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# Hydrogeology of the Sistema Huautla Karst Groundwater Basin Association for Mexican Cave Studies Bulletin, Vol. 9, 2002

James H. Smith Jr.

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Cover photo: Andy Grubbs injects fluorescein dye into the San Andrés swallet.

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# CONTENTS



(continued)

# CONTENTS
continued

# CONTENTS

continued



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# CONTENTS
continued

# FIGURES



(continued)

# FIGURES
**(continued)**

# FIGURES
**(continued)**

# TABLES

# PLATES
(photographs)

# FOREWORD TO THE AMCS BULLETIN

This Bulletin of the Association for Mexican Cave Studies contains a complete master's thesis submitted in December 1994 to Western Kentucky University, under the supervision of Nicholas Crawford. The full original title was *Hydrogeology of the Sistema Huautla Karst Groundwater Basin, Sierra Mazateca, Oaxaca, Mexico*. The AMCS appreciates the author's permission to publish it in this form.

The typed original was scanned and read by computer. The resulting text has been checked by two people. We apologize for any remaining errors. I have lightly edited the text, and the author has made a couple of minor revisions. Reformatting has reduced the number of pages from the original 338.

Additional cave discoveries in the Huautla area since the thesis was written have been relatively modest. The cave behind the Agua Fría spring (section 5.5) has been explored (*1*) and the map published (*2*). Extensive bolt climbing disclosed some new passage in Cueva de San Agustín, and a new map has been published (*3*). An attempt to follow the water deeper inside Sótano de Río Iglesia was unsuccessful (*3*). The Sistema Huautla Resurgence, previously known as the Southern Resurgence (section 5.9), has been dived to an underwater distance of 1059 meters, with a maximum water depth of 65 meters. At the present end of exploration there, the passage surfaces in two air-filled domes, where no one has so far been able to get out of the water (*1,3*).

*Bill Mixon, AMCS Editor, May 2002*

*1.* Bill Stone. The 1995 Río Tuerto Expedition. *AMCS Activities Newsletter* 22 (May 1997), pp. 163–172.

*2.* Mexico News. *AMCS Activities Newsletter* 25 (May 2002), p. 9.

*3.* Bev Shade and Bill Stone. 2001 InnerSpace Odyssey Expedition. *AMCS Activities Newsletter* 25 (May 2002), pp. 53–71.

## ABSTRACT

Sistema Huautla, in 2002 the world's seventh deepest cave, at 1,475 meters, is one of the most complex vertical drainage systems in the world. The focus of this research was to study the geology, karst hydrology, and speleology of the Sistema Huautla cave system. Literature review and subsequent field mapping identified the geologic formations and tectonic structures that Sistema Huautla and tributary caves are developed within. Structural geology studies within the aquifer indicate that base-level conduits in the mapped portion of the aquifer are formed along a major normal fault system called the Sistema Huautla Fault. Conduits in other sections of Sistema Huautla are formed along the strike and dip of steeply dipping bedding planes. The trend of the cave system is north-south along the strike of steeply dipping limestone beds and the Sistema Huautla Fault system.

The karst hydrology was studied by using nontoxic dyes to trace groundwater flow paths within the aquifer. The direction of groundwater flow in the karst groundwater basin was determined by dye tracing Sistema Huautla to its resurgence to the south. Additional dye-trace studies established flow paths from tributary caves to confluences deep within the cave system. The tributary caves Nita He and Nita Nashi were determined to have 1,100-meter-deep flow paths before intersecting the Scorpion Sump in Sistema Huautla.

The hydrologic boundaries of the karst groundwater basin were defined by mapping the structure and dye tracing. To the west, overthrusted noncarbonate rocks of the Huautla Santa Rosa Fault represents the western structural and hydrologic boundary of the karst groundwater basin. The Agua de Cerro Fault represents the eastern structural boundary of the groundwater basin, as substantiated by dye tracing. The northern boundary is hypothesized to be a structural boundary of the Plan de Escoba Fault.

The cave system was formed along the margin of a retreating clastic cap rock during a period of sustained uplift beginning in the Miocene. The Sierra Mazateca was uplifted approximately 700 meters before the cap rock overlying the limestone was removed by erosion, thus allowing the phreatic skeleton of the Sistema Huautla dendritic vertical drainage system to receive allogenic and autogenic recharge. Gradual drawdown of the water table permitted a complex cave development scenario consisting of elements of the invasion-vadose, drawdown-vadose, and phreatic-water-table theories. Most of the vertical extent of the cave system was developed under vadose conditions not associated with the regional water table as controlled by the Rio Santo Domingo. Drainage from vadose shafts contribute recharge to base-level phreatic passages. Base-level passages are controlled by the potentiometric surface and lithology. Base-level conduits in the northern part of the basin are perched on shale.

Phreatic passage development is not under the influence of exogenetic processes (ideal water table cave development at the regional base level). Instead, phreatic loops with approximately 100 meters of amplitude imply deep phreatic development. The hydraulic gradient of the phreatic portion of the groundwater basin is 3 to 5 percent. Eight kilometers from the basin spring, phreatic passage development occurs 240 meters above the present regional water table.

## ACKNOWLEDGEMENTS

The author wishes to express his gratitude to all of the following: the Huautla cave explorers who gathered cave survey data on twenty-eight expeditions that enabled development of the Sistema Huautla cave map; Mark Minton for countless hours at the computer terminal; field assistants Don Coons, Bill Steele, Mason Estees, Lee Perry, Ed Holladay, and Laura Campbell; Bill Stone for detailed information on the Peña Colorada and Río Santo Domingo; Adreana Bankalti and Gary Napper for translations of professional papers from Spaniosh to English; Nicholas C. Crawford, PhD, Director of the Center for Cave and Karst Studies at Western Kentucky University, for directing my thesis, assistance in supplying equipment for the study, enduring the editing of this voluminous work, and insightful suggestions; thesis committee members Chris Groves, PhD, Wayne Hoffman, PhD, and Kenneth W. Keuhn, PhD, for advice in improving the final product; to granting institutions the Explorers Club, Cave Research Foundation, Richmond Area Speleological Society, Dogwood City Grotto, and Western Kentucky University; and finally to my wife Laura Smith for her love and understanding during the many hours of writing and map drafting.

# CHAPTER 1

# INTRODUCTION AND STUDY AREA

## 1.0 Introduction

In 29 years American cave explorers have conducted 27 expeditions to the highland karst of the Sierra Mazateca of Oaxaca, Mexico, to explore the caves of the region (Figure 1.1). As a result of this effort, in different caves, more than 90 kilometers of cave passages and 600 vertical shafts have been explored and surveyed. Through exploration, separate vertical drainages have been integrated into a single vertical drainage system 1,475 meters deep (Stone, 1994). This drainage system is known as Sistema Huautla. It is currently the fifth deepest cave in the world and the deepest cave in the Western Hemisphere. It is one of 46 caves over 1,000 meters deep (Table 1.1) and one of 250 caves over 500 meters deep in the world (Courbon et al., 1989).

Since the 1950s, caves with great vertical extent have been pursued by both cave explorers and scientists. Cave explorers are mainly interested in exploring the limits of physical exploration in search of ever greater depths and penetration. In the case of the Sierra Mazateca, where some of the greatest depth potential in the world exists, a world depth record is pursued. To be able to measure these great depths, accurate surveys are conducted by cave explorers who in essence become amateur scientists. Scientists, on the other hand, attempt to explain physical processes that have occurred. They have the desire and education to expand the knowledge about the physical nature of caves by studying the interrelationships between geology, hydrology, and speleogenesis. Apart from the cave surveys of cave explorers, little other work has been accomplished with respect to karst hydrology in Mexico in areas with great vertical relief. Hose (1981) detailed the structural geology and hydrology of Sistema Purificación in Tamaulipas, Mexico. Sistema Purificación is a vertical drainage system located in the northern part of the Sierra Madre Oriental and has over 1,000 meters of relief between recharge inputs and hypothesized spring resurgences. East of the Sierra Madre Oriental, Fish (1977) conducted an exhaustive study detailing the hydrogeology of the Sierra de El Abra. The Sierra de El Abra has a hydrologic relief of approximately 700 meters.

Basic investigations of deep caves often involve drainage basin delineation and flow direction studies. Geologic field mapping and dye tracing of subsurface streams are the most commonly used tools to investigate the karst hydrogeology. Dye tracing is one of two ways to determine the direction of karst groundwater flow. Some of the world's deepest dye traces have occurred in Mexico, the former Soviet Union, France, Austria, Lebanon, and Spain (Table 1.2). Dye tracing allows a linear relationship between input and output to be determined. The exact flow path geometry between the input and recovery point is not established.

Physical exploration and survey are the only methods by which a cave stream's precise course can be charted. Exploration and survey are therefore valuable scientific tools, because they often result in a model that permits the major physical features of the aquifer to be visualized. Dye tracing can be used to improve the quantitative model by defining the hydrologic boundaries of the karst groundwater basin.

In the Sistema Huautla, 90 kilometers of active and inactive paleo-conduits have been surveyed. This huge data base, which includes over ten thousand survey stations, when reduced and plotted by computer, produces a precise spatial view of one of the world's most complex vertical karst drainage systems.

Exploration and mapping of Sistema Huautla have resulted in many important questions about the hydrology, geology, speleogenesis, and geomorphology of Sistema Huautla. How does the local structure and stratigraphy relate to cave development? What role, if any, does a retreating clastic cap rock play in karstification and cave development? Where does this

vast system of vertical shafts ultimately drain to, and where are the springs? In what areas of Sistema Huautla do other unconnected deep caves and streams originating from swallets enter the system? This investigation is an attempt to answer these and other questions about Sistema Huautla.

### 1.1 Purpose

The major goal of this thesis was to identify and explain the hydrogeology of the Sistema Huautla Karst Groundwater Basin. The following are the primary objectives used to achieve this goal.

- Determine the location of the spring, or springs, of Sistema Huautla and the vertical extent of drainage within the karst groundwater basin.
- Determine the type of subterranean outflow for the system (i.e., single conduit outflow or multiple outflow conduits signifying a distributary discharge system).
- Delimit the areal extent of the karst groundwater basin.
- Establish the geologic structure and stratigraphy of the karst groundwater basin from geologic field mapping and determine the influence it has on cave development.
- Estimate geologic time of karstification in the Sierra Madre Oriental and relative age of the cave system.
- Determine speleogenesis and prepare a model of cave development for this part of the Sierra Madre Oriental based on cave development of Sistema Huautla in the Sierra Mazateca and Sistema Cuicateco in the Sierra Cuicateco.
- Determine the hydrologic routes of explored caves not physically connected into Sistema Huautla to confluences within Sistema Huautla.
- Determine the precise location of inputs into Sistema Huautla from sinking surface streams.

### 1.2 Study Area

The Sistema Huautla Karst Groundwater Basin is located in the northeast corner of the state of Oaxaca, Mexico. Situated in the interior of the Sierra Mazateca, the karst highlands are home to 100,000 Mazatec Indians. The largest town and seat of municipal authority

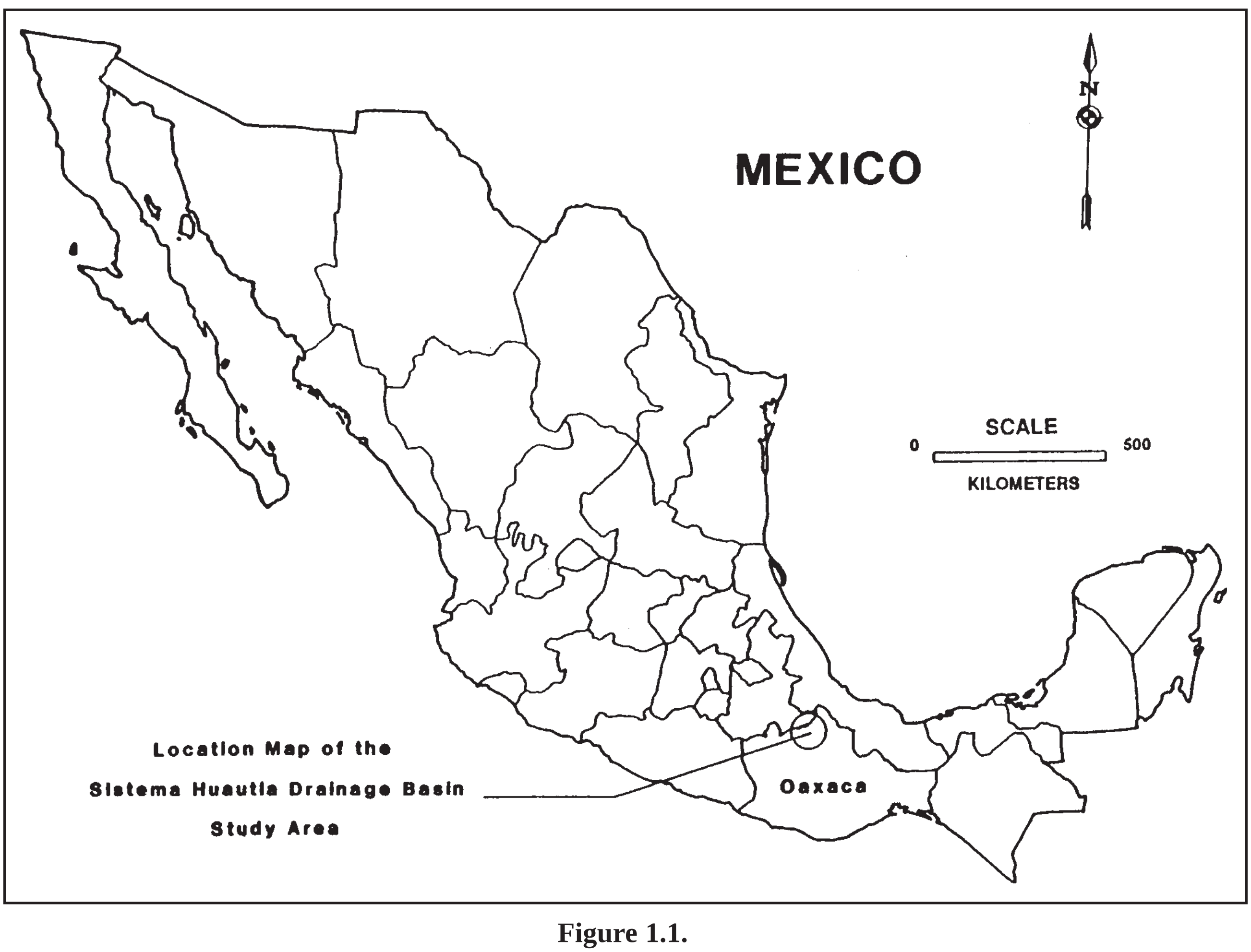



**Figure 1.1.**

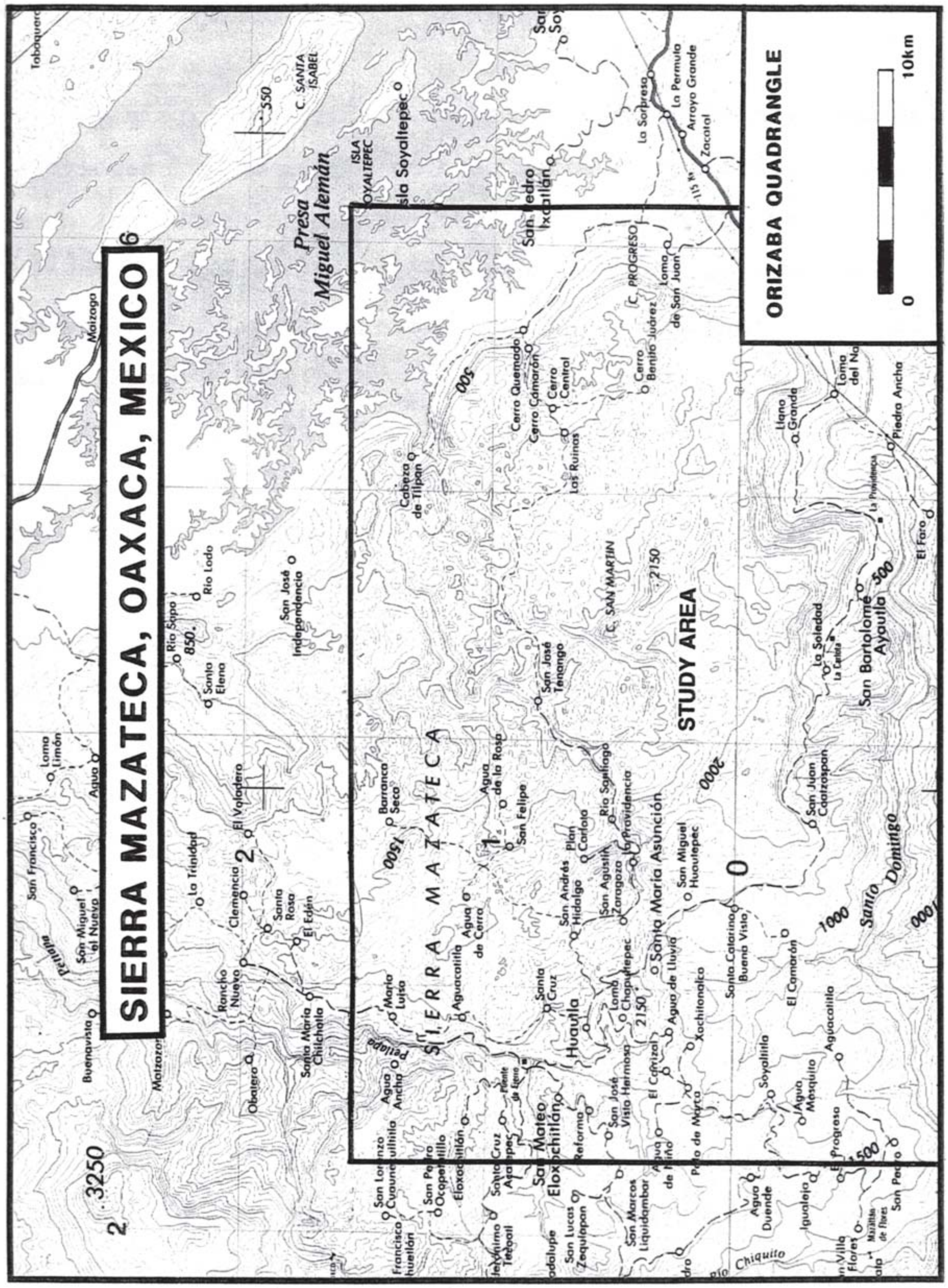

SIERRA MAZATECA, OAXACA, MEXICO
STUDY AREA
ORIZABA QUADRANGLE
0
10km
Presa Miguel Alemán
SIERRA MAZATECA
Huautla
San Mateo Eloxochitlán
San Bartolomé Ayautla
Santa María Asunción
San José Tenango
C. SAN MARTIN
C. PROGRESO
Cerro Quemado
Cerro Camarón
Cerro Central
Cerro Benito Juárez
Loma de San Juan
Las Ruinas
Cabeza de Tilpan
San Pedro Ixcatlán
Isla Soyaltepec
Santo Domingo
Río Santiago
Plan Carlota
San Andrés Hidalgo
San Agustín Zaragoza
Agua de Cerro
Agua de la Rosa
San Felipe
Barranca Seca
Santa Cruz
Loma Chapultepec
Agua de Lluvia
Xochitonalco
San Miguel Huautepec
Santa Catarina Buena Vista
El Camarón
La Soledad
San Juan Coatzospan
El Faro
Piedra Ancha
Llano Grande
Santa Elena
Río Sapo
Río Lodo
San José Independencia
El Voladero
Clemencia
La Trinidad
Santa Rosa
El Edén
Rancho Nuevo
Santa María Chilchotla
Buenavista
San Miguel el Nuevo
San Francisco
Loma Limón
Obsidero
Agua Ancha
Aguacatitla
María Lujo
Soyaltitla
Agua Mosquito
Aguacatitla
Progreso
Igualeja
Agua Duende
Chiquito
Moizogo
C. SANTA ISABEL
La Sorpresa
La Permuta
Arroyo Grande
Zacatal
Loma del No
El Canizal
San José Vista Hermosa
Reforma
Palo de Marca
3250
1500
2150
2000
1000
500
850
550

Figure 1.2.

**Table 1.1.** Deepest Surveyed Caves in the World (June 1994)

| | Cave | Depth (meters) |
|---|---|---|
| 1. | Reseau Jean-Bernard, France | 1602 |
| 2. | Gouffre Mirolda, France | 1520 |
| 3. | Vjacheslav Pantjukhin, Georgia | 1508 |
| 4. | Lamprechtsofen, Austria | 1483 |
| 5. | **Sistema Huautla, Mexico** | 1475 |
| 6. | Sistema del Trave, Spain | 1441 |
| 7. | Boj-Bulok, Uzbekistan | 1415 |
| 8. | Sima de Las Puertas de Illamina, Spain | 1408 |
| 9. | Sistema Cheve, Mexico | 1386 |
| 10. | Snieznaja Pieszciera–Mezhonnogo, Georgia | 1370 |
| 11. | Cehi 2, Slovenia | 1370 |
| 12. | Lukina Jama, Croatia | 1355 |
| 13. | Reseau de la Pierre Saint-Martin, France and Spain | 1342 |
| 14. | Kievskaja, Russia | 1330 |
| 15. | Siebenhengste-Hohganthohlonsystem, Switzerland | 1324 |
| 16. | Gouffre Berger–Reseau Rhododendrons, France | 1278 |
| 17. | Cosa Nostra Loch, Austria | 1265 |
| 18. | Torca de los Rebecos, Spain | 1255 |
| 19. | Vladimir Iljukhin, Georgia | 1240 |
| 20. | Akemati, Mexico | 1226 |
| 21. | Abisso Olivifer, Italy | 1220 |
| 22. | Schwersystem, Austria | 1219 |
| 23. | Abisso Veliko Sbrego, Slovenia | 1198 |
| 24. | Complesso Fighiera–Farol–Antro del Corchia, Italy | 1190 |
| 25. | Sistema Aranonera, Spain | 1185 |
| 26. | Dachstain-Mammuthole, Austria | 1180 |
| 27. | Jubilaumsschacht, Austria | 1173 |
| 28. | Anou Ifflis, Algeria | 1170 |
| 29. | Sima 56 de Andara, Spain | 1169 |
| 30. | Kijahe Xontjoa, Mexico | 1160 |
| 31. | Gouffre de la Bordure de Tourugne No. 6, France | 1157 |
| 32. | Abisso W. Le Donne, Italy | 1156 |
| 33. | Sistema Badalona, Spain | 1150 |
| 34. | Sistema del Xitu, Spain | 1148 |
| 35. | Arabikskaja Kujbyshevskaja, Georgia | 1110 |
| 36. | Schneeloch, Austria | 1101 |
| 37. | Sima G.E.S.M., Spain | 1198 |
| 38. | Jagerbrunn (en) Trogsystem, Austria | 1078 |
| 39. | Sotano de Ocatempa, Mexico | 1064 |
| 40. | Muttseehohle, Switzerland | 1060 |
| 41. | Pozzo della Neve, Italy | 1050 |
| 42. | Akemabis, Mexico | 1050 |
| 43. | Vandima, Slovenia | 1042 |
| 44. | Sotano de Olbastl, Mexico | 1040 |
| 45. | Cukurpinar Dudeni, Turkey | 1037 |
| 46. | Meanderhole, Austria | 1028 |
| 47. | Torca Urriello, Spain | 1022 |
| 48. | Coumo d’ Hyouernedo, France | 1018 |
| 49. | Abisso Ulivifer, Italy | 1007 |

Sources: Minton (1991), Steele (1994)

**Table 1.2.** Deepest Dye Traces in the World

| | Cave | Depth (meters) |
|---|---|---|
| 1. | Sistema Cheve, Mexico | 2450[1] |
| 2. | Napra Cave, Russia | 2345[2] |
| 3. | V. V. Ilujukhina–Reproa, Arabika | 2308[3] |
| 4. | Ural'skaja-Macaj, Russia | 1800[3] |
| 5. | Gouffre de Pourtet–Bentia, France | 1622[3] |
| 6. | Lamprechtsofen, Austria | 1600[3] |
| 7. | Gouffre Touya de Lietfontaine des Fees, France | 1598[3] |
| 8. | Houet Faouar Dara-Antelias, Lebanon | 1573[3] |
| 9. | Laminako Ateak–Illamina, France and Spain | 1538[3] |
| 10. | Gouffre Des Trios Dents–Iscoo, France | 1520[3] |

Sources: 1. Smith (1990 and 1991b).
2. *Caves and Caving*, #47, p. 33, spring 1990.
3. Courbon, et al. (1989).

in the region is Huautla de Jiménez, a highland city of 10,000 inhabitants.

The Municipio of Huautla de Jiménez is located 240 kilometers south of Mexico City, 150 kilometers north of the city of Oaxaca, and 179 kilometers west of Veracruz (Figure 1.2). Huautla is world famous for an ancient Mazatec Indian culture and its psychoactive mushroom religion that gained notoriety in the 1960s with counter-culture groups. Historically, they were one of the few Indian tribes to remain unconquerable in their mountain setting. Archaeologists found that the caves of Huautla had an important function in religious ceremonies and as burial caves. The artifacts found in the caves establish that the highland communities of Huautla were an important crossroads of trade between the Gulf Coastal and Interior Basin civilizations (J. Steele, 1987).

More recently, the region has become world famous for its deep caves. Huautla is also the namesake for Sistema Huautla, a labyrinth consisting of 55.9 kilometers of mapped cave passages (Stone, 1994). It is also the name given to the karst groundwater basin.

### 1.2.1 Physiography

Viniegra (1965) defined and described the physiographic provinces in the region of the Cuenca de Veracruz. The mountains south of Mexico City, situated in the Neovolcanic Transverse Range, are an extension of the Sierra Madre Oriental and have been named the Sierra Madre Oriental del Sur. Ramos (1983) refers to the mountains west of the Cuenca de Veracruz as the Sierra Juárez subrange and geologic subprovince of the Sierra Madre Oriental del Sur. Recent Mexican topographic maps of the Sierra Madre Oriental del Sur have subdivided the mountain range into a series of ranges extending from the Neovolcanic Plateau to the Isthmus of Tehuantepec. The study area is in the Sierra Mazateca, which is bordered to the north by the Sierra Zongolica, to the south by the Sierra Juárez, to the west by the Tehuacán Valley, and to the east by the Gulf Coastal Plain in the Cuenca de Veracruz.

### 1.2.2 Climate

The Sierra Mazateca are the closest mountains to the Gulf of Mexico and receive tremendous rainfall from orographic precipitation. Huautla is situated between the arid western ranges and the wet front ranges of the Sierra Mazateca. Rainfall averages range from 400 millimeters on the western side of the range to 4.5 meters on the eastern flank of the Sierra Mazateca at Cerro Rabón. Servicio Meteorológico Nacional has monitored precipitation in Huautla de Jiménez with 24 years of continuous record. Isohyetal information from the Orizaba 1:250,000 hydrology map indicates the mean annual rainfall in the study area is 2,661 millimeters. The highest annual rainfall ever recorded in the area occurred in 1969 with measured precipitation of 3,872 millimeters. The lowest rainfall occurred during 1959 with 1,869 millimeters. Located 10 kilometers east of Huautla de Jiménez (map distance) is Tenango. Lower in elevation and located towards the wet gulf coastal lowlands, Tenango has a mean annual rainfall of 5,002 millimeters. The highest recorded rainfall was measured in 1960 at 6,536 millimeters and the lowest extreme was measured in 1967 at 3,052 millimeters.

The Sistema Huautla Karst Groundwater Basin is located between the two rainfall recording stations at Huautla and Tenango and their respective averages of

2,661 and 5,002 millimeters. This range in rainfall, averaged over 10 kilometers of linear distance, reveals a steep precipitation gradient of 233 millimeters per kilometer.

Isotherms across the Sierra Mazateca range from 16 degrees centigrade on the highest portion of the Sierra Mazateca to the west to 24 degrees centigrade on the eastern escarpment. The mean annual temperature for Huautla de Jiménez is 17.25 degrees centigrade.

### 1.3 Regional Hydrology

Discharge from the Sistema Huautla Karst Groundwater Basin is a contributor to one of the most significant southern Gulf drainage basins in Mexico, the Papaloapan Drainage Basin. Tamayo and West (1964) state that the Papaloapan drainage basin has its origin in the Sierra Juárez. The headwaters are drained by interior structural basins of Tehuacán and Cuicatlán by the Río Salado and Río Tomellin and unite to form the Río Santo Domingo, which flows west to east through a 1.5-kilometer-deep canyon in the Sierra Madre Oriental of Oaxaca. Ultimately, the Río Santo Domingo empties into the Río Papaloapan in the Valle Nacional and discharges into Laguna de Alvarado in the Gulf of Mexico.

It was hypothesized that the Sistema Huautla Groundwater Basin discharges into the Río Santo Domingo to the south of the drainage basin. South of the Río Santo Domingo, the Sistema Cuicateco Karst Groundwater Basin was proven by a dye trace to also discharge into the Río Santo Domingo to the north (Smith, 1991(b)).

Three kilometers north of Huautla de Jiménez, several karst groundwater basins share a common divide with the Sistema Huautla Karst Groundwater Basin. They are hypothesized to drain to the Río Petlapa. The Río Petlapa drains to the northeast and flows into the Presa Miguel Alemán reservoir located along the east side of the Sierra Mazateca front range.

### 1.4 Caves of Huautla

It is appropriate at the onset of this thesis to describe the caves of the Huautla Plateau. Table 1.3 lists the cave entrances of Sistema Huautla. The names that appear under Sistema Huautla are entrances of tributary stream caves that have been integrated by survey into Sistema Huautla (Figures 1.3 and 1.4). The name of the entrance to the system is indicated on Table 1.3 followed by the depth from that entrance to the deepest explored point. Then the depth at which this entrance connects with the main drainage cave, Sótano de San Agustín, or into another tributary stream cave, is provided. The overall depth of the cave system is 1,475 meters from Nita Nanta to the bottom of Sótano de San Agustín. Tributary streams flow into this dendritic vertical drainage system at various locations.

In all, there are 17 entrances to the system. The

**Table 1.3.** Cave Entrances of Sistema Huautla

| Entrance | Information |
|---|---|
| Sótano de San Agustín | 859 meters deep |
| La Grieta | 984 meters deep and connected to Sótano de San Agustín at 720 meters |
| Nita Nanta | 1,475 meters deep and connected to Sótano de San Agustín at 1,098 meters |
| Li Nita | 1,242 meters deep and connected to Sótano de San Agustín at 1,030 meters |
| Nita Sa | 586 meters deep before connecting to Nita Nanta |
| Nita Zan | 216 meters deep before connecting to Nita Sa |
| Bernardo’s Cave | 647 meters deep before connecting to Nita Nanta |
| Nita Ina | 277 meters deep before connecting to Bernardo’s Cave |
| Nita Lajao | 73 meters deep before connecting to Li Nita |
| Nita Mazateca | 146 meters deep before connecting to Nita Sa |
| Nita Lata | 95 meters deep before connecting to Nita Zan |

previously mentioned cave entrances to Sistema Huautla are the major entrances. Next, there are a number of major deep caves that are hypothesized to be a part of Sistema Huautla hydrologic drainage system or enter the main hydrologic flow route at some point between Sistema Huautla and its springs. To avoid confusion between these caves and the entrances of Sistema Huautla, the caves and their depths are listed in Table 1.4. The location and names of all of the caves in the Huautla area are indicated on Figures 1.5 and 1.6.

### 1.5 Cave Exploration in the Huautla Area

The first cave explorers in the Huautla area were ancient Indians who migrated into the mountains before the Classical Period, A.D. 200–900. It is not clear why they settled in this area, since the terrain is difficult and the soil is poor for agriculture. Artifacts found in Blade Cave are from the Classic Period between A.D. 200 and 900 and from the Early Post Classic Period dated at A.D. 1250. The artifacts reveal that the use of the caves was ceremonial in nature, and they constitute the earliest record of the Mazateca culture (J. Steele, 1987). Man-made structures, terraces, and walls of undetermined age are found in local caves and indicate that they served a more utilitarian function that is not clearly understood. It is thought that people may have used caves as fortifications for temporary refuge from hostile neighbors. Because of the location of artifacts in remote and nearly inaccessible reaches of the local caves, the ancient Indians must have been daring and intrepid explorers. Another example of their audaciousness toward cave exploration is the evidence left in Vine Cave and Alter Cave. The Indians were able to access cave entrances in the middle of a 200-meter-high sheer cliff and build stone alters (Stone, 1984).

Cave exploration of modern times has taken on a different function, with the primary interests being more on sport and scientific research. Sport enthusiasts are concerned with total exploration of the cave. The scientific aspects of cave exploration involve attempts to understand the hydrology and geology of the caves. The following sections highlight the significant contributions to the knowledge of the caves of Huautla.

#### 1.5.1 Pre–Huautla Project

From 1964 to 1971 American and Canadian cave explorers conducted eight expeditions and field trips to the cloud-forest elevation, karst highlands of the Sierra Mazateca, for the purpose of investigating the

**Table 1.4.** Caves in the Hypothesized Karst Groundwater Basin

| Cave | Information |
|---|---|
| Sótano de Agua de Carrizo | 843 meters deep, including Nita Ske; only 6 meters from Scorpion Sump in Sótano de San Agustín; 3,748 meters long |
| Nita Ske | 258 meters deep before connection to Sótano de Agua de Carrizo; 728 meters long |
| Nita Ka | 760 meters deep and 1,813 meters long; 80 vertical meters and 100 meters from connecting to the Scorpion Sump of Sótano de San Agustín |
| Nita He | 594 meters deep and 1,554 meters long |
| Nita Nashi | 640 meters deep and 3,523 meters long |
| Nita Ntau | 306 meters deep and 540 meters long; connects to Nita Nido at the bottom of the cave |
| Nita Nido | 309 meters deep and 755 meters long; connects to Nita Ntau |
| Cueva de San Agustín | 478 meters deep and 1,426 meters long |
| Sótano del Río Iglesia | 531 meters deep and 4,205 meters long |
| Cueva del Zapato | 253 meters deep and 716 meters long |
| Cueva de Agua Carlota | 504 meters deep and 4,400 meters long |

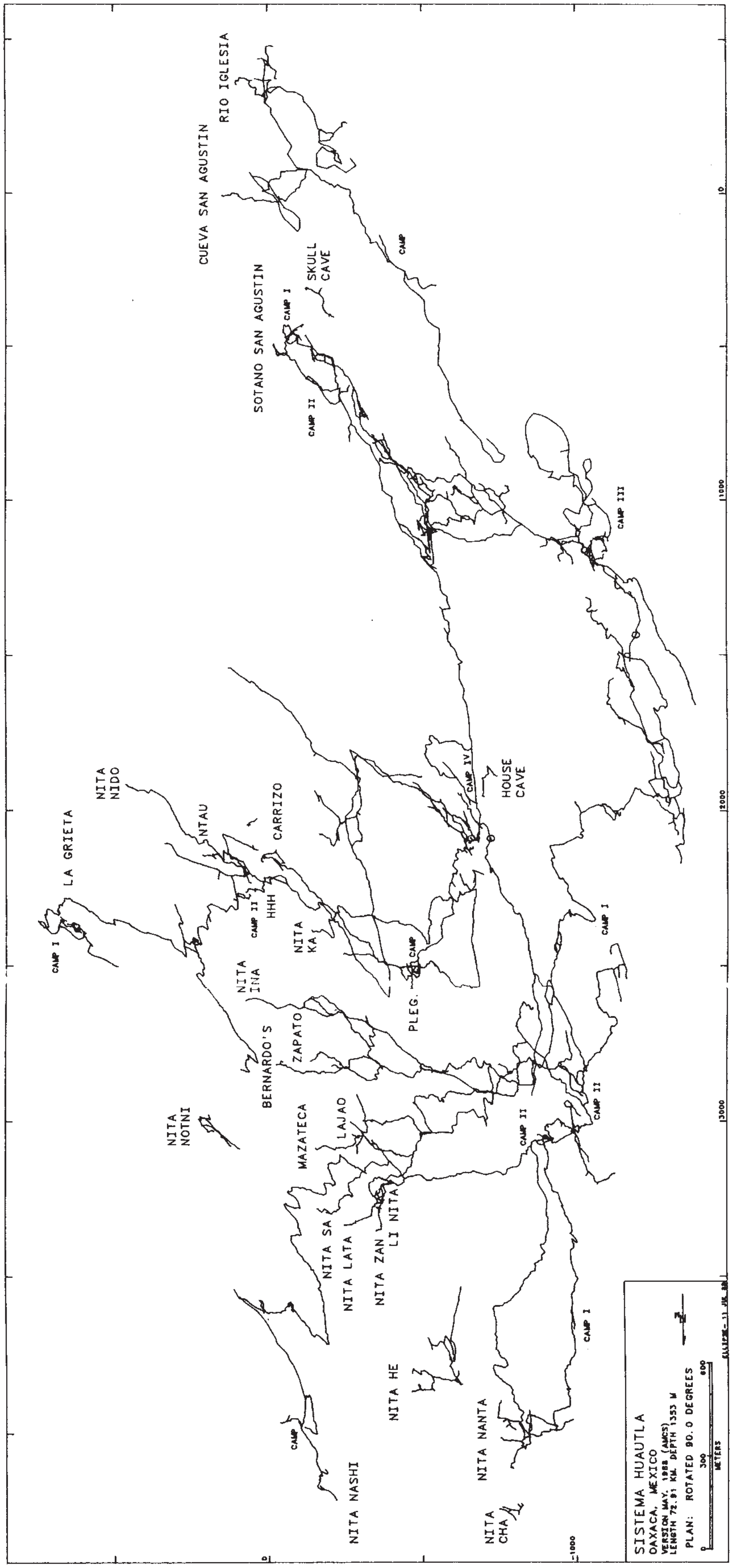



**Figure 1.3.** Plan view of Sistema Huautla. Source: Smith 1988c.

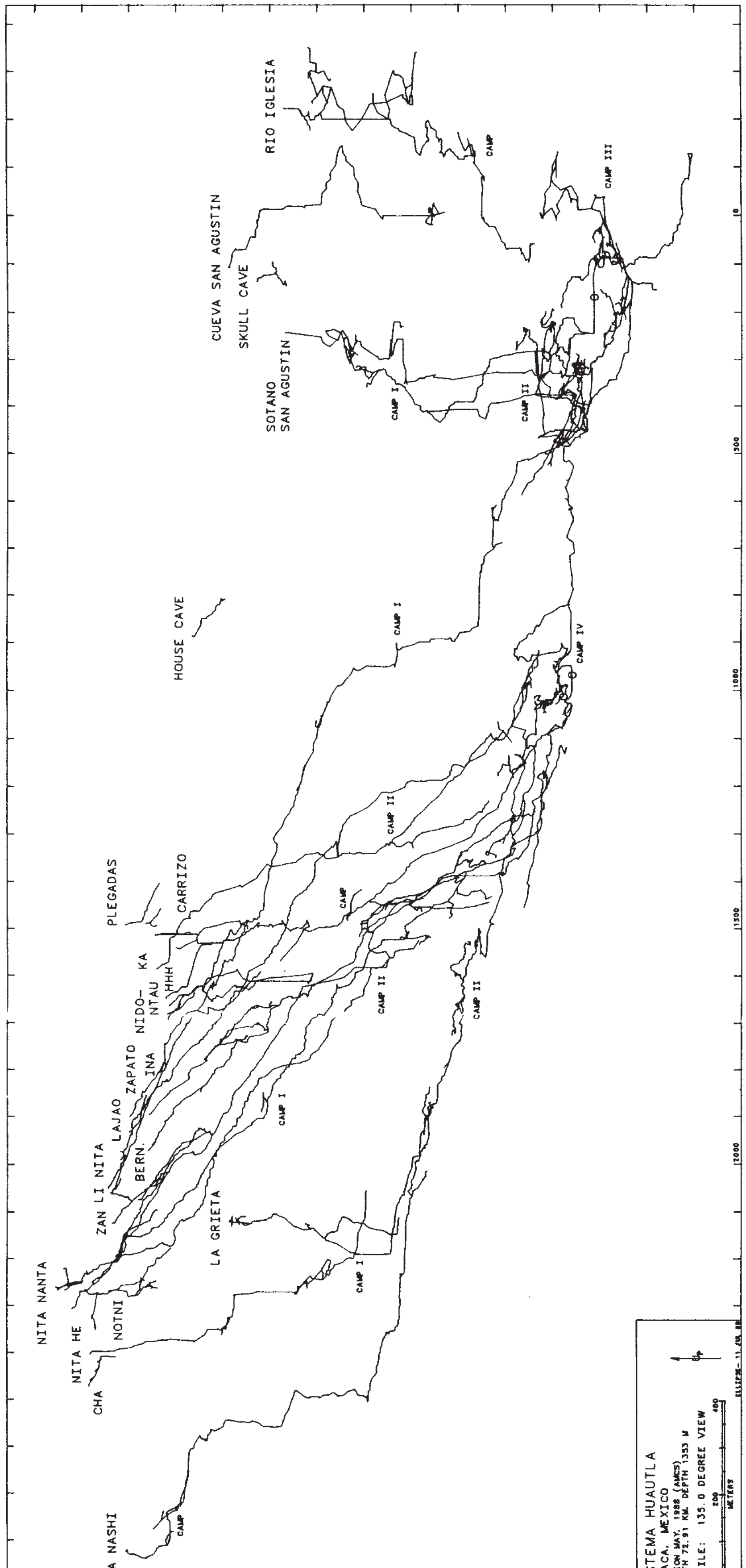



**Figure 1.4.** Vertical profile of Sistema Huautla. Source: Smith 1988c.

caves of the region.

The Huautla karst area was discovered by locating karst features on 1:250,000 scale topographic maps. In an effort to verify the discovery, the first explorers ventured to Huautla de Jiménez in 1965 for the purpose of finding high altitude karst with world-class vertical cave development potential. Many large cave entrances in huge dolinas were discovered (Russell, 1964 and 1965).

After the initial investigation of the Huautla area, a later expedition reported that the cave Sótano de San Agustín was explored to a depth of approximately 200 meters, with good leads remaining for further exploration. Maps were published showing locations of caves, stream sinks, and dolinas (Fish, 1966; Fish and Russell, 1966).

In 1967, Sótano de San Agustín was explored to a depth of 447 meters. The cave continued, but exploration was discontinued due to a lack of rope (Fish, 1967). During Christmas of 1967 Canadian cavers reached the bottom of Sótano del Río Iglesia at –533 meters for a Western Hemisphere depth record (Boon, 1969; Drummond, 1968). They made observations about Sótano del Río Iglesia with respect to the geomorphology and speleogenesis and concluded that the largest chambers were formed phreatically (Morris, 1968).

Cave explorations in Sótano de San Agustín during 1968 by American and Canadian cave explorers reached a depth of 620 meters at a sump, a new hemisphere depth record. However, there was doubt that the true bottom had been reached (Fish, 1970). Cueva San Agustín, explored to –150 meters, was thought to be a possible paleohydrologic link to Sótano de San Agustín (Boon, 1969). Cueva de Agua Carlota was explored to –150 meters and a length of 1.4 kilometers. It was thought that there was little hope of extending the cave beyond a sump (Coward, 1971).

Cueva de San Agustín was revisited in 1970. The cave was explored to a depth of –457 meters and ended in an enormous chamber of boulders. Cueva de Santa Cruz, the northernmost cave of the area visited, was explored to –300 meters and ended in a sump (Finn, 1971).

### 1.5.2 Huautla Project Cave Explorations

After a five year moratorium of the Huautla caving area due to problems with the local Indians, an expedition during the Christmas season of 1976 marked the beginning of the Huautla Project. More than 21 expeditions were to return yearly for the next 18 years.

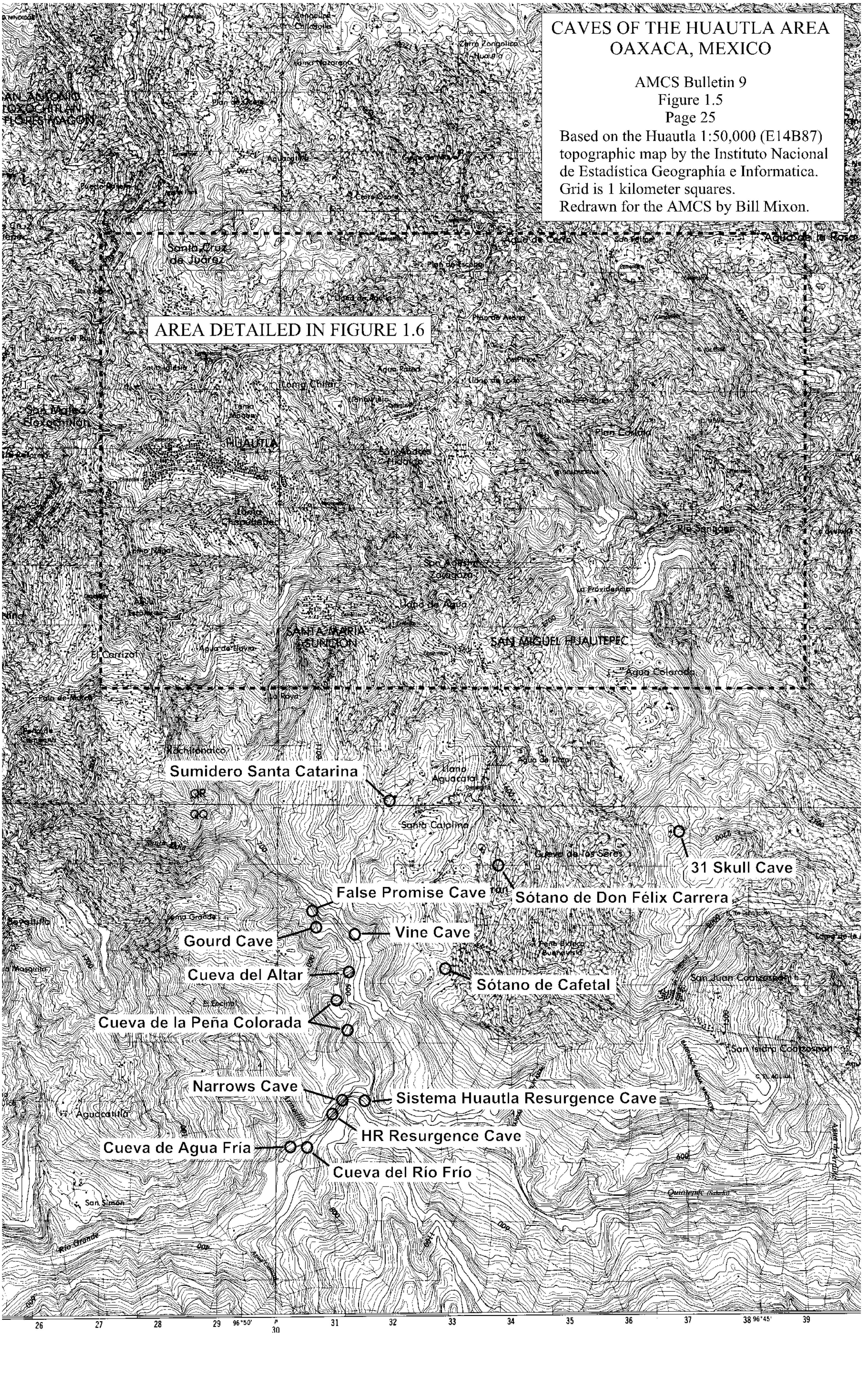
It was believed in 1968 that Sótano de San Agustín had not been fully explored. It was revisited in 1976, and exploration was initiated from the deepest cave camp in the Western Hemisphere at –520 meters. Exploration stopped at the top of a shaft at –760 meters, thus setting a new depth record. La Grieta was also revisited, and exploration stopped at the top of a 60-meter-deep shaft at –250 meters (Stone, 1977; Smith, 1977).

With many options for cave exploration in the Huautla area, Sótano de San Agustín was revisited in the spring of 1977. Exploration was conducted from Camp II, expanding the length and depth of the cave. It was realized during this exploration that many infeeding streams indicated many more vertical drainage routes and thus the probability of higher entrances. Most of the cavers up to that time thought of each cave as an individual stream system. Progress towards pushing San Agustín deeper was terminated by a sump at –859 meters that resulted in a new depth record. Exploration strategy changed, and cave entrances higher in elevation than Sótano de San Agustín were explored. The Huautla Project was formally organized in the spring of 1977 (W. Steele, 1977(a), Smith, 1977).

New exploration in May of 1977 in the cave La Grieta produced a 665-meter-deep cave and four kilometers of surveyed passage extending from Camp I at –280 meters (W. Steele, 1977(b)). During Christmas of 1977, exploration in La Grieta revealed a vertical drainage route 760 meters deep and 10 kilometers long. Exploration of the lower conduits of La Grieta was accomplished from a ten-day camp at Camp II at –520 meters (W. Steele, 1977(b); Smith, 1977). Australian cavers explored Sótano de Agua de Carrizo to –778 meters, without a camp.

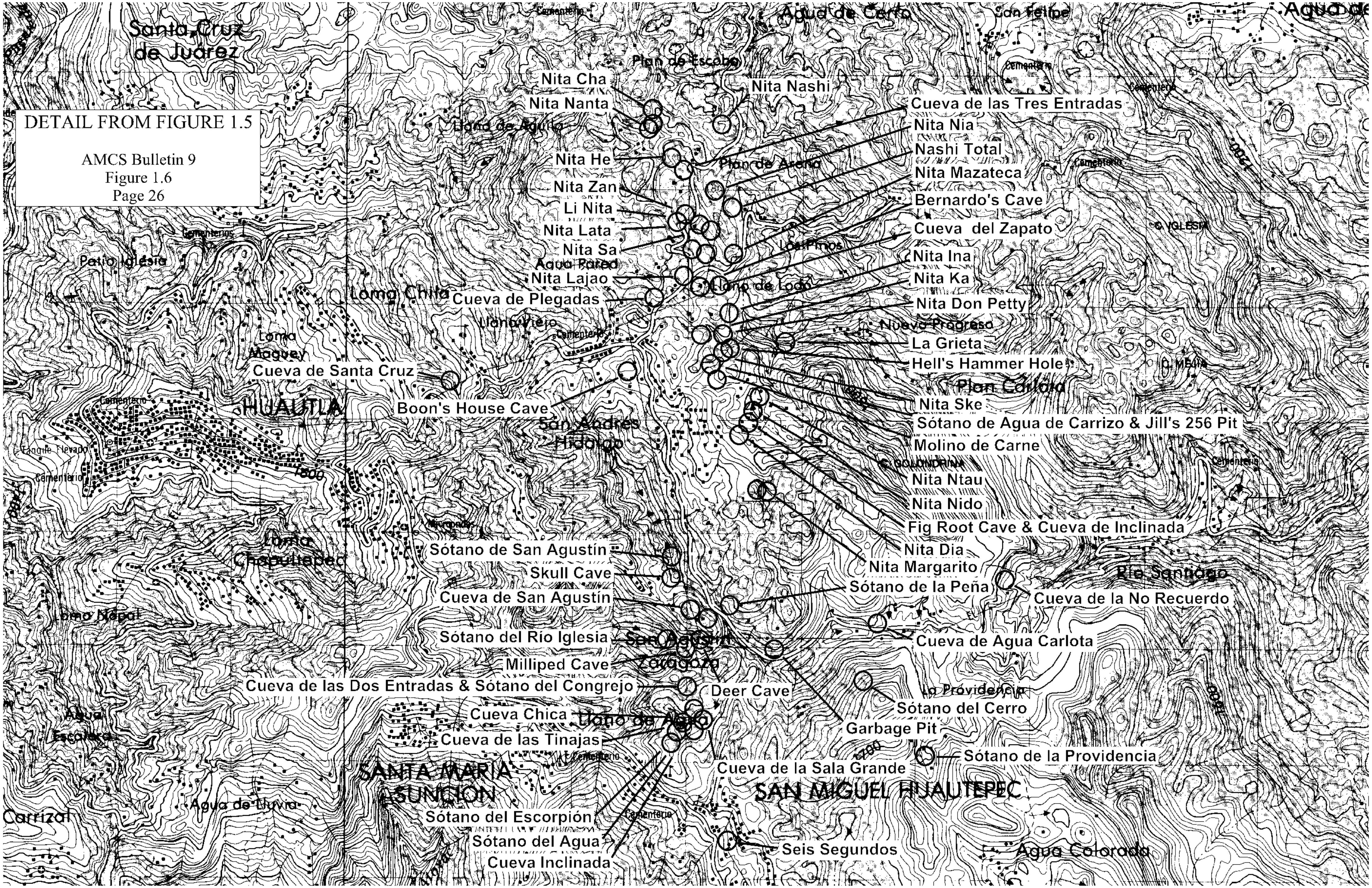
In the spring of 1978, a six-week-long expedition to Sótano de Agua de Carrizo revealed the most complex vertical drainage system yet discovered in the Sierra Mazateca. The cave was explored down three vertical shaft series to bottoms at 843, 841, 676 meters in depth. The cave was surveyed to a length of 3.5 kilometers. A five-day camp at –347 meters continued the exploration after the deepest route was bottomed from surface-originated trips (Stone, 1978; Smith, 1978).

During the spring of 1977, an expedition to Sótano de San Agustín to the –859 sump revealed that a diving expedition was required to explore the flooded conduit. The expedition was the first Explorers Club sponsored Huautla Project expedition. Other discoveries in Sótano de San Agustín included finding the largest chamber in the Sierras. Anthodite Hall, which is larger than the Astrodome, was discovered from Camp III at –700 meters. Two additional camps, each lasting eight days, were fielded from Camp II, and Kinepak Canyon was discovered. Kinepak Canyon is


CAVES OF THE HUAUTLA AREA
OAXACA, MEXICO
AMCS Bulletin 9
Figure 1.5
Page 25
Based on the Huautla 1:50,000 (E14B87) topographic map by the Instituto Nacional de Estadística Geographía e Informatica.
Grid is 1 kilometer squares.
Redrawn for the AMCS by Bill Mixon.
AREA DETAILED IN FIGURE 1.6
Santa Cruz de Juárez
HUAUTLA
SAN MIGUEL HUAUTEPEC
Agua Colorada
Sumidero Santa Catarina
Santa Catalina
31 Skull Cave
False Promise Cave
Sótano de Don Félix Carrera
Gourd Cave
Vine Cave
Cueva del Altar
Sótano de Cafetal
Cueva de la Peña Colorada
San Juan Coatzospan
San Isidro Coatzospan
Narrows Cave
Sistema Huautla Resurgence Cave
HR Resurgence Cave
Cueva de Agua Fria
Cueva del Río Frío
Aguacatitla
San Simón
Río Grande
26
27
28
29
96°50'
30
31
32
33
34
35
36
37
38
96°45'
39

DETAIL FROM FIGURE 1.5

AMCS Bulletin 9
Figure 1.6
Page 26



the hydrologic link to the ridge-top vertical drainages of La Grieta and Sótano de Agua de Carrizo. La Grieta and Sótano de Aqua de Carrizo are separated by collapse only a few meters apart (Stone, 1979; Smith, 1978).

1.5.3 Sistema Huautla

In the spring of 1980, the Explorers Club–sponsored Río Iglesia Expedition explored the highest entrances of the Huautla area, Nita Nanta and Li Nita. Nita Nanta, the highest ridgetop entrance, was explored to –520 meters and still continued at the end of the expedition.

Li Nita was physically connected to Sótano de San Agustín from Camp I at –620 meters during three camps lasting seven, seven, and thirteen days. The connection formed a system collectively named Sistema Huautla 1,221 meters deep, the third deepest cave in the world (Stone, 1982; W. Steele, 1981; Smith, 1980).

Stone (1982) wrote after the 1981 Expedition that "Nita Nanta is the most difficult cave in the System." Nita Nanta was bottomed at –927 meters from Camp I at –520 meters. The 927-meter route was to later be called the historic route. Li Nita produced a new deep vertical shaft series to a depth of 920 meters. The Sótano de San Agustín sump was dove and the system's depth increased to 1,250 meters (Stone, 1982).

In 1982, a return trip to Nita Nanta yielded a new deep vertical shaft series that was bottomed at –760 meters, below the Football Stadium. The Football Stadium Chamber is the junction of several large waterfalls entering from unseen heights. A paleo-passage was explored to a constriction from which strong wind blew (W. Steele, 1983).

During the spring of 1983, the Huautla Project fielded two expeditions. Bill Stone and others dove the Cueva de Peña Colorada, which had been discovered in May 1981, and found a large phreatic cave passage. It was thought that Cueva de Peña Colorada was a likely resurgence cave for Sistema Huautla, located 10 kilometers to the north (Stone, 1983(a) and 1983(b)).

Meanwhile, exploration in the Huautla area continued, and a connection of Nita Sa to Nita Nanta at –587 meters revealed a new deep tributary drainage system. Nita Nanta was explored beyond the terminus of 1982 in the Football Stadium to –950 meters via the Rat Tail File Series, a paleo-shaft series. Below the shaft series, a base-level stream was discovered (Smith, 1983).

During 1984, Nita Nanta was explored from a new entrance called Nita Zan, and Nanta was explored to –1,080 meters to a sump from Camp II at –587 meters (Smith, 1984).

Also in the spring of 1984, Cueva de Peña Colorada was surveyed to a length of 7.8 kilometers and explored in a northerly direction towards Sistema Huautla for 3.5 kilometers, before progress was terminated at the limit of SCUBA diving technology, 150 meters into sump VII at 50 meters depth (Stone, 1984).

In 1985, a connection between Sótano de San Agustín and La Grieta was made at the end of Kinepak Canyon from Camp II, –520 meters, on one of two eight-day camps. The La Grieta–Sótano de San Agustín connection was the second big connection into Sistema Huautla. The connection added 10 kilometers of length to Sistema Huautla (Smith, 1987).

The next expedition to Huautla was in 1987. A SCUBA dive between Nita Nanta and Sistema Huautla was the third big connection into Sistema Huautla. The dive was supported from Camp IV at –600 meters in Sótano de San Agustín. Sistema Huautla became the fourth deepest cave in the world at 1,353 meters deep (Smith and Steele, 1988).

In 1988, field work for this Master's thesis was conducted. From an eleven-day cave camp at –700 meters in Sótano de San Agustín, high leads were climbed to access otherwise inaccessible passages. Dye traces were conducted to the karst groundwater basin's spring and to confluences in Sistema Huautla in an attempt to integrate unconnected tributary caves. Nita Ka was explored to –758 meters (Smith, 1988(b)).

During the 1989 expedition, Nita Ka was revisited and explored to –760 meters. Other small caves were explored in an attempt to find a way into La Grieta's Do Da Dome (Smith, 1991(c)).

In 1990, Cueva de Agua Carlota was explored to –504 meters and surveyed to a length of 4.4 kilometers. Dye tracing and groundwater chemistry studies were also conducted in the area (Smith, 1991(a)).

The 1994 Sótano de San Agustín Expedition dove two sumps, 430 and 165 meters in length, and mapped 3.5 kilometers of passage beyond the –859 sump of Sótano de San Agustín. The explorers bypassed six sumps and extended the depth of Sistema Huautla to 1,475 meters at Sump 9. The expedition extended Sistema Huautla due south 1.5 kilometers. It was reported that the passage zig-zagged NW-SW before sump nine was reached. A major infeeding stream was encountered with a greater discharge than any stream previously known in Sistema Huautla (Stone, 1994). Cueva de Santa Cruz, explored to a depth of 312 meters and 1.44 kilometers long in 1970, was revisited in 1994 to find that there was no possibility of extending the cave (Smith, 1994).

# CHAPTER 2

# IMPORTANT IDEAS OF KARST HYDROLOGY

## 2.0 Introduction

The science of karst hydrogeology has greatly advanced from the early days when karst philosophers attempted to explain the origin of caves and their development relative to the water table. Those ideas were so provocative that some researchers even argued the existence of a water table in karst landscapes. Modern karst scientists recognize karst as being a product of geomorphic processes. The end result of these processes is dependant on many natural physical parameters. Because these physical parameters are so numerous, many are a science unto themselves. To fully investigate karst requires many scientific disciplines, including mineralogy, structural geology, stratigraphy, geomorphology, hydrology, chemistry, cartography, meteorology, physics, mathematics, and engineering.

In order to understand how caves develop, karst hydrology, geology, and chemistry have become interdependent. It is the purpose in this chapter to acknowledge many of the significant ideas in the development of karst hydrogeology as a science that have a bearing on the development of ideas in this thesis.

The literature review addresses different types of models for cave development (e.g., phreatic, vadose, artesian etc.), phases of cave development, types of karst aquifers, groundwater flow in flat and folded limestones, dissolution kinetics, and karstification (e.g., sinkhole development). A brief review is also provided of the classical theories of cave development. These concepts provide a useful framework for understanding the complex hydrogeology of the Sistema Huautla Karst Groundwater Basin.

## 2.1 Karst

The term *karst* is a German modification of the original Slavic word *kras*, which was defined as a bleak, waterless place. This was the descriptive term to describe the Dinaric landscape east of Trieste, Italy, the site of classic karst investigations (Sweeting, 1973).

The term karst can be used to describe both surface and subsurface geomorphology. Karst may be defined as a terrain consisting generally of limestone or dolomite, gypsum, calcareous sandstone, halite, anhydrite, quartzite, other igneous and metamorphic rocks in which the landscape has been shaped by corrosive processes of solution, resulting in karren, closed depressions, dry valleys, influent drainage, subsurface drainage, caves, and point discharge (springs). Variations of this definition are offered by Sweeting (1973), Jennings (1985), Milanovic (1981), and many others. Mylroie (1984) described karst landscapes as fluvial in origin, shaped by solubility that results from chemical weathering and subsurface water flow.

### 2.1.1 Classifications of Karst

Karst researchers have attempted to classify karst according to morphology, structure, tectogenetic factors, geography, and environment of deposition. European researchers classified karst according to geographic and structural setting.

Cvijic (1925) provided a morphological classification of karst. He defined three types of karst, holokarst, merokarst, and transitional karst. Holokarst, or complete karst, is developed entirely in soluble rocks and has solution features on the land surface as well as underground. Merokarst, or incomplete karst, is a covered or mantled karst, soluble rocks that are covered by thick residual soils and exhibit little evidence of solutional modification on the surface. Karstification is shallow and not well developed. Transitional karst represents a landscape that has both mantled karst and exposed karst. Transitional karst is found in carbonates that are overlain or bordered by less soluble rocks. Underground solution features tend to be well developed.

Herak (1977) proposed a classification scheme for karst terrains that involved a tectogenetic approach. He classified epi-orogenic karst and orogenic karst.

Komatina (1973) classified karst as either platform or geosyncline karst. His definition was based on a broad structural interpretation of karst formed in flat-bedded carbonates, folded rocks, shear zones, or compressional zones.

Herak, Bahun, and Magdelenic (1969) described continental karst as being formed in three belts, littoral, central, and internal.

Other researchers have taken a close-up view of karst and associated features and attempted to classify karst according to geomorphology, structure, lithology, form, covering, function, etc. Bretz (1942) described cave features in relation to the water table as either vadose or phreatic in origin. Powell (1970) interpreted caves in terms of geomorphic setting and lithology. Jennings (1971) classified karst as dammed-in and covered. He also classified caves as inflow and outflow. Quinlan (1978) expanded Jennings work and divided karst into subsoil karst, mantled karst, buried karst, and interstratal karst. Mylroie (1984) classified karst according to function (i.e., surficial forms, interface forms, subsurface forms). Palmer (1984) provided a geomorphic interpretation of karst features with respect to their formation in the phreatic and vadose zones.

Day (1977) classified tropical karst in terms of classes of positive and negative landform units. These include Type I, terrain characterized by enclosed depressions of all types and subdued hills; Type II, terrain in which enclosed depressions and residual hills attain approximately equal prominence; and Type III, terrain characterized by isolated residual hills separated by extensive near planar surfaces.

Sweeting (1973) classified caves as phreatic, vadose, and vertical. Monroe (1970) developed a glossary of karst terminology including terminology used in Europe and United States.

## 2.2 Classical Cave Development Theories

### 2.2.1 Vadose Theories

The first scientific ideas concerning cave genesis were an attempt to explain the relationship of conduit and shaft development to the water table. Even though they recognized the existence of cave streams, other researchers denied the existence of a water table in karst and thought that caves were formed entirely in an air-filled environment (Figure 2.1).

At the turn of the century, Grund (1903) studied karst hydrology in Yugoslavia. He theorized that a karst aquifer had two zones separated by a water table. The upper zone was the zone of active groundwater movement. Water from the upper zone recharged the oceans. The water in the lower zone was stagnant. Water flowed through sinkholes and formed caves enroute. His observations resulted in a model that demonstrated that meteoric water invaded nonsaturated rocks to the water table and then flowed laterally toward the sea during seasonal fluctuations. He considered the water table inactive or immobile (Sweeting, 1973).

Martel (1921), Katzer (1909), and Von Knebel (1906) denied the existence of a water table in karst. They stated that water simply flowed from the surface through sinkholes to cave passages to springs. Dwerryhouse (1907) and Martel (1921) suggested that caves large enough to be explored were formed largely in the vadose zone (unsaturated zone) above the water table. At the interface where water first enters the subsurface, its solvent capacity and velocity of flow are at its optimum, enhancing passage enlargement by solution and mechanical corrasion. Mallot (1937) hypothesized that caves were formed by invading streams into the vadose zone.

Gardner (1935) thought that big caves were formed on the updip side of surface valleys by vadose water. Cave development was along bedding planes and trended down dip. He also advanced the idea that

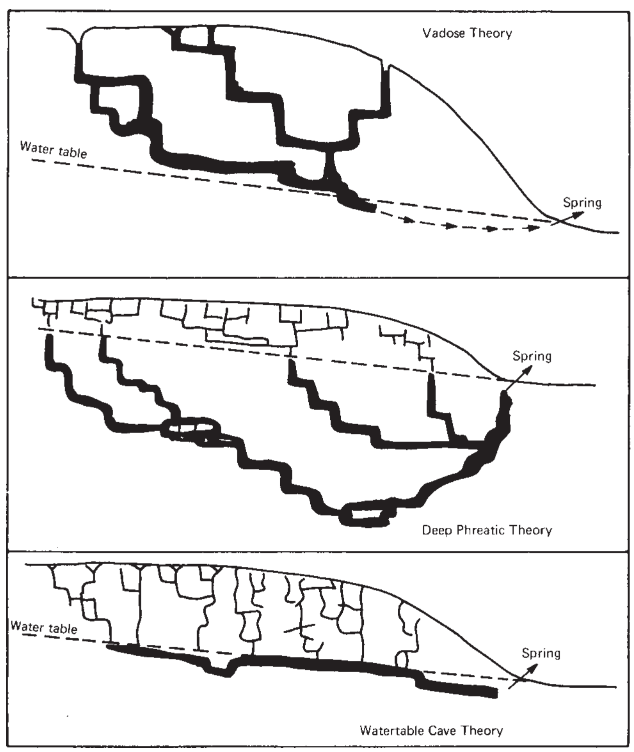



**Figure 2.1.** Three general models of cave development: vadose theory, deep phreatic theory, and water table cave theory. Source: Ford and Ewers 1978.

as down-cutting occurred, different passage levels were formed by stream piracy. Woodward (1961) thought that cave development occurred by sinking streams and that cave development was a response to rapid changes in base level. Pohl (1955) proposed that vertical shaft development in caves occurred as a result of the vertical transfer of water under air filled conditions in the vadose zone.

