HYDROGEOLOGY AND EVOLUTION OF CAVES AND KARST IN THE SOUTHWESTERN EDWARDS PLATEAU, TEXAS

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ABSTRACT

The southwestern Edwards Plateau is delimited to the east by the Nueces River, to the south by the Rio Grande and Balcones Escarpment, to the west by the Pecos River, and to the north by 30°N latitude, the approximate northern extent of the Nueces River basin. The Plateau is comprised of predominantly undeformed Cretaceous carbonate rocks. Subsidence sinkholes and caves are the major karst features. The subsidence sinkholes occurred as early as the Miocene and resulted from the collapse of large conduits formed by slowly circulating phreatic waters in massive limestone beds. The uncollapsed or partially collapsed segments of these caves include the largest passages in Texas. They occur where the Del Rio Clay is absent from above the Edwards Limestone and downgradient from that area. The absence of the Del Rio allowed diffuse, undersaturated recharge to slowly develop the conduits. Despite the significance of the known karst features, most have not been geologically examined. Field research is needed to better reconstruct the karst evolution of the Plateau and to better determine how that evolution relates to modern processes.

INTRODUCTION

The southwestern Edwards Plateau is a major yet poorly studied karst area. Only about 130 caves are known mainly because of its distance from population centers, but these include most of the largest rooms and passages in the state.

The region is characterized by a dry subtropical climate. Exposed rocks are nearly flat-lying Cretaceous limestone strata poorly exposed in level uplands in the northern portion of the area. The southern portion is deeply dissected by streams flowing off the Balcones Escarpment. Most of the limestone is exposed in canyon walls, which can exceed 100 m in relief.

The Edwards Plateau is one of the largest continuous karst regions in the U.S.A. In this study, cave morphology and surface and groundwater hydrology are used to define its southwestern section as the area bounded to the east by the Nueces River, to the south by the Rio Grande, Balcones Escarpment and limit of Cretaceous carbonate rocks, to the west by the Pecos River, and to the north by 30°N latitude, the approximate northern extent of the Nueces River basin (see maps in "Karst Regions of Texas" and in "The Waltz Across Texas", this volume.)

Limited mineral resources, lack of geologic complexity, and low population in the southwestern Edwards Plateau have provided little incentive for detailed geologic investigations. The intent of this report is not only to provide background information for the NSS Convention geology field trip, but to consolidate the available data and construct a model of the area's karst hydrogeologic and geomorphic evolution. This model is not offered as a conclusive account, but in the hope that it will spur discussion and ideas during the trip and from future readers to promote further research in this interesting area.

REGIONAL GEOLOGY

The Edwards Plateau lies in the southernmost part of the Great Plains Physiographic Province, where

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relatively undeformed Cretaceous carbonate and clastic rocks deeply bury a thick sequence of fractured and intensely folded Paleozoic metasediments. The Edwards Limestone is the primary cavernous unit; its aquifer extends throughout the region as the major public water supply. Streams incise the Plateau as they flow south into the Rio Grande or Nueces River.

Stratigraphy

Figure 1 summarizes the Cretaceous stratigraphy of the southwestern Edwards Plateau, and Figure 2 is a simplified geologic map of the area. Additional details provided below are derived from Lonsdale (1927), Freeman (1968), Barnes (1977, 1981), Wilson (1982), Humphreys (1984), Miller (1984), Hudson (1986), and Veni (1988), with the nomenclature following the work of Barnes (1977, 1981) and Rose (1972).

The Glen Rose Formation of the Trinity Group is the lowermost unit of interest. It is exposed in the study area in the Nueces River valley. Although the Glen Rose is cavernous 150 km to the east in the San Antonio area, in this section of the Edwards Plateau it is a non-cavernous suite of interbedded limestone, dolomite, and marl, and serves as the lower confining boundary to groundwater in the Edwards Limestone. The upper member of the Glen Rose is characterized by its distinctive stair-step topography.

The primary stratigraphic unit of interest in this report is the Edwards Group or Edwards Limestone, also described as the Fredericksburg Division. Most caves in the area are in the roughly 200-m-thick Edwards, which crops out as three east-west bands of roughly time-equivalent formations. Facies changes occur south to north, indicating changes in depositional environments. The Salmon Peak, McKnight, and West Nueces formations are the southernmost units and were deposited within the Maverick Basin; the Devils River Limestone follows the margin of the basin along the Devils River Trend; and the Segovia and Fort Terrett members of the Edwards were deposited in the shallow waters of the Comanche Shelf (Figure 3). Some geologists also recognize the Fort Lancaster Formation as a Segovia equivalent unit present in the southwestern Edwards Plateau (e.g., Webster, 1982). The limestones of the Edwards Group are generally fossiliferous, thick-bedded to massive, and cherty. Unless notation of the specific units is important to the discussion, the equivalent members and formations will generally not be differentiated and simply described as Edwards Limestone or Group.

