

GEOLOGY OF A LARGE, HIGH-RELIEF, SUB-TROPICAL CAVE SYSTEM: SISTEMA PURIFICACION, TAMAULIPAS, MEXICO

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Sistema Purificación, a large cave system in the northern Sierra Madre Oriental of México, is developed in the middle Cretaceous Tamaulipas and overlying Tamabra Formations. The 400 m thick sequence of carbonates formed in a basinal to peri-platform environment north and northeast of the simultaneously developing, large carbonate Miquihuana Platform. The Tamaulipas Formation is stratigraphically underlain by shaly limestone, shale, sandstone, and conglomerate of the Early Cretaceous Taraises, the Late Jurassic La Caja, and the Late Jurassic La Joya Formations.

The cave system is within the west flank of the Huizachal-Peregrina anticlinorium, one of many large Laramide folds making up the Sierra Madre Oriental. Most of the lateral shortening within the carbonates was accommodated by slippage along décollement surfaces and abundant second-, third-, and fourth-order folds. Except along décollement surfaces, faults are rare and have separations of less than three meters. Steeply inclined joints mostly trend ~N5°W and represent axial plane cleavage resulting from Laramide folding.

The principal geologic factors controlling the development of the Sistema Purificación are the stratigraphy and structure of the area. Passages in the upper and lower cave commonly form along the intersection of joints and bedding planes, sub-parallel to the dip. The middle part of the cave is within a third-order, anticlinal-synclinal pair whose north-south trending axial surfaces are about 150 m apart. Passages are mostly developed sub-parallel to the axial surfaces where cleavage provides zones of permeability and enhanced conduit development.

The objective of this study was to determine the geologic controls on development of the Sistema Purificación, the longest known cave system in Mexico (Sprouse, 1992). Total surveyed length is 79.1 km, which places Sistema Purificación as the 6th longest known cave system in the Western Hemisphere and the 13th longest in the world (Gulden, 1992). The cave system has been described in numerous articles concerning the original exploration (Sprouse, 1977a, 1977b; Sprouse, Ubico, & Cavanaugh, 1977; Treacy, 1979, 1980) and in the annual journal, *Death Coral Caver*, which covers cave exploration activities in the area and is published by Proyecto Espeleológico Purificación. Sixty-seven other caves have been explored within the area of this investigation.

Sistema Purificación is developed in a thick carbonate section within the front range of the Sierra Madre Oriental. The rugged area, approximately 50 km northwest of Ciudad Victoria (Fig. 1), rises two kilometers above the coastal plain. Presently, the total mapped depth of 955 m makes this cave the seventh most vertically developed system in the Western Hemisphere.

STRATIGRAPHY

INTRODUCTION

The total stratigraphic section of the study area is approximately 800 m of marine sedimentary rocks, mostly carbonates.

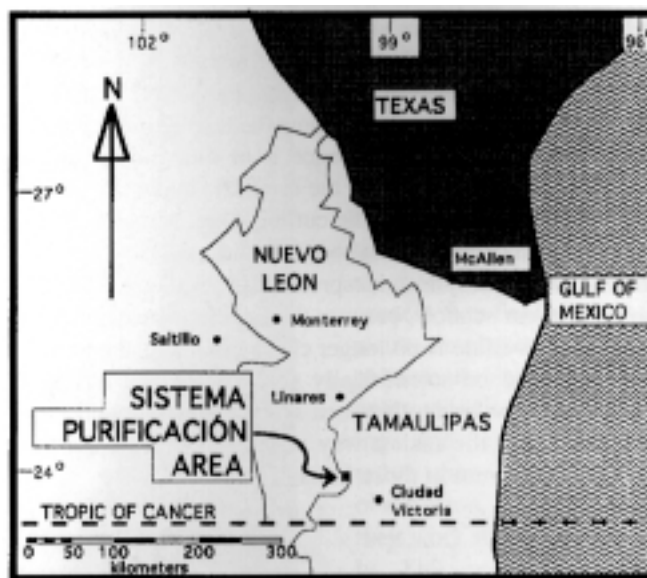


Figure 1. Location map of the Purificación Area.

Shaly limestone, shale, sandstone, and conglomerate make up the oldest unit, the Upper Jurassic La Joya Formation. The Upper Jurassic La Caja and the Lower Cretaceous Taraises and Tamaulipas, consisting of basinal limestone and shale, overlie the La Joya. The youngest rocks are overbank deposits of the

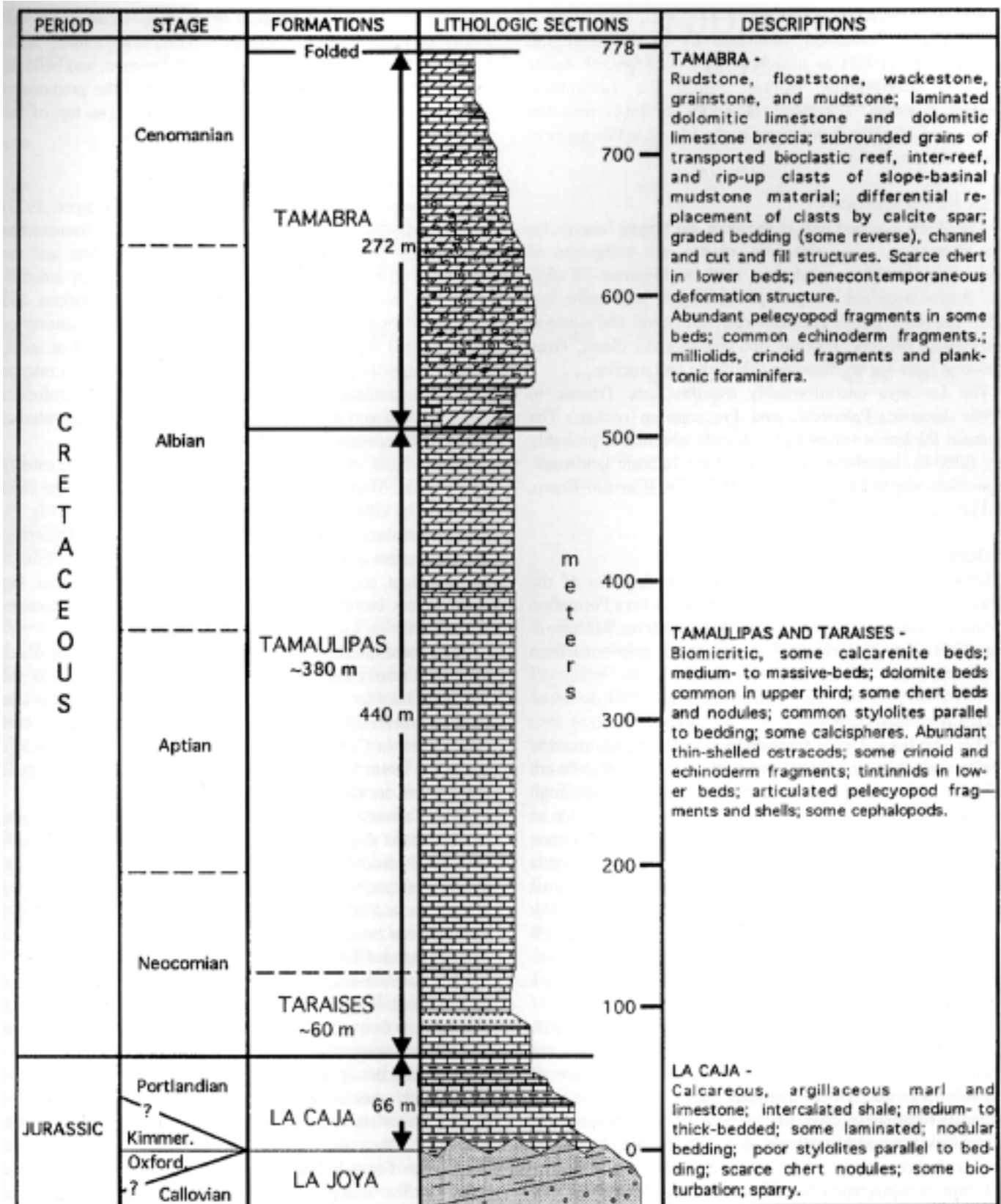


Figure 2. Generalized lithologic section and age boundaries near Conrado Castillo, Tamaulipas, México. Fossil identifications and stage divisions are based on work by Atkinson (1982).

middle Cretaceous Tamabra Formation (Fig. 2).

The Otates Formation, described by Enos (1974) and Carrillo-Bravo (1961) as a well-defined, widespread, easily mappable stratigraphic marker within the Tamaulipas sequence, is absent. The entire calcareous section between the Taraises and Tamabra Formations is considered in this paper to be the Tamaulipas Formation.

LA JOYA FORMATION

The oldest exposed unit in the area, the Upper Jurassic La Joya Formation, is a calcareous, clastic unit composed of shale, shaly limestone, sandstone, and conglomerate. It typically forms steep but not precipitous slopes, with some low cliffs. The red to purple conglomerate, sandstone, and siltstone beds contain siltstone, igneous, and metamorphic clasts. Gray limestone beds are argillaceous calcilutite and micrite.