### 2.2.2 Deep Phreatic Theories

W. Davis (1930) and Bretz (1942) believed in the Deep Phreatic Theory and suggested that the "majority of large caves and systems are developed at a random depth in the phreatic zone under permanent water filled conditions" (Figure 2.1). "When erosional processes affect the topography to a point that the water table is lowered then air and surface water may enter the evacuated conduits and modify the original conduit by corrosion". They also stated that vertical shafts were developed at great depth below the water table.

W. Davis (1930) believed that groundwater flow paths in the phreatic zone are governed by Darcy's Law. Davis proposed a two-cycle theory for the development of caves. In the first cycle, caves develop along flow lines that curve deeply into the phreatic zone in the old age stage of the geomorphic cycle. In the second cycle, uplift allows meandering streams to erode into water-filled caves and drain them. He stated that cave development is not related to surface drainage.

Bretz (1942) developed the deep phreatic theory further by adding a third stage of development. He stated that conduits were filled by sediments transported from streams meandering across the peneplain. Further uplift partially drained the sediments from the cave.

### 2.2.3 Shallow Phreatic Theory

Swinnerton (1932) stated that Darcy's law does not apply in the limestone medium because the system is anisotropic and inhomogeneous. He further stated that cave development is proximate and parallel to the water table (Figure 2.1). Cave development propagates from input to spring in a shallow phreatic medium. In concert with his views of cave development, he hypothesized that vertical shaft development was the result of stream capture and adjustment from one cave level to another as a result of lowering the water table.

Rhodes and Sinacori (1941) also supported the Shallow Phreatic Theory. They contended that Darcy's law applies in the initial stage of cave development and maximum conduit enlargement occurs where small flow paths converge at the spring. This type of conduit development occurs along stream grade at the water table and facilitates passage development from the spring headward. The interface of maximum cave passage development is along and parallel to the water table.

Thrailkill (1968) supported the idea that all phreatic flow in karst aquifers is proximate to the water table. He proposed a different model from the views of W. Davis (1930), Swinnerton (1932) and Rhodes and Sinacori (1941). Thrailkill stated that under prescribed conditions, when input is either close to or far from a karst spring, the discharge is not significantly greater from a shallow phreatic zone than from a deep phreatic zone.

## 2.3 Karst Aquifers

There has been considerable debate among European karst hydrologists as to the existence of a water table in alpine aquifers. Careful geochemical work by Zötl (1961) has demonstrated that Alpine aquifers have water tables. American, Canadian, and British researchers have all recognized the important influence the water table has on cave development. Only after the scientific community began to agree in general on the existence of a water table in karst could water-bearing rock in karst landscapes be considered an aquifer. Karst aquifers have been explained and modeled by Thrailkill (1968), White (1969, 1977), Smith, Atkinson, and Drew (1976), Ford and Ewers (1978), T. Atkinson and Smart (1981), Mylroie (1984), Smart and Hobbs (1986), and Quinlan et al. (1992).

White (1969, 1977) developed conceptual models for carbonate aquifers based on hydrologic parameters of flow type and hydrologic control and gave examples of each based on associated cave types. He identified the main distinguishing characteristics of carbonate aquifers on the basis of structural complexity, areal extent, thickness, and conduit permeability. White (1969) also described karst aquifers as diffuse flow, free flow, and confined flow. Gunn (1985) argued that free-flow aquifers are the only true karstic aquifers. Schuster and White (1971, 1972) described groundwater flow discharging from a karst aquifer as diffuse flow and conduit (turbulent) flow.

Smith, Atkinson, and Drew (1976) stated that crystalline limestones are markedly anisotropic, showing very high values of permeability and hydraulic conductivity along joints, faults, and bedding planes with almost no permeability and porosity within the undisturbed rock. Limestone regions are dominated by both diffuse and conduit flow with regard to subterranean drainage and the occurrence of one or the other alone is uncommon.

Ford and Ewers (1978) describe cavern bearing limestones as functioning initially as fractured aquifers, while Thrailkill (1968) described each cave as a separate leaky aquifer.

Jakucs (1977) described recharge of karst aquifers in terms of allogenic and autogenic sources. Allogenic recharge is water derived from noncarbonate rocks. Autogenic recharge is meteoric precipitation onto the karst.

Gunn (1985) developed a conceptual model for free-flow karst aquifers. His model described four modes of recharge to free-flow aquifers, diffuse autogenic, concentrated autogenic, diffuse allogenic, and concentrated allogenic, and six types of transfer mechanisms for groundwater flow through the karst aquifer, overland flow, through-flow, subcutaneous flow, shaft flow, vadose flow, and vadose seepage.

Quinlan and Ewers (1985) described a third type of groundwater flow, mixed flow, occurring between diffuse flow and conduit flow end members.

Smart and Hobbs (1986) developed a conceptual model of a karst aquifer, recognizing the independent variables of recharge, storage, and flow. Quinlan et al. (1992) expanded the conceptual model of Smart and Hobbs by adding physical characteristics of a karst aquifer. He proposed to retire the terms conduit and diffuse flow aquifers under the premise the terms only describe flow type. They propose describing karst aquifers in terms of vulnerability. Quinlan et al. (1992) also maintained that dye tracer studies in many areas that would be classified as nonkarst based on their geomorphological definition have proven otherwise, and they proposed a new definition for a karst aquifer from a hydrologic perspective. “A karst aquifer is an aquifer in which the flow of water is or can be appreciable through one or more of the following: joints, faults, bedding planes, and cavities, any or all of which have been enlarged by the dissolution of bedrock.”

## 2.4 Modern Cave Development Theory

Modern cave development theorists critically reviewed the ideas of past researchers and changed their approach of classifying entire caves as vadose, phreatic, or deep phreatic. While these concepts are important, modern theorists began to recognize the hydrogeologic controlling variables in the formation of caves through field observations and careful measurement.

### 2.4.1 Hydrologic Models

Rhodes and Sinacori (1941) may be the first of the modern theorists because they approached cave development ideas from a hydrologic perspective. They were the first to advance the idea that conduit network development occurs from the spring headward, while individual conduits form in the downstream direction. The premise for their theory is that conduit tributary systems advance headward as flow lines are intersected.

White and Longyear (1962) developed the idea that groundwater flow becomes turbulent at critical velocity and that velocity is a function of pipe diameter and gradient. They calculated that turbulent flow threshold occurred at a pipe diameter between 5 and 10 millimeters. They advanced the idea that turbulent flow is critical to advancing dissolutional processes.

Thrailkill (1968) found that flow rates in pipes of equal size throughout the network were the same when calculated using both the Hagen Poiseuille and D’Arcy-Weisbach equations. He suggested that groundwater flow through an anisotropic media would produce the same deeply curved flow lines as in a homogenous isotropic aquifer. These flow lines would follow the tortuous path of the joint bedding plane network.

Chorley and Kennedy (1971) defined caves as a cascading system. The system is composed of protoconduits connected to cave system or spring. As the developing tubes intersect the main conduit the local flow field and hydraulic gradient are reoriented.

Ford and Ewers (1978) stated that the path of conduit development is not rigidly controlled by curvilinear flow lines.

Ewers (1978) proposed a model for the development of broad-scale networks of groundwater flow in steeply dipping carbonate aquifers. He proposed that broad-scale networks draining over 100 $km^2$ are formed by incorporating smaller networks that propagate from discrete input sources as distributary systems. Integration of the smaller networks proceeds headward from the resurgence as determined by the hydrogeologic constraints. The direction and rate of growth of the smaller networks are determined by the anisotropic framework and geometry of the inputs and resurgences. The overall drainage pattern is controlled by these factors, as well as the existing boundary conditions. This model was based on electric analog, flow envelope, and solution experiments.

### 2.4.2 Cave Development Associated with Base Level

Karst researchers have recognized a relationship between passage development position or level within limestone aquifers and base levels. It has also been demonstrated that passage levels may not be controlled

by base level, but instead by lithology.

Davies (1960) hypothesized that there are four stages of cave development: 1) Random solution at depth to produce nonintegrated caves. 2) Integration of tubes into mature conduits at the top of the zone of saturation during periods when the water table is constant with the direction of groundwater flow toward major valleys. 3) Deposition of clastic fill under alternating conditions of saturation and aeration. 4) Relative uplift of caves above the zone of saturation with modification of passage by deposition of speleothems, erosion of fill material, and collapse.

White (1960) found that caves in the Appalachians were formed primarily in the shallow phreatic and controlled by local base level. Caves formed relative to base level are primarily horizontal and terminated in the up-dip and down-dip directions.

Sweeting (1950), Krieg (1954, 1955), Droppa (1957), Davies (1957), White and White, (1974, 1983), Bögli (1966), Miotke and Palmer (1972), Ford and Ewers (1978), Bögli (1980), and Palmer (1984), demonstrated that levels in caves could be correlated to river terraces, signifying that paleo base levels were where passage development occurred, proximate to the former water table.

Milanovic (1981) postulated that the base level of erosion determines the ultimate direction of circulation for underground water in karst. Major erosion base levels include deep river valleys and canyons for continental regions. Waltham (1970) demonstrated that cave levels thought to be controlled by base level were in fact formed on top of perching beds above the water table. Smith and Crawford (1989) found that horizontal development of cave passages is controlled by lithology and occurs well above present base levels in the Cumberland Plateau. Palmer (1987) provided a method for determining past base levels by determining the relationship between vadose-phreatic transition points or "piezometric limit."

It has been thought that cave levels or tiers formed in ideal water-table caves were a response to exogenetic processes such as the lowering of local base level by fluvial processes. These exogenetic sources are challenged by Worthington (1991), who favors an endogenetic model for the development of cave levels. The development of cave tiers is a function of the original flow net within the aquifer and has little to do with conduit development at the water table. In fact, most submerged conduits investigated were developed 20 to 50 meters below the current base level or water table.

### 2.4.3 Modern Models of Cave Development

Jennings (1985) concluded that the conditions for cave development vary considerably with local relief, climate, and geology, and because these conditions are not uniform globally, the traditional theories of cave development may not apply to every hydrologic karst system. It is mutually agreed by most workers in karst that caves can exhibit one or more characteristics from all three theories, vadose, deep phreatic, and shallow phreatic. Palmer (1984) recognized that conduits may have polymodal development and concluded that vadose and phreatic solution often occur simultaneously along the same flow path.

Ford (1965, 1968, 1971), Ford and Ewers (1978), and Ewers (1978) developed cave models based on geology, hydrology, and topography. Ford and Ewers (1978) contended there is no general model of cave system genesis applicable to every cave. Instead, there are vadose caves, water table caves, and phreatic caves that may have been formed under the partial influence of one or more of the classical theories. For example, vadose caves may develop in a previously established phreatic system.

Caves developed with great vertical relief are usually multiphase in development. A multiphase system consists of vadose streams contributing recharge to phreatic streams. As a mountain range uplifts or base level lowers by erosion, fossil phreatic levels may be found above an existing water table, indicating old base-level passage development deep within a vertical cave dominated by vadose shaft development.

White (1988) stated that folded or faulted rocks in areas of high relief often contain conduit systems of great complexity. Conduits often develop under high hydrostatic heads. Ford et al. (1983) identified dry phreatic lift tubes in Castleguard Cave, Canada. Smith (1991b) observed dry lift tubes 1,000 meters above base level springs in the Sierra Cuicateco, Mexico. Stone (1984) noted the presence of phreatic lift tubes in Cueva de Peña Colorada that were isolated from the main hydrologic flow path. These conduits became active as overflow routes during high flow.

Ford and Ewers (1978) described two types of vadose cave development, drawdown vadose and invasion vadose (Figure 2.2). A drawdown vadose cave is one that is developed initially from phreatic conduits that are drained by lowering of the water table. Further conduit enlargement occurs entirely in the vadose zone. Features of initial phreatic conduit development are preserved in ceilings of conduits. An invasion vadose cave is also formed from an initial

phreatic conduit, but is enlarged by invading streams that flow from noncarbonate rocks through conduits and shafts well above an established water table. This type of vadose development is common in mountain regions of the world, where great vertical relief exists between input and output.

Ford (1977) developed the four-state model to distinguish between phreatic and water table caves (Figure 2.3). The premise for his model was based on different states of fissure frequency. In state 1, bathyphreatic, the fissure frequency is low and the groundwater moves preferentially along a single fissure. Deep preferential flow occurs to depths hundreds of meters below the water table. Nacimiento Mante, Mexico, is an example (Fish, 1977). A state 2, phreatic cave with multiple loops occurs when there is a significantly higher fissure frequency, as in thin-bedded limestones and joint swarms. Tops of loops define the stable position of the water table. State 3 caves, with a mixture of shorter shallower loops and quasi-horizontal canal passages, are a third higher state of fissure frequency, with greatly diminished groundwater circulation. Passages propagate along strike or in bedding planes. In state 4, fissure frequency is so high or resistance is so low that ideal water-table caves are formed. Ideal water-table caves receive all runoff, and the potentiometric surface is lowered into them.

Ford and Ewers (1978) proposed scenarios of cave development for vadose, phreatic, pocket, and artesian caves.

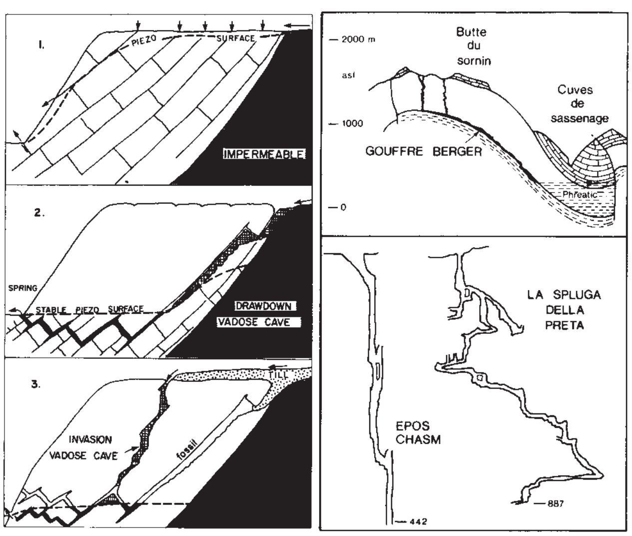



**Figure 2.2.** Development of drawdown and invasion vadose caves. The Gouffre Berger, France, is mostly a drawdown vadose cave. Epos Chasm, Greece, and Spluga della Preta, Italy, are examples of invasion vadose cave. Source: Ford and Williams 1989.

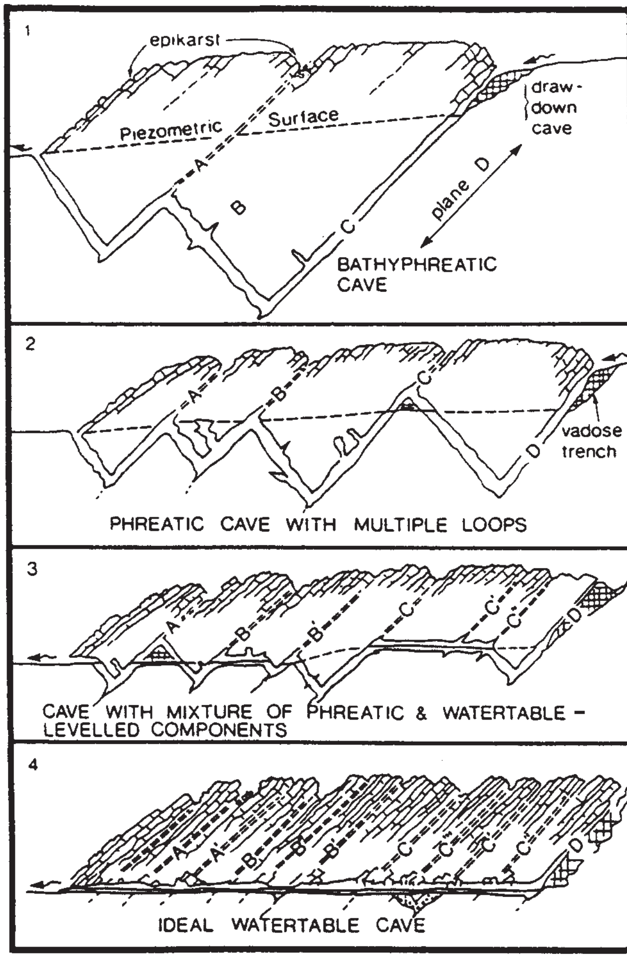



**Figure 2.3.** Four-state model of speleogenesis. Source: Ford 1977.

Howard (1964) described the caves of the Black Hills as artesian in origin. Palmer and Palmer (1989) agreed with Howard that the Black Hills are artesian, but also suggested that rising thermal waters may have had an influence on speleogenesis. Ford (1989) proposed a very different mode of genesis for the caves of the Black Hills (Jewel and Wind Caves) suggesting that they were formed from deep phreatic circulation.

Renault (1967–1968) and Ford and Ewers (1978) proposed a second stage of phreatic loop development called paragenesis. As sediment is deposited on the floor of the phreatic loop, solution of the ceiling occurs as insoluble mantle retards solution of the floor. When the floor becomes covered by sediment, the conduit enlarges in cross sectional area above the sediment, and flow velocities decrease, since hydrostatic head has not changed. A balance is developed between cross section of the paragenetic passage and sediment load.

Worthington (1991) proposed a model for the development of conduits in structurally influenced flow fields within a karst aquifer and their response to

lowering of the water table. The model describes flow at any time in the life of the aquifer and predicts the spatial occurrence of low and high discharge-variability springs, of low and high sulfate springs, low and high temperature springs, and of low and high Coefficient of Variation of Hardness springs. The model is based on nine principles: 1) Locus of cave conduits below the water table is primarily a function of aquifer length and stratal dip. 2) Phreatic conditions describe a single loop below the water table at the time of formation. 3) A synchronous tier of active conduits is active for a time span that ranges between $3 \times 10^5$–$10^7$ years. 4) Active conduits are mostly flooded. 5) As base level lowers, the first conduits that appear act as the input and output end of the aquifer. 6) A flow field develops below existing conduits. 7) Flooded conduits may exist in the vadose zone well above the water table. 8) Spacing between tiers is equal. 9) The flow field beneath existing conduits is laminar, and has smaller discharge variation, higher temperatures, and higher sulfate loads than existing conduits.

### 2.4.4 Cave Patterns

Palmer (1991) discussed the origin of basic cave patterns. He classified caves as branchwork, network, anastomotic, ramiform and spongework (Figure 2.4). Palmer stated the following: cave morphology is controlled by location, and extent; a cave's over-all trend is controlled by distribution of soluble rocks and recharge and discharge points; the passage pattern depends on the mode of groundwater recharge; and the orientation of individual passages is controlled by geologic structure, distribution of vadose and phreatic flow, and geomorphic history. Basic cave patterns may only be determined by physical exploration and cave survey.

### 2.4.5 Structural Influence for Cave and Passage Development

It has been realized that structure has some influence on the hydrology of most karst aquifers and consequently on cave development. Caves are formed in both flat-lying limestones, inclined strata, and rock units that have been intensely folded. The orientations of passages and patterns of cave development are controlled by the attitude of beds, permeability along bedding planes, jointing, and faults. Cave development is a response to the influences of the local hydrogeology. Patterns of mapped caves can be related to the structural style of a region or to specific structures. When considering different segments of a cave, the development of individual cave passages may be influenced by different types of structure and changes in lithology. The influences of structure on cave development have been well documented by Davies (1960), Waltham (1970), Palmer (1975), Powell (1976), Kastning (1977), Smith and Crawford (1989), Palmer (1991) and others.

Ford (1971) has shown that groundwater flow and consequently passage development in steeply dipping beds is parallel to the strike of bedding. Passage development occurs along steeply dipping beds and forms slanting passages, dip tubes, and phreatic loops. On the other hand, in flat-lying, poorly jointed limestones, cave passages are developed along bedding planes (Ewers, 1969). The dominant morphology consists of braided tubes developing headward toward groundwater basin boundaries.

Davies (1960) found that most passage development of caves formed in folded limestones is not fault controlled but instead is influenced by joint control. Deike (1960) and Howard (1964) described cave development along or across synclines and the influence of jointing. Palmer (1972) investigated Onesquethaw Cave and determined that only 20 percent of the cave was formed along faults and joints, while the remaining 80 percent was formed along bedding planes along a strike dominated flow path.

Hose (1981) determined that the controlling factors for the hydrology of 904-meter-deep Sistema Purificación, Mexico, are structure, stratigraphy and lithology. She stated that the most important elements for cave development are folds and fractures formed

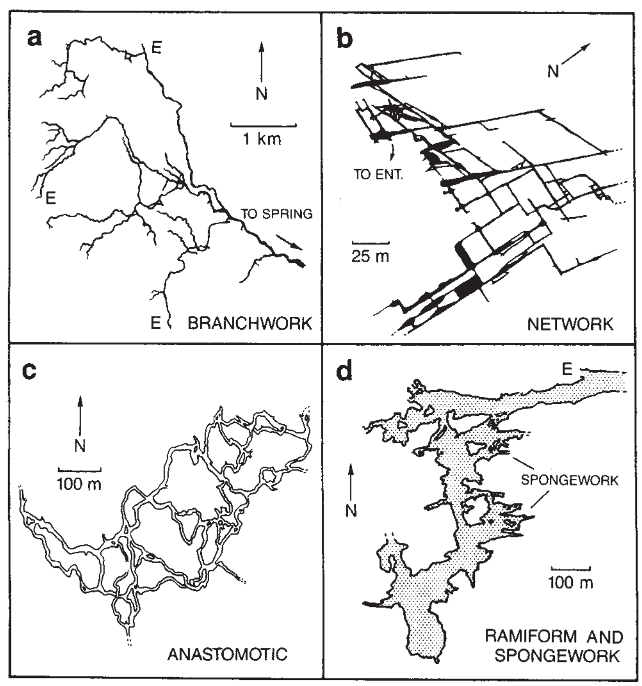



**Figure 2.4.** Common patterns of solutional caves. Source: Palmer 1991.

near the axial hinge surfaces. Some cave passages were formed in the troughs of synclines.

## 2.5 Karst Processes

As cave science advanced, researchers became aware that the speleogenesis of caves is complex and process dependent. Cave development is defined by the hydrogeologic conditions at the time of initial development and subsequent dynamic geologic conditions, plus the complex dissolution kinetics of limestone dissolution.

Kaye (1957) recognized that caves are formed by dissolutional processes of a weak acid with calcium carbonate and suggested that as the velocity of fluid flow increases the rate of solution increases under diffuse flow conditions. It is important to note that this condition is not true for turbulent flow conditions. Karst processes have been explained in detail by Sweeting (1973), Bögli (1980), Jennings (1985), White (1988), Ford and Williams (1989), and Dreybrodt (1988).

Nearly all cave formation is thought to be dominated by a carbonate dissolution chemistry consisting of weak acids formed by the hydration of atmospheric and soil carbon dioxide (Roques 1962, 1964 in Ford and Williams, 1989). Dissolution of carbonate rocks has been explained by White (1977), Plummer et al. (1978, 1979), Palmer (1981, 1984), and Dreybrodt (1981, 1988). Carbonate dissolution processes appear to be the most dominant corrosive process for the development of caves, but some special cases for cave development are unique and dependent on very different chemistry.

The development of some caves in Iowa, Wyoming, and New Mexico has been attributed to dissolution by weak sulfuric acid (Durov, 1956; Morehouse, 1968; D. Davis, 1980; Hill, 1981, 1987; and Egemeier, 1973, 1981). Hill and Egemeier hypothesized that caves of the Guadalupe Mountains (Carlsbad Cavern and Lechuguilla Cave in New Mexico) were formed by hydrogen sulfide rising from the oil fields of the Permian Basin forming sulfuric acid. Other workers have suggested that sulfuric acid was derived from water reacting with pyrite and sulfates in the rock.

# CHAPTER 3

# STRATIGRAPHY OF THE STUDY AREA

### 3.0 Introduction

To study the complex hydrology of the Sistema Huautla Karst Groundwater Basin, it is first necessary to understand the geology of the area, especially the stratigraphy. Stratigraphic controls and structural geology play an integral part in understanding cave development and hydrologic flow patterns in the Sistema Huautla Karst Groundwater Basin.

Upon investigating the available geological literature for this region, it was found that much of the specific literature of the study area is in Petróleos Mexicana (PEMEX) files and therefore inaccessible. The previous work that was available was integrated with observations in the field to arrive at conclusions concerning the stratigraphy of the study area.

### 3.1 Prior Work

The first geological field investigation of the Sierra Juárez, including the Huautla de Jiménez area, concluded that the surface rocks are Cretaceous limestones overlaid by allochthonous clastics of the Jurassic (Mena and Maldonado, 1959).

Echanove (1963) described the stratigraphy and structure from Teotitlán del Camino to Huautla de Jiménez. Viniegra (1965), in a very detailed study, described the stratigraphic relationships and paleontology of the rock units in the Sierra Madre Oriental del Sur and Cuenca de Veracruz. In a later work, Viniegra (1966) provided a paleogeographic and structural geology survey of the Sierra Juárez Geologic Subprovince that serves as the most comprehensive interpretation to date. This work included the Huautla de Jiménez karst. Complex structures and stratigraphy of the Cordoba Platform buried beneath the foothills of the Sierra Madre Oriental and their relationship to complex structures of the Tertiary age Veracruz Basin were described by Mossman and Viniegra (1976). Seismic and borehole studies in the Veracruz Basin determined that Miocene conglomerates originated from Cretaceous carbonates and clastics of the ancient Papaloapan Drainage Basin (Helu et al., 1977).

Moreno (1980), in a master's thesis, described the stratigraphy and structure of the proposed Sistema Huautla Karst Groundwater Basin from Huautla de Jiménez, east to Río Santiago, and south to the Río Santo Domingo. The geologic investigation defined relationships between overthrusted Jurassic flysch and Cretaceous rocks.

Charleston (1980) studied the stratigraphy and tectonics of the Río Santo Domingo area and defined the age of allochthonous rocks of the Cuicateco Complex. Ramos (1983) attempted to standardize the nomenclature of rock units of the Sierra Madre Oriental that provide a general stratigraphic column for the Sierra Madre Oriental del Sur. Ramirez (1991) described the stratigraphy and geologic history of the Pegaso asbestos deposit located south of the Río Santo Domingo at Concepción Pápalo, Cuicatlán, Oaxaca.

### 3.2 Study Area

The Sistema Huautla Karst Groundwater Basin is situated within the Sierra Juárez Geologic Subprovince, a part of the Cuenca de Veracruz Geologic Province (Ramos, 1983). The Sierra Juárez consists of homogeneous rock units that are dominated by carbonate rocks of the Cordoba Platform. While a large portion of the Cordoba Platform is exposed in the Sierra Juárez, the rest is buried beneath Tertiary sediments of the Veracruz Basin (Alvarado, 1976).

The geologic subprovince was originally defined as a part of the Southern Sierra Madre Geologic Province (Eardley, 1951). This definition of the subprovince was based on corresponding geomorphologic and regional structural features. The most recent definition of the geologic province is based on homogeneous rock units (Ramos, 1983).

The Sierra Juárez Geologic Subprovince encompasses that portion of the Sierra Madre Oriental del Sur south of the Trans Neovolcanic Belt, the area west

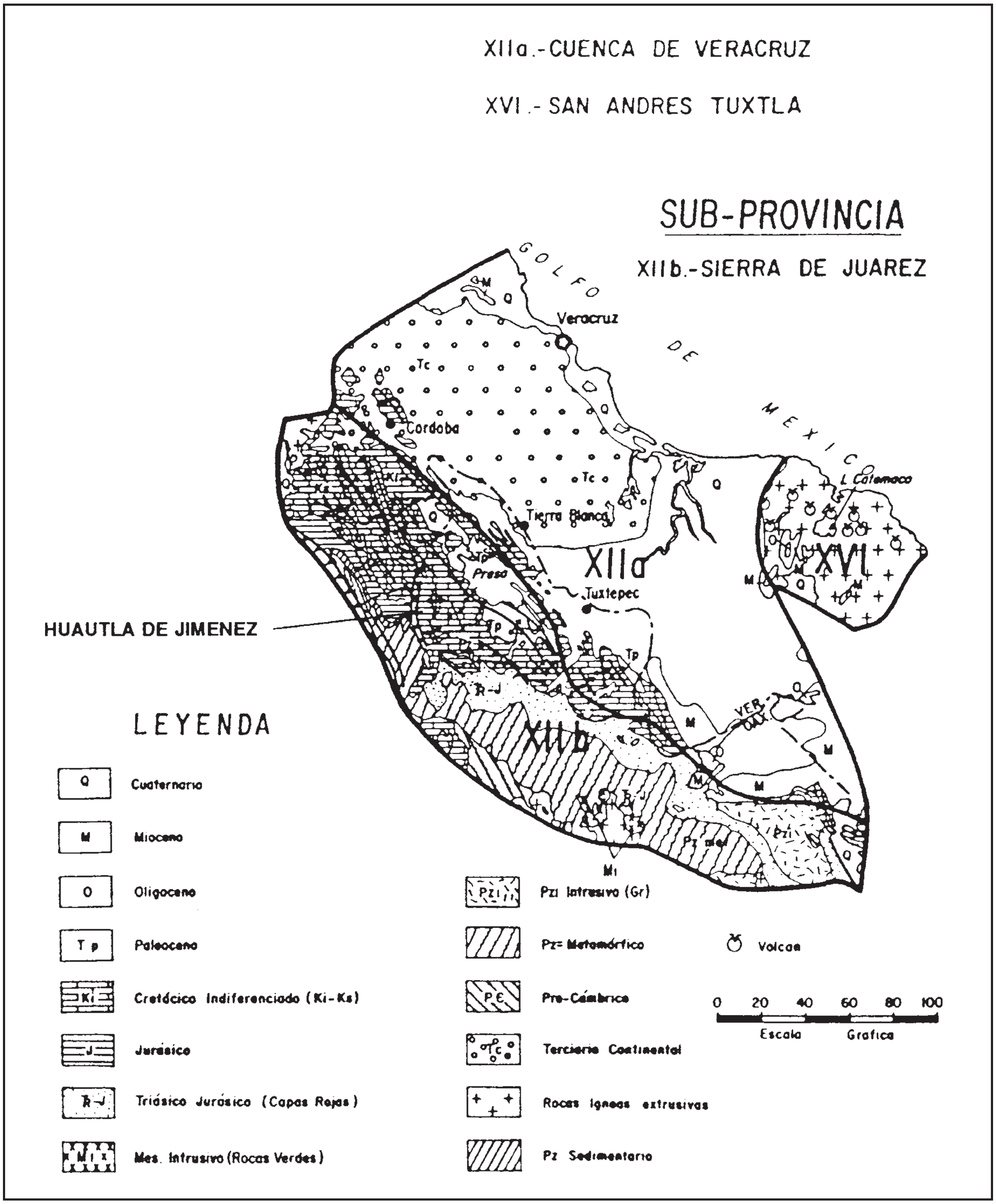



**Figure 3.1.** Geologic provinces, Cuenca de Veracruz, San Andrés Tuxtla, and Sierra Juárez. Source: Ramos 1983.

of Cordoba, the area east of Tehuacán, and the mountainous area north of the Isthmus of Tehuantepec (Figure 3.1). The subprovince includes the subranges Sierra Zongolica, Sierra Mazateca, and Sierra Juárez.

### 3.3 Paleogeography and Stratigraphy

The Sistema Huautla Karst Aquifer is developed within carbonate rocks of the Mesozoic System. Mesozoic miogeoclinal sediments were deposited in an elongate trough on the east side of the ancient Oaxacan Peninsula (Viniegra, 1966). The Oaxacan Peninsula or Oaxacan Terrain (McCabe et al., 1988) consists of Precambrian basement rocks of granulite metamorphic facies owing their provenance to the Grenville Province of North America (Fries et al., 1962; Gutierrez, 1981).

During the Early Mesozoic, the landmass of the Oaxacan Peninsula was irregularly shaped, having an orientation north to south. The eastern perimeter and shoreline extended from Tuxtepec, Oaxaca, to the west along the present-day Río Santo Domingo and to the north along the western edge of the Tehuacán Valley to where it disappears under the Neovolcanic Axis (Viniegra, 1966). The emergent continental mass and unconformably overlaying Paleozoic rocks are the source material for early Mesozoic clastics.

During the Late Triassic and Early Jurassic, an influx of clastics reshaped the sedimentary framework in eastern Mexico, forming a continental molasse. The exposed continental landmass of the Oaxacan Peninsula eroded and deposited sediments during marine transgressions into epeirogenic seas and onto the continental shelf adjacent to the eastern shoreline. These continental rocks are red beds.

In east-central Mexico, the sedimentary clastics are marine in origin (Cserna, 1976). Associated with marine clastics are evaporite deposits located north of Veracruz (Hernandez-Garcia, 1973). The deposition of marine sediments during the Lower Jurassic marked the beginning of the formation of the north-south trending Mexican miogeocline (Maldonado-Koerdell, 1958).

During the Middle Jurassic, clastics rich in ferromagnesium minerals continued to be deposited along the eastern shoreline of the Oaxacan Peninsula. These red beds correlate to the Todos Santos Formation of Honduras and Huizachal Formation of northeastern Mexico to form the sedimentary base of the Mexican Miogeocline (Mullerried, 1936; Imlay, 1943; Erben, 1956).

By the Late Jurassic, transgressive seas partially inundated the Oaxacan Peninsula as rifting occurred, forming epeirogenic seas related to the opening of the Gulf of Mexico (Effing, 1980). Tepexilotla Formation shales, siltstones and arkosic sandstones were deposited from eroding highlands. The formation increases in thickness to the east up to several kilometers thick (Viniegra, 1965).

During the Early Cretaceous, a cessation in uplift and marine transgression gave rise to more stable conditions and the formation of an extensive series of carbonate platforms along the Mexican Miogeocline. The present day Sierra Mazateca is a part of the extensive Cordoba Platform (Gonzalez, 1976).

Overlying the Jurassic System are basin facies carbonates of Lower Cretaceous (Neocomian-Aptian). Black limestones (intercalated with chert) of the Tuxpanguillo (Xonamaca) and Capolucan Formations were deposited as the platform slowly subsided. Slow subsidence of the platform continued through the Albian-Cenomanian. At this time, large tabular reefs grew to form the United Orizaba Formation of the Escamala Series (Viniegra, 1965).

During the Turonian and Coniacian, additional reef build-up continued, to form the Guzmantla Formation. Simultaneous deposition of black cherty limestones of the Maltrata Formation indicated facies change within the platform sediments.

An influx of terrigenous sediments produced mudstones intercalated with thin-bedded limestones of the Necoxtla Formation during the Santonian and Campanian (Viniegra, 1965).

Overlying the Necoxtla Formation are reef rocks of the Atoyac Formation. The reefs were constructed during the Campanian and Maestrichtian. By this time, the marine transgression had covered the entire Oaxacan Peninsula. An increase in regional tectonics at the beginning of the Laramide Orogeny resulted in cessation of platform construction. Ramos (1983) estimated the total thickness of the Cordoba Platform to range up to 3,000 meters, while Charleston (1980) estimated the total miogeocline to be 5,000 meters thick.

### 3.4 Mesozoic Stratigraphy

In this section, the Mesozoic stratigraphy of the Cordoba Platform, as it pertains to the geologic section of the Sierra Juárez, will be described. To generalize the geologic section of the Sierra Mazateca portion of the Sierra Juárez, a composite stratigraphic column was constructed from stratigraphic sections by Viniegra (1965), Moreno (1980), and Ramos (1983) (Figure 3.2).

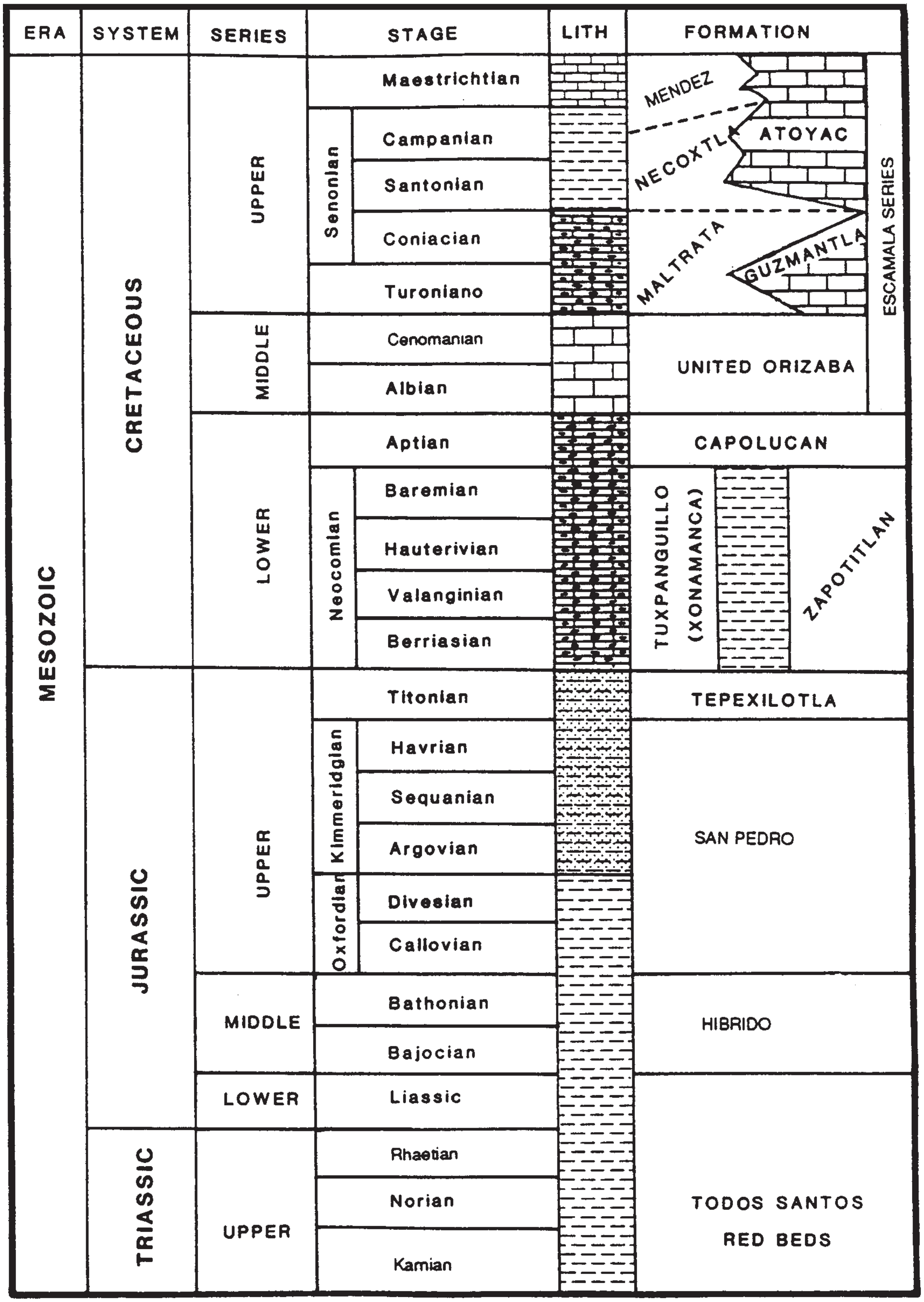
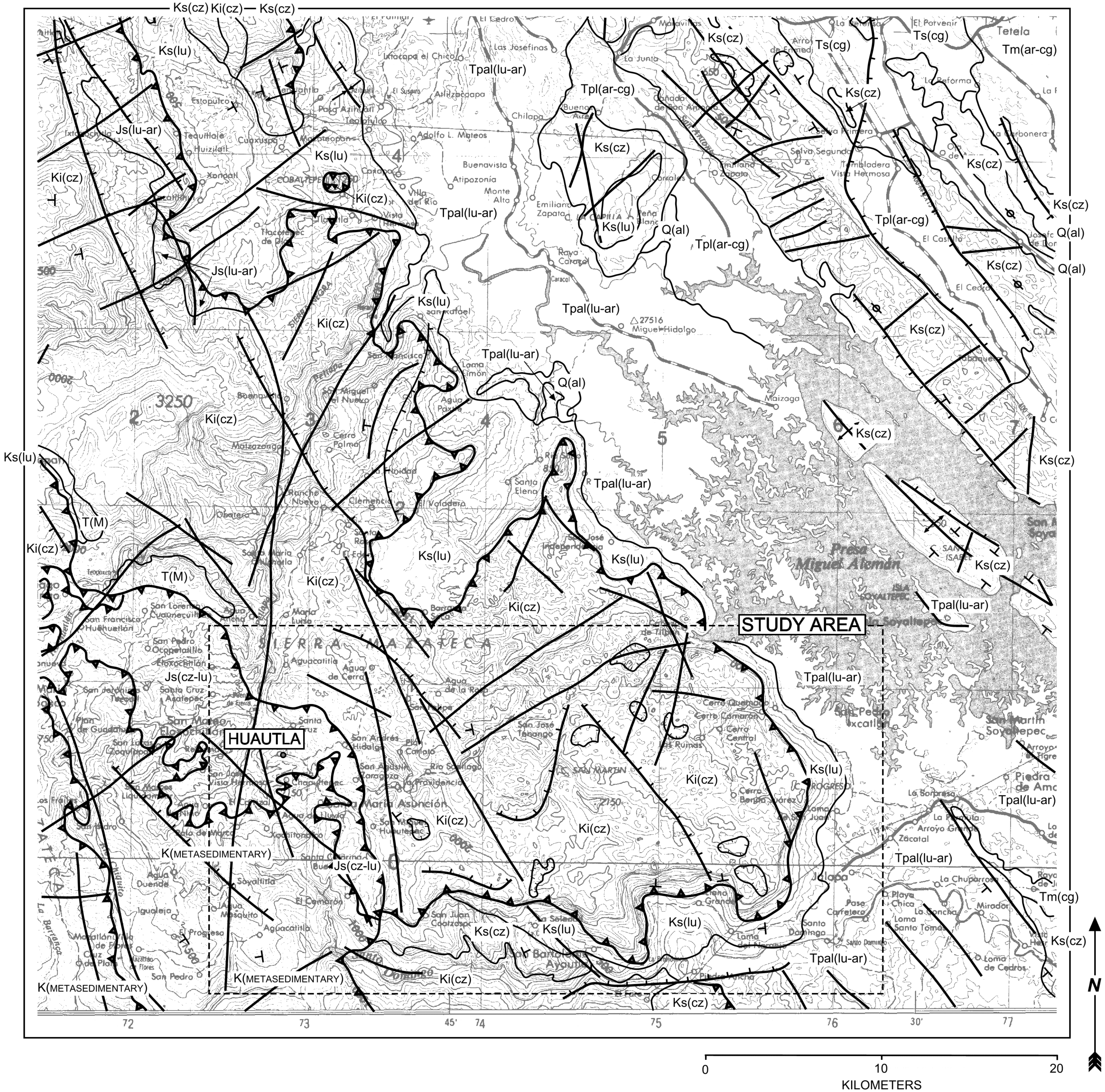



**Figure 3.2.** Stratigraphic column of the Sierra Juárez. Compiled from Echanove 1963, Viniegra 1965, Moreno 1980, and Ramos 1983.




# GEOLOGY MAP
# SIERRA MAZATECA
# OAXACA, MEXICO

AMCS Bulletin 9
Figure 3.3
Page 41

anticline
syncline
fracture
normal fault
reverse fault
contact

dip 10 to 80
dip 80 to 90
doline

| | |
|---|---|
| Q | Quaternary |
| T | Tertiary |
| Ts | Upper Tertiary |
| Tpl | Pliocene |
| Tm | Miocene |
| Tpal | Paleocene |
| K | Cretaceous |
| Ks | Upper Cretaceous |
| Ki | Lower Cretaceous |
| Js | Upper Jurassic |

| | |
|---|---|
| al | alluvium |
| ar | sandstone |
| cg | conglomerate |
| cz | limestone |
| lu | shale |
| M | marble |

Based on the Orizaba 1:250,000 (E14-6) topographic and geologic maps from the Instituto Nacional de Estadística Geographía e Informatica.
Redrawn for the AMCS by Bill Mixon.

3.4.1 Triassic System

The oldest of the Mesozoic rocks present in the study area are Triassic red beds. Red beds of the Todos Santos Formation are shales and siltstones rich in ferromagnesium minerals derived from an eroding continental landmass deposited in highly oxygenated, shallow-water environment. The Todos Santos Formation correlates to the Huizachal Formation in the states of Hidalgo and Tamaulipas in northern Mexico (Orizaba Geologic Quadrangle). Mullerried (1957) attributed the Todos Santos Formation to the Middle Jurassic. Ramos (1979) defines the Todos Santos Formation as Triassic–Middle Jurassic. The Todos Santos Formation is found on the eastern flank of the Sierra Juárez 10 kilometers south of the study area. It is believed that the Todos Santos Formation extends to the north and underlies the Sierra Mazateca.

3.4.2 Jurassic System

The Jurassic System is divided into Lower, Middle, and Upper Series based on faunal assemblages. Jurassic sedimentary rocks are predominately shales, anhydrites, and sandstones that may be described based on environment of deposition. Jurassic rocks of southern Mexico are primarily of continental and marine facies (Imlay, 1943). Jurassic rocks are found in outcrop throughout the western edge of the Sierra Juárez as allochthonous rocks and tend to occupy some of the greatest altitudes (Figure 3.3). They are also found on the eastern edge in outcrop. Rocks of the Jurassic may be subdivided in the vicinity of the study area.

3.4.2.1 Lower Jurassic

Lower Jurassic rocks are of both the continental and marine type. In western Oaxaca, the continental facies, consisting of shales, sandstones, and conglomerates, has been identified. Marine sedimentary rocks of the Lower Jurassic, distributed in a narrow embayment from Veracruz to Guerrero, were deposited in transgressive seas (Imlay, 1943).

Lower Jurassic marine shales with ammonites are found in outcrops between Teotitlán del Camino and Huautla de Jiménez in the Sierra Mazateca. The Lower Jurassic section thickness is estimated between 600 and 900 meters in the vicinity of Huautla, but averages 300 meters in thickness near Tierra Blanca, Puebla (Echanove, 1963).

Ramos (1979) described Lower Jurassic folded slates north of the study area between Tehuacán and Zongolica. Mullerried (1957) described red beds of the Early-Middle Jurassic correlated to the Todos Santos Formation south of the Río Santo Domingo. These outcrops are believed to extend as a basal unit under the Sierra Juárez.

3.4.2.2 Middle Jurassic

Middle Jurassic sediments in south-central Mexico indicate a marine transgression due to a shift from littoral sediments in the lower portion of the section to predominately marine sediments towards the upper end of the section (Imlay, 1943). Rocks of the Hibrido Group are the only units known for the Middle Jurassic.

Between Teotitlán del Camino and Huautla de Jiménez, rocks belonging to the Hibrido Group have been assigned to the Middle Jurassic. The Hibrido Group, thin-bedded black slates 3 to 5 centimeters thick, are intercalated with lenses of fine-grained sand and yellow slates 2 to 4 centimeters thick. The thickness of the Hibrido Group is estimated at 200 to 300 meters (Echanove, 1963).

3.4.2.3 Upper Jurassic

The Upper Jurassic of southern Mexico is characterized by rocks that are marine in origin and have extensive distribution, with thicknesses exceeding 1,000 meters (Imlay, 1943). In the vicinity of study area, mixed clastics and carbonates of the San Pedro and Tepexilotla Formations characterize the stratigraphy of the Late Jurassic.

Rodriguez (1975) described the lithology and type locations of the San Pedro Formation. The formation is found in outcrop along the banks of the Río Santo Domingo Canyon near Agua de Español.

Moreno (1980) described the San Pedro Formation as consisting of limestones and dolostones of medium bedding (30 to 120 centimeters). The formation is found to discordantly underlie the Lower Cretaceous Tuxpanguillo Formation. San Pedro is assigned to the Titonian Age because of its relationship to the Tuxpanguillo Formation.

Upper Jurassic rocks were described near Tepexilotla. The type locality for the Tepexilotla Formation (Mena, 1960) is located 50 kilometers north of the study area. The Tepexilotla Formation is found between Teotitlán del Camino and above the city of Huautla de Jiménez overlying Lower Cretaceous carbonates as allochthonous strata (Mena, 1960; Echanove, 1963; Moreno, 1980). The formation is elongate in outcrop, following the NW-SE regional strike and is found on the western edge of the Sierra Juárez from Rancho Nuevo, Puebla, to just north of the Río Santo Domingo at El Camarón (Orizaba Geologic Quadrangle). It is also hypothesized to underlie the Sierra Juárez. Late Jurassic rocks north of the study

area at Zongolica were described as black limestones with intercalations of sand and clay with diagnostic ammonites (Viniegra, 1965).

In the study area, the Tepexilotla Formation is estimated to be 600 meters thick due to intense folding and erosion (Echanove, 1963). Bazan (1981) described the Late Jurassic and Early Cretaceous to have a thickness of 2,500 meters in the buried portion of the Cordoba Platform in the Veracruz Basin.

Echanove (1963) described the rocks of the Tepexilotla Formation as being composed of shales and arkoses. The basal unit of the formation is brecciated, consisting of black angular limestone and chert fragments with white angular quartz in an arkose sandstone matrix. The beds are 1 to 2 meters thick and are interbedded with yellow to pink shale. The rest of the formation varies from fine to coarse grained and has subrounded quartz and feldspar crystals. The matrix is clay or a calcareous cement, pink to red in color. This allochthonous formation overlies Lower and Middle Cretaceous limestones between San Agustín and Huautla de Jiménez.

### 3.4.3 Cretaceous System

The Sierra Juárez consists of carbonate rocks representing each geologic age throughout the Cretaceous Period. Viniegra (1965) recognized each formation that constitutes the Cordoba Platform (Alvarado, 1976). Viniegra described the Tuxpanguillo (Xonomaca of Ramos (1983)) (Neocomian), Capolucan (Aptian), United Orizaba (Albian-Cenomanian), Maltrata and Guzmantla (Turonian-Coniacian), Necoxtla (Santonian-Campanian) and the Atoyac (Campanian-Maestrichtian).

Field observations by the author suggest that the Cretaceous outcrops in the study area are the Tuxpanguillo-Capolucan (undifferentiated), United Orizaba, and Maltrata Formations. A metamorphic equivalent to the United Orizaba is also believed to be present. This is in contradiction to field studies presented by Moreno, who described the outcrops in the study area as belonging to the Orizaba Formation.

#### 3.4.3.1 Tuxpanguillo Formation

The Neocomian is represented by the Tuxpanguillo Formation described by Mena (1961), Flores (1961), Echanove (1963), and Viniegra (1965) at various locations in the Sierra Juárez. Rocks of this age vary in lithology from shale to limestone in a facies change from the western edge of the Veracruz Basin to the eastern edge of the Tehuacán Canyon (Echanove, 1963) or Tehuacán-Zapotitlán Basin (Viniegra, 1966). In the Tehuacán-Zapotitlán Basin, the reef limestone facies was named the Zapotitlán Formation.

To the east, the reef facies changes into a basin facies. The basin facies is represented by the Tuxpanguillo Formation (Echanove, 1963). The Tuxpanguillo is found in outcrop within the study area (Echanove, 1963).

Gonzalez (1976) referred to the Tuxpanguillo Formation as the Xonomaca Formation. This change in lexicon is supported by Ramos (1983). However, it is important to distinguish between the Tuxpanguillo and the Xonamaca Formations. The Xonomaca Formation is Berriasian-Valangin in age (Early Cretaceous) and consists primarily of tuffs, bentonite, and feldspathic and lithic graywackes, which reflect the influence of volcanism near the present day La Fortin–Zongolica area of Veracruz (Carrasco et al., 1975).

In this thesis, the Neocomian intercalated limestones will be referred to as the Tuxpanguillo Formation following Viniegra (1965). The lower contact of the Tuxpanguillo is transitional with the underlying Tepexilotla Formation (Viniegra, 1965). The upper contact is gradational into the Capolucan Formation and is only identifiable by a change in index microfauna.

Near Tepexilotla, 40 kilometers north of the study area, the Tuxpanguillo Formation is described as a thin-bedded dark gray cryptocrystalline limestone intercalated with lenticular and nodular cherts (Viniegra, 1965).

At the northern end of the Sierra Juárez, at La Perla near Orizaba, there is a facies change in the Tuxpanguillo Formation. It changes from a thin-bedded black limestone intercalated with chert to a calcareous mudstone (Flores, 1961).

The Tuxpanguillo Formation between San Jerónimo and Huautla de Jiménez is a mixed facies (similar to Flores( 1961) description) consisting of alternating sandstones, some of which are gray arkose up to 1.5 meters thick, intercalated with coffee-colored shales and black limestones interbeds from 10 to 30 centimeters thick (Echanove, 1963). The total formation is estimated to be 500 meters thick (Figure 3.4).

#### 3.4.3.2 Capolucan Formation

The Capolucan Formation is Aptian in age, as indicated by microfaunal assemblages described by Mena and Flores in Viniegra (1965). The Capolucan Formation is named for the community where the formation was described. The Capolucan Formation overlies the Tuxpanguillo Formation with a gradational contact that is not recognizable in the field. The contact is only detectable by a change of index microfossils (Flores, 1961). The Capolucan Formation is easily

mistaken for the Tuxpanguillo Formation, and in this research the Tuxpanguillo-Capolucan Formations will be referred to simply as the Tuxpanguillo Formation.

The Capolucan Formation is described as a dark gray to black, cryptocrystalline, well-stratified limestone intercalated with thin beds of black chert. The strata are intensely folded and contain calcite fracture fillings and intraformational breccias. The formation thickness has not been determined.

#### 3.4.3.3 Orizaba Formation

Rocks of Middle Cretaceous age are the most studied group in Mexico because they are both the source and reservoir rocks of prolific petroleum resources. Viniegra (1965) studied rocks of the United Orizaba of Albian and Cenomanian age belonging to the Escamala Series. The Escamala Series is 2,500 meters thick and consists of basal dolomites. The middle and upper portion of the series consists of richly fossiliferous limestones.

The Orizaba Formation consists of limestones that are cream white to light gray in color. The bedding is massively stratified, with beds 1 to 2 meters thick consisting of dolomite, wackstones, and boundstones. Viniegra (1965) described the macrofossils as rudists, paquidontes of the Genera (Caprina), gastropods, and coelenterates.

The formation ranges in thickness from 200 to 400 meters in outcrops and up to 840 meters thick in stratigraphic tests (Ramos, 1983). The Orizaba Formation correlates to the Aurora Formation of Chihuahua, Mexico, the El Doctor Limestone of Central Mexico, and the Morelos Limestone in the Sierra Madre de Chiapas and Tabasco of southern Mexico (Ramos, 1983).

The Orizaba Formation is also found as a metamorphic rock or marble in a one-kilometer-wide band north of Huautla de Jiménez from Agua Ancha to Zoquitlán in the Sierra Mazateca (Figure 3.3). The marmoritized protolith of the Orizaba Formation is found adjacent to overthrusted Jurassic strata. The metamorphic equivalent of the Orizaba Formation has formed in recumbently folded strata beneath thrust-faulted strata of the Tuxpanguillo Formation.

#### 3.4.3.4 Maltrata Formation

The beginning stages of the Late Cretaceous extend from the Turonian to the Coniacian age. A facies change occurring from west to east is described as two formations, Maltrata and Guzmantla. The Maltrata Formation is a deep-water basin facies that grades laterally into a platform facies of the Guzmantla Formation (Ramos, 1983). It correlates to the Agua Nueva Formation in the northern Sierra Madre Oriental (Tarango, 1971). The Maltrata Formation is described in the valleys of Acultzingo and Maltrata northwest of the study area. Its widespread appearance from Acultzingo to the Río Santo Domingo is not continuous due to overthrusting and erosion (Viniegra, 1965). In a lithofacies map by Viniegra (1965), the Maltrata Formation is located five kilometers north and east of Huautla de Jiménez and is found near Chilchotla Zongolica. It is often found resting conformably over the United Orizaba Formation.

The Maltrata Formation consists of black, cryptocrystalline limestones, siltstones, and mudstones, which are bedded in thicknesses from 10 to 40 centimeters. Thin-bedded limestones are intercalated with nodular and bedded black chert. In places the thin-bedded strata are observed as chevron folds.

The upper contact of the Maltrata Formation is with the Necoxtla Formation. The Maltrata Formation has been confused with the Capolucan Formation in the field. Total thickness is estimated to be 400 meters (Viniegra, 1965).

#### 3.4.3.5 Guzmantla Formation

The time equivalent of the Maltrata Formation is the Guzmantla Formation. The Guzmantla is of the platform facies that consists of grainstones and packstones of oolites, pellets, and bioclastic limestone. The color is cream to light gray. It is bedded in thicknesses of one meter.

The Guzmantla Formation has been described from Cordoba to Tepexilotla. It has also been described southeast of Huautla de Jiménez below the Cerro Rabón thrust fault near San Juan Coatzospan along the Río Santo Domingo. Overlying the Guzmantla Formation are the Necoxtla slates. The Guzmantla Formation is found in thickness up to 1,000 meters near Cordoba.

#### 3.4.3.6 Necoxtla Formation

In Ramos (1983), Risser identified the Necoxtla slates from faunal assemblages as belonging to the Late Cretaceous. Thalmann and Ayala-Castañares (1959) assigned the Necoxtla Formation to the Sononian-Campanian stage based on micropaleontological studies. The Necoxtla slates extend from Santa Rosa to Tepetzingo to the Río Santo Domingo.

The Late Cretaceous Necoxtla Formation is found deformed beneath middle Cretaceous sediments of the Cerro Rabón Thrust Fault. Outcrops are located in the pediment of the front range below the Cerro Rabón escarpment. They are also located to the east of the study area and along the banks of the Río Santo

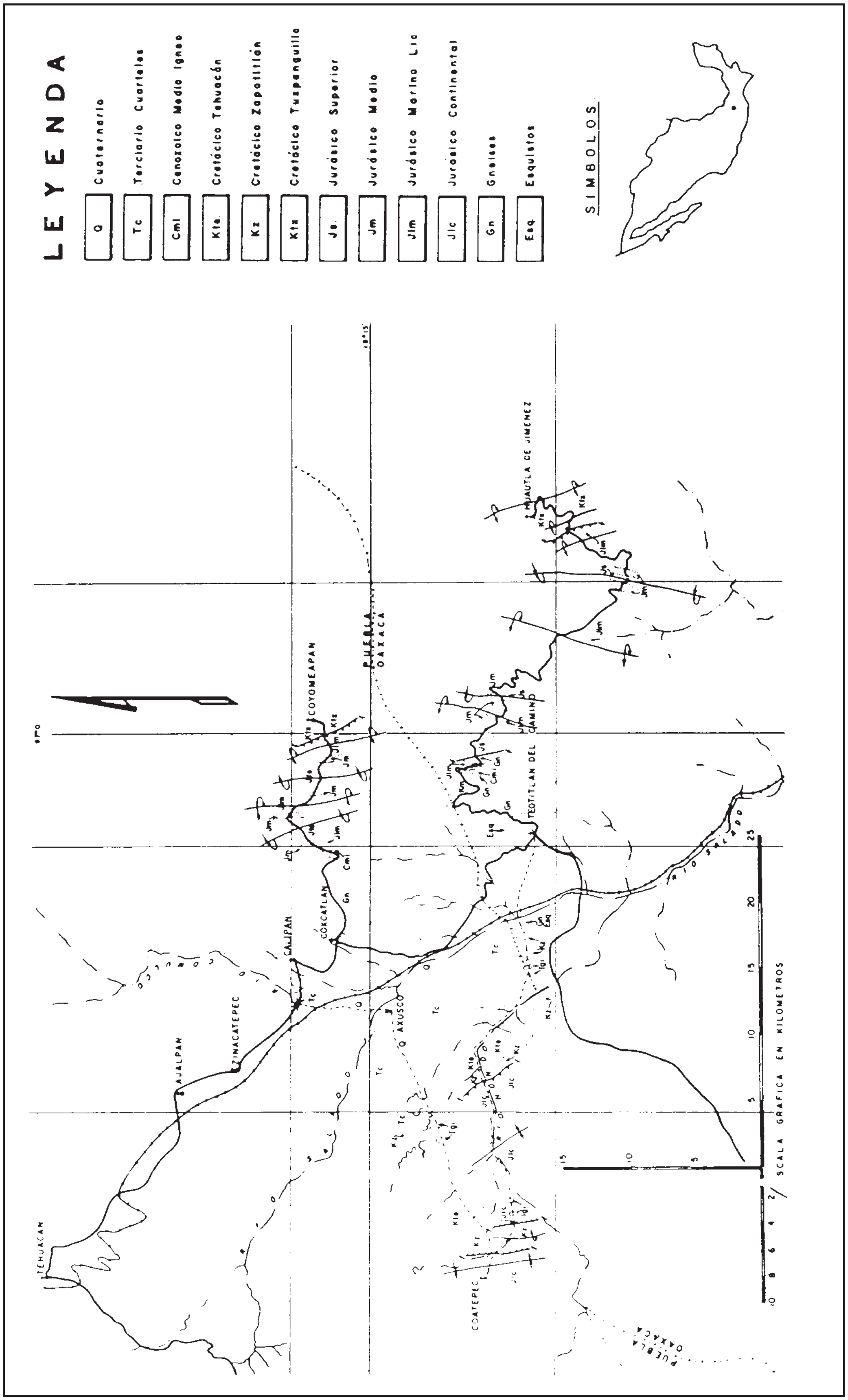



**Figure 3.4.** Stratigraphy and structural geology from Coatepec, Puebla, to Huautla de Jiménez, Oaxaca. Source: Echanove 1963.

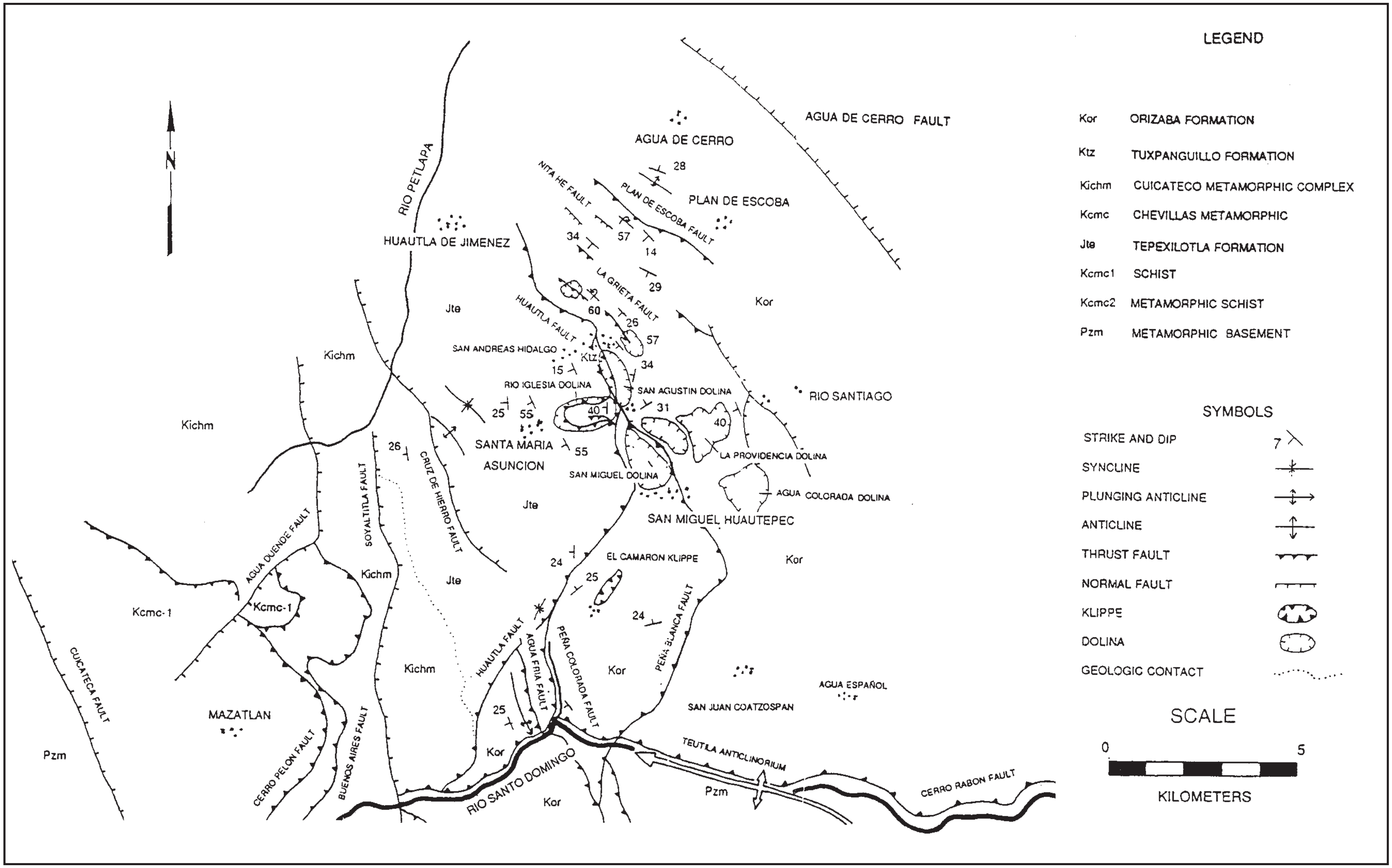



**Figure 3.5.** Stratigraphy and structure of the Sierra Mazateca, Oaxaca, Mexico. Source: Moreno 1980 and Smith 1988f and 1989b.

Domingo to the southwest of the San Juan Coatzospan (Viniegra, 1966).

The Necoxtla Formation consists of pink and yellow variegated silty slates and mudstones with calcareous and ferruginous concretions that are gray to olive green (Viniegra, 1965). The thickness of the unit is not known due to intense folding.

3.4.3.7 Atoyac Formation

The Atoyac formation was identified by Mena (1958 in Ramos 1983, pp 121–122) and Tarango(1971) as a reef limestone in the locality of Sierra Atoyac in Veracruz. The formation comprises dark gray mudstones and wackstones containing pellets, bioclastic fragments, and clasts of quartz. The limestone exists in beds of 40 to 80 centimeters.

The common fossils of the formation are *Spiroloculina* (ostracods), ammonites, and mats of the algal *Ouinaueloculina*. Index fossils *Spiroculina*, *Sulcoperculina globosa*, and *Sulconerculina vermunti* in the Atoyac Formation correlate to Campanian-Maestrichtian age.

The Atoyac Formation was identified 30 kilometers to the east of the study area near Agua Español (Moreno, 1980). The Atoyac Formation overlies the Orizaba Formation and ranges in thickness from 200 to 800 meters (Ramos, 1983).

## 3.5 Quaternary System

The surface terrain of the Sistema Huautla Karst Groundwater Basin consists of solutionally eroded limestones that have formed a cherty orange clay soil ranging from a few centimeters to 10 meters in thickness. Within the soil profile are colluvial fragments of limestone and blocky chert. Most limestone areas form deep red terra rossa soils, but this is not the case in the limestone region of the Sierra Mazateca.