Noteworthy units that overlay the Edwards Group are the Del Rio Clay, Buda Limestone, Eagle Ford Group/Boquillas Flags, and Austin Chalk. The Del Rio, where present, is the upper confining unit for the Edwards, and is a calcareous, pyritic, gypsiferous siltstone, up to 21 m thick, that contains many *Ilymatogyra* (formerly *Exogyra*) *arietina* and other marine megafossils. The Buda is a massive to nodular limestone with an average thickness of 20 m. It is generally not cavernous except in the northern section of the study area where the Del Rio is missing and allows direct hydrologic continuity with the Edwards. Lake Amistad roughly marks the facies boundary of the Eagle Ford Group (east of the lake) with the Boquillas Flags (to the west); the boundary also turns so that the Boquillas is present northeast of the lake. These time-equivalent units are sequences of thin, interbedded limestone, siltstone, and shale, up to 61 m thick, which become more flaggy westward. The Austin Chalk is a pyritic, fossiliferous, hard lime mudstone to soft chalk; only its lower 60 m are exposed at the surface while its upper portion is removed by erosion or covered by other units. The Austin contains at least five caves in the study area; none have been visited by the author and are only minimally examined within this paper.

Cross-cutting the Cretaceous sedimentary rocks are late Cretaceous basalts that formed sills, dikes, laccoliths, and small volcanoes. The igneous rocks rose along fractures in the Balcones Fault Zone, and Brackettville marks their western limit. Outcrops of columnar basalt are mined and crushed along U.S. Highway 90 in Knippa, 82 km east of Brackettville. Some minor mineral deposits (e.g., gold, silver, mercury) are apparently related to fluids associated with this igneous episode.

Deposited on the above described units is the Uvalde Gravel. Barnes (1977) describes it as Tertiary in age, but it has not been well studied and Freeman (1968) places it as Pliocene to Pleistocene. This unit consists of caliche-cemented cobble to sand-sized sediments, some of which were eroded from the Edwards Plateau. This material occurs as erosional remnants on uplands near the Plateau's southern margin and as outwash below the Plateau.

Structure

The southwestern Edwards Plateau region is characterized by roughly flat-lying beds interrupted by three large-scale structural features: the Balcones Fault Zone, Carta Valley Fault Zone, and the Devils River Uplift (Figure 2).

The Balcones Fault Zone, of probable Miocene age, generally marks the southern and eastern boundary of the Edwards Plateau. This zone runs east from Brackettville to San Antonio, where it turns northeast and extends into Oklahoma. The zone is predominantly a series of en echelon short, normal NE-SW trending faults, down-thrown toward the southeast with local displacements up to 23 m. Faulting occurred at the homoclinal hinge between the stable craton and the subsiding Gulf Coast basin (Bennett and Sayre, 1962; Abbott and Woodruff, 1986).

The Carta Valley Fault Zone trends east-west for about 120 km from western Edwards County through central Val Verde County. The zone is a 1.5- to 8.0-km-wide wrench fault system consisting of en echelon, high-angle faults and fault grabens predominantly oriented N50°E. The fault zone is aligned along the northern faulted boundary of the Devils River Uplift. Webster (1982) believed that it formed by movement of a wrench fault that underlies the Cretaceous rocks, probably related to the Laramide orogen 130 km to the west.

The Devils River Uplift occupies much of the area between Brackettville and the Pecos River and south from the Carta Valley Fault Zone almost to the Rio Grande. The uplift formed as a resistant buttress during early Paleozoic deformation and continued to have upward movement through the Cretaceous (Flawn, 1959; Nicholas and Rozendal, 1975).

Vertical jointing is the dominant fracture type of the region. Freeman (1968) and Leonard (1977) correlated fracture orientations to the principal NE-SW stresses of the Balcones and Carta Valley Fault zones and to the Devils River Uplift.

Small folds and local changes in dip occur within the fault zones and the uplift, otherwise the Cretaceous strata in the southwestern Edwards Plateau have remained largely undeformed since deposition. The units are nearly horizontal, dipping between 0.25° and 1° to the southeast and southwest in the respective east and west portions of the area (Sharps and Freeman, 1965; Barnes, 1977). Some broad apparent folds are actually water-swollen Boquillas clay-rich beds that have tilted the overlying Austin and can be seen along roads cut through the Boquillas-Austin contact (Freeman, 1968). Hydration of clay or anhydrite has also been hypothesized to explain the occurrence of tepee structures (Johnston, 1983) and other minor folds in the Boquillas Formation.

Hydrogeology

The Edwards-Trinity (Plateau) Aquifer is the primary source of potable groundwater in the southwestern Edwards Plateau. Other strata in the area also produce water, but this report will only consider groundwater within the cavernous Edwards section of the Edwards-Trinity. Water in the aquifer is a calcium bicarbonate type with low to moderate levels of total dissolved solids. Low usage of groundwater in the region has caused no significant drawdown of the water table.

The Edwards-Trinity is an unconfined to confined aquifer with recharge occurring via precipitation throughout the outcrop. Groundwater flow varies locally in direction and velocity, but overall moves slowly downdip from north to south, discharging at springs along the Balcones Fault Zone or near the Rio Grande. Potentiometric maps of individual counties in the area are provided by Bennett and Sayre (1962), Long (1962), and Reeves and Small (1973); regional mapping by Walker (1979) does not include Kinney County due to insufficient data points.