The La Joya unconformably overlies Late Triassic to Middle Jurassic, Paleozoic, and Precambrian rocks. The sequence thickness varies and is locally absent. It probably only filled in depressions in the pre-Late Jurassic landscape. Deposition stopped early in the Oxfordian (Carrillo-Bravo, 1961).

OLVIDO AND ZULOAGA FORMATIONS

Upper Jurassic carbonate and evaporite deposits of the Olvido and Zuloaga Formations overlie the La Joya Formation in some canyons to the east and southeast (Mixon, Murray, & Diaz, 1959; Carrillo-Bravo, 1961) but do not crop out within the study area.

LA CAJA FORMATION

The 70 m thick, Upper Jurassic La Caja Formation consists of calcareous shale and shaly limestone. Beds are 10 to 50 cm thick with ubiquitous, poorly developed stylolites. Although the unit is similar to the age-equivalent La Casita Formation as described by Carrillo-Bravo (1961) in Cañones Esperanza, Rosario, and Olmo, it is called the La Caja Formation in this report because of its low clastic content, low-energy depositional characteristics, and basin facies fossils (Imlay, 1943). Tan to steel-gray micrites are commonly altered to pink or yellow. Vugs and fractures, largely filled by sparry calcite, are common. Pyrite grains and small, sparse nodules of chert are throughout the section. Iron from weathered pyrite probably causes the pink and yellow color of the altered rock. The calcium-magnesium ratio of 23:1 in one sample represents the presence of some dolomite (Table 1). Ferrous carbonate in solid solution with the dolomite is another potential source of iron. Approximately 17% of the sample was insoluble in hydrochloric acid and consisted of quartz, pyrite, chert fragments, and clay.

A broken topography of steep slopes and cliffs is formed by the alternating calcareous shale and limestone. Shale beds form slopes that are commonly covered by soil. A 20 cm thick bed of fissile, non-calcareous (probably bentonitic) shale is

about six meters above the base of the unit. In the upper half of the formation, wavy to nodular bedding is moderately well-developed. Shale and stylolites are less common, and bedding is more clearly defined within five meters of the gradational upper contact with the Taraises Formation. The top of the highest wavy bed marks the top of the La Caja.

TARAISES AND TAMAULIPAS FORMATIONS

The Neocomian-Aptian Stage limestone (Gamper, 1977) between the La Caja and Tamabra Formations is discussed as one unit in this report. The Otates is not present and the Taraises and lower Tamaulipas Formations are mostly indistinguishable in the field. The 380 m thick Tamaulipas and Taraises Formations comprise limestone and minor quantities of shale that represent a long, uninterrupted period of quiet, basinal deposition. The limestone is predominantly a micrite with some calcilutite in the upper Tamaulipas. Microfossils are abundant and compose as much as 90% of the volume. Upper beds contain large fossils and fossil fragments.

Some beds in the lowest 50 m of the section are mostly black shale. They are best exposed and thickest on the road between the villages of Galindo and Conrado Castillo (Fig. 3). Laminated black shale and siltstone beds with a total thickness of eight meters also form a slope southeast of Galindo. Fossils are abundant, including bivalves and possible fish scales, but there is no bioturbation. This is apparently the Taraises Formation.

The shale interfingers with a sequence of alternating black shale and nearly pure limestone only three kilometers to the south of Galindo. To the northwest, the shale sequence is less than one meter thick west of La Curva and less than one-half meter thick in Cañon los Hervores. Common shale partings are in the lower half of the Tamaulipas Formation throughout the area but are rare in the upper half of the formation.

The Taraises Formation is a nearly pure carbonate unit, except for the shale beds. Samples contained only 5.2% insoluble (in hydrochloric acid) residue of chert, clay minerals, pyrite, rare quartz grains, and petroliferous material. Pyrite is ubiquitous and makes up between 1% and 2% of the volume. Petroliferous residue was present in all but one of the seven Tamaulipas and Taraises samples.

The calcium-magnesium ratio ranges from 140:1 to 100:1 in the Taraises and lower three-fourths of the Tamaulipas Formation. Two samples from near the top of the Tamaulipas had calcium-magnesium ratios of 8.5:1 and 4.3:1.

The middle of the section locally contains calcarenite matrix with some rounded, micritic intra-clasts. The longest dimension of these intra-clasts is less than one centimeter. Large lithoclasts are reported in the middle section of the Tamaulipas Formation in Cañon de la Peregrina by Gamper (1977). She interpreted them as "evidence of a tectonic episode in the area". The isolated and apparently discontinuous distribution of these breccias along the edge of the developing reefs is more likely the distant products of turbidite

Table 1. Chemical Analysis of Rock Samples from the Sistema Purificación Area as Determined by Atomic Absorption.

SAMPLE	LOCATION	(elements in ppm)							Cu	%	Ca/Mg
		Fe	Mg	Ca	Na	K	Mn	Al			
75aP	Tamabra calcarenite	650	33000	320000	210	140	45	4	3	Insoluble 6.5%	9.7:1
54P	Tamabra sand	590	64000	290000	330	180	83	4	5	7.7%	4.5:1
24P	Tamabra breccia	790	92000	240000	200	68	160	4	4	7.7%	2.6:1
66P	Tamabra breccia	930	110000	210000	240	110	170	4	3	9.0%	1.9:1
75P	Tamaulipas	550	2900	350000	230	50	63	4	4	9.7%	120:1
56p	Tamaulipas upper	470	34000	290000	160	48	100	4	4	13.5%	8.5:1
72aP	Tamaulipas breccia	6900	63000	270000	220	80	160	4	3	8.4%	4.3:1
79bP	Tamaulipas lower	1200	2700	270000	160	110	76	4	4	15.5%	100:1
26P	Tamaulipas lower	460	2600	370000	102	140	80	4	1	5.2%	140:1
40P	Taraises	3700	2500	350000	140	100	170	4	1	12.0%	140:1
PEP14	La Caja	3700	13000	310000	330	160	460	4	4	16.8%	23:1

Analytical technique - Atomic Absorption
Hydrochloric acid used to dissolve samples

flows derived from the incipient Miquihuana Platform (Fig. 4).

Bedding in the Tamaulipas ranges from thick to massive. Stylolites are well-developed, common, and have amplitudes up to ten centimeters. Most, though not all, stylolites are parallel to bedding. Vugs and fractures, particularly in the upper Tamaulipas, are commonly filled by sparry calcite cement. Depositional ripple marks on tops of beds are rare.

Chert nodules are common throughout the section. Most are black, although creamy white chert nodules are exposed in one bed near the middle of the formation south of the village of Desmontes. Near the top of the Tamaulipas, along the road between Galindo and La Canoa, there are ellipsoidal nodules of black and white, coarse-grained calcite about ten x seven x seven centimeters. One nodule has a small nucleus of black chert. The nodules of calcite are probably related to the development of chert nodules in the limestone. Similar occurrences have been interpreted by Lancelot (1973) and Waisley (1978) as forming by penecontemporaneous diagenetic replacement of calcite by silica and dolomite early in the burial history.

Rillenkarrren, zanjones, solution pockets, and other karstic features are common in the middle and upper beds of the Tamaulipas Formation. They are prevalent in dolomitic beds near the top of the formation. However, there are no known cave entrances in the upper part of this Formation. Although much of Sistema Purificación is within the Tamaulipas Formation, the Cueva de Infiernillo is the only one of the system's twelve known entrances that is in the Tamaulipas. Two small caves with less than 100 m of passage each are the only other known caves within this formation (Hose, 1981).

TAMABRA FORMATION

The middle Cretaceous limestone in the Huizachal-Peregrina anticlinorium has been called the Tamaulipas Superior, Tamaulipas, and Cuesta del Cura Formations by various workers. Although a breccia has been locally recognized between the El Abra Formation and the basinal limestone to the east, previous investigators have not identified this unit as the Tamabra Formation.

In the Purificación area, the youngest unit is a thick sequence of autochthonous mudstone, massive allochthonous channelized debris flow deposits, bedded allochthonous debris flow deposits, and turbidity current deposits composed of dolomite and limestone. These rocks are considered a part of the Tamabra Formation in this investigation. Modifying the definition provided by Barnette and Illing (1956), the Tamabra Formation is defined as, "a dominantly bioclastic-lithoclastic limestone-dolomite sequence that underlies the Agua Nueva limestone and shale and laterally merges away from the Cretaceous platform into the basinal Tamaulipas Superior or Cuesta del Cura Formation."

The contact between the Tamaulipas and Tamabra Formations is always sharp, conformable, but slightly uneven. Channels, filled with clastic Tamabra carbonates, cut into the underlying limestone.

