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HYDROLOGY OF A LARGE, HIGH RELIEF, SUBTROPICAL CAVE SYSTEM: SISTEMA PURIFICACION, TAMAULIPAS, MEXICO

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Sistema Purificación, a 82 km long and 955 m deep cave system in the northern Sierra Madre Oriental of México, is developed on the western flank of the Huizachal-Peregrina anticlinorium in the middle Cretaceous Tamabra and underlying Tamaulipas Formations. Impervious beds above and below the cave cause groundwater to flow to the surface, resulting in many small springs. Larger springs emerge from karst conduits in the lower Tamaulipas Formation, particularly during and after intense rains.

Streams in the upper portion of the system mostly follow the dip of bedding near the Tamabra-Tamaulipas contact until trapped in the trough of a third-order syncline. Vadose flow in the middle part of the cave system follows axial plane fractures. The trough of the north-trending Infiernillo syncline, and the impervious underlying La Joya beds act as a local hydrologic barrier perching water in the lower carbonates and filling chambers in the lowest parts of Sistema Purificación.

The Sistema Purificación is the sixth longest (82 km of explored passage) and seventh most vertically extensive (955 m deep) cave system surveyed in the Western Hemisphere. Elevations within the area, which is 50 km northwest of Cuidad Victoria, Tamaulipas, México, range from 490 m msl in Cañon los Hervores to 2780 m msl on Mesas Juárez (Fig. 1).

Most of the area is a well-developed karst terrain with little surface drainage despite moderate rainfall. No permanent surface streams flow into the area although a river in the Arroyo Luna enters during heavy flooding. Rainwater mostly sinks underground before accumulating into streams. Even during heavy rains, water rapidly disappears into the ground at cave entrances, dolines, or along slightly enlarged joints in the limestone. Impermeable chert beds and shale layers force the water to the surface, generally as small (one to five liters per second) seeps.

Controlling factors for the development of the hydrologic system are the structure, stratigraphy, and lithology. Specifically, they are:

1. The folding and joints that have developed near the axial surface.
2. Bedding planes and their orientations.
3. The initial permeability of the limestone units.
4. The solubility of the limestone units.
5. The low permeability of chert beds in the Tamabra Formation and the shale layers in the Taraíses, La Caja, and La Joya Formations.

CLIMATE

The climate is temperate with moderate annual precipitation. The closest weather station, Estación El Barretal at an elevation of 196 m along the Río Purificación, has a mean annual rainfall of 780 mm. Rainfall is greatest in the summer

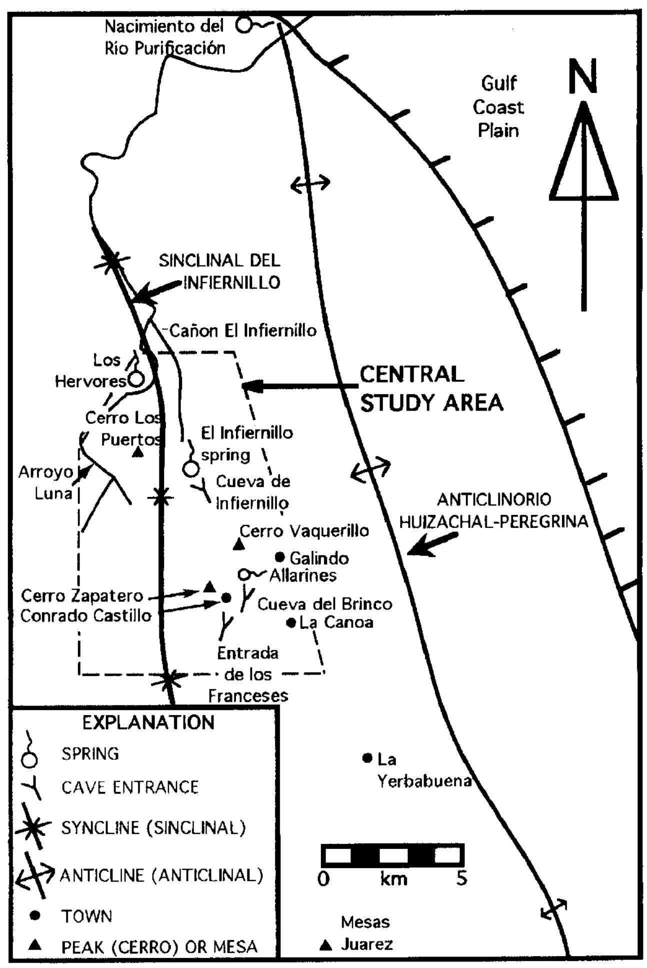

Figure 1. Map of geographic features in the Purificación area.

months and the dry season extends from approximately November through March (Fig. 2). The surface is rugged and mostly a pine-oak forest. Frost is common during winter nights but snow is rare. Moisture from the coastal plain to the east often causes clouds to engulf the mountains and humid, subtropical undergrowth covers shaded areas.