Highway 674 heading north from Brackettville lies over the groundwater divide between the confined portion of the aquifer to the east and the unconfined aquifer to the west. Recharge along the Plateau enters the artesian portion of the aquifer where dip and down-faulted blocks confine the Edwards Limestone. This groundwater rises along faults through the overlying impermeable units to form artesian springs. Las Moras Spring in Brackettville is a typical spring of the confined Edwards (Balcones Fault Zone) Aquifer (Figure 4). More intense faulting to the east fully separates the Fault Zone aquifer from the unconfined Plateau aquifer.

Numerous gravity-drained springs occur throughout the region, especially in the unconfined Plateau aquifer west of the groundwater divide. The majority of these springs are perched and drain uplands to adjacent, deeply incised valleys; at most springs this discharge is re-absorbed into the regional aquifer a short distance downstream. Several springs were inundated by Lake Amistad when its dam was built in 1969; the San Felipe Springs are the largest remaining subaerial springs with a combined average discharge of 121 million m^3/year—a marked increase from the pre-dam mean of 84 million m^3/year (Richard Peace, International Boundary Commission, personal communication, 1993). Although some investigators have described the springs as artesian because they rise from solutionally enlarged openings, the Edwards Limestone is not confined at that location and its water is “confined” only within its conduits.

Water in the Edwards-Trinity (Plateau) Aquifer generally has <500 ppm of total dissolved solids. Concentrations increase downgradient, commonly with proportional increases in sulfate and chloride (Ground Water Protection Unit, 1989). Overall, the aquifer is a calcium bicarbonate groundwater of moderate to high hardness and good drinking-water quality.

Geomorphology

From east to west, the Nueces River, Rio Grande, Devils River, and Pecos River are the master streams that dominate geomorphic development of the southwestern Edwards Plateau. During the Tertiary these stream systems planed much of the region, and major incision of the Cretaceous strata began in the post-Miocene following the subsidence of the Gulf Coast Basin (Thomas, 1972; Belcher, 1975; Woodruff, 1977). The Balcones Fault Zone marked the boundary of the subsidence as the Balcones Escarpment developed in that location, defining the margin where less resistant rocks were down-thrown against the resistant rocks of the Plateau. The shapes of established meanders among the western streams were maintained during downcutting, with some realignment along fractures. Most tributaries to the rivers are shallow and not yet graded to river level owing to intermittent flows over hard limestone.

The southwestern Edwards Plateau has no major alluvial fans or playa deposits commonly associated with dry climates. Some Quaternary gravel has accumulated on valley floors, but gradients are steep enough to prevent excessive aggradation. Most of the units are hard, cliff-forming limestones which weather largely by dissolution and generate little sediment except residual clay. The Del Rio Clay and the Boquillas Formation are softer, slope-forming, better vegetated units that release more sediments to erosion. Low stream flows and sediment loads also result from internal drainage throughout the karsted Plateau surface.

KARST FEATURES

Karst features rank among the significant geomorphic features of the southwestern Edwards Plateau. The surface karst is very subdued, but caves and paleo-subsidence sinkholes are dramatically large. Both the caves and subsidences are hydrologic relicts, although some smaller caves are recently developed.

Karst features of the southwestern Edwards Plateau have been described and recognized since the work of Roberts and Nash (1918), but usually only brief notes have been written. Some exceptions include a review of Texas karst regions (Smith, 1971), Kastning's dissertation (1983a) and resulting papers on the Edwards Plateau karst (e.g., 1983b), Byrd's (1988) sedimentologic and morphologic investigation of Seminole Sink, and overviews of the karst geology and the cataloguing of caves in Edwards County (Reddell and Smith, 1965), Kinney County (Smith and Reddell, 1965), Uvalde County (Reddell, 1961), Val Verde County (Reddell, 1963), along the Devils River (Deal and Fieseler, 1975a), and in the Devil's Sinkhole area (Deal and Fieseler, 1975b; Byrd, 1983). Despite the above work, prior to this study there has been no detailed, comprehensive investigation of karst development in the southwestern Edwards Plateau.

Karren

Karren, the solutional sculpting of surface bedrock, are poorly- to moderately-well developed. The low-gradient upland topography and low annual rainfall promote the formation of soil-filled cleft karren as the most common type. Many solution pans or tinajas also occur; some have formed overflow channels, and some are elongated along joints. Tinajas on valley floors are elongated in the direction of stream flow similar to solution scallops.

Other types of karren on the Plateau include rain pits, rills, and steps. Like cleft karren and tinajas, rain pits are common in arid climates and on low slopes, but are often overlooked as just "rough" rock. On steeper surfaces of the Plateau some poorly developed rill karren and stepped karren are present. Pit and tunnel karren are uncommon.

Sinkholes

Three primary types of sinkholes occur in the southwestern Plateau: solution, subsidence, and collapse. Few solution sinkholes are known in the area, an absence resulting from three factors: high fracture permeability, low precipitation, and lithology.