In the bottoms of large dolinas such as the Río Iglesia, San Miguel, and San Agustín that are located adjacent to the overthrusted clastic cap rock, fluvial systems flow on top of alluvial and colluvial regolith consisting of conglomerates of shale, angular limestone cobbles, and arkose pebbles and cobbles. The angularity of the bedload indicates a source of close proximity. The soil on the hill slopes attains a thickness of 1.5 meters. The soil profiles exposed from erosion in the bottoms of large dolinas are found to exceed several meters in thickness.

Other large dolinas with intermittent and perennial streams, such as the Agua Carlota and La Grieta dolinas, that are not located adjacent to allochthonous clastics contain both colluvial and alluvial sediments. Alluvial sediments consist of poorly sorted, angular limestone, shale, and chert fragments, indicating short transportation. Residual soils in the dolinas have been deposited by sheet wash from steep slopes. Local agriculture has contributed to the erosion of these slopes.

The bed of the Río Santo Domingo, located at the southern edge of the Sistema Huautla Karst Groundwater Basin, contains unconsolidated Quaternary sediments consisting of boulder conglomerates and alluvium derived from interior basins and metamorphic highlands to the west. These conglomerates represent most of the rock types of the region. They consist chiefly of metamorphics, such as schists, greenstones, and metavolcanics, sedimentary rocks, such as limestones, sandstones, and shales, intrusive plutonic rocks, such as granites, granodiorites, diorites and pegmatites, and extrusive plutonic rocks such as rhyolites, andesites, and tuffs. An unusual occurrence is an impure form of jadeite found in the alluvial gravels of the Río Santo Domingo (Smith, 1989a).

## 3.6 Stratigraphy of Sistema Huautla Karst Groundwater Basin

Based on field observations and literature review, the stratigraphy of the karst groundwater basin is found to consist of the Jurassic, Cretaceous, and Quaternary Systems. The rocks distributed across the Sistema Huautla Karst Groundwater Basin vary in composition from insoluble shales and sandstones to soluble limestones and dolostones.

The siliceous clastic rocks tend to occupy the western portion of the basin and follow a north-south distribution along the regional structural axis. Exposed to the east are soluble carbonates that form the Sistema Huautla Karst Groundwater Basin. The distribution of the carbonates lies parallel to the silica clastic rocks. A complicating factor in identifying the rock units of the Sistema Huautla Karst Groundwater Basin is a series of subparallel reverse faults and subperpendicular normal faults (Figure 3.5).

The rocks across the basin may be grouped based on physical characteristics. The rocks forming the western margin of the groundwater basin are thin-bedded mudstones, shales, and sandstones, with minor limestone beds. Lying in narrow bands to the east are thin-bedded micritic limestones and bedded chert intercalated with thin shale partings. Exposed by erosion in the bottom of dolinas are massive bedded limestones and dolostones with minor chert beds and nodules.

### 3.6.1 Western Margin of the Sistema Huautla Karst Groundwater Basin

The stratigraphy from San Andrés to San Agustín Zaragoza consists of Jurassic clastics on the western margin of the Sistema Huautla Karst Groundwater Basin and Cretaceous limestones and dolostones to the east (Figure 3.6).

The siliciclastic rocks are composed of shales and sandstones with beds of limestone of the Jurassic. These rocks have been identified by Echanove (1963) and Moreno (1980) as belonging to the Tepexilotla Formation. These rocks tend to form the western limit of the karst groundwater basin and provide a cap rock overlying allochthonous Cretaceous carbonates. The Tepexilotla Formation occupies the highest elevations west of the San Agustín, Río Iglesia, and San Miguel dolinas and extends south toward the Río Santo Domingo, crowning the peaks of Cerro Quemado. These rocks consist of arkosic sandstones, shales, limestones, and thin-bedded black mudstones with quartz veins. These rocks are allochthonous and form the hanging wall of the thrust sheet. The thrust fault is the Huautla–Santa Rosa Fault (Moreno, 1980) and overlies Cretaceous limestones. The contacts between different formations are buried by regolith.

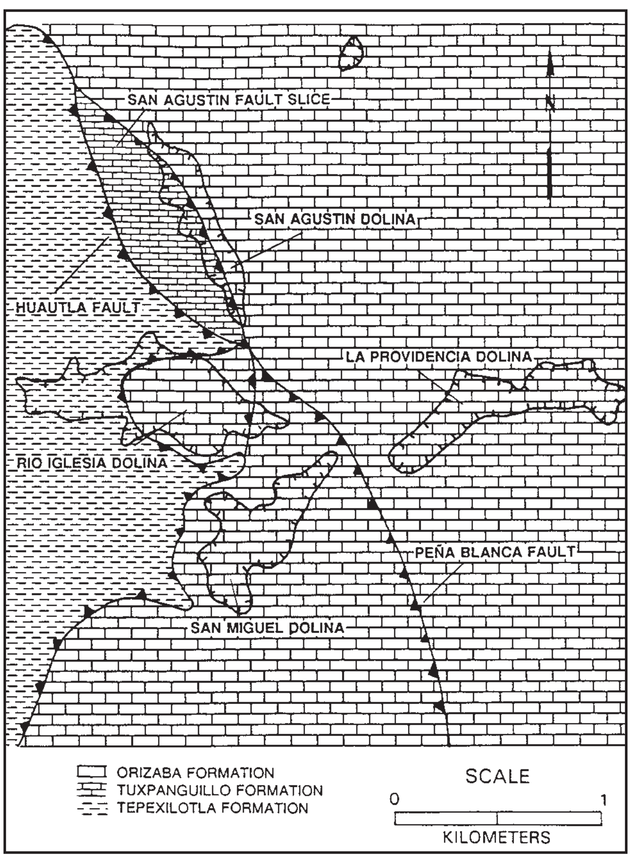



**Figure 3.6.** Lithofacies map of San Agustín, Río Iglesia, San Miguel, and La Providencia dolinas.

Beneath the hanging wall of the Huautla Fault are Lower Cretaceous limestones of the Tuxpanguillo and Capolucan Formations (undifferentiated) and the Orizaba Formation. On the east side of the fault are thin-bedded dark gray micritic limestones believed to be the Tuxpanguillo Formation. The outcropping rocks are different in appearance from rocks on either side of the fault. The Tuxpanguillo Formation forms cliffs above the San Agustín Dolina on the west side. The outcrop may be traced from the west side of the Río Iglesia Dolina to the north to San Andrés. The outcrop also borders the road from San Andrés to Huautla de Jiménez (Echanove, 1963).

East of the Huautla Fault, identified by Moreno (1980), is the Falla de Peña Blanca or Peña Blanca Fault. The fault marks the eastern limit of the outcrop of the Tuxpanguillo Formation. The Tuxpanguillo Formation may be a fault slice, since it appears in outcrop for a limited areal extent. The presence of the Tuxpanguillo Formation implies the existence of two faults.

To the east of the high-angle reverse Peña Blanca Fault, the physical characteristics of the limestones change abruptly. The rocks were observed to consist of thin to thick-bedded limestones, 4 centimeters to 1.5 meters thick, intercalated with thin shales 2 millimeters thick and bedded cherts 2 to 6 centimeters thick of the Orizaba Formation.

Moreno (1980) described the surface rocks from San Andrés to San Miguel Huautepec to the Río Santo Domingo and concluded that the rocks belong to the Orizaba Formation. He does not identify the rocks sandwiched between overthrusted Jurassic rocks and the identified units of the Orizaba Formation. Moreno did not make reference to Echanove's work, which extended up the fringe of the Sistema Huautla Karst Groundwater Basin (Figure 3.4).

When Moreno conducted his field investigations, he found that the fossils in the outcropping limestones are poorly preserved due to recrystallization. He based his findings on identifying the fossil, Caprinida, of the Albian-Cenomanian near the community of San Agustín. It is not known where he obtained his samples for identifying the surface rocks.

The outcrop of the Orizaba contains both dolostone and limestone beds that alternate in color from cream white to medium gray (Plate 3.1). The rock has been recrystallized to form a low-grade marble. This marmoratization occurs chiefly in folds

and in zones adjacent to faults. Internal structures of fossils found in the rock were not identifiable due to recrystallization. The lack of abundant fossil beds and dolomitic limestones in the outcrops near San Agustín indicate a backreef facies.

In the area between San Andrés and San Miguel are the entrances to several deep vertical caves, including Sótano de San Agustín and Sótano del Río Iglesia. While these entrances are positioned adjacent to the allochthonous clastic cap rock, they are located in the Orizaba Formation.

### 3.6.2 Stratigraphy East of the Road from San Andrés to Nuevo Progreso and North to Agua de Cerro

The area east of San Andrés is topographically and structurally higher than the rock units found south of San Andrés to San Miguel, with the notable exception of the topographically higher Jurassic rocks on the western margin of the basin (Figure 3.5). The rock units lying to the east are situated up to 400 meters higher topographically and structurally up dip. The rocks are either the upper Orizaba Formation or rocks of the Maltrata Formation (Viniegra, 1965). It appears that Moreno did not extend his field studies northeast of San Andrés and relied on photogeologic interpretation.

On the road from San Andrés to San Felipe the rock units consist of black thin-bedded micritic limestones from 2 to 6 centimeters thick, intercalated with bedded chert and shales. Thin-bedded limestones are interbedded with a massive-bedded limestones one kilometer north of San Andrés. The massive beds are between 2 and 3 meters thick and contain breccia beds with angular fragments up to 8 centimeters across.

Overlying and underlying the breccia beds are thick sequences of thin-bedded limestones intercalated with white to cream to black bedded chert estimated to be 400 meters thick. The intercalated limestones have been observed in caves that drain into Sistema Huautla (i.e., Li Nita, Nita Zan, Sótano de Agua de Carrizo, Nita Ka, Nita Nanta, and Nita He). The rock units found in Sótano de San Agustín are more massive-bedded and less cherty in the upper levels and shafts in the cave.

It was originally thought that the thin-bedded cherty limestones were the United Orizaba Formation. It is possible the cherty limestones are an extension of the rocks described by Viniegra (1965) as the Maltrata Formation. The formation is found in outcrop 5 kilometers north of Huautla near Zongolica Chilchotla (Viniegra, 1965). The northeast portion of the Sistema Huautla Karst Groundwater Basin is near the boundary of outcrop for the Maltrata Formation.

The closest outcrop of fossiliferous limestones is one kilometer southeast of San Andrés in the La Grieta Dolina. The floor of the dolina is 90 meters higher than the floor of the San Agustín Dolina. Fossiliferous limestones composed of rudist clams belonging to the Orizaba Formation are seen near the entrance of the cave La Grieta and in surface outcrops near Plan Carlota. This lateral variation indicates a facies change from west to east from a back reef facies to a reef facies.

Most of the cave entrances located in the northern portion of the karst groundwater basin are located in thin-bedded cherty limestones of possibly the Maltrata Formation or upper Orizaba Limestone.

### 3.6.3 Stratigraphy from San Miguel Huautepec to Río Santo Domingo

In the southern portion of the Sistema Huautla Karst Groundwater Basin, the surface rocks are composed primarily of Jurassic rocks on the western margin and massive-bedded units of the Orizaba Formation, as described by Moreno (1980). However, field investigation during this study has indicated that the area is more complex than Moreno described. The presence of additional allochthonous units and contacts between allochthonous units is in question.

Near the community of El Camarón, the surface rocks consist of two distinct limestone formations. The upper limestone unit is a dark gray thin-bedded shaley limestone 2 to 6 centimeters thick that is intensely folded and contains vein calcite fracture filling. This rock unit overlies massive-bedded rock 1.5 to 2 meters thick of the Orizaba Formation. The highly deformed thin-bedded limestones are believed to be a klippe or erosional remnant of Jurassic limestones and shales of Tepexilotla Formation. These rocks are similar to the rocks overlying the Huautla Fault. The klippe outcrops in a road cut and quarry near the square in the town of El Camarón. The intensely deformed rocks extend for approximately 500 meters along a narrow ridge that is less than 100 meters thick (Figure 3.5).

In the vicinity of El Camarón and the Peña Colorada Canyon, the Orizaba Formation is estimated at a thickness of 600 meters. Moreno (1980) provided a map showing the areal distribution of the Orizaba Formation. His map, constructed from field investigation and interpreting aerial photos, does not adequately define the areal distribution of the rock outcrop as related to the position of defined faults. Moreno drew the Huautla Fault down the center of the Peña Colorada Canyon. He described the hanging wall of the fault as consisting of the Tepexilotla

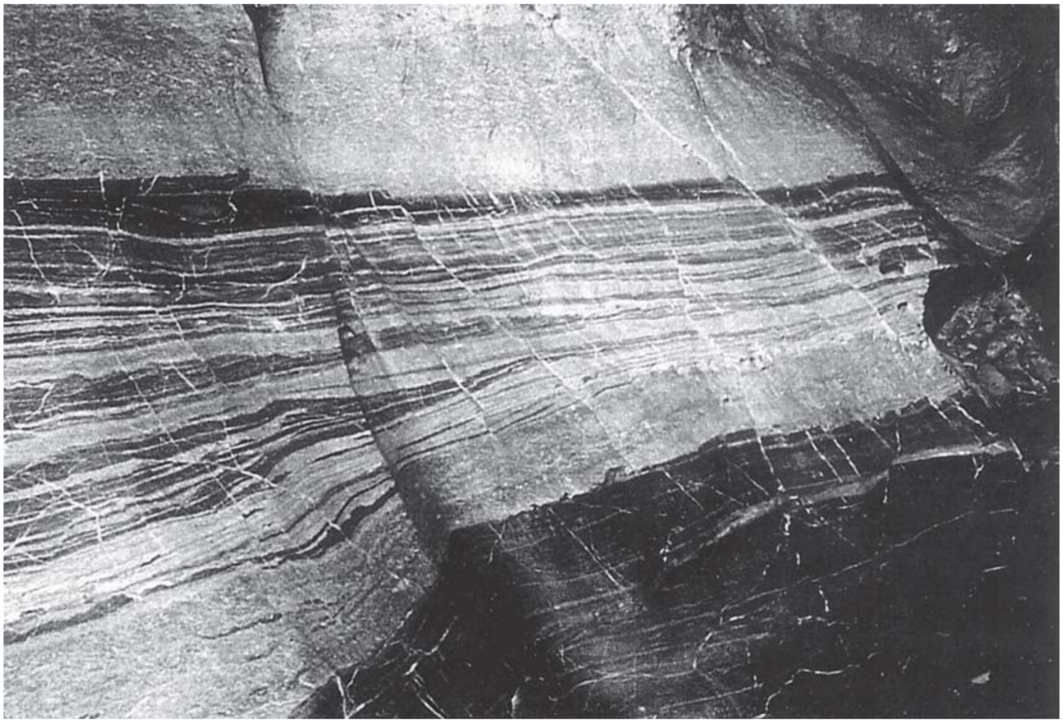


**Plate 3.1.** Limestones and dolostones 1.5 to 2 meters thick are characteristic of the Orizaba Formation.

Formation. While it was not obvious from traversing the Peña Colorada Canyon that a major reverse fault exists down the center of the canyon, the alleged hanging wall does consist of massive units of the Orizaba Formation. In the western wall of the Peña Colorada Canyon are a number of caves, most notably Cueva de Peña Colorada, an overflow resurgence cave of Sistema Huautla.

From the junction of the Peña Colorada Canyon and Río Santo Domingo, the massive units of the Orizaba Formation may be traced for two kilometers to the west, until a definite contact between underlying black slates are found in outcrop at river level. Near this junction to the west are metamorphics of the Cuicatlán Complex that lie as allochthonous strata over Cretaceous rocks. It was hypothesized that the outcrop of massive beds of the Orizaba west of the Peña Colorada–Río Santo Domingo confluence was in a separate groundwater basin than the Sistema Huautla Basin. The western limit of the basin may be defined by a thrust fault located 1.5 kilometers west of Peña Colorada Canyon and east of Cueva de Agua Fría (Figure 3.5).

The proposed position of the Jurassic outcrop of the Tepexilotla Formation is west of the present boundary, as indicated by the position of the Huautla Fault according to Moreno. Hence, the Huautla Fault is probably located farther to the west, defining the contact between the allochthonous rocks of the Jurassic and the underlying Cretaceous limestones.

### 3.7 Conclusions

Due to the structural complexity, the stratigraphic units of the Sistema Huautla Karst Groundwater Basin need to be better identified by index fossils to be able to confidently determine their sequence and to accurately locate the stratigraphic positions of cave entrances. One could infer by the law of superposition that the Orizaba Formation is overlaid by the Maltrata Formation in the study area, based on detailed descriptions of the lithology of type localities. Work by Echanove (1963) and Viniegra (1965) extended up to the edges of the study area, and their findings could be extended into the study area provided attention was paid to the appropriate structural boundaries. The Maltrata Formation is a deep-water facies that overlies the Orizaba Formation concordantly at locations north of the study area. The Maltrata is also composed of mud and siltstones in the areas it was identified. In the Huautla area there are few silt- and mudstones associated with the thin-bedded black cherty limestones. If this is the Maltrata Formation, this location could have been free of terrigenous influx of sediments and represents a facies change.

It was beyond the scope of this study to do detailed stratigraphic mapping, which would require

paleontological studies, possibly of microfossils. The work by previous investigators has resulted in a positive identification of rock units where sampled. Their work is important as a base-line stratigraphic interpretation. Unfortunately, their work is not definitive in this respect. They did not extend their fossil collecting into the surrounding hillsides. Field investigations as part of this research have indicated that there may be inconsistencies in previous interpretation of the stratigraphic position of rock units as related to structure compared to what was observed in the field.

Identifying the stratigraphic positions of soluble and insoluble rocks is important for interpreting the boundaries of the karst groundwater basin and for providing an explanation of the genesis of cave development, as discussed in a subsequent chapter.

In this study, the following contributions were made to the knowledge of stratigraphy of the Sistema Huautla Karst Groundwater Basin: Description of rock units in the field. Location of rock units that are stratigraphically different from one another. New interpretation of the location of stratigraphic units with respect to fault contacts; this interpretation is different than is provided on any geologic map by previous workers. Tentatively identified the formations of rock units the cave entrances are located within. Identified which rock units may provide allogenic recharge or perennial springs to karst swallets. Provided an English translation of the geologic research presented in Spanish-language professional journals.

# CHAPTER 4

# STRUCTURAL GEOLOGY

## 4.0 Introduction

Pertinent to the study of the hydrology of the Sistema Huautla Karst Groundwater Basin is the study of its internal and external structures. It is believed by this researcher that structural elements define the limits of the karst groundwater basin. Prominent faults and folds control the hydrologic flow paths and thus the overall hydrologic pattern of the karst groundwater basin.

Mapping faults and folds in the subsurface of the Sistema Huautla Karst Groundwater Basin provided a basis for comparison with faults and folds mapped at the surface and produced a more comprehensive interpretation of the geology of the karst groundwater basin. Previous work by Echanove (1963) and Moreno (1980) provided cross sections through the study area that generalize the geologic interpretation of the complex structural geology. They did not have the advantage of being able to see the internal structure of the Sierra Mazateca from within the vertically extensive caves of the study area.

Fortunately, 20 years of cave exploration and mapping have provided a tremendous database on hydrologic flow paths through the karst aquifer. Analysis of local structures and their orientation aids in the interpretation of the three-dimensional quantitative model represented by a computer line plot of Sistema Huautla and other caves in the karst groundwater basin. The line plots illustrate 100 kilometers of flow paths that were physically surveyed and explored by cave explorers (Figures 1.3 and 1.4). The cave surveys represent flow paths that are active or currently inactive, as water has abandoned one fracture- or bedding-plane-controlled flow path for another.

To understand the local structural geology, a good interpretation of the stratigraphy and regional tectonic history is necessary. In Chapter 3, stratigraphy and structure as related to stratigraphic position of the rocks were addressed. In this chapter, the regional tectonic history and local structural geology as interpreted by previous workers are presented.

Many additional structures of both large and small scale were identified based on comparing offsets between opposite bedding planes and in some cases between offset formations. Consequently, the structural style is recognizable. The results of the field investigation are presented in the following sections.

## 4.1 Regional Tectonic History

Carfantan (1981a) stated that structures found in south-central Mexico may be attributed to four tectonic-evolutionary phases from the Mesozoic to recent: a compressional phase during the Middle Cretaceous that resulted in regional metamorphism and volcanic intrusion, compression occurring during the Laramide Orogeny, basement folding during the Late Miocene, and an extensional phase during the Miocene-Quaternary interval. Demant (1978) related the structures to the development of the Neovolcanic Plateau. Moreno (1980) described four stages of structural evolution of the Sierra Juárez, uplift of the basement rock and marine regression during the Late Cretaceous, uplift and compression during the Laramide Revolution in the Paleocene, folding and faulting during the Paleocene and Eocene, and a taphrogenic phase from Late Oligocene through the Miocene that resulted in the uplift of the Sierra Juárez and subsidence of the Veracruz Basin to the east (Figure 4.1).

The two most important events shaping the structural style of the Sierra Juárez occurred during a compressional phase in the Laramide Orogeny of the Early Tertiary and during the extensional phase in the Miocene-Quaternary interval.

The structural evolution of south-central Mexico is very complex and poorly understood. It is believed that complex structures that formed during the Laramide orogeny are a result of plate collision and

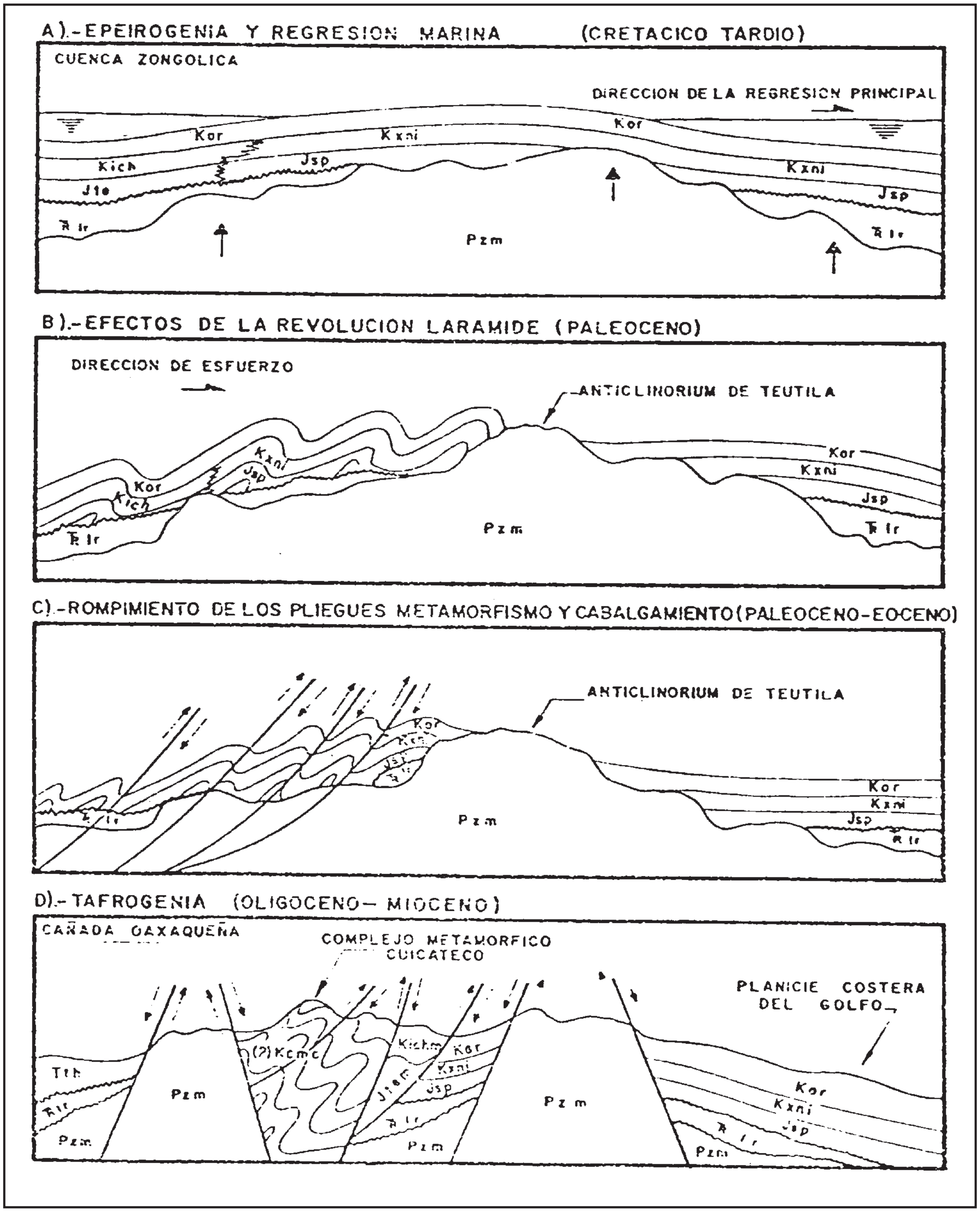



**Figure 4.1.** Structural evolution of the Sierra Juárez.
Source: Moreno 1980.

the accretion of exotic terrains, which, according to Campa and Coney (1983), is what makes paleogeographic reconstruction of south-central Mexico so difficult. The area south of Mexico City is composed of a number of distinct basement terrains (Campa and Coney, 1983), with the oldest being the Oaxaca Complex of Grenville age (Fries et al., 1962). The Oaxaca Terrain provided the continental cortex during the Mesozoic upon which the rest of Mexico accreted or evolved.

The Laramide Orogeny of the Early Tertiary gave rise to the folded and faulted structures present in the Sierra Juárez. There are two hypothesized mechanisms that may have been responsible for the development of structures in the Sierra Juárez. The first hypothesis, developed by Campa and Ramirez (1979), attributed the Mesozoic deformation to the development of a western andesitic island arc, the Arco Alisitos. This island arc was associated with easterly subduction adjacent to the Mexican continental cortex in the western portion of south-central Mexico.

In the second hypothesis, Urrutia (1980) and Campa (1983) postulated that the arco-insular system developed by accretion as the result of obduction in the Pacific until its collision with the Mexican continental cortex.

Back-arc uplift of basement rocks, the Oaxacan Complex, resulted from plate collision and subduction of the Pacific Plate (Coney, 1976). Rise of the Oaxacan Peninsula provided the mechanism for gravity sliding of sedimentary rocks over a decollement strata consisting of Jurassic shales (Mossman and Viniegra, 1976). Gravity sliding occurred from west to east.

The structural style of deformation in the Sierra Juárez is complex, consisting chiefly of two distinct styles, thin-skinned and block faulting. Thin-skinned deformation formed during the compressional phase of the Laramide Orogeny during the Paleocene and

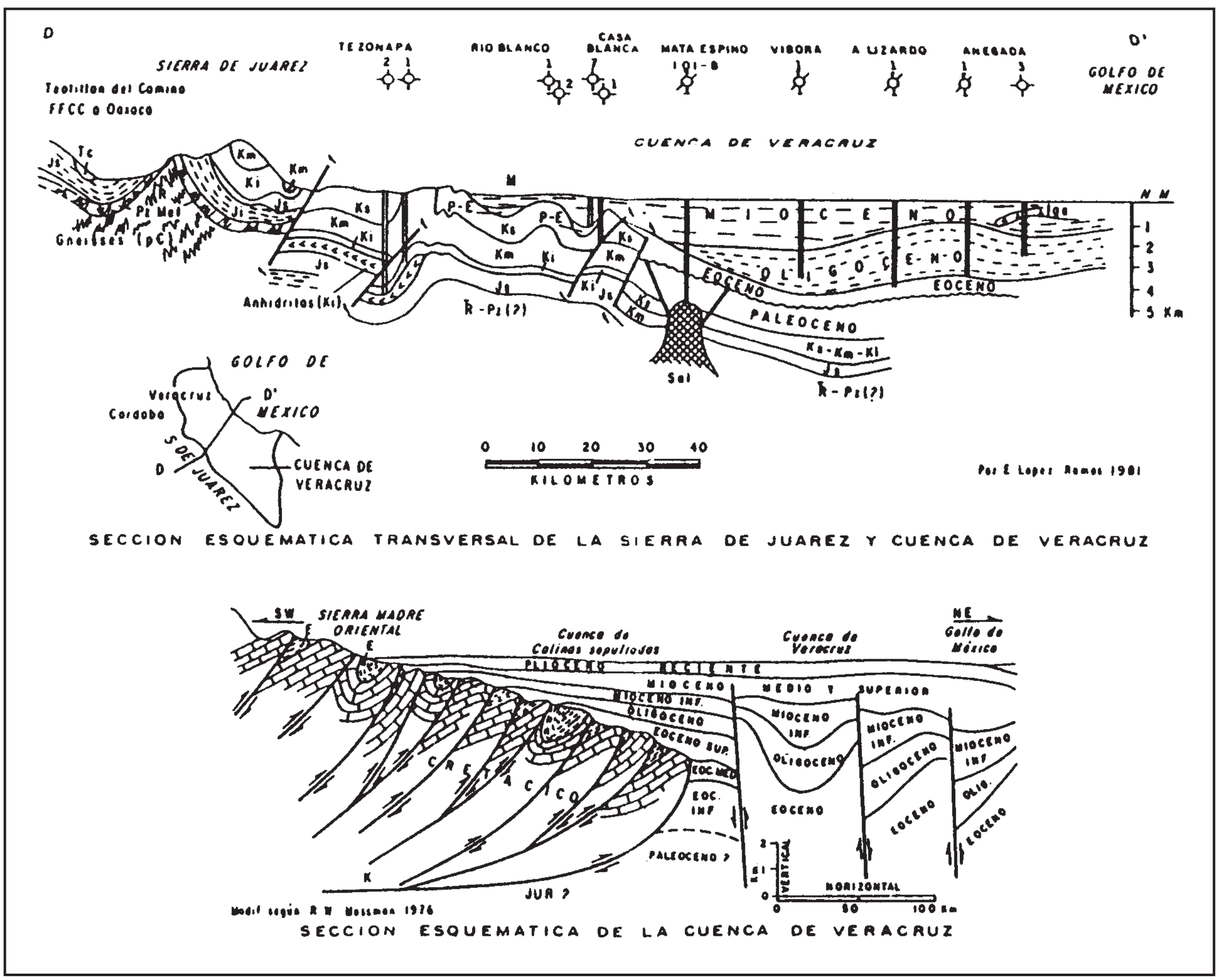



**Figure 4.2.** Geologic cross-section of the Sierra Juárez and Cuenca de Veracruz. Source: Mossman and Viniegra 1976.

Eocene, and block faulting occurred during the Miocene-Quaternary Interval (Figure 4.2). The compressive effects on ridged limestone produced an extensive fold belt striking NW-SE that consists in general of westerly-regional-dip, asymmetrical folds, overturned folds bound by reverse faults, basal thrust faulting, and overthrusting and imbrication similar to the Alberta Foothills structures in the Canadian Rockies (Mossman and Viniegra, 1976).

Charleston (1980) studied allochthonous metamorphic rocks that outcrop on the western edge of the Sierra Juárez. The rocks rest disconformably over Mesozoic carbonates south of the Río Santo Domingo in the Sierra Juárez. These rocks were originally Lower Cretaceous pelitic sediments deposited in a eugeocline. Metamorphism took place in an ancestral Benioff zone.

Charleston (1980) radiometrically dated gneiss and schist from the Cuicateco Complex and attributed the deformation to the Late Cretaceous and Early Tertiary, corresponding to the Laramide Orogeny. The metamorphic rock on the western flank of the Sierra Juárez represent a wide mylonitic band that separates the Maya terrain from the Oaxaca terrain (Campa and Coney, 1983). Carfantan (1981a) postulates that the wide mylonitic band is related to the opening and closing of an ocean basin and rift development during Turonian time. However, the origin of these cataclastic rocks is poorly understood.

The second phase of deformation occurred during the Miocene-Quaternary interval at a time when the Cocos Plate was subducting beneath the continental cortex of Mexico (Demant, 1978). At this time, the Neovolcanic Axis was formed and regional uplift occurred.

The uplift of the Sierra Juárez may also be attributed to the reactivation of two structural basins, the Veracruz Basin and the Tehuacán-Oaxaca Basin. The former initially developed in the Lower Cretaceous during the opening of the Gulf of Mexico and separation of the Chiapanaca Plate from the Mexicana Plate (Carfantan, 1981a). Both of these basins form extensional tectonic boundaries to the east and west of Sierra Juárez. The Sierra Juárez is a horst block between the Tehuacán and Veracruz Grabens.

On the eastern edge of the Sierra Juárez is the Veracruz Basin, which began accumulating thick sequences of sediments at the beginning of the Tertiary due to the initial uplift and subsequent erosion occurring during the Laramide Orogeny. This orogenic phase introduced large volumes of sediments onto the continental margin. Since its initiation, more than 8,000 meters of sediments have accumulated unconformably over Jurassic sediments in the Huayacocotla Aulacogen (Veracruz Graben) (Hoffman et al., 1974). The Huayacocotla Aulacogen was formed during the initial rifting that opened the Gulf of Mexico during the beginning of the Jurassic (Effing, 1980). Great influxes of Tertiary sediments may have reactivated the graben during the Miocene. The rise of the Sierra Juárez during the Tertiary may be attributed to a regional uplift having been influenced from the reactivation and subsidence of the Veracruz and Tehuacán-Oaxaca Basins. The uplift resulted in block faulting and north-south-oriented normal faults throughout the Sierra Juárez. The north-south orientation of normal faulting may be the result of isostatic adjustment between the subsiding Veracruz Basin and the rising Sierra Juárez.

### 4.2 Structures of the Sierra Mazateca

The previous section described the origin of structural deformation of the Sierra Juárez and the largest geologic structural features including the fold belt, graben of the Tehuacan-Oaxaca Basin, and the Veracruz Basin. This section provides a closer look at the structures of the Sierra Juárez Geologic Subprovince as they pertain to the Sierra Mazateca.

The Sierra Juárez is a fold belt that consists of structures formed from both compressional and extensional deformation. The fold belt is deformed into a series of parallel asymmetrical folds with complex internal structures, bounded by high-angle reverse faults, tear faults formed from tangential compression, thrust faults, normal faults, and large block faults.

The largest structures within the fold belt are thrust faults. Viniegra (1966) described two major thrust faults associated with the study area. These are the aerially extensive Cerro Rabón and Huautla Thrust Faults. Charleston (1981) described a major thrust fault, the Cuicateco Fault, south of the Río Santo Domingo. Echanove (1963) described a thrust fault on the western boundary of the study area but did not assign a name to the fault. To the south of the Sistema Huautla Karst Groundwater Basin lies a major tectonic boundary interpreted to be a transcurrent fault. The major faults associated with the study area are described in the following sections.

#### 4.2.1 Cerro Rabón Thrust Fault

Viniegra (1966) described the Cerro Rabón Thrust Fault as having exposures in the front range of the Sierra Mazateca (Figure 3.3). Traces of the thrust fault extend 40 kilometers to the north, where they disappear near Zongolica. The Cerro Rabón thrust fault has been found 35 kilometers west of the study area along

the front range and 10 kilometers southwest of Huautla de Jiménez at exposures west of El Camarón along the Río Santo Domingo (Figure 3.5).

Several kilometers to the west of El Camarón, the Cerro Rabón thrust fault disappears under two thrust sheets composed of cataclastic rocks of the Cuicateco Fault, a reverse fault (Charleston, 1981), and Jurassic clastics of the Huautla Fault, also a reverse fault (Viniegra, 1966). The aerial extent and low angle of the fault suggest that this is a sole fault. It is believed that the Cerro Rabón Fault underlies the Sistema Huautla Karst Groundwater Basin. There is no evidence that this fault extends south of the Río Santo Domingo into the Sierra Juárez.

In the front range, the hanging-wall strata consists of the Tuxpanguillo-Capolucan and Orizaba Formations (Early to Middle Cretaceous), which rest on top of intensely folded decollement strata of the Upper Cretaceous Necoxtla slates (Viniegra, 1966). Three kilometers west of El Camarón, intensely folded thin-bedded black slates are found in the river bed of the Río Santo Domingo. The slates are overlaid by massive-bedded limestones of the Orizaba Formation. It is believed that the contact between the two units is the Cerro Rabón Thrust Fault.

### 4.2.2 The Huautla–Santa Rosa Fault

Viniegra (1966) found that the rocks of the upper Cretaceous Maltrata Formation rest discordantly over Necoxtla slates near Santa Rosa, 90 kilometers north of the study area. Viniegra hypothesized that the fault extends south to the Río Santo Domingo. Based on this hypothesis, he named the fault the Huautla–Santa Rosa Fault.

Echanove (1963), whose study area encompassed the geologic sections between Teotitlán del Camino and Huautla de Jiménez, mapped a large reverse fault 1.5 kilometers west of Huautla de Jiménez. He found Jurassic rocks resting discordantly over lower Cretaceous rocks of the Tuxpanguillo Formation (Figure 4.3). Moreno (1980) described the Huautla Fault as a thrust fault with a hanging wall consisting of Jurassic rocks of the Tepexiltotla Formation (Figure 3.5). The foot wall consists of rocks of the Orizaba Formation. Moreno positioned the fault east of Huautla de Jiménez. The fault was traced from San Andrés to the Río Santo Domingo along the Peña Colorada Canyon. It is believed that the fault contact was verified in the field by Moreno only in the San Andrés–San Miguel Huautepec areas.

The Orizaba geologic map indicates a major thrust (unnamed) with hanging wall rocks belonging to the Jurassic overlying Cretaceous rocks. The fault extends from 45 kilometers north of Mazatianquisco to Huautla de Jiménez and south across the Río Santo Domingo. South of the river the hanging wall of the Huautla Fault is depicted as being composed of Cretaceous rocks (Figure 3.3). In this area, the contact between the cataclastics and Cretaceous limestones may in fact represent the contact of the regionally extensive Huautla Fault.

It is believed that the fold belt has a thin-skinned structural style (Mossman and Viniegra, 1976), with ruptured overturned folds with many parallel reverse faults. Consequently, the thrust fault Echanove described 1.5 kilometers west of Huautla de Jiménez may not be the Huautla Fault as described by Viniegra (1965) and Moreno (1980) (Figure 4.3). For this research, the allochthonous Jurassic rocks will be referred to as the Huautla Thrust Fault.

The Huautla–Santa Rosa Fault is the most important major fault of the study area because the fault has allowed noncarbonate rocks to overlie soluble carbonates (Figure 4.4). The position of noncarbonate rocks relative to soluble carbonates is significant because the clastic aquifer provides allogenic recharge aggressive to the dissolution of limestone. Hence, this relationship has contributed to the development of large dolinas and the hydrologic framework of the subterranean drainage system. The Huautla–Santa Rosa Fault is not seen in Sistema Huautla or any other cave in the karst groundwater basin and therefore has no direct influence in the development of cave passages.

### 4.2.3 Río Santo Domingo Transcurrent Fault

This fault is not described in the literature, but its presence is obvious when examining the 1:250000 Oaxaca and Orizaba geologic quadrangles. On the north side of the Río Santo Domingo, the stratigraphy indicates that massive Early and Middle Cretaceous limestones have overthrusted Late Cretaceous limestones and Paleocene shales and sandstones. On the south side of the Río Santo Domingo, Paleocene sediments conformably overlie Cretaceous carbonates and maintain their superposition. While overthrusting occurs all along the western side of the range, the sedimentary rocks south of the river have not undergone the same degree of deformation as the sedimentary rocks north of the river. The Cerro Rabón Sole Fault may not extend south of the river (Vinegra, 1966), suggesting that a shear zone has developed normal to the thrust front along the present day course of the Río Santo Domingo. Mossman and Viniegra (1976) noted that transcurrent faults may exist, based on aerial photographs of the Sierra Juárez. Viniegra (1966) noted the existence of straight U-shaped valleys west

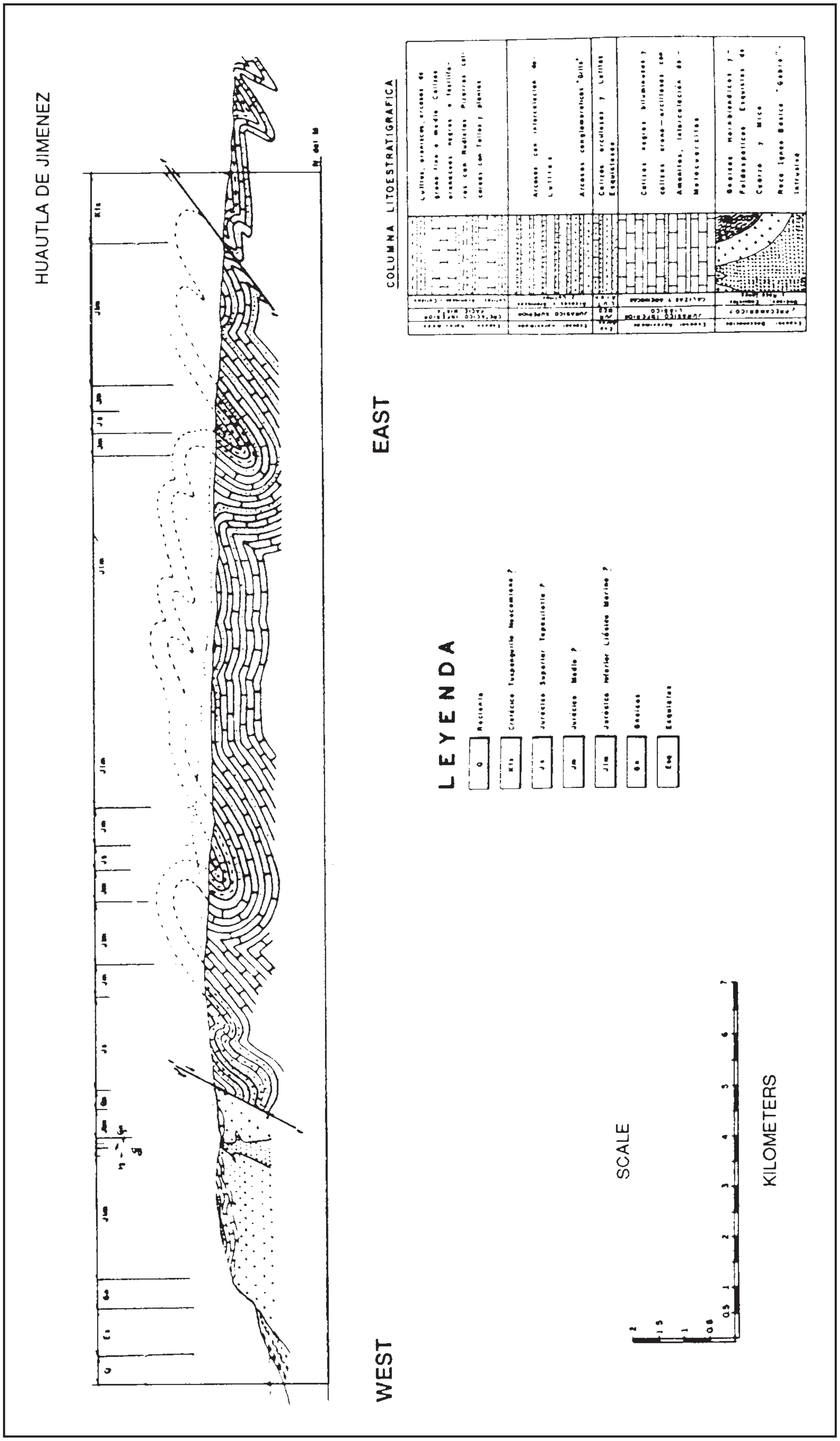



**Figure 4.3.** Structural cross-section of Huautla de Jiménez to Teotitlan del Camino, Oaxaca. Source: Echanove 1963.

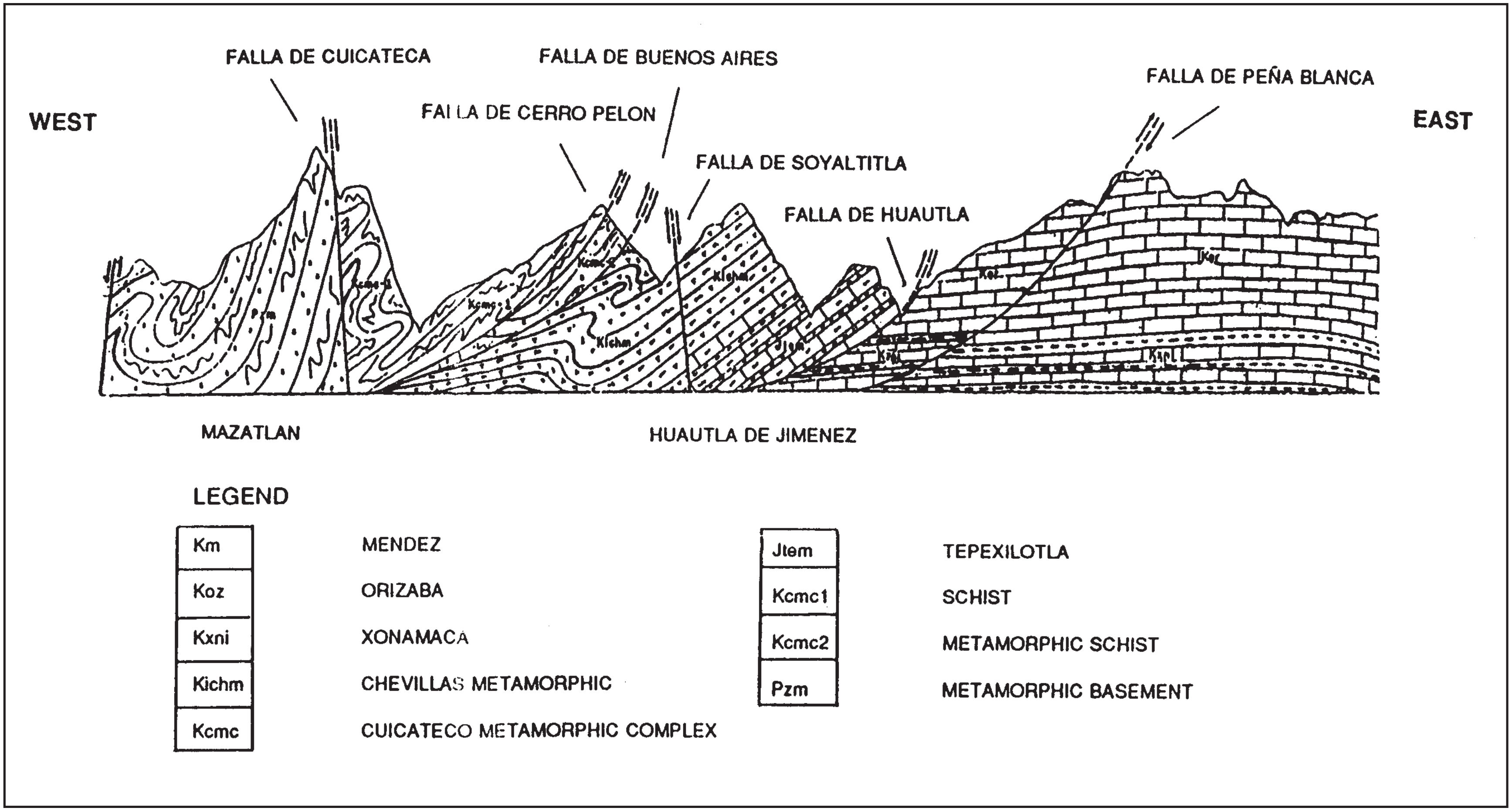



**Figure 4.4.** Structural cross-section of Peña Blanca to Loma Grande. Source: Moreno 1980.

of Orizaba. He considered the Acultzingo Valley to be developed along a transcurrent fault. It is suggested that the Río Santo Domingo is also formed along a transcurrent fault.

#### 4.2.4 Faults Between the Huautla–Santa Rosa Fault and the Cuicateco Fault

Located west of the study area are faults described by previous workers (Figure 3.5). The faults are significant because they have been recognized and mapped. Any attempt at field mapping west of the Huautla Fault will require knowledge of known faults.

Echanove (1963), Viniegra (1966), Moreno (1980), and Charleston (1980) have described and assigned names to numerous faults located between the Huautla–Santa Rosa Fault and the Cuicateco Fault.

Moreno (1980) described two thrust faults located west of the normal fault, Falla de Soyaltitla. The thrust faults are named Falla de Cerro Pelón and Falla de Buenos Aires. It is important to recognize the existence and position of these faults as a baseline for studies conducted in the field.

##### 4.2.4.1 Falla de Hierro

Moreno (1980) described three normal faults west of Huautla de Jiménez (Figure 3.5). These are the Falla de Hierro, Falla de Soyaltitla, and Falla de Agua de Duende. The hanging wall of each normal fault drops to the east toward Huautla. Only the Falla de Hierro is described here since its trace is within the study area.

Falla de Hierro is described by Moreno (1980) as a normal fault existing approximately one kilometer west of Huautla de Jiménez. Moreno traced the fault from north of Huautla to the southeast towards El Camarón. East of the fault is an anticline and a syncline. It appears this is the same fault described by Echanove (1963) as a thrust fault since the position of the anticline and syncline are similar.

##### 4.2.4.2 Cuicateco Fault

Charleston (1980) described metamorphic rocks of the Cuicateco Complex located on the western side of the Sierra Juárez (Figure 3.5). The Cuicateco Complex consists originally of eugeoclinal sandstones, shales, and volcanic flows tentatively assigned to the Early Cretaceous. The sedimentary strata were subsequently metamorphosed into schist and metavolcanics.

Carfantan (1981a) and Campa and Coney (1983) described the rocks on the west side of the Sierra Juárez from Concepción Pápalo to Teotitlán del Camino as consisting of lenses of ophiolites (serpentines) that were mined for asbestos.

The Cuicateco Fault is subparallel to all of the major thrust faults of the region and considered to be genetically related to all other thrust faults occurring during the Laramide Orogeny. The Cuicateco Fault is subparallel to the Huautla–Santa Rosa Fault and the Cerro Rabón Fault and has the largest known areal extent of reverse faults in the sierras. The trace of the fault extends north to Orizaba and south of Cuicatlán. The fault is identified on the 1:250,000 Orizaba and Oaxaca geologic quadrangles as the thrust fault that separates cataclastic rocks from metasedimentary rocks on either side of the Río Santo Domingo.

The rocks of the Cuicatlán Complex are allochthonous and rest over Jurassic metasedimentary flysch deposits on the western slopes of the Sierra Mazateca and carbonates south of the Río Santo Domingo in the Sierra Cuicateco near Cueva Cheve.

Description of this fault is significant because it is one of the largest faults in the region and is genetically related to the structural evolution of the area. However, the fault does not outcrop in the Sistema Huautla Basin.

#### 4.2.5 Faults Of the Sistema Huautla Karst Groundwater Basin

Moreno (1980) described only one important fault in the Sistema Huautla Karst Groundwater Basin; he called it Falla de Peña Blanca. He described the fault in the east-central portion of the Sierra Mazateca at San Juan Coatzoapan. The fault is then traced to the northwest and joins the Huautla–Santa Rosa Fault at San Agustín. The hanging wall of the fault consists of the Orizaba Formation, which overlies the Mendez Formation, which correlates to the Maltrata Formation of the Late Cretaceous (Figure 3.5).

### 4.3 Preliminary Geologic Field Investigations

The literature review is fundamental to the understanding of the geologic history, the tectonics of the region, and past research conducted in the study area. Little geologic information was available on the area hypothesized to be the Sistema Huautla Karst Groundwater Basin. It was therefore necessary to define the geology of the study area by interpretation of geologic features from available maps and then conduct geologic field investigations to understand the influence of these features in the karst groundwater basin. The field investigations were necessary to determine the structure of the karst groundwater basin, the area of probable groundwater output, the structural influences on flow patterns within the basin, and the hydrogeologic setting for the development of a model for speleogenesis.

4.3.1 Lineament Analyses

It has been recognized by numerous researchers that solutional features (e.g., cave passages, shafts, solutional crevices) are formed primarily along fractures defined as bedding planes, joints, and faults (Pohl, 1955; Merrill, 1960; Ford, 1971; Palmer, 1972; Mylroie, 1977; Ford and Ewers, 1978; Crawford, 1980; and Palmer, 1991). Of major importance to this thesis was an investigation of the relationship between 72.91 kilometers (Minton, 1988) of mapped cave passage in the Sistema Huautla Karst Groundwater Basin to the regional structural development. Are the cave passages strike-orientated along steeply inclined beds, aligned along joints, and/or aligned along faults? Does the pattern of mapped cave passages follow any regional fracture-pattern trends expressed as topographic lineaments? Are topographic lineaments an expression of regional fracture patterns?

Most researchers believe there is a correlation between topographic lineaments and structure, and some karst researchers have described a correlation between topographic lineaments, structure, and cave passage trend. However, there are hydrogeologic situations where there is no apparent correlation between any of these features.

Boyer and McQueen (1964) determined that there is a relationship between topographic lineaments and mapped joints in flat-lying rocks. In the Appalachian fold belt of Pennsylvania, it was found that there is no correlation between topographic linears and joint sets in tightly folded areas (Lattman and Matzke, 1961). Lattman and Parizek (1964) describe lineaments as a zone of closely spaced fractures. They found that wells located on topographic lineaments hypothesized to be fracture traces in carbonate aquifers had greater yields and intersected more conduits than in other areas within the same aquifer.

Wermund and Cepeda (1977) found that the development of caves correlated with fractures measured in the field and from air photos in the Edwards Aquifer of Texas. Miller (1981) in his study of Caves Branch Karst found a strong correlation between photo lineations and the alignment of cockpit karst features. Barlow and Ogden (1982) found a correlation between the position of cave systems and their orientation with fracture traces in Arkansas. Ogden and Redman (1993) found a strong correlation between orientation of cave passage segments, topographic lineaments, and fractures in dolostones of the eastern overthrust of Tennessee. Nelson and Monroe (1966) correlated a large erosional feature observed on a topographic map with a major fault.

Viniegra (1966) described several U-shaped west-east trending valleys in the Sierra Madre Oriental. One is the Acultzingo Valley, which is located north of the study area, near Orizaba. The limestone valley is oriented normal to the regional strike and is thought to have been formed by chemical erosion along fractures. It is suggested by the orientation of the valley and lack of vertical offset between stratigraphic units across the valley that erosion occurred along a strike-slip fault.

Brown (1961) found that lineaments mapped from aerial photos almost always indicate the presence of faults, but that they are not always consistent with joint sets in West Virginia and Pennsylvania. Deike (1989) studied Mammoth Cave and found that there is little correlation between minor joint sets and straight passage segments. No cave passages are aligned with topographic lineaments thought to be fracture traces. There was a correlation between alignment of sinkholes and some cave passages. Ford and Williams (1989) found from intensive literature review that in most instances there is no correlation between the location and position of cave systems in limestone with fracture traces.

An investigation was made to determine the significance of linear features in the Sistema Huautla Karst Groundwater Basin as mapped from surface strike and fault measurements, topographic maps, and cave maps. The approach used was a comparative analysis based on number of segments and their orientation. Topographic lineament orientations distributed across the karst groundwater basin were measured to determine the influence these probable structural features have on the direction of subterranean drainage of the region. The most informative map available for this purpose is the 1:50,000 scale Huautla Topographic Map prepared by the Mexican Topographic Service.

Ford and Williams (1989) defined fracture traces, fracture linears, and fracture lineaments as narrow linear trends that are detectable from aerial photography or topographic maps (Figures 1.5, 1.6).

El-Etr (1974) defined a lineament as any natural feature less than 10 kilometers long. This definition for describing lineaments was adopted by Miller (1981) during his structural interpretation of Caves Branch Karst in Belize. El-Etr's definition of a lineament is expanded to include straight-line cave-passage segments, faults, and bedding-plane orientations.

The method used to determine topographic lineaments in this study was to measure straight line segments of stream valleys, karst valleys, narrow ridges, sinkholes that appear to be aligned, and dissected ridge lines that are 500 meters long or longer. Straight line

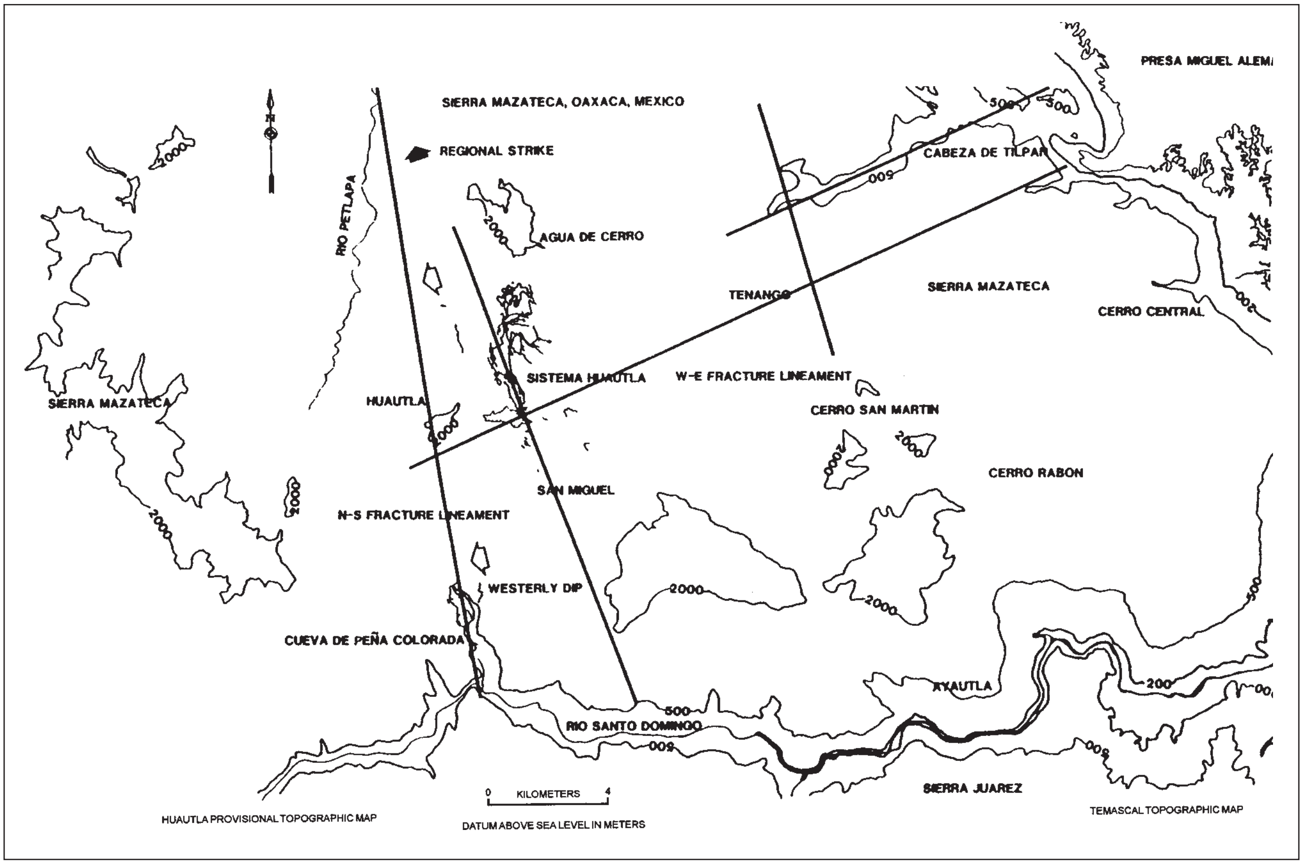



**Figure 4.5.** Major lineaments of the Huautla and Temascal topographic maps.

segments over 500 meters long were given a greater weight. This weight was determined by adding the number of 500-meter segments along the length and dividing by 500 meters. This method emphasizes the importance of long segments. The azimuth of each straight line segment was measured. The data for faults mapped in the cave and on the surface were compared based on the number of faults and their orientation. The number of strike measurements was compared to their orientation. All azimuth readings were adjusted for an 8 degree magnetic declination, as indicted on the Huautla Topographic Map. There were two prominent lineaments oriented to the northwest and two to the southwest (Figure 4.5).

A total of 286 topographic lineaments 500 meters or longer were traced on the Huautla Topographic Map. The dominant orientation was along an azimuth between 330 and 350 degrees (Figure 4.6). The second-order orientation was between 300 and 310 degrees. The third-order lineament orientation was between 20 and 30 degrees.

The computer line plot of mapped cave passages yielded 476 hundred-meter-long straight line segments. Cave passage orientations were dominant in several directions (Figure 4.6). The dominant cave passage orientation was 320 to 340 degrees orientation, the second order of dominance was from 340 to 360 degrees, the third order was 300 to 310 degrees, and the fourth dominant orientation was from 20 to 30 degrees.

Twenty-three fault planes mapped at the surface and in the subsurface, consisting mostly of normal faults, were dominant in several directions (Figure 4.6). Faults were dominant along two sets of azimuths, from 340 to 350 degrees and from 320 to 330 degrees. Second-order fault orientation was from 330 to 340 degrees. A minor fault orientation occurs from 0 to 40 degrees.

One hundred seventy-nine strike measurements were taken across the groundwater basin (Figure 4.6). The strike of bedding planes had a dominant orientation between 30 and 40 degrees. However, the greatest number of strike measurements are oriented between 300 and 360 degrees with a dominant orientation between 320 and 340 degrees.

4.3.2 Conclusions

Analysis of topographic lineaments, faults, straight-line cave passage segments, and strike and dip measurements indicates that there is a correlation

between all of the mapped features. A direct correlation occurs between topographic lineaments, faults, and straight-line cave passage segments. The correlation indicates that topographic lineaments oriented between 320 and 350 degrees are probably fault-related. No joints have been observed in the study area because of the degree of structural deformation. All fractures have observable displacement.

This analysis may also lead to the conclusion that all cave passages are fault related. However, the dominant strike orientation is also in the same plane as most mapped faults, between 300 and 360 degrees, which is also parallel to the regional strike. There are insufficient structural data for segments of mapped cave passages to determine if they are fault-controlled or strike-controlled. The data suggest that the longest straight-line cave segments are formed along the dominant fault orientation. However, one can only conclude that the cave system is formed along major faults striking between 320 to 350 degrees and subparallel to steeply inclined beds striking between a range of 300 and 360 degrees. Many of the cave passages located to the east and northeast of the junction of most of the ridge-top drainage in Sótano de San Agustín follow the dip of steeply inclined beds. The passages zigzag along the NW-SE strike of the steep bedding planes, following the southwesterly dip. The dip controls the ultimate direction of conduit development, because water flows down the least resistant plane. Conduits intersect NW-SE trending faults, and the hydraulic gradient radically changes locally as a consequence of shaft development. Ultimately, the strike of the folded and overthrusted limestone beds controls the north-south alignment of the karst groundwater basin. However, the role faults play in the branchwork pattern of the cave system is significant.

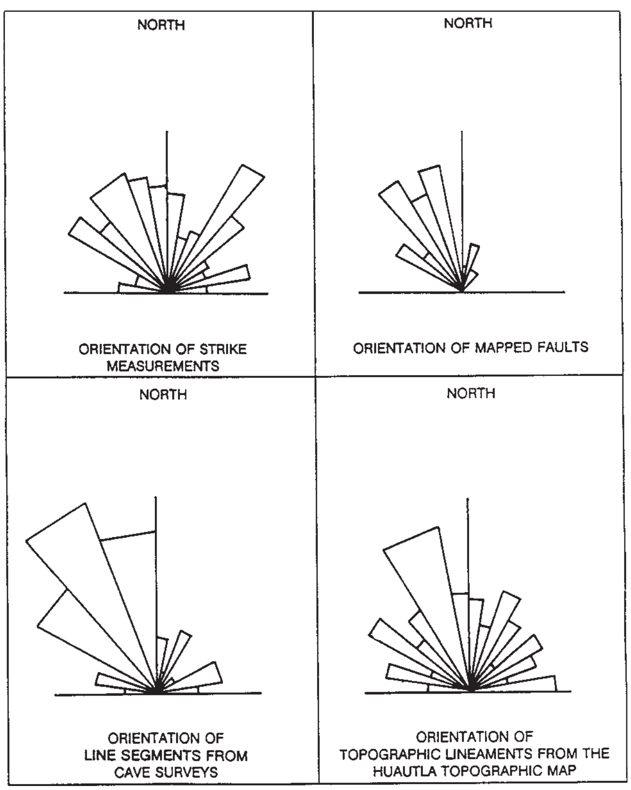



**Figure 4.6.** Rose diagram of faults, strikes, topographic lineaments, and straight line segments of caves in the Sistema Huautla Karst Groundwater Basin, Oaxaca.

The overthrust sheet consists of imbricated plates of Cretaceous limestones. Horizontal movement occurred along a regional decollement on top of Jurassic red beds. The compressive forces that thrusted the Sierras eastward were not of equal intensity along the regional north-south strike, which resulted in differential displacement of fault plates. Thrust-fault plates are bounded by east-west-oriented tear faults occurring normal to the overthrust plates (Mossman and Viniegra, 1976).

Based on this interpretation, lineaments formed perpendicular to the regional strike may be strike-slip or tear faults. They may also be interpreted as normal faults resulting from block faulting. A field study is needed for an accurate interpretation.

### 4.4 Geologic Field Mapping

Geologic field mapping in karst topography is difficult at best. The methodology used in the study area included mapping of the stratigraphy, location of lithostratigraphic contacts, measurement of strike and dip on outcrops, and measurement of orientations of faults and folds. Geologic field mapping was accomplished by mapping structures in the field with a Brunton compass and a hand level. The stratigraphy was mapped and compared to descriptions of rock units in the area by Echanove (1963), Viniegra (1966), Moreno (1980), and G. Atkinson (1980b). An attempt was made to locate all faults described by these researchers in the study area. A 1:50,000 provisional topographic map from Instituto Nacional de Estadística Geographía e Informatica, Huautla E14B87 (1984), not available to previous workers, was utilized to locate faults they had described and depicted on large scale maps with little topographic reference. Enlargements of the Huautla Provisional map was used for mapping in the field.

Underground field mapping was accomplished with the same instrumentation as used on the surface. Structures located in caves were recorded in survey notebooks along with detailed sketches of the structure and descriptions of the stratigraphy. Strike and

dip measurements were recorded on both sides of the faults, on fault planes, and on the limbs of folds. Structural information was then transferred to a computer line-plot of the cave for assigning the exact position in the subsurface.