The top of the Tamabra Formation has been removed by erosion throughout the area making the original thickness indeterminable. A measured section in the village of Conrado Castillo is 272 m thick, probably close to the maximum thickness within the Purificación area (Atkinson, 1982). Lateral

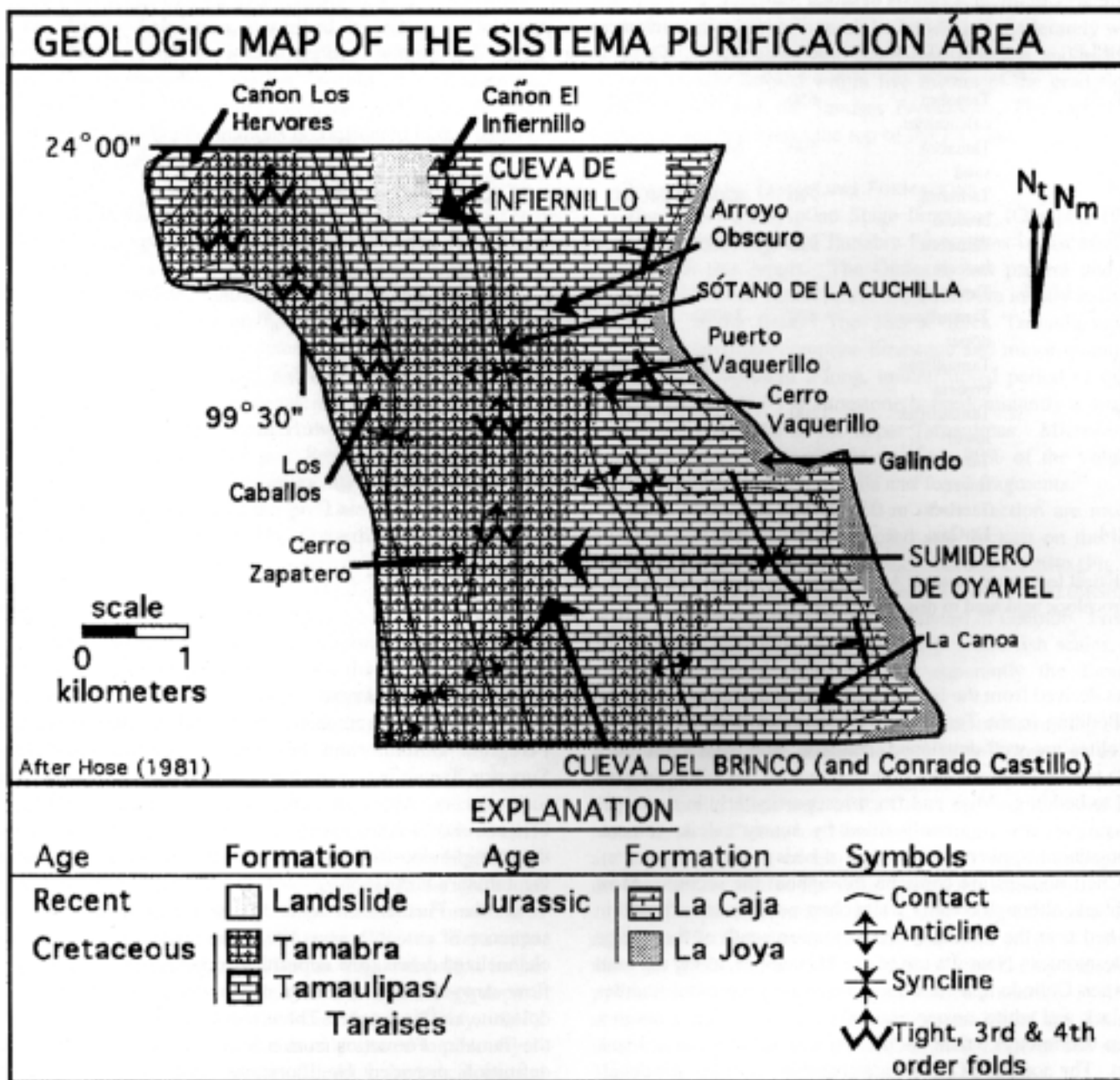


Figure 3. Geologic map of the Sistema Purificación area.

variation within the formation is dramatic. In Conrado Castillo, the lowest 100 m is a sequence of predominantly tabular and laterally discontinuous calcirudite beds. Channels, cut and fill structures, rip-up clasts, graded bedding, and sole-marked surfaces (Fig. 5) indicate that at least some of these beds are products of turbidity currents. Open framework, random orientation of clasts, and contorted bedding in some breccia layers indicate deposition as massive channelized debris flows.

The longest dimensions of the equant to tabular clasts range from one centimeter to one-and-a-half meters. They are predominantly sub-rounded but range from sub-angular to rounded (Fig. 6). Imbricated clasts, soft sediment deformation, and channel geometry of the calcirudite beds indicate a southern source.

Clasts were derived from two terrains. Many contain rudists and other bioherm material from the carbonate platform (Atkinson, 1982). Others are intraclasts of calcarenite and cal-

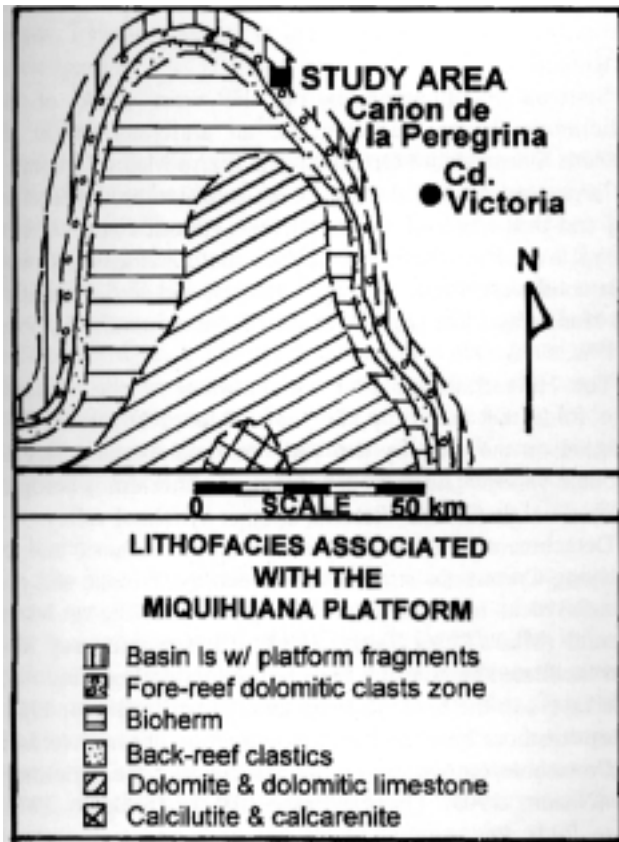


Figure 4. Lithofacies of middle Cretaceous units associated with the Miquihuana Platform. After Carrillo-Bravo (1971).

calutite, similar to the surrounding matrix and the channel walls. Relative solubility of the clasts and matrix varies. On some weathered surfaces, clasts form positive features relative to the matrices but mostly the clasts are negative features or there is no change in relief at the clast-matrix contact.

Medium to massive calcarenite beds with thin laminations commonly form channel walls in the lower Tamabra. Calcirudite beds are missing in the northern parts of the area and only calcarenite beds overlie the Tamaulipas Formation. The upper Tamabra Formation is dominantly calcarenites. Channel structures, crossbedding, and graded bedding, locally topped by micrite and minor shale, are common. Contorted beds of calcarenite (soft sediment deformation) are associated with the channelized breccia.

The constituents of the calcarenite beds are sub-angular to rounded, but predominantly sub-rounded. Pressure solution along grain contacts in some samples has caused slight molding of the grains. Microfossils are prevalent in many samples, although fragments of megafossils compose more than 80% of some channel fillings. Rip-up clasts are also common in some channels.

The Tamabra Formation is mostly composed of dolomite



Figure 5. Channel structure in the Tamabra Formation.

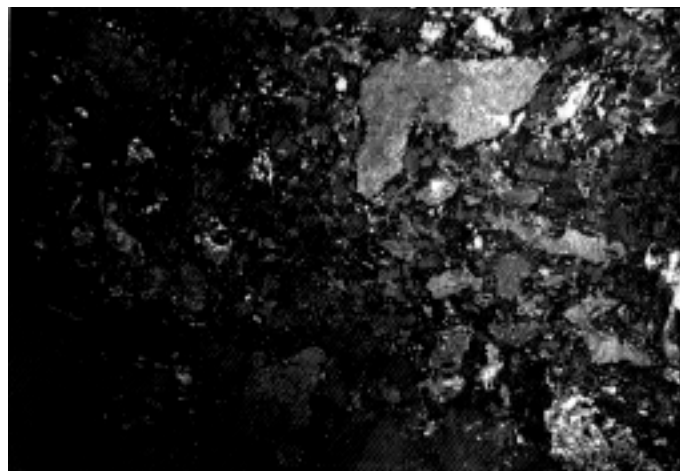


Figure 6. Breccia unit in the Tamabra Formation.

and dolomitic limestone with mostly low calcium-magnesium ratios. Breccia beds in the lower part of the formation are strongly dolomitic with a calcium-magnesium ratio of 1.9:1. Insoluble residue ranges from 6.5% to 9.0% and is composed of clay, chert, and, in most samples, a large amount of petro-liferous material with minor quartz and pyrite. Clay is prevalent at the top of graded beds, as fillings along fractures, and along stylolites which are often poorly developed in the calcirudite and calcarenite beds. Black chert, in beds up to 12 cm thick and in nodules from one millimeter to tens of centimeters in their longest dimension, is abundant in the calcarenite beds. The calcirudite beds contain minor amounts of black chert nodules. Silica within the chert is commonly mixed with abundant dolomite rhombs.