Geologic Setting

The Purificación area is on the western flank of the approximately north-south-trending Huizachal-Peregrina anticlinorium (first-order fold). Differential compression caused by the broad folding of the range in front of the Laramide Thrust Belt resulted in a major, second-order syncline called Sinclinal de Infiernillo about one kilometer west of the cave. This fold caused abundant third-order folds that significantly influence the development of the cave system .

The cave is contained within an ~800 m thick sequence of Upper Jurassic to middle Cretaceous marine sedimentary rocks, mostly carbonates (Carrillo-Bravo, 1961). Detailed descriptions of the stratigraphy and structure of the area are provided (Hose, 1996).

Surface Drainage

There is no surface water flowing into the area and all springs, with the exception of Los Hervores, return underground within the central study area. During and after heavy rains, surface water flows down Arroyo Luna. Runoff also floods the subterranean conduit system and the excess water flows through the lower surface canyon, el Infiernillo. All water ultimately joins the Río Purificación to the north (Fig. 1) and flows eastward to the Gulf of Mexico.

Sinks (Input Areas)

Water flows underground at sinks that are common in the carbonate terrains. Most sinks are fractures in the rocks. Some are only a few centimeters across while others are dolines tens of meters in diameter and greater than 100 meters deep. A few sinks are also the entrances to large caves (Sumidero de Oyamel) or deep pits (Pozo Obscuro). Many of the larger dolines have vegetated floors.

Sinks in the highest unit in the area, the Tamabra Formation, captures surface water before any large streams form, even during heavy rains. The water enters fissures and caves and in many places joins the streams in Sistema Purificación. The karst in the region is sufficiently developed to pirate rainfall quickly underground as nearly diffuse input and accounts for the lack of surface streams.

The underlying Tamaulipas Formation does not have any cave entrances that take water and surface water generally enters the subterranean system as diffuse flow through small fissures. However, at several places in the Cañones el

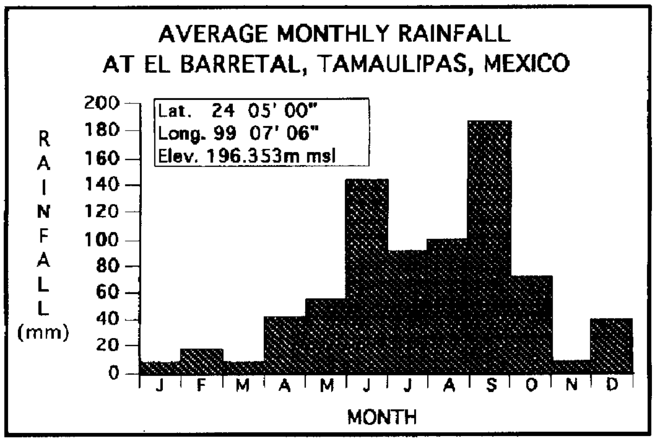

Figure 2. Average monthly rainfall at El Barretal, Tamaulipas, México over a sixteen year period (1960 to 1975).

Infiernillo and los Hervores, large streams sink in the gravel streambed within the Tamaulipas. Surface streams flow beyond these points after heavy rains either because the conduit system is not sufficiently developed to handle the flow or input zones are partially blocked.

The shale beds in the Taraíses and La Caja Formations below the Tamaulipas inhibit the development of karst conduits. Surface water goes underground in a diffuse manner, often reappearing on the surface above shale beds. Dolines with vegetation and soil on the bottoms are common in the La Caja near Galindo. Water flows quickly into the subsurface and does not pool at the bottom of these depressions.

Surface streams on the Cretaceous carbonate terrains are rare throughout the surrounding mountains. While this study includes the surface overlying all of the known passage of Sistema Purificación, the total system probably extends beyond these boundaries to the south. The plateaus of Mesas Juárez have well-developed karst surfaces that pirate rainfall underground (Fig. 3). The probable destination of that water is Sistema Purificación.

