Speleogenesis of Critchfield Bat Caves and Associated Hydrogeology of the Northern Edwards Aquifer, Williamson County, Texas

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Speleogenesis of Critchfield Bat Caves and Associated Hydrogeology of the
Northern Edwards Aquifer, Williamson County, Texas

By

Ashley Landers, B.S.

Presented to the Faculty of the Graduate School of
Stephen F. Austin State University
In Partial Fulfillment
Of the Requirements
For the Degree of
Masters of Science

STEPHEN F. AUSTIN STATE UNIVERSITY
May, 2016
Speleogenesis of Critchfield Bat Caves and Associated Hydrogeology of the
Northern Edwards Aquifer, Williamson County, Texas

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ABSTRACT

Karst development in the Edwards Aquifer has been significantly studied in the San Antonio and Barton Spring Segments; however, karst development remains poorly studied in the Northern Segment. Detailed characterization of the Northern Segment is vital for future water conservation because of increasing urban sprawl along the Interstate 35 corridor. The Northern Segment of the Edwards Aquifer consists of Lower Cretaceous strata of the Comanche Peak, Edwards, and Georgetown formations. The stratigraphy is dominated by Edwards Limestone as it is the only formation that crops out in the study area.

Karst, stratigraphic, GIS, and geochemical studies were conducted to evaluate development of karst and hydrogeology in the Salado Creek Watershed. GIS analyses included interpretations of digital elevation models derived from LiDAR data of the study area. Karst features found in the study area were analyzed and mapped as an assessment of the speleogenesis of specific features. Stratigraphic analyses found there are eight facies total on Critchfield Ranch ranging from low-energy depositional environments with the mudstones and wackestones to high-energy depositional environments with the packstones and grainstones. One facies found has a high vuggy porosity that limits cave development in the area, but promotes development of significant high
permeability horizons. Geochemistry data suggested that there is a longer residence time of groundwater between the springs based on the differences in their chemistries. Of the three caves found on Critchfield Ranch, it was determined that they are all epigene caves with vadose and phreatic morphologies.
ACKNOWLEDGEMENT

First and foremost I would like to thank the Critchfields for allowing me to do field work and research on their ranch. Specifically I would like to recognize Grant, Steve, and their parents Chester and Betty Critchfield. They all made sure we had anything and everything we needed and were very welcoming and supportive of the research. They are also some of the nicest people I have ever met and I am so glad I got the opportunity to conduct research on their property.

I would like to acknowledge my parents John and Libby Landers as well as my best friends who have supported and motivated me throughout the whole graduate school process. I would also like to thank Jessica Shields, Derek Sullivan, Ingrid Eckhoff, Asa Vermeulen, and Aubrey Jones for their help with field work and invaluable GIS knowledge and experience. My thesis committee for being there and helping with any questions I had.

Lastly I would like to thank Dr. Kevin Stafford. He has been the most help with this thesis. With so much knowledge and passion for his field of study, he has made the whole course of the thesis, from field work to defending, a fun, interesting, and unforgettable experience.
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INTRODUCTION

Critchfield Bat Caves in Williamson County, Texas are approximately 15 km south of Salado, Texas on the west side of Interstate 35, near Jarrell Texas (Figure 1). They have a combined known length of 91.4 m and known depth of 6.5 m, but there are possibly more undiscovered caves in the proximal region, which is dominated by private ranches and small limestone quarries. The caves are located on the southeastern margin of the Edwards Plateau and adjacent to the Balcones Fault Zone. They are developed in the Cretaceous Edwards limestone and lie above the Northern Edwards Aquifer. Speleogenesis of the Critchfield Bat Caves, distribution of related proximal karst, and hydrogeology of the Northern Edwards Aquifer are the focus of this study.

The goals of this study focus on four questions involving karst formation in the Northern Edwards Aquifer. Speleogenesis and associated karst processes will be analyzed through detailed research of the Edwards Limestone near the caves.

1. What is the speleogenetic evolution of Critchfield Bat Caves?

Determination of how Critchfield Bat Caves formed and identification of the processes involved in the development of these caves is the main
Figure 1: Location of Salado Creek Watershed and Critchfield property.
focus of this study. The question is answered through a combination of fieldwork and remote sensing.

2. **What are the structural and stratigraphic controls on groundwater flow and karst development in the Salado Creek Watershed?**

Composition and structure of the study area’s outcrops and their impacts on local hydrogeology will be determined through a combination of remote sensing analyses and site studies proximal to Critchfield Bat Caves. These data are used as proxies for predicting the effects of changes in lithology, faults, and fractures on groundwater behavior.

