criss-cross the surface of the Caves Branch karst, and have a significant orientation peak (65-80°NE) that is similar to regional structural fault trends and fracture-aligned cave passages. Measurement of distances between lineations and cockpit nodes (the bases of the depressions) was done in one area of the Caves Branch; it was found that over 25% of the nodes were within the area that would be covered by lineations of 25 m width. The width used was similar to that of known fracture traces in rocks, and the number of dolines in these areas was found to be significantly greater than that expected from a random distribution.

A dispersion analysis of cockpit nodes was performed on 853 dolines in the Caves Branch, and on 400 others in two areas in western Belize (Vaca Plateau) and Guatemala (Searranx). Clark and Evans (1954) 'R' was used as a measure of spatial dispersion, where R ranges from 0 to 2.14 -- values less than 0.5 demonstrate clustering, above 1.57 uniformity, and 1.0 shows operation of a random process. The Caves Branch, Vaca Plateau, and Searranx cockpit karsts had values of 1.39, 1.20, and 1.51, respectively, indicating a significant departure towards uniformity from that expected in a random network. These are results similar to those from 8 New Guinea karsts (Williams, 1972). Both Searranx and the Vaca Plateau were holo-karsts with definite paleo-fluvial networks; for the 11 New Guinea and Central American karsts, it was found that those with partial or complete paleo-fluvial networks were generally those with the greatest indication of departure from a random process of dispersion. The indication of these results is that, rather than being due to development by competition of swallets in a dynamic equilibrium, many cockpit karsts may have been initiated by disaggregation of existing topographic lows originally formed by fluvial action. The fluvial channels may have been directed by favorable sites of joint/ fracture intersection, as in any stream channel, but they preceded the cockpits and dolines. The former channels appear to have been favorable sites of concentration of aggressive water necessary for development.

VI. Cavern Morphology

Beneath the surface of the karst lies an extensive hydrologic system that ultimately integrates into allogenic trunk conduits. Several score caves have been examined in the study area, and others visited elsewhere in Belize. Nearly 40 km of cave passage have been mapped in Belize, of which 33 are located in the study area. The caves are an important consideration of the hydrology and hydrochemistry because all discharge is ultimately transported through them, and a significant amount of the total solution of the limestone by authigenic waters occurs there.

Presently active caverns can be subdivided into three types, dependent upon their hydrologic function and resulting hydrochemistry; 1) trunk conduits, which transport allogenic flow through the karst area and in the process act as collectors of authigenic flow (and piratic flow), 2) swallets on the karst, or margins of the limestone, which direct the numerous discrete inputs of solutionally unsaturated authigenic runoff from the surface into the karst interior, and 3) zuhuyhas, which collect and integrate the authigenic swallet inputs within the aquifer, and transport it through the karst to the points where it emerges as solutionally saturated flow.

A number of distinct phases in the cavernous history of the Caves

Branch were noted. The first was the development of numerous small isolated phreatic caverns situated at varying elevations in the upper 80+ m of the limestone. This was followed by 1) solution of very large cavities (the Chamber Stratum), also apparently unintegrated by conduit flow, 2) development of the allogenic trunk conduits through the karst, 3) integration of smaller conduit systems such as zuhuyhas and pirates into the main trunk conduit network, and 4) the last of several major alluvial infillings, this one virtually plugging the downstream and of the Chac Be Haabil system and creating paragenetic conditions there as well as a consequent widespread niche feature. Radiometric dating of stalagmites using Uranium/Thorium decay ratios has shown that major cavernous development of the bottom 30 meters of the karst was well advanced by no later than 140-215 ky B.P. The filling episodes seem to have occurred about 60-105 ky. Relating phases from cave to cave is difficult, and the individual sequence events listed above are merely the most discernible, and are not necessarily of comparable importance. The transition from diffuse to integrated flow appears to have occurred relatively suddenly, as though a threshold had been crossed.

As previously mentioned, bedding is an uncommon feature of the frequently brecciated host rock, and joint or other fracture controls (e.g. faulting) is dominant in controlling cave passage alignments. This lack of obvious lateral or horizontal control has resulted in the trunk conduit networks being oriented primarily by regional fracture patterns, and relative topographic dip. In spite of the obvious relations of trunk conduits and cockpits/dolines with regional fracture patterns, the former generally lie beneath ridges rather than the cockpits, which are obviously favorable sites for runoff penetration and solution. This is as yet unexplained.