Veni (1987) found that limestones with high fracture permeabilities do not readily form solution sinkholes. Efficient recharge via multiple fractures minimizes runoff that would otherwise enlarge only a few fractures or cave entrances into sinkholes. In arid or semi-arid regions like the southwestern Edwards Plateau, the low annual precipitation also limits the available runoff to incipient sinkholes. Arid regions also lack sufficient vegetation and soil that could retain runoff and charge it with CO_2 for greater corrosional ability. Arid regions containing solution sinkholes generally have fewer permeable fractures, allogenic recharge, sufficiently long periods of limestone exposure to weathering, and/or reflect prior wetter climates (Veni and Associates, 1991). Most solution sinkholes in the study area occur in low-gradient topography and near the top of the Edwards Limestone where eroded Del Rio Clay may fill some fractures, encouraging runoff to a smaller number of open fractures.

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Subsidence Sinkholes

Many collapse sinkholes occur throughout the southwestern Edwards Plateau; the oldest and largest are subsidence sinkholes. Freeman (1968) mapped 101 subsidence sinkholes in the study area within 38 km of the Rio Grande. Some of these structures are linear, but most are oval, circular, or irregular in shape; they range in size from <100 m in diameter to 15 km long by 7 km wide.

By studying which units are displaced by the sinkholes, Freeman (1968) determined that subsidence occurred sometime between the end of the Cretaceous and the deposition of the Plio-Pleistocene Uvalde Gravel. Displacement of 12-15 m is common, but more than 70 m is also evident in some sinkholes. In spite of the substantial subsidence associated with these features, none have any topographic expression. Erosion has long since removed evidence of any depressions which may have formed on the land surface (Figure 5).

Kastning (1987) was the first to postulate that the subsidence sinkholes probably occurred by collapse into phreatically-formed cavities. Additional research by Veni and Associates (1991) revealed that the level of phreatic cave development occurred 90-120 m below the top of the Edwards Group in the Stockton Plateau (the extension of the Edwards Plateau west of the Pecos River). Brecciated strata in subsidence sinkholes had been displaced by various amounts, depending on the volume of collapse breccia removed by solution. Subsidences were predominantly linear and converged toward the Pecos River; they formed in Miocene-Pliocene time down a paleohydraulic gradient from the ancestral Rio Grande to the ancestral Pecos River.

Unlike the Stockton Plateau subsidences, the pattern of subsidence sinkholes east of the Pecos River in the southwestern Edwards Plateau implies different groundwater flow conditions. A few linear subsidences are in the northwestern area and are similar in size, scale, and orientation as those of the Stockton Plateau. They also probably formed under a hydraulic gradient leading to the Pecos River. To the south near the city of Del Rio are circular to oblong subsidences, which have a general east-west orientation but no distinct pattern. They probably were formed by very slow groundwater movement along a low and poorly defined gradient. The largest known subsidence features are located between these groups within the Carta Valley Fault Zone. While the scale of the other subsidences suggests development by the collapse of single, large conduits, the 2-7 km widths of these giant features imply a different origin. These features show only minor displacement, suggesting limestone dissolution throughout the highly fractured zone and gradual settling of the overburden as conduits interconnected and collapsed. No correlation of subsidence sinkholes with modern caves has been found in the southwestern Edwards Plateau (Kastning, 1987) or the Stockton Plateau (Veni and Associates, 1991).

Collapse sinkholes

Most cave entrances in the southwestern Edwards Plateau are collapse sinkholes. Their origin is generally attributed to the drainage of water from phreatically formed caves, but this is not wholly accurate. Substantial collapse commonly occurs with the loss of phreatic water, yet speleothem development on or relative to the collapses indicates that these breakdowns are much older than the entrances. Generally, cave ceilings stope upward to stable configurations and do not intersect the land surface. Collapse entrances usually develop much later as a combination of surface erosion intersecting caves, with increased vadose flow along joints that destabilizes the thinning limestone roofs.

A few collapse sinkholes can be classified as subsidence shafts because their breakdown floors slowly sink as they are dissolved and removed by groundwater. The most famous cave in the area, the Devil's Sinkhole, is one such cave (see cave descriptions), though solutional removal of the breakdown is proceeding at a sluggish rate given the groundwater's slow circulation and probable near-saturation with respect to calcite.

In the northwest portion of the study area where the Buda Limestone rests directly on the Edwards, collapse entrances form within the overlying non-cavernous Boquillas Flags (Figure 6). After phreatic waters drain from caves along the Buda-Boquillas contact, vadose water flows through the Boquillas, collapses it, and transports it underground. The best known examples occur on the Stockton Plateau near Langtry (see descriptions of Langtry Lead, Langtry Quarry Cave, and Montgomery Gypsum Cave). The Abominable Sinkhole, a Devil's Sinkhole size collapse near Comstock, has also collapsed through the Boquillas, even though the Del Rio Clay is present between the Buda and the Edwards Limestone. The minimal erosion of the Uvalde Gravel, which overlies the Boquillas Flags at the entrance, indicates this is a recently formed feature, but the specific cause for this atypical, active collapse is not yet clear.

Collapse sinkholes vary considerably in size in the southwestern Edwards Plateau. The smallest are less than a meter in diameter, but sometimes even the largest collapses are not evident on the surface. Collapses within valleys are readily filled by debris and hidden from view; the truncated, 24-m-wide passage of Kickapoo Cavern is the best example, marked only by a 2 m in diameter

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depression at its entrance (see map in cave descriptions). One limitation to the distribution of large collapses is that they occur in old, phreatically formed caves, since recent vadose cave development produces structurally stable, narrow, passages.