3. **What is the spring geochemistry of the Critchfield Ranch property related to the Salado Creek Watershed portion of the Northern Edwards Aquifer karst system?**

Geochemistry of groundwater spring discharge within the Critchfield property and near the study area were evaluated to characterize groundwater resources within the study area. Fluid geochemistry was measured utilizing a combination of portable meters and laboratory analyses.

4. **What is the spatial distribution of karst features in the Salado Creek Watershed?**

Analyses of GIS data, including LIDAR analyses, were used to delineate regional trends in surficial karst manifestations, including identification of
sinkholes on properties were physical access is not available. Physical mapping of surficial karst manifestations on the Critchfield property document spatial distribution of karst features at a small scale. These data are used for comparison of karst density and lithology changes based on remote sensing techniques across the Salado Creek Watershed.
STUDY AREA

Critchfield Bat Caves in Williamson County, Texas are approximately 15 km south of Salado, Texas on the west side of Interstate 35, near Jarrell, Texas and are contained within Critchfield Ranch. Critchfield Ranch encompasses 0.8 km² near Jarrell, Texas within the Salado Creek watershed. Salado Creek watershed is 371.94 km² and is located in parts of northern Williamson County and southern Bell County in the western and central areas of the counties encompassing the towns Jarrell and Salado. The base point of the watershed is located in Salado, Texas where Salado Springs is discharging into Salado Creek.

Seven physiographic provinces make up Texas based on geologic structure, rock and soil types, vegetation, and climate. Each province or landscape reflects a unified geologic history of depositional and erosional processes (Wermund, 1996). The study area is located in the Edwards Plateau province directly adjacent to the Blackland Prairie in the Balcones Escarpment (Figure 2). The study area is surrounded by the Grand Prairie to the north, Interior Coastal Plain to the east, and Central Texas Uplift to the west. In Williamson County and farther to the north, the Jollyville Plateau is dissected by eastward-flowing creeks, becoming similar to the Lampasas Cutplain’s terrain to the west and north (Woodruff et al., 1985).
Figure 2: Location of study area within the physiographic regions of Texas.
The Balcones Escarpment surrounds the Edwards Plateau to the east and south. Its principle area includes the hill country and a broad plateau (Wermund, 1996). Erosion from streams shape the area from Waco to Del Rio, through the central Texas region. Cretaceous limestones make up the Edwards Plateau, while streams entrench the area. The upper drainages of streams are largely waterless draws that open into box canyons where springs provide permanently flowing water (Wermund, 1996). Karst features, including sinkholes and caves, are common in the limestone terranes (Wermund, 1996). The dominant soil types in the study area are clays to clay loams on the surface and rocky clay beneath the surface. Due to erosion in the area, approximately 25 cm of soil is present before encountering solid limestone. Vegetation in the Edwards Plateau is a mixture of many types from tall, medium, and short grasses to different kinds of hardwood trees like live oak, Texas oak, honey mesquite, ashe juniper and many others. On the eastern portion of the plateau, where springs and creeks are predominant, bald cypress, sycamore, and black willow can be found.

Because the study area is within the transition between Blackland Prarie and Edwards Plateau, land use varies from Interstate 35 travelling westward. At Interstate 35, the main land use is agriculture and urban development. Agriculture is dominant in the Blackland Prarie because of the fertile soil; main crops grown in the area include corn, sorghum, and cotton. Urban development in the region is accelerating rapidly. From 2000 to 2010 the population in Bell
County grew from 237,974 to 310,235 and in Williamson County 249,967 to 422,679. Traveling west away from Interstate 35, the main land use becomes mining, ranching, and wildlife conservation. There are more limestone quarries to the west and since the soils become shallower, many agricultural crops cannot be grown, thus landowners resort to ranching.

Climate varies significantly across Texas. It ranges from arid and dry in the west to humid and wet in the east. The National Climatic Data Center divides Texas into ten climate divisions (Vaughan et al., 2012). The study area is in the North Central or Cross Timbers region; climate in the study area is humid, subtropical, with hot summers and mild winters. Average annual temperature ranges from 27°C for the high and 15°C for the low. Average annual precipitation varies throughout the year from 59 cm to 89 cm. Precipitation is not uniform and there can be bursts of rainfall where flash flooding can occur.
GEOLOGIC SETTING

Central Texas is characterized by Cretaceous strata on the surface and shallow subsurface throughout the Edwards Plateau and the nearby Balcones Fault Zone. Cretaceous sedimentation of the study area began approximately 110 mya on the Comanche Shelf in lee of the Stuart City Reef (Collins, 2005). In the Tertiary, the Edwards Plateau was uplifted relative to the Coastal Plain due to Balcones Faulting which influenced regional karst processes.