White rhombs of calcite are prevalent in the calcirudite as vug and fracture fillings, and clast replacements. Similar but less conspicuous recrystallization is also present in the Tamabra calcarenite and the highest beds of the Tamaulipas

Formation. Calcite rhombs are more resistant to dissolution than their surrounding material and, on the walls of the Historic Section of Cueva del Brinco, they form small positive features in the rooms formed by phreatic dissolution.

Contemporaneous chert and dolomite precipitation in an environment with organic decomposition products, followed by dedolomitization is congruent with the evidence from the Tamabra Formation. All analyzed samples that contained calcite rhombs were petroliferous and had abundant dolomite.

Pelagic caprinids in the Tamabra Formation confirm a basin or basin-margin depositional environment (Atkinson, 1982). The steep-sided Miquihuana Platform provided high relief a few kilometers to the south and west during the middle and Late Cretaceous. The bioherm probably accreted rapidly upward on a pre-existing topographic high, such as a horst proposed by Belcher (1979). Along the edge of much of the carbonate platform, the Tamabra Formation formed from debris flows and turbidity currents that carried material from the oversteep platform slopes into the surrounding basins (Carrillo-Bravo, 1961, 1971; Enos, 1974). The calcirudite is the product of both channelized turbidite flows and massive channelized debris flows derived from the shallow-water platform. The coherent clasts indicate that the source terrane had been at least partially cemented before the Tamabra Formation was formed. Submarine cementation of the rocks of the Miquihuana Platform has been documented by Enos (1974). However, differential cementation may have contributed to the building of a steep-sided, but unstable, platform.

While much of the material derived from the shallow-water platform was carried down submarine canyons and formed calcirudite, some fine-grained material was deposited on submarine overbanks and outwash plains, resulting in calcarenite beds. Channels filled with overbank deposits after the flow was pirated upstream. Stream flow sometimes returned to the original channel. This channel evolution is represented by dramatic changes in the section from calcirudite to calcarenite, and vice versa. Calcirudite deposits throughout the section are the result of quiet basinal deposition between turbidity and debris flows.

The Tamabra Formation tends to form slopes. Dolomitic breccia forms local karst grike and kegelkarst fields with little or no soil cover. Insoluble and impermeable bedded chert in the calcarenite often causes subterranean water to flow to the surface. However, each stream returns underground within one hundred meters of flowing onto the Tamabra terrain.

Eleven of the 12 known entrances to the Sistema Purificación and nearly all of the known caves in the study area are in the Tamabra Formation. Most of the caves have developed along bedding planes, gradually gaining depth. However, Pozo Oscuro, a 120 m deep pit, and Sótano de la Cuchilla, which drops 164 m in a traversable distance in only 400 m from the entrance, are also developed in the Tamabra Formation.

REGIONAL

Sistema Purificación is on the west flank of the Anticlinorio Huizachal-Peregrina, an anticlinorium in the northern Sierra Madre Oriental. The Sierra Madre Oriental is the largest segment of the early Cenozoic (Laramide) foreland fold and thrust belt of southern North America and northern Central America. The range extends south and southeastward from southwest Texas, through Chiapas, and into Guatemala and Honduras. The general trend of the mountains is about N14°W.

The Huizachal-Peregrina anticlinorium is one of many large folds that make up the Sierra Madre Oriental. It is bounded on the west by the Valle de Jaumave, an elongate, synclinal valley. The east side of the anticlinorium is bordered by Sinclinal de Ciudad Victoria, another synclinal valley.

Detachment surfaces between the Upper Jurassic and the overlying Cretaceous strata and between the Triassic and pre-Triassic rocks are common throughout the Sierra Madre Oriental (Muir, 1936; Tardy, 1980). Separations may have been facilitated by gypsum beds in the Olvido Formation and shale layers in the La Joya Formation (Carrillo-Bravo, 1961). Various authors have recognized numerous chevron folds in the Cretaceous carbonates on the east flank of the anticlinorium (Nason, 1909; Carrillo-Bravo, 1971; Conklin, 1974). These folds are reported to be smoother and less common towards the synclinal axis. The frequency of folding also reduces with depth, indicating the importance of bedding detachment surfaces (Carrillo-Bravo, 1961). Folding on the gentler west flank had not been recognized prior to this study and the Cretaceous rocks had been assumed to dip uniformly to the west (Conklin, 1974).

Belcher (1979) documented a horst within the core of the anticlinorium. The western boundary of the horst is about one kilometer east of Conrado Castillo and Cueva de Infiernillo. He proposed that local horsts developed between the Late Permian and Middle Jurassic and acted as buttresses that interrupted tectonic transport of allochthonous strata during the Laramide Orogeny. Folds on top of positive elements are broad and low amplitude, reflecting the local absence of thick, incompetent sequences below the Aptian-Albian limestone. Although the Cretaceous rocks were folded and uplifted up to 3000 m, few faults are recorded in these younger rocks. Folding apparently accommodated most of the lateral shortening.

STUDY AREA

Located on the western flank of the Huizachal-Peregrina anticlinorium, the overall dip of the beds is to the west. Faults oblique to bedding are rare and typically have separations of less than three meters. Faults along bedding planes are common and the offsets are not known. Décollement surfaces in the carbonates formed during the Laramide Orogeny, accom-

modating lateral shortening by folds and bedding plane slippages. Folds and joints are important factors influencing speleogenesis.

FOLDS

Folds in the area are spectacular and abundant. Concentric folds with amplitudes of up to 250 m are accompanied by tight chevron, similar, and disharmonic folds. The average hinge line trend of most major folds, as well as most small folds, is $N6^{\circ}W \pm 2^{\circ}$. Axial surfaces mostly verge towards the east.

A lineament from Los Caballos through Cañon El Infiernillo marks a dramatic change in the abundance and type of folds. To the east, folds are rare and, generally, concentric with shallow-dipping limbs. West of the lineament, folds with steeply dipping limbs are common and have variable styles, including concentric, similar, disharmonic, and chevron.

Second-order fold - Sinclinal de Infiernillo

The fold that most influences speleogenesis is a second-order syncline, Sinclinal de Infiernillo. Its axis trends about $N8^{\circ}W$, one kilometer west of Conrado Castillo. The Infiernillo syncline is continuous along the entire north-south extent of the known cave system and through the Tamabra, Tamaulipas, and most, or all, of the Taraises Formations. It caused the sumps in Cueva de Infiernillo by perching water above underlying, impermeable beds, and probably has prevented further westward development of Sistema Purificación.

Third-order and fourth-order folds

Most of the other folds in the area are parasitic folds associated with the Infiernillo syncline. Third-order folds were caused by upwardly increased compressive stress along the limbs and near the axial surface of this major syncline. Most of the folds decrease in amplitude with depth, some terminating in the lower beds. A large, third-order fold to the east is an anticline that trends about $N8^{\circ}W$ and terminates at Cerro Vaquerillo to the north. The fold has acted as a drainage divide for subterranean flow to the upper parts of the Sistema Purificación. East of Conrado Castillo, the west limb of the fold has an amplitude of about 200 m.

The next major fold to the west is a syncline that trends about $N4^{\circ}W$ through Conrado Castillo and along Cuchilla El Angel, the ridge west of Arroyo Oscuro. The east limb has a moderate dip, averaging between 20° and 30° to the west. The axial surface dips steeply to the west. The west limb is steeply dipping to vertical, and is terminated by a similar trending anticline that passes through Cerro Zapatero. The west limb of the anticline is gentler than its east limb, with an average dip between 35° and 45° . The amplitude between these folds is about 250 m near Conrado Castillo and about 150 m below the La Curva-Los Caballos road, terminating at about 1200 m msl along a décollement surface (Fig. 7).

Small, fourth-order folds near synclinal axial surfaces of the higher order folds are common. They crop out at higher



Figure 7. Looking south at the head of Cañon El Infiernillo. The World Beyond and Dragon River have formed along the axial cleavage of the syncline in the major third-order synclinal-anticlinal fold pair shown in the upper central part of the photograph. The crest of the anticline is exposed in the Monkey Walk. The Cueva de Infiernillo entrance is prominent near the center of the photo.

elevations in the Tamabra Formation and die out with depth. Sótano de la Cuchilla has excellent exposures of these localized structures. Chevron folds formed in the alternating beds of chert and limestone. Joints are also well-developed near the axial surfaces. There are minor folds with little linear extent on the east limb of the syncline that terminate downward along décollement surfaces.

Ubiquitous third- and fourth-order folding along the west limb of the Sinclinal de Infiernillo is well-exposed in the west walls of the El Infiernillo and los Hervores canyons (Fig. 8). These east-verging folds have steeply dipping limbs and axial surfaces. Hinge lines trend parallel or sub-parallel to the major syncline. Some folds are concentric or chevron, but similar and disharmonic folds are more common in the nearly isotropic Tamaulipas Formation.

The amplitudes of the folds in the western part of the area range from less than one meter to about 100 m. Regional dip is to the east. Almost all axial surfaces strike between $N15^{\circ}W$ and $N5^{\circ}E$ and dip steeply to the west, although some dip to the east. Some of the folds can be traced down to décollement surfaces. Others terminate in manners that are most readily explained by slippage along bedding planes.