Caves

Most caves of the southwestern Edwards Plateau preferentially developed during phreatic conditions in massive limestone, commonly along the contact between the Segovia and Fort Terrett, or stratigraphically equivalent horizons. The caves form along joints oriented down local hydraulic gradients. The larger caves are hydrologic relicts. They formed in areas where the Del Rio Clay is thin or missing, which allowed diffuse recharge into the limestone through overlying units.

Lithologic Controls on Cave Development

Lithologic controls can be estimated by examining the strata or by mapping for zones of greater or lesser solubility. In the study area some general interpretations are possible based on field observations, but the elevations of caves relative to marker beds within the Edwards Limestone are not generally known with enough precision to establish exact lithologic correlations. Veni and Associates (1991) were able to establish such correlations on the adjacent Stockton Plateau and found some intervals of preferential passage development that tentatively explain the stratigraphic location of many caves in the study area.

The stratigraphic interval of greatest conduit development in the Stockton Plateau is along the contact of the Segovia and Fort Terrett members of the Edwards Limestone, which becomes marly to the west. This is also the hypothesized zone where phreatic solution created large conduits which collapsed to form the subsidence sinkholes. The large passages of Fawcett's Cave (see cave descriptions) may be part of the conduit systems that formed between the Miocene and Pliocene. Although the current cave is above the contact, it formed by collapse into solutionally formed conduits that were probably located at the contact. Less significant, yet prominent levels of passage development within the Edwards Group also occur at 15-22 m, 39-47 m, and 58-66 m below the top of the unit. The large, breakdown-floored passages of Fern Cave (see cave descriptions) probably formed at the same time as Fawcett's Cave, but more likely at the 58-66 m horizon.

In the northeast portion of the study area, the primary solution zone may be the Edwards' Kirschberg Evaporite at the top of the Fort Terrett. Byrd (1983) hypothesized that the original cham-ber which collapsed to create the Devil's Sinkhole was formed in the Kirschberg. However, no significant phreatically-formed passages have yet been observed within the unit. Most area caves occur in massive, relatively pure limestone, that provide the structural competency for large rooms and passages to develop with minimal collapse, or with collapse that may obscure the solutionally-formed void, yet often leaves a cave that preserves the original conduit's general orientation and extent.

Extensive passage development occurs at the base of the Buda Limestone in the northwest section of the study area, where the Del Rio Clay is missing between the Buda and Edwards Limestone. Freeman (1968) notes that argillaceous and dolomitized beds occur along this basal contact. Smith (1968) and Kastning (1983a) relate these beds to alteration during the erosion of the Edwards and deposition of the Buda, possibly from Del Rio Clay reworked into the base of the Buda. The resulting low solubility and permeability of the beds perches groundwater, which increases solution of the overlying strata.

Structural Controls on Cave Development

The effect of strike and dip on cave development in the area is not known. Bedding attitude has not been measured in most caves because it is nearly horizontal. The effect of the low dip on groundwater flow is also probably masked by the greater influence of joints.

Vertical joints generally guide the development of caves in the southwestern Edwards Plateau. They are especially evident in passages less than 5 m wide; in wider passages solution along joints is obscured by collapse, or the passages form along sets of parallel joints that are not individually prominent. Only Kickapoo Cavern and Diablo Cave are known to be intersected by faults, and only Diablo's development is affected by faulting.

The orientation of joints in area caves has rarely been measured. However, since most passage segments are joint-guided, the trends of the segments can be used to approximate joints and determine which orientations are more prone to conduit development. To assess joints' effect on cave development, the bearings of 40 passage segments measured in 23 study area caves were compiled and are presented in Figure 7. Up to three different major bearings were measured in each cave; multiple segments along the same bearing within a cave counted as one measurement. The results show greatest development along bearings of 100-119° and 60-79°, but the values are not high enough to be significant. Adjusting the data to favor a cave's most prominent bearing (if there was more than one) did not significantly alter the results. Although the study area may extend over too many different structural features to produce meaningful data, geographic comparison of the caves and their segment orientations shows little correlation to local structure or even to similar bearings among nearby caves. (See the maps of Alamo Village Cave and Webb Cave in the cave descriptions where bearings of the linear, strongly joint-guided passages differ by about 20-30°), though the caves are less than 5 km apart.

Hydrologic Controls on Cave Development

The Rio Grande, Pecos River, Devils River, and Nueces River are the primary hydrologic controls on cave development in the southwestern Edwards Plateau. Planation of the ancestral Edwards Plateau by the Devils and Nueces rivers allowed ground-water recharge into the Edwards Limestone through the overlying Buda and Boquillas formations where the Del Rio Clay is thin or absent in the northern portion of the study area. The distribution of large phreatic passages in the Edwards Plateau correlates with areas where the Del Rio is absent or is present but down the paleo-potentiometric gradient from those areas.