Springs (Discharge Areas)

Two factors force the subterranean water to the surface. The more common reason is that water, following a path along fractures and bedding planes enlarged by dissolution, encounters a chert or shale bed with low permeability and is forced to the surface. The second, and larger, type of spring only flows after heavy rains overload the lower, phreatic portion of Sistema Purificación.

Springs within the Tamabra Formation are small and result from groundwater moving through solutionally enlarged fractures until reaching an insoluble and impermeable chert bed where the water is perched and sometimes overflows to the surface. These springs are important water supplies to the

Figure 3. Karst field on Mesas Juárez.

people living nearby but they occasionally cease flowing in the spring months after the relatively dry winter.

Karst floodwater springs are restricted to the lower part of the Tamaulipas Formation. Four springs are known to flow after heavy rains. They are within 400 m of each other, near the head of Cañon el Infiernillo. Water issues from the entrance to Cueva el Infiernillo as a result of a rise in the water table during and after heavy rain. The cave entrance has the highest elevation of the four springs and is the first to quit flowing as the local water table level recedes. The other three flow for periods of up to several months, the lowest in elevation flowing for the longest period. Their geographic locations and behavior indicate a connection with the phreatic system in the cave.

A permanent spring of about 30 liters per second base flow rises in Cañon los Hervores but sinks into the gravel of the streambed before the canyon joins the Río Purificación. Los Hervores is a vauclusian, or boiling, spring. Water wells up through a tube in either the lowest Tamaulipas or highest Taraíses limestones under hydrostatic pressure. The forced flow causes a "boiling" effect, for which the spring is named. Such springs have been interpreted as rising from large underground reservoirs (Sweeting, 1973). This spring, the largest permanent water source in the central study area, is along the hinge line of one of the many tight, third-order anticlines west of Cañon el Infiernillo (Hose, 1996). The source of the flow is probably a streambed gravel and sand sink about 1500 m upstream and other sinks further south in Arroyo Luna. As the spring is located west of the second-order Infiernillo syncline trough, it is doubtful that the water in Sistema Purificación finds its way to this spring. Arroyo Luna drains 228 km² of surface area upstream from Los Hervores. While permanent streams do not flow through most of the channel, there are several permanent stream segments that rise and sink upstream from Los Hervores. This water and phreatic flow through the limestone near the stream channel are probably the sources of Los Hervores.

All of the known springs in Arroyo Luna and Cañon los Hervores are near the Tamaulipas-Taraíses contact. The water is apparently forced to the surface by the shale beds in the Taraíses Formation. The spring water flows along the surface channel to the point where the shale beds in the Taraíses Formation dip underground. Where the water again flows over the nearly homogeneous Tamaulipas Formation, the stream sinks in the stream alluvium and small fractures in the limestone.

The only other springs near the Tamaulipas-Taraíses contact are near La Canoa. There are several small seeps formed by groundwater flowing down dip above shale partings within the limestone until the water intersects the cliff. Unlike other springs in the area, these springs are supersaturated with respect to calcite when they reach the surface and large travertine deposits have formed below them.

There are many small springs and seeps in the limestone and interbedded shale of the Taraíses and La Caja Formations. They are the result of flow along bedding planes and fractures where groundwater is perched above shale layers. Many of these springs do not flow in the relatively dry spring months. Nearly permanent springs of this type are about 200 m west of La Curva, 300 m southwest of Puerto Purificación, 300 m west of Galindo, and in Cañon los Hervores.

The shale beds within the La Joya Formation cause small springs throughout its exposures. Groundwater passes through the sandstone and conglomerate beds as diffuse flow but is perched above the shale layers. Flow continues downdip until it reaches the surface. The largest spring in the La Joya Formation within the central study area is about ten meters below the contact of the La Caja and the La Joya Formations (1000 m msl) in the upper Cañon el Infiernillo. This is the probable resurgence of the Sistema Purificación. The rising water continues to flow northward along the surface channel as it crosses the outcrops of the La Joya and La Caja Formations downstream. The stream sinks downstream in alluvium above bedrock of either the Taraíses or Tamaulipas Formations.

During and after heavy rains, the flow from springs in Cañones los Hervores and el Infiernillo is too large to be handled by the sinks. At these times, some of the water sinks and the remainder continues to flow across the limestone in the surface channels. However, even at these times the streams sink again, to the north of the central study area. Whether surface flow is ever continuous to the Nacimiento del Río Purificación during intense rainfall, such as hurricanes, is not known.