The Edwards Formation of the Fredericksburg Group is the main focus of this research (Figure 3 and 4) and is characterized as a cherty-limestone and dolomite with a thickness varying from 91 m to 27 m that thins northward (Collins, 2005). The Edwards Group has three members, the Comanche Peak Formation, Edwards Formation, and Georgetown Formation. The Comanche Peak and Edwards formations are part of the Fredericksburg Group and the Georgetown Formation is part of the lower Washita Group. However, Texas has a long and complex geologic history with multiple transgressions, regressions, orogenies and periods of subaerial exposure: these are summarized below.

During the Precambrian, the Grenville Orogeny created mountains and what is now crystalline basement rock that is exposed in the Llano Uplift along the western-northwestern boundary of the Edwards Plateau today. Massive
Figure 3: Generalized stratigraphic column of study area (from Collins, 2005).
Figure 4: Geologic map of Bell and Williamson Counties watershed.
granitic structures and mountains were created from plate collisions and
metamorphism during the Grenville Orogeny (Figure 5) (Walker, 1979). Coarse-
to fine-grained sediments eroded and washed to what is now Texas from the
continental core during the Precambrian. Seas transgressed into Texas by late
Cambrian and sediments were deposited until the Ordovician, but the region was
uplifted by late Ordovician and subaerially exposed. In the Mississippian, seas
transgressed, shown by thick sequences of limestone, and later regressed
forming an unconformity. Then in the Pennsylvanian, another transgression
occurred, depositing sediments over the unconformity.

Tectonic plate collisions occurred between the North American, European,
and African-South American continental plates beginning in the Pennsylvanian
(Anaya and Jones, 2009). This tectonic event, known as the Ouachita Orogeny,
uplifted, faulted, and folded the Paleozoic landscape into the ancestral Ouachita
mountain range (Anaya and Jones, 2009). This mountain range extended from
the Ouachita Mountains of southern Oklahoma and Arkansas, along the present
day Balcones Fault zone, to northern Mexico. Gradual tilting of landmass toward
the Tobosa Basin in west Texas in the late Pennsylvanian continued into the
early Permian (Figure 6) (Walker, 1979). Terrigenous lands appeared from
Permian seas and erosion of Paleozoic sediments dominated the early Mesozoic
of Texas.
Figure 5: North America during Late Precambrian (550 m.y.) (from Blakey, 2010).
Figure 6: North America during Permian (275 m.y.) (from Blakey, 2010).
The Ouachita Tectonic cycle ended in the Triassic and initiated the Gulfian Tectonic Cycle (Anaya and Jones, 2009). This cycle started to separate the European and African plates to form the proto Atlantic Ocean. This rifting changed regional drainage direction from northwest into Permian inland seas to southeast into the developing Gulf of Mexico (Anaya and Jones, 2009). During the Jurassic, the region was completely exposed subaerially and erosion of Triassic and Paleozoic sediments formed a rolling landscape known as the Wichita Peneplain (Walker, 1979). By the end of the Jurassic, tilting toward the southeast provided the setting for new continental shelf deposits of Cretaceous age. The Gulf of Mexico continued to develop and regional subsidence and global rise in sea level allowed a broad epicontinental sea, the Western Interior Seaway, to cover the region (Walker, 1979).

The Comanche Shelf started to form as Cretaceous seas transgressed (Figure 7). The Trinity Group and overlying Fredericksburg Group sediments became part of the Llano Uplift. The Trinity Group was deposited in three cycles of transgressive-regressive stages across the base of the Llano Uplift (Anaya and Jones, 2009). The Stuart City Reef formed 241 km from the Gulf Coast and provided protection for Edwards Group sediments to deposit behind the reef. The lower Cretaceous sediments were deposited mostly in marine-shelf and shelf margin settings (Collins, 2005). The Comanche Shelf can be divided into smaller platforms including the Central Texas Platform, San Marcos Platform, Devils
Figure 7: Map of North America during Cretaceous (115 m.y.) (from Blakey, 2010).
River Platform, and Coahuila Platform. Other depositional influences were the North Texas – Tyler Basin and the Maverick Basin which were located on the northeast and southwest side of the Comanche Shelf (Figure 8). The Edwards reef trend is composed mainly of rudist patch reefs that extend up through Bell County, Texas. Prior to deposition of upper Cretaceous sediments, much of the Edwards Plateau region was subaerially exposed allowing initial dissolution and karsting of lower Cretaceous carbonate sediment (Anaya and Jones, 2009).