Byrd's (1988) study of Seminole Sink produced the only analyses of cave sediments from the study area. His Zone 9 sediments are predominantly the insoluble fraction of the limestone left from the solutional development of the phreatic conduits. The gross characteristics of most sediments in other paleo-phreatic caves are similar to those deposits and are probably of the same origin. The lack of detrital material in these ancient sediments further indicates that recharge did not initially enter these caves through point sources but instead diffused downward.

Most conduit development occurred in the Edwards, probably because it was the most soluble unit below the water table relative to the zones of greatest groundwater circulation. The seemingly random orientation of passage segments illustrated by Figure 7 likely reflects slow groundwater movement along a poorly defined or nearly flat hydraulic gradient. Passages developed in varied directions probably in response to minor differences in the gradient or in fracture permeability. Large scallop sizes indicate slow paleo-velocities, but they have not been defined because the scallops are nearly symmetrical, have limited exposures, and lack measurements.

During this period of phreatic cave development, most groundwater probably moved toward the ancestral Rio Grande or ancestral Pecos River to discharge upward through overlying units. The incision of the rivers into the Edwards Limestone created more sites for groundwater discharge, allowing increased groundwater circulation to enlarge the caves. However, continued incision of the rivers lowered the potentiometric surface, and drainage through caves was either altered or abandoned. Most of the caves have undergone relatively little vadose modification following the regional groundwater decline, indicating rapid abandonment and diversion of groundwater. Except for initial collapse following the draining of phreatic waters, most modifications occurred as the land surface intersected, collapsed or truncated the caves, and subsequently filled them with locally derived sediments. Although the area has large passages, few caves extend farther than a few hundred meters due to the highly dissected terrain and the sediment fills.

Active cave development by the recharge, transmission, or discharge of groundwater is seldom found in vadose caves of the southwestern Edwards Plateau. Recharge tends to be limited by the generally steep terrain which encourages runoff instead of infiltration, and the high fracture permeability which discourages preferential enlargement of fractures by overland flow. H.T. Miers Cave (see cave descriptions), located in an area of low relief, is a major exception. Brackettville Sink is another exception, probably due to its occurrence in the less permeable Austin Chalk. This cave accepts considerable floodwater and probably recharges the Edwards Aquifer, as indicated by the level of the terminal pool which apparently responds to changes in the aquifer's potentiometric surface (Smith and Reddell, 1965).

Most of the caves recently formed by ground-water discharge are small, occur near the base of major river valleys, and result from groundwater moving down locally steep hydraulic gradients toward the rivers. These caves are rapidly abandoned as the rivers continue to incise and groundwater shifts to lower elevations to discharge from even more recently developed conduits. Caves associated with major Edwards Aquifer springs have not been well investigated. The San Felipe Springs require scuba, and their outflow velocity spits out would-be explorers (Ron Kerbo, personal communication, 1993). Divers in Del Rio report that Goodenough Spring discharges from a cave, despite its inundation by Lake Amistad. Exploration is currently difficult because of its depth at 44 m beneath the lake surface. Hydrograph analysis and geochemical modeling of the springs have not been conducted.

Types and Origins of Speleothems

Speleothems in the southwestern Edwards Plateau are mainly calcium carbonate or sulfate. Among the carbonates, aragonite is uncommon and is usually limited to small needles. Calcite speleothems are by far the most common and include stalactites, stalagmites, columns, flowstone, and drapery, with some spectacular displays of helictites (Figure 8). Some speleothems achieve dimensions over 10 m in height or diameter (see cover photograph); white to brown colors are typical. Many have macrocrystalline or monocrystalline structure.

Based on work in Caverns of Sonora just north of the study area, Hill et al. (1989) hypothesized that macro- and monocrystalline speleothems tend to develop in caves high in both humidity and carbon dioxide, which is more likely in caves that have recently formed entrances. They also postulate that certain types of helictites are more likely to grow from macro- or monocrystalline bases; Hill and Forti (1986) describe helictites that also grow from calcite wall crusts. That these conditions are frequently present in caves of the area helps explain why helictites are relatively abundant. Kastning (1983a) speculated that the upper beds of the Segovia Member may prevent helictite development in underlying passages, but closer study has since disproved this hypothesis. Some speleothems in the southwestern Edwards Plateau appear to be recrystallized, but considerably more research is needed before making conclusive statements about most of the region's cave mineralogy.

Gypsum flowers, crusts, and blisters are the only reported sulfate speleothems in the area. They are only known where the Del Rio Clay is missing and the Boquillas Flags is present or only recently eroded off the Buda Limestone. Mineralogic analyses have not been made to demonstrate the presence of sulfates in the Boquillas, but the fetid odor of some beds strongly suggest their occurrence. Vadose seepage through the Boquillas probably leaches the sulfates and carries them down into Edwards caves, where the solution reacts with the limestone walls to create gypsum. Once the overlying Boquillas is removed, undersaturated vadose water begins to seep into the caves and dissolve the gypsum. These speleothems are rare in the Edwards Plateau since much of the Boquillas has already been stripped, although they are common across the Pecos River in the eastern Stockton Plateau where the Boquillas is generally present (Figure 9).

Relict Karst and the Dating of Karst Processes

At least three periods of paleokarst and relict karst development have been identified on the Stockton Plateau and occurred during the Middle Tertiary, Late Tertiary, and Late Pleistocene.