VII. Solution Erosion and Development

Estimates of the mean solutional erosion rate in the Caves Branch produce a figure of approximately 90 mm/ky (or $m^3/km^2/y$), assuming this is all surficial. Comparison with recent estimates from other humid tropical areas suggest these regions may have significantly higher rates than temperate climates. Because 1) CO_2 solubilities in water are lower in the warmer tropical waters, 2) tropical soil P_{CO_2} does not seem significantly greater than in temperate soils, and 3) aquifers with open system calcite solution appear to predominate in both temperate and tropical climates, the higher tropical solution rates are due to greater runoff discharges. Given the lack of carbonate clasts in most tropical karst soils relative to soils in glaciated areas, the open system aquifer in the humid tropics may be due chiefly to fundamental differences in rainfall regime. The brief, very intense rainstorms of the tropics are viewed as more likely to concentrate runoff and vegetal litter at sites favorable to deep penetration of karst aquifer. The resulting boost in CO_2 because of intra-aquifer biogenic production, combined with greater penetration distance of solutionally aggressive water, would allow open system conditions to prevail, as well as creating a basic difference in distribution of solution between temperate and tropical karsts.

A tentative development sequence proposed for the Caves Branch includes an initial fluvial net developed on the limestone, with valleys eroded to 50-100 m. Any caves in this phase would be small and isolated while the aquifer transport fissures were being enlarged to the point that surface runoff and biotic litter could be accepted. Once this point was reached, the concentration of solutionally aggressive runoff combined with internal CO_2 production would redistribute the locus of solution so radically that the present baselevel authigenic network would develop without a significant intervening cavern system. The surface would remain a site of predominantly fluvial origin, increasingly transformed by imposing sites of concentrated solution, the cockpits.

VIII. Suggestions for Future Research

As an area where the basic elements of the morphology, hydrology, and hydrochemistry are well known, the Caves Branch is an excellent site for future study of solution processes. This study has suggested a possible interaction between the influence of the morphology and climate upon hydrologic routing, and the location and intensity of solution in a section of the Caves Branch River catchment. Because of the rarity of runoff in cockpit swallet catchments in the tropics, their importance is not fully understood. Future research (in Belize and elsewhere) should concentrate on 1) determining the frequency of occurrence of swallets with catchments in cockpits, 2) their threshold of flow during rainfall, and 3) the proportion of runoff channeled by swallets as compared to the hilltop areas. At present, the area and outline of the authigenic catchment contributing to the Boiling Hole is unknown -- a program of dye-tracing, possibly using several dye types simultaneously, could be used to define the approximate flow routes of the swallet waters, as well as those of the pirating sub-conduits. Delays in the passage of the dyes through the aquifer would give information concerning amounts and duration of internal storage. Using different dyes for hilltop vs. swallet catchment areas, comparisons of flow regimes would be practicable. The hydrologic importance of each could be determined from the resulting calculated runoff coefficients, and information concerning the slow or fast, conduit or diffuse, nature of the percolation water.

In addition to the hydrologic importance of the cockpits, their function as avenues of ingress of vegetal matter should be investigated. If the aquifer is a site of internal CO_2 production, the oxygen demand and carbon content of flow entering and leaving could be compared (re Bray and O'Reilly, 1974). Combined with additional permanent measuring sites and spot samplings of soil CO_2, the relative and absolute contribution of the CO_2 flux to the aquifer could be more accurately measured.

It is important that future research in the wet season be lengthened to continue past July and August. This would enable the determination of the maximum CO_2 levels reached in the soil, to compare with P_{CO_2} of resurging waters. Storage estimates derived from estimated and calculated runoff ratios would also be more accurate using the additional discharge data.

Additional hydrochemical sampling could consider analysis for other than bicarbonate ions as a methods of discriminating between flow sources, and use temperature measurement at a finer resolution. Use of SPC and pH meters with automatic recorders to provide continuous sampling of the Caves Branch River, Boiling Hole, and Crooked Bend would establish more precise and accurate loading curves, as well as provide continuous monitoring of SI_c and P_{CO_2}. Local and temporal variations in solutional erosion could be estimated from the above information to see if they are fundamentally different enough in quality and magnitude in this tropical area to create any climatic morphologic variability.

The morphology presently being altered by these solutional processes could use further investigations as well. Among these could be an improved survey of the geology/mineralogy and extent of bedding, brecciation, fracturing and other structural features to relate to variations in surface form and texture. Pedologic analysis of the clay and other fills in the cockpits might aid in confirming or denying a fluvial origin. Relation of the cavern morphology to the surface morphology as an indicator of past solutional regimes primarily needs more subterranean exploration to check if morphologically important segments have been overlooked. An allied, expanded program of speleothem radiometric dating is needed to introduce an adequate framework of known absolute time; if other Belizean caves are included, regional patterns and periods of tectonic or eustatic disturbance could be established.

The Caves Branch still has much potential as a natural laboratory for future research into karst processes.