Geologic Factors Controlling Folding

The eastern edge of the Laramide Thrust Belt is approximately 20 km west of the cave (Tardy, 1980). A scarcity of faults in this intensely folded region and the presence of disharmonic, similar, and chevron folds are evidence that the rocks responded plastically during folding. Apparently, the stress that caused large thrust faults to the west was accommo-



Figure 8. Disharmonic folds in the Tamaulipas Formation in Cañon los Hervores.

dated by folding and bedding plane slippage in the Purificación area. Since the Laramide Orogeny in northern Mexico began towards the end of the Cretaceous, the rocks may not have been firmly cemented. Also, Carrillo-Bravo (1961) reported that up to 1200 m of sediments were deposited over the top of the Tamabra Formation. The overburden pressure on these youthful rocks caused them to behave plastically and probably was responsible for the lack of faults in the limestone. However, the abundant joints parallel to the fold axes indicate that the stress did cause incipient axial cleavage planes that enlarged as stress was released and the overburden eroded. A few, small-separation faults are sub-parallel to these trends.

Lithology determined the type of folding that occurred. The Tamabra Formation has primarily steep-angle chevron folds due to its mixture of bedded chert and limestone. The chert beds acted as the more competent layer, determining the form of the folds. Similarly, chevron folds in the Taraises and lower Tamaulipas Formations resulted from limestone beds acting more competently and determining the style of folding while the thin shale interbeds plastically deformed, particularly near the hinge line.

Similar and disharmonic folds are predominant in the massive bedded upper Tamaulipas Formation. Individual beds were passive and the type of folding was not controlled by changes in lithology in this nearly isotropic limestone. Low-amplitude concentric folds also formed in the Tamaulipas.

Anticlines flatten with decreasing elevations until the structures are non-existent. The necessary adjustments were made by bedding plane slippages and plastic flow within the beds. Bedding plane slippage often occurred within shale layers, but many slippage surfaces are marked by calcite gouge between limestone beds.

There is a dramatic change in style and intensity of folding between the west and east walls of Cañon El Infiernillo that must represent some change between the areas, since both sides experienced the Laramide stress (Fig. 9). As the



Figure 9. Looking northeast into Cañon Los Hervores showing the two structural regimes in the Sistema Purificación area. The cave system and all other large caves are in the nearly homogeneously west-dipping limestone beds on the right of the photo. No large (longer than 100 m) caves are known in the tightly folded limestone on the left of the photo.

Cretaceous sediments do not appear to change from east to west, the difference apparently is at depth. Belcher (1979) has proposed that the Purificación area lies near the western edge of a north- or northwest-trending, Jurassic age horst. He recognized changes in fold styles with broad, low-amplitude folds over the proposed horst and tightly folded strata to the west and attributed the difference to a change in the underlying stratigraphic sequence. Thick sequences of Upper Jurassic evaporites and shale were deposited within the graben to the west but are thin or absent on the horst. Tight, high-amplitude folds formed over the incompetent strata within the basins. Where the Lower Cretaceous carbonates are in contact with the basement, transport of allochthonous beds was inhibited.

The Jurassic Olvido and Zuloaga Formations are absent in Cañon El Infiernillo and to the east of the study area, suggesting that the area was elevated during the Late Jurassic. However, Carrillo-Bravo (1961) reported their presence on the east side of the anticlinorium, southeast of the study area. The Olvido Formation is 100 to 160 m thick in canyons seven to 12 km east of the cave. Thus, the Olvido may thicken dramatically away from the paleo-high. The conspicuous change in intensity and style of folding in the Cretaceous limestone west of the canyon may indicate such a change in lithology at depth (Fig. 10).

Alternatively, if there is a horst in the eastern part of the area, the Olvido Formation may be absent and the carbonates moved over the La Joya and La Caja Formations. The change in folding style may be caused by a facies change in the La Joya. Sediments to the west, deposited closer to the Jurassic basin, may be finer-grained than those near the paleo-high. Evidence for such a facies change is provided by conglomer-

CROSS-SECTION THROUGH CAÑON EL INFIERNILLO

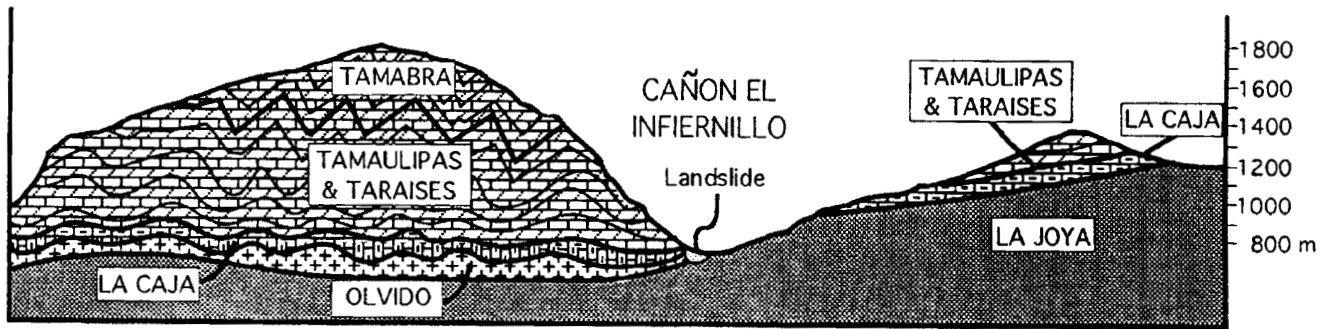


Figure 10. Cross-section through Cañon El Infiernillo.

ates with clasts up to 15 cm in diameter in the upper La Joya along the eastern boundary of the area but only shale, siltstone, and some sandstone are exposed in Cañon El Infiernillo. Finer-grained sediments to the west may have promoted transport of the overlying beds.

Either way, as described elsewhere in the Sierra Madre Oriental, the folds in the Cretaceous carbonates are probably formed above large décollement surfaces in the underlying Jurassic strata above thrust faults in the older rocks (Fig. 11).

FAULTS

During the extensive Laramide folding, much of the displacement of allochthonous units was along bedding planes. Slickensides between beds are common and are most frequently oriented about N78°E (Fig. 12). Faults, other than décollements, are rare. All observed faults that cut across beds have stratigraphic separations of less than three meters. In no case was the net displacement determinable. Most of the faults dip 70° to 85° and their strikes cluster around N9°W. The faults have both normal and reverse separations with some down on the east and others down on the west.

The largest fault has a gouge zone five to 50 cm wide and is within the Tamabra Formation. The trend of the fault is N86°W 84°S and the maximum stratigraphic separation is 2.95 m. Slickensides indicate that the most recent movement was strike-slip. If no vertical movement has occurred along this fault, the left-lateral displacement is 7.8 m. The fault is visible in the Historic Section from near the Brinco entrance into the Helictite Passage. The fault splits near the entrance of the Helictite Passage and one branch passes into the south wall of the Historic Section.

Several passages in the cave that are known to have developed along small displacement faults including the Carrot Tube and the 17 Hour Tube, two of the Confusion Tubes in Cueva de Infiernillo, and the Callisto Borehole. The fault in the 17 Hour Tube is a high-angle reverse separation fault with the south side up approximately 2.5 m. Most faults seem to have had no effects on either the surface or sub-surface morphology.

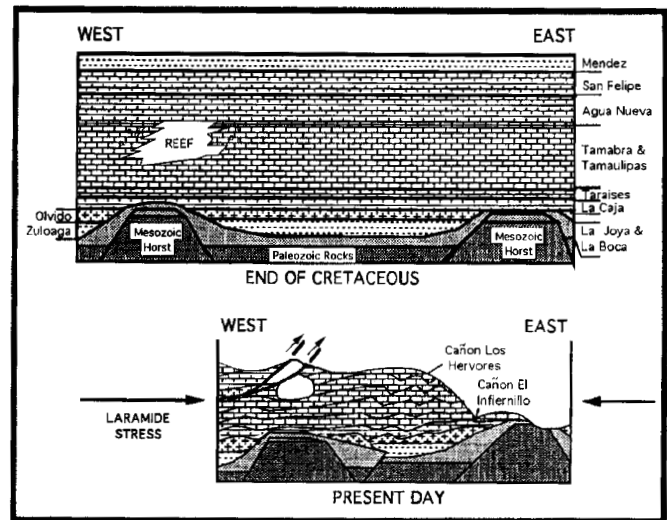


Figure 11. Schematic profile of Laramide folding.

JOINTS

The thick and massive beds of the Tamabra and Tamaulipas Formations have been extensively fractured. Orientations of the two resulting joint sets cluster around N8°W and N85°E (Fig. 13), nearly parallel and perpendicular to the regional strike. The dips of most joints are perpendicular to the dip of the beds. Joints are abundant near the axial surfaces of the folds.

The joints developed along axial surfaces have influenced the speleogenesis. Most of the passages in the Sistema Purificación and Sótano de la Cuchilla are formed along joints. Many of the long, linear passages in the system, including the World Beyond, the Columbia, the Monkey Walk, and the Jersey Turnpike (Fig. 14), developed along joints that are near and parallel to axial surfaces. The highly fractured areas near the hinge lines are conducive to cave development.