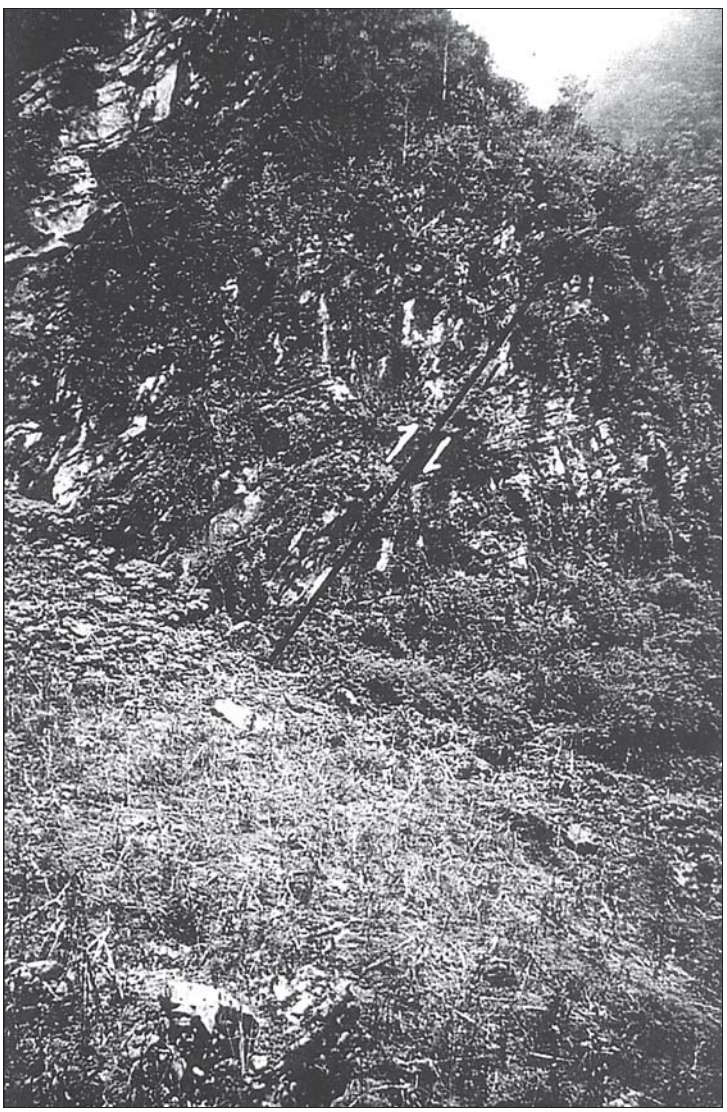
Once faults described by the previous researchers were located on the topographic map, then all other faults discovered during the geologic investigation could be assigned a position on the map with the security of knowing that they had not been described previously.

### 4.4.1 Structure

Echanove (1963) described the stratigraphy between Teotitlán del Camino and Huautla de Jiménez. Viniegra (1965) presented a lithofacies map defining the surface rocks across the Sierra Mazateca. Moreno (1980) conducted field studies across the study area that followed the road from Huautla to San Agustín. G. Atkinson (1980b) field mapped from San Agustín to La Providencia. Although he did not produce any structure maps of the area, the author was able to refer to his field notes from Huautla Project survey files. Echanove, Viniegra, and Moreno concluded that Jurassic allochthonous rocks cap the hills overlooking Huautla de Jiménez. Echanove and Viniegra extended the Tuxpanguillo Formation of the Lower Cretaceous, described west of Huautla de Jiménez, toward the proposed karst groundwater basin to the east.

Moreno (1980) determined that clastic surface rocks of the Tepexilotla Formation form the overthrust sheet of Falla de Huautla and lie concordantly over the Orizaba Formation exposed east of the fault.

As described in Chapter 3, Moreno (1980) provided the interpretation that the Huautla Fault is traced to the Río Santo Domingo along the Peña Colorada Canyon.



### 4.4.2 Structures in the Overthrust Sheet of Huautla–Santa Rosa Fault

The surface rocks capping the hills west of the San Agustín Dolina, Río Iglesia Dolina, and San Miguel Dolina adjacent to the karst consist of arkose sandstone up to a meter thick, thin-bedded shales, and thin-bedded limestones of the Late Jurassic Tepexilotla Formation. The incompetent strata are extremely deformed and exhibit fan and box folding. The contact with underlying limestones is the Huautla overthrust fault.

### 4.4.3 San Agustín Fault Slice

As described in Chapter 3, there is a stratigraphic change between rocks capping the hills overlooking the San Agustín Dolina and those directly underlying (Figure 3.6). These rocks consist primarily of shale, arkosic sandstone, and thin beds of limestone, lying discordantly over limestones. Echanove (1963) and Viniegra (1966) described limestones similar to the Tuxpanguillo Formation as those found below the allochthonous clastics.

Stratigraphic units below the Huautla Fault are thin-bedded dark gray to black limestones

**Plate 4.1.** San Agustín fault slice, Peña Blanca fault. The picture is looking north toward San Andrés. The entrnace to Sótano de San Agustín is beyond the saddle. The fault slice or wedge is located to the left of the fault plane on the hangingwall.

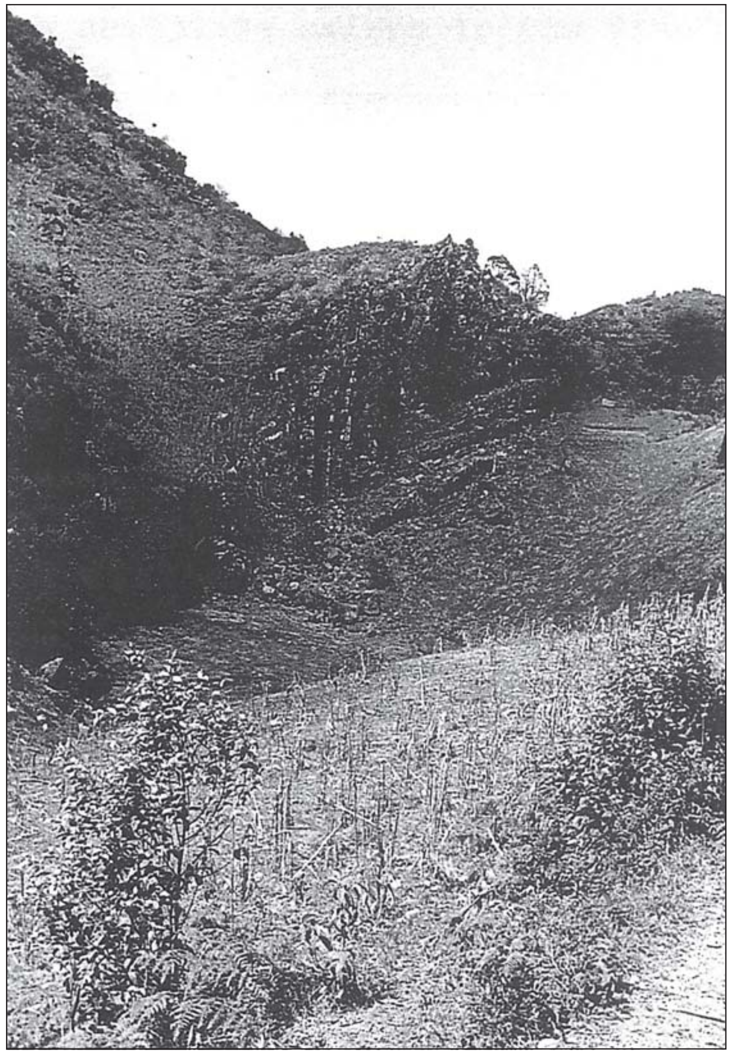


**Plate 4.2.** Plan de Escoba fault. Folded beds are the hangingwall block of a reverse fault. The Plan de Escoba fault is located in a karst valley between Agua de Cerro and Nita Nanta.

1 to 10 centimeters thick. They are micrite limestones intercalated with thin-bedded black cherts. The rock units are recrystallized and contain abundant fractures filled with calcite. These rocks will be referred to as the Tuxpanguillo Formation.

The areal extent of black cherty limestones is restricted to the western wall of the San Agustín Dolina. Its position lies between two thrust faults, the Huautla Fault and the Peña Blanca Fault. The eastern fault boundary forming the San Agustín Fault Slice may be the same fault as the Peña Blanca Fault described by Moreno (1980).

Outcrops of more massive-bedded strata of the Orizaba Formation occur below the Peña Blanca Fault and are the same rocks that the entrance to Sótano de San Agustín is formed in. The fault is traceable along the length of the San Agustín Dolina and disappears to the north at San Andrés. The strike of the fault is north-south, and it is traceable to the south where it disappears in the southern portion of the San Agustín Dolina. The amount of displacement of the Peña Blanca Fault is unknown.

It is hypothesized that the outcropping Tuxpanguillo Formation is a fault slice that occurs between the Huautla–Santa Rosa Fault and the Peña Blanca Fault (Figure 3.6). The Huautla Fault contact is buried beneath soils and exposed on cliffs too sheer to access (Plate 4.1).

### 4.4.4 Río Iglesia Fault

The Río Iglesia Fault is a thrust fault exposed on the south side of the Río Iglesia Dolina. The rocks in the hanging wall and the foot wall consist of massive-bedded limestones 1 to 2 meters thick of the Orizaba Formation. Allochthonous Jurassic rocks outcrop on the hilltops above the Río Iglesia Fault.

The Río Iglesia Fault, with an east-west strike, is perpendicular to the Peña Blanca Fault and subparallel to the Huautla Fault (Figure 3.6). The Huautla Fault follows the contour of the topography in a north-to-south direction. The Río Iglesia fault was found only in the Río Iglesia Dolina. The amount of displacement on the fault is unknown, and it disappears under regolith at the end of the outcrop.

### 4.4.5 Plan de Escoba Fault

North of Nita Nanta and Nita Nashi is the community of Plan de Escoba. At Plan de Escoba, the deformation of the strata is extreme, with large overturned folds (Plate 4.2). The area of deformation occurs on the hanging wall of a significant high-angle reverse fault. The rocks of the hanging wall are thin-bedded black limestones intercalated with chert.

The fault plane is not visible and is only inferred by a change in attitude of the beds. On the foot-wall side, the beds dip gently to the northeast. On the hanging-wall side the beds are vertical and overturned, and where intensity of the deformation decreases away from the fault, the beds dip to the northwest. Many small reverse faults are seen in outcrop and in the caves near the fault.

The Plan de Escoba Fault may be the structural limit of the Sistema Huautla Karst Groundwater Basin. No dye traces have been conducted to confirm

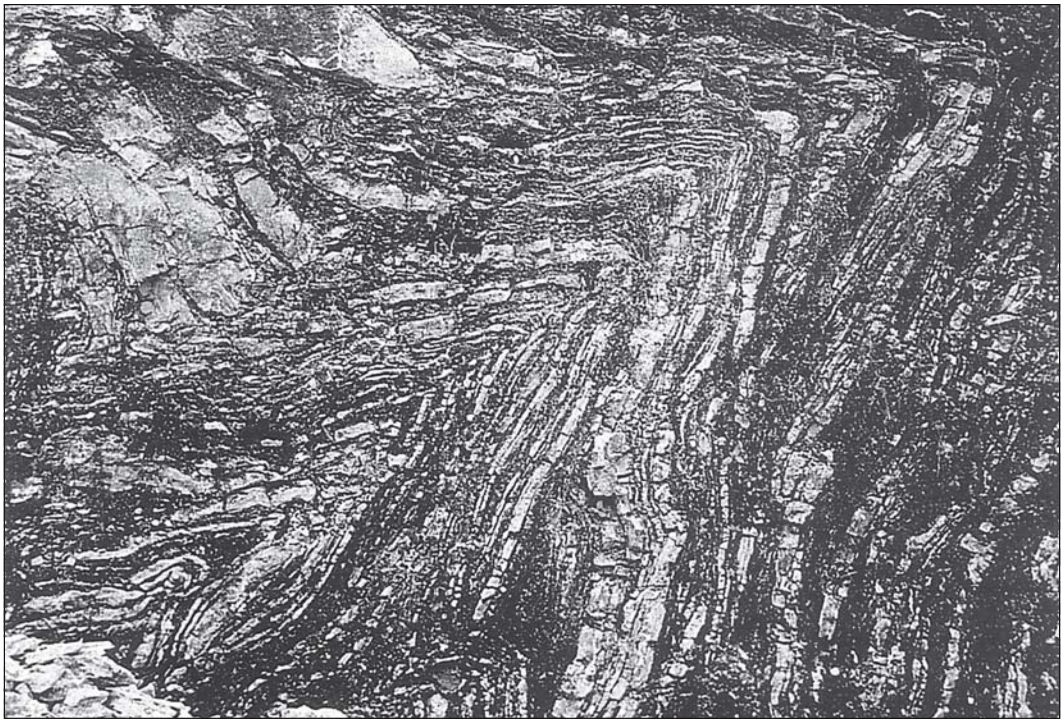


**Plate 4.3.** The El Camarón Klippe consists of intensely deformed limestones and shales of the Tepexilotla Formation. The klippe is underlain by the Orizaba Formation.

the hydrologic boundary of the Sistema Huautla Karst Groundwater Basin on the opposite side of the fault.

### 4.4.6 Agua de Cerro Anticline

In the discussion of the Plan de Escoba Fault, it was noted that the limestone beds dip to the northeast opposite the regional dip on the foot-wall side of the thrust fault, implying that an anticline exists in the Plan de Escoba–Agua de Cerro area. The axis of the anticline strikes to the northwest. Strike and dip measurements indicate that the anticlinal fold occurs from Agua de Cerro to La Providencia (Figure 3.5).

### 4.4.7 Agua de Cerro Fault

The Agua de Cerro Fault is marked on the 1:250,000 Orizaba geologic quadrangle. The author has assigned the name Agua de Cerro to the fault since there is no reference to it in the literature. The fault is a major normal fault that occurs east of Agua de Cerro and San Felipe and trends to the southeast toward Río Santiago. The areas west of the fault represent the footwall side of a large fault block formed by regional uplift during the Miocene-Quaternary interval. The displacement on the Agua de Cerro Fault is unknown. This fault is significant to this study since it may represent the eastern structural limit of the Sistema Huautla Karst Groundwater Basin (Figure 3.5).

### 4.4.8 La Grieta Fault

The La Grieta Fault is a reverse fault found along the trail from San Andrés to La Grieta in the La Grieta Dolina. This fault is well exposed along a trail that descends to the floor of the La Grieta Dolina. Deformed thin-bedded limestones of what may be the Maltrata Formation overlie massive fossiliferous limestone of the Orizaba Formation. The thrust fault strikes north-south, and the hanging wall beds exhibit folding. The massive-bedded rock units underlying the fault plane are relatively undeformed. The amount of displacement is unknown (Figure 3.5).

### 4.4.9 Structures Found Near El Camarón

The El Camarón Klippe, an erosional remnant of a thrust sheet consisting of incompetent Jurassic limestones intercalated with shales, extends along a narrow ridge for a distance of 500 meters near the town square of El Camarón (Figure 3.5). The limestone and shale unit consists of approximately 60 percent limestone and 40 percent shale. The thin-bedded limestones and shales are intensely folded and underlain by inclined strata of the Orizaba Formation (Figure 7.4). The structures found in the klippe consist of overturned and polyclinal folds. Dip taken on one of the inclined limbs of the polyclinal fold is 26

degrees at an azimuth of 145 degrees. Cleavages on the shale are oriented at 254 degrees. The dip of the folded limestones and shales is opposite the southwest dip of the underlying massive-bedded limestones of the Orizaba Formation (Plate 4.3).

Approximately 1.5 kilometers west of the Peña Colorada Canyon on the north wall of the Río Santo Domingo Canyon is a spring called Cueva de Agua Fría (Stone, 1984). The spring discharges from the center of an anticlinal fold. The steep limb of the fold lies to the east, and a small ridge extends down the axis of the asymmetrical anticlinal fold. The anticlinal fold is a drag fold for a thrust fault, the Agua Fría Thrust, occurring to the east. A ravine called El Armadillo lies on the east side of the ridge and is formed on the fault plane of the thrust fault (Figure 3.5).

Viniegra (1966) and Moreno (1980) illustrated the Huautla–Santa Rosa Fault as having a north-south strike with the fault structurally separating the Jurassic clastics from the Cretaceous carbonates. The fault is visible on the edge of the San Miguel Dolina and is traceable south toward the Peña Colorada Canyon. They traced the fault by utilizing aerial photos and placed the position of the fault down the center of the Peña Colorada Canyon.

Field investigations by the author revealed a fault in the Peña Colorada. On both sides of the canyon, the walls are massive-bedded limestones of the Orizaba Formation. On the trail toward the community of Loma Grande, the limestones disappear under regolith and float material consisting of shales and sandstones. The Huautla–Santa Rosa Fault plane is hidden under this regolith. The position of the fault must be moved out of the canyon and to the west. The Huautla Fault outcrops in the Río Santo Domingo 3 kilometers west of the Peña Colorada Canyon (Figure 3.5).

#### 4.4.10 Minor Structures

Many minor structures, mostly thrust faults, were mapped across the karst groundwater basin. They are considered minor because the displacements are from a few meters to tens of meters. Associated with many of the faults are drag folds that range from simple asymmetrical folds to recumbent folds where the beds thicken in the hinge area. Other folds seen along the historic route in Nita Nanta are box folds.

In some of the folds, the core has been deformed into limestone rods or boudinage. In the caves, many of the thin-bedded cherts associated with folds have been stretched to form chert boudins. The boudins have been formed by the shearing of thin-bedded limestones between competent beds of limestones and by folding of thin-bedded limestones adjacent to a fault plane.

Where less movement occurred between competent beds, thin-bedded limestones are folded between competent beds that show little to no deformation.

All of the minor faults seen in outcrop across the basin have not been described. However, they are illustrated in Figure 3.5.

### 4.5 Major Structures Found In Sistema Huautla

Sistema Huautla is a dendritic vertical drainage system that conveys surface water down a multitude of vertical shafts. Field observations have determined that in different areas of the basin one type of structure appears more dominant than another, at least from the standpoint of the development of shafts and cave passages.

In the northern portion of the basin, which is drained by Sótano de San Agustín, most of the shaft series are formed along normal faults that strike roughly north-south. This includes the largest shafts in the cave system.

Deep shafts formed on normal faults include Christmas Shaft in Sótano del Río Iglesia, the Fissure and the Bowl Hole Series in Sótano de San Agustín, Sima Larga and Flip Pits in Sótano de Agua de Carrizo, TAG Shaft in Nita Ntau and Nita Nido, Flaky Shaft and Maelstrom Shaft in Nita Nanta, and Electric Shaft in Nita He. In these shafts, displacements along faults are as large as 10 meters.

#### 4.5.1 Yellow-Bag Dome Fault

At –600 meters in Sótano de San Agustín, a large passage called Tommy’s Borehole intersects Yellow Bag Dome (Figure 4.7). The intersection is formed on two large normal faults. The foot wall of the largest fault reveals the core of a large overturned fold of massive-bedded limestones of the Orizaba Formation. On the other side of the fault, the hanging wall is composed of thin-bedded cherty limestones. The displacement along the fault is estimated to be 100 meters.

The Bowl Hole shaft series has formed along the same normal faults as Tommy’s Borehole. It is hypothesized that this overturned fold is the core of a large overturned syncline formed by the overthrusting of the Peña Blanca Fault.

In the northern half of the Sistema Huautla Karst Groundwater Basin, the western edge has formed along this overturned syncline. The overturned fold described in Tommy’s Borehole is hypothesized to be the core of a potentially extensive fold associated with overthrusting of the Huautla Fault.

Ten kilometers north of the study area, at San Lorenzo, are similar geologic conditions. At this

location a large overturned syncline occurs beneath the overthrusted Tuxpanguillo Formation. The core of the syncline has been recrystallized or marmoratized. The protolith is the United Orizaba Formation. Similar conditions exist all along the Huautla–Santa Rosa Fault 40 kilometers north of the study area (Figure 3.3).

Recrystallized limestones are found throughout the Sistema Huautla Karst Groundwater Basin. The strata in localized areas within Sistema Huautla have been recrystallized to the point of becoming a low-to-medium-grade marble along fault contacts and in folded strata. Marble is defined as a metamorphic rock consisting predominantly of fine to coarse-grained recrystallized calcite and/or dolomite, usually with a granoblastic, saccharoidal texture (Batson and Jackson, 1987).

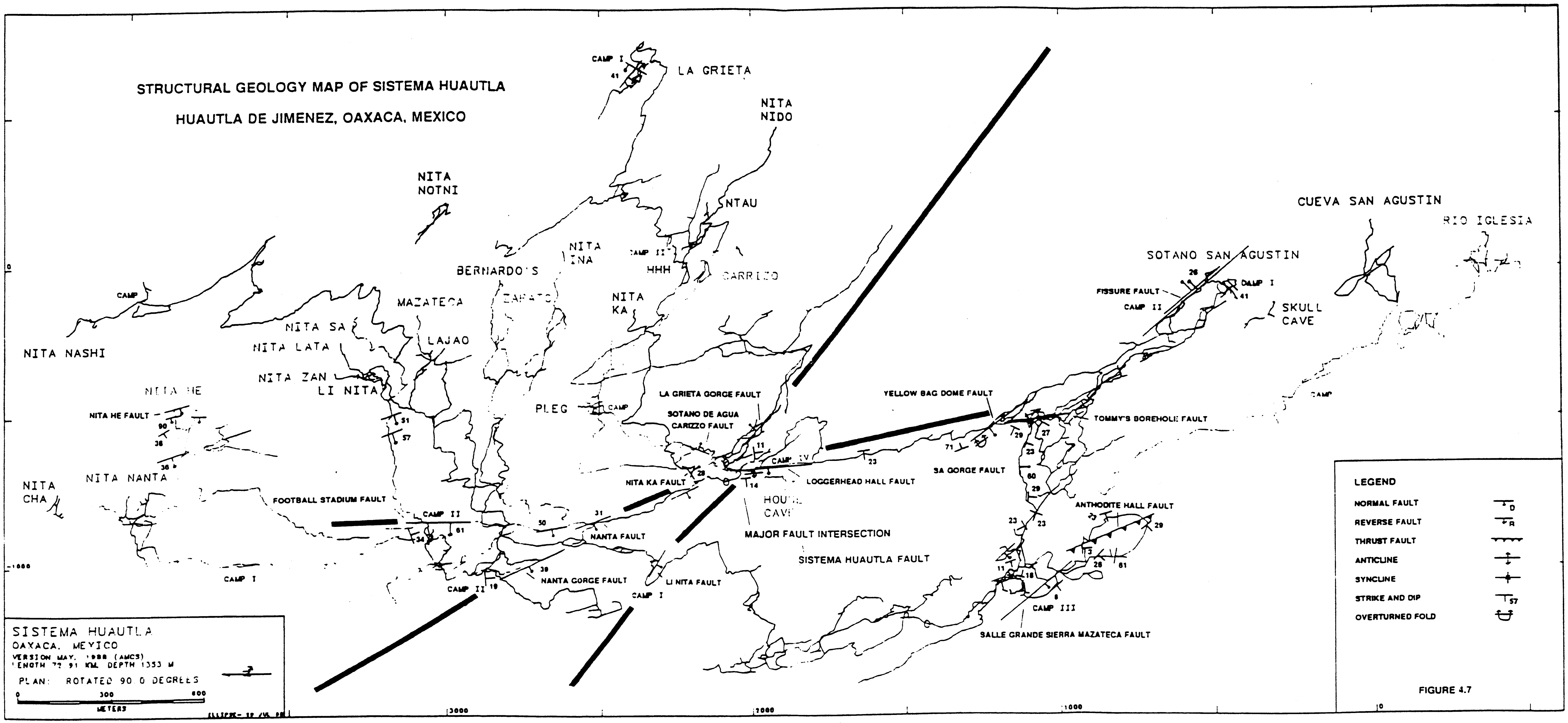
Sedimentary breccias of the Orizaba Formation located near fault contacts in Sótano de San Agustín are intensely deformed and show flow lineations (Plate 4.4). While the structural style of the Sistema Huautla Karst Groundwater Basin is similar to the folded strata north of the basin, marmoratization is not as extensive. The limestones of the Sistema Huautla Karst Groundwater Basin exhibit varying degrees of recrystallization and may be considered transitional between limestone and low grade marble.

4.5.2 Loggerhead Hall Fault

A normal fault with undetermined displacement occurs in Loggerhead Hall (Figure 4.7). This area in the cave system is significant because it is the hydrologic junction for many of the streams whithatch flow from the ridgetop caves. The fault is exposed at the north end of the chamber. The fault plane strikes 345 degrees and dips at 74 degrees. A zone of brecciation one meter thick occurs in the fault (Plate 4.5). On the hanging-wall side of the fault is a series of parallel folds that have a frequency of two meters and an amplitude of one meter. On the foot-wall side is a drag fold consisting of thin-bedded limestones 20 centimeters in thickness.

The Loggerhead Hall Fault is the junction of several normal faults that make up the Sistema Huautla Fault System. The Sistema Huautla Fault System is composed of normal faults observed in the lower portions of the caves La Grieta, Sótano de Agua de Carrizo, Nita Ka, and Nita Nanta. Normal faults were mapped in Nita Ka and Nita Nanta in the vicinity of Loggerhead Hall (Figure 4.7). Although faults were not mapped near the hydrologic connection between La Grieta and Sótano de Agua de Carrizo, faults are hypothesized to exist in the lower sections. This hypothesis fits the structural style of the area as defined by mapped faults in the previously mentioned caves and the trends of mapped passages. The following rationale also supports the hypothesis. In Sótano de Agua de Carrizo, Sima Larga and the Flip Pits are formed along normal faults, and the trend of a line extended through these shafts is toward the hydrologic junction. The Gorge of La Grieta is fracture-controlled and hypothesized to be formed on a normal fault.

**Plate 4.4.** Richard Schrieber climbing over a wall exhibiting flow lineation of breccia in Fissure Fault.


STRUCTURAL GEOLOGY MAP OF SISTEMA HUAUTLA
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
LA GRIETA
NITA NIDO
NITA NOTNI
NTAU
CUEVA SAN AGUSTIN
RIO IGLESIA
SOTANO SAN AGUSTIN
FISSURE FAULT
SKULL CAVE
BERNARDO'S
MAZATECA
NITA SA
NITA LATA
LAJAO
NITA NASHI
NITA ZAN
LI NITA
NITA HE
NITA HE FAULT
PLEG
LA GRIETA GORGE FAULT
SOTANO DE AGUA CARIZZO FAULT
YELLOW BAG DOME FAULT
TOMMY'S BOREHOLE FAULT
SA GORGE FAULT
LOGGERHEAD HALL FAULT
NITA KA FAULT
NITA CHA
NITA NANTA
FOOTBALL STADIUM FAULT
NANTA FAULT
MAJOR FAULT INTERSECTION
SISTEMA HUAUTLA FAULT
ANTHODITE HALL FAULT
NANTA GORGE FAULT
LI NITA FAULT
SALLE GRANDE SIERRA MAZATECA FAULT
SISTEMA HUAUTLA
OAXACA, MEXICO
PLAN: ROTATED 90.0 DEGREES
METERS
LEGEND
NORMAL FAULT
REVERSE FAULT
THRUST FAULT
ANTICLINE
SYNCLINE
STRIKE AND DIP
OVERTURNED FOLD
FIGURE 4.7

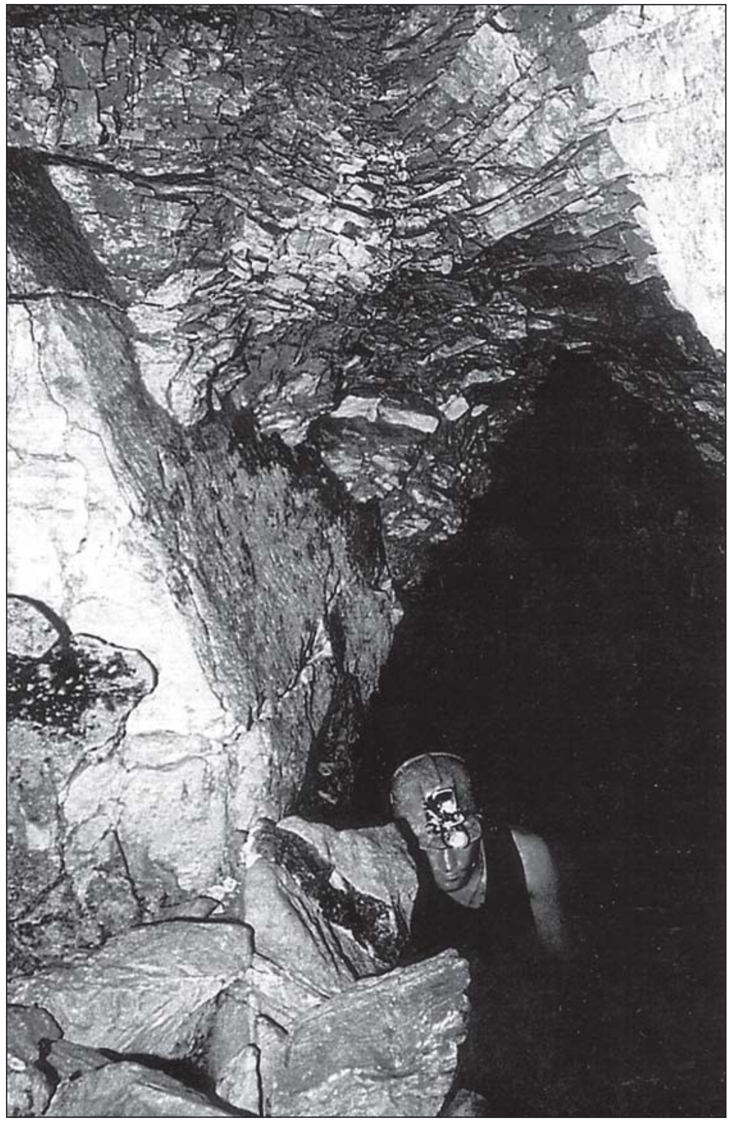


**Plate 4.5.** Mason Estees in the Loggerhead Hall Fault.

Cave survey of passage segments in the bottom levels of La Grieta, Nita Nanta, Sótano de San Agustín, Sótano de Agua de Carrizo, and Nita Ka indicate that Loggerhead Hall is the hydrologic junction for most of the drainage at the northern end of the groundwater basin. It is also hypothesized that there is a structural explanation for this occurrence. The hydrologic junction area is the structural junction of two large normal faults and quite possibly a zone of accompanying conjugate normal faults as indicated by the number of parallel passages mapped at the junction area (Figure 4.7).

The base level for the northern half of the karst groundwater basin is on top of shales that are phyllitic in appearance and texture. The fault that Nita Nanta drains through has 2 meters of displacement in this shale. The fault plane in the carbonates is a slickensided surface with vertical striations and trends northwest-southeast. The Nanta drainage remains on top of shales until it reaches the Loggerhead Hall fault junction. From Loggerhead Hall, groundwater flows on top of limestone to the lakes at 640 meters depth below Tommy's Borehole. The phyllitic shale is not seen again on the way to the sump at –845 meters in Sótano de San Agustín.

West of Loggerhead Hall Fault is the down-thrown side of the fault block. The basal limestone beds in Nita Nanta are massive-bedded black limestones. This distinctive unit is not seen again until it is exposed in the route to the bottom of Sótano de San Agustín via the 845 meters sump. A displacement of approximately 100 meters may have occurred on the down-thrown portion of the Loggerhead Hall Fault.

### 4.5.3 Anthodite Hall Thrust Fault

Anthodite Hall is the largest chamber in Sistema Huautla and is located at a depth of 600 meters below the entrance of Sótano de San Agustín (Figure 4.7). Anthodite Hall measures 250 meters long by 150 meters wide and is 80 meters high. Exposed in the western wall of the chamber is a large thrust fault plane (Plate 4.6). The fault plane strikes northeast-southwest and dips 20 degrees to the northwest. The fault is not exposed on the eastern side of Anthodite Hall due to collapse and flowstone obscuring the fault trace.

Along the foot-wall block below the fault plane, thin-bedded limestones are intensely deformed as overturned folds and truncate at the fault plane. The beds of the overturned folds strike northeast-southwest, and the limbs of the fold vary in dip from 20 to 60 degrees, with a dip direction to the southeast or southwest, depending on where the measurement was taken on the fold.

It was not possible to determine the displacement along the fault. It is speculated that it is a major thrust fault, and it is possible that it is the subsurface exposure of the Peña Blanca Fault, since the position of this fault is down dip, 600 meters lower, and to the west of its surface exposure.

### 4.5.4 Sala Grande de Sierra Mazateca Fault

The Sala Grande de Sierra Mazateca is a large chamber located at a depth of 700 meters below the entrance of Sótano de San Agustín (Figure 4.7). It is

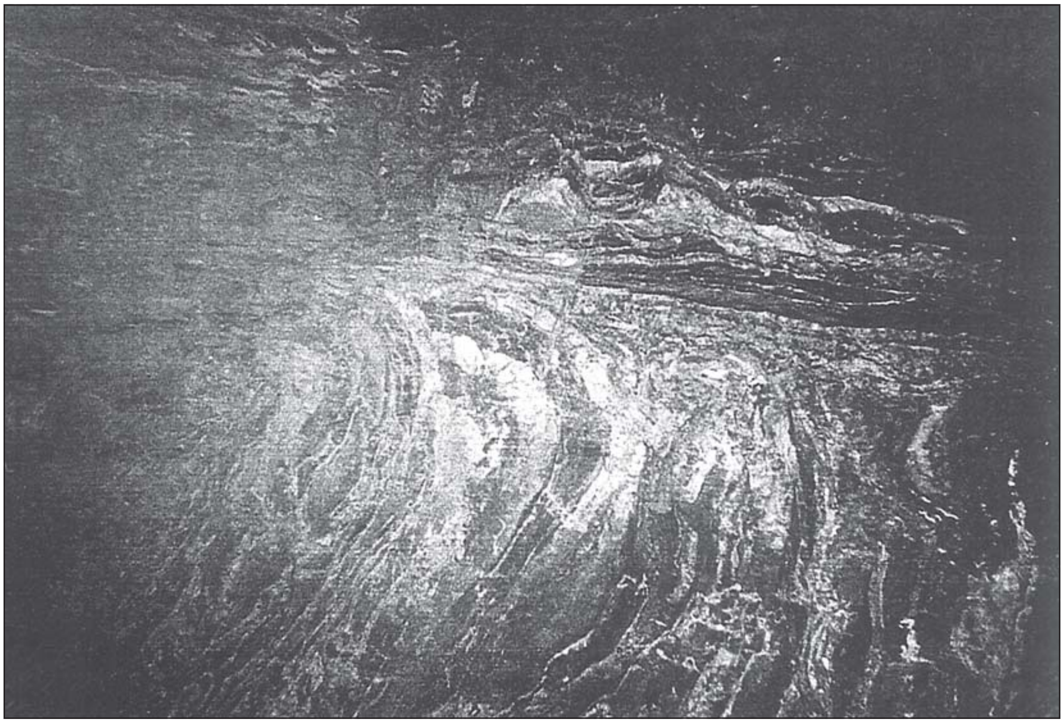


**Plate 4.6.** Anthodite Hall thrust fault.

the site of Camp III and is 60 meters below and adjacent to Anthodite Hall. The Sala Grande is also located beneath the allochthonous rocks of the Huautla Fault.

In the walls of the Sala Grande is a large normal fault that is exposed for a vertical distance of 60 meters. The Sala Grande de Sierra Mazateca Fault strikes northwest-southeast along an azimuth of 140 degrees and dips 75 degrees. The northeast side of the fault is the foot wall. The limestone beds are 0.5 meter thick, with 2.5-centimeters-thick chert beds that exhibit drag folding and dip to the southeast 14 to 28 degrees. The hanging wall, or down-dropped block of the fault, has beds that also dip to the southeast. On the opposite side, off the Sala Grande de Sierra Mazateca near Anthodite Hall, on the hanging-wall side of the fault, the beds dip to the southwest. The fault plane consists of a zone of fault breccia one meter thick. High on the wall, a large horse block exists near the center of the fault (Plate 4.7). The horse block is 5 meters across and 20 meters high. The fault may also extend into Anthodite Hall, although it was not noticed during investigations.

### 4.5.5 Fissure Fault

A vertically extensive fault zone was discovered in the Fissure Shaft Series of Sótano de San Agustín. The faults are exposed for a vertical extent of 300 meters in the Fissure Shaft Series. The shafts are oriented along the strike of the fault zone, which contains at least two faults. Exposed in the wall of the 318 Shaft is a normal fault with one meter of displacement between massive beds of the Orizaba Formation. The fault strikes along an azimuth of 315 degrees (Figure 4.7).

Below the 318 Shaft is the 180 Shaft. A second fault, Fissure Fault, strikes roughly parallel to the fault in the 318 Shaft and lies west of the fault. The large-scale displacement along this normal fault has not been determined. The foot-wall side of Fissure Fault has a large reverse drag fold on the northeast side of the fault plane. Along the fault plane, the limestone is recrystallized, has a granoblastic texture, and sedimentary breccias are deformed, having lost the angularity of the fragments. The fragments exhibit flow lineation produced by the strain of deformation.

### 4.5.6 The Gorge Fault

The Gorge is located in the lower third of the vertical extent of Sótano de San Agustín. The Gorge begins at –640 meters and ends at –760 meters at the beginning of the Metro. The structural significance of this passage is that it has formed along a normal fault that is subperpendicular to the strike of the beds. The Gorge Fault strikes along an azimuth of 265 degrees. The recrystallized limestones of the Orizaba Formation have an average strike of 350 degrees and a dip of 23 degrees. The south side of the fault is the down-thrown

side, with a displacement of one meter (Figure 4.7).

4.5.7 Nita He Fault

To the north of San Andrés is the community of Plan Arena, where the upper cave entrances to the labyrinth of Sistema Huautla are located. One cave entrance that was proven to be hydrologically connected, although not physically connected, to Sistema Huautla is Nita He. G. Atkinson (1980b) mapped two normal faults in the entrance shaft series of Nita He (Plate 4.8).

The faults at the entrance exhibit compressional drag folding on the hanging-wall block that is related to the fault block changing position or reversing movement. The faults appear to be normal faults.

Nita He (Deep Pit) has two entrances leading into one shaft. The shafts are both formed on faults that are genetically related to one large fault. The entrance shaft, 130 meters deep, and the Vortex Shaft, 50 meters deep, are formed on this normal fault. The bedding on the north side of the fault (the foot wall) dips to the southeast at 29 degrees. On the south side of the fault, on the hanging-wall block, the beds are vertical from reverse drag. There are no obvious vertical beds outcropping at the surface. To the southwest, perpendicular to the fault, the dip of the beds lessens to 25 degrees.

The Electric Shaft, a 90-meter-deep pit in Nita He, is also formed on a large normal fault, which strikes 340 degrees and is subparallel to the Nita He Fault. The displacement was not determined (Figure 4.7).

4.5.8 Football Stadium Fault

In Nita Nanta there is a large dome pit called the Football Stadium. This room may also by accessed from the Nita Zan or Nita Sa cave entrances via two deep shafts, Flaky Shaft and the Maelstrom Shaft. These shafts are formed on a large normal fault. Flaky Shaft is formed on a parallel fault that is comparatively minor in comparison to the Football Stadium Fault. The Flaky Shaft fault strikes north-south. It intersects the side of the Football Stadium as a window 90 meters above the floor, and the Maelstrom Shaft does the same 60 meters above the floor.

A large fold is observed where the Naranja Passage enters the Football Stadium along the north side. The Naranja Passage is formed in the vertical limb of the large fold. The fold is observable up to 40 meters on the north side of the Football Stadium and is formed as a result of the hanging-wall block dragging the beds of the foot-wall block upward. The fault is a normal fault that strikes 350 degrees. On the foot-wall block, the beds are vertical adjacent to the fault plane and dip 34 degrees away from the fault plane. The beds on the up-thrown side of the fault are contorted and loose, making a strike and dip measurement unfeasible (Figure 4.7).

4.5.9 Nanta Gorge Fault

Another significant fault observed in Nita Nanta occurs at the stratigraphic and hydrologic base level of the karst groundwater basin. A normal fault is found in the Nanta Gorge 1,006 meters below the highest entrance of the cave. The rocks that form the stratigraphic base level are light to medium gray phyllitic shales. In the stream of the Nanta Gorge, a fault with 2.5 meters of displacement is observed between

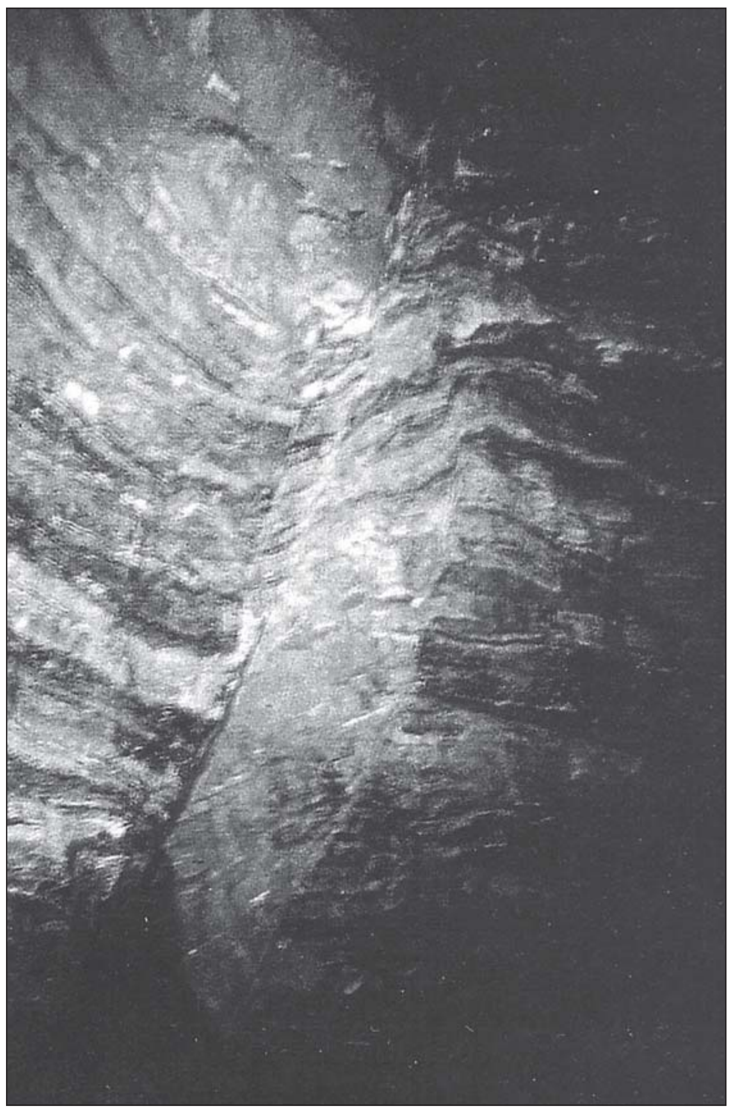


**Plate 4.7.** Sala Grande Sierra Mazateca Fault.

**Plate 4.8.** The Nita He Fault is displayed in the entrance to Nita He.

transpositional stratigraphic units. The Nanta Gorge Fault strikes 335 degrees and the fault plane dips 39 degrees. Slickensides are found on the fault plane in the limestone. and striations are oriented vertically (Figure 4.7).

At the junction of the ED Survey another normal fault is observed. The fault has a low angle at the Nanta Gorge and ED Survey junction, with a dip of 39 degrees and approximately 2 meters of displacement. Upstream in the ED Survey, the fault plane is observed to have a strike of 350 degrees and a dip of 50 degrees.

### 4.6 Conclusions

The structure of the study area determines the hydrologic east-west boundaries of the karst groundwater basin. The structural boundaries consist of both compressional and tensional structures. To the west is the Huautla–Santa Rosa reverse fault, and to the east is the Agua de Cerro normal fault (Figure 4.8). It is possible that the groundwater divide for the northern end of the basin is the Plan de Escoba reverse fault. However, dye tracing needs to be conducted to

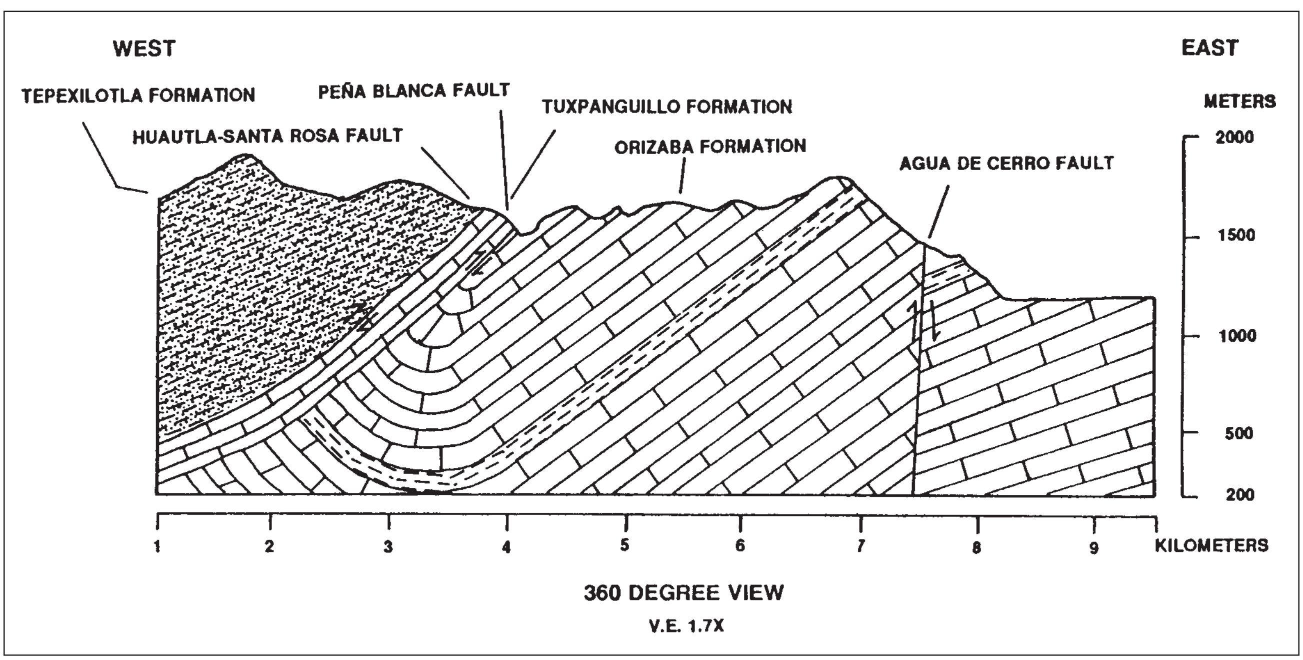



**Figure 4.8.** Structural cross-section of Sierra Mazateca and Sistema Huautla, Huautla de Jiménez, Oaxaca.

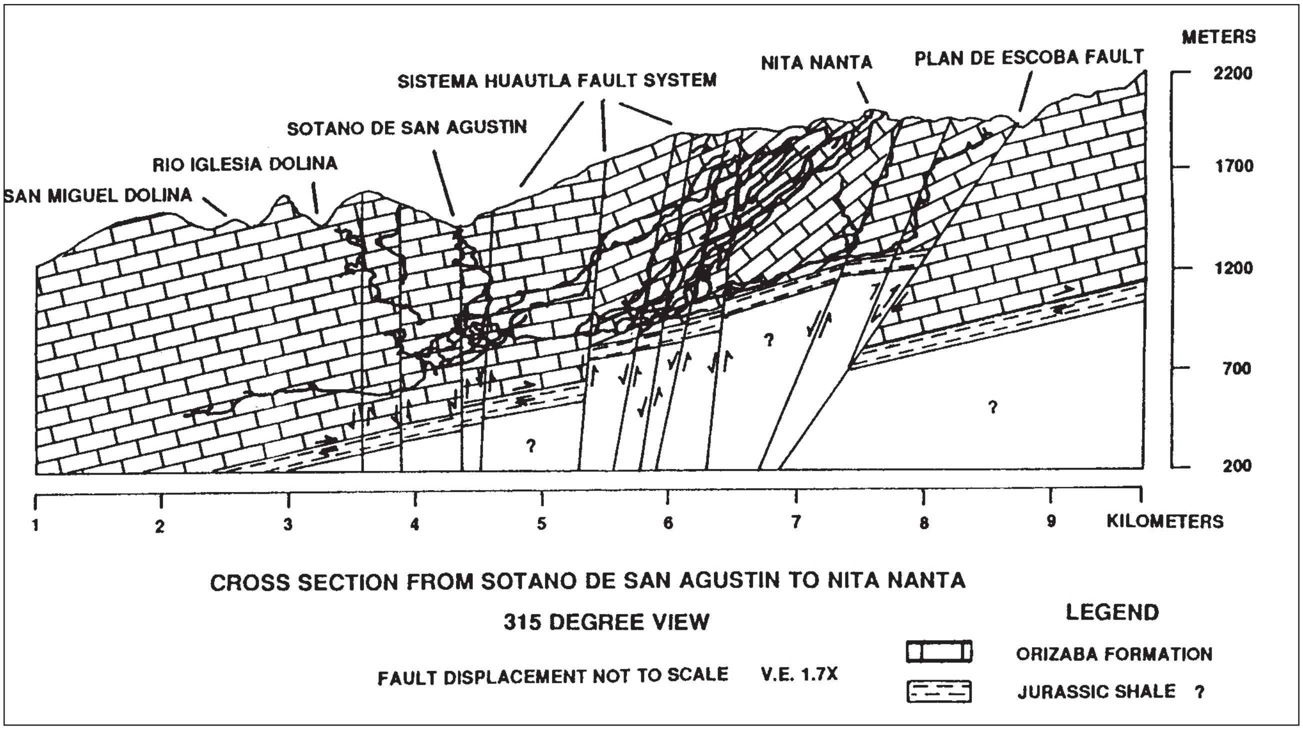



**Figure 4.9.** Structural cross-section of Sierra Mazateca and Sistema Huautla, Huautla de Jiménez, Oaxaca.

determine if the area between the Plan de Escoba Fault and Agua de Cerro is within the karst groundwater basin.

The lower boundary for subterranean dissolution of limestone is determined by the Cerro Rabón Fault, below which exist metamorphosed black shale of the Nexcolta Slates and phyllitic shales belonging to the Jurassic. This base level was discovered by exploration of caves in the northern part of the Huautla Karst Groundwater Basin. The shales dip to the southwest at 20 to 30 degrees, 300 to 450 vertical meters per kilometer.

At the southern end of the basin, limestone is exposed along the floor of the canyon. The Cerro Rabón Fault is exposed in the floor of the canyon three kilometers to the west.

Groundwater flow is controlled by the structural development of the basin. Conduit development occurs along fault trends parallel to the strike, and down the dip of inclined bedding planes (Figure 4.9). While groundwater flow is down the dip of the beds in the upper portion of the cave, and along the strike of the bedding in the lower portion, it is commonly altered by numerous intersecting faults and is underlain by shales. Occasionally passages cut across faults that have no bearing on the trend of the passage. For the most part, passage development in Sistema Huautla appears to occur along the strike and down the dip of bedding planes. Groundwater flow is locally dominated by following the strike of the bedding for short distances of 800 meters or less before changing direction and continuing to flow down the dip of the beds. Hydrological development therefore follows a zig-zag pattern generally down dip to the fault-controlled base-level passages. At base level, conduits intersect a major north-south-trending fault system, the Sistema Huautla Fault System, which consist of the Nanta–Loggerhead Hall–Tommy's Borehole Faults (Figure 4.7).

A major fault intersection consisting of normal faults occurs at the junction of Nita Nanta, La Grieta, Sótano de Agua de Carrizo, and Nita Ka at Loggerhead Hall in Sótano de San Agustín. The fault intersection has been assigned the name Sistema Huautla Fault and consists of a system of faults related to regional uplift. The base level passages of each of the major tributary caves are controlled by normal faults. West of the Loggerhead Hall Fault, the shales that form the hydrologic base level for all caves east of the fault disappear. The west side of the Loggerhead Hall Fault is the down-thrown block of the normal fault. Black limestones of the lower Orizaba Formation found in the Nanta Gorge are not seen again until the Lower Gorge of Sótano de San Agustín. The displacement is estimated at approximately l00 meters. This major fault intersection controls the hydrology of Sistema Huautla at the base level and in shafts and passages where the faults are encountered.

At different locations in Sistema Huautla, shafts are formed along different types of faults. In the northern portion of the groundwater basin, some of the deep shafts are formed along normal and high-angle reverse faults. A swarm of subparallel thrust faults and normal faults occurs from San Andrés to the Plan de Escoba thrust fault. While there are hundreds of shafts in the caves along the northern end of the groundwater basin, many are formed down steeply inclined bedding. The caves located at the north and northeast portion of the basin trend down the dip of the beds. Faults allow water to descend to a lower stratigraphic position to more permeable inclined bedding planes that allow water to flow along the strike.

In the southern portion of the system, shafts are formed along normal faults related to the complex fault system of the Sistema Huautla Fault. Little is known about the internal structure of the southern portion of the Sistema Huautla Karst Groundwater Basin. The development of conduits in Cueva de Peña Colorada is likely to be related to the Peña Colorada Fault. The passages are developed along the strike of the fault plane and strike of the inclined beds.

The following ideas are key to understanding the hydrology of the Sistema Huautla Karst Groundwater Basin:

- The study area has undergone two stages of deformation that include compression during the Laramide Orogeny and crustal extension and block faulting during Oligocene and Miocene.
- Folding and rotation of the fault blocks has determined the direction of the overall drainage of the karst groundwater basin.
- The karst groundwater basin is formed along the axis of a thrusted faulted syncline.
- Allochthonous sandstones and shales of the Huautla–Santa Rosa Fault form the western structural boundary of the karst groundwater basin.
- Agua de Cerro Fault forms the eastern structural boundary of the karst groundwater basin.
- The overall dip of the rocks in the basin are to the west.
- The largest fault structures in the basin are thrust and reverse faults and the smallest are normal faults.
- The overall pattern or X-configuration of base level conduits in the map plan of Sistema Huautla is attributed to a system of normal faults related to block faulting.
- The zigzag pattern of tributary conduits is determined by the strike and dip of steeply dipping bedding planes.
- Deep shafts are formed along vertically extensive normal faults. Shaft development along faults steepens the vertical profile of the cave map.
- The majority of the conduit development in Sistema Huautla is along steeply dipping bedding planes. The stratigraphy is characterized by thin-bedded limestones 2 centimeters to 2 meters in thickness. The density of bedding plane fractures is proportionally greater than the density of faults and joints. Therefore, more bedding planes are exposed to autogenic and allogenic recharge.
- The tortuosity of groundwater flow is determined by faults, strike and dip of the strata, and only locally by folding.
- Base level development is partially defined by dipping shales in the eastern portion of the basin and hydraulic gradient in the western portion of the basin.
- The vertical extent of the drainage system has been determined by the dip of the strata. The 1,760 meter deep drainage system is formed in 700 to 800 meters of limestone.

# CHAPTER 5

# KARST HYDROLOGY OF THE SISTEMA HUAUTLA KARST GROUNDWATER BASIN

## 5.0 Introduction

Geologic field studies outlined in the previous chapters have indicated that the Sistema Huautla Karst Groundwater Basin may be confined to a large thrust sheet. Internal drainage and the ultimate discharge of groundwater is controlled by the attitude of beds within the dipping strata and normal faults. Topographic drainage divides within the structurally defined karst groundwater basin serve only to divide surface runoff into discrete inputs before it sinks into the karst landscape. These small inputs from the surface ultimately unite to form the large underground streams of Sistema Huautla. Therefore, knowledge of the geologic structure is of major importance in accurately establishing the perimeter of the karst groundwater basin and in predicting the general location of the main resurgences.

To test the hypothesis that groundwater flow is primarily along a north-to-south strike, extensive field investigation would be required to locate springs south of the cave system.

Because the caves of the Huautla area are located in an interior mountain karst groundwater basin, there were areas other than south of the cave system that could be the resurgence for Sistema Huautla. The size of the area that had to be searched for springs spanned two 1:50000 scale topographic maps, approximately 1,316 square kilometers (Figure 5.1). Once the springs were located, activated coconut charcoal and unbleached cotton dye receptors were placed in all springs. Fluorescein dye (Color Index: Acid Yellow 73) was injected into a subsurface stream accessible through the Sótano de San Agustín entrance of Sistema Huautla to establish the groundwater flow direction from that stream to one or more springs. After the dye receptors were retrieved and replaced with fresh ones, the receptors were analyzed for dye in a portable field laboratory.

## 5.1 Previous Work

Huautla Project cave explorers made the first attempts to find the springs that drain the caves located in the communities of San Agustín Zaragoza and San Andrés Hidalgo in 1980. For the cave explorers, finding the springs meant that the true depth potential of the cave system could be ascertained. Old military topographic maps, aerial reconnaissance by cave explorers, and stories by local Indians indicated that there were at least two locations in which the springs might exist. These were near the town of Agua Español below San Juan Coatzospan and the Peña Colorada Canyon near the town of El Camarón, each located 10 kilometers south of San Agustín. A huge spring was also reported to be located over 20 kilometers to the east, below the angular buttress of Cerro Rabón.

In the spring of 1980, Dino Lowery, Jill Dorman, Bob Jefferys, Ron Simmons, and Jerry Atkinson hiked along the road from San Miguel Huautepec to Jalapa de Diaz and found the large spring at the base of Cerro Rabón. It was thought that this spring was an unlikely resurgence for the caves in the Huautla area (Stone, 1983b).

In March of 1981, Steve Zeman, Dino Lowery, Bob West, Robert Hemperly, Jean Jancewicz, and Bob Benedict investigated the rumor of springs below Agua Español. They were unable to find any springs. At the end of the 1981 expedition in May, Bill Stone and Pat Wiedeman hiked into the Peña Colorada Canyon below the town of El Camarón and discovered Cueva de Peña Colorada (Stone, 1983a). The cave did not have a flowing stream, but instead a huge sump 140 meters into the cave.

In April of 1982, Bill Stone, Pat Wiedeman, Sergio Zembrano, and John Zumrick returned to the Peña Colorada Canyon and Río Santo Domingo and scouted the canyon walls for springs. Three springs were found,

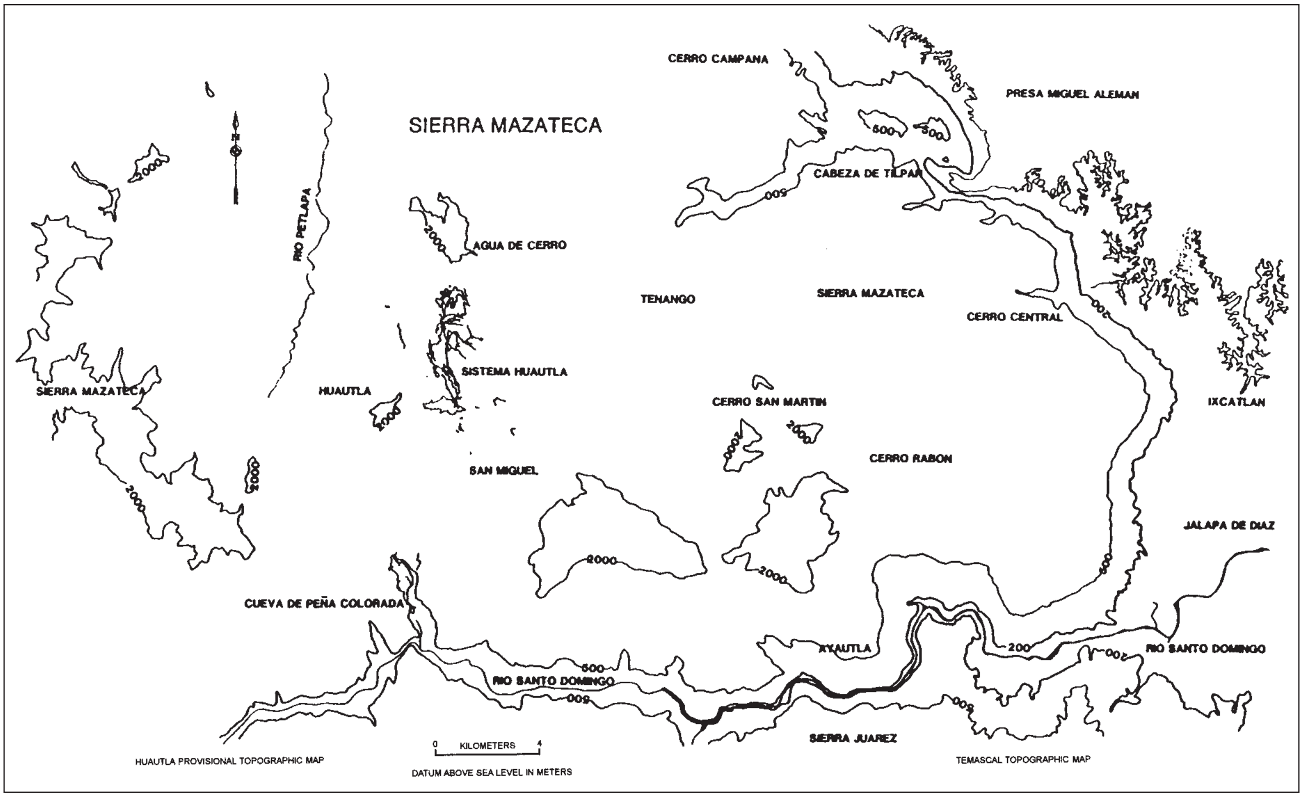



**Figure 5.1.** Sistema Huautla Karst Groundwater Basin study area, Huautla de Jiménez, Oaxaca, Mexico.

Western Resurgence, HR Resurgence Cave, and Southern Resurgence, including two large ones. Stone attempted to do the first dye trace in the area. He placed dye receptors in the three springs and injected three kilograms of fluorescein dye in the Río Iglesia Dolina. The dye trace was inconclusive, because the team recovered the charcoal dye receptors after only one week and all were negative (Stone, 1983a). The team also dove the sump in Cueva de Peña Colorada and found large dry passage and a second entrance to the cave beyond a 500-meter-long sump. They also passed a second sump and explored the cave to a third sump.

In 1984, Stone returned with a large expedition and spent three months exploring Cueva de Peña Colorada and other caves found in the canyon walls. They also discovered an additional spring, Agua Fría, the westernmost spring of the area (Stone, 1984). Vine Cave, another overflow cave like Cueva de Peña Colorada, was also explored (Stone, 1984, 1988). The expedition explored and surveyed 7 kilometers of cave passages and seven sumps. The survey of Cueva de Peña Colorada indicated that the cave was trending toward Sistema Huautla. Explorations also indicated that the first six sumps were not flowing and may therefore be perched. In the last sump, divers noted some flow.

### 5.2 Preliminary Investigation for Springs

Based on geologic observations and the previous work of Huautla Project cave explorers, the areas of interest were ranked according to the most likely location of drainage output for the Sistema Huautla Karst Groundwater Basin (Figure 5.2).

The areas considered the most likely location for springs are south of Sistema Huautla. This area is also along the strike of strata dipping to the west. The area south of Sistema Huautla is divided into two areas: the Peña Colorada Canyon itself and areas west of the Peña Colorada–Río Santo Domingo confluence along the north wall of the canyon to the limestone-metamorphic contact located 3 kilometers to the west (lA and 1B on Figure 5.2). Springs and caves had been reported by Stone (1984) southwest of the Sistema Huautla Karst Groundwater Basin in the Peña Colorada Canyon and on the south and north walls of the Río Santo Domingo canyons.

The second most important location for springs was directly southeast of Sistema Huautla and east of the major intermontane trail system that connects El Camarón in the Sierra Mazateca with Chiquhuihuitlan in the Sierra Juárez. No information was available in this area pertaining to springs. This area of spring

potential covers a distance of 2 kilometers from the trail to the east (2 on Figure 5.2).

The third area was along the unexplored canyon walls of the Río Santo Domingo for a distance of 35 kilometers to the east (3 on Figure 5.2). The only known spring previous to this investigation is the enormous Nacimiento Río Uruapan at the base of a 1,500-meter escarpment (Stone, 1983a and 1984). Stone (1987) stated that he felt that the Río Uruapan was the main resurgence for Sistema Huautla, a change in position from his earlier hypothesis.

The fourth area was located at the front range of the Sierra Mazateca from the Río Uruapan to beyond Campaña to San José de la Independencia for distance of 35 kilometers (4 on Figure 5.2). Bordering the front range is the Presa Miguel Alemán. The Presa is a flood control project controlled by the Temascal Dam. It is reported that large springs were inundated when the reservoir was created. The lake occupies a shoreline from Ixcatlán to San José de la Independencia.

The fifth area was located north of the Sistema Huautla Karst Groundwater Basin along the southern canyon walls of the Río Petlapa (5 on Figure 5.2). The river drains the highlands north and northwest of Huautla and the area to the northeast to the front range at San Rafel. The fifth area was considered unlikely, because subterranean drainage in Sistema Huautla is to the south and northern drainage would be up the structural dip. After the fact, Warild (1989) reported that no large springs were found in the Río Petlapa Canyon from María Luisa to the front range in a reconnaissance during the Australian 1988 Chilchotla Expedition.

The sixth area was located due west of the karst groundwater basin in the Tehuacán Valley (6 on Figure 5.2). This area is the most unlikely of all, since valley floor elevations average 800 meters above sea level. It is higher than the deepest point in Sistema Huautla and is covered by metamorphic rocks on the eastern slopes and valley floor.

After prioritizing potential locations of springs, it was concluded that the areas most likely to be the drainage output of the Sistema Huautla Karst Groundwater Basin needed to be examined physically. These areas were the Peña Colorada Canyon, Río Santo Domingo from the limestone-metamorphic contact to the west, the length of the Río Santo Domingo to the east, the front range from Cerro Rabón to a few kilometers north of Campaña, and the Tenango Valley from Campaña to Tenango. These areas were covered on foot by traversing a largely undescribed canyon and by motorboat on the Presa Miguel Alemán, a total distance of 140 kilometers (Figure 5.3).