The waters from Sistema Purificación, Cañon el Infiernillo, and Cañon los Hervores probably surface as part of the Nacimiento del Río Purificación, about 12 km north of the central study area. This large spring is the source of the large, southernmost tributary that makes up the Río Purificación (Fig. 4). The quantity of water and the different chemical components indicate that the Nacimiento receives water, at least in part, from different terrains than the Purificación area (Table 1).

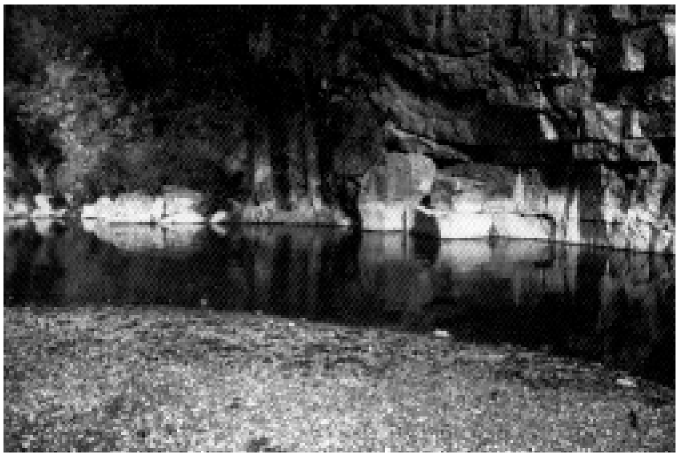

Figure 4. Nacimiento del Río Purificación. Water rises from fissures at the base of the cliff.

HYDROLOGY OF SISTEMA PURIFICACION

The hydrologic system of Sistema Purificación can be divided into three components: 1. input streams in the upper cave; 2. middle cave streams; and 3. phreatic system and lower cave.

UPPER CAVE

Input streams, commonly within the Tamabra Formation, generally flow from east to west down the dip of bedding planes along intersecting fractures in the limestone. These streams are small and have base level flows of only a few liters per second or less. The Valkyrie River, First Stream, and Río Verde are permanent input streams which have unknown sources and destinations (Fig. 5). They probably result from collections of diffuse flow, but the water has not been traced. Many other smaller streams flow during, and for a few days after, heavy rains. The input streams flow westward to the trough in bedding caused by the third-order syncline at the Canal and the Nose Dives. Water that has penetrated to the Tamabra-Tamaulipas contact is pooled in this trough, forming two near-sumps.

MIDDLE CAVE

Several stream segments make up the middle cave streams. These streams flow along a trend between N5°W and N10°W, following fractures near the axial surfaces of the anticline and syncline that crop out at the surface near Conrado Castillo (Hose, 1996). This axial plane cleavage has provided zones in the limestone of high permeability, enhancing water flow, dissolution, and the development of conduits along these joints. The streams mostly flow parallel to the folds, along the strike of beds and lose elevation along joints.

Table 1. Hydrochemistry of the Sistema Purificación area. Samples PW9 and PW10 are interpreted by this study to not be associated with the Purificación system. Sample 7 is a major resurgence that drains a large portion of the mountain range, probably including waters from the Purificación system.

SAMPLE	LOCATION	ELEVATION	pH	Conductivity	°C	Fe	Mg	Ca	Na	K	HCO_3	SO_4	Cl	log PCO_2
	Upper Springs													
PW2	Allarines	1980 m	7.4	210	16	0	5	105	4	<0.5	85	4	<50	-2.5
PW5	Conrado Castillo Well	1945 m	7.1	220	13	0	7	104	1	1.9	85	<1	<50	-2.2
	Cave													
PW3	Laguna Verde	1806 m	8.1	135	16	0	11	95	2	1.0	82	4	—	-3.2
PW8	World Beyond	1715 m	8.0	170	16	0	20	83	1	<0.5	73	2	<50	-3.1
PW4	Turkey Lake	1296 m	—	—	17	0	18	53	1	<0.5	—	<1	<50	-3.3
PW6	Isopod River	1290 m	8.3	210	17	0	27	77	1	<0.5	92	3	<50	-3.3
PW12	Main Sump	1070 m	8.3	190	17.25	0	27	85	1	<0.5	86	3	<50	-3.4
	Lower Springs													
PW11	Canon El Infiernillo	635 m	8.5	200	21.5	0	18	73	1	<0.5	73	2	<50	-3.6
PW9	Arroyo Luna	530 m	8.2	175	22	0	15	87	1	<0.5	79	0	<50	-3.3
PW10	Los Hervores (Fall 1979)	490 m	—	—	18	0	9	64	1	<0.5	—	<1	<50	—
PW1	Los Hervores	490 m	7.8	200	19.5	0	17	90	1	<0.5	85	<1	<50	-2.9