Middle Tertiary Karst Development

The subsidence sinkholes and their associated large phreatic conduits are the oldest karst features in the southwestern Edwards Plateau. Their development has no apparent correlation to modern structure or groundwater movement; the sinkholes and their fills are graded to the present land surface with no topographic indications of the substantial collapse displacements. Some of these features are classified as paleokarst because they were buried and exhumed from under the Plio-Pleistocene age gravel; others were never buried and are thus classified as relict karst.

The origin of the large conduits may date to the onset of Eocene entrenchment of the Pecos River, but the timing of the subsequent collapses is uncertain. Fawcett's Cave, Fern Cave, Green Cave, and Kickapoo Cavern are examples of remnants of collapsed conduit systems. These caves are preserved because they were probably not wide enough to totally lose their structural integrity; collapse ended once the passages had stoped upward to more stable configurations. Radiometric dating of speleothems in Green and Kickapoo (courtesy of Dr. Derek Ford, 1992) show that dripstone deposition on the breakdown began prior to 350,000 B.P., the limit of the age determination technique (Veni, 1992).

Another means of determining the age of caves is by evaluating the rate of stream incision into the karst. Based on the current elevation of relatively undissected portions of the Edwards Plateau just north of the study area, the average paleo-elevation for the Plateau in its southwestern corner was about 750 m above present mean sea level. As a gross approximation (disregarding climatic variations and other effects), local denudation rates can be calculated by taking the difference between the current elevation of the major stream in an area of interest and the 750 m elevation, and dividing by 20 million years (the time between the uplift of the Plateau to the present). At Green Cave and Kickapoo Cavern the gross denudation rate is 1.13 cm/ka (thousand years). To determine when groundwater began to drain out of these caves, the elevation of the local major streambed can be used to approximate the elevation of the ancient water table. Based on this relationship and the estimated incision rate, water began to drain out of Green and

Kickapoo about 3.9 Ma (million years ago) and the caves began to form sometime prior to that date. Caves farther up the hydraulic gradient would be older, having been drained earlier. For example, at Fern Cave the estimated gross denudation rate of 1.41 cm/ka is higher due to its proximity to the Devils River, but the time when phreatic waters drained from the system was around 4.9 Ma.

Late Tertiary Karst Development

Additional paleokarst on the southwestern Edwards Plateau originated prior to the deposition of the Uvalde Gravel during the Pliocene or Pleistocene. Roberts and Nash (1918) and Freeman (1968) describe sinkholes and caves that formed in the Buda and Edwards limestones along N40°E joints, common to that area, and subsequently filled with clay- to boulder-sized sediments. The sediments are cemented by manganese minerals and yield low-grade manganese ore, which was mined intermittently from the early 1900s through the 1950s. Warren (1942) found similar manganese cement in the Uvalde Gravel. It is uncertain if the manganese in the paleokarst caves and sinkholes was deposited during sedimentation or was later introduced by groundwater.

Late Pleistocene Karst Development

Relict caves dating from the Late Pleistocene occur throughout the southwestern Edwards Plateau, especially near the Rio Grande and Pecos River and their entrenched tributaries. Stream incision at the Plateau margins has intersected many caves and diverted sources of groundwater and surface water to other locations. This process has also been active on the Plateau uplands since before the Late Pleistocene downcutting, but there the process is more subdued. The process of relict cave development in the nearby Langtry and Sonora areas is well described by Kastning (1983a, 1983b).

Some sediment-filled caves of unknown age occur at the top of the Edwards Group. An excellent example is exposed in a road cut along U.S. Highway 90 a couple hundred meters east of the Pecos River. Its sediments have not been examined chronologically so their age is unknown. Kettenbrink (1983) speculates that the caves are Cretaceous in age and that infilling occurred during the deposition of the Del Rio Clay; however, Freeman (1968) notes soft-sediment deformations that indicate the Edwards was not lithified and was probably unable to form caves at that time. If the Del Rio Clay does fill these caves, it could have been deposited following more recent erosion. The elevations of these caves suggests they may have formed contemporaneous with the caves filled with the manganese ore.

KARST EVOLUTION ON THE SOUTHWESTERN EDWARDS PLATEAU

The origin and evolution of the southwestern Plateau karst extends from the Early Cretaceous deposition of carbonate sediments to the present. The following sequence of events describes a possible evolution based on previous research and the findings of this report.

1) Lower Cretaceous deposition of carbonate and clastic sediments of the Trinity Group was followed by deposition of Edwards carbonate sediments.

2) Regional uplift near the boundary between the Lower and Upper Cretaceous resulted in partial erosion of upper Edwards sediments and nondeposition of the Del Rio Clay in the northern and western portion of the area. Some karst features may have formed at this time.

3) Subsequent marine carbonate and clastic sediments were deposited during Upper Cretaceous time. Periods of no deposition occurred between Buda and Boquillas deposition, and between Boquillas and Austin deposition. The Devils River Uplift resulted in less deposition of the Buda and overlying Cretaceous units than in adjacent areas.