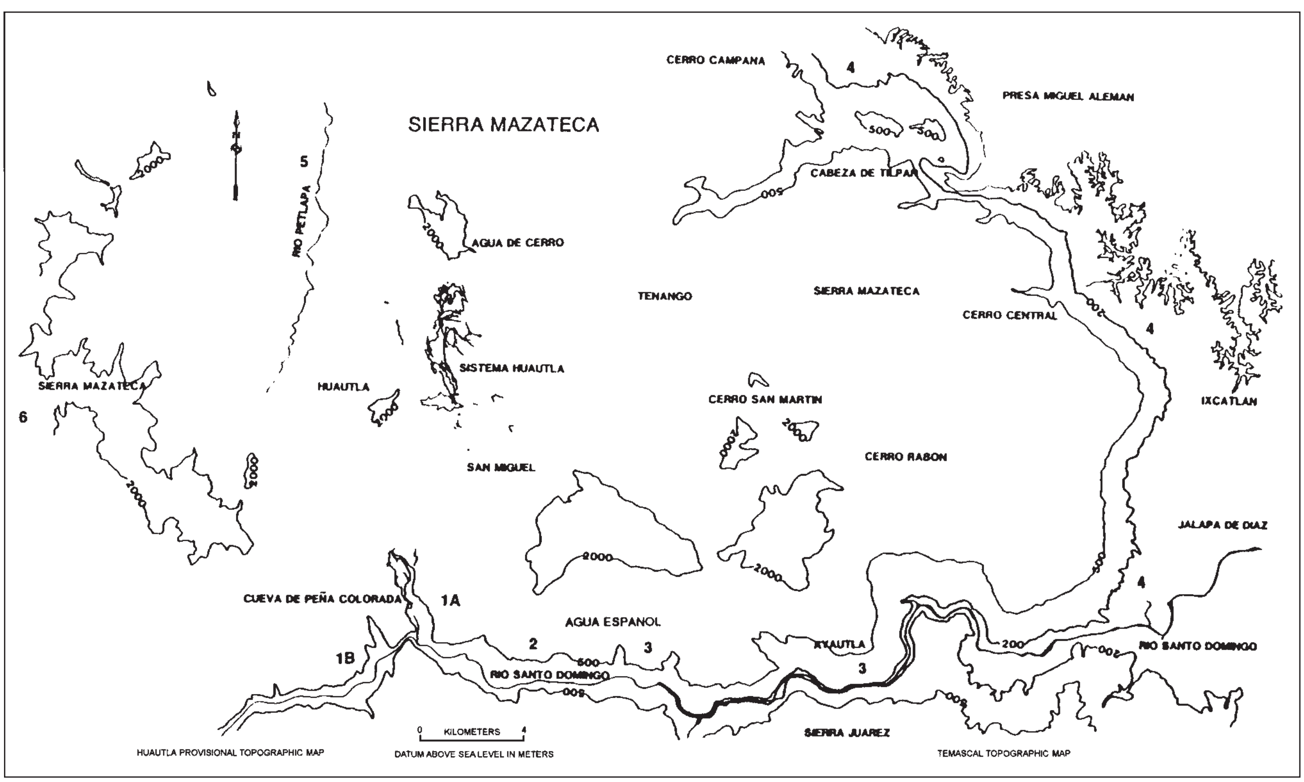



**Figure 5.2.** Legend for karst groundwater basin study area.

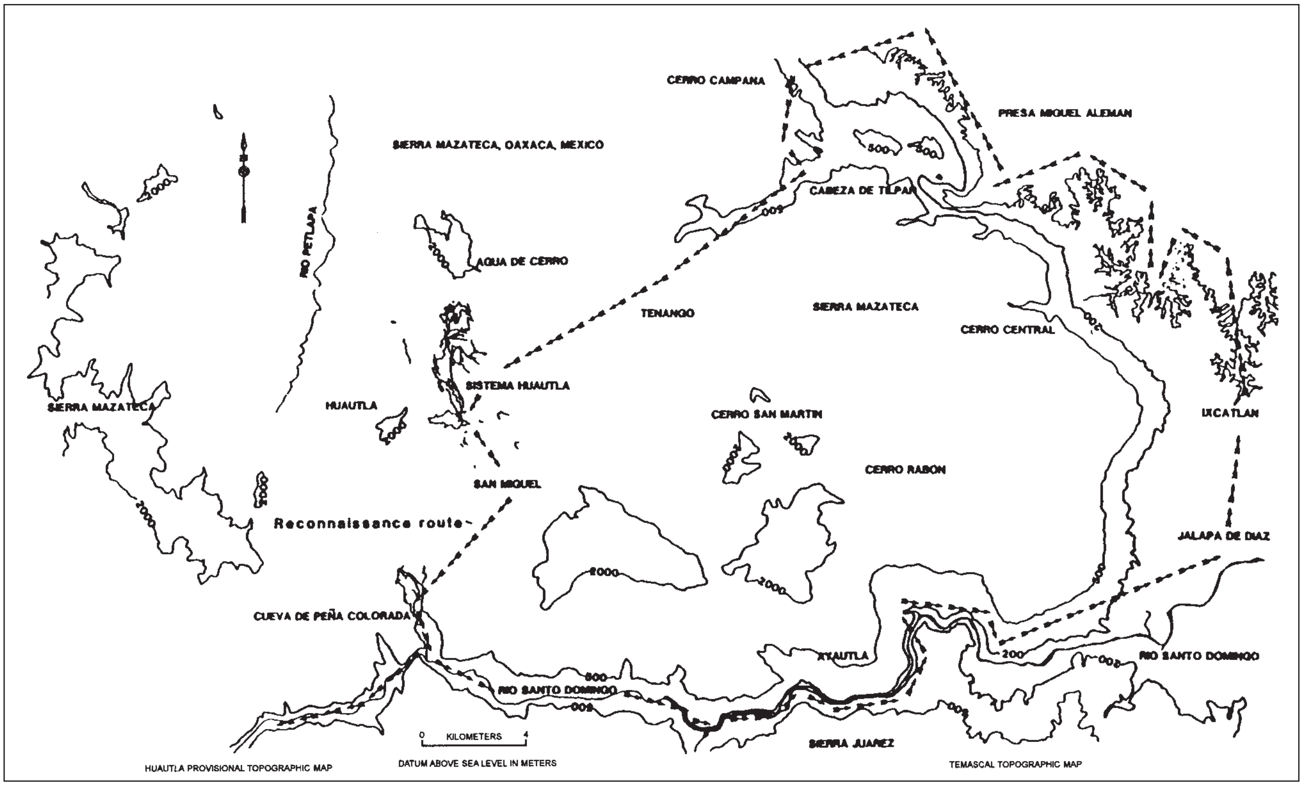



**Figure 5.3.** Reconnaissance route of the Sistema Huautla Karst Groundwater Basin investigation.

### 5.3 Location of Springs

A multi-day wilderness reconnaissance was made for investigating springs and their physical characteristics. It included recording spring locations, recording the temperature of each spring and surface stream, estimating discharge, and placement of charcoal dye receptors in springs and surface streams. During the course of field studies, all springs and surface streams receiving charcoal dye receptors were precisely located on the Huautla and Soyaltepec Provisional Topographic Maps.

### 5.4 Peña Colorada Canyon

South of Sistema Huautla is the large north-south trending Cañón de Peña Colorada. The canyon receives surface drainage from the surrounding highlands of El Camarón, San Miguel Huautepec, Santa María Asunción, El Carrizal, Soyaltitla, and Aguacatitla, a surface drainage area of approximately 65 square kilometers. The canyon is 500 to 1,400 meters deep from the highest topographic prominence and derives its name from a 300-meter-high orange- and red-stained limestone wall. There are numerous caves in the canyon and on its slopes (Stone, 1984) (Figure 5.4 and Plate 5.1).

There are two resurgence caves in the Peña Colorada Canyon, Cueva de Peña Colorada and Vine Cave (Figure 1.5). The latter, although believed to be hydrologically related to the former (Stone, 1984), was not relocated because its access would have required technical wall climbing to reach the entrance.

To study the hydrologic relationship between Sistema Huautla and Cueva de Peña Colorada, charcoal dye receptors were placed in Cueva de Peña Colorada at the first sump (Figure 5.5 and Plate 5.2). Charcoal dye receptors were also placed in the surface stream to detect leakage from the aquifer upstream and at a small spring, Spring #1 on the east side of the Peña Colorada Canyon 200 meters downstream from the Cueva de Peña Colorada entrance.

The temperature of Peña Colorada's cave water was measured at 20 degrees centigrade. The water temperature in Sistema Huautla is 18 degrees centigrade. Temperature variations between Spring #1, measured at 21 degrees centigrade, and the cave water indicated an unlikely relationship (Table 5.1).

Investigations downstream in the Peña Colorada Canyon along the walls of the canyon revealed numerous small seeps along the east wall.

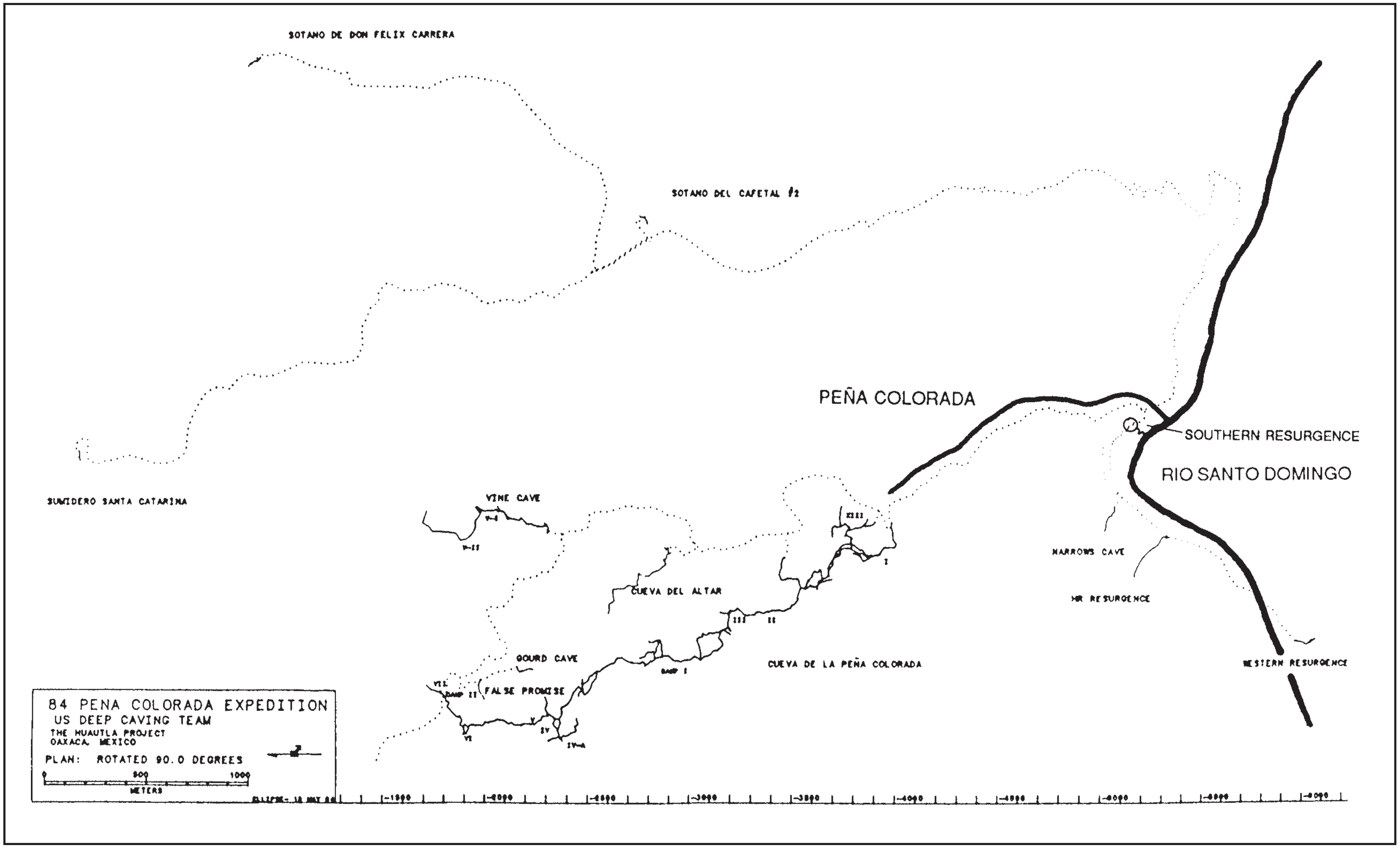



**Figure 5.4.** Cave locations in the Peña Colorada and Río Santo Domingo canyons. Source: Stone 1984.

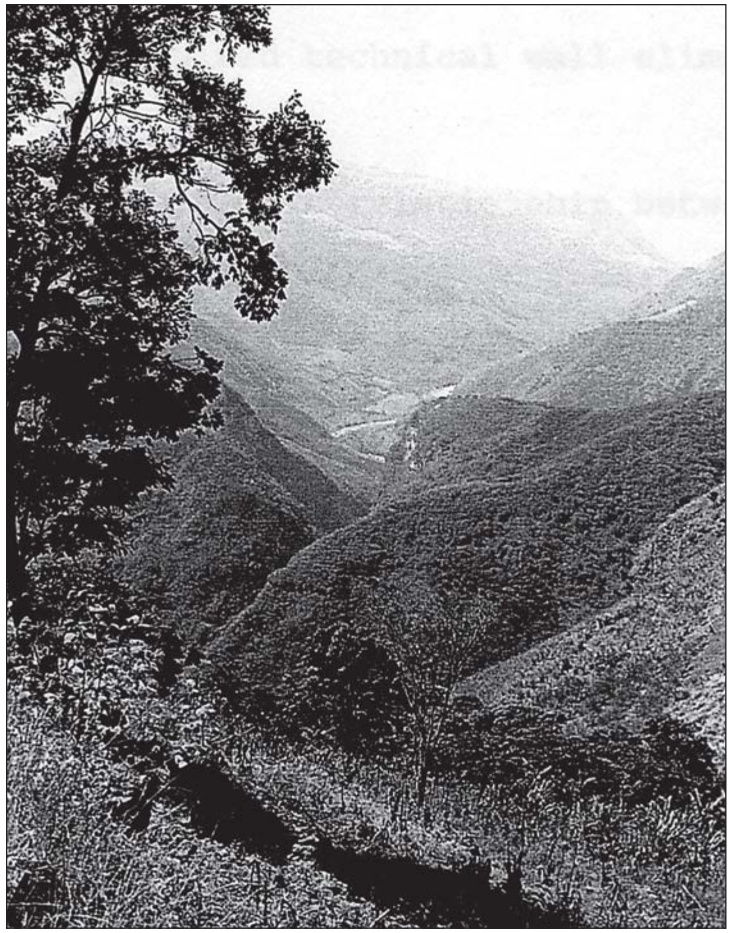


**Plate 5.1.** The north-south trending Peña Colorada Canyon intersects the east-west trending Río Santo Domingo Canyon.

### 5.5 Río Santo Domingo Canyon

At the confluence of the Peña Colorada and Río Santo Domingo a large spring, called the Southern Resurgence (Stone, 1984), was located (Figure 5.4 and Plate 5.3). The discharge from this large spring was reported at 0.3 $m^3$/sec (Stone, 1984) during base flow conditions (Table 5.2). This author estimated the spring's discharge at a minimum of 1.25 $m^3$/sec. Due to irregular channel characteristics, the discharge may be 30 percent higher. The temperature of the spring was measured at 18.5 degrees centigrade. The Southern Resurgence was a likely candidate for the Sistema Huautla resurgence, based on significant discharge and similarities between temperatures at the spring and Sistema Huautla. Two charcoal dye receptors were placed in the spring (Figure 5.5).

Due to the remote locations of these springs and their difficulty of access, use of flow-metering equipment was not feasible. During this investigation, discharge was estimated by determining the cross-sectional area and by timing a floating object on the surface along a predetermined distance to determine velocity. At all springs, the discharge was estimated in this fashion, and a table was constructed to compare reported discharges with observations (Table 5.3).

$$\text{Width} \times \text{Depth} \times \text{Stream Velocity} = Q \text{ (Discharge)}$$
or
$$Q = VA$$

One half kilometer upstream and to the west, on the north wall of the Río Santo Domingo, is HR Resurgence Cave (Figure 5.4). Its temperature was 20 degrees centigrade, two degrees cooler than the Río Santo Domingo. Charcoal dye receptors were placed in the spring.

One and a half kilometers west of the confluence of the Río Santo Domingo and Peña Colorada Canyon on the south wall of the Río Santo Domingo is the Western Resurgence (Stone, 1984) (Figure 5.4 and Plate 5.4). The temperature of the spring, 17.5 degrees, indicated a recharge area, higher than the Sistema Huautla Karst Groundwater Basin, located in the Sierra Juárez to the south. Charcoal dye receptors were placed in the spring. Discharge measurements indicated a discharge of 1.25 $m^3$/sec, similar to that of the

**Table 5.1.** Temperature Measurements of Springs and Streams along the Peña Colorado and Río Santo Domingo Canyons

| Spring | Temperature (°C) |
|---|---|
| Cueva de Peña Colorada | 20 |
| Surface stream in Peña Colorada | 21 |
| Spring on east side of P. C. #1 | 21 |
| Southern Resurgence | 18.5 |
| Río Santo Domingo | 22 |
| Agua Fria, C-8 | 19.25 |
| Western Resurgence, C-5 | 17.5 |
| HR Resurgence Cave | 20 |
| Sistema Huautla | 18 |

**Table 5.2.** Estimated Discharge of Springs Located During the 1994 Peña Colorada Expedition, Base Flow Conditions

| Spring | Discharge ($m^3$/s) |
|---|---|
| Southern Resurgence | 0.37 |
| Western Resurgence, C-5 | 1.85 |
| Agua Fria, C-8 | 1.11 |
| HR Resurgence Cave | 0.55 |

Southern Resurgence.

Several cave entrances were seen above and in the vicinity of the Western Resurgence during this investigation. One of the caves, Cueva del Mano, was explored for 500 meters and trends in a southeast direction. The cave has strong air flow. The Western Resurgence was renamed Nacimiento de Río Frío de Santa Ana by Bill Farr (1989). In 1990, the author dye-traced the stream from Cueva Cheve to Nacimiento de Río Frío de Santa Ana. The trace was the world's deepest dye trace at 2,650 meters (Smith 1991b).

Almost a kilometer farther to the west and on the north side of the Río Santo Domingo is the Agua Fría Spring or C-8 (Figure 5.5). Agua Fría's temperature was 19 degrees centigrade, or one degree warmer than Sistema Huautla and the Southern Resurgence. The estimated discharge was 0.3 $m^3$/sec. Charcoal dye receptors were also placed in this spring.

**Table 5.3.** Discharge Estimates of Springs Located during the Winter 1988 Hydrologic Field Studies

| Spring | Discharge ($m^3$/s) |
|---|---|
| Peña Colorada Stream | 0.18 |
| Spring on east side of P. C. Canyon | 0.09 |
| Southern Resurgence | 1.25 |
| Western Resurgence, C-5 | 1.25 |
| Agua Fria, C-8 | 0.37 |
| HR Resurgence Cave | 0.22 |

A reconnaissance was conducted for an additional 1.5 kilometers west until the contact between metamorphic and limestone rocks was encountered. No additional springs or caves were found along the north and south walls of the Río Santo Domingo in these areas.

East of the trail that links the Sierra Mazateca with the Sierra Juárez, the Río Santo Domingo is not confined by a narrow canyon, and a large, flat flood plain exists for two kilometers before the river becomes confined by a narrow channel between 150-meter-high canyon walls. One small spring cave with an estimated discharge of 0.05 $m^3$/sec was discovered 500 meters beyond the trail on the north wall (Figure 5.5). The temperature of the spring, 22 degrees centigrade, indicated a low-elevation recharge area. No other springs were discovered in this area.

For the next 35 kilometers several small springs were discovered that discharged from talus. All springs were as warm as the Río Santo Domingo at 22 degrees centigrade, suggesting recharge areas that are low in elevation. In addition, four horizontal caves were discovered. Two are located on the south wall and two located on the north wall. Three of the caves were entered, while the fourth was inaccessible, located on a cliff wall 50 meters above the river (Figure 5.4).

At the end of the fourth day of reconnaissance, the Río Uruapan was reached, and two dye receptors were placed in the stream below the spring (Figure 5.5). The estimated discharge was approximately 2 $m^3$/sec. The Nacimiento de Río Uruapan is located at an elevation of 500 meters above sea level, or 200 meters above the

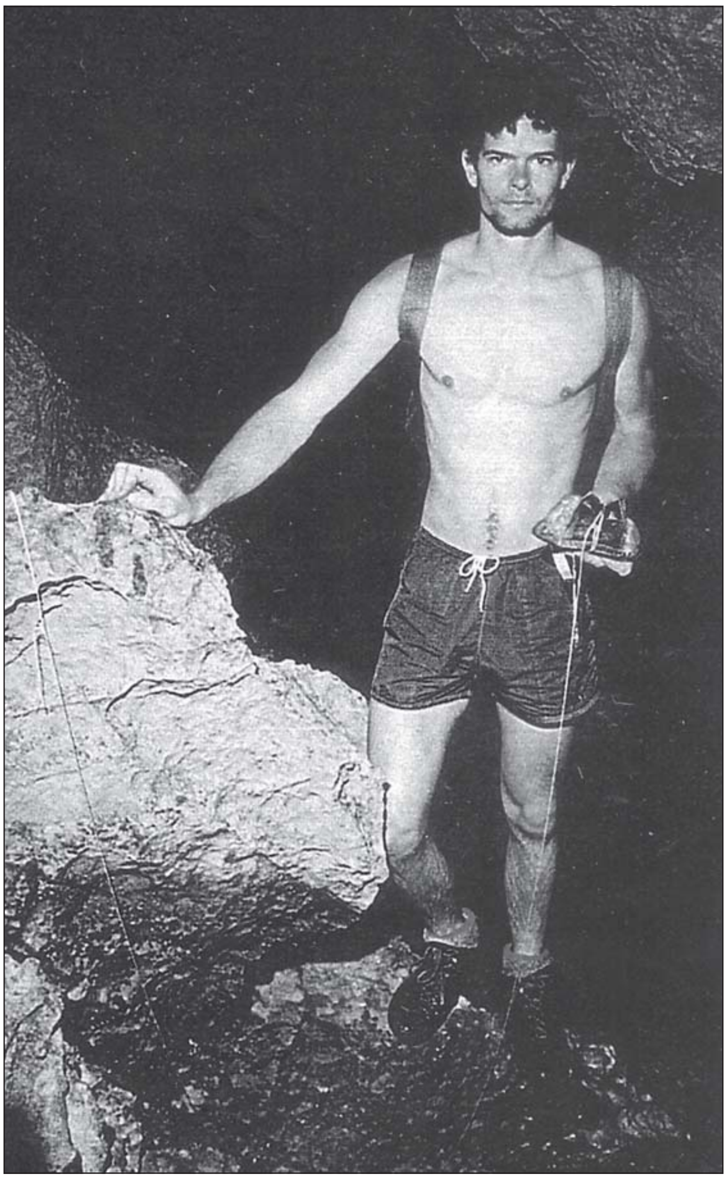


**Plate 5.2.** Lee Perry placing a dye receptor in the first sump of Cueva de Peña Colorada.

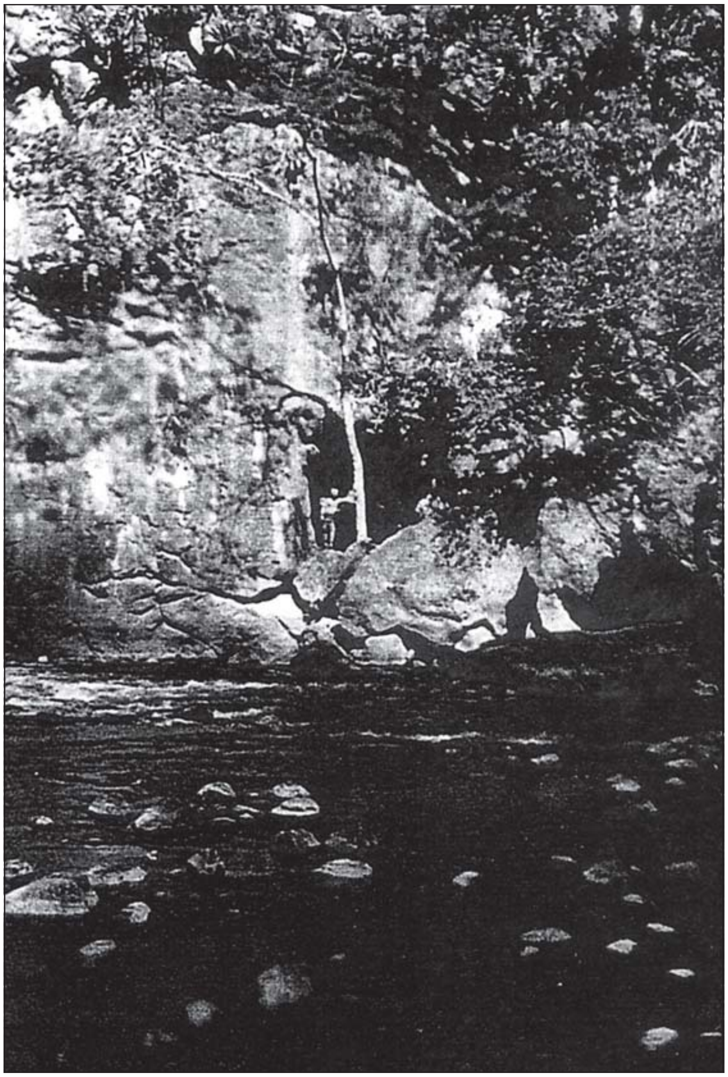


**Plate 5.3.** Río Santo Domingo and the Southern Resurgence.

Southern Resurgence. It is believed that this resurgence is located up dip and is an unlikely resurgence for the Sistema Huautla Karst Groundwater Basin. The Río Uruapan resurgence likely drains the Cerro Rabón Karst Groundwater Basin.

### 5.6 Front Range of the Sierra Mazateca

In the community of Ixcatlán, a motorboat was rented, and a search along the banks of the Presa Miguel Alemán revealed no springs or streams discharging into the reservoir (Figure 5.3). North of Campaña, a horizontal cave was discovered five meters above lake level and explored for 150 meters to a flooded passage.

From Campaña, the inland trek involved traversing from 400 meters to 1,000 meters above sea level to the town of Tenango. Enroute, local Indians revealed springs that were small seepages supplying villages. They told of caves in the mountains and displayed jade beads recovered from them. The largest spring discovered was west of Tenango at 1,300 meters elevation. It flowed across the surface for 500 meters before sinking at a swallet in the karst. The estimated discharge was 0.5 $m^3$/sec. This spring is located in the town of Río Santiago, 6 kilometers to the east of San Agustín. It is called Nacimiento de Río Santiago (Figure 6.6).

### 5.7 Dye Tracing Sistema Huautla

After charcoal dye receptors were placed in springs, fluorescein dye was injected into a subsurface stream located in Sótano de San Agustín (Figure 5.6). Sótano de San Agustín is the historic entrance to Sistema Huautla and is the focal point for drainage from the northern, eastern, and western drainage divides of the karst groundwater basin. It was determined that the cave stream in the Upper Gorge in Sótano de San Agustín, with a gradient of approximately 25 percent consisting of many cascades and an estimated discharge of 0.3 $m^3$/sec, was the best location for introducing the dye. To reach the Upper Gorge to inject dye, 24 vertical shafts, the deepest being 110 meters, were descended.

The rule of thumb on a dye trace is 0.5 kilograms per 1.5 kilometers. The closest potential springs were 10 kilometers straight line distance to the south and the most distant were approximately 40 kilometers to the east. It was decided that since access to the injection site and springs was so difficult it was best to use more than enough dye to ensure success. The amount of dye selected was 18.1 kilograms.

On January 22, 1988, 18.1 kilograms of dye were injected in the Upper Gorge at a depth of 620 meters below the entrance of Sótano de San Agustín (Plate 5.5).

### 5.8 Analysis of Charcoal Dye Receptors

All dye receptors except the Río Uruapan were recovered on February 4, 1988. In order to elute dye from the activated charcoal dye receptors, a solution of 5 percent potassium hydroxide (KOH) and 95 percent of 70 percent isopropyl alcohol was formulated. Each of the seven samples was immersed in the eluent. Almost immediately, the elutant from one of the activated charcoal samples turned bright fluorescent green. The positive test was from the Southern Resurgence dye receptor. No other samples were visibly positive after 24 hours.

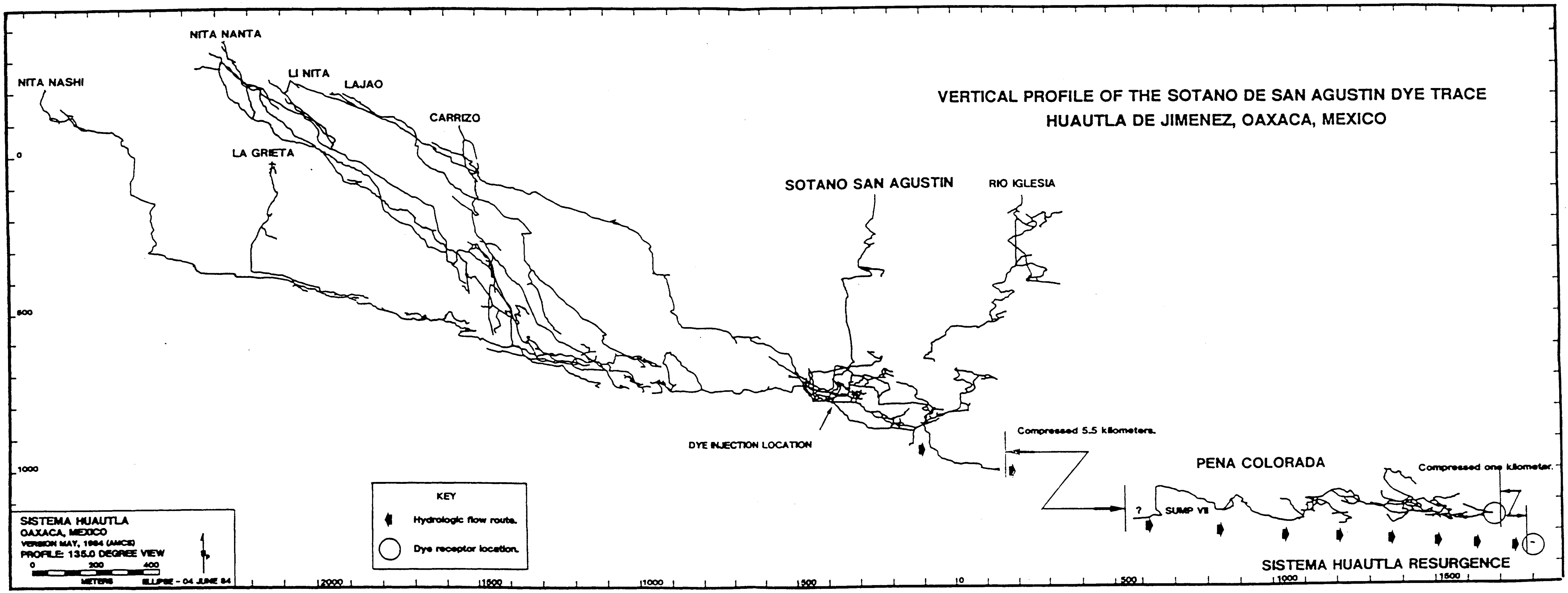

VERTICAL PROFILE OF THE SOTANO DE SAN AGUSTIN DYE TRACE
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
NITA NASHI
NITA NANTA
LI NITA
LAJAO
CARRIZO
LA GRIETA
SOTANO SAN AGUSTIN
RIO IGLESIA
DYE INJECTION LOCATION
Compressed 5.5 kilometers.
PENA COLORADA
Compressed one kilometer.
SUMP VII
SISTEMA HUAUTLA RESURGENCE
KEY
Hydrologic flow route.
Dye receptor location.
SISTEMA HUAUTLA
OAXACA, MEXICO
PROFILE: 135.0 DEGREE VIEW
METERS
0
500
1000


Figure 5.6

Analysis on a Turner Fluorometer at Western Kentucky University's Center For Cave and Karst Studies also revealed negative results for these dye receptors.

### 5.9 Conclusions

The dye-trace results support the hypothesis that groundwater flow in the Sistema Huautla Karst Groundwater Basin is controlled by the strike of steeply dipping beds. The Southern Resurgence, a perennial spring, was then renamed the Sistema Huautla Resurgence to identify it as the resurgence for the karst groundwater basin.

Because dye was recovered from only one dye receptor, the conclusion was drawn that the Sistema Huautla Karst Groundwater Basin is drained by single-conduit drainage from a perennial spring at base level (Figure 5.7). Regional base level is the elevation of the Río Santo Domingo at 300 meters above sea level.

What relationship does Cueva de Peña Colorada have to the Sistema Huautla Resurgence? A 1:50,000 scale computer-generated line plot of Cueva de Peña Colorada and Sistema Huautla with the hypothesized hydrologic flow route of the subsurface stream superimposed on the map shows the interrelationship between end members of the mapped hydrologic systems (Figure 5.7). It appears that the flow route of Sistema Huautla's drainage is directly below the Cueva de Peña Colorada.

Stone (1984) stated that of the seven sumps explored in Cueva de Peña Colorada, the last sump was the only one to have noticeable flow. The water level in Sump VII has the highest elevation of all the sumps in the cave. It is believed that the explorers had reached the active hydrologic flow route deep in Sump VII. The other six sumps are separated by air-filled tunnels and are perched at different elevations. Dye tracing revealed that Sump I is cut off hydrologically from the other sumps. Stone (1984) hypothesized that all six sumps are hydrologically isolated from each other. The sumps occur in phreatic lift tubes that are formed along steeply inclined bedding planes.

It seems likely that Cueva de Peña Colorada is hydrologically related to Sistema Huautla at Sump VII. Based on exploration (Stone, 1984) and the author's personal observations, Cueva de Peña Colorada is considered to be a cave stream overflow route (an intermittent spring) that is active only after intense rainfall events. Cueva de Peña Colorada and possibly Vine Cave may have been the perennial spring for Sistema Huautla in the past, before the conduit was abandoned as base level was lowered as a result of uplift of the Sierra Madre Oriental. The base level is not a stratigraphic confining layer such as the shale found at base level conduits in Sistema Huautla. The

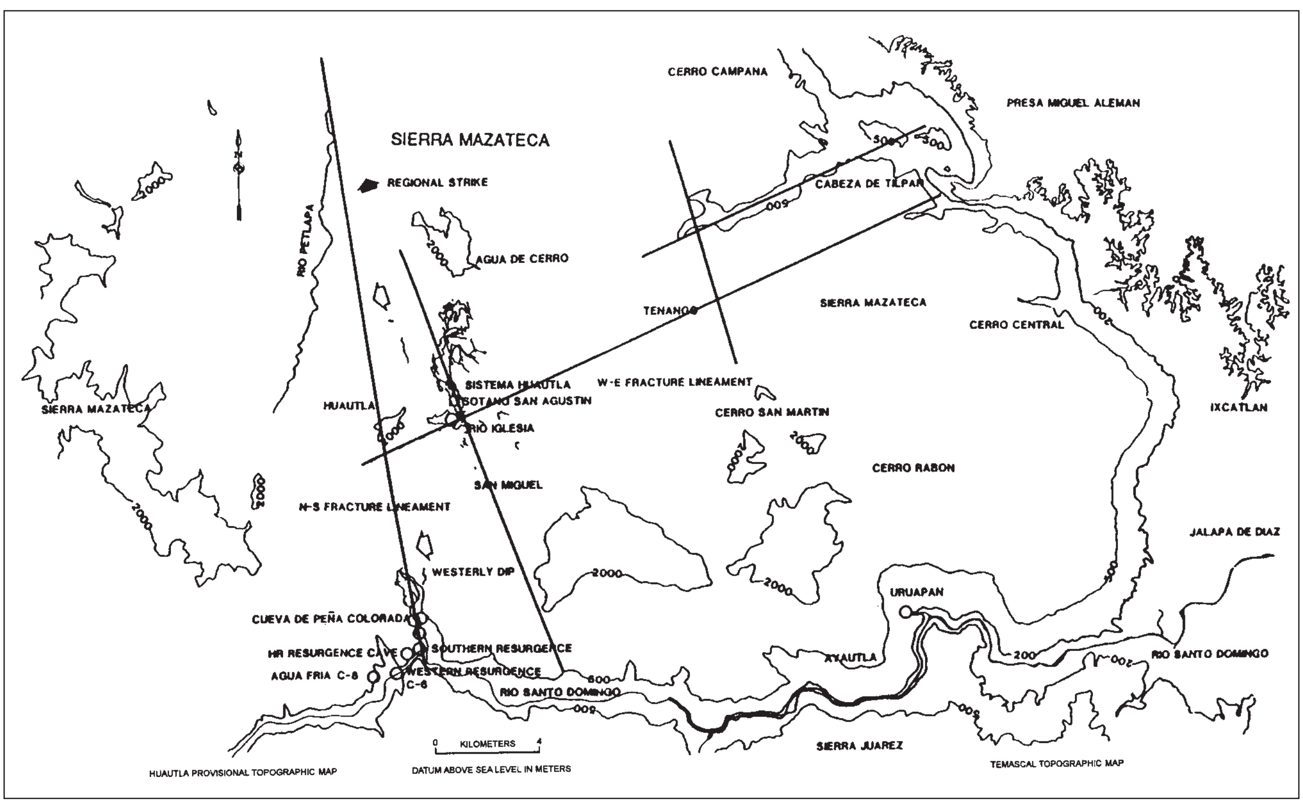



**Figure 5.5.** Dye receptor location map.

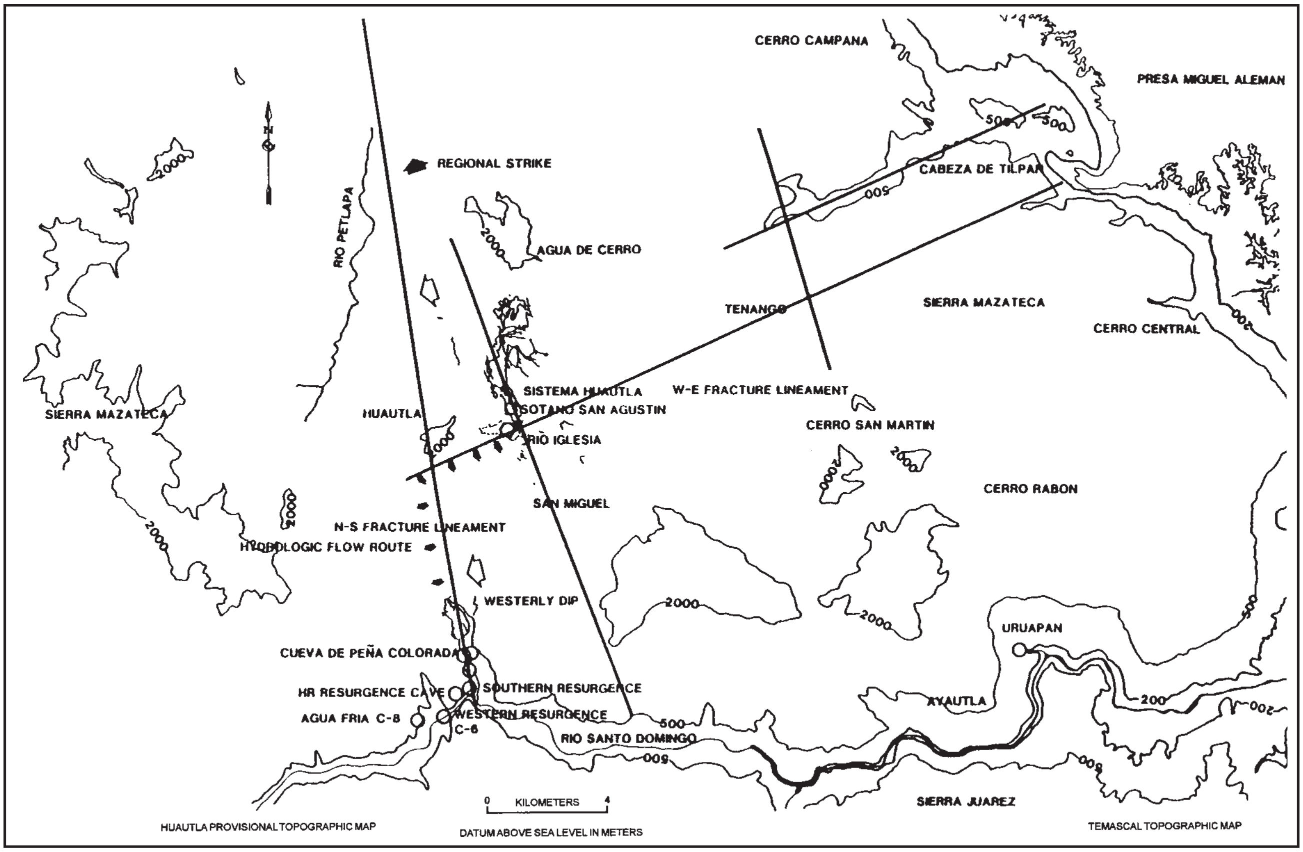



**Figure 5.7.** Sótano de San Agustín dye trace.

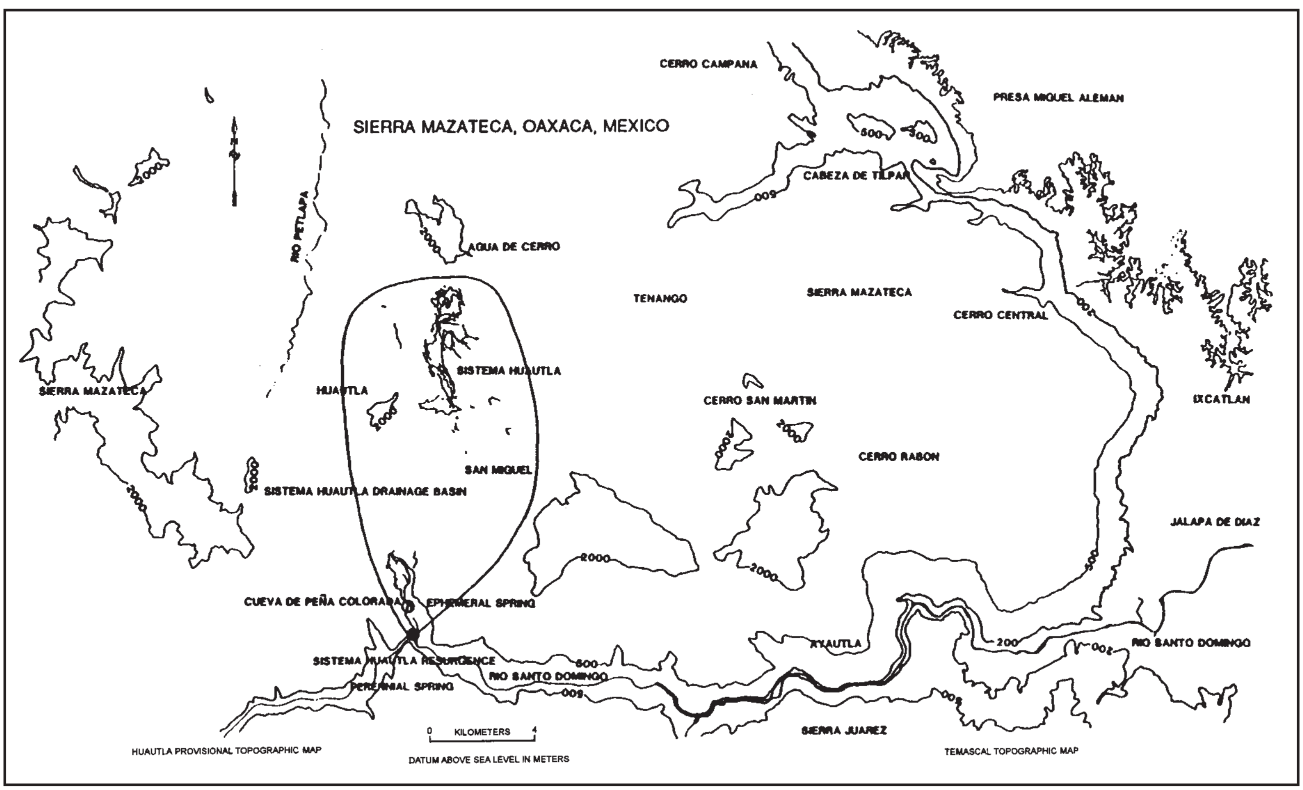


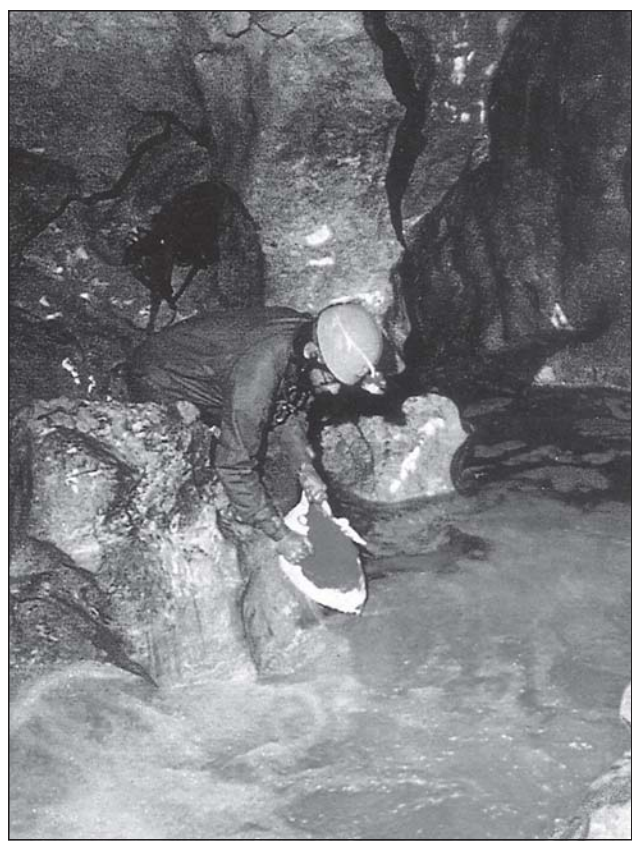

**Figure 5.8.** Hypothesized karst groundwater basin boundary.

base level in Cueva de Peña Colorada is controlled by the potentiometric gradient, with passage development between 50 and 80 meters below the water table. The evidence for this is two-fold: lack of a shale confining layer seen in geologic field studies and the ability of the active hydrologic flow route to migrate lower in the limestone as regional uplift occurs . The location of Cueva de Peña Colorada with respect to the Peña Colorada Canyon leads to the conjecture that the segment of canyon south of the cave may have been a subterranean conduit breached during canyon development. Evidence for this lies in solutional features, sculpturing, and eroded travertine found high above flood stage on the canyon walls and the narrow canyon width of 10 to 20 meters.

Cueva de Peña Colorada is located over a kilometer from the Sistema Huautla Resurgence and 92 meters higher. The elevation and topographic position of Cueva de Peña Colorada relative to the perennial spring revealed that the active hydrologic flow route follows a hydraulic gradient of 6.66 percent. The hydraulic gradient of the Sistema Huautla Drainage (north-south) is determined by the highest input into the groundwater basin divided by the distance to the resurgence. The highest entrance is located at approximately 2,060 meters, and from that location it is 13.4 kilometers to the resurgence. The hydraulic gradient is 15.37 percent.

The boundaries of the Sistema Huautla Karst Groundwater Basin are tentatively defined by structural and lithologic considerations. The western divide is the western-most location of Sistema Huautla's mapped cave passages. The Li Nita portion of Sistema Huautla passes under the overthrusted clastic cap rock. The eastern boundary lies between La Providencia and Río Santiago. A large normal fault presents a structural divide delineating the eastern divide. Subsequent dye tracing of Cueva de Agua Carlota confirmed that groundwater flows to the southwest. The northern divide has not been established, but is hypothesized to lie between Plan de Escoba and Agua de Cerro. Additional dye tracing is needed to test this hypothesis. Figure 5.8 illustrates the tentative boundaries of the Sistema Huautla Karst Groundwater Basin.

**Plate 5.4** (left). The Western Resurgence is located on the south side of the Río Santo Domingo.
**Plate 5.5** (below). Don Coons injecting fluorescein dye into the Upper Gorge of Sótano de San Agustín.



# CHAPTER 6

# HYDROLOGIC FLOW PATTERNS

## 6.0 Introduction

The structural geology of the Sistema Huautla Karst Groundwater Basin controls the direction of flow of subsurface streams. Groundwater flow routes that define the basin are oriented along the strike of thrust-faulted limestones and faults. In general, groundwater flows from north to south to resurge at one perennial spring. However, it would be too simplistic to say that all groundwater of the karst groundwater basin flows from north to south. Examination of the quantitative model of the aquifer (cave surveys) reveals a complex flow pattern (Figure 6.1). The subsurface survey of cave passages defines quantitatively the three-dimensional characteristics of conduit flow within the aquifer and the structural influence on flow patterns.

It is possible to form hypotheses from the Sistema Huautla model and hypothesize flow paths from sink points at the surface and from streams within unconnected caves to stream confluences within the aquifer. To test the flow-route hypotheses, qualitative dye traces establish precise confluence locations of swallet and tributary cave streams with the major streams within Sistema Huautla or to the Sistema Huautla Resurgence.

It is the purpose of this chapter to report on the findings of dye traces from surface stream sinks, separate stream caves, and sink points in Sistema Huautla to confluences within Sistema Huautla. By conducting dye traces, the quantitative model of the aquifer (cave survey) may be refined by establishing the relationship of hydrologic input from other cave stream sources, defining the outermost stream input to delimit the karst groundwater basin, and integrating sinking surface streams into the system.

## 6.1 Methodology

To determine the relationship between surface and subsurface inputs into Sistema Huautla, dye receptors were placed at confluences deep within the cave system, and dyes were injected into various surface stream sinks and cave streams. Because of the extreme logistics involved with placing and retrieving dye receptors, multiple dyes were used for simultaneous traces. The following dyes were used to trace groundwater flow: fluorescein (Color Index: Acid Yellow 73), optical brightener Tinopal SEM GX (Fabric Brightening Agent 22), rhodamine WT (Color Index: Acid Red 388), and diphenyl brilliant flavine 7 GFF (Color Index: Direct Yellow 96). The majority of the surface springs where dye might resurge were remote and of little use as a water resource, but several were major water supplies for the local population. Therefore, an important factor in the selection of dyes was their nontoxicity (Smart and Laidlaw, 1977; Smart, 1984).

Dye receptors were placed at major stream confluences deep within the labyrinth of Sistema Huautla. Because of the complex hydrology of the karst groundwater basin, dye receptors were also placed at the outlet of the Sistema Huautla Karst Groundwater Basin (Sistema Huautla Resurgence) and at other spring locations outside the basin. Placing dye receptors at all practical resurgences was necessary due to the possibility of dye tracers bypassing dye receptors in Sistema Huautla and its spring. Dye receptors were placed to the south at springs along the Río Santo Domingo and the Peña Colorada Canyon, and to the east in a large spring on the Río Santiago, east of La Providencia.

Once dye receptors were retrieved, they were treated with the appropriate eluent for the elution of

dye from the charcoal for visual detection. The unbleached-cotton dye receptors were viewed under an ultraviolet light for fluorescence. To test charcoal dye receptors, two types of eluents, the Smart solution and a KOH solution, were used. The Smart solution is propanol, ammonia hydroxide, and distilled water in a 5:3:2 mixture. This eluent is best for recovering rhodamine WT dye. To recover fluorescein dye from charcoal, an eluent of 5 percent potassium hydroxide mixed with 95 percent isopropyl alcohol (70 percent solution) was used. Direct Yellow 96 and optical brightener are visually detectable with UV light. The elutants for all charcoal receptors were also analyzed on a Turner Fluorometer.

## 6.2 Sinking Surface Streams

Within the hypothesized Sistema Huautla Karst Groundwater Basin are spring-fed perennial streams (Figure 6.2). All of these streams disappear into sinkholes. However, the points of input may be classified into two categories, cave swallets and influent stream swallets. The following dye traces of sinking streams will be described according to their category.

### 6.2.1 Cave Swallets

Some of the largest surface streams of the karst groundwater basin sink into cave swallets. These spring-fed streams and locations are as follows: The Río Iglesia (Río Iglesia Dolina) in the community of San Agustín Zaragoza, Cueva de Agua Carlota surface stream (La Providencia Dolina) in the community of La Providencia, and Sótano del Cangrejo (San Miguel Dolina or Llano de Agua) in the community of San Miguel Huautepec.

#### 6.2.1.1 Río Iglesia

Río Iglesia is the largest perennial stream in the Sistema Huautla Karst Groundwater Basin. It owes its provenance to a clastic-cap-rock aquifer of allochthonous rocks of the Tepexilotla Formation and mixed carbonates-clastics of the Tuxpanguillo Formation. Many small springs and percolation drainage from steep slopes of the Río Iglesia Dolina contribute allogenic recharge to form this large spring-fed surface stream. The Río Iglesia Dolina has a surface drainage basin that measures 3 by 1 kilometers. From

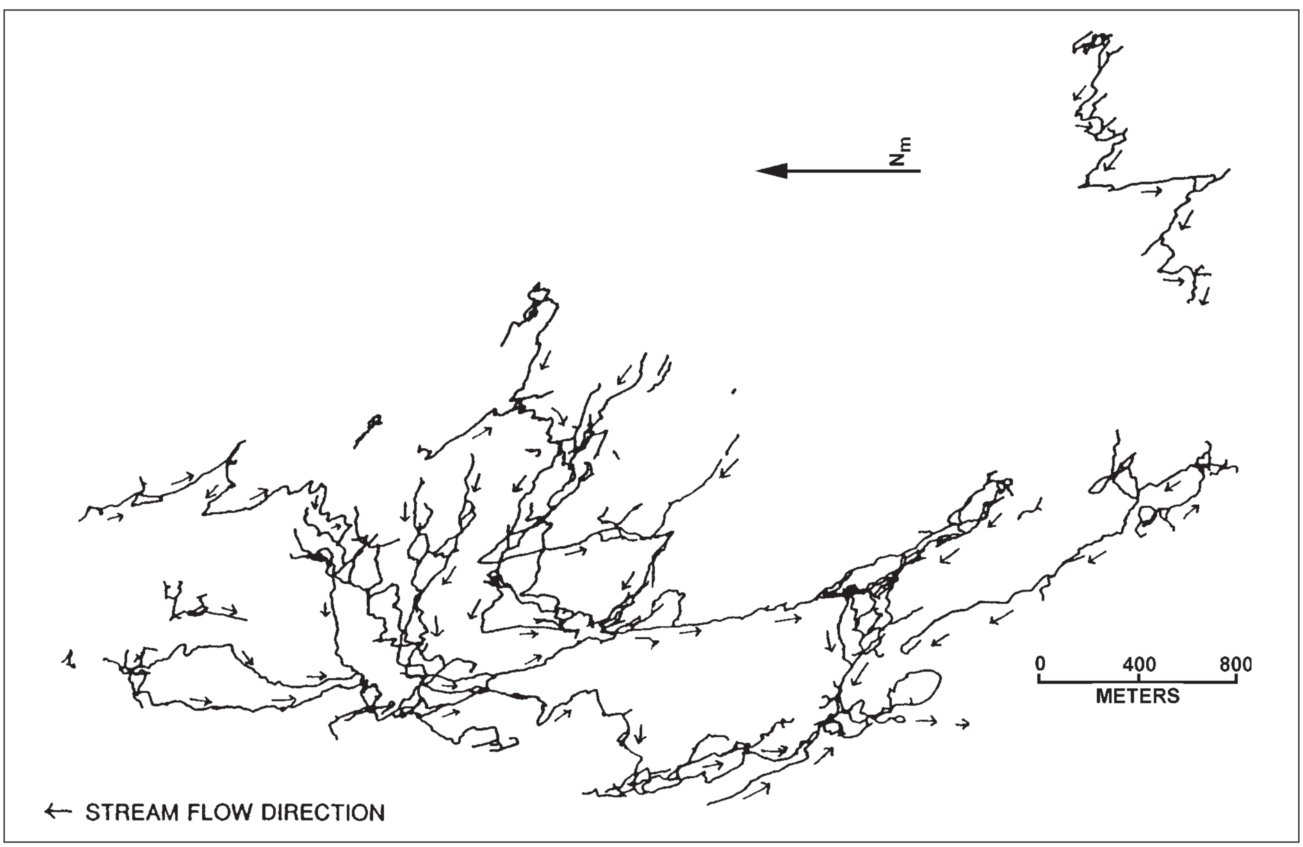



**Figure 6.1.** Complex flow patterns in the caves of the Sistema Huautla Karst Groundwater Basin.

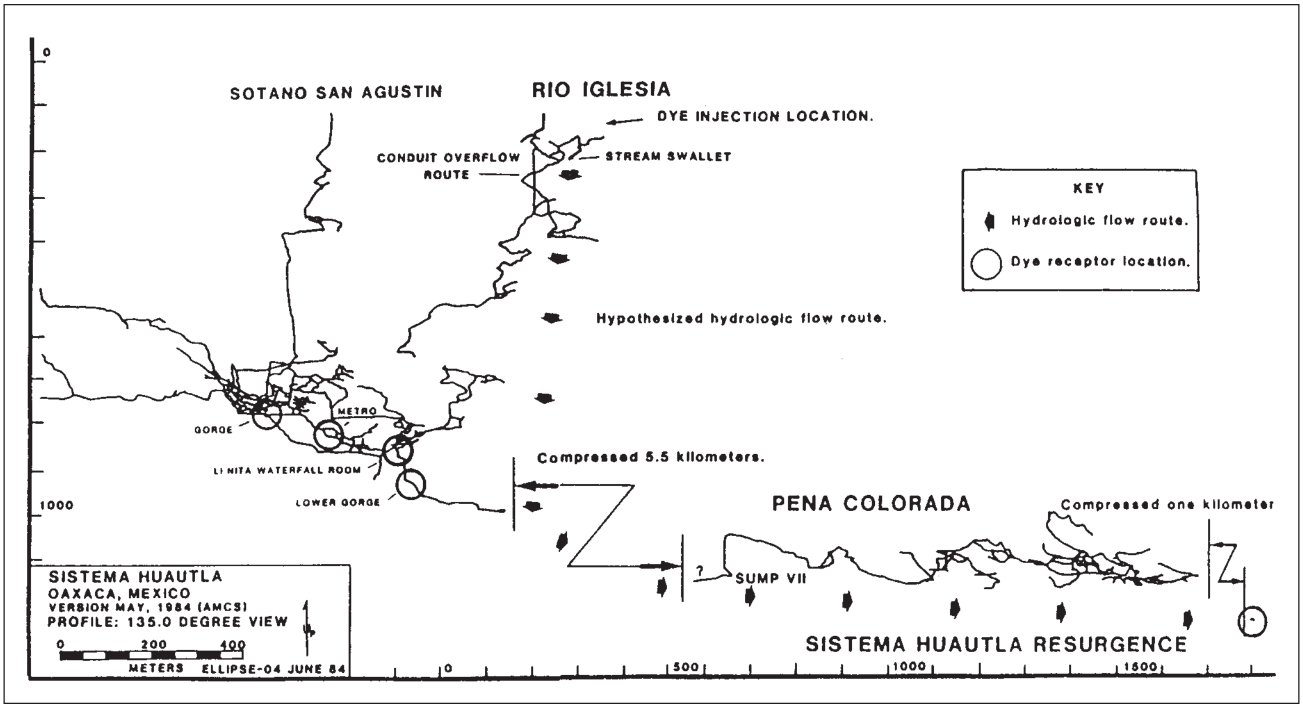



**Figure 6.3.** Vertical profile of Sótano del Río Iglasia dye trace.

the highest topographic divide to the floor of the dolina, the total vertical relief is 620 meters. The Río Iglesia surface stream flows down hill slopes and across the dolina floor for 2 kilometers and sinks into the cave, Sótano del Río Iglesia, at an elevation of 1,480 meters. The stream disappears at the base of a 30 meter shaft within sight of daylight. Sótano del Río Iglesia was the Western Hemisphere's deepest cave in the late 1960s. It has a surveyed length of 4.205 kilometers and a depth of 531 meters.

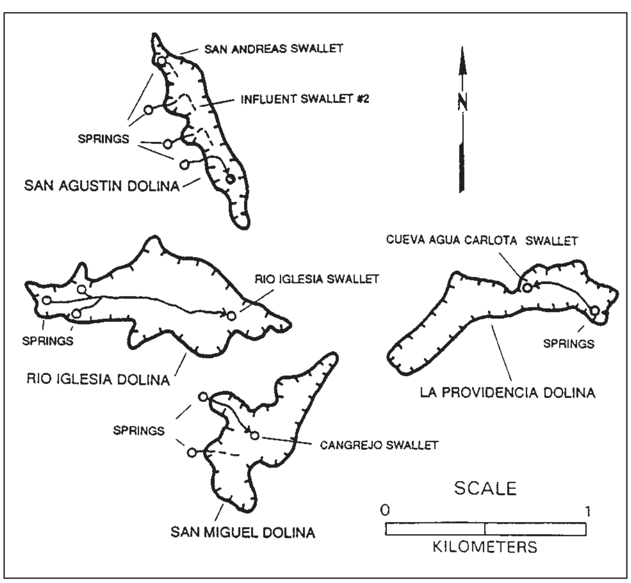



**Figure 6.2.** Cave stream swallets and influent stream swallets.

There is no known infeeding stream within Sistema Huautla's Sótano de San Agustín that has an input comparable to the volume of water that sinks in the entrance of Sótano del Río Iglesia. To test the hypothesis that Sótano del Río Iglesia provides input to the confluence in the Lower Gorge of Sótano de San Agustín, dye receptors were located at all major stream confluences in Sistema Huautla (Figure 6.3). Dye receptors were also located at the Sistema Huautla Resurgence and at other spring locations.

**Table 6.1.** Río Iglesia Dye Trace

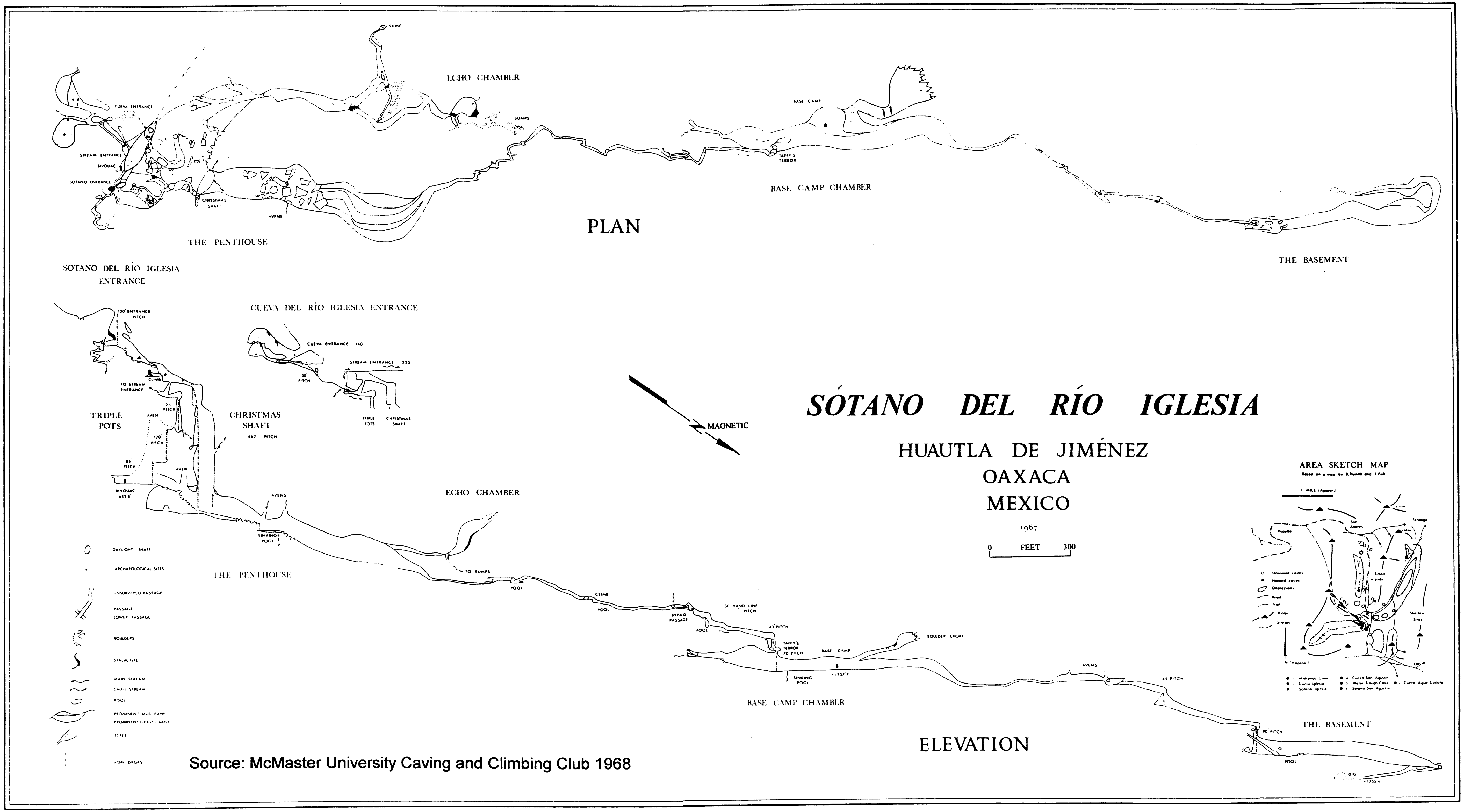
| Result | Dye receptor locations |
|---|---|
| – | Lower Gorge |
| – | Metro |
| – | Upper Gorge |
| – | Lower Gorge #1 |
| – | Lower Gorge #2 |
| – | ED Survey |
| – | Nanta Gorge |
| – | Camp IV |
| + | Sistema Huautla resurgence |
| – | Peña Colorada Sump 1 |
| – | HR Resurgence Cave |
| – | Peña Colorada surface stream |
| – | Peña Colorada spring #1 |

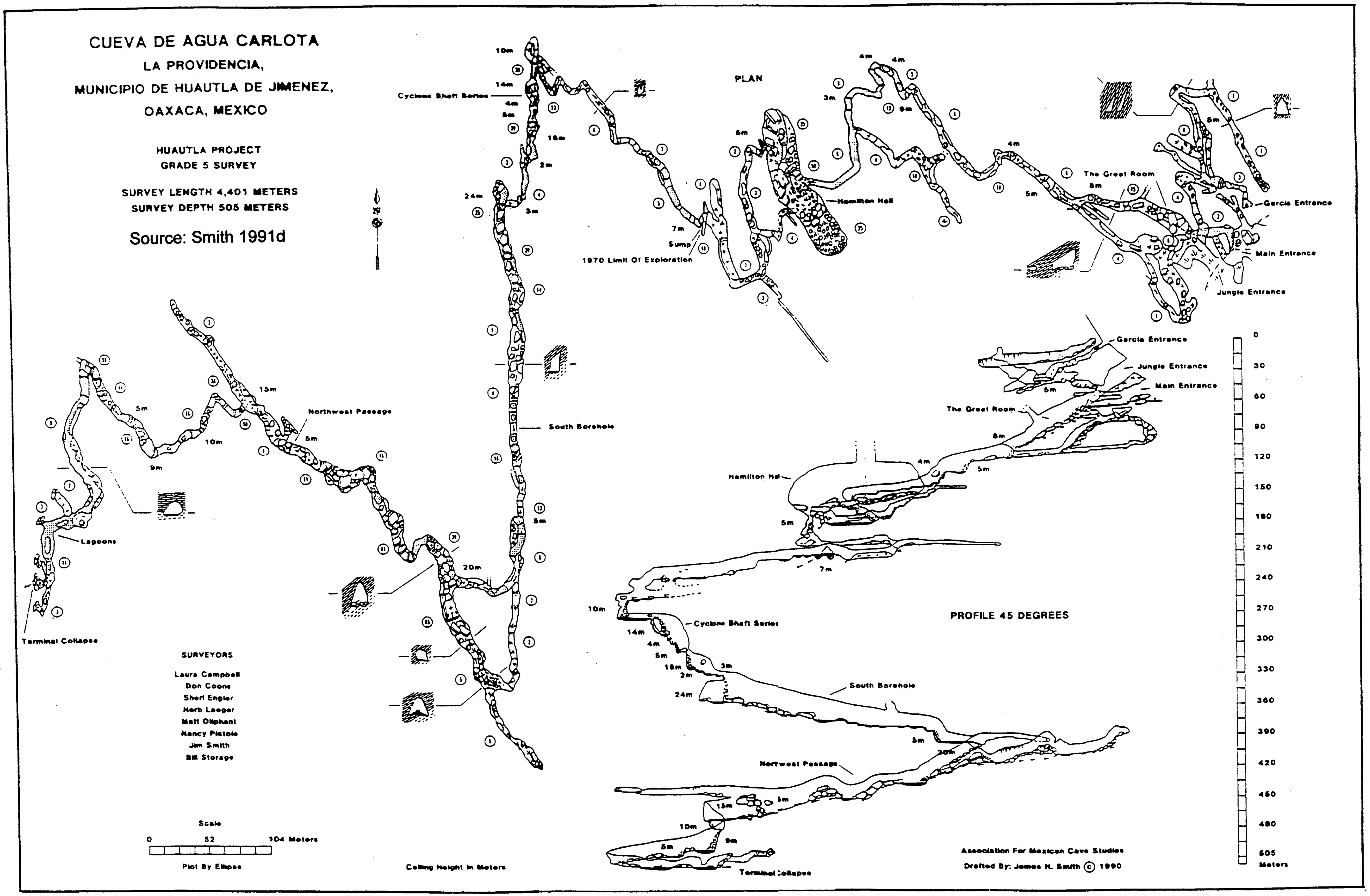
**Plate 6.1** (above). James Smith injecting rhodamine WT dye into the swallet stream of Sótano de Río Iglesia. **Plate 6.2** (right). A surface stream sinks into the entrance of Cueva de Agua Carlota.