The passage morphology within the system is also affected by the concentration and orientation of joints. Phreatic ceiling domes and wider passages have formed where two or more joints intersect. The largest room in the cave, the Netherhall,

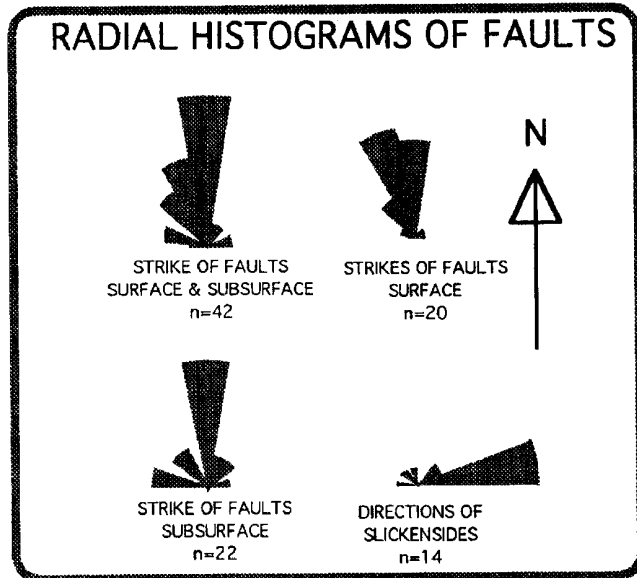


Figure 12. Radial histograms of faults in the Purificación area.

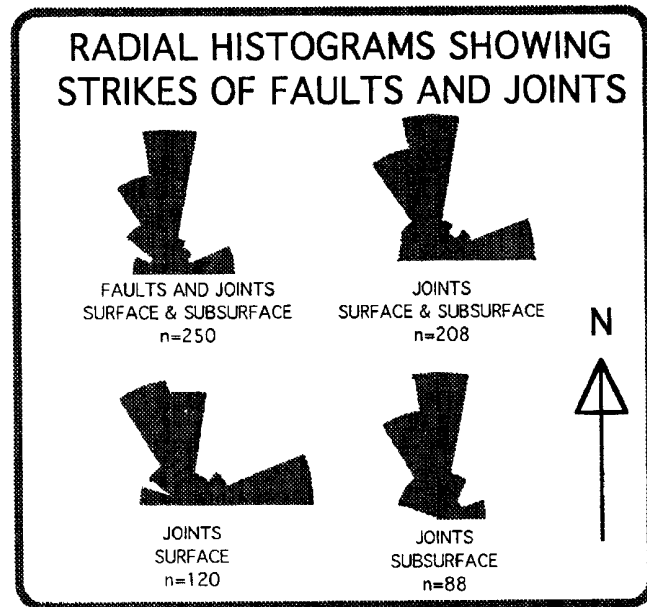


Figure 13. Radial histograms of tectonic features.

is forming by ceiling and wall collapse and solutional removal of the debris. The collapse process is aided by steep bedding and abundant joints. In addition to being weakened zones, joints and bedding planes provide voids in which gypsum develops and crystal-wedging is occurring (White & White, 1969).

The local geomorphology resulted from combined actions of fluvial and karst erosional processes. Karst landforms that were produced dominantly by solutional processes mark portions of the Tamabra, lower Tamaulipas, and Taraises Formations, but fluviokarst, formed by both fluvial and solutional processes, is more abundant.

LA JOYA, LA CAJA, AND TARAISES FORMATIONS

The most striking feature of the terrain is the rugged topography. The La Joya Formation forms irregular contour patterns, often recognizable on aerial photos and topographic sheets. Because of the numerous springs near the top of the La Joya Formation, many small drainages have eroded deep into the hillsides below. The orientation of joints, a significant factor in the development of linear features in the overlying carbonate formations, gives less control of the erosion in the La Joya resulting in more rounded and irregular landforms.

In Cañon El Infiernillo, headward erosion has formed a waterfall, approximately 25 m high, at the La Caja-La Joya contact. A permanent stream, the resurgence from Sistema Purificación (Hose, 1996), emerges through the rubble at the base of the cliff. The waterfall is the result of water undermining the less resistant, underlying La Joya Formation by sapping at the spring and by the surface river waterfall during floods and the wet season. The more resistant La Caja limestone forms the cliff.

The calcareous shale and limestone sequence of the La Caja Formation forms steep, covered slopes broken by two to five meter high cliffs. Shallow dolines are the only karst features that have been noted in this unit. The overlying, shale-bearing Taraises has numerous springs and dendritic drainage patterns.

TAMAULIPAS AND TAMABRA FORMATIONS

Joints have greatly influenced the surface morphology, resulting in a rectilinear pattern of topography and drainage development within the cave-bearing Tamaulipas and Tamabra Formations. Cliffs in the Tamaulipas Formation have developed along joints and their development is associated with solutional activity within the joints. Surface drainages over these formations also follow the joint set trends, resulting in a rectilinear pattern of dry streamways. The canyon Arroyo Oscuro, the Puerto Vaquerillo saddle, and the cave entrances to Sumidero de Oyamel (Fig. 3) are formed along a prominent fracture. Although no offset is apparent, the lineament is conspicuous on aerial photographs and topographic maps and has dramatically affected the surface morphology.

The Tamaulipas Formation is a cliff-former. Canyons incised into the Tamaulipas Formation are steep-walled and broken by waterfalls. Cliffs are typically parallel to major joint trends. Shale in the lower part of the unit has contributed to slope failures. Groundwater moving through joints in the mas-

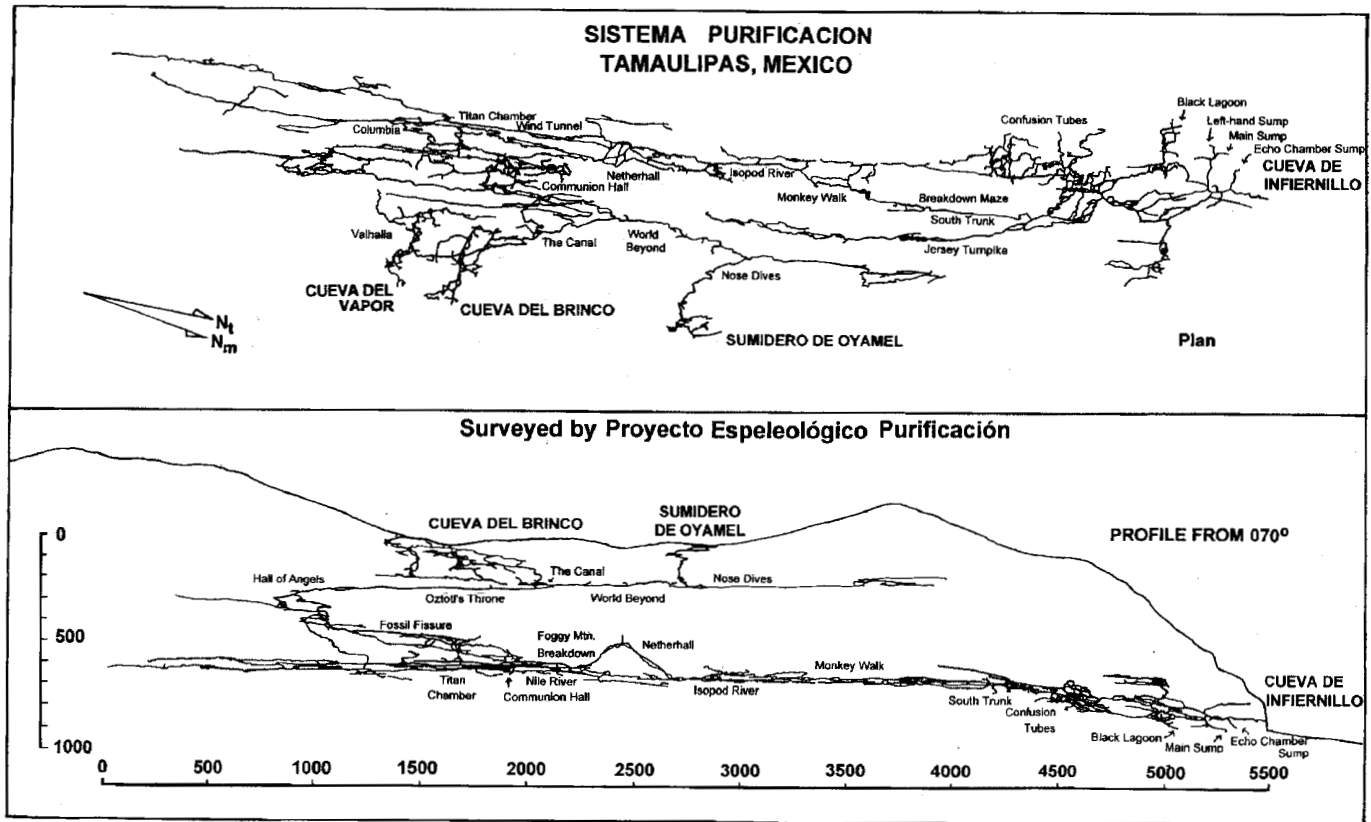


Figure 14. Plan view and profile view of Sistema Purificación.

sive limestone dissolves material along these fractures, enlarging them, until the water reaches the nearly impermeable shale layers. The limestone is undermined by the less competent shale beds and lacks lateral continuity because of the enlarged joints. This removal of support results in landslides occurring mostly in the lower half of the Tamaulipas.