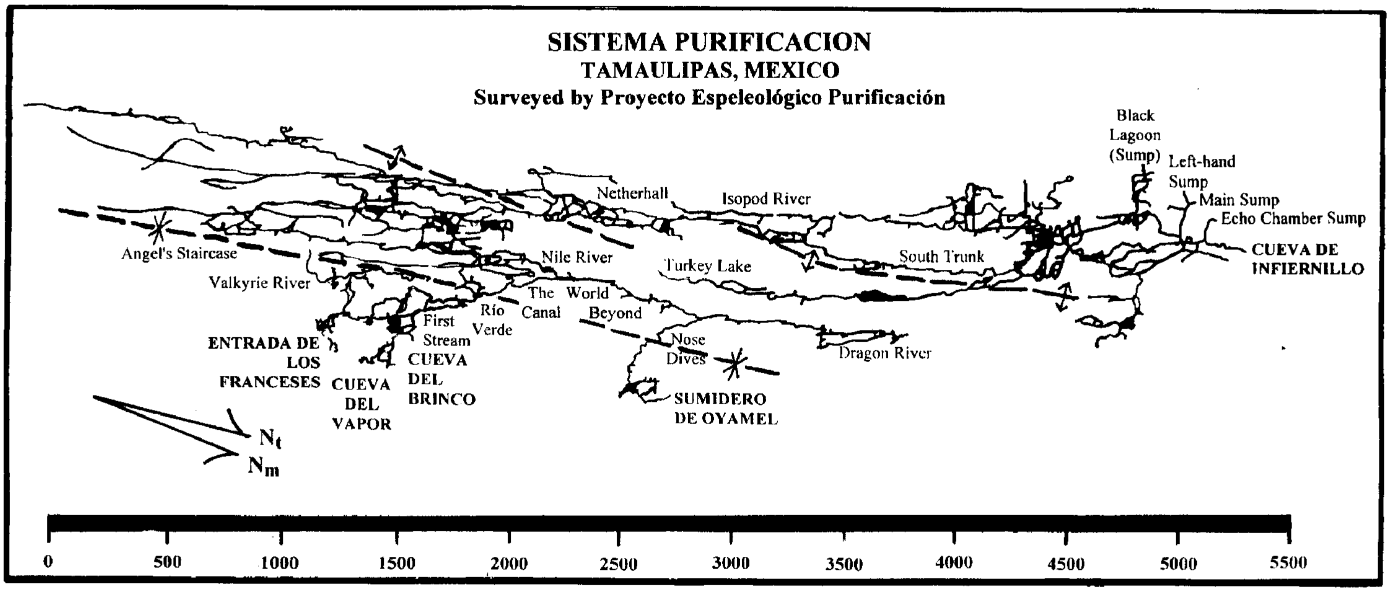

Figure 5. Plan view of Sistema Purificación showing crests and troughs of major folds.

Dragon River, The World Beyond, Nile River, and Isopod River are the major middle cave streams. Dragon River is formed in the lower part of the Tamabra Formation. Compression of the limestone near the synclinal axial plane resulted in numerous smaller, complementary folds, exposed in the walls and ceilings of the cave passage. Whether Dragon River water joins the World Beyond stream, or where the water may reappear within the system, is unknown.

The stream in the World Beyond flows along strike near the top of the Tamaulipas Formation. Water from the World Beyond passes into a pinch before reappearing slightly west and to the north where it flows down the Angel's Staircase, losing elevation through joints. The terminal sump of the Angel's Staircase is lower than Lake Victoria, the source of the Nile River. It is not known where, or if, the World Beyond water reappears in the known cave.

Tens of liters of water per second were added to the World Beyond at about six sites during a heavy, 12-hour, summer rain (Hose, 1994). Most of the sites are marked by flowstone deposits (Oztotl's Throne and Hall of Angels) and/or minor dripping during the dry season. Sites of numerous smaller waterfalls during the flood have no flow during the dry season. Densely fractured rock along the synclinal axial plane above the World Beyond provides convenient, dispersed paths for rapid input into the system during heavy rains.