After dye receptors were placed at the cave stream confluences and at springs, four liters of rhodamine WT were injected into Río Iglesia (Plate 6.1). Dye receptors were retrieved and treated with Smart Solution (Smart, 1972; Smart and Brown, 1973). All dye receptors were visually negative at the field laboratory. Dye receptors were treated at the Center for Cave and Karst Studies laboratory and tested on a Turner Fluorometer. Dye was detected, below the visible range, in the Sistema Huautla Resurgence dye receptor (Table 6.1). It was therefore concluded that the sinking stream of Río Iglesia does not flow to any of the known stream confluences of Sistema Huautla, but likely joins the main hydrologic flow route between Sistema Huautla and the Sistema Huautla Resurgence. However, Stone (1994) writes that a large confluence was discovered between Sump 2 and the Sump 9 in the newly discovered part of Sistema Huautla. He speculates that the stream may be the water from Río Iglesia.

6.2.1.2 Discussion

The direction of stream-flow in Sótano del Río Iglesia is south to north, following the strike, which is opposite the dominant north-to-south trend of groundwater flow in the basin (Figure 6.1). Strike and dip


PLAN
ECHO CHAMBER
BASE CAMP CHAMBER
THE PENTHOUSE
THE BASEMENT
SÓTANO DEL RÍO IGLESIA ENTRANCE
CUEVA DEL RÍO IGLESIA ENTRANCE
TRIPLE POTS
CHRISTMAS SHAFT
MAGNETIC
SÓTANO DEL RÍO IGLESIA
HUAUTLA DE JIMÉNEZ
OAXACA
MEXICO
1967
0 FEET 300
AREA SKETCH MAP
ELEVATION
Source: McMaster University Caving and Climbing Club 1968


CUEVA DE AGUA CARLOTA
LA PROVIDENCIA,
MUNICIPIO DE HUAUTLA DE JIMENEZ,
OAXACA, MEXICO
HUAUTLA PROJECT
GRADE 5 SURVEY
SURVEY LENGTH 4,401 METERS
SURVEY DEPTH 505 METERS
Source: Smith 1991d
PLAN
Cyclone Shaft Series
Hamilton Hall
1970 Limit Of Exploration
Sump
The Great Room
Garcia Entrance
Main Entrance
Jungle Entrance
Northwest Passage
South Borehole
Lagoons
Terminal Collapse
PROFILE 45 DEGREES
SURVEYORS
Laura Campbell
Don Coons
Sheri Engler
Herb Laeger
Matt Oliphant
Nancy Pistole
Jim Smith
Bill Storage
Scale
0
52
104 Meters
Plot By Ellipse
Ceiling Height In Meters
Association For Mexican Cave Studies
Drafted By: James H. Smith © 1990
Meters

measurements indicate a change in dip direction to the northwest. Surface measurements indicate that a synclinal fold may account for the change in groundwater flow direction to the north if the conduits are developed along the strike of the strata.

The major control of cave orientation is believed to be fault control. Río Iglesia is hypothesized to be formed along the strike of a normal fault. The north-south orientation is also parallel to a system of normal faults related to the Sistema Huautla Fault. It was not determined during this study if a normal fault controls passage development in Río Iglesia, but it is likely.

The Penthouse and the Echo Chamber, two large vertical shafts 130 and 150 meters deep, respectively, are formed along normal faults (Figure 6.4). The end of Río Iglesia (overflow conduit) plots near Anthodite Hall, the largest chamber in Sótano de San Agustín of Sistema Huautla. It seems likely that the overflow conduit, the largest passage in Río Iglesia, is an overflow for the Río Iglesia surface stream. It appears that Río Iglesia's surface stream at one time followed the main passage trend before stream piracy at the entrance. During the rainy season, the sinking surface stream bypasses the point of stream piracy and flows downa the main trunk as overflow. It is hypothesized that before Anthodite Hall began stoping to form the large chamber it is today, Río Iglesia's cave stream contributed to the development of the Sala Grande de Sierra Mazateca and Anthodite Hall.

**Table 6.2.** Cueva de Agua Carlota Dye Trace

| Result | Dye receptor locations |
|---|---|
| – | Río Santiago |
| + | Sistema Huautla resurgence |
| – | HR Resurgence Cave |
| – | Cueva de Peña Colorada |
| – | Agua Fría |
| – | Nacimiento Río Frío de Santa Ana |
| – | Surface stream Peña Colorada |

#### 6.2.1.3 Cueva de Agua Carlota

Two kilometers east of San Agustín Zaragoza is the community of La Providencia (Figure 1.6). The community is situated around a perennial surface stream on the flanks of a shallow llano (flat-floored dolina) that is 800 meters long and 300 meters wide. A stream with an estimated discharge of 0.07 $m^3/sec$ flows on top of Cretaceous shales and sinks into the large cave entrance of Cueva de Agua Carlota at an elevation of 1480 meters (Plate 6.2).

A cave survey conducted in 1970–71 by Canadian cavers from McMaster University and by the

**Plate 6.3.** James Smith injecting optical brightener dye into the stream swallet of Cueva de Agua Carlota during the first attempt at dye-tracing the swallet.

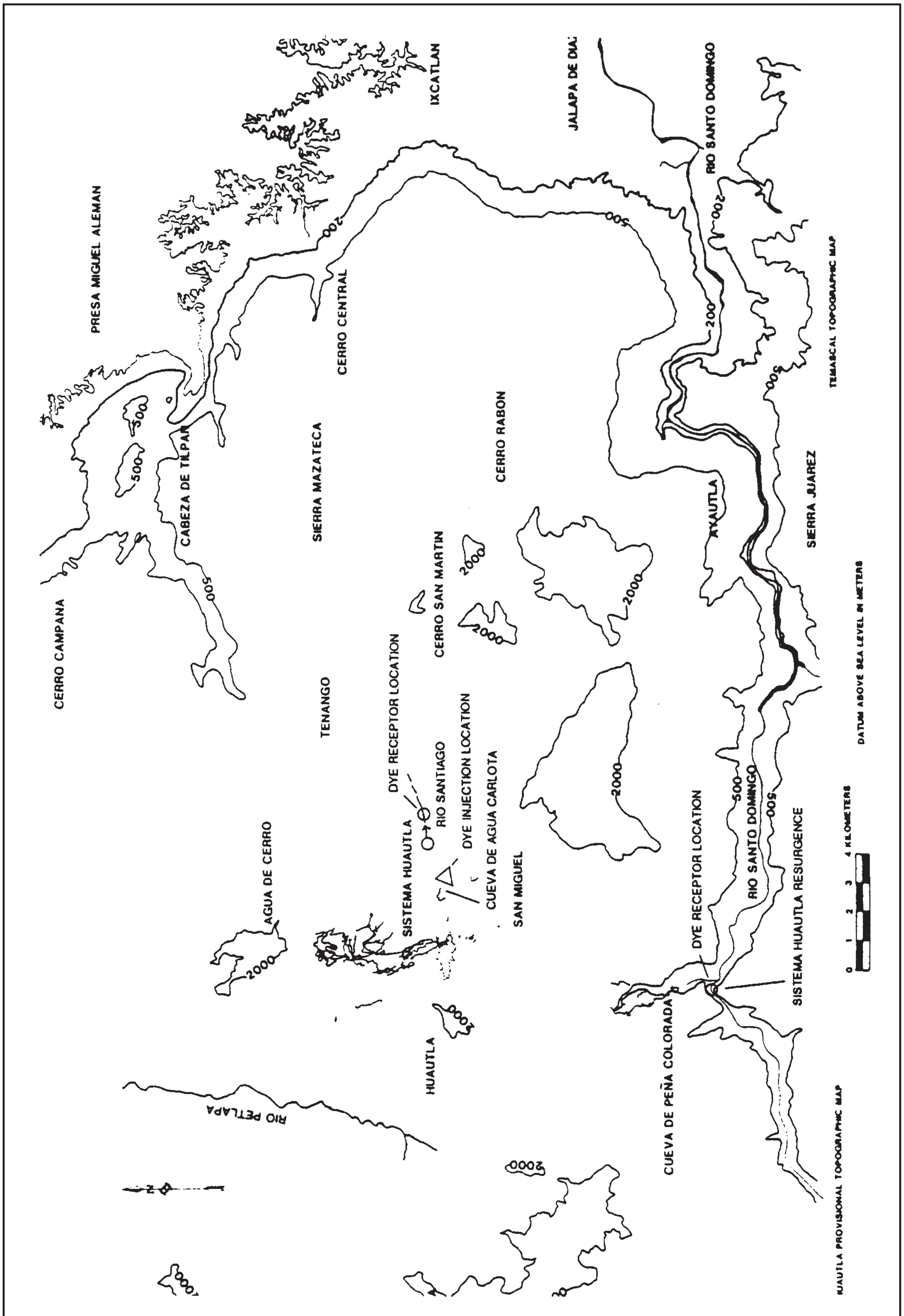



**Figure 6.6.** Dye receptor locations for the Cueva de Agua Carlota dye trace.

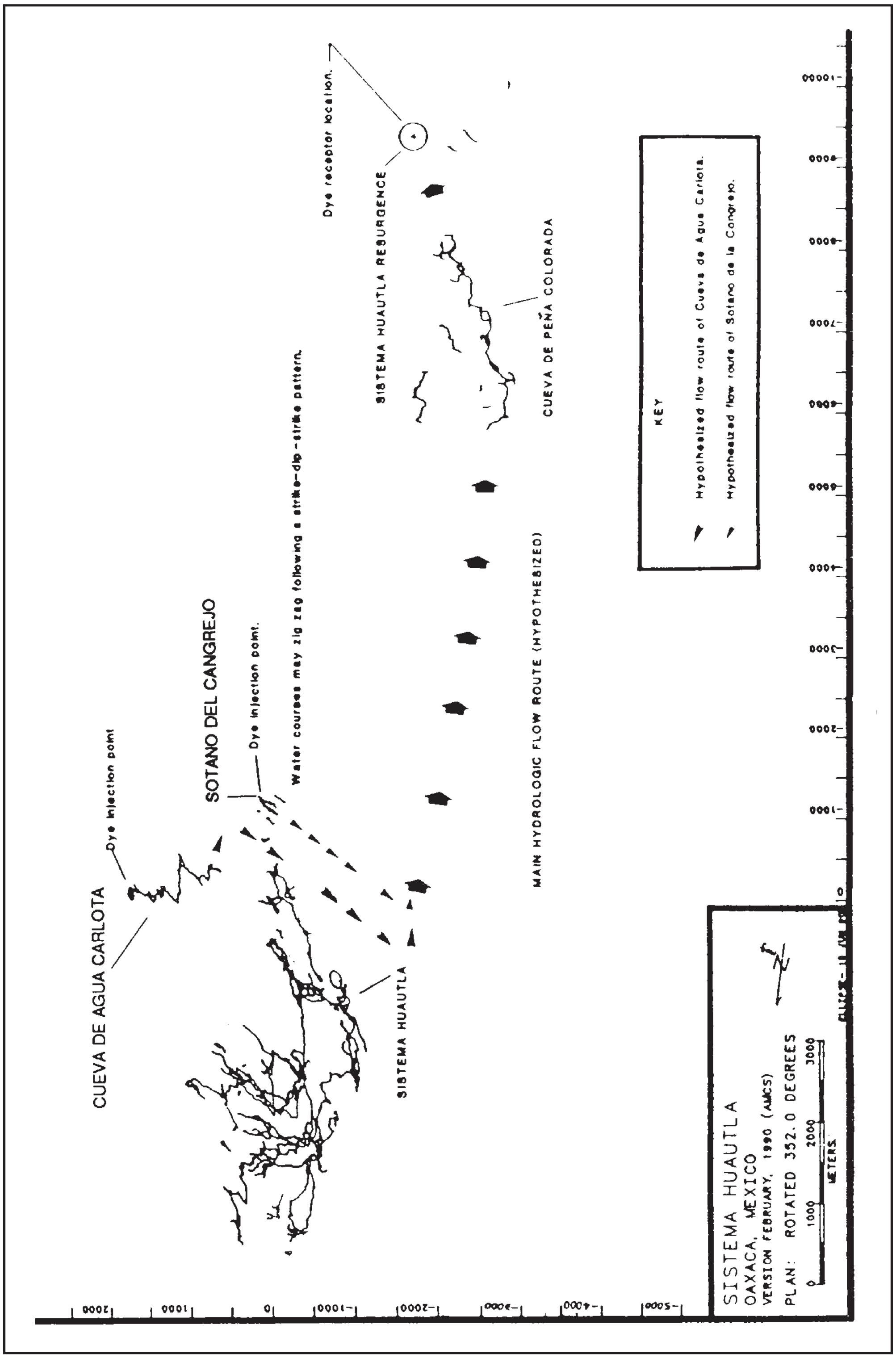



**Figure 6.7.** Dye trace flow path of Cueva de Agua Carlota and Sótano del Cangrejo.

Huautla Project in 1990 (Figure 6.5) indicated that groundwater flow in Cueva de Agua Carlota trends to the southwest in the direction of the Sistema Huautla Resurgence. The following hypothesis was developed based on the cave survey: Cueva de Agua Carlota is the easternmost perennial surface stream in the Sistema Huautla Karst Groundwater Basin and ultimately discharges to the Sistema Huautla Resurgence. The cave survey indicated that conduit development follows both north and south trends as the cave stream zigzags along the strike of the strata and in the down-dip direction to the southwest towards the main hydrologic flow route of Sistema Huautla.

To identify this flow route, charcoal dye receptors were placed in springs and surface streams (Figure 5.5, Figure 6.6, and Table 6.2). Two principal areas where dye receptors were located are to the south, at the proven resurgence (Sistema Huautla Resurgence) and other springs in the Peña Colorada Canyon and along the banks of the Río Santo Domingo, and to the east, at a large spring near the community of Río Santiago. At Cueva de Agua Carlota 5.9 kilograms of fluorescein dye was injected into the surface stream (Plate 6.3). Dye receptors were recovered and analyzed at the field laboratory. The only positive dye receptor was located at the Sistema Huautla Resurgence.

6.2.1.4 Discussion

Dye tracing Cueva de Agua Carlota's stream swallet was attempted three times at various discharge rates in 1988, 1989, and successfully in 1990. In the first two attempts, dye receptors were left in place for at least three weeks at conditions of normal discharge (discharge rates normal for April and December, respectively). Late April and early May are the driest months of the water year and normally have base-flow conditions, while discharge rates during December are nominally higher.

It took one month for dye to discharge from the Sistema Huautla Resurgence during the successful 1990 attempt. The dye trace from Sótano de San Agustín to the Sistema Huautla resurgence took only two weeks. Discharge rates were different during the two dye trace attempts. The dye trace from Sótano de San Agustín occurred during higher discharge. There is no way to know without physical exploration what the conduit characteristics are like beyond the known surveys of the two caves and how the movement of water through the aquifer may be impacted by the cave passage morphology.

However, the following physical characteristics of Cueva de Agua Carlota and Sótano de San Agustín and their relative position to structure within the karst groundwater basin may account for the time differential for dye exiting the cave system.

Cueva de Agua Carlota: It was observed that cave conduits alternate between strike and dip. The cave is located at the eastern edge of the karst groundwater basin and is structurally higher. Dye was injected at the entrance of the cave at 1480 meters above sea level. Deep potholes are located at the base of shafts which impound dye within pools.

Sótano de San Agustín: Cave is located down dip of thrust faulted limestones and is strike dominated. Conduit development at base level is the main channel for groundwater flow from structurally higher inputs from the north and northeast. Sótano de San Agustín has greater discharge. It is closer to the output of the system. Dye was injected at 640 meters depth or 880 meters above sea level. The stream sumps at the bottom of the cave.

Cueva de Agua Carlota is located on the eastern limb of thrusted, faulted limestones 3 kilometers from the western edge of the groundwater basin. It is also approximately 800 meters above base level and approximately 1,200 meters above the spring for the karst groundwater basin. If Cueva de Agua Carlota's 4 kilometers of cave passage follows a zigzagging north-south trend to the hypothesized hydrologic axis, a linear distance of 3 kilometers, then there may be 12 kilometers of passage (assuming the same hydrologic pattern) by the time the water from the cave reaches the main hydrologic flow route.

Cueva de Aqua Carlota has a zigzag pattern following the strike and dip. The alternation between north and south orientation along strike oriented passage occurs in steeply dipping strata with dips that vary from 20 degrees to vertical. As cave development progresses toward the western limit of the groundwater basin toward base level, the zigzag pattern should change into a more linear development following the axis of the plunging fold. Water from Cueva de Agua Carlota may intersect a master conduit that transmits the entire drainage of the karst groundwater basin to its discharge point (Figure 6.7 and Figure 6.8).

The length of the flow route and impoundment time before the main hydrologic flow route is reached is greater than was observed in Sótano de San Agustín. Dye in Cueva de Agua Carlota was still observed three days after injection in deep potholes below cascades and shafts. Impounded dye was slowly released from the potholes by circulation.

Although no dye receptors were placed in Sistema Huautla during the Cueva de Agua Carlota dye trace, it is believed that water from Cueva de Agua Carlota

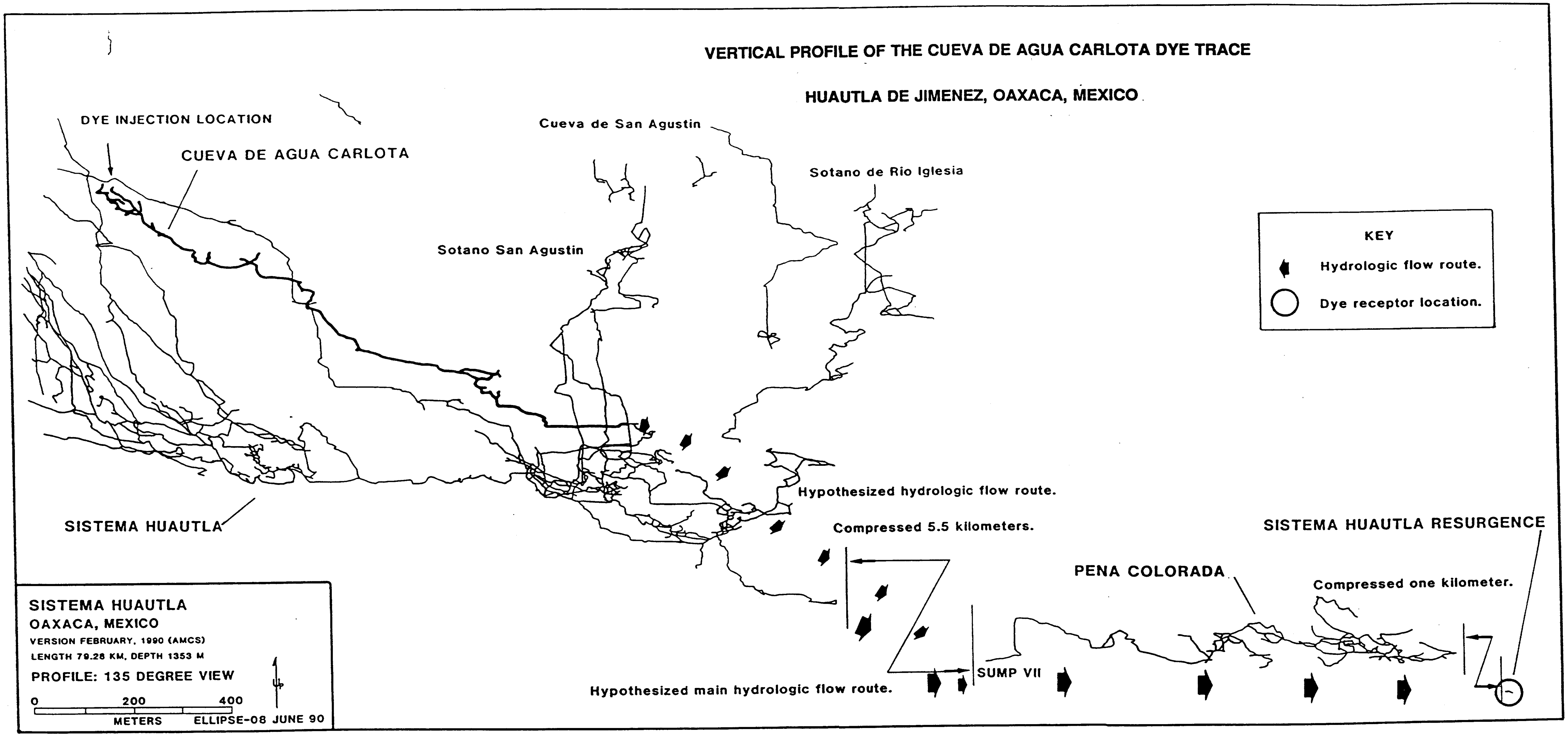

VERTICAL PROFILE OF THE CUEVA DE AGUA CARLOTA DYE TRACE
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
DYE INJECTION LOCATION
CUEVA DE AGUA CARLOTA
Cueva de San Agustin
Sotano de Rio Iglesia
Sotano San Agustin
KEY
Hydrologic flow route.
Dye receptor location.
Hypothesized hydrologic flow route.
Compressed 5.5 kilometers.
SISTEMA HUAUTLA
SISTEMA HUAUTLA RESURGENCE
PENA COLORADA
Compressed one kilometer.
SUMP VII
Hypothesized main hydrologic flow route.
SISTEMA HUAUTLA
OAXACA, MEXICO
VERSION FEBRUARY, 1990 (AMCS)
LENGTH 79.28 KM, DEPTH 1353 M
PROFILE: 135 DEGREE VIEW
0 200 400
METERS
ELLIPSE-08 JUNE 90


Figure 6.8

**Table 6.3.** Sótano del Cangrejo Dye Trace

| Result | Dye receptor locations |
|---|---|
| + | Sistema Huautla resurgence |
| – | Cueva de Peña Colorada |
| – | Peña Colorada stream |

does not enter into Sistema Huautla as tributary input, because Cueva de Agua Carlota's drainage is south of the terminus of Sótano de San Agustín and there are no sizable tributary inputs below Upper Gorge.

It is concluded that the conduit drainage of Cueva de Agua Carlota enters the main hydrologic flow route for the karst groundwater basin between the northern drainage system of Sistema Huautla and the Sistema Huautla Resurgence.

#### 6.2.1.5 Sótano del Cangrejo

In the San Miguel Dolina or Llano de Agua are seven explored caves (Jameson and Mothes, 1981). The caves are Cueva Inclinada, Sótano del Agua, Sótano del Escorpión, Cueva de la Sala Grande, Sótano del Cangrejo, Cueva Chica, and Cueva de las Tinajas (Figure 1.6). A spring flows from the clastic cap rock aquifer and sinks into the cave swallet of Sótano de Cangrejo at an elevation of 1540 meters.

Llano de Agua is located south of the Río Iglesia and San Agustín Dolinas near the community of San Miguel Huautepec (Figure 1.6). The dolina's position is between Sistema Huautla and its resurgence. Stream sinks in the San Miguel Dolina are hypothesized to enter into the main hydrologic flow route between Sistema Huautla and the karst groundwater basin's spring. To test this hypothesis, 6.8 kilograms of optical brightener dye were injected in Sótano del Cangrejo (Figure 6.7 and Table 6.3). Dye receptors were retrieved and analyzed under UV light at the field laboratory. The Sistema Huautla Resurgence dye receptor tested positive.

#### 6.2.1.6 Discussion

The hydrologic flow route between Sistema Huautla and the resurgence has only hypothetically been reached via sump VII in Peña Colorada (Stone 1984). There are no other segments of the main conduit drainage explored thus far. Sótano del Cangrejo is situated half way between the two known endpoints of the hydrologic system. The positive dye trace to the Sistema Huautla Resurgence indicates that the subsurface stream drainage of Sótano del Congrejo, and probably the other stream caves in the San Miguel Dolina, intersect the main conduit drainage of the karst groundwater basin.

### 6.2.2 Influent Stream Swallets

There are a number of influent stream swallets within the karst groundwater basin (Figure 6.2). An influent stream swallet is defined as a surface stream that loses discharge along its flow net. This phenomenon results from streams flowing for a distance on top of a clayey conglomeratic stream bed over fractured limestone. As the impervious stream bed thins or changes into a poorly cemented conglomerate, the surface stream diminishes until completely lost into the fractured stratum. The springs feeding these surface streams result from both perched clastic cap rock aquifers and from perched springs originating from cherty limestones.

Two major influent streams were dye traced. Both of these influent streams are located in the San Agustín Dolina and were hypothesized to be the source of cave stream tributaries within Sistema Huautla. These will be referred to in the text as the San Andrés Swallet (Influent Stream Swallet #1) and Influent Stream Swallet #2 (Figure 6.2).

#### 6.2.2.1 San Andrés Swallet

The San Agustín Dolina trends north-south and has dimensions 1 by 2.5 kilometers. The west side of the dolina is composed of Jurassic flyschs and Early Cretaceous limestones of the Tuxpanguillo Formation. Perennial springs discharge from the flysch and flow down steep slopes of the dolina onto the floor, where they slowly lose water to the subsurface before disappearing. San Andrés Swallet (Influent Stream Swallet #1) is located at the north end of the San Agustín Dolina at 1660 meters elevation (Figure 6.2). It flows overland from its spring for 500 meters and diminishes in discharge before sinking. The discharge of the influent stream was measured at 0.07 $m^3$/sec before flowing onto alluvium.

It was hypothesized that the water from San Andrés Swallet reappears in Sistema Huautla near

**Table 6.4.** San Andrés Swallet Dye Trace

| Result | Dye receptor locations |
|---|---|
| + | Sistema Huautla resurgence |
| – | Camp IV |
| – | Upper Gorge |
| – | Lower Gorge #1 |
| – | Lower Gorge #2 |
| – | Metro |
| – | Nanta Gorge |
| – | ED Survey |
| + | Li Nita Waterfall Room |

Camp III in Sótano de San Agustín at the Li Nita Waterfall Room. The influent swallet is above and in the vicinity of the Li Nita Waterfall Room, which is the juncture for some of the ridge-top drainage inputs located at the north end of the Sistema Huautla Karst Groundwater Basin. There are also a series of north-south-trending normal faults mapped in Sótano de San Agustín. Although these faults are not visible on the surface, they may provide vertical access for subsurface drainage that discharges to the Li Nita Waterfall Room.

To test this hypothesis, a dye trace was conducted. Charcoal dye receptors were located at all the main stream confluences within Sistema Huautla and at the resurgence (Figure 6.9 and Table 6.4). Less than 1 kilogram (0.9 kilograms) of fluorescein dye was injected at Influent Stream Swallet #1 (Plate 6.4). Dye receptors were recovered and tested in the field laboratory. Two dye receptors were positive, the Li Nita Waterfall Room and the Sistema Huautla Resurgence (Figure 6.10).

6.2.2.2 Discussion

Water from the San Andrés Swallet was hypothesized to enter Sistema Huautla at the Li Nita Waterfall Room near Camp III. This hypothesis was accepted based on a positive dye trace to the Li Nita Waterfall Room at –700 meters or 840 meters elevation (Figure 6.10). The reason for the hydrologic connection to the Li Nita Waterfall Room of Sistema Huautla may be the relationship of passage development to the structural geology. The passages in Li Nita and Sótano de San Agustín have the westernmost strike-oriented passage development in the aquifer. The passages that are developed at the western edge of the groundwater basin are the Upper and Lower Red Ball Canyon streams which feed the waterfall in the Li Nita Waterfall Room and the Mil Metro in Li Nita.

Stream piracy at the San Andrés Swallet allows water to enter the aquifer and flow through conduits down the dip to the west to an eventual intersection with a larger strike-oriented conduit. The water that sinks at the San Andrés Swallet is probably one of the sources for one of three major streams that join to form the large waterfall in the Li Nita Waterfall Room. It is less likely that Li Nita is the route of flow, since there were never any large stream confluences discovered during exploration. Therefore, the dye probably flowed in the streams in either Upper or Lower Red Ball Canyon. It was not possible to pinpoint which of the three streams the dye traveled in due to logistics. Both Red Ball Canyon streams were explored upstream to sumps. A red ball was found in one of the streams, hence the name of the passages.

The dye trace to the Li Nita Waterfall Room from Influent Swallet #1 is significant in that an additional tributary has been traced into the system, indicating a relationship between input and output within the system. It also indicates that there is additional input into Sistema Huautla, other than the entrance shaft, from within the subdrainage basin of the San Agustín Dolina.

**Plate 6.4.** Andy Grubbs injecting dye in the San Andrés swallet.

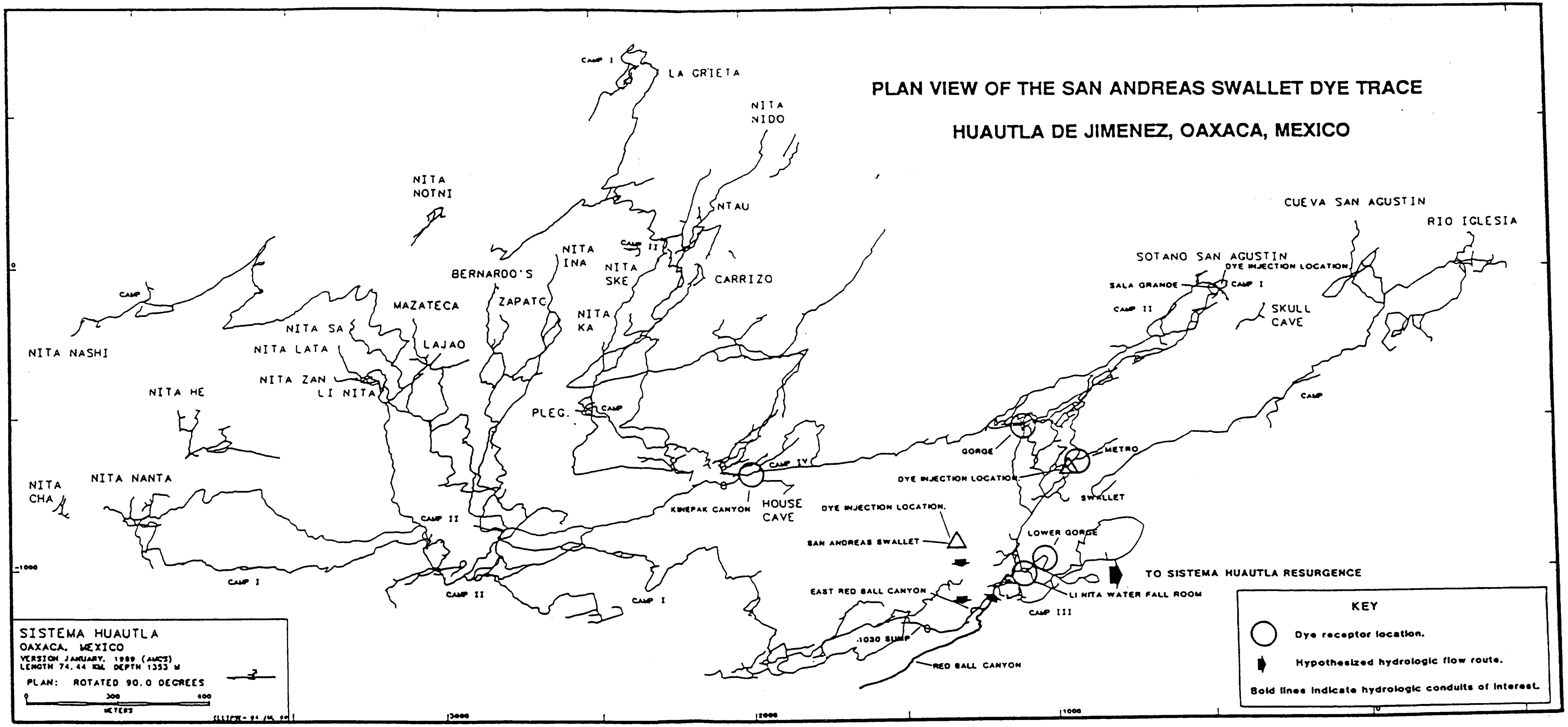
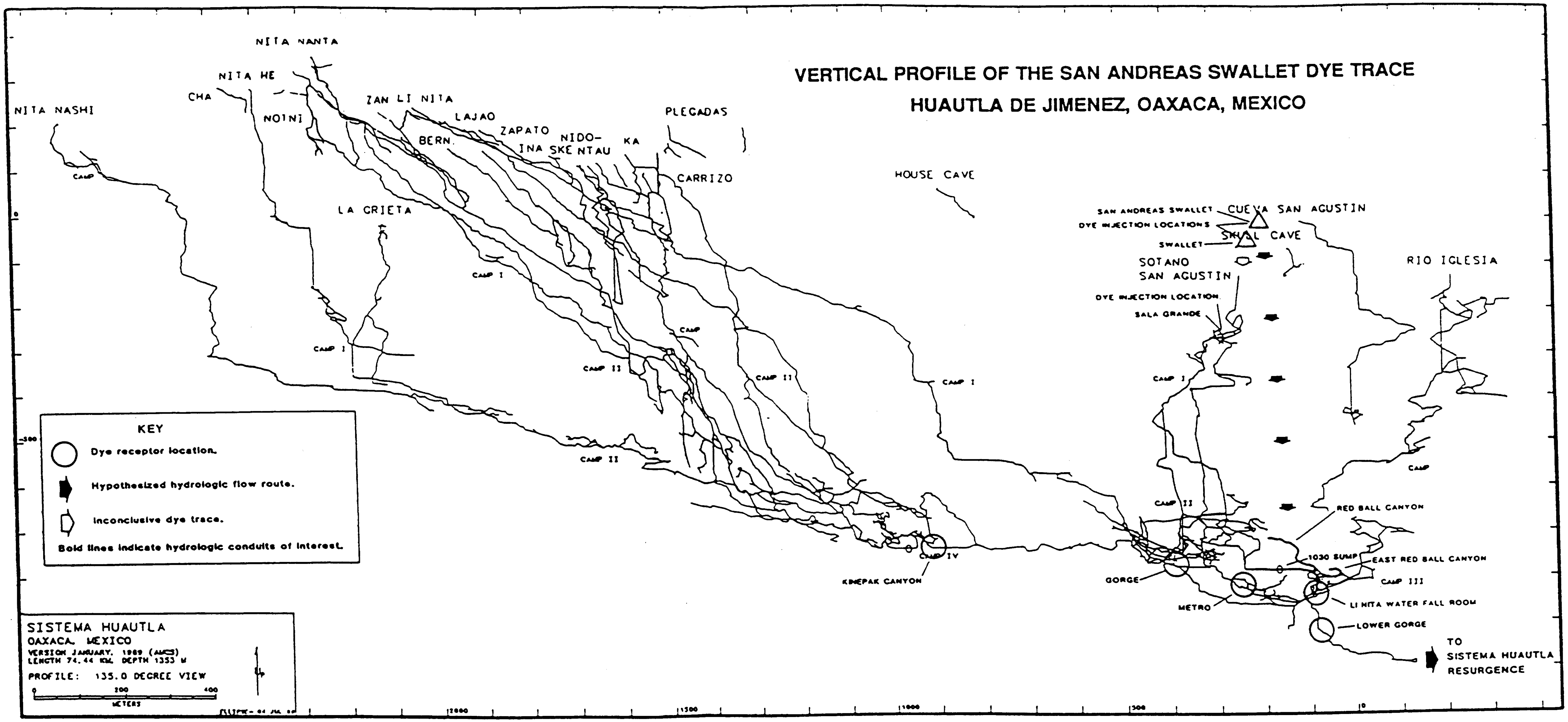

PLAN VIEW OF THE SAN ANDREAS SWALLET DYE TRACE
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
LA GRIETA
CAMP I
NITA NIDO
NITA NOTNI
NTAU
CARRIZO
NITA INA
NITA SKE
NITA KA
BERNARDO'S
ZAPATC
MAZATECA
NITA SA
NITA LATA
LAJAO
NITA ZAN
LI NITA
PLEG.
CAMP
NITA NASHI
NITA HE
NITA NANTA
NITA CHA
CAMP II
CAMP I
KINEPAK CANYON
HOUSE CAVE
CAMP IV
DYE INJECTION LOCATION.
SAN ANDREAS SWALLET
EAST RED BALL CANYON
1030 SUMP
RED BALL CANYON
CAMP III
LI NITA WATER FALL ROOM
LOWER GORGE
TO SISTEMA HUAUTLA RESURGENCE
GORGE
DYE INJECTION LOCATION
METRO
SWALLET
CUEVA SAN AGUSTIN
RIO IGLESIA
SOTANO SAN AGUSTIN
DYE INJECTION LOCATION
SALA GRANDE
CAMP I
CAMP II
SKULL CAVE
KEY
Dye receptor location.
Hypothesized hydrologic flow route.
Bold lines indicate hydrologic conduits of interest.
SISTEMA HUAUTLA
OAXACA, MEXICO
VERSION JANUARY, 1989 (AMCS)
LENGTH 74.44 KM. DEPTH 1353 M
PLAN: ROTATED 90.0 DEGREES
0 300 600
METERS


Figure 6.9



VERTICAL PROFILE OF THE SAN ANDREAS SWALLET DYE TRACE
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
NITA NANTA
NITA HE
CHA
NITA NASHI
NOINI
ZAN LI NITA
LAJAO
ZAPATO
BERN.
INA
NIDO-
SKE NTAU
KA
PLECADAS
CARRIZO
HOUSE CAVE
LA CRIETA
SAN ANDREAS SWALLET
DYE INJECTION LOCATIONS
CUEVA SAN AGUSTIN
SWALLET
SKIAL CAVE
SOTANO
SAN AGUSTIN
DYE INJECTION LOCATION
SALA GRANDE
RIO IGLESIA
CAMP I
CAMP II
CAMP III
CAMP IV
RED BALL CANYON
1030 SUMP
EAST RED BALL CANYON
GORGE
METRO
LI NITA WATER FALL ROOM
LOWER GORGE
KNEPAK CANYON
TO
SISTEMA HUAUTLA
RESURGENCE
KEY
Dye receptor location.
Hypothesized hydrologic flow route.
Inconclusive dye trace.
Bold lines indicate hydrologic conduits of interest.
SISTEMA HUAUTLA
OAXACA MEXICO
VERSION JANUARY, 1989 (AMCS)
LENGTH 74.44 KM. DEPTH 1353 M
PROFILE: 135.0 DECREE VIEW
0
200
400
METERS



Figure 6.10

The cave Li Nita is located in the northernmost section of the aquifer, compared to the San Andrés Swallet, which is situated west of Li Nita. Conduit development in Li Nita is controlled by strike and dip relationships and less by the influence of faults. The Li Nita stream passage trends southwest along the strike and crosses many small faults. Eventually, the cave stream is captured by faults and flows down shafts at –500 meters. At this level the drainage profile steepens. Those caves with steep drainage profiles tend to be steeper than the dip of the beds. However, that is not the case where the strata is vertical. It may be that conduit development at the western extremes of the karst groundwater basin is located closer to the overturned axis of the synclinal fold hypothesized to exist. Conduits have a less steep profile following the strike in a generally down-dip direction. Li Nita follows this example.

The dye trace of the San Andrés Swallet reveals the complexity of the western section of the aquifer and redefines the hydrologic schematic of the aquifer. It indicates that there is conduit development under the cap rock of overthrusted Jurassic flyschs. There is most likely a labyrinth of conduits present under the cap rock due to the many sink points along the sandstone-limestone contact.

#### 6.2.2.3 Influent Stream Swallet #2

The previous section described the largest sinking stream in the San Agustín Dolina. This section will describe the second largest sinking stream in the dolina, Influent Stream Swallet #2. The sinking stream is located on the western side of the San Agustín Dolina and discharges from a spring that originates in the Jurassic flysch cap rock (Figure 6.9). The stream sinks 400 meters from its spring at 1560 meters elevation. At sink point, the stream had a discharge of 0.018 $m^3$/sec, but it lost most of its volume before finally sinking. It was hypothesized that the sinking stream at Influent Stream Swallet #2 connected with the Li Nita Waterfall Room, as did Influent Stream Swallet #1. The hypothesis was tested by injecting 2.2 kilograms of optical brightener into the stream sink. Unfortunately the optical brightener dye was never recovered. Therefore, another trace will be necessary if this hypothesis is to be properly tested.

## 6.3 Dye-Tracing Other Tributary Cave Streams into Sistema Huautla

Sistema Huautla consists of 55.9 kilometers of conduits and shafts accessible through seventeen entrances. Most of these entrances represent access points for separate tributary streams that eventually unite at base level 800 to 1,100 meters below the entrance. These separate stream systems usually have many small tributaries and trickle inputs, as seen during low flow conditions. Each tributary defines an individual sub-drainage basin. All known tributary streams have been followed physically and surveyed to present a quantitative model of the aquifer. The survey also includes many individual caves that have been explored, but not connected because constrictions of the conduit or shaft did not permit further physical exploration.

It is the purpose of this section to determine the groundwater flow from these individual cave streams to stream inputs within Sistema Huautla (Figure 6.11). The significant caves that have not been physically connected to Sistema Huautla are Nita He, Nita Nashi, Sótano de Agua de Carrizo, Nita Ka, Nita Nido and Ntau, and Cueva de San Agustín.

Nita He and Nita Nashi were subjected to dye traces. The others are discussed in this section with respect to hydrology.

### 6.3.1 Nita He

Nita He is a vertical drainage system consisting of shafts and conduits that have a depth of 594 meters and a length of 1,554 meters (Figure 6.12). It is located between Li Nita and Nita Nanta in the community of Plan Arena at an altitude of 1960 meters (Figure 1.6). The elevation of the Nita He entrance is one of the highest in the karst groundwater basin, second only to the ridge entrances of Nita Nanta, located at an elevation of 2060 meters.

Nita He is located in an area with numerous cave entrances, some of which are entrances to Sistema Huautla. When the cave is viewed with respect to other cave conduits on a computer-generated line plot of the system, it is seen as unconnected with Sistema Huautla (Figure 6.11). The cave has the steepest profile of any cave in the area, with its vertical extent having developed along faults and steeply dipping bedding with dips from vertical to 25 degrees (G. Atkinson, 1980a). At the lowest level of Nita He, it

**Table 6.5.** Nite He Dye Trace

| Result | Dye receptor locations |
|---|---|
| – | ED Survey |
| + | Camp IV |
| – | Metro |
| + | Upper Gorge |
| – | Lower Gorge #1 |
| + | Lower Gorge #2 |
| – | Nanta Gorge |

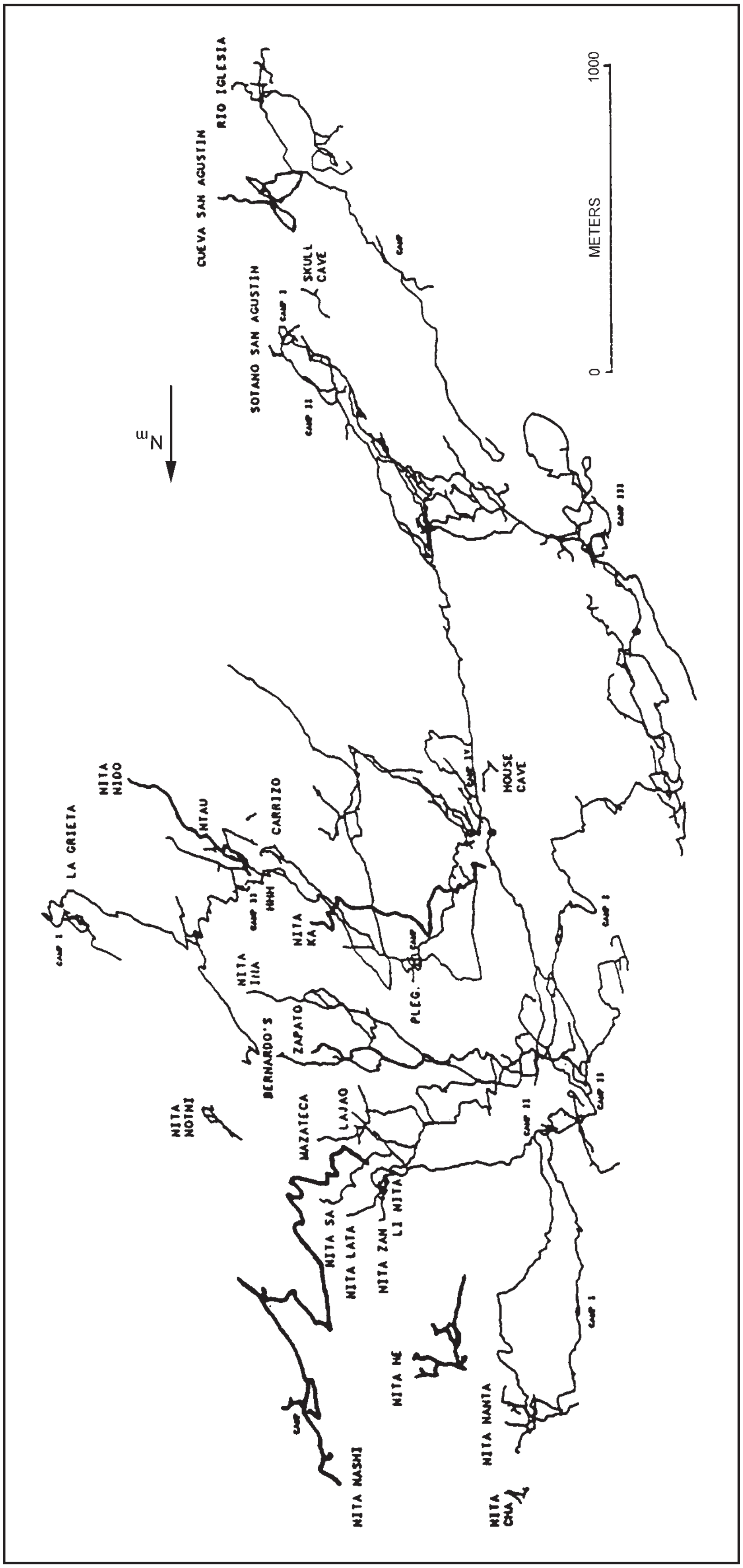



**Figure 6.11.** Caves not physically connected to Sistema Huautla. Bold lines are caves subject to dye traces.

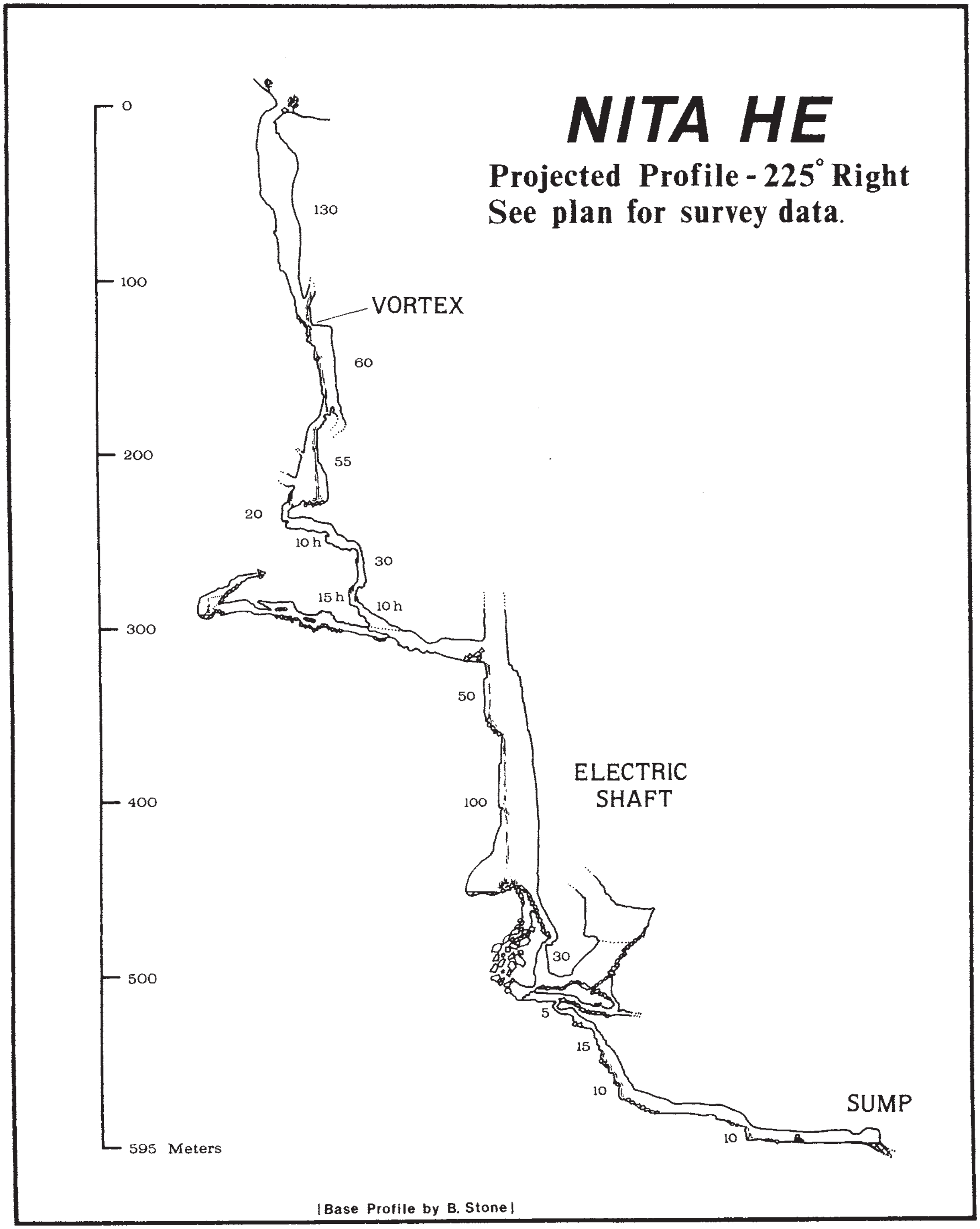



**Figure 6.12.** Source: G. Atkinson 1983.

was observed that conduit development is on top of a shale layer assumed to be the base level from Nita Nanta to Tommy's Borehole in Sótano de San Agustín. It was hypothesized that the north-south passage orientation supplied conduit drainage to Sistema Huautla's Nita Nanta at the ED Survey confluence (Figure 6.13). To test this hypothesis, 0.9 kilogram of fluorescein dye was introduced into the cave stream and charcoal receptors were stationed at stream confluences in Sistema Huautla to receive the dye (Table 6.5).

6.3.2 Discussion

Dye receptors at Camp IV, Upper Gorge, and Lower Gorge tested positive for fluorescein dye injected at the entrance of Nita He (Figure 6.14). The hypothesis that the ED Survey confluence was a part the hydrology of Nita He was rejected because Nita He's stream flowed to the Camp IV dye receptor through the Scorpion Sump (Figure 6.15). Scorpion Sump at 700 meters elevation above sea level and at –640 meters via the Sótano de San Agustín entrance is the junction for numerous conduit streams. The significance of the dye trace from Nita He to Scorpion Sump is as follows: Nita He is a separate conduit drainage. The drainage system has 1,100 meters of vertical relief before joining with the main hydrologic conduit. It is a separate subdrainage basin. It is a vertical drainage system developed within the complex anisotropic framework of local structure (i.e., strike and fault controlled). It may represent strike-controlled conduit development. It is an example of lithologic base-level control of conduit development on a shale confining layer. The ultimate hydraulic gradient is controlled by the dip of the shales.

6.3.3 Nita Nashi

The northernmost significant vertical drainage system known to exist in the Sistema Huautla Karst Groundwater Basin is Nita Nashi, located at an approximate elevation of 1920 meters. The cave is located in Plan de Escoba, north of the ridge in which Nita Nanta, highest and northernmost entrance to Sistema Huautla is located, (Figure 1.6). The cave is 640 meters deep and 3,523 meters long. The explored terminus of Nita Nashi is 570 meters (map distance) from the ED Survey stream confluence of Nita Nanta, 740 meters from the confluence of the Nanta Gorge stream, and 1,150 meters (straight line map distance) from the Scorpion Sump near Camp IV of Sótano de San Agustín.

It was hypothesized that the stream of Nita Nashi is tributary to the ED Survey (Figure 6.13). To test the hypothesis, 4.5 kilograms of Direct Yellow 96 dye were introduced into Nita Nashi's cave stream, and unbleached cotton dye receptors were placed at some tributary streams within Sistema Huautla (Table 6.6).

**Table 6.6.** Nita Nashi Dye Trace

| Result | Dye receptor locations |
|---|---|
| – | Nanta Gorge |
| – | ED Survey |
| + | Camp IV |
| + | Upper Gorge |
| – | Lower Gorge #1 |
| + | Lower Gorge #2 |
| – | Metro |

6.3.4 Discussion

The hypothesis stating that Nita Nashi's stream is tributary to the ED Survey confluence was rejected based on a positive dye trace to the Camp IV cotton dye receptor (Figure 6.14 and Figure 6.15). The significance of this dye trace is as follows: It extends the northern limit of the karst groundwater basin. It proves the location of tributary input into the system. It defines a separate tributary route with a vertical extent of at least 1,100 meters before connecting to the Scorpion Sump. It defines a separate subdrainage basin.

## 6.4 Dye Traces of Stream Sinks within Sistema Huautla

Despite the exploration of many cave passages within the labyrinth of Sistema Huautla, it has not been possible to follow all streams; thus many questions remain as to their relationship to the hydrologic pattern of the karst groundwater basin. The disappearing streams in question are the Nita Zan stream, which disappears into breakdown in the Football Stadium of Nita Nanta, Sótano de San Agustín's stream from the Fissure Route, which disappears at the –620 meters sump, and Sótano de San Agustín's main stream, which

**Table 6.7.** Nita Zan Dye Trace

| Result | Dye receptor locations |
|---|---|
| – | Nanta Gorge |
| + | ED Survey |
| + | Camp IV |
| – | Metro |
| + | Upper Gorge |
| – | Lower Gorge #1 |
| + | Lower Gorge #2 |

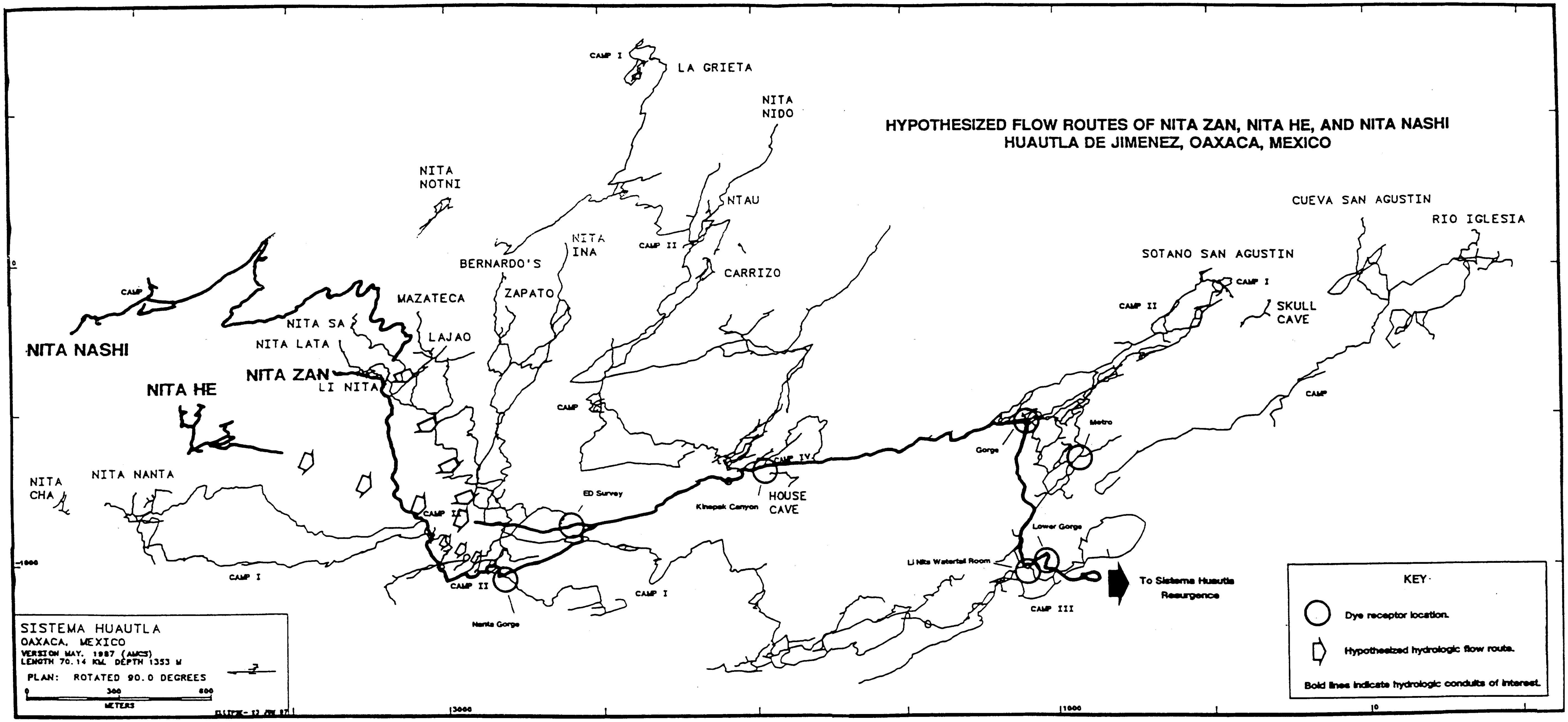

HYPOTHESIZED FLOW ROUTES OF NITA ZAN, NITA HE, AND NITA NASHI
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
LA GRIETA
NITA NIDO
NITA NOTNI
NTAU
NITA INA
BERNARDO'S
ZAPATO
CARRIZO
MAZATECA
NITA SA
NITA LATA
LAJAO
NITA NASHI
NITA ZAN
LI NITA
NITA HE
NITA NANTA
NITA CHA
ED Survey
Kinepak Canyon
HOUSE CAVE
Nanta Gorge
CUEVA SAN AGUSTIN
RIO IGLESIA
SOTANO SAN AGUSTIN
SKULL CAVE
Gorge
Metro
Lower Gorge
Li Nita Waterfall Room
To Sistema Huautla Resurgence
KEY
Dye receptor location.
Hypothesized hydrologic flow route.
Bold lines indicate hydrologic conduits of interest.
SISTEMA HUAUTLA
OAXACA, MEXICO
VERSION MAY, 1987 (AMCS)
LENGTH 70.14 KM DEPTH 1353 M
PLAN: ROTATED 90.0 DEGREES
METERS


Figure 6.13

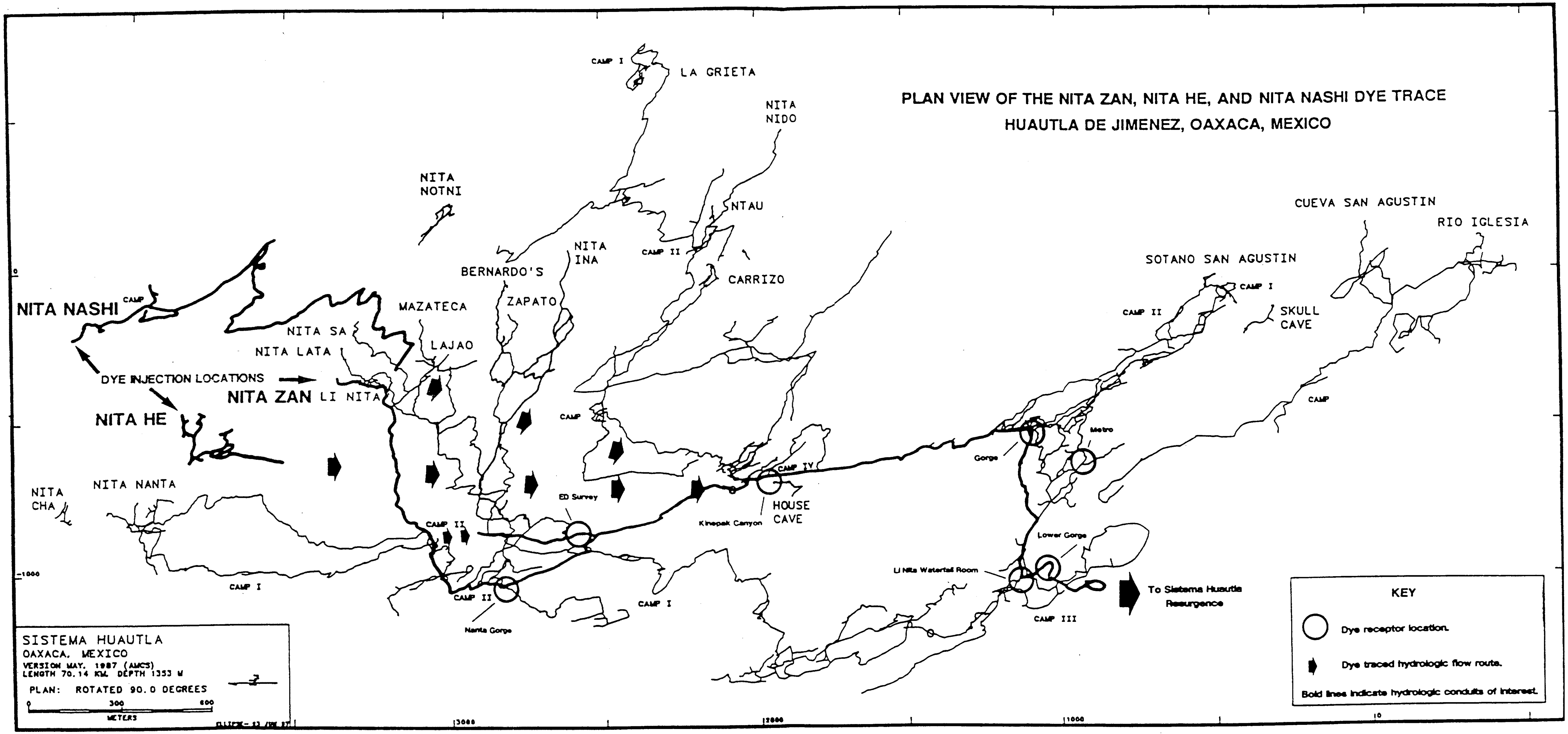
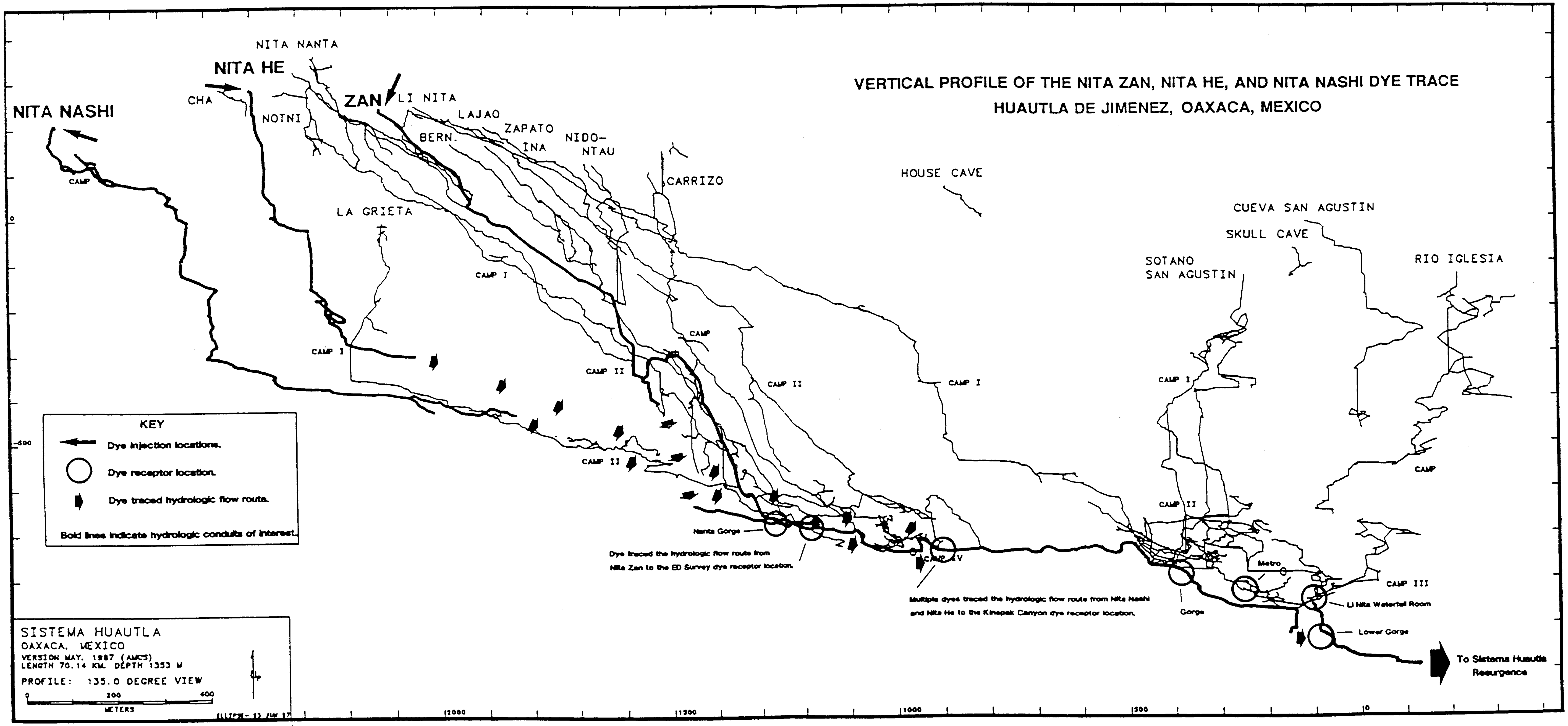

PLAN VIEW OF THE NITA ZAN, NITA HE, AND NITA NASHI DYE TRACE
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
LA GRIETA
CAMP I
NITA NIDO
NITA NOTNI
NTAU
NITA INA
CAMP II
CARRIZO
BERNARDO'S
ZAPATO
MAZATECA
LAJAO
NITA NASHI
CAMP
NITA SA
NITA LATA
DYE INJECTION LOCATIONS
NITA ZAN
LI NITA
NITA HE
NITA NANTA
NITA CHA
CAMP I
CAMP II
Nanta Gorge
ED Survey
CAMP I
Kinepak Canyon
HOUSE CAVE
CAMP IV
CUEVA SAN AGUSTIN
RIO IGLESIA
SOTANO SAN AGUSTIN
CAMP I
CAMP II
SKULL CAVE
CAMP
Metro
Gorge
Lower Gorge
Li Nita Waterfall Room
CAMP III
To Sistema Huautla Resurgence
KEY
Dye receptor location.
Dye traced hydrologic flow route.
Bold lines indicate hydrologic conduits of interest.
SISTEMA HUAUTLA
OAXACA, MEXICO
VERSION MAY, 1987 (AMCS)
LENGTH 70.14 KM. DEPTH 1353 M
PLAN: ROTATED 90.0 DEGREES
0 300 600
METERS


Figure 6.14



VERTICAL PROFILE OF THE NITA ZAN, NITA HE, AND NITA NASHI DYE TRACE
HUAUTLA DE JIMENEZ, OAXACA, MEXICO
NITA NASHI
CHA
NITA HE
NITA NANTA
NOTNI
ZAN
LI NITA
LAJAO
BERN.
ZAPATO
INA
NIDO-
NTAU
CARRIZO
LA GRIETA
HOUSE CAVE
CUEVA SAN AGUSTIN
SKULL CAVE
SOTANO
SAN AGUSTIN
RIO IGLESIA
CAMP
CAMP I
CAMP II
CAMP III
KEY
Dye injection locations.
Dye receptor location.
Dye traced hydrologic flow route.
Bold lines indicate hydrologic conduits of interest.
Nanta Gorge
Dye traced the hydrologic flow route from
Nita Zan to the ED Survey dye receptor location.
Multiple dyes traced the hydrologic flow route from Nita Nashi
and Nita He to the Kinepak Canyon dye receptor location.
Gorge
Metro
Li Nita Waterfall Room
Lower Gorge
To Sistema Huautla
Resurgence
SISTEMA HUAUTLA
OAXACA, MEXICO
VERSION MAY, 1987 (AMCS)
LENGTH 70.14 KM DEPTH 1353 M
PROFILE: 135.0 DEGREE VIEW
0
200
400
METERS
-500
2000
1500
1000
500
0



Figure 6.15

disappears at –805 meters in a sump.