4) Regional uplift began during the Laramide orogen (Late Cretaceous to Early Tertiary). Cretaceous strata throughout most of the region were tilted slightly to the southeast and fractured. Tension joints were the dominant structural elements. Erosion of Upper Cretaceous strata began, including the solutional widening of fractures in carbonate rocks by surface or groundwater.

5) Laramide mountain-building to the west initiated major stream development. By Eocene time the Pecos River and the ancestral Rio Grande were established as the dominant stream systems draining west Texas, northern Mexico, and much of New Mexico.

6) During the Miocene, Balcones faulting was most active. Also during this time the ancestral Pecos River was probably beginning to cut into the Edwards and associated carbonates. Continued incision of the Pecos and ancestral Rio Grande enhanced groundwater circulation by developing new outlets for groundwater discharge. Water leaking down into the Edwards through overlying formations began to flow down the potentiometric surface to discharge at the rivers; en route, a system of large phreatic conduits began to form.

7) The phreatic conduits enlarged to the point of large-scale collapse with ongoing solutional removal of the collapse debris. Upward stoping progressed through as much as 90 m of strata, into the formations overlying the Edwards, to create subsidence sinkholes. Artesian conditions may have aided the collapse through upward solution. It is not known if the subsidence sinkholes reached the land surface of that time. Modern streams

Veni, G. 1994. Hydrogeology and evolution of caves and karst in the southwestern Edwards Plateau, Texas. Pp. 13–30, *in* The Caves and Karst of Texas (W. R. Elliott and G. Veni, *eds.*). National Speleological Society, Huntsville, Alabama. 252 pp.

or karst features show no correlation with the sinkholes.

8) The meanders of the ancestral Pecos River and Rio Grande were preserved during their Late Miocene to Early Pliocene incision into the hard carbonate rocks, and delimited the southwestern boundaries of the Edwards Plateau. Much of the Buda Limestone and small portions of the Edwards Group were exposed at the surface and extensive karstification began.

9) Late Pliocene and Early Pleistocene gravels and related sediments were broadly deposited throughout the major stream valleys, filling many of the newly-formed caves. Manganese associated with the gravels was carried in solution and concentrated within some of the sediment-filled caves and sinkholes.

10) Stream incision resumed during the Early Pleistocene and deep phreatic conduit loops were initiated. Conduits developed at levels along lithologic zones of greater solubility and groundwater circulation.

11) River terraces developed during pauses in river down-cutting. Such pauses promoted conduit and spring development near those levels, but the resumption of valley incision left them as relict features by the concurrent lowering of the potentiometric surface or by removing sources of groundwater.

12) The lower potentiometric surface caused passage incision and the formation of shafts in caves. Caves also underwent other vadose modifications such as the deposition of calcite speleothems and the collapse of wide passages and rooms.

13) As certain caves became phreatic relicts, the degree of their vadose modification varied according to the rate of groundwater flow through the caves and the length of time that flow was sustained. Sediment aggradation occluded some cave passages. Groundwater seepage from the Boquillas resulted in the growth of gypsum speleothems.

14) Much of the relationship between the modern land surface and the entrances to presently accessible caves began to form during the Wisconsin, according to sedimentologic studies by Frank (1965) and the vertebrate paleontology investigations of Lundelius and Slaughter (1971).

15) During the Wisconsin period the climate of the southwestern Edwards Plateau was more temperate; consequently, the caves were more hydrologically active, and the regional potentiometric surface was higher.

16) Since the close of the Wisconsin, the climate of central Texas has become drier according to cave sediment and paleontologic studies (Frank, 1965; Toomey, Blum, and Valastro, 1993). Water levels have continued to drop, but no significant collapses are known to have resulted. Decline in spring discharge may have contributed to the alluviation of some springs along the Pecos River and Rio Grande.

CONCLUSIONS

The southwestern Edwards Plateau presents an interesting but relatively simple history of karst development. Significant karst features range in age and origin from the Middle Tertiary to the present; some of its caves are among the largest known in Texas. Uncertainties about the extent, age, or development of the area's karst evolution stem from the minimal field data available.

RECOMMENDATIONS FOR FUTURE RESEARCH

1) More caves and springs need to be examined to refine the results of this study, and to better guide future research.

2) Lithologic mapping of caves is needed for better correlation of levels for hydrologic and morphologic studies.

3) More precise age analysis of the Uvalde Gravel is needed to better date the occurrence of and reconstruct the history of regional geomorphic events.

4) Palynologic and isotopic analysis of sediments and speleothems from selected caves and relict sediment-filled caves may allow determination of regional paleoclimatic conditions and past and present rates of cave and aquifer development.

5) Drilling into subsidence sinkholes may yield pre-Pliocene sediments that could better date the drop in water level in the ancestral aquifer and the subsequent collapse of the sinkholes.

6) Geophysical prospecting around subsidence sinkholes may locate uncollapsed conduits, which can then be studied by sample analysis and/or exploration to pursue the research objectives of recommendation #5.

7) Dye tracing from selected caves to springs would define aquifer flowpaths, time of travel, groundwater dispersion, and groundwater volume.

8) Hydrographic and geochemical analysis of cave streams and fracture-flow in water wells is needed to determine aquifer response to recharge.

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