The Nile River flows through nearly flat-bedded Tamaulipas limestone near a décollement under the third-order folds. The beds are only gently folded, but the stream flows parallel to the axial surface along complementary fractures. Flow in the Nile River in the dry season (early spring) has been estimated to be between eight and 30 liters per second. The Nile River is last seen in a pinch and its destination is uncertain.

Isopod River is approximately the same size as the Nile to its south and flows through the Tamaulipas Formation in a structurally similar position. Although a hydrologic connection has not been proven, it is likely that the two streams are the same water and much of the missing stream segment flows through the breakdown on the floor of the Netherhall. The Isopod River passes through a sump and re-emerges as the Babylon River (Sprouse, 1994, written communication).

Four new streams have been discovered and explored in the middle portion of the cave during the last decade. The relationships between Midnight, Flaming Nose, Tokamak/Texas, and Enigma streams have not yet been determined.

Lower Cave

The lowest part of the exposed hydrologic system is a group of sumps in Cueva el Infiernillo. Four sumps are known and have water at or near the same elevation at any given time, although the water levels appear to constantly fluctuate. The sumps are the manifestation of a perched water table that results from the underlying impermeable shales in the Taraíses, La Caja, and La Joya Formations, and the trough formed by the Infiernillo syncline, about 200 m west of the sumps. Recent underwater exploration of two of the sumps reached ~1005 m msl, only about five meters above the probable resurgence for the system in Cañon el Infiernillo. Exploration ended at a large, upward sloping breakdown pile (Sloan, 1993). About 40 m above this depth, the diver noted that "the wall no longer appeared as solid rock" and instead appeared to be calcite encrusted mud, possibly marking the transition from the Tara'ses limestone to the underlying, argillaceous La Caja Formation.

FLOODING EVENTS

During and after hurricanes and other heavy rains, many of the explored passages are flooded. One flood that resulted from a storm of 19 cm of rain in a 50 hour period in Conrado Castillo was observed by the author in December 1979 (Hose, 1994). Input and middle cave streams increased in volume and new streams flowed. The Canal and the Nose Dives filled to the ceiling and closed access to the middle cave. The middle streams were not observed, but water-filled depressions in the cave indicated that the streams rose tens of meters into what must have been raging rivers. (Waterlines in the normally dry Netherhall record floods in the past where water, probably from the Nile/Isopod River, has risen more than 60 m as it flowed through the breakdown-filled floor.) Most of the input and middle streams subsided to near-normal flow levels within three days after the rain stopped.

The sumps in the Cueva el Infiernillo rise tens of meters during heavy rains. Such a rise of the sumps during the December 1979 storm caused the system to back-up and flow out the entrance of Cueva el Infiernillo. Following a relatively dry summer and fall, the Main and Left-hand Sumps are believed to have been at approximately 1058 m msl and rose ~64 m to an elevation of 1122 m msl within three-and-a-half days after the rain started (Fig. 6). The rise stopped at this level as the system found a balance between the water entering the sumps from the higher streams and the water leaving the system through the springs in Cañon el Infiernillo, including the large cave entrance at 1102 m msl (Fig. 7). The flood rose to ~1268 m msl in the South Trunk.

The first spring to ceased flowing after the rain stopped was the highest, the Cueva el Infiernillo entrance. The sump level in the cave rapidly retreated, dropping as fast as one centimeter per minute in a passage 12 m wide and 10 m high. The consequent opening of previously flooded rooms to the cave's barometric system caused great movement of air and resulted in an occasional roaring wind that created waves up to five millimeters in amplitude on the surface of the water.

By the time the water level dropped to Camp I, ~1086 m above msl, the easternmost spring quit flowing. The middle spring was the next to dry up. The spring below the cave entrance has been observed to flow for more than two months after a flood (Treacy, 1979).

The decline curve in Figure 6 is based on only five measured levels of the Main and Left-hand Sumps and on high-water marks. Water in the Echo Chamber Sump was approximately the same elevation as the others at all times. The disruption in the curve at 170 hours may have been due to a delayed pulse of water being added from the upper system or by a change in the total area of the passages being drained. If a fixed amount of water is draining from the system, at levels of small tubes with steep slopes the water will drop in elevation quicker than when draining large rooms. It is possible that large rooms or passages were being drained at about 170 hours and temporarily slowed the rate of decline without a change in the input/output ratio for the system.