To determine the relationship of these streams to confluences within the system dye traces were conducted.

6.4.1 Nita Zan

Nita Zan is a vertical drainage route that connects into a tributary stream of Nita Sa after 650 meters, at –200 meters depth. The combined streams of Nita Zan and Nita Sa flow through steeply descending passages and shafts to Nita Nanta's Football Stadium at –586 meters. That is the juncture point for Nita Nanta's Naranja Passage cave stream as well as several waterfalls that originate from a height greater than 150 meters in the Football Stadium's roof. Nita Zan's water, as well as the other sources, sinks into the boulder floor of the Football Stadium. It was assumed that this water was the source of the Nanta Gorge confluence, which is the largest stream in Nita Nanta (Figure 6.13). Nita Nanta's lower stream passage is developed at base level on top of a shale confining layer. It serves as the main conduit through which tributaries of the Nita Nanta subdrainage basin drain. To test the hypothesis that Nita Zan's water drains to the Nanta Gorge, 4.5 kilograms of optical brightener dye were injected into Nita Zan's stream to be received by cotton dye receptors placed at various confluences throughout the system (Table 6.7).

6.4.2 Discussion

The hypothesis was rejected, as the ED Survey confluence tested positive (Figure 6.14 and Figure 6.15). The significance of this trace is as follows: It defines the location of the hydrologic input of streams from Nita Zan and the Naranja Passage into Nita Nanta's main stream. It indicates that the hydraulic gradient between the point of entry into the breakdown and output at the ED Survey is very steep, possibly vertical.

Defining the course of Nita Zan's stream and additional converging streams to the ED Survey Confluence is significant in that the stream's position is extrapolated three dimensionally from known inputs and is recognized as a flow route comprising many inputs from many smaller subdrainage basins.

6.4.3 Sótano de San Agustín Fissure Dye Trace

Sótano de San Agustín is a complex vertical stream cave with several shaft series that converge to Tommy's Borehole level at –600 meters. The active hydrologic route occurs in the Fissure Series which consists of 350 meters of vertical shafts. The stream that falls down these shafts eventually sumps at –620 meters. It was hypothesized that the water at the sump flows to the Upper Gorge. To test this hypothesis, one liter of rhodamine WT dye was injected into a stream in the Sala Grande. The dye was never recovered at any dye receptor location. It is possible that there is another independent stream route draining the sump that bypassed all dye receptors. The dye trace is therefore inconclusive.

**Table 6.8.** Dye Trace of the Metro Stream to the Lower Gorge

| Result | Dye receptor locations |
|---|---|
| – | Lower Gorge #1 |
| + | Lower Gorge #2 |

6.4.4 Dye Trace of Sótano de San Agustín's 805 Sump

Most of the known drainage of the Sistema Huautla Karst Groundwater Basin flows through Sótano de San Agustín. The northern portion of the basin contributes water from many conduit tributaries through the Scorpion Sump near Camp IV at –640 meters in Sótano de San Agustín. Additional tributaries at other locations along the flow route enter along its length in Sótano de San Agustín. Other flow routes enter at the Li Nita Waterfall Room, potentially bypassing the main drainage. It is believed that the water from the Li Nita Waterfall Room is tributary to the main hydrologic flow and reaches it by dropping into the Lower Gorge where it intersects a large stream.

It is hypothesized that the water of the main hydrologic flow route in the Metro, a large conduit at –760 meters that sumps at –805 meters, enters into the Lower Gorge as the main stream. To test this hypothesis half a kilogram of fluorescein dye was injected into the Metro stream. Dye receptors were located in the Lower Gorge (Table 6.8).

6.4.5 Discussion

The hypothesis was accepted since a dye receptor located at Lower Gorge #2 site tested positive (Figure 6.15). The significance of the dye trace is that it confirmed what was suspected, a connection between the 805 Sump and the Lower Gorge. The conduit between the input and output may be totally water-filled. The distance between the two known points is estimated from the cave survey to be 250 meters.

## 6.5 Tributary Stream Caves

Dye tracing of influent stream swallets, cave swallets, stream sinks within Sistema Huautla, and caves has defined complex relationships between input and output within the karst aquifer. Not all possibilities for additional dye traces were exhausted, but due

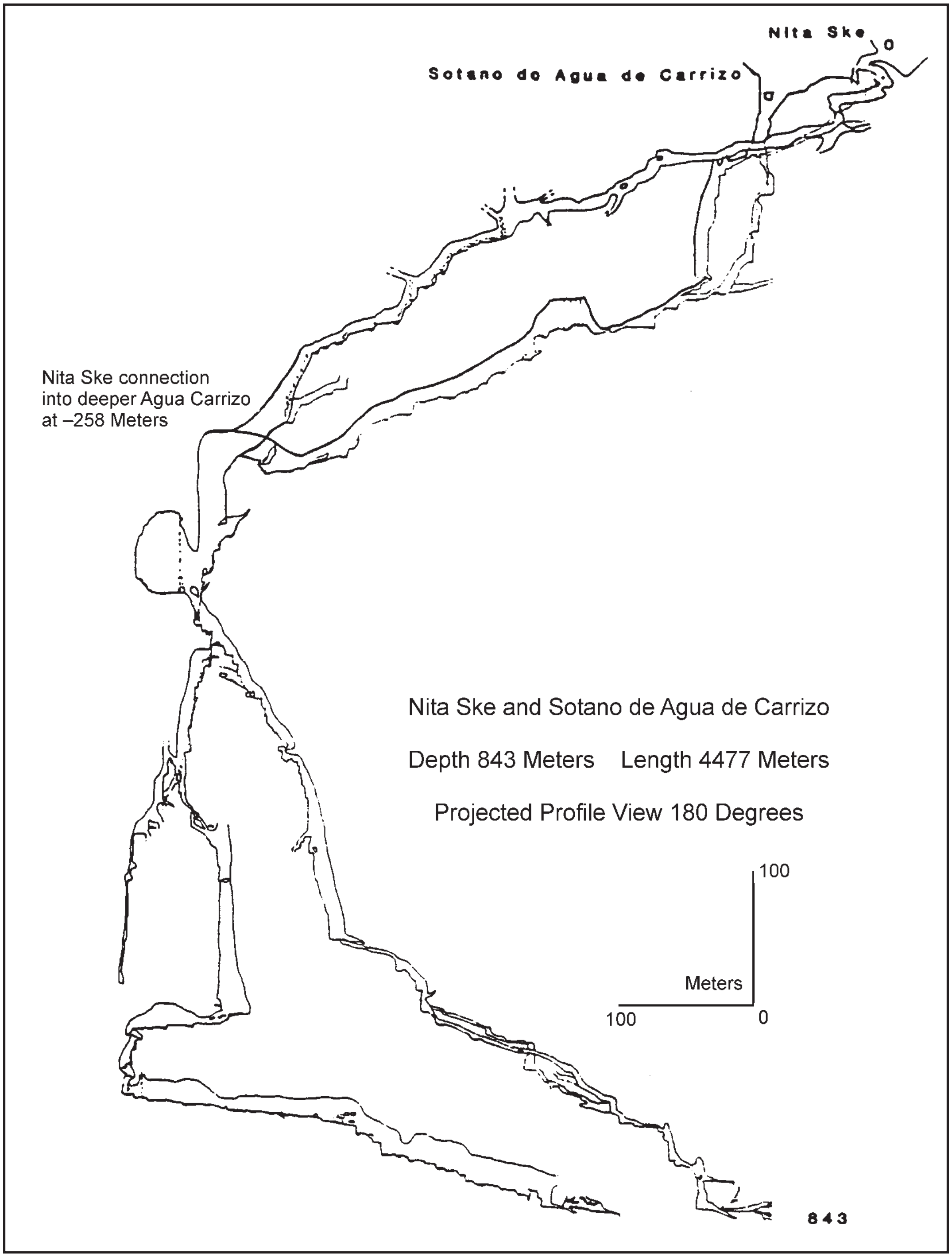



**Figure 6.16.** Sótano de Carrizo map based on Stone 1978. Nita She from Smith 1991c.

to time and logistics they were not feasible. There are a number of major caves that appear to be tributary drainage to Sistema Huautla. These caves will be briefly discussed with respect to hydrologic relationships to known tributaries within Sistema Huautla. These caves are Sótano de Agua de Carrizo, Cueva del Zapato, Nita Ka, Nita Nido and Nita Ntau, Cueva de Santa Cruz, and Cueva de San Agustín (Figure 1.6).

6.5.1 Sótano de Agua de Carrizo

The four entrances of Sótano de Agua de Carrizo, two of which are parallel shafts, are located between San Andrés Hidalgo and Nuevo Progreso on a ridge that separates the San Agustín Dolina from the La Grieta Dolina (Figure 1.6). The two highest entrances to Sótano de Agua de Carrizo are Nita Ske and Tarantula Cave (Figure 6.16). The caves from the two entrances eventually connect with Sótano de Agua de Carrizo at –235 meters as a tributary stream.

The main stream in the cave is joined by several smaller streams on their way to the base-level conduit at –800 meters. At –536 meters there is a bifurcation of the hydrologic flow, with separate shaft series terminating at –841 and –843 meters. The main stream follows the 841-meter route. The deepest point of the cave, at –843 meters, carries a small stream, but it is not the main stream of the cave that is followed from the entrance. Another parallel shaft series is encountered at –600 meters above the Sima Larga, a 130-meter-deep shaft, in the 841-meter route. It ends at –678 meters. The separate shaft series may have been formed by the same stream pirated down more permeable bedding planes or faults.

Carrizo's conduit development follows the basic trend of passage development seen throughout the Sistema Huautla Karst Groundwater Basin. Passage and shaft development follows a northwest-southeast strike of bedding planes and zigzags following a strike-dip-strike trend in steeply dipping rocks. The stream-gradient profile increases as shaft development occurs along a fault. Ultimately, conduit development changes direction and trends to the southeast to end within 60 meters of the Scorpion Sump. The Scorpion Sump is a major hydrologic junction between Sótano de Agua de Carrizo, La Grieta, Nita Ka, Nita Nashi, and Nita He. A dye trace was not necessary to establish the hydrologic connection to Sistema Huautla due to the close proximity of the surveys.

6.5.2 Cueva del Zapato

Cueva del Zapato is located near the community of Los Pinos (Figure 1.6). Cueva del Zapato is a 300 meter deep stream cave. This cave follows a northwest trend along the strike of the strata. It has not been completely explored, but enough survey has been accomplished to establish a trend and a potential location for connection into Sistema Huautla. It is possible that Cueva del Zapato will connect to Bernardo's Cave (Figure 6.11).

6.5.3 Nita Ka

Nita Ka is located near San Andrés at the north end of the karst groundwater basin in a ridge that separates the San Agustín Dolina from the La Grieta Dolina (Figure 1.6). Nita Ka is a 760-meter-deep cave formed predominately as a series of shafts down steeply dipping limestone (Figure 6.17). Some of the shafts are formed at intersecting normal faults that are parallel to the strike of the strata. The drainage pattern follows the same attitude as the overall drainage pattern of Sistema Huautla. The cave passages trend predominantly to the northwest, then to the southwest. The cave was not dye traced into the system because of its close proximity to Sistema Huautla (Figure 6.11). Nita Ka lies about 100 meters horizontally and 130 meters above the Scorpion Sump. It is hypothesized that the water from Nita Ka finds its way to the Scorpion Sump. The Scorpion Sump is the hydrologic confluence for many of the vertical drainage systems in the northeastern part of the karst groundwater basin.

6.5.4 Nita Nido and Nita Ntau

Nita Nido and Nita Ntau are located in the community of Nuevo Progreso, which is situated on the ridge that separates the San Agustín Dolina from the La Grieta Dolina (Figure 1.6). The streams from each of the two caves, Nita Nido and Nita Ntau, unite at the base of a 130-meter-deep shaft before the cave becomes impassable (Figure 6.18). The passages from the two entrances follow a northwest trend similar to the conduit development of the rest of the caves in the area to the northwest. It is interesting to note the alignment and overlap of passage trends with La Grieta, Carrizo, and Nita Ka, all of which have extensive vertical cave development (Figure 6.11). Each of these caves represents development at different elevations within the vertically extensive aquifer along the strike of steeply dipping beds. These conduits were probably formed at the same time. Although each of the two caves carries a small stream, no dye tracing was accomplished due to time constraints. It is hard to speculate a likely confluence for Nita Nido and Nita Ntau based on the limited amount of surveyed passage. If the cave continues to drop abruptly, then the confluence may be near Camp II in La Grieta. There is a dome complex with a waterfall entering the L Room of La Grieta. If the cave continues to follow

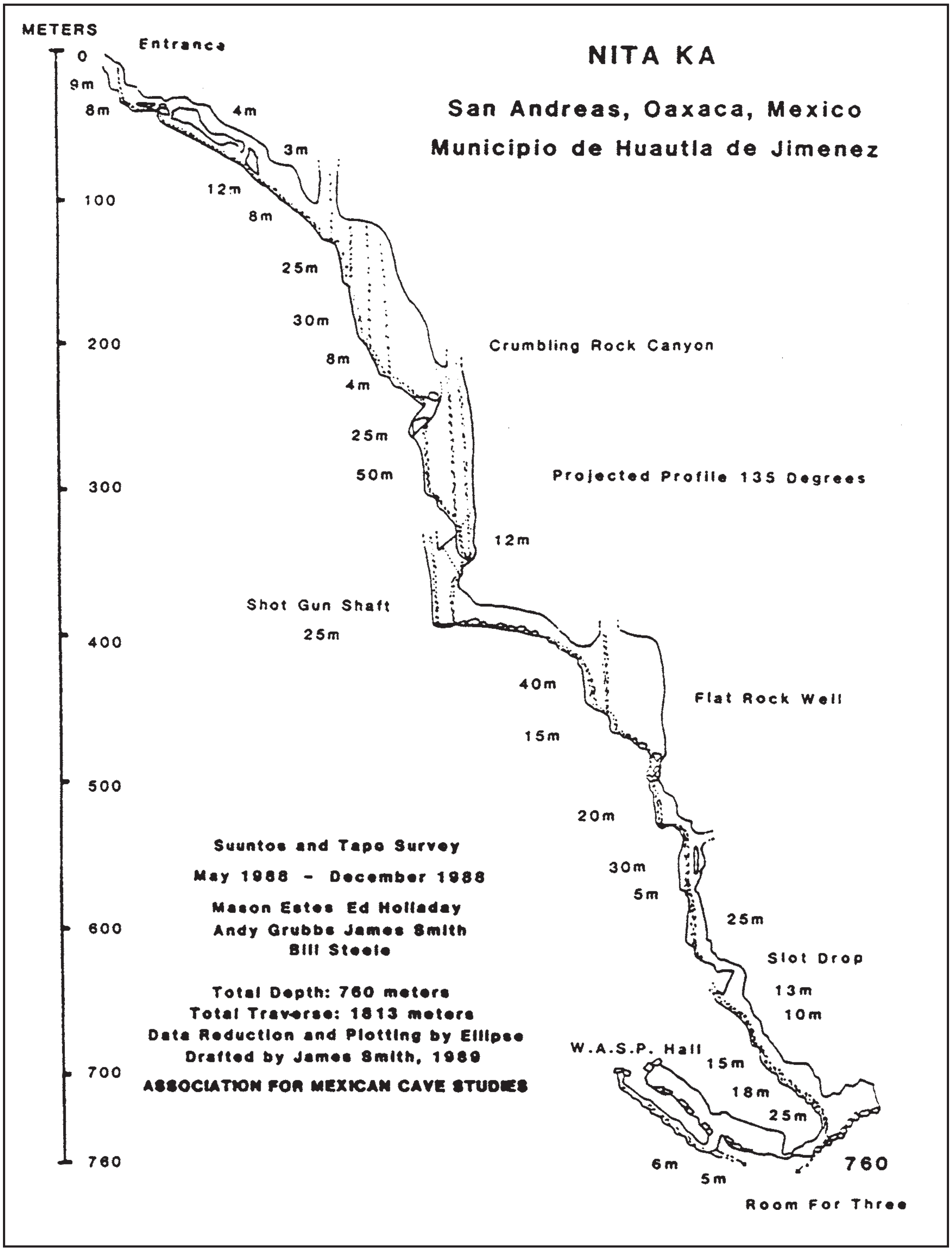



**Figure 6.17.** Source Smith 1991c.

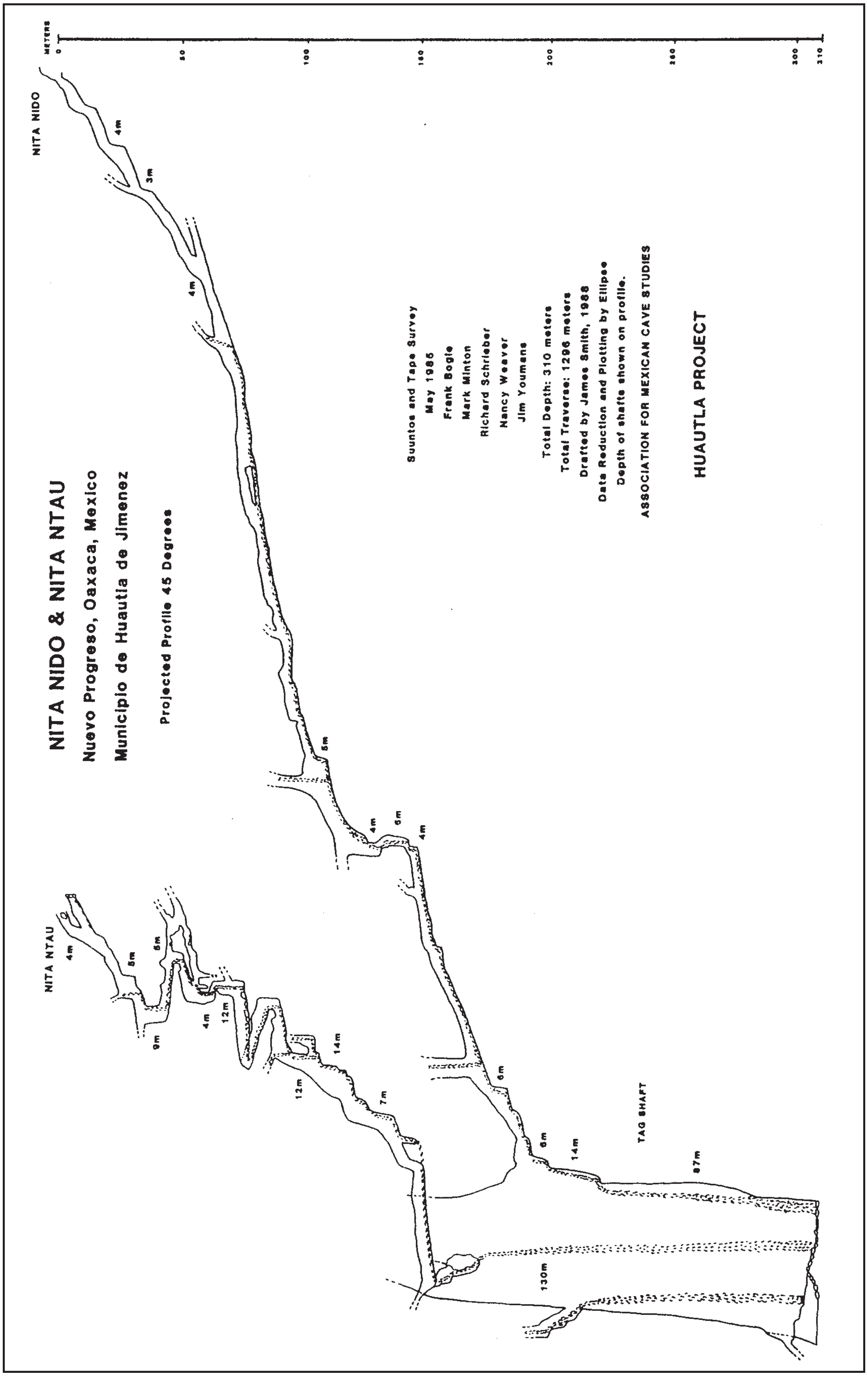

NITA NIDO & NITA NTAU
Nuevo Progreso, Oaxaca, Mexico
Municipio de Huautla de Jimenez
Projected Profile 45 Degrees
Suuntos and Tape Survey
May 1986
Frank Bogle
Mark Minton
Richard Schrieber
Nancy Weaver
Jim Youmans
Total Depth: 310 meters
Total Traverse: 1296 meters
Drafted by James Smith, 1988
Data Reduction and Plotting by Ellipse
Depth of shafts shown on profile.
ASSOCIATION FOR MEXICAN CAVE STUDIES
HUAUTLA PROJECT
NITA NIDO
NITA NTAU
TAG SHAFT
METERS
130m
87m

**Figure 6.18.**

the same trends to the northwest and then to the southeast, the water may enter into another area farther downstream within La Grieta or take its own independent course towards the main hydrologic route. However, it is believed that Nita Nido and Nita Ntau will connect into the Scorpion Sump but this hypothesis has not been tested.

### 6.5.5 Cueva de Santa Cruz

Cueva de Santa Cruz is located one kilometer northwest of San Andrés Hidalgo near Llano Viejo (Figure 1.6). Cueva de Santa Cruz is 312 meters deep and 1,443 meters long (Figure 6.19). It is noteworthy because it is the westernmost cave believed to lie within the Sistema Huautla Karst Groundwater Basin. Cueva de Santa Cruz is thought to drain into the karst groundwater basin because it lies within the structure the cave system is formed in. Passage orientation follows a north-south orientation subparallel to the strike of steeply dipping strata. Because the cave lies closer to the axis of the syncline, it is hypothesized that Cueva de Santa Cruz may bypass the drainage of Sótano de San Agustín and intersect the main conduit drainage of the karst groundwater basin. However, this hypothesis has not been tested.

### 6.5.6 Cueva de San Agustín

Cueva de San Agustín is located in San Agustín Zaragoza on the south rim of the San Agustín Dolina south of Sótano de San Agustín (Figure 1.6). Cueva de San Agustín is 875 meters long and 457 meters deep (Figure 6.20). The cave trends west to east in the down-dip direction along steeply dipping beds. The cave passage trends due east along near-vertical beds and encounters a normal-fault-controlled 109-meter-deep shaft that is oriented northwest-southeast. The cave is largely a paleostream conduit, as there is no stream flow down the shafts into Sala Doble. There are, however, two small streams that make a brief appearance in The Big Steps and in Sala Doble. It is unknown where these small streams enter into Sistema Huautla. It is hypothesized that Cueva de San Agustín water enters Sótano de San Agustín in the Tommy's Borehole stream or the Camp II shaft in the Fissure Route of Sótano de San Agustín. This hypothesis was not tested due to time constraints.

## 6.6 Conclusions

In Chapter 4, it was demonstrated by field mapping on the surface and in the subsurface that the regional structure largely controls the groundwater basin size and shape. The strike and dip of the strata and local structures such as folds and faults control the orientation of conduit development and the flow pattern within the aquifer. The following is an attempt to simply summarize the relation of the hydrologic flow patterns to the structure.

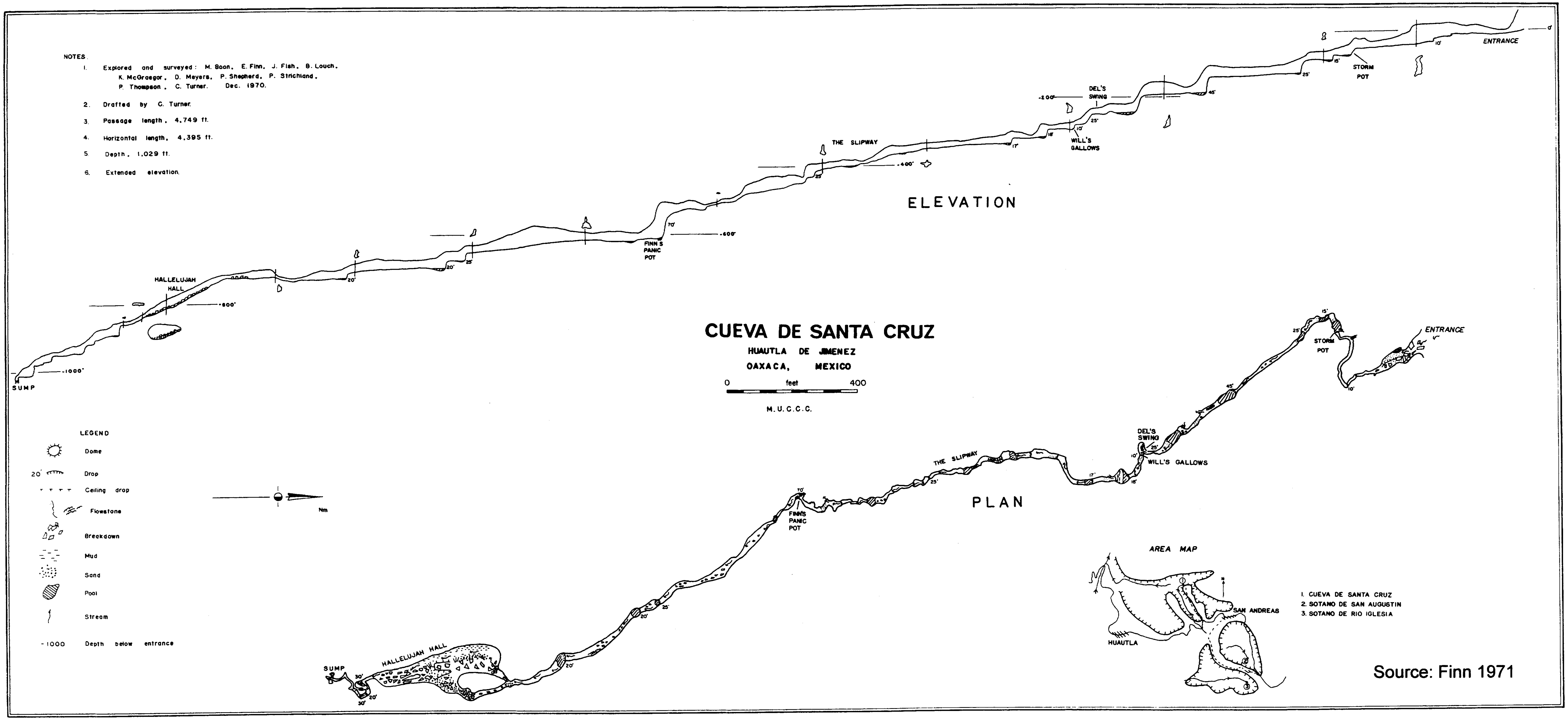
The Sistema Huautla Karst Groundwater Basin lies within the structurally highest portion of thrust-faulted strata. The dendritic vertical drainage system has formed on the east limb of thrust-faulted strata.

Conduits have formed principally along the strike of steeply dipping bedding planes, faults, and joints. Joints are, however, the least significant, due to the degree of deformation translating joints into faults. Consequently, most conduits have formed along the most permeable bedding planes. In the upper 300 to 500 vertical meters of the cave system, the limestone is thin-bedded and intercalated with bedded chert of the upper Orizaba Formation or the Maltrata Formation. Locally, chert provides a confining layer that prevents the hydraulic gradient from exceeding the structural gradient. Water may flow any direction along the plane if the right hydrologic conditions are met.

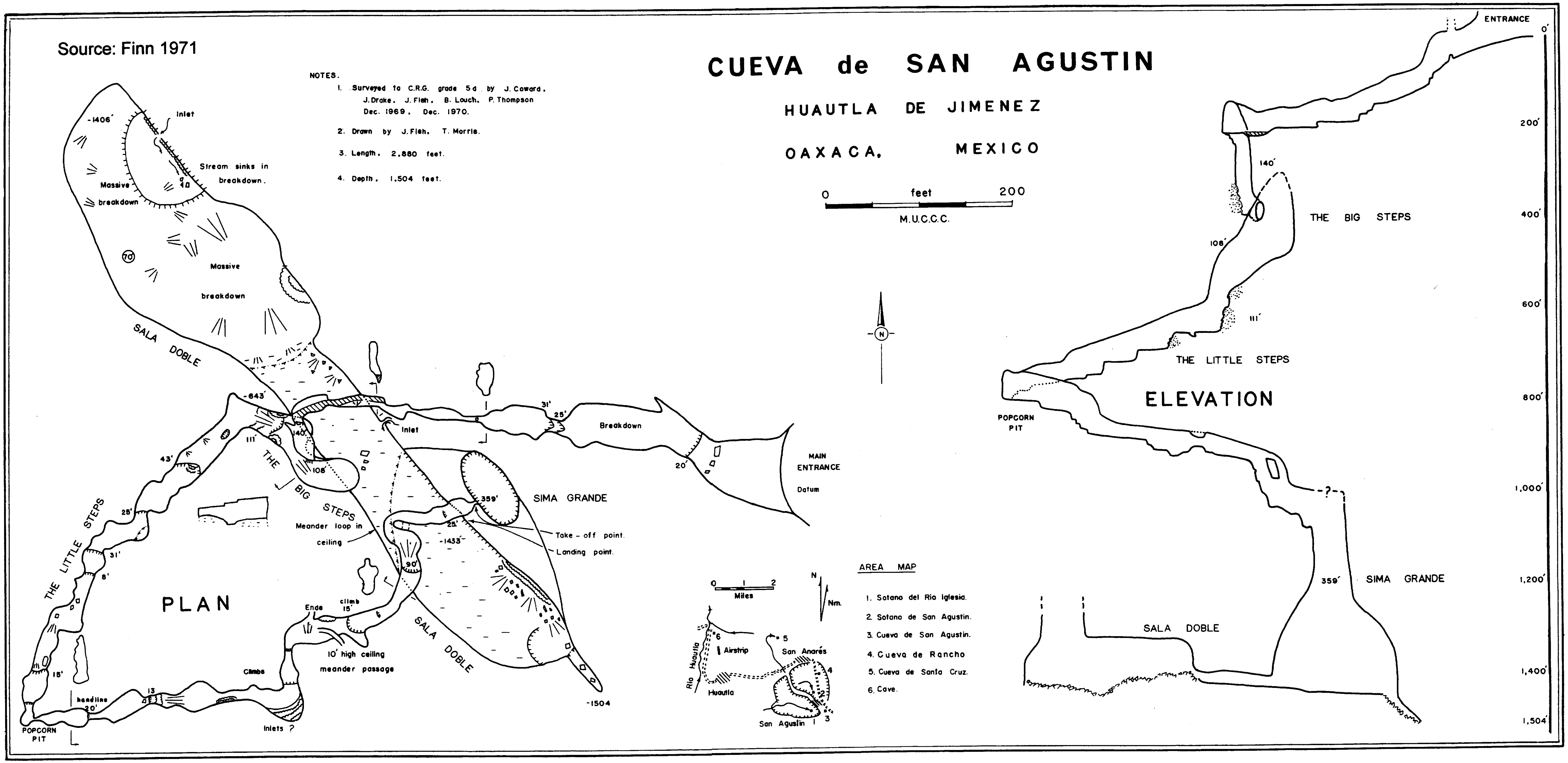
In the case of the conduits developed along inclined strata, they are formed oblique to the strike. The general trend of passage development is to the northwest and southeast in a zigzag pattern. This zigzag pattern occurs as the result of conduit development following the strike of steeply dipping strata (25 degrees to vertical). Water follows the strike and changes direction of flow when it intersects a fracture with sufficient permeability to influence the direction of solutional processes. The change in flow direction may also be attributed to folding.

When a normal or high-angle reverse fault is encountered, the hydraulic gradient may exceed the structural gradient by becoming vertical. However, as observed in the field, faults may seal themselves with calcite and a shaft may not form. If the seal is a leaky one, then the shaft may form until the seal is completely cemented and the water is pirated into a more permeable bedding plane or fracture. Generally, large shafts greater than 30 meters depth are formed along normal faults. A shaft series consisting of small shafts may also be fault-controlled. Many of the numerous shafts in the caves at the north end of Sistema Huautla have formed along steeply dipping beds of limestone intercalated with chert.

By definition, Sistema Huautla has a branchwork cave pattern (Palmer, 1991) where many separate streams converge into a central drainage conduit. The origin of the branchwork pattern of Sistema Huautla and tributary caves is related to the inclined strata and influenced by fracture patterns associated with the Sistema Huautla Fault.



CUEVA DE SANTA CRUZ
HUAUTLA DE JIMENEZ
OAXACA, MEXICO
0 feet 400
M.U.C.C.C.
NOTES.
1. Explored and surveyed: M. Boon, E. Finn, J. Fish, B. Louch, K. McGraegor, D. Meyers, P. Shepherd, P. Strichland, P. Thompson, C. Turner. Dec. 1970.
2. Drafted by C. Turner.
3. Passage length, 4,749 ft.
4. Horizontal length, 4,395 ft.
5. Depth, 1,029 ft.
6. Extended elevation.
ELEVATION
ENTRANCE
STORM POT
DEL'S SWING
WILL'S GALLOWS
THE SLIPWAY
FINN'S PANIC POT
HALLELUJAH HALL
SUMP
-200'
-400'
-600'
-800'
-1000'
PLAN
LEGEND
Dome
Drop
Ceiling drop
Flowstone
Breakdown
Mud
Sand
Pool
Stream
-1000 Depth below entrance
Nm
AREA MAP
1. CUEVA DE SANTA CRUZ
2. SOTANO DE SAN AUGUSTIN
3. SOTANO DE RIO IGLESIA
SAN ANDREAS
HUAUTLA
Source: Finn 1971


Source: Finn 1971
CUEVA de SAN AGUSTIN
HUAUTLA DE JIMENEZ
OAXACA, MEXICO
NOTES.
1. Surveyed to C.R.G. grade 5d by J. Coward, J. Drake, J. Fish, B. Louch, P. Thompson Dec. 1969, Dec. 1970.
2. Drawn by J. Fish, T. Morris.
3. Length, 2,880 feet.
4. Depth, 1,504 feet.
0 feet 200
M.U.C.C.C.
PLAN
ELEVATION
SALA DOBLE
THE BIG STEPS
THE LITTLE STEPS
SIMA GRANDE
POPCORN PIT
MAIN ENTRANCE
Datum
ENTRANCE
Massive breakdown
Stream sinks in breakdown.
Inlet
Breakdown
Take - off point.
Landing point.
Meander loop in ceiling
10' high ceiling meander passage
Inlets ?
handline
Climbs
Ends
climb 15'
AREA MAP
1. Sotano del Rio Iglesia.
2. Sotano de San Agustin.
3. Cueva de San Agustin.
4. Cueva de Rancho
5. Cueva de Santa Cruz.
6. Cave.
Miles
Airstrip
San Andrés
Huautla
Rio Huautla
San Agustin
-1406'
-643'
-1433'
-1504
0'
200'
400'
600'
800'
1,000'
1,200'
1,400'
1,504'

# CHAPTER 7

# GEOMORPHOLOGY AND SPELEOGENESIS OF THE SISTEMA HUAUTLA KARST GROUNDWATER BASIN

## 7.0 Introduction

In order to understand how the caves of the Sistema Huautla Basin developed, it is necessary to understand the geomorphic evolution of the karst groundwater basin. Integral to this understanding is the relationship of surface topography, surface drainage, and subsurface drainage systems in the Sierra Juárez. First, it is necessary to identify the relationship between regional tectonic forces and geomorphic processes that have shaped the present landscape. Evidence has been gathered across the region to reconstruct the neotectonics and subsequent geomorphic response to those changes. This evidence is based on studies in the adjacent Veracruz Basin and observations in the study area.

It is the purpose of this chapter to provide a timeframe for karst development in the Sierra Juárez and a model delineating the phases of Sistema Huautla's speleogenesis. The speleogenesis of Sistema Huautla is addressed from a conceptual viewpoint in an attempt to explain the position of conduits or cave levels and their association with the water table.

## 7.1 Geomorphic Evolution of the Sierra Juárez

From the end of the Laramide Orogeny to the present, the Sierra Juárez and Veracruz Basin have episodically uplifted, as indicated by unconformities and an influx of conglomerates to the Veracruz Basin. Helu et al. (1977) studied seismic profiles and cores from sediments in the Veracruz Basin near Tuxtepec, Veracruz, and found a regionally extensive unconformity in Lower Miocene sediments above which there are 1,000 meters of pebble conglomerates. These conglomerates are comprised of Jurassic and Cretaceous limestones and shales. Paleocurrent studies indicate that they are derived from source areas to the west (Figure 7.1).

The conglomerates were transported by fluvial tributaries that drained the emerging Sierra Juárez and intermountain basins. The fluvial systems ultimately deposited their loads into deep submarine canyons and formed prograding fanglomerates in the bathyal environment of the Veracruz Basin. These submarine fans and canyons are end members of the ancient Papaloapan fluvial system that was formed during the early Tertiary (Helu et al., 1977). The conglomerates are relic to the formation of the ancient Papaloapan Drainage Basin and all of its tributaries.

The modern Papaloapan drainage system consists of many large rivers, including the Río Blanco and Río Santo Domingo, that drain to the east to the Laguna de Alvarado on the Gulf Coast (Tamayo and West, 1964).

One of the large modern day tributaries of the Papaloapan Drainage Basin is the Río Santo Domingo. While the Río Santo Domingo probably began flowing from the emerging highlands during the Eocene and Paleocene, it was during the Late Oligocene and Early Miocene that the Río Santo Domingo began to dramatically shape the landscape of the Sierra Juárez, as indicated by the deposition of thick sequences of conglomerates in the Veracruz Basin. Most of the conglomerates identified near Tuxtepec were derived from the Río Santo Domingo as the river carved a 2,000-meter-deep canyon across the Sierra Juárez and transported bedload from intermountain basins. However, paleo-reconstruction of the submarine fans in the Veracruz Basin indicates that there were other parallel tributaries contributing fluvial material (Figure 7.1).

The relief of the Sierra Juárez must have been relatively subdued initially, with the rate of uplift being relatively gradual in the Late Oligocene. Formation of fluvial Oligocene and Early to Middle Miocene pebble conglomerates, consisting of Jurassic clastics and Cretaceous carbonates with a minor percentage of volcanics and metamorphics (Helu et al., 1977),

indicate that the Sierra Juárez began a major phase of erosion during the post–Laramide Orogeny uplift. Moreno (1980) referred to the uplift as a taphrogenic phase belonging to the Oligocene and Miocene. Regional uplift and/or marine regression occurred in the Early Miocene, as Late Oligocene sediments were eroded in the Veracruz Basin. Uplift rates must have dramatically increased in the Early and Middle Miocene, and erosion of the Sierra Juárez began in earnest, as indicated by the deposition of thick sequences of conglomerates.

The predominantly carbonate conglomerates during the Early and Middle Miocene were replaced by volcanic sands and gravels in the Late Miocene, as identified in seismic profiles and corings (Helu et al., 1977). The Late Miocene Filisola and Paraje Solo Formations are distributed across the Veracruz Basin and overlie Middle and Lower Miocene sediments. These formations consist of consolidated volcanic sands and gravels and conglomerates in a calcarious matrix (Ramos, 1983). A change in grain size from conglomerates to mostly sand-size particles indicates that the energy to transport conglomerates from highland areas was substantially reduced, signaling a time of tectonic quiescence. During the Late Miocene–Quaternary, uplift rates dramatically increased and produced widespread block faulting of the Sierra Juárez (Carfantan, 1981(b)).

A marine regression at the end of the Miocene is punctuated by an unconformity and by Quaternary alluviation. The shoreline of the Gulf of Mexico retreated to its present position at the end of the Pleistocene.

## 7.2 Paleo-Fluvial Evidence

Another indicator of an increase in uplift rates is the disappearance of some of the fluvial systems flowing across carbonate rocks. Researchers have reported evidence of paleo-fluvial features in many tropical areas of the world (Lehmann, 1936; Lasserre, 1954; Williams, 1971; Monroe, 1973 and 1974; Day, 1978; and Miller, 1981). Williams (1972) stated that in the polygon karst of New Guinea evidence of paleo-fluvial drainage systems is imprinted in the topography. Miller (1981) determined that the Caves Branch Karst of Belize contained paleo-fluvial karst features, but the influence of fluvial activity in developing the present landscape is uncertain. However, Miller's reconstruction of paleo-drainage lines from the polygonal karst provided indirect evidence of paleo-fluvial activity. Paleo-drainage patterns across the Sierra Juárez are not as difficult to interpret as those in the Searranx, Guatemala, and the Vaca Plateau, Belize, described by Miller (1981).

Analysis of linear features occurring across the Sierra Juárez in both carbonate and noncarbonate rocks indicates the presence of features interpreted to be fluvial remnants of the ancient Papaloapan Drainage Basin (Figure 7.2). The drainage pattern is dendritic,

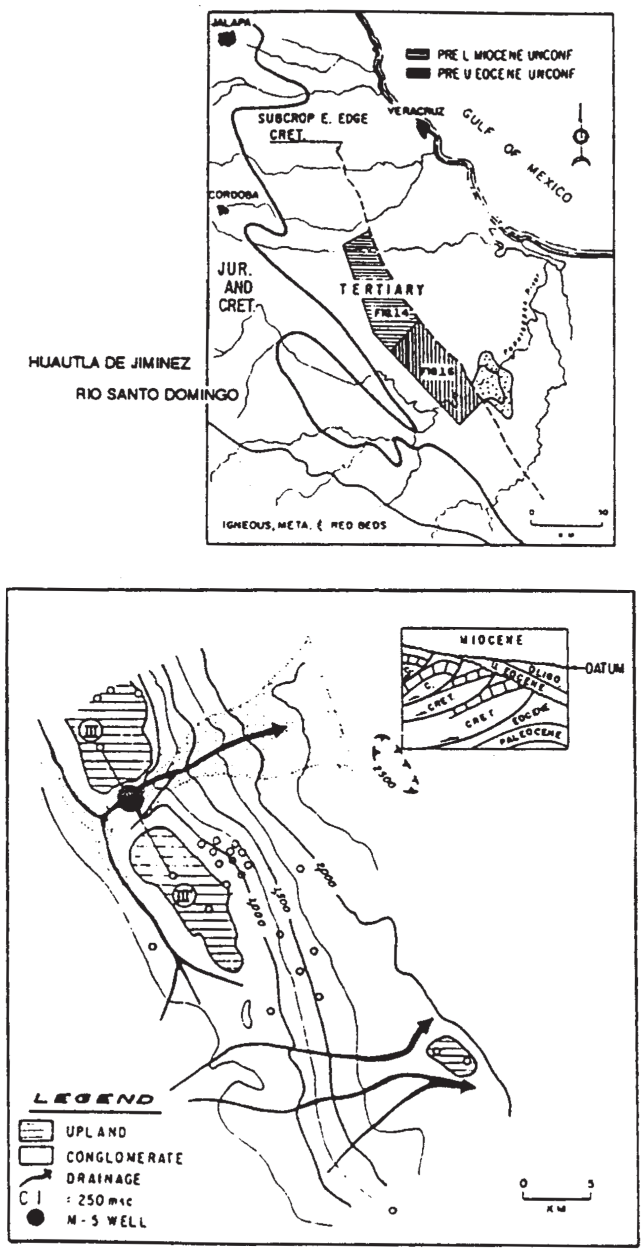



**Figure 7.1.** Top: Generalized map of Veracruz basin and adjacent area. Heavy black line indicates eastern limit of Mesozoic outcrops. Dashed line is eastern limit of Cretaceous sedimentary rocks in subsurface. Area in which unconformities were mapped seismically is shown by diagonal lines. Bottom: Seismic-structure map of pre–Early Miocene unconformity in part of western margin of Veracruz basis. Source: Helu, et al. 1977.

with an orientation from west to east. This relic drainage system will be referred to as the Tenango tributary of the ancient Papaloapan drainage system. The headwaters of the drainage system appear to have originated in the vicinity of the clastic cap rock near the San Agustín Dolina. The west-to-east drainage course ends at Cabeza de Tilpan in the foreland area of the Sierra Juárez. The ancient Tenango Fluvial System is a series of large linear sinkholes forming a long karst valley. The drainage system has numerous infeeding ephemeral tributaries.

A less extensive drainage system occurs from north to south from San Miguel to Río Santo Domingo via the Peña Colorada canyon. This modern drainage system is ephemeral and is active only during the wet season and after large rains. It is reasonable to assume that this drainage system was also active during the Miocene.

Relic fluvial features are probably Late Oligocene or Early Miocene and were active when the first conglomerates were deposited in the Veracruz Basin. The Tenango fluvial system flowing across limestones probably disappeared during a period of widespread erosion corresponding to the Lower Miocene unconformity. The unconformity indicates that there was regionally extensive uplift and erosion. As the mountain range uplifted, karst processes developed and the streams began to lose water into the underlying limestone aquifer. Although the present topography is the result of active corrosional processes, the drainage lines of a tributary of the ancient Papaloapan Drainage System are indelible on the topography of the area.

### 7.3 Karst Development

Miller (1981) postulated that the polygonal karsts of New Guinea, Guatemala, Puerto Rico, and Belize are suggestive of millions of years of exposure and denudation. Karst development in the emerging Sierra Juárez probably first occurred 27 million years ago during the Late Oligocene and Early Miocene. This estimate is based on the quantity of limestone conglomerate in the subsurface of today's foreland area of the Sierra Juárez and the associated paleo-fluvial expression. Karst processes and the first caves developed as many of the tributary systems flowing across the limestone disappeared.

Although karstification may have begun in the Sierra Juárez 27 million years ago, it occurred only in areas where carbonate rocks were exposed. Karstification was likely to have been in the eastern portion of the emerging mountain range. Caves are integral to the karstification processes in well developed karst terrains. It is unknown how old the caves are in the Sierra Juárez. Miller (1981) dated speleothems from cave passages in the Caves Branch Karst of Belize and determined that the base level passage was in an advanced stage of development 140–215 thousand years B.P. If uplift rates could be determined, then the difference between successive base levels could be used to estimate the age of the cave system. However, further work remains to be done in this area.

### 7.4 Allochthonous Clastic Cap Rock

The Laramide Orogeny marked the end of the Cretaceous with dynamic forces that compressed and folded the platform sediments of the Mexican miogeocline. During the Laramide Orogeny, Early Cretaceous schists (Carfantan, 1981(a)) and Jurassic shales were thrusted over Cretaceous carbonates from west to east (Echanove, 1963; Viniegra, 1965; Mossman and Viniegra, 1976; Moreno, 1980; Zenteno, 1984). The easterly extent of the overriding clastics and metamorphics is unclear in the Sierra Juárez, since the easternmost outliers in the study area are the western boundary of the karst groundwater basin.

It is also not known how thick the overriding plate was, but remnants of Jurassic formations indicate rock 300–500 meters thick. This estimate is based on measurements of intensely folded and eroded Jurassic rocks located on the westerly fringe of the Sistema Huautla Karst Groundwater Basin between San Jerónimo and Huautla de Jiménez (Echanove, 1963). It is postulated that the clastics were of considerable thickness and may have extended partially or completely across the Sistema Huautla Basin.

### 7.5 Retreat of Allochthonous Clastic Cap Rock

Karstification probably began in the Early Miocene in the front range of the Sierra Juárez, where carbonate rocks were exposed to erosion. As previously mentioned, there is a definite topographic expression of what is interpreted to be a fluvial overprint of the relic Papaloapan Drainage Basin across the Sierra Juárez as well as the study area. Based on topographic features, it is hypothesized that allochthonous clastics may have extended across the Sistema Huautla Karst Groundwater Basin from one to three kilometers (Figure 7.3). The present position of the clastic cap rock defines the western limit of the exposure of limestone outcrop and thus surficial karstification in the Sistema Huautla Karst Groundwater Basin. Echanove (1963) described rocks west of the Huautla–Santa Rosa Fault in the tributaries of the Río Petlapa as belonging to the Lower Cretaceous Tuxpanguillo Formation. The resistant rocks of the Tepexilotla Formation form

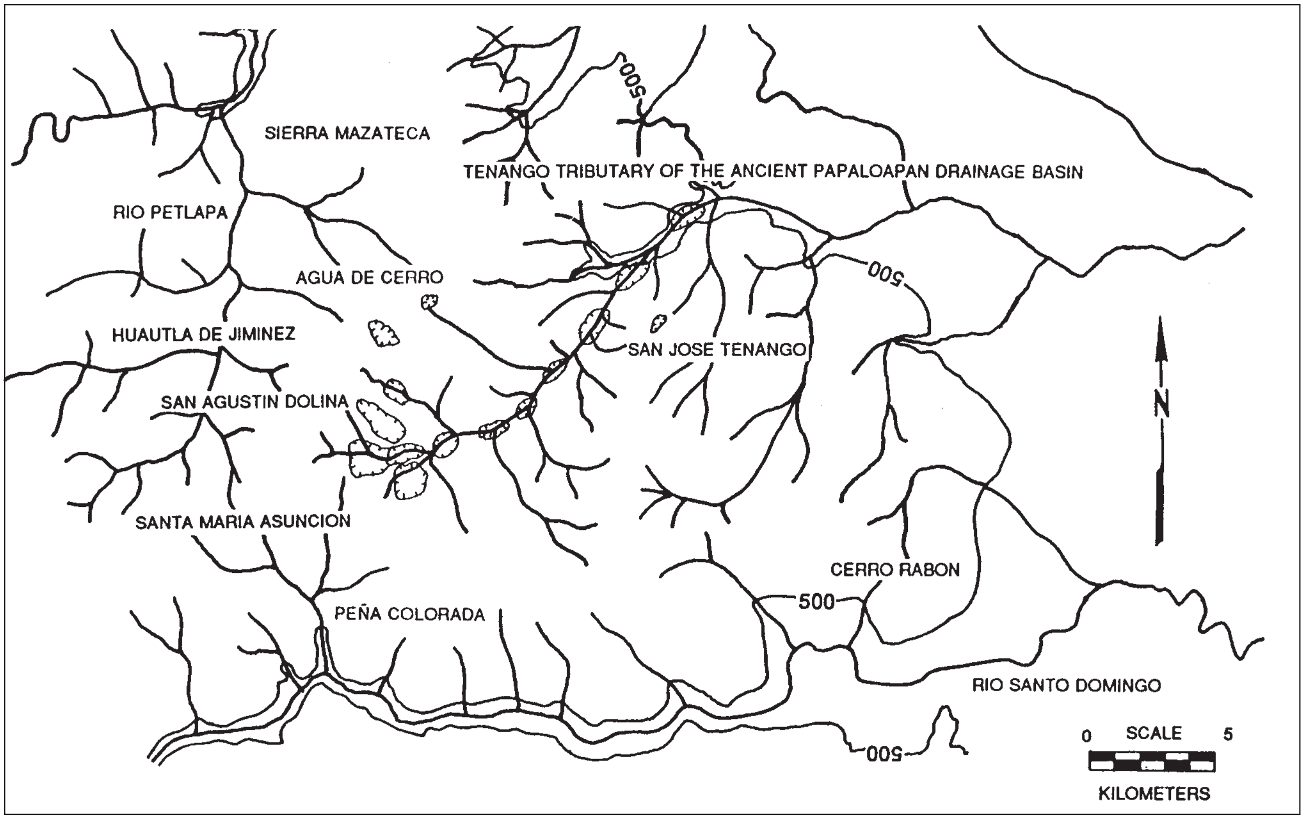



**Figure 7.2.** Fluvial drainage map of the Sierra Mezateca.

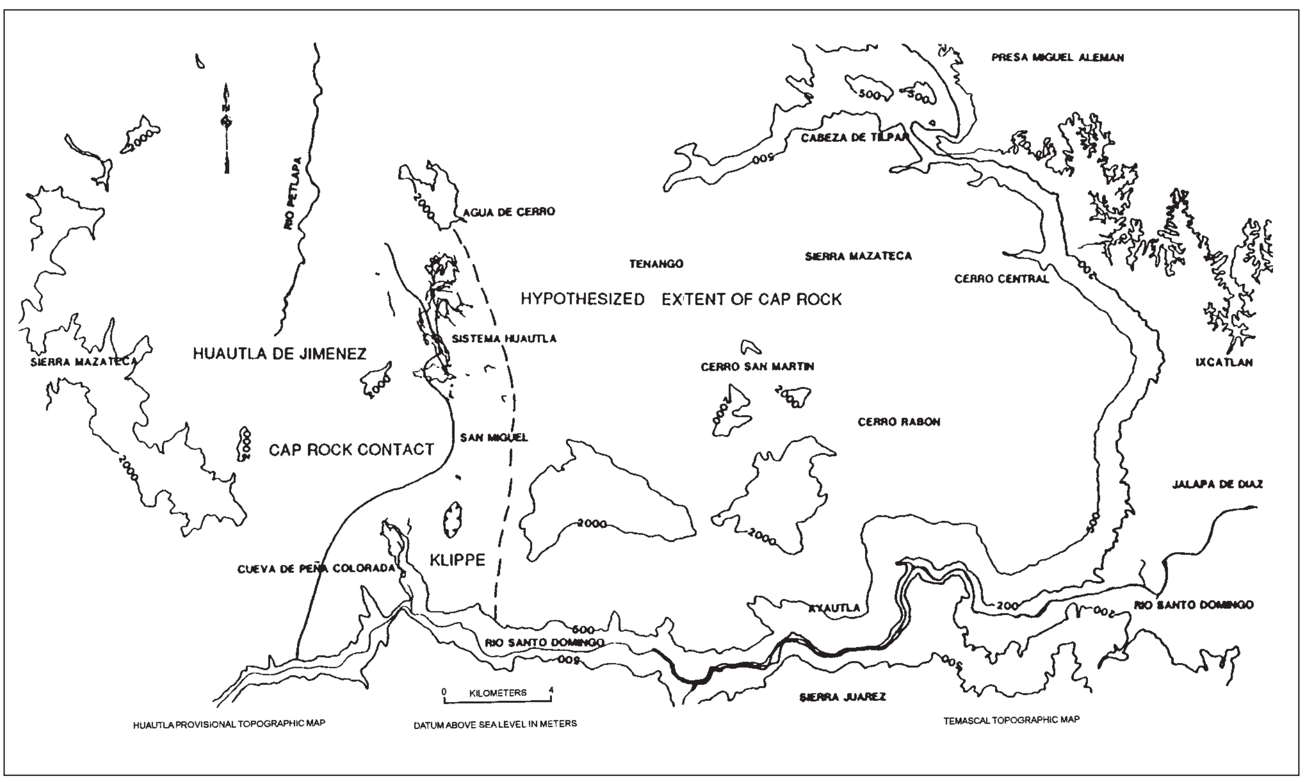



**Figure 7.3.** Hypothesized extent of the allochthonous clastic cap rock.

the cap rock and surface drainage divide between the Sistema Huautla Groundwater Basin and the Río Petlapa. Erosion through the thrust sheet by the Río Petlapa has exposed Lower Cretaceous limestones. Erosion is vertically dissecting and isolating fragments of the overthrust sheet. These outliers, or klippes, form the cap rock for many of the mountaintops on the west side of the karst groundwater basin. Where the cap rock is not isolated, it forms the western contact between limestones and shales.

In the western portion of the range, noncarbonate rocks retreated as surficial fluvial systems incised the cap rock. Surface streams flowing over shales and sandstones, like the one in the bottom of the Río Iglesia Dolina, sink at the edge of clastic cap rock (Plate 7.1). Springs discharging from the clastic cap-rock aquifer also sink at the edge of the clastic cap rock. Mass wasting of the clastic cap rock occurred by mechanical weathering, and the debris was deposited as colluvium and alluvium in the adjacent dolinas. An example of this occurs in the San Miguel Dolina, where the floor of the dolina is flat and the soils consist of mass wasted material from the clastic cap rock (Plate 7.2). Slope retreat along the cap rock and limestone valley wall is parallel to the hillslope (Hack, 1960).

Adjacent to the clastic cap rock, large dolinas have formed along the western boundary of carbonate rocks from the community of San Andrés to the south to San Miguel. These dolinas occur at an average elevation of 1600 meters.

Another large dolina has formed at an elevation of 1100 meters near Santa Catarina in the southern portion of the Sistema Huautla Karst Groundwater Basin. In this area, mixed carbonate and clastic rocks occur west and east of the Santa Catarina Dolina. On the east side, at 1320 meters elevation, the El Camarón Klippe, a remnant of the Huautla–Santa Rosa Fault, is the easternmost exposure of detached clastics in the southern portion of the basin. The klippe is no farther east than the noncarbonate rocks situated to the north along the western edge of the San Miguel Dolina. The overriding fault plane of the Huautla–Santa Rosa Fault, as seen in the El Camarón Klippe, is fairly low-angle (Figure 7.4). Erosional processes have carved a deep side canyon (Peña Colorada Canyon) through the thrust sheet into the underlying limestones. Limestone outcrops 2 kilometers west of the El Camarón Klippe on the other side of the Peña Colorada Canyon (Figure 3.5). The Huautla–Santa Rosa Fault in the El Camarón area has a low-angle fault plane. The low angle of the overthrust may have allowed the overriding thrust sheet to travel farther than would have a steeply inclined fault plane. This is indirect evidence that allochthonous rocks could have extended farther east than their present position.

Additional evidence for a more easterly extent of a clastic cap rock may be deduced from the size and width of dolinas and the location of cave entrances on the tops and sides of narrow ridges.

In the northern portion of the Sistema Huautla Karst Groundwater Basin, the San Agustín Dolina is one kilometer wide, with a long dimension of 2.5 kilometers (Plate 7.3). The axis of the dolina strikes north to south.

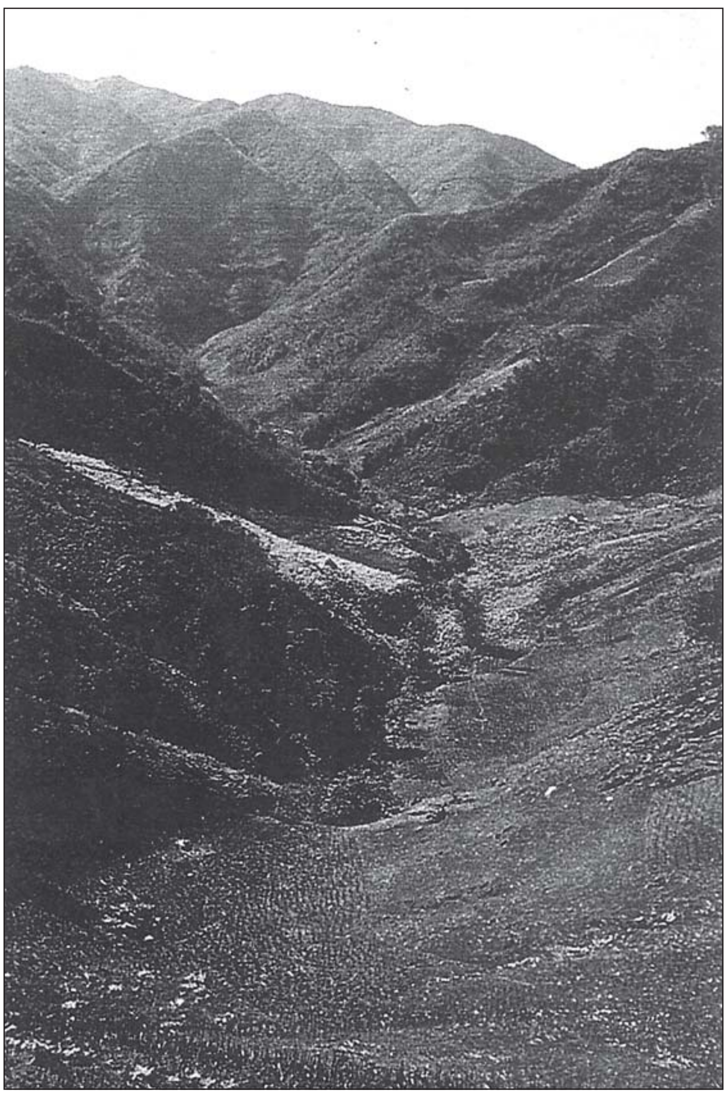


**Plate 7.1.** The Río Iglesia Dolina. The surface stream in the dolina originates from diffuse-flow springs dischanging from the Tepexilotla Formation. The surface stream is the largest in the Sistema Huautla Karst Groundwater Basin.

**Plate 7.2** (above). The San Miguel dolina is a composite of several dolinas that have amalgamated to form one large dolina. The dolina is recharged from small springs originating from the clastic cap rock.

**Plate 7.3** (below). Three springs discharge from the allochthonous clastic cap rock aquifer into the San Agustín dolina. The springs sink as influent swallets before they are able to sink into the entrance to Sótano de San Agustín.

The west side of the dolina is capped by noncarbonate rocks. The dolina is approximately 500 meters deep from the highest drainage divide.

The Río Iglesia Dolina has similar dimensions to the San Agustín Dolina, but it strikes west to east. Two thirds of the dolina is actually in noncarbonate rocks of the Tepexilotla Formation. The dolina is 600 meters deep from the drainage divide.

The San Miguel Dolina, almost 2 kilometers long and one kilometer wide, is oriented northeast to southwest and consists of several large dolinas that extend from La Providencia to San Miguel.

The size of the dolinas is attributed to aggressive dissolutional processes of allogenic recharge from springs and surface runoff originating from within and on top of the clastic cap rock aquifer. As the clastic cap rock aquifer retreated, the width of the dolinas increased by parallel slope retreat to the west. The width of the dolina may represent the eastern extent of the thrust sheet.

The depth of the dolinas may be attributed to dissolution of faulted carbonate rocks and the development of conduit systems that are able to transport mass-wasted material through the aquifer. If significant conduit systems were not present or if the conduits were choked by collapse, the floor of the dolina would accumulate sediments and fill up, forming a flat-floored llano.

Agriculture in the Sierra Mazateca has increased erosion of the slopes, and the influx of soil into the aquifer is occurring at a rate that exceeds the natural rate. Sótano del Río Iglesia is a prime example. At the end of the Penthouse Chamber, the large passage dimensions are reduced to a series of sand crawls choked with corn stalks and sediment. Occasionally, this passage becomes impassable.

Additional evidence for a more easterly extent of overthrust clastics beyond the eastern edge of the large dolinas Río Iglesia, San Agustín, and San Miguel may be deduced from the position of cave entrances relative to drainage catchment size. The caves Sótano de San Agustín and Sótano del Río Iglesia are located in enormous dolinas next to the clastic cap rock aquifer, and both have surface streams originating from springs in the clastic cap rock aquifer that sink into the entrance or along the stream bed before reaching the entrance. Both caves have the largest diameter passages in the Huautla area.

Caves located in the northern portion of the basin have entrances located in a variety of topographic settings, from the bottoms of large dolinas (La Grieta) to locations on the sides of narrow ridges (Nita Nanta). Generally, the passage sizes in the upper portions of the drainage systems of the caves located in the northeastern portion of the basin are much smaller than those located adjacent to the cap rock.

One could reason that caves and their entrances should not form on the sides of narrow ridges because their catchments are so small that they could not concentrate enough recharge to develop conduits or shafts. Hillslopes consisting of noncarbonate and carbonate rocks were measured across the basin, with slopes that ranged from 20 to 54 degrees. Williams (1971) found that dolina slopes averaged between 30 and 50 degrees in the polygonal karst of New Guinea. The entrance sinks to Nita Nanta's entrances are less than 10 meters across. Nita Nanta is the uppermost entrance to Sistema Huautla and 446 meters higher than the entrance to Sótano de San Agustín.

It is hypothesized that the entrance of Nita Nanta and cave entrances located on the side of the karst hills and steep sides of dolinas are indicators that there had to have been a more extensive catchment for the conduits to have evolved. The original catchments have been eroded away and, consequently, the cave entrances are relic geomorphological features and therefore older than the topography. The position of a cave entrance with respect to its location within a dolina catchment provides a clue to the evolution of

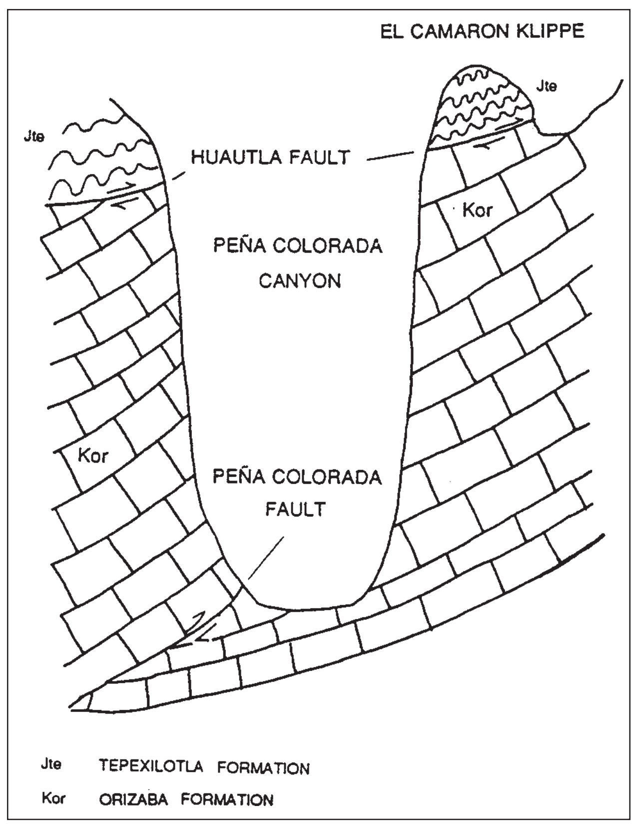



**Figure 7.4.** The El Camarón Klippe.

the dolina (Figure 7.5). In the earliest stage of dolina development, the cave entrance receives all drainage from the slopes of the drainage catchment. As the dolina evolves, drainage is lost to fractures, and a new low point in the dolina is formed. Entrances located on the dolina walls are representative of a middle erosional stage of the dolina. Eventually, erosion will strand the cave entrance on the side of karst hills or ridges, and all evidence of the past drainage catchment may be lost.