The prominent cliff at the head of Cañon El Infiernillo resulted from similar processes (Fig. 7). Surface drainage south of the cliff enters the limestone through joints in the rock. These joints are enlarged by dissolution from the surface down. The shale beds and argillaceous limestone at the top of the Taraises Formation, which is immediately below the base of the cliff, weathers and weakens quicker than the Tamaulipas. This less competent rock below the massive limestone causes collapse of the upper strata along the solutionally enlarged and weakened joints.

Cañon El Infiernillo is notable because it lacks the usual permanent stream at the head of a blind valley (Jennings, 1971; Sweeting, 1973). Four springs flow from the Infiernillo cliff during flood conditions. Three of the springs, including the Cueva de Infiernillo entrance, issue from karst conduits part-way up the cliff. The fourth spring, and the last to stop flowing after a flood, issues from rockfall debris at the head of the stream channel, below the Infiernillo entrance. This spring has probably assisted in the undermining of the cliff. The water

from all of the springs has removed fallen debris as either chemical or clastic load. Since flood water quickly pulses through the underground system (Hose, 1996), water issuing from these springs may be undersaturated and capable of further dissolution of limestone.

During heavy rainfall, the local groundwater table fluctuates radically and rapidly. This change in the water level causes a rapid change in the hydrostatic pressure within the rocks, providing additional stress along fractures. An almost constant barrage of rocks, 70 cm in diameter and smaller, fell from the cliffs following a heavy rain in December 1979. The most active retreat of the cliff occurs during and immediately following voluminous rains. Recent large rock slide deposits in the canyon are further indications of the ongoing retreat of the surrounding cliffs (Hose, 1981).

Rockfalls of Tamaulipas limestone in the lower canyons are common even during the dry season. Four fresh, small rockfalls were seen in the normally dry segments of Cañones los Hervores and El Infiernillo in April 1980. Since large rivers flowed through these channels in December 1979, these four rockfalls must have occurred in the intervening four months. During a three-day visit to these canyons in April 1980, three separate rockfalls were heard. Since human visitation is rare and there are few grazing animals in the canyons, most of these rockfalls were probably unprovoked by people or domestic

animals. Although these are technically "dry valleys" during most of the year (White, 1988), the lower canyons are actively enlarging and floodwater is carrying the fallen debris further downstream.

The upper one-third of the Tamaulipas Formation is dolomitic and less of a cliff-former. Karst features are more common than in lower beds. Enlargement of vertical joints in the massive carbonate rocks by dissolution from the surface downward formed bogaz or zanjones in the upper Tamaulipas Formation and Tamabra Formation (Cvijic, 1893; Monroe, 1964). The zanjones in the area are parallel trenches, about one to three-and-a-half meters wide, up to two meters deep and several tens of meters long with nearly vertical walls and a soil-covered floor. Some of the best developed zanjones cross the road between the villages of La Curva and Los Caballos. Rillenkarren and solution pockets are prevalent in the more dolomitic massive beds near the top of the Tamaulipas Formation.

The Tamabra Formation forms slopes with an abundance of karst features. Almost all of the known caves in the area and all but one of the known entrances to Sistema Purificación, are in this Formation. Dolines, both solutional and collapse, and pits up to 120 m deep are developed in the Tamabra. Grike fields and karst pinnacles are commonly developed in the dolomite units.

Present drainage is from the south and west. However, a small travertine deposit on the road one kilometer south of Puerto Vaquerillo contains well-rounded stream pebbles of reddish sandstone, apparently derived from the core of the anticlinorium to the east. After the thick carbonate section had been stripped along the axis, the Jurassic sediments were exposed above 2040 m, the elevation of the travertine deposit. Drainage, carrying clastic material from the east or northeast, passed through the Puerto Vaquerillo and flowed towards Conrado Castillo. Remnants of this ancestral drainage pattern are preserved in the travertine.

GEOLOGIC FACTORS CONTROLLING THE SPELEOGENESIS

The principal geologic factors controlling the development of the Sistema Purificación are the stratigraphy and structure. Cave-forming affinities vary in the carbonate rocks. Portions of the heterogeneous Tamabra Formation are more susceptible to conduit development than others. The nearly homogeneous, thick-bedded Tamaulipas Formation resists passage development except along fractures. The poor conduit-developing characteristics of the underlying Taraises and La Caja Formations and the impermeable shale beds in the La Joya Formation change the manner of groundwater flow in the lower parts of the system.

Structure complements the effects of the stratigraphy. Most important are the folds and the associated fractures. One set of joints formed parallel to and near the axial hinge surfaces and the complementary set trends perpendicular to strike at

approximately N85°E. The limestone above a décollement surface in the lower Tamaulipas is also fractured parallel to the trend of the folds and, thus, developed many conduits in the lower part of the middle cave. A few passages have formed along the trend of a fault. However, most faults exposed in the cave have caused only minor effects on passage development. No observed fault appears to have inhibited passage development.

THE UPPER CAVE

The upper part of the known system is in the heterogeneous Tamabra Formation. Passage development was influenced by both lateral and stratigraphic changes, apparently facilitated in more soluble and/or permeable units, and tends to follow the intersections of preferred bedding planes and prominent joints. Although the passages are commonly developed along bedding planes, the cave drops to lower strata to the west until reaching the Tamabra-Tamaulipas contact (Fig. 15). The transition from the upper cave to the middle cave is along the contact at the Valkyrie River, The Canal, and the Nose Dives (Fig. 14).

The common joint sets in the cave are N5°W and N85°E, respectively parallel and perpendicular to the regional westward dip (Fig. 13). Many of the passages in the upper part of the cave follow joints along bedding planes and drop to lower beds along local fractures. As a result, the cave is generally deeper to the west. The main passage near the Brinco entrance is formed along a small fault that has a stratigraphic offset of approximately three meters. The fault zone apparently enhanced conduit development.

Permanent pools of water are formed in the trough of a third-order syncline including two near-sumps in the westernmost parts of the upper cave, The Canal and the Nose Dives. The water is perched on the less permeable Tamaulipas limestone. Fourth-order folds associated with this syncline have also influenced cave development in the Tamabra. Tin Can Alley is perched along the trough of a fourth-order fold. Chert beds up to 12 cm thick in the middle and upper beds of the formation act as hydrologic barriers. Chevron folds in Sótano de la Cuchilla, which is probably part of Purificación's hydrologic system, have fractured the chert, thus allowing water infiltration and cave development.

The Historic Section and Valhalla were formed when the phreatic base level was higher and the core of the anticlinorium was not exposed. As erosion continued and the water table dropped, streams flowed through the upper cave and deposited abundant flowstone. Small fragments of red siltstone cemented in travertine in Cueva del Brinco appear to be derived from the La Joya and, thus, represent drainage into the cave from the east when the La Joya was exposed at an elevation higher than 1900 m above present mean sea level.

THE MIDDLE CAVE

Passages from the World Beyond and Dragon River to southeast of the Confusion Tubes are mostly long, nearly

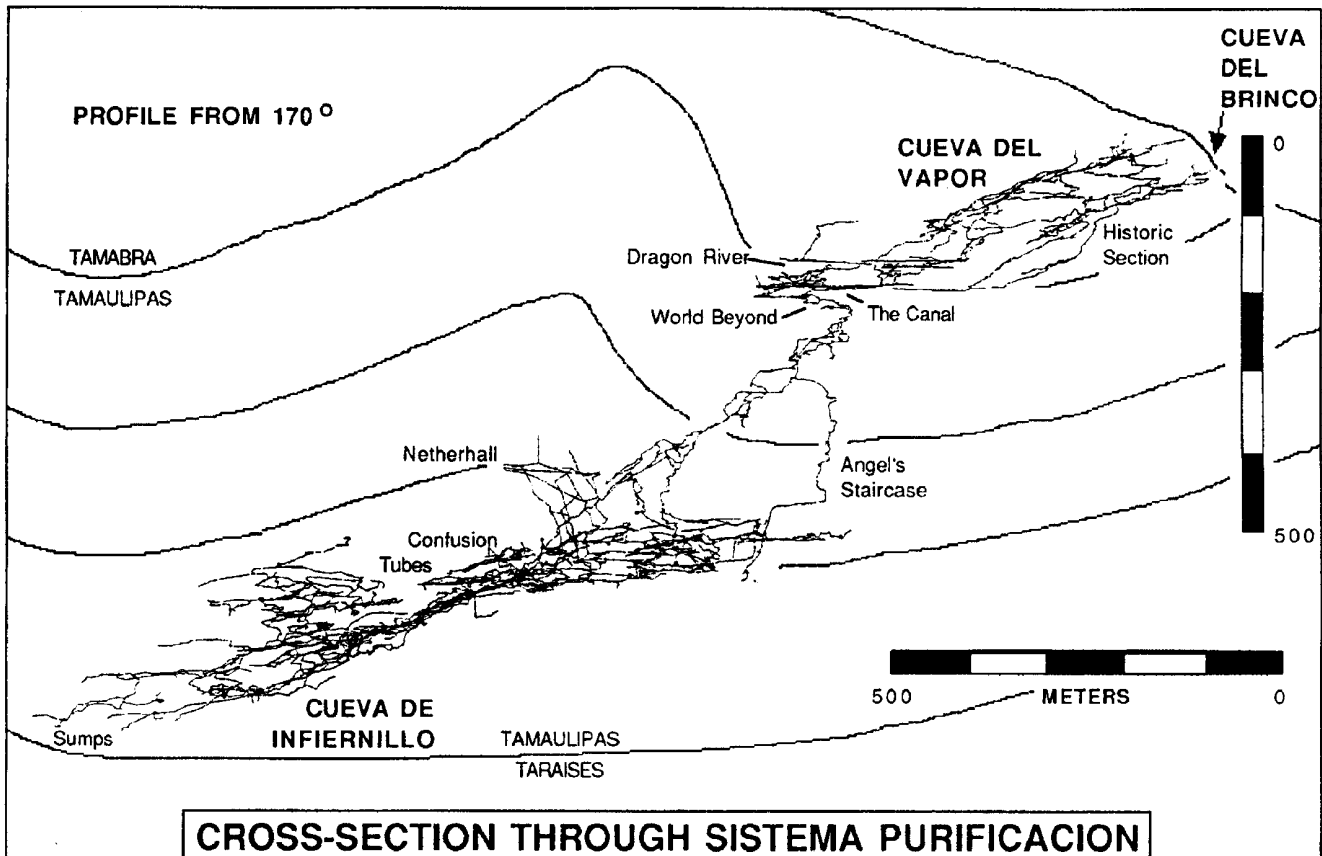


Figure 15. Cross-section through Sistema Purificación.