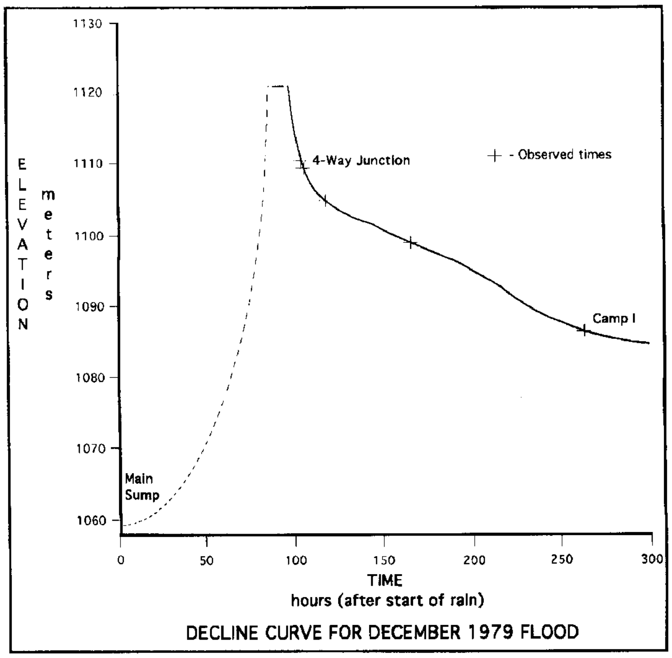

Figure 6. Decline curve for the December 1979 flood. Data used in the graph were measurements made on the Main Sump/Left-hand Sump as the combined sumps receded from the Four-Way Junction area in Cueva el Infiernillo.

HYDROCHEMISTRY

The chemical analyses presented in Table 1 are the results from a single sampling from each site during March and April 1980, except Los Hervores which was sampled on two occasions. The waters were collected in new, clean plastic bottles that were rinsed with the sample waters and drained three times before collecting. The bottles were filled and capped while held at least 15 cm below the water surface. A second sample bottle was filled and nitric acid added later to lower the pH and prevent precipitation of calcite. The samples were not filtered, thus the reported values of Ca^{+2} represent total calcium, includiing particulates. The temperatures of the waters were measured by a field thermometer graduated in 1° C intervals. Values of pH were determined by using a digital read-out pH meter using double buffer calibration which is accurate to within ±0.05 units. The meter was calibrated for each reading, and buffers were at the same temperature as the samples. Conductivities, indicating the total dissolved solids contents, were measured by a small field conductivity meter. All these measurements, except pH for the Laguna Verde, World Beyond, and Isopod River waters, were done at the sites. Bicarbonate measurements, either at the sites or within a half-hour after sampling, were made by potentiometric titration with an estimated error of ±10% (Hess, 1994, written commu-

Figure 7. Entrance to Cueva de Infiernillo. An ephemeral pool of water rises from behind boulders to the immediate right of the photograph.

nication). Cations were determined later by an atomic absorption spectrophotometer, and sulfate and chloride concentrations were measured using a Hach water quality kit in the lab. Several samples contained less sulfate and chloride than the minimum detection limits of one milligram per liter and 50 milligrams per liter, respectively.

All of the water collected in the central study area had a low total dissolved solids content and was slightly alkaline (Table 1). All but sample PW1 were collected in the spring of 1980 during low water flow and while the levels in the sumps were dropping. Iron, sodium, potassium, and chloride concentrations were generally too low to be accurately measured by the methods used. Sulfate concentrations were also low, even in the sump and lower springs, and indicate that the waters do not reach the level of the evaporites of the Olvido Formation, if they exist under Arroyo Luna and the Cerro Los Puertos ridge.

Samples PW2 and PW5 had relatively high calcium values and were collected at the two highest elevations. Both sources are water forced to the surface, or near it, by beds of chert in the Tamabra Formation. Agua los Allarines is a flowing spring and the Conrado Castillo well, where water pools in a small solution pocket, is only about three meters deep. The lower pH of these two samples probably indicates relatively short passage in the underground and close proximity to the source areas.

The partial pressure of carbon dioxide progressively decreases with decreasing elevation. It is important to note, however, that these samples represent low, dry season flow, which is probably not directly relevant to speleogenesis. Dry season samples probably accentuate the contributions of diffuse groundwater flow and minimize the characteristics of conduit waters. The only site sampled in Fall 1979, at the end of the wet season, contained 41% lower concentration of Ca and was more than a degree Celsius lower temperature than the same site three months into the dry season (Table 1, PW1 and PW10). These data suggest that the average residence time for the groundwater feeding Los Hervores is much longer during the dry season than during the wet season. This is probably also true within Sistema Purificación.