Appendix A - Soil CO_2 Sampling

The soil sampling instrument consisted of two nested stainless steel rods, both with alignable holes at their tips. When unaligned, the meter-long rod was inserted into the ground until resistance was met. Then, the inner rod was rotated into alignment and a flexible hose connected its upper end to a Dräeger tube inserted in a Dräeger hand pump of 100 cc capacity. The device has similarities to the progenitor designed by Miotke (1972), but may be slightly less accurate at smaller sampled volumes because of the greater initial volume of atmospheric air contained in the interior rod. This can be compensated for by a correction factor, however, and when the sample volumes are large (500 cc) the contaminating atmospheric air is minimal.

Each permanent sampling site consisted of an area of a few inches radius. Before insertion, the soil was exposed through removal of dead leaves, etc., then carefully replaced. The ground was tamped down about the rod, and wetted as needed (generally unnecessary in the wet season) to prevent diffusion of atmospheric air into the soil voids caused by the sampling.

Appendix B - Hydrochemical Sampling

The variables measured during field research were, as noted in Chapter IV, date, location, discharge (flow volume), temperature, pH, specific conductivity (SPC), and calcium, magnesium, and bicarbonate ion concentrations. Temperature was measured with a standard mercury laboratory thermometer, graduated at 0.1°C intervals in the range of 0-50°C. SPC was taken with a Yellow Springs Instrument Co. Model 33 meter. This latter was a portable, battery-powered instrument with an error of about ±4.5%/reading.

Samples were collected in 500 ml polythene bottles, and tightly capped when filled, below the water surface. They were analyzed for specific ion content on the day of, or day following, collection. Analysis used standard titration methods as outlined by Diehl, Goetz, and Hach (1950) and the ABCM-SAC Joint Committee (1956). Each analysis value was the mean of at least two titrations that differed by less than 3 mg/L. Total and calcium hardnesses were obtained with the Schwarzenbach method using a British Drug Houses kit. Magnesium was obtained by subtraction of calcium from total hardness. Titratable alkalinity was assumed to be HCO_3^- at the pH ranges encountered, and obtained through use of dilute HCl and a suitable indicator. Although individual samples were stood for settling before titration, none was filtered. Alkalinity could not be analyzed in the field.

The pH could often not be measured properly in the caves or jungle settings where samples were collected. To guard against disequilibrium effects, the samples were, as noted, tightly capped upon collection below the water surface. Care was exercised in their transport to the lab, and because of the narrow temperature range of the climate, no significant changes in temperature were introduced. Tests by the researcher, Ford (1971a), Ogden (1976), and Fish (1978) indicate that pH drift is insignificant if these precautions are taken and pH measured within 1-2 days. A Sargent-Welch Model PBL meter was used, calibrated with pH 4 and pH 10 buffer solutions. The meter has a given accuracy of ±0.1 units.

Further analytical treatment of the data involved the calculation of calcium-magnesium ratios, aqueous carbon-dioxide partial pressures (P_{CO_2}), and calcite and dolomite saturation indices (SI_c, SI_d). Calculations were made with a computer program (MILLKEM) written by the author, and based upon the carbonate equilibria approach as reviewed by Langmuir (1971) and Thrailkill (1976). Equilibrium dissociation constants were obtained from the latter author. Because of the bicarbonate nature of the water in the field area, common-ion, and ion-pairing effects were ignored, and comparisons with more complex programs (e.g. WATSPEC, Wigley, 1977) produced little or no difference in calculated values obtained. Drake (1974) estimates the accuracy of careful SI_c and P_{CO_2} calculations from reliable data to be about 0.1 units, where SI_c is calculated as given in Equation 4.1 of this thesis.

Appendix C - Hydrologic Instrumentation

Discharge velocities were measured with a Price AA-type current meter, manufactured by Scientific Instruments Co. Standard error is listed as .002 m/sec. The procedures followed were those of Church and Kellerhals (1970), using the "six-tenths depth" method. Although Church and Kellerhals recommend at least 20 vertical stations to ensure a 5% measurement accuracy, this is not practicable in narrow streams. At the Boiling Hole, from 7-9 vertical stations were used per reading, spaced at 0.5 to 1.0 m intervals.

For stage monitoring, a Stevens Type F recorder (Model 68) was used. It used a spring-driven clock, and float pulley/recording drum arrangement.

Meteorological instruments used were two tipping-bucket gauges, built by AES Engineering, and a Lambrecht thermo-hygrograph, Model 252 C. All used spring-driven clock mechanisms, with charts replaced weekly. The accuracy of the rain recorder was given as ±0.5% error at 12.5 mm/hour, and ±2% at 50 mm/hour. Listed hygrothermograph error was ±1.5% for the total temperature range, and ±2.5% for the humidity.

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