Most of the caves developed in Plan Arena, such as Nita He, Nita Zan, Nita Sa, and Li Nita, are located in the bottom of large dolinas 50 meters across or greater. All of these are located in a large enclosed drainage basin or dolina 800 meters across.

Nita Nanta and Nita Nashi are located on the south side of the Plan de Escoba Fault valley. Nita Nanta is located 20 meters below the summit of the south wall, a narrow ridge, of the Plan de Escoba karst valley. The large karst valley separates Agua de Cerro from the Nanta Ridge, has a northwest-to-southeast strike, and is one kilometer across. The valley has a depth of approximately 100 meters from its drainage divides.

The Plan de Escoba karst valley is a conglomeration of large dolinas, conical hills, and narrow ridges. Some of the large dolinas are 300 meters across and 60 meters deep. The dolinas vary from linear to circular to polygonal. The polygonal shapes are similar to descriptions of the cockpit karst of Jamaica (Sweeting, 1958). Williams (1972) referred to the tropical karst of the Dari Hills in New Guinea as polygonal karst. He based his descriptive nomenclature on the shapes of sinkholes and the configuration of their topographic drainage divides. Gerstenhauer (1960) found that cockpits are generally formed along joints or faults.

The linear-shaped dolinas of the study area occur as a result of solution along the strike of steeply dipping bedding planes, along the strike of faults, and at the contact with noncarbonate rocks. Examples of the latter are the San Agustín, Río Iglesia, and San Miguel Dolinas. The dolinas are often separated by pyramidal hills with a much lower hillslope declivity than the Puerto Rican conical hills, described by Monroe (1976) as having nearly vertical slopes. Lehmann (1927) named the conical-shaped hills he found in his world-wide studies kegelkarst.

The slopes of twenty-six pyramidal or conical shaped hills were measured across the study area. The average hillslope is 30 degrees. These residual hills are formed from chemical weathering and erosion during the retreat of the clastic cap rock. Consequently, karst hills are an artifact of dolina development. Residual karst hills are found in the San Miguel Dolina on the floor and slopes. Large residual karst hills are located between the San Agustín and Río Iglesia dolinas. Pyramidal karst hills are also found between the erosional remnant of the El Camarón Klippe and the overthrusted clastics of the Huautla–Santa Rosa Fault.

As the clastic cap rock retreated, large dolinas and karst valleys were left as traces of the cap rock's former position in the study area. It is hypothesized that the clastic cap rock of the Cerro Rabón Overthrust

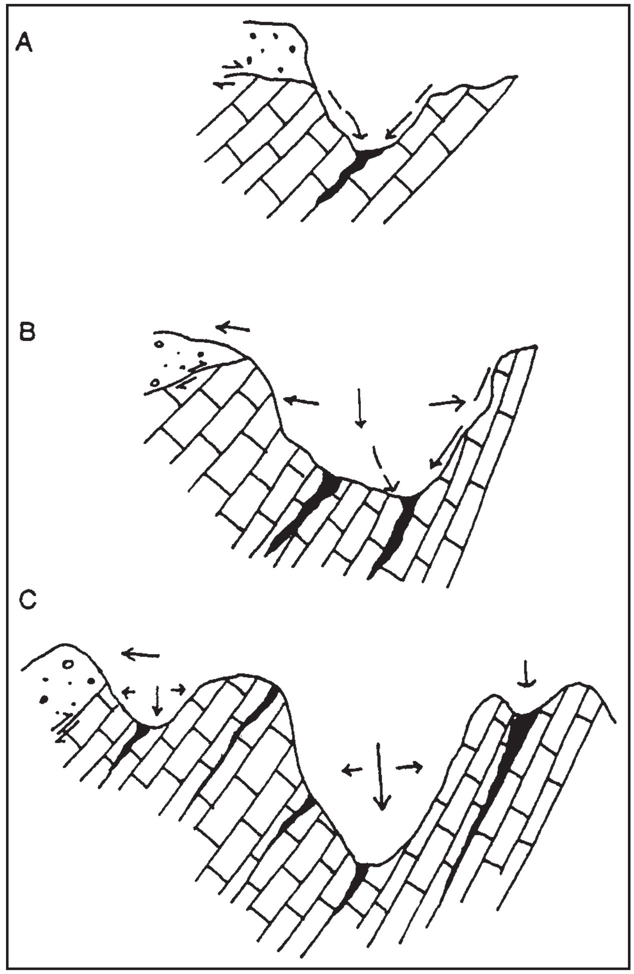



**Figure 7.5.** Evolution of a dolina in steeply dipping limestone and the corresponding relationship of cave entrances located on ridge tops and cone-karst hills. A. Dolina forms next to allochthonous clastics from allogenic recharge. B. As the clastic cap rock retreats, the dolina enlarges in depth and width. The original drainage outlet is abandoned and stranded higher on the dolina wall, as allogenic recharge drains at the bottom of the dolina through a newly formed conduit. C. Remnant to the retreat of the cap rock are numerous dolinas. Original vadose conduits formed by allogenic recharge are enlarged by autogenic input.

extended across the Nanta Ridge to Agua de Cerro and to the east of San Agustín to La Providencia. In evidence for this are large dolinas and karst valleys that may have been formed adjacent to the clastic cap rock.

## 7.6 Cavern Development Theories

It is only appropriate to introduce the chapter on speleogenesis with a brief review of cave development theories. With an understanding of these ideas, observations made deep in the caves of Sistema Huautla can be incorporated into a theory of its speleogenesis.

Early researchers at the turn of the century were embroiled in controversy as to whether caves were developed in the vadose zone above the water table or below the water table in the phreatic zone, while others even debated the existence of a water table in karst terrain. Grund (1903), Dwerryhouse (1907), Katzer (1909), Martel (1921), and Mallot (1937) stated that water simply flowed from the surface through sinkholes to cave passages to springs and suggested that caves large enough to be explored were formed largely in the unsaturated zone above the water table.

Gardner (1935) thought that big caves were formed on the up-dip side of surface valleys by vadose water along bedding planes and passage development trended down dip. Gardner (1935) and Woodward (1961) thought that cave development was a response to rapid changes in base level.

Swinnerton (1932) felt that caves were formed in the shallow phreatic zone proximate and parallel to the water table. Rhodes and Sinacori (1941) contended that Darcy's Law applies in the initial stage of cave development and maximum conduit enlargement occurs where Darcy stream tubes converge at the spring. Thrailkill (1968) supported the idea that most phreatic flow is proximate to the water table and proposed a different model from the views of Swinnerton (1932) and Rhodes and Sinacori (1941). When input is either close or far from a karst spring, the discharge is not significantly greater from a shallow phreatic zone than from a deep phreatic zone.

W. Davis (1930) and Bretz (1942) believed that caves were formed in the deep phreatic zone under permanently water-filled conditions under the influence of Darcy's Law.

Modern cave theorists Ford (1968, 1971), Ford and Ewers (1978), Palmer (1984), and Jennings (1985) concluded that the conditions for cave development vary considerably with local relief, climate, and geology; therefore, because these conditions are not uniform globally, the traditional theories of cave development may not apply to every hydrologic karst system. Conduits may have polymodal development. Vadose and phreatic solution often occurs simultaneously along the same flow path (Palmer, 1984).

Ford and Ewers (1978) contend there is no general model of speleogenesis applicable to every cave. Instead, there are vadose caves, water table caves, and phreatic caves that may have been formed under the partial influence of one or more of the classical theories. Caves developed with great vertical relief are usually multiphase in development. A multiphase system consists of vadose streams contributing recharge to phreatic streams.

Ford and Ewers (1978) described drawdown-vadose cave and invasion-vadose cave-development theories. Ford (1977) developed the four-state model based on low to high fissure frequency to distinguish between phreatic and water-table caves. Worthington (1991) proposed a model for the development of conduits in structurally influenced flow fields within a karst aquifer and their response to lowering of the water table.

## 7.7 Other Caves Developed in a Similar Hydrogeologic Setting

Speleogenesis in the Sierra Juárez may be similar in other areas of the mountain range, depending on the location of the cave with respect to the retreating clastic cap rock. Explorations to date have yielded numerous vertical drainage systems across the sierras, and many of these cave systems have developed adjacent to clastic or metamorphic cap rock.

Sistema Cuicateco, located south of the Río Santo Domingo (Smith, 1991b), is developed adjacent to a cap rock of schist and metavolcanics of the Cuicateco Complex (Charleston, 1980). Caves in excess of 1,000 meters depth, Pozo de Ocatempa and Akemati, are located near Alcomunga, 40 kilometers north of Huautla. They are also developed in the vicinity of the clastic cap rock of the Tepexilotla Formation (Smith, 1988e) (Figure 3.3). The 445-meter-deep cave, Xongo Dwini, located at Santa Ana Atiextlahuaca (Warild, 1992), is developed adjacent to the clastic cap rock of the Huautla–Santa Rosa Fault (Figure 3.3).

Caves developed in areas where no clastic cap rock appears to have existed are located at Cerro Rabón. Kijahe Xontjoa is currently 1,160 meters deep (Bitterli et al., 1990). Vertically extensive but poorly integrated cave drainage systems are developed near Zongolica Chilchotla (Warild, 1991). These caves appear to be developed in the vicinity of Late Cretaceous shales and more recent volcanics.

## 7.8 Speleogenesis

The fundamental questions of cave development in the Sistema Huautla Karst Groundwater Basin are: Were the caves formed as the clastic cap rock retreated, or were the caves formed after the clastic cap rock had retreated to its present position? What role does the water table play in the evolution of Sistema Huautla? Was the evolution of the cave system penecontemporaneous with development of the regional base level, or did the cave system evolve after the regional base level had developed to near its present position? Is there evidence of conduit development below the water table? Is there evidence of conduit development above the water table? Are there levels in the cave system that may be attributed to former base levels? In order to answer these questions two scenarios of cave development are proposed.

### 7.8.1 Scenario I Cave Development

Initially, the entire karst groundwater basin was covered by an allochthonous clastic cap rock. As the mountain range uplifted, the clastics were eroded by fluvial drainage systems. Eventually, thick deposits of sandstone and shale were eroded into the underlying carbonates. Uplift was continuous during the erosion of the clastic caprock. The regional base level was 500 to 700 meters below the clastic cap rock when the cap rock was finally breached by erosion. Surface streams and springs discharged into the limestone, saturating the underlying fracture system. Protoconduits were developed in a diffuse flow system. Basin-wide flow fields were established along the structural gradient of steeply dipping bedding planes and along a system of faults that were forming penecontemporaneous with uplift associated with block faulting. Fracture-controlled Hagen-Poiseulle flow fields determined the location of conduit development. Groundwater circulation was deep to springs forming at regional base level in the Río Santo Domingo. Once the hydrologic circuit was complete, the flow fields of steeply dipping dip tubes were drawn down into the water table. The water table of the groundwater basin was established from the spring headward into the groundwater basin. The hydraulic gradient of the water table was less than 10 percent. Enlargement of steeply dipping vadose conduits began in the upper portion of the aquifer from allogenic and autogenic recharge. Vadose conduits provided recharge to a base level phreatic conduit system developing below the water table. The phreatic conduit system channeled all internal drainage in the aquifer to the Río Santo Domingo.

New conduits were developed at the edge of a retreating clastic cap rock. The conduits formed first or to the east are the oldest conduits of the system. Caves formed to the east of the present position of the clastic cap rock tend to be smaller than those conduits located next to noncarbonate rocks. Cave entrances on the sides of steep ridges and ridge tops were formed from larger drainage catchments located adjacent to the clastic cap rack.

The cap rock to the east may have been much thinner and eroded much faster than the western exposures because it was structurally higher. Current elevations of the limestones on the east side of the basin range from 1,800 to 2,000 meters. On the western side of the basin, the Huautla–Santa Rosa Fault is exposed at 1,500 meters elevation in the Río Iglesia Dolina.

Each subsurface drain in the cave system is vertical until a definite level of horizontal development occurs. All caves except Sótano del Río Iglesia have significant vertical development before horizontal development occurs at depths between 600 and 1,000 meters below the entrance. In Sótano del Río Iglesia, horizontal development begins at a depth of 150 meters below the entrance.

In this scenario, caves were formed initially by allogenic recharge as the cap rock retreated and then modified by mostly autogenic recharge. Even though the vertical drainage system was formed in the early stages by diffuse flow through fractures to the water table, the vertical extent of the cave system was formed primarily in the vadose zone (Figure 7.6).

### 7.8.2 Scenario II Cave Development

In the second scenario, the allochthonous clastic cap rock did not extend much farther east than its present position. All caves were formed at the same time. The regional water table was uniform across the Sierra Juárez and consistent with regional paleo-fluvial systems. Regional uplift was rapid, and the fluvial systems flowing across the corrosional plane disappeared as their allogenic sources sank at the edge of the carbonate basin. Initially, the fracture networks were saturated and created a phreatic skeleton proximate to the water table. Tectonic uplift rejuvenated erosional activity, and groundwater flow was to springs at the regional base level as defined by the Río Santo Domingo. Shallow conduit systems were developed proximate to the water table.

As the mountain range continued to uplift, different conduit levels were formed and new springs developed at each successive base level. The spring representing the previous base level may have served as

an overflow spring or was abandoned completely. As each level drained, a vadose system was developed and was modified by allogenic and autogenic recharge. Consequently, the cave was formed by multi-phase development.

The problem with Scenario II is that there should be successive horizontal levels of phreatic lift tube development throughout the vertical extent of the cave system. Phreatic lift tubes were observed only in the lower portion of the system. The fact that phreatic lift tubes were not observed at different levels throughout the vertical extent may either be attributed to exploration bias or nonexistence in the areas of the caves visited. Cave explorers interested in deep caves tend to concentrate on going down rather than going up. There appear to be incoming shafts located at many points along the vertical drainage system. However, the shafts are considered to be of vadose origin.

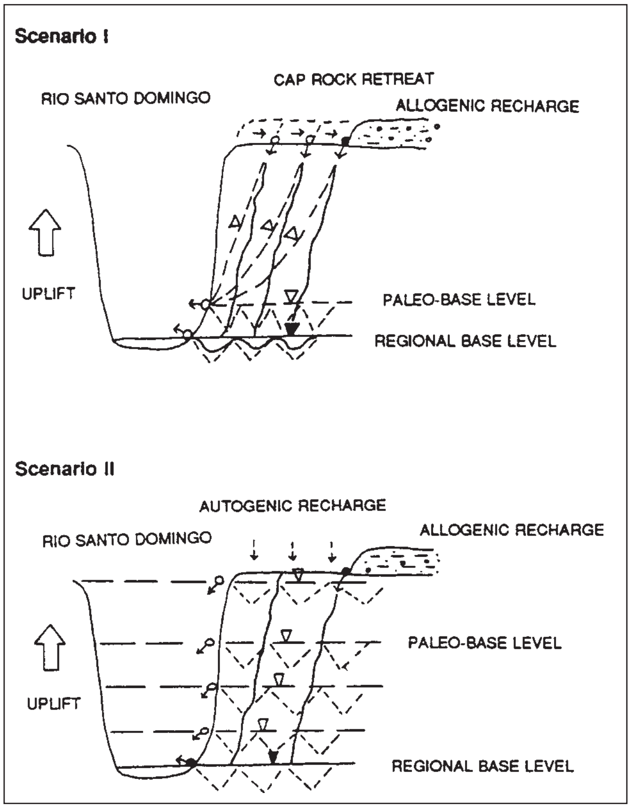



**Figure 7.6.** Two hypotheses of speleogenesis for Sistema Huautla. Scenario I: The Sierra Juárez uplifted 700 meters before the clastic cap rock was removed by erosion. Saturated fractures were drained, and the potentiometric surface drew down to a developing spring at regional base level when the hydrologic circuit was completed. The cave system was formed initially under phreatic conditions and later underwent vadose modification. Vadose conduits drain to base-level phreatic conduit system. Scenario II: The clastic cap rock was eroded to near its present position. The cave system was formed under phreatic conditions relative to the regional base level. Successive levels were drained during continuous uplift. Conduits developed at former base levels were subsequently modified under vadose conditions. Each level in the cave was formed relative to the regional base level. Vadose conduits connecting former base levels drain to a base-level phreatic conduit system.

The size of the conduits is merely a function of the subdrainage basin catchment size or the integration of subdrainage basin drains. The conduit size may also be attributed to its development relative to its position to the clastic cap rock. Conduits receiving a continuous source of allogenic recharge tend to develop faster, and the passage diameters are larger (Miller, 1981). Caves developed in smaller drainage-basin catchments were developed by autogenic input. Cave entrances located on the sides of ridges and ridge tops were formed in much larger catchments than those that presently exist. They were, however, limestone drainage catchments that were removed by dissolutional processes. The vertical extent of the cave was formed primarily by lowering of successive base levels under phreatic conditions and then modified under vadose conditions (Figure 7.6).

### 7.8.3 Water Table Relative to Cave Development

The difference between the two scenarios is the vertical extent of groundwater circulation. The morphology of the cave system should provide the evidence of the type of circulation during speleogenesis.

As seen in the vertical profile of the caves of the Sistema Huautla Karst Groundwater Basin, there are three basic morphological characteristics (Figure 1.4). The conduits in the cave system are steeply inclined, vertical, and horizontal. These features are developed in steeply dipping limestones that range from 10 to 90 degrees, as indicated by field mapping. Steeply dipping passages and vertical shafts occur in the upper portion of the system, while horizontal development occurs near the lower. Several distinct levels are apparent, giving rise to the question of passage development relative to a water table (Figure 7.7).

Ford (1971) pointed out that in the development of conduits in steeply dipping rocks where the structural gradient is usually steeper than the existing topographic or hydraulic gradient, conduits develop along structural weaknesses and flow paths of circulating groundwater. He also developed a four-state model to differentiate phreatic and water-table caves. This model was based on density of the fracture network (Ford, 1977). Ford and Ewers (1978) described

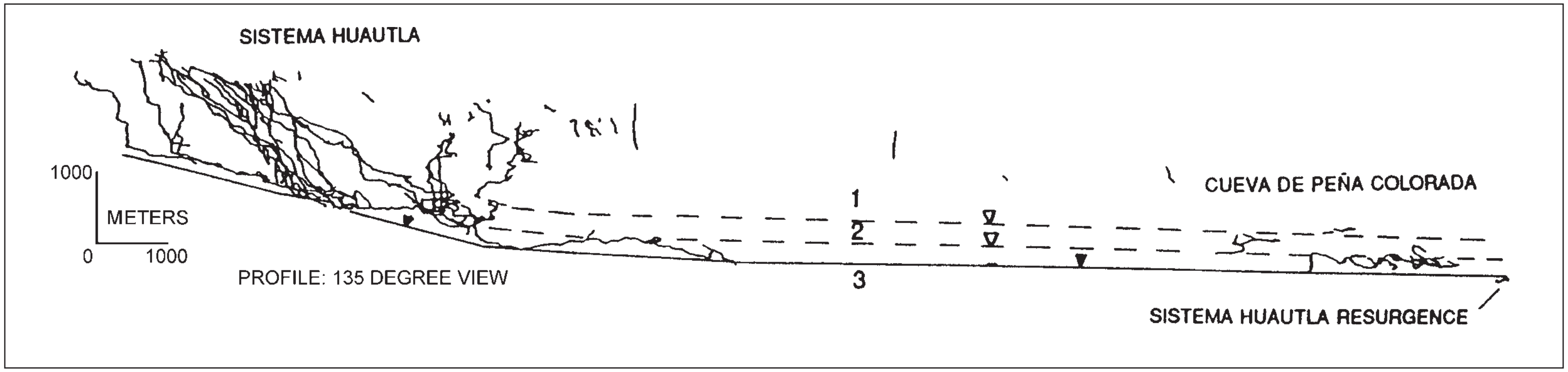



**Figure 7.7.** Profile of Sistema Huautla, Cueva de Peña Colorada, and the Sistema Huautla Resurgence: the development of cave levels relative to the water table.

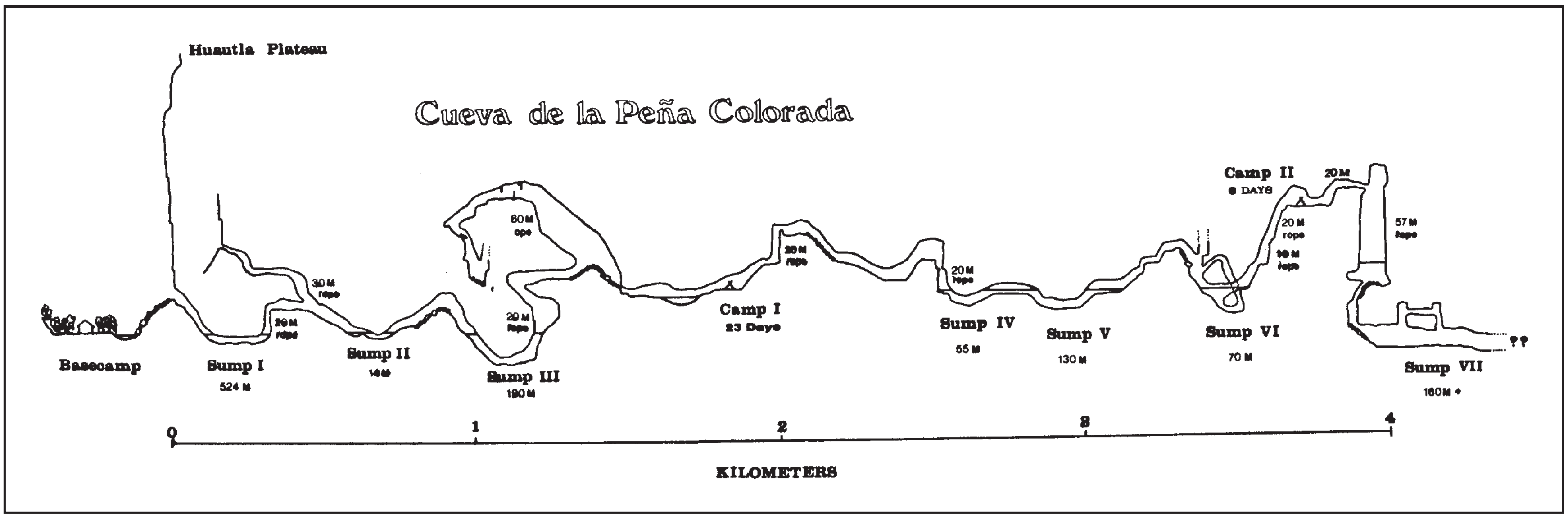



Figure 7.8. Profile view from Stone 1984.

two types of vadose caves, drawdown-vadose caves and invasion-vadose.

Cave mapping and the geology in the study area indicate that a high fissure frequency occurs. The hydrologic profile of the system is dominated by steep vadose drainage to base-level horizontal development. The lower portions of Sistema Huautla and Cueva de Peña Colorada are similar to Ford's State 2 model as defined by multiple loop phreatic caves (Figure 2.3 and Figure 7.8).

Bögli (1966, 1980) described three distinctive cave levels developed at three former base levels in the Hölloch Cave, Switzerland, within a vertical extent of 600 meters. The morphology of each of these levels is characterized by undulating phreatic loops. Ford (1989) refers to Hölloch as representing State 2 development. If the entire vertical development of Sistema Huautla was initiated at the regional base level, the caves in the groundwater basin should be very similar to Hölloch, with multiple levels of undulating phreatic lift tubes.

Fish (1977) described the development of a deep phreatic shaft or "lift" at Nacimiento Mante. Exley (1988) has proven by his world-record dive that Mante is a deep phreatic vertical shaft that is over 243 meters deep. It is hypothesized that Mante exhibits Ford's State 1 model, where the cave is developed along a low fissure frequency at a stable spring position. Worthington (1991) described a phreatic "drop" of 600 meters in a single conduit in Gouffre Touya de Liet and Gouffre de la Consolation, France, which follows a bedding plane with a dip of 50 degrees. He also described Castleguard Cave as being 370 meters below the water table when it was formed.

Also fundamental to the problem of speleogenesis in the Huautla area is the cave development of Sistema Cuicateco. Located across the Río Santo Domingo, its highest entrances are almost 1,000 meters higher than those at Huautla. Sistema Cuicateco is drained by steeply descending passages and shafts to –900 meters, where a large borehole passage is underlain by phreatic loops with an amplitude of 30 meters (Smith, 1991b). With this in mind, one could project a regional water table from the highest crest of the phreatic loop across to Huautla, where the entrances of the caves are located. The master trunk of Sistema Cuicateco descends at a gradient of 10 degrees toward the spring, the Nacimiento Río Frío de Santa Ana of Vesely (1990) or the Western Resurgence of Stone (1984), which was proven by a dye trace to be its resurgence (Smith, 1991b).

The Sistema Cuicateco Karst Groundwater Basin occurs in a 3-kilometer-wide strip of limestone exposed by erosion along the Huautla Fault. It is bordered to the west by the Cuicateco Complex and to the east by Paleocene shales and sandstones. The explanation for the occurrence of phreatic loops and trunk passage in Sistema Cuicateco may be a perched water table formed by concentrating a tremendous

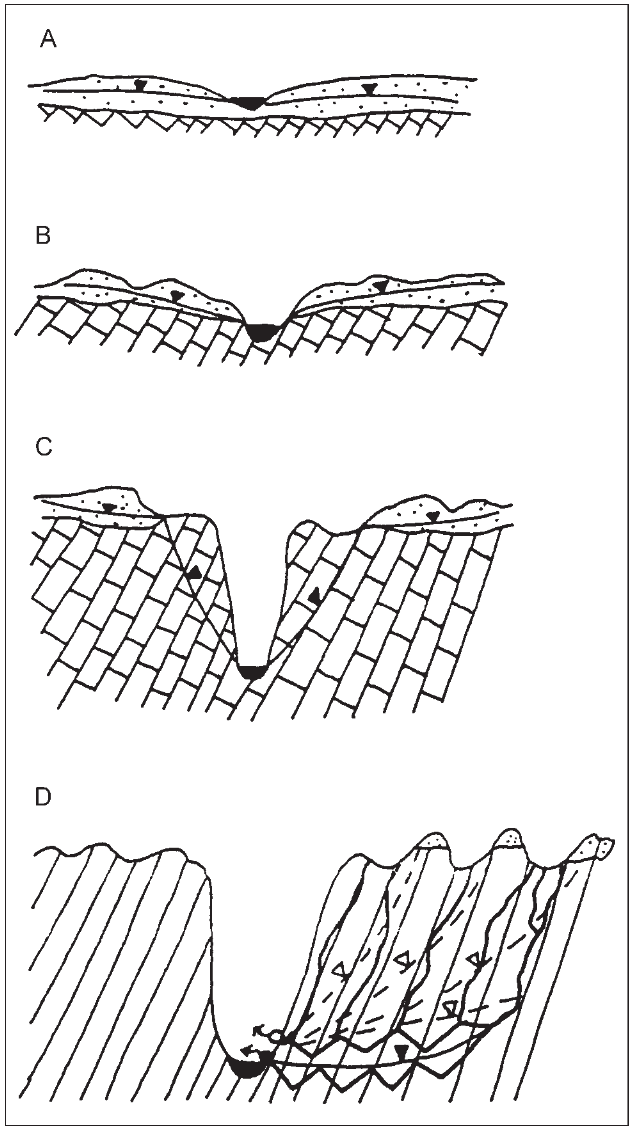



**Figure 7.9.** Evolution of Río Santo Domingo Canyon, slope retreat of the clastic cap rock, and the development of conduits relative to the water table. A. Río Santo Domingo flowed across the emerging Sierra Juárez on clastics and metamorphics from the west onto limestones to the east. B. Uplift rates are faster than erosion rates. The Río Santo Domingo represents regional base level. C. Cap rock is removed by erosion, and allogenic recharge saturates underlying limestones. D. Hydrologic circuit is complete between input and output as gravity drainage recharges water table.

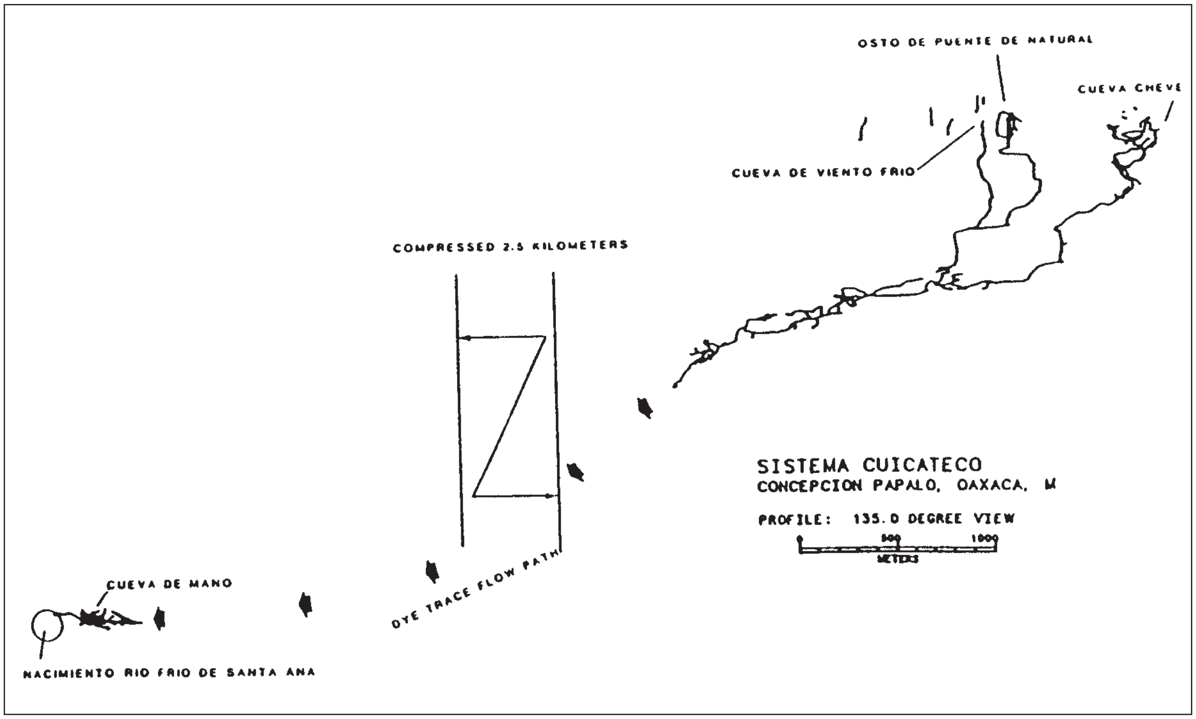



**Figure 7.10.**

volume of allogenic recharge from the slopes of noncarbonate rocks on the east and west sides of the basin. The volume of recharge was so great that it exceeded the capacity of the conduit and created a constant head pressure, enlarging the trunk passage under water-filled conditions. There appear to be two paleo-base-level positions in Sistema Cuicateco. Each level may be related to a period of tectonic uplift. The large upper-level borehole was formed under phreatic conditions. The enormous size of this conduit may be attributed to a wetter climate than currently prevails. The clastic cap rock bordering both the east and west sides of the karst groundwater basin may have been much narrower, and allogenic recharge more concentrated. Below the highest phreatic level is an entrenched canyon. Phreatic loops are well preserved in the vicinity of the Black Borehole (Smith et al., 1991).

In conclusion, the speleogenesis of Sistema Cuicateco appears to be similar to Sistema Huautla in its development adjacent to a clastic cap rock. However, the altitudes of the respective levels or tiers of conduit development do not correlate between adjacent basins. In both cave systems, there is active conduit development 50 meters below the water table near the springs. Farther up the hydrologic gradient, the tops of phreatic loops 5 to 10 kilometers from the springs have been dove to depths of 30 meters (Stone, 1994, Farr, 1994, and Smith et al., 1991). In both cave systems, paleo and active tiers appear to be equidistant, thereby supporting the endogenetic model that cave tiers are a function of the original flow net (Worthington, 1991) (Figure 7.7 and Figure 7.10).

Because of Sistema Huautla's fissure frequency and tectonic history, it is highly unlikely that it was formed by deep phreatic flow as at Mante or shallow phreatic flow at regional base level. Only the protoconduits were formed below a water table. If Sistema Huautla had been formed by the lowering of successive base levels, the morphology of the conduits and the development of multiple levels should have been similar to Hölloch. Because there are distinct levels in the lower portion of Sistema Huautla and Cueva de Peña Colorada, it is hypothesized that passage development and significant conduit enlargement occurred in the phreatic zone at depths less than 200 meters below the water table. The upper portion of the cave system, being more vertical in morphology, is hypothesized to have been formed primarily under the influence of vadose conditions.

### 7.8.4 Protoconduit Development

Ford (1971) stated that structural gradients are the only real gradients that exist at the early stage of cave development and that in steeply dipping rocks the structural gradient is steeper than the existing topographic or hydraulic gradient. The more steeply dipping the strata, the deeper the flow path of groundwater (Ford and Ewers, 1978). He found that dip tubes and

anastomotic bands are the first conduits to develop under diffuse-flow conditions. Groundwater flow at this stage is Darcian flow through fractures and steeply dipping bedding planes. Groundwater flow may be explained by a Hagen-Poiseuille flow field, which demonstrates that deep flow in catchments larger than 3 kilometers is more efficient than shallow flow (Worthington, 1991). White and Longyear (1962) state that once the transition occurs between laminar flow and turbulent flow in a conduit, dissolutional processes are seven orders of magnitude more efficient. As conduits enlarge and the hydrologic circuit is completed from input to output, the flow regime changes from diffuse flow to a turbulent flow system.

Studies have shown that anastomotic bands are formed in strata with dips less than 5 percent, which are not described in the study area. Influenced by steeply inclined strata and a high state of available fissure frequency, multiple dip tubes enlarged in diameter as the piezometric surface rapidly drew down. Drawdown and reorientation of tributary flow fields increased the permeability of the limestone and created ideal conditions for the development of vadose cave systems above base level. Worthington (1991) suggests that spacing between low-potential areas, where there are primary tubes or anastamoses, is critical to the development of primary dip tubes. The distribution of sinkholes across the Sistema Huautla Karst Groundwater Basin may represent low-potential areas for the development of primary dip tubes. Ford (1971), Ewers (1982), and Worthington (1991) suggest that the 100-meter spacing of sinkholes above Hölloch are indicative of primary dip-tube spacing. Ford (1965) and Jameson (1985) mapped primary dip tubes at sink points. Dip tubes were observed draining sink points in most of the dolinas in the study area. Dip tubes were observed to be formed along steeply inclined bedding planes at most of the paleo sink points throughout the basin (e.g., Li Nita, Nita Zan, etc.). Where sink points were located along faults (Nita He), dip tubes were not observed.

The proto-dip-tube conduits that would later form major conduits of the dendritic network of Sistema Huautla and related caves were formed during diffuse flow conditions prior to drawdown of the piezometric surface in the same manner as described by Ewers (1982) and Ford and Williams (1989). As the piezometric surface drew down and flow fields reoriented to establish the most efficient flow path, the hydrologic network was established. The flow field was routed through primary tubes of the hydrologic system. Worthington (1991) wrote that dissolutional processes will increase from by from $10^3$ to $10^6$ along the principal flow path once the hydrologic circuit has been completed.

Ewers wrote that the reorientation of flow fields during drawdown establishes a more efficient flow path along a single plane. The dendritic system in the study area is developed along successive parallel planes that are linked together by a highly integrated fracture system.

It is hypothesized that the regional base level was well below the piezometric surface that developed the primary dip tubes that formed the phreatic skeleton of the cave system (Figure 7.9). Well after drawdown of the piezometric surface, those hydrologic flow routes abandoned during flow field reorientation were later connected into the main flow system by gravity drainage and recharge. This process is currently ongoing in the form of tributary input from trickles and small streamlets under the influence of vadose conditions.

When the piezometric gradient lowered to a stabilized position, as was the case in the study area, the protoconduits consisting of dip tubes and slanted conduits provided efficient path ways for allogenic and autogenic recharge (Palmer, 1991). Under vadose conditions in steeply dipping rock, the hydraulic gradient where groundwater flows down shafts may be steeper locally than the structural gradient. Palmer (1991) indicated that vadose passages are formed by gravitational flow and follow the steepest available openings. Direct input into the conduits and a complete hydrologic circuit to springs facilitated the formation of conduits and shafts.

The hydraulic gradient for the vadose stream passages in Sistema Huautla is 42 percent. The hydraulic gradient of the water table is at 3.7 percent (Figure 7.7). When considering both the vadose zone and the water table, the hydraulic gradient for the basin is approximately 14 percent. The hydraulic gradient for the whole basin is less than the structural gradient, which averages 40 percent.

Ford (1971) described conduit development in steeply dipping limestones as having two basic morphological characteristics. There are dip tubes that are long linear tubes that occur parallel to the structural dip and aslant tubes that are formed parallel to the strike of dipping beds. In the caves of the Sistema Huautla Karst Groundwater Basin, both of these morphological types may be found, either in their active state in sumps or inferred as relic features in vadose conduits. The protoconduit dip tubes provided the most efficient route for water to flow. Field mapping across the basin indicates a southeast dip direction. Within the ridge -top caves (e.g., Nita He, Nita Mazateca, Nita Zapato, Nita Ka, Nita Nido and Nita Ntau, Sótano de

Agua Carrizo, Nita Notni, Nita Lajao, Li Nita, Nita Zan, Nita Sa, Cueva de Bernardo, and Nita Ina) passage development trend is down dip, with minor strike dominated aslant passage development. The dendritic nature of Sistema Huautla and hydrologically related caves is largely related to the development of protoconduits during saturation of the rock mass. Dip tubes are formed under phreatic conditions. The inclined passages and shafts in the study area are vadose modifications of protoconduit development.

To summarize the process of protoconduit development, a phreatic skeleton of dip tubes was formed in a totally saturated fracture system. The mountain range uplifted rapidly and gravity drainage to base level spring(s) completed the hydrologic circuit. Dip tubes were evacuated, and vadose conduit development was initiated.

### 7.8.5 Vadose Passage Development

Ford and Williams (1989) postulated that vadose systems develop after primary dip-tube systems complete the hydrologic circuit and that water flowing from input to spring subsequently enlarges the tubes, increasing their capacity and facilitating drawdown of the piezometric surface. Palmer (1984) stated that vadose and phreatic solution often occurs simultaneously along the same flow path. Ford and Ewers (1978) described two basic types of vadose caves formed in drained rock. These are drawdown-vadose caves and invasion-vadose caves. Drawdown-vadose caves are formed where vadose development occurs in a phreatic skeleton that has been evacuated due to drawdown of the piezometric surface. Ford and Williams (1989) cited the Gouffre Berger and Gouffre Jean Bernard as examples of drawdown-vadose caves (Figure 2.2). They also stated that an invasion-vadose cave is formed by allogenic streams sinking into rock that had been previously drained. This type of system lacks a primary tube network. In rock with dipping beds, the caves tend to have steeper profiles than drawdown-vadose caves. Ford and Ewers (1978) refer to the Spluga della Preta, Italy, and Epos Chasm, Greece, as two examples of invasion-vadose caves (Figure 2.2). Ford and Williams (1989) contend that invasion-vadose caves occur in young mountain systems characterized by rapid uplift and high fracture permeability. Crawford (1978) described invasion-vadose caves formed in relatively old limestones of Mississippian age in the Cumberland Plateau of Tennessee.

In considering the water table and the relative position of cave tiers in the study area, it is hypothesized that there had to have been great vertical relief between base level and input, because the profiles of Sistema Huautla indicate extensive vertical development without the development of significant intermediate levels. No phreatic levels or levels with obvious phreatic characteristics have been found between the entrances of the caves in the groundwater basin and the levels in the cave where base-level horizontal passage development occur. One could argue that the steeply dipping passages and shafts were originally phreatic dip tubes at the protoconduit stage. Steeply dipping dip tubes and shafts represent between 500 and 900 meters of vertical relief to where the first significant horizontal passages or levels are developed.

Based on physical evidence, Sistema Huautla's speleogenesis reveals a multiphase development. The cave system comprises elements of the drawdown-vadose model, which implies an initial phreatic skeleton, and the invasion-vadose model with conduit development and modification from allogenic and autogenic recharge. The base level of the cave system exhibits both vadose and phreatic elements. In the upper portion of the cave system's base level, from Nita Nanta to the 859 Sump in Sótano de San Agustín, the water table is perched on shales and has a hydraulic gradient of 28 percent.

These vadose drains recharge a phreatic system that may be partially inundated for 10 kilometers. Ford and Williams (1989) described the Gouffre Jean Bernard as having a comparable complexity.

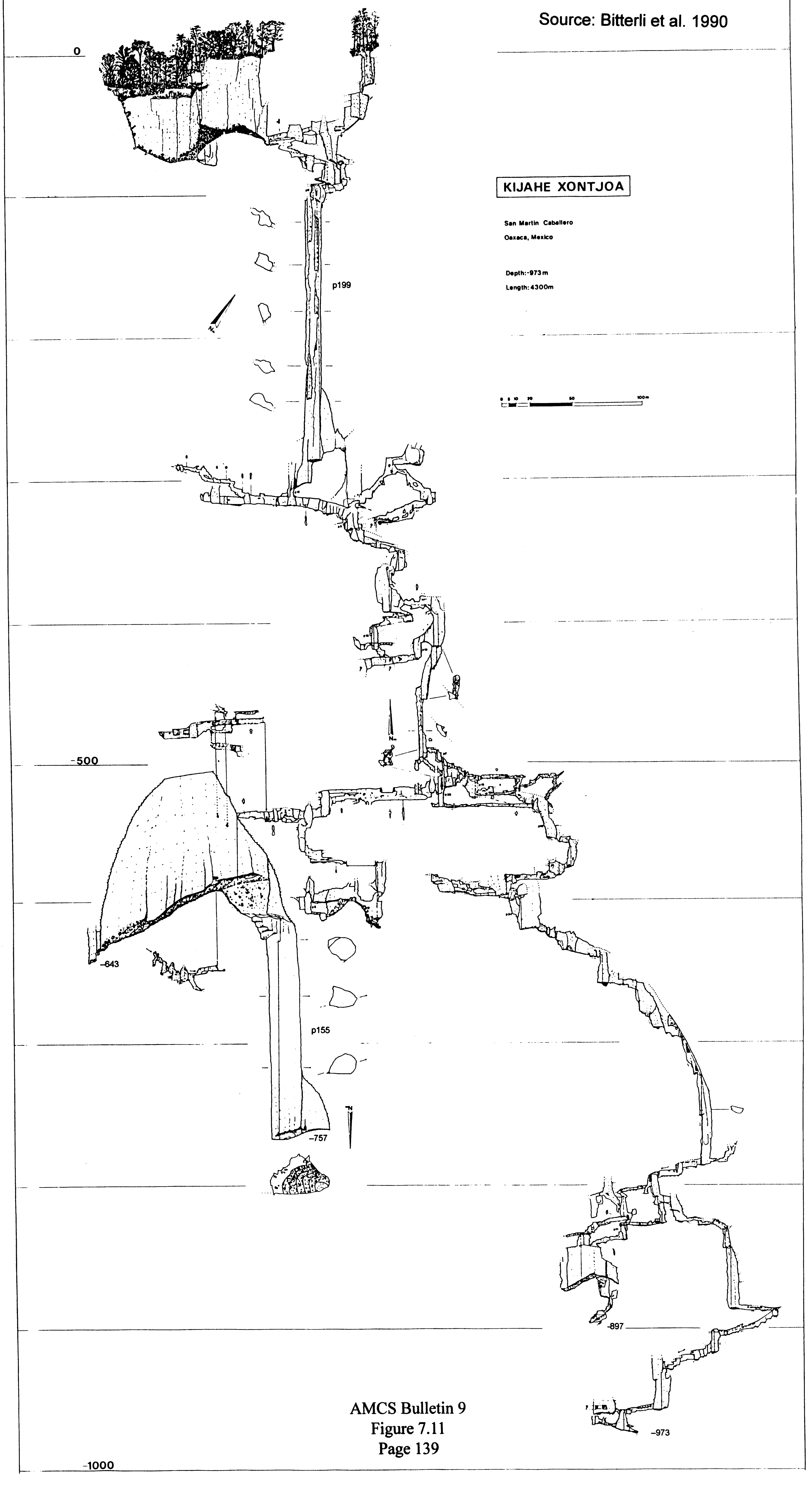
### 7.8.6 Phreatic Segments

Ford and Williams (1989) stated that short sections of phreatic cave that are associated with lithologic perching or local phreatic lifting occur within vadose caves. In Sistema Huautla and related caves there are sumps at many levels in the cave that are not associated with the base-level water table (e.g., –826 meters in Li Nita's Scorpion Way, –1,030 meters at the Li Nita–San Agustín connection, –1,080 meters in downstream Scorpion Sump, –900 meters in upstream Red Ball Canyon in Sótano de San Agustín, and –805 meters in Sótano de San Agustín). These sumps are formed in localized structural features such as folds, along faults, or in the lower levels of a horizontal passage. They represent a perched water table where active phreatic development is occurring.

### 7.8.7 Field Evidence for Phreatic Passages

An example of active and abandoned phreatic lift tubes occurs in Cueva de Peña Colorada (Figure 7.8). Vine Cave, located in the Cañón de Peña Colorada, has a phreatic loop morphology and perched sumps (Figure 7.7). It seems that Vine Cave may connect into Cueva de Peña Colorada by virtue of its trend (Stone,

Source: Bitterli et al. 1990



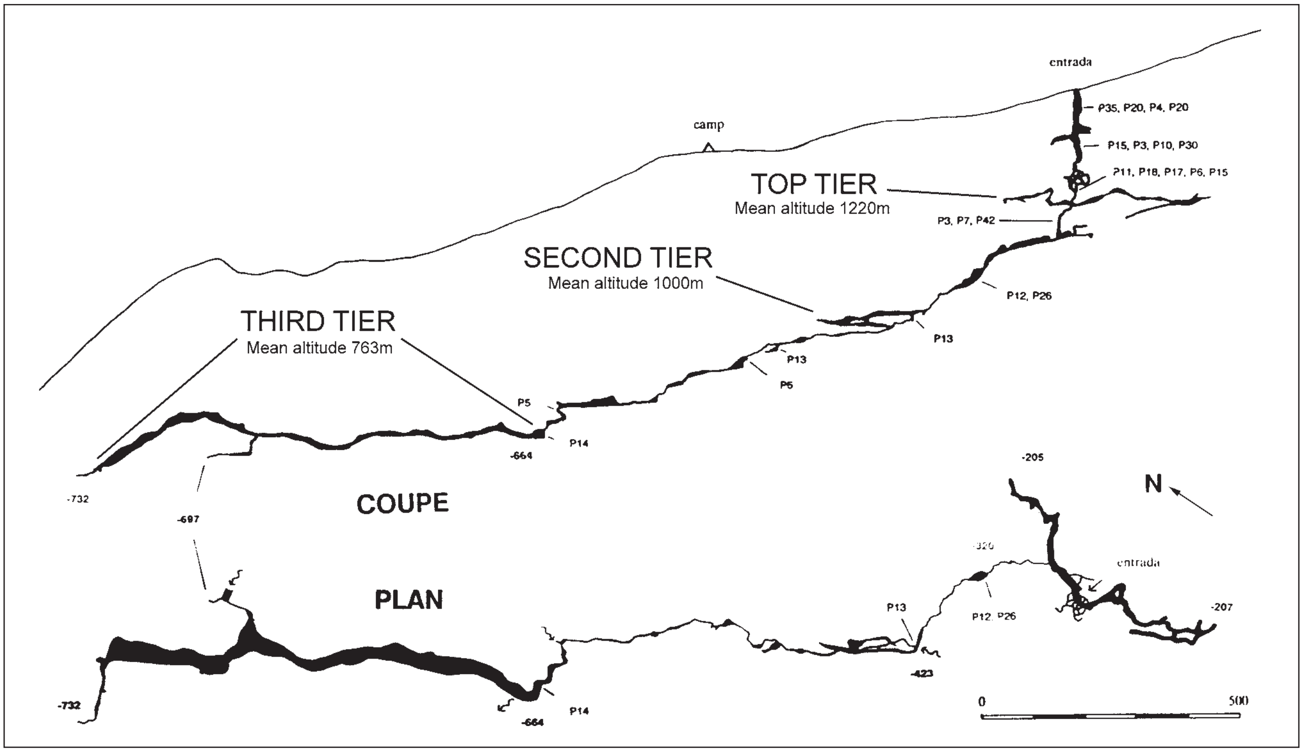



**Figure 7.12.** Nelfastle de Nieva, Tepepa de Zaragoza, Coyomeapan, Puebla: Tiers of passage development. Source: Worthington 1991.

1988). Vine Cave may be a second overflow spring for the Sistema Huautla Karst Groundwater Basin.

A permanently water-filled passage occurs at –854 meters in Sótano de San Agustín and represents the phreatic base level of Sistema Huautla. At –854 meters, Stone followed this underwater route for 400 meters at a depth of 28 meters before surfacing into a 150-meter-long airbell. Beyod a second sump, the tunnel headed due south for 1.5 kilometers and bypassed six sumps to Sump 9. At this level numerous long sumps were encountered along a hydraulic gradient less than 5 degrees (Stone, 1994). The San Agustín sump is 250 meters above the Sistema Huautla Resurgence at the regional base level as defined by the Río Santo Domingo.

Other examples of phreatic tubes occurring in the Sierra Juárez are described by Bitterli et al. (1990) in Kijahe Xontjoa at –1,160 meters (Figure 7.10) and Sistema Cuicateco at –1,000 meters (Smith, 1991b) (Figure 7.11).

The Nacimiento Uruapan below Cerro Rabón is an example of a partially explored phreatic spring cave perched 400 meters above regional base level. The segment of the conduit that was explored was 40 meters in diameter and 220 meters long (Stone, 1993).

In the Sierra Negra, 732-meter-deep Nelfastla de Nieva is described as having three distinct cave tiers with phreatic loops with an amplitude of 30 meters (Figure 7.12). All of these lift tubes represent past base levels of the cave system (Worthington, 1991).

7.8.8 Previous Work Relating Cave Levels to Water Table

Researchers have demonstrated that cave levels can be controlled by impermeable strata of shale, sandstone, chert, and limestone above the regional water table (White, 1969; Waltham, 1971; Crawford, 1978).

Karst researchers have recognized a relationship between passage development, position or level within limestone aquifers, and relationship to base levels.

Davies (1960) hypothesized four stages of cave development, random solution at depth to produce nonintegrated caves, integration of tubes into mature conduits at the top of the zone of saturation during periods when the water table is constant, deposition of clastic fill under alternating conditions of saturation and aeration, and relative uplift of the cave above the zone of saturation, with modification of the passage by deposition of speleothems, erosion of till material, and collapse.

Sweeting (1950), Krieg (1954, 1955), Droppa (1957), Davies (1957), Davies (1960), White (1960), White and White, (1974, 1983), Bögli (1966), Miotke and Palmer (1972), Ford and Ewers (1978), Bögli

(1980), and Palmer (1984) demonstrated that levels in caves could be correlated to river terraces, signifying that paleo base levels were where passage development occurred proximate to the former water table.

Milanovic (1981) postulated that the base level of erosion determines the ultimate direction of circulation for underground water in karst. Major erosion bases in continental regions include deep river valleys and canyons . Worthington (1991) described a surface analog to low-gradient river caves. He used the Río Santo Domingo and Río Petlapa as examples of low-gradient allogenic water flowing across karst outcrops. He states that the rivers are able to entrench fast enough to prevent capture to a lower course below the river bed. Smith and Crawford (1989) found that significant horizontal development of cave passages controlled by lithology may occur well above present base levels in the Cumberland Plateau Margin Fluvial Karst.

Palmer (1987) provided a method for determining past base levels by determining the relationship between vadose-phreatic transition points or the "piezometric limit."

It has been thought that cave levels or tiers were a response to exogenetic processes such as the lowering of local base level by fluvial processes. These exogenetic sources are challenged by Worthington (1991), who favors an endogenetic model for the development of cave levels. He maintained that the development of a cave tier is a function of the original flow net within the aquifer and has little to do with regional base level. In fact, of the submerged conduits he investigated, most were developed 20 to 50 meters below the current base level or water table.

### 7.8.9 Base Level Development of Sistema Huautla

Morris et al. (1968) made geomorphological observations in Sótano del Río Iglesia and hypothesized that the large chambers in the cave were phreatically formed and modified by vadose streams. His evidence for phreatic development is the occurrence of wall and roof pocketing at three different levels. White (1988) described flood-water-generated features as consisting of sharp-edged residual blades, rock spans, and scoured pockets. Palmer (1975 and 1991) demonstrated that pocketing and solution pendants can also be formed from flood water in vadose passages.

Morris described phreatic levels in Sótano del Río Iglesia. He based his interpretation on the occurrence of pocketing in the ceiling and walls. Because Sótano del Río Iglesia is virtually surrounded by noncarbonate rocks and completely enclosed by the steep walls of the dolina, the pocket features are therefore more logically formed by flood waters and are likely not phreatic features. The rest of the caves in the system are more vertically oriented than Sótano del Río Iglesia and were formed above the water table. It is suggested that Sótano del Río Iglesia was also formed above the water table and that the horizontal levels are controlled by development along the strike of the beds and parallel faults. The northeast dip of the beds may be due to local warping of the strata due to overthrust faulting of the Huautla–Santa Rosa Fault.

Horizontal development of cave passages in Sistema Huautla occurs at approximately 900 meters above sea level or between –500 and –650 meters below the entrance of Sótano San Agustín. La Grieta has significant horizontal development approximately 400 meters below its entrance or 200 meters above the levels formed in Sótano de San Agustín.

The main question is whether these levels were phreatically formed and are representative of old base levels or passages whose control is either structural or stratigraphic. As previously discussed, phreatic lift tubes are found in caves throughout the Sierra Juárez at active or former base levels.

In Cueva de Peña Colorada there are at least two well-defined phreatic levels. The lowest level is the active hydrologic route and has only been explored at the spring and at Sump VII (Stone, 1984). The morphology of these passages, as defined by cave survey, indicates that the flow path of the water is steep. The water flowed along the strike of steeply inclined bedding planes and faults creating phreatic lifts (Ford, 1971) or drops (Jameson, 1985). Ford (1971) defined a loop with a combination of one or more dip tubes and joint chimneys between successive piezometric surfaces along a trunk as a "phreatic loop." According to Worthington (1991), where groundwater flow is parallel to the strike, phreatic loops may form along singular planes or in combinations of multiple planes.

The upper paleo-phreatic level of Cueva de Peña Colorada contains six perched sumps with different water level elevations. Flow through the perched sumps is active only during high discharge and acts as an overflow conduit system. Indians have seen the entrance of Cueva de Peña Colorada discharging a huge river of water during the rainy season. The cave survey of the upper phreatic level reveals a profile of undulating phreatic tubes, with the lower portion of the loops water filled and static until a significant storm event occurs and the tubes serve as an overflow route. The upper level represents the original hydrologic route which has now been abandoned by continuous flow.

The entrance to Cueva de Peña Colorada is 92

meters above the spring level of the Sistema Huautla Resurgence (Stone, 1984). The original base level, as indicated by the crest of the highest phreatic loop, is at least 240 meters higher than the Sistema Huautla Resurgence. This estimate is based on the vertical position of the top of the Whacking Great Chamber. Ford and Williams (1989) stated that the elevation of the top of the highest phreatic loops defines the stable position of the piezometric surface. It is suggested that the development of phreatic tubes at the base level in Cueva de Peña Colorada represents a mode of development to be expected in other parts of the system. There may be one or more levels of phreatic tubes associated with the present base level (Figure 7.7).

Phreatic tubes have been located in other caves and at various levels in the hydrologic basin. In Cueva de Agua Carlota, the cave stream follows a steep canyon until the passage trend turns horizontal at –500 meters (Smith, 1991d). The horizontal passage is a 10-meter-diameter tube. In La Grieta above the Gorge is a 300-meter-long, 20-by5-meter-diameter elliptical phreatic tube. In Nita Nanta at –1080 meters, near the Scorpion Sump, there is a 200-meter-long phreatic tube.

The rest of the horizontal drainage is through large rectangular trunk passages (e.g., in Nita Nanta, Lower Nanta Gorge, in Sótano de San Agustín, Route 68, Kinepak Canyon, Tommy's Borehole, and the Metro, in La Grieta, K-Borehole, in Sótano del Río Iglesia, Penthouse, Base Camp Chamber, and The Basement, and in Li Nita, Mil Metro). All of these passages except those in Sótano del Río Iglesia and Li Nita's Mil Metro represent the present base level and have active stream routes. The base levels of these passages are controlled by lithology and a structural gradient that is steeper than the hydraulic gradient.

None of these passages have the same phreatic passage morphology as Cueva de Peña Colorada. Were these base level passages modified by vadose streams that removed all evidence of phreatic morphology? The multilevel undulating tubes of Cueva de Peña Colorada are not present anywhere in Sistema Huautla above the 859 sump or in caves traced into the northern portion of the system. The only complex multilevel development occurs where La Grieta, Nita Nanta, and Sótano de Agua de Carrizo connect to Sótano de San Agustín and where Li Nita connects to Sótano de San Agustín. This complex passage development may be associated with the convergence of most of the vadose drainage routes of the east and north portion of the basin. However, the horizontal development is significant and is controlled by two factors: Northeast of the Loggerhead Hall Fault, the lower drainages of the Nanta Gorge, Nita He, and La Grieta's Grease Rock Canyon are developed at the stratigraphic base level as defined by shale; these appear to be vadose passages and not phreatic tubes. On the west side of the Loggerhead Hall Fault no shales are present, and the base level is controlled by a former water table.

The hydraulic gradient from the Sistema Huautla Resurgence to Sump VII of Cueva de Peña Colorada is 3 percent. From the Sistema Huautla Resurgence to the Sótano San Agustín sump the hydraulic gradient is 3.7 percent, suggesting that for phreatic loops to develop a very low hydraulic gradient is necessary. There are 138 vertical meters of air-filled passage in Cueva de Peña Colorada from the top of the Whacking Great Chamber to the water level at Sump VII. From the water level in Sótano de San Agustín at –825 meters to Camp IV at –640 meters is 185 vertical meters. The hydraulic gradient from Camp IV, Sótano de San Agustín, to the top of the phreatic loop of the Whacking Great Chamber is 3.2 percent. From –520 meters in the bottom of Sótano de San Agustín's Fissure Series, the hydraulic gradient is 4 percent, only 0.3 percentage points different from the present base level (Figure 7.7). The amplitudes of the phreatic loops vary from 100 to 150 meters.

It is the author's opinion that Cueva de Peña Colorada and possibly Vine Cave were phreatic conduit systems that integrated somewhere in the Peña Colorada Canyon. That opinion suggests that erosional processes incised the canyon and intersected the conduit system. Cueva de Peña Colorada is currently the overflow system to the active hydrologic drainage. The conduit system most likely continued to a spring at the base level of the Río Santo Domingo.

In conclusion it seems likely that the hydraulic gradient has been more or less uniform as the water table has lowered to its present position (Figure 7.7). The upper-level horizontal passage development of Sistema Huautla is a relict of former base levels. Despite the fact that there is very little morphological evidence for phreatic development in the various levels, the uniform hydraulic gradient indicates that these cave tiers could have formed below a water table. It is hypothesized that most of the physical evidence of phreatic morphology in the base-level passages of Sistema Huautla has been removed by vadose modification as the system channels an average of 3.5 meters of annual rainfall through its conduits.

The current base level in phreatic portion of Sótano de San Agustín (854 Sump) does not correlate to the base level of the Río Santo Domingo. The phreatic base level passages in Sótano de San Agustín are over 300 meters higher than the base level of the Río Santo Domingo. Phreatic development from the

Sistema Huautla Resurgence to the 854 Sump of Sótano de San Agustín consists of multiple phreatic loops with varying amplitudes. In Cueva de Peña Colorada, phreatic loops have high amplitude and high frequency. The base-level phreatic loops of Sótano de San Agustín have high amplitude and low frequency (Figure 7.7).

7.8.10 Evidence of Vertical Uplift

From the highest drainage divide in the Sierra Juárez to the Río Santo Domingo, the vertical elevation differential is 2,700 meters. Since the Laramide Orogeny at the end of the Eocene, the Sierra Juárez has emerged a minimum of 2,700 meters of elevation above the regional base level as defined by the Río Santo Domingo. Helu et al. (1977) documented thick deposits of Early Miocene conglomerates in the Veracruz Basin originating from the Sierra Juárez.

This research suggests that the uppermost phreatic loop in Cueva de Peña Colorada represents a previous base level that corresponded to the regional base level. There is a 92-meter vertical difference between the entrance to Cueva de Peña Colorada (overflow spring) and the Sistema Huautla Resurgence. The vertical distance from the highest known phreatic loop in Cueva de Peña Colorada to the Sistema Huautla Resurgence is 240 meters. Since the development of the caves in the Sistema Huautla Karst Groundwater Basin, the base level has lowered at least 240 meters.

One of the largest resurgences on the east side of the Sierra Juárez is the Nacimiento Uruapan. The spring is located 400 meters above the Río Santo Domingo. Worthington (1991) stated that springs located well above base level may be indicative of uplift rates that are greater than down cutting or karstification rates. He described examples in Papua New Guinea and southwest China springs that discharge from the sides of cliffs.

The east side of the Sierra Juárez has had a greater uplift than the western portion of the range, as shown by the difference in elevation between the Sistema Huautla Resurgence at 306 meters and Nacimiento Uruapan at 500 meters elevation. The regional base level as defined by the Río Santo Domingo does not correlate with the base level of the Nacimiento Uruapan. The lack of correlation between base levels suggests that uplift has occurred since the initial development of the caves and that the eastern portion of the range is rising faster than the western portion. The rate of uplift is unknown. South of the Río Santo Domingo, uplift rates appear to be greater and may be influenced by uplift of Oaxacan basement complex. If the rate of uplift were quantified, then the age of the cave system could be ascertained. Worthington (1989, 1990, and 1991) determined the occupancy time for three cave tiers in 732-meter-deep Nelfastla de Nieva, Coyomeapan, Puebla, as having an average age of 2.5 to 4 million years.

## 7.9 Conclusion

Evidence indicates that Sistema Huautla's development is related to the regional tectonics. Fluvial systems flowing across the carbonates disappeared during the Early Miocene as the mountain range uplifted. While the rate of uplift is unknown, it must have been consistent enough to saturate almost 1,000 vertical meters of rock fractures and bedding planes. Early protoconduit development indicates a deep circulation to a base level spring followed by gravity drainage of the phreatic skeleton (Figure 7.9).

Slope retreat of a clastic cap rock provided early allogenic input to some point east of the present position of the cap rock. Allogenic recharge and more than 3 meters of annual autogenic recharge are responsible for vadose passage development.

Karstification processes in the development of dolinas have isolated cave entrances on the sides of dolinas and on narrow ridges. Surface karst features are more recent than the subterranean drainage system.

Uplift has been more or less continuous since the cave system has developed, as determined by the presence of cave levels and the elevation of the largest spring in the sierras, Nacimiento Uruapan, which is well above present base level. Diving in the Nacimiento Río Frío de Santa Ana has revealed that stalactites occur 30 meters below the water table at regional base level (Farr, 1994). The presence of stalactites in flooded passage may indicate that the passage was uplifted and the conduit was drained allowing the stalactites to form. Subsequent flooding of the conduit may be attributed to tectonic lowering of the base level. Reflooding of the conduit implies that uplift has not been uniform and that a lower phreatic level may exist below the present level. As an alternative to tectonic uplift and subsidence, the base level of the Río Santo Domingo could have been 60 meters deeper and then buried by an influx of sediments or alluviated. Alluviation would also raise the water table and reflood paleo-phreatic tubes. If the base level of the Río Santo Domingo was once lower than the present level, then a lower tier of phreatic passage may exist below the explored phreatic level at Sistema Cuicateco and Cueva de Peña Colorada.

There are at least two recognizable base levels and a hypothesized third lower level below the presently active phreatic system in the Sistema Huautla

Karst Groundwater Basin. The present base level as defined by the Río Santo Domingo slopes up into the basin to the lowest level of Sistema Huautla with a hydraulic gradient of 3.7 percent.

A calculated hydraulic gradient of 4 percent from the top of the highest phreatic loop in Cueva de Peña Colorada to the –600 meter level in Sótano de San Agustín defines the highest original base level for Sistema Huautla. The levels in the cave system may not be related to regional base level, but instead be levels as defined by the original flow net. When comparing cave tiers in Sistema Huautla to Sistema Cuicateco and Nelfastla de Nieva, none of the caves show levels correlatable to past regional base levels. Distinct tiers within each cave also show no correlation to each other.

The entrances of Cueva de Peña Colorada and possibly Vine Cave are the original conduits that fed springs along the Río Santo Domingo.

The caves of the Sistema Huautla Karst Groundwater Basin reveal a multi-phase development, comprising elements of a drawdown-vadose cave, invasion-vadose cave, paleo-phreatic levels, seasonally active paleo-phreatic caves with multiple loops, and phreatic levels that are largely unexplored.

Worthington (1991) indirectly established the age of the deep vertical Nelfastla de Nieva between 7.5 and 12 million years from the occupancy time for three cave tiers. The lower section of the cave is at 732 meters above sea level or 432 meters above the elevation of the Sistema Huautla Resurgence. Worthington stated that the tiers are separated by a mean of 230 meters. There should be two more tiers to regional base level if there is uniform cyclicity. If so, then the age range for cave development is between 10 and 16 million years, which correlates to the Early-Middle Miocene uplift. Other caves in the Sierra Juárez Geologic Subprovince way be of comparable age.

However, Sistema Huautla may not be 10 to 16 million years old. It is hypothesized that Sistema Huautla developed as the clastic cap rock was removed. As a result there was 700 to 800 meters of relief above the active phreatic base level in the karst aquifer. If there was an average of 1 millimeter of uplift per year, then it would only take 700,000 to 800,000 years for the Sierra Mazateca to rise 700 to 800 meters. Two hundred meters of relief between the uppermost paleophreatic level and the bottom of the active phreatic level in Cueva de Peña Colorada may have developed in 200,000 years. It is hypothesized that Sistema Huautla is less than two million years old. More work is necessary to determine the age of Sistema Huautla.

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