straight tunnels of varying diameter along joints that are physically and probably genetically related to the syncline and anticline exposed on the surface at Conrado Castillo (Fig. 3). These third-order folds, caused by compression in the upper beds on the east limb of the Infiernillo syncline, decrease in amplitude and disappear at depth. Due to the asymmetry of the fold, the synclinal axis is about 100 m west of the trough. The anticlinal axis is about the same distance east of the crest. Fractures near the synclinal hinge line, possibly enlarged since the Laramide Orogeny by the reduction in lithostatic stress, provided greater initial permeability and enhanced the conduit-forming potential of the rock. Dragon River and the World Beyond are formed along the axis of the syncline near the Tamabra-Tamaulipas contact (Fig. 15).

At the southern end of the World Beyond, the cave abandons its low-gradient, north-south trend near the top of the Tamaulipas limestone and rapidly drops in elevation and stratigraphic level along fractures in the west limb of the syncline. Water is locally perched on less permeable beds and flows along strike until reaching fractures that provide paths downward.

Much of the lower part of the middle section, including the Titan Chamber, Communion Hall, Nile River, Wind Tunnels, and Isopod River, formed near or along the décollement sur-

face below the two folds. The crest of the anticline passes through Foggy Mountain Breakdown, south of the Netherhall. It is also exposed in the South Trunk, a passage formed along a joint near the décollement surface. Slickensides and calcite gouge between beds, evidence of bedding plane slippage, is abundant in this passage, as well as the Monkey Walk, the Wind Tunnels, Foggy Mountain Breakdown, and the Netherhall. The crest of anticline is exposed at two places in the Monkey Walk, which also formed near the décollement.

The entrance to the Jersey Turnpike crosses from the west-dipping to the east-dipping limb of the anticline in the South Trunk. Like the Fossil Fissure, the Jersey Turnpike is probably developed along an enlarged fracture near the hinge line surface of the anticline. The passage, higher than the Breakdown Maze, is above the décollement surface and within the east-dipping Tamaulipas limestone.

THE NETHERHALL

México is well-known for some of the largest and deepest open-air natural pits in the world (Courbon, Chabert, Bosted, & Lindsley, 1989). Several pits in the country are more than 300 m deep, including the enormous 455 m deep El Sótano del Rancho del Barro in the state of Querétaro. The Netherhall, a unique feature in Sistema Purificación, is an interesting exam-

ple of a grand, open-air pit in its incipient stage (Hose, 1988).

The Netherhall, about 330 m long and up to 130 m across, is the largest known room in the system. Its floor consists entirely of breakdown. The top of the breakdown pile is at 1500 m msl. The floor descends to 1345 m to the south and 1300 m to the north before a bedrock floor appears. Most of the system formed by phreatic and epiphreatic dissolution but the walls and ceiling of the Netherhall have been formed by collapse into an underlying void (Fig. 16). The room is in the west-dipping limb of the third-order anticline, immediately adjacent to the axial plane.

A stream apparently flows through the breakdown under the Netherhall and emerges from breakdown as the Isopod River at the north end of the giant room. It has been an important contributor to the speleogenesis of the Netherhall. Although there is no direct evidence in the Netherhall of a permanent underlying stream, waterlines on the walls of the southern part of the room indicate that water is occasionally dammed by the breakdown and rises into the lower parts of the room. The room is forming by upward stoping from an underlying void. The initial chamber below the present Netherhall might not have been large, but its ceiling was sufficiently weak to facilitate collapse. Since the Isopod River flows along the décollement surface, the ceiling failures exposed the folded, more fractured rocks of the overlying anticline and stoping continued into these rocks. If an active stream had not been present, the collapsed rocks would have filled the void and stoping would have stopped. Thus, a stream must pass through the breakdown and remove material by dissolution and, possibly, as clastic load. Thus, dissolution and stoping continue.

Evidence of gypsum crystal-wedging causing wall and roof collapse in the Netherhall has been documented (Hose, 1981). White and White (1969) state that this process is only active when the passage is high above the floodwater zone and well-protected by an overlying caprock. Most of the Netherhall is above any flood and the waterlines in the southern portion of the room are below the gypsum. Unlike other areas where mineral-activated breakdown in caves has been described, however, the Netherhall has no obvious caprock. The process seems to be the fortuitous result of thin beds of impervious chert in the Tamabra Formation, the overlying Tamaulipas Formation that resists conduit development, and the room's proximity to the hinge line surface of the anticline. The structure tends to divert groundwater along bedding planes and away from the hinge. A high evaporation-transpiration rate on the surface above the Netherhall may also contribute to this process.

The Netherhall ceiling is approximately 200 m above the Isopod River. If the process continues, the Netherhall could eventually reach the surface, creating an open-air pit. Once exposed to the surface, drainage into the hole would promote dissolution of the breakdown floor and deepen the pit. However, since the Netherhall is under Cerro Zapatero, nearly 700 m of stoping and surface erosion will be required to form

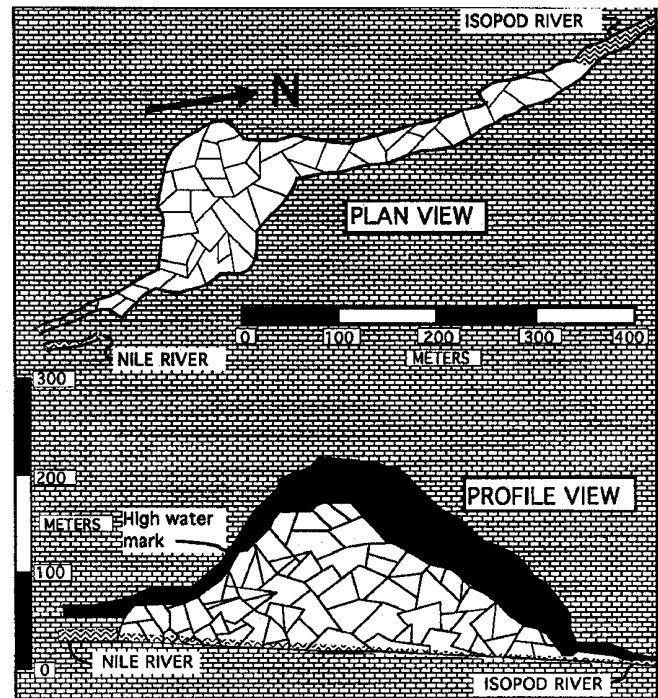


Figure 16. Plan view and profile view of the Netherhall in Sistema Purificación.

such a pit.

THE LOWER CAVE

The lower cave, including the Confusion Tubes and all passages north and west of them, are in the lower third of the Tamaulipas Formation. Beds dip 15° to 32° west. The Infiernillo syncline, which forms a trough in the less soluble, more impervious, underlying Taraises, La Caja, and La Joya Formations to the west, causes the sumps.

Most of the known passages in the lower part of the cave form an irregular network-type maze, appropriately named the Confusion Tubes. Like most of the system, the passages are formed along the intersections of joints or small faults and bedding planes. These phreatic tubes have solution domes and scallops in their ceilings. Flowstone deposits, which have been partially dissolved, record episodes of later vadose flow. These passages were probably formed by floodwater recharge as described by Palmer (1975) and some probably still carry water during floods, although they did not receive water during a 1979 flood or a 1988 hurricane (Hose, 1981; T.W. Raines, 1988, personal communication).

The entrance passage of Cueva de Infiernillo is unique in the system as it is not closely associated with any folds. It is a linear, north-south trending conduit with numerous feeders. The ephemeral river passage presently serves as an overflow route when the phreatic reservoir cannot pass water through the underlying Taraises and La Caja Formations to the permanent discharge point as fast as floodwaters enter the system.

Before adequate paths formed through the underlying units and when Cañon El Infiernillo was not as deep as present, the local water table was probably drained by a spring at the present cave entrance. The entrance passage may represent an old local water table level. The passages west of the Main Passage are younger features presently being enlarged by aggressive floodwaters rising from the sumps.

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