One water sample (PW7) was collected and measured from north of the central study area at the river resurgence, Nacimiento del Río Purificación (Fig. 1). The water showed substantially different chemical concentrations than the others in this study. Although the waters from Infiernillo canyon and from Los Hervores probably re-emerge at the Nacimiento, the chemical signatures indicate other sources as well. A sulfate concentration of 100 milligrams per liter may result from dissolution of evaporite beds in the Olvido Formation.

Discussion

The central study area is divided into several hydrologic systems, all of which ultimately drain into the Río Purificación to the northeast (Fig. 1). Rain falling near the eastern boundary flows along the surface to the east, over the La Joya Formation. The shale beds in this unit are nearly impermeable and forcing the rising of many springs. Similarly, the shale beds in the La Caja and Taraíses Formations commonly force groundwater to the surface. The La Caja and Taraíses are poor cave formers and probably cause the restrictions in the phreatic passages of Sistema Purificación that force the water to rise and overflow out Cueva el Infiernillo during heavy rains. However, the system's water at base flow apparently is not forced to the surface until it reaches the La Joya Formation and emerges at the bottom of the La Caja at ~1000 m msl in Cañon el Infiernillo.

Bedding planes and joints in the thick-bedded Tamaulipas Formation provide good conduits. Water flows down the dip, along the intersection of joints and bedding planes, on the flanks of folds. Near the axial surfaces of the anticlines and synclines, the passage development is nearly along strike, typically along the intersection of a bedding plane and a joint parallel to the folding, or dropping along fractures.

Groundwater flow in the Tamabra is enhanced by its susceptibility to karst development but inhibited by beds of chert. Water entering the ground above the chert beds either continues flowing downward through fractures in the chert near axial surfaces, as in the physically unconnected cave Sótano de la Cuchilla, or is forced to the surface after perching on the chert. Surface flow returns to the subterranean system after passing the chert bed. Water entering the Tamabra Formation below the bedded chert gathers in karst conduits and joins the karst hydrologic systems in the underlying Tamaulipas Formation.

The water flowing out of the central study area travels in two directions. Along the eastern boundary, the water leaving the area mostly travels on the surface to the east into Cañones El Rosario and El Olmo, and Cañada Guayabas. All these streams continue eastward to join the Río Purificación. The water from Sistema Purificación and Cañon el Infiernillo travels a subterranean route after leaving the central study area, except during floods. The flow from Los Hervores leaves the area on the surface but also goes underground to the north during base flow conditions. Although not confirmed, this water probably re-emerges from the karst springs at the Nacimiento del Río Purificación, along with waters from other parts of the mountain range.

The sumps in the lowest portions of Sistema Purificación are exposures of a localized, perched water table resulting from underlying, impermeable shale beds and the Infiernillo syncline to the west. The structure prevents groundwater from migrating to the east or west. Groundwater flow is further slowed in its downward progress by the poor conduit-forming limestone and interbedded shale in the Taraíses and La Caja Formations. The water probably passes through constricted passages in these units and emerges in Cañon el Infiernillo, approximately 800 m north of the Echo Chamber Sump.

The spring in Cañon el Infiernillo is probably only a part of the flow leaving Sistema Purificación. Some phreatic water may pass through the Taraíses and La Caja Formations and partially enters the clastic sediments of the La Joya Formation. Perched by the shale beds in this unit, some of the water overflows at the spring in Cañon el Infiernillo. The rest of the water probably flows through the conglomerate and sandstone beds of the upper La Joya northward along the trough formed by the Infiernillo syncline. If the Olvido Formation is present west of Cañon el Infiernillo, the water may gain sulfate ions. Such water probably emerges at the Nacimiento del Río Purificación, since none of the springs in the central study area have measurable sulfate ion concentrations.

The Infiernillo syncline and accompanying folds west of Sistema Purificación prevent the water from joining the hydrologic system in Arroyo Luna. The water at Los Hervores is probably from sources west of the cave system. Intense folding along the west limb of the syncline prevents water from flowing eastward into the Purificación system.

The southern boundary of the source area for the water in Sistema Purificación is unrecognized and further study is needed to identify it. Most of the groundwater in the study area south of Cañon el Infiernillo and between the Infiernillo syncline and an anticline through Cerro Vaquerillo probably enters the cave system. The source area probably extends south along a structural corridor approximately two or three kilometers wide.

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