During the mid-Tertiary, regional uplift and accumulation of sediments in the Gulf of Mexico basin created tensional stress along the ancestral Ouachita fold and thrust belt (Anaya and Jones, 2009). This tensional stress created the Balcones Fault Zone in the early Miocene, as Lower Tertiary, Cretaceous and older sediments were displaced by about 183 m along a narrow zone of en echelon normal faults in the study area (Collins, 2005). Extending from Dallas, south through Waco and Austin, and southwest to Del Rio is the Balcones Fault Zone, with fault displacement creating two distinct regions, the upthrown fault block to the west named the Edwards Plateau and the downthrown block to the east named the Texas Coastal Plain (Collins, 2005). The bedrock fractured as the Gulf of Mexico loaded it with increasing amounts of sediment; it was placed under significant tension by this sediment coupled with Gulf Coast salt migration and Basin and Range extension (Stafford and Arens, 2014). The faulting also increased stream gradients, which increased rates of erosion and incision, but by
Figure 8: Regional features influencing deposition of Edwards strata on the Comanche Shelf (from Bryant, 2012).
late Pliocene to early Pleistocene, stream gradient and erosion rates decreased (Collins, 2005). The study area was shaped into its current form through weathering and erosion in the Quaternary.

Stratigraphy

The lower and upper Cretaceous rocks that dominate the study area include approximately 610 m of marine shelf deposition that spanned 30 Ma and began 110 mya (Collins, 2005). These rocks represent seven, third order depositional sequences that extend from Albian through Campanian chronostratigraphic stages (Collins, 2005). Transgressive facies, under highstand facies, are contained in these depositional sequences and are bounded by unconformities. The upper Glen Rose is the basal formation in the study area and represents highstand carbonate-platform facies of a third order depositional sequence (Collins, 2005). The Glen Rose sediments are under the Paluxy siliciclastic sediments, Walnut and Comanche Peak rocks, and Edwards carbonate facies. The Georgetown deposits overlay these sediments and represent another third order depositional sequence (Collins, 2005).

The lower Cretaceous strata in the study area are the Glen Rose Formation, which consist of limestone, argillaceous limestone, and dolomitic limestone. They contain wackestone, packstone, and lesser grainstone textures and have an average thickness of 244 m (Collins, 2005). Common fossils in the
Glen Rose include mollusks, rudists, oysters, echinoids, and foraminifer *Orbitolina* (Collins, 2005). The upper and lower Glen Rose is divided throughout central Texas by one to three thin beds containing the bivalve *Corbula* (Collins, 2005). Some strata have vuggy porosity and karst features.

Overlying the Glen Rose is a three meter thick interval of fine quartz sandstone cemented with calcium carbonate called the Paluxy Formation. It is interbedded with shale and grades upward into interbedded marl and limestone of the Walnut Formation. The Paluxy and lower Walnut strata have a geometry representative of a small delta. Sands and clays were transported to marginal marine and oxidizing coastal plain environments and deposited as the Paluxy Formation (Caughey, 1977).

The Walnut Formation overlies the Paluxy and Glen Rose, and is the confining unit under the Edwards Group. It contains limestone, argillaceous limestone, and marl. Walnut deposits represent transgressive facies and are subdivided into six members: Bull Creek Limestone, Bee Cave Marl, Cedar Park Limestone, Whitestone Limestone, Keys Valley Marl, and Upper Marl (Collins, 2005). These individual members range in thickness from 9 m to 15 m (Collins, 2005). Mudstone, wackestone, and packstone textures are common throughout Walnut carbonates and include fossils of oysters, clams, echinoids, and gastropods. Strata of the Walnut Formation are not considered aquifer units of
the Northern Edwards Aquifer, although limestone intervals can locally contain water and contribute to aquifer recharge (Collins, 2005).

Above the Walnut is the Comanche Peak Formation. It consists of nodular, fossiliferous limestone, fine-grained limestone and marl, is 12 to 21 m thick and is the bottom unit of the Northern Edwards Aquifer. The Comanche Peak thins to the south and can be seen in scarps along Salado Creek under the Edwards Formation. This formation exhibits wackestone and packstone textures (Collins, 2005).

The Edwards Formation lies above the Walnut Formation and contains massive- to thick-bedded limestone, dolomitic limestone, dolomite, and minor argillaceous limestone. Strata exhibit wackestone, packstone, and grainstone textures. The Edwards thins northward from about 91 m to 27 m thick and is divided informally into four members based on lithology: (1) a lower interval of chert-rich, thin- to thick-bedded, porous dolomite and limestone; (2) a unit of interbedded, thin- to thick-bedded cherty limestone containing rudists, miliolid foraminifera and thin-bedded, flaggy limestone; (3) a unit of nodular, fossiliferous, burrowed, argillaceous limestone, and marl; (4) an upper interval of thin- to thick-bedded limestone, dolomitic limestone, and dolomite (Collins, 2005). Vuggy textures, collapse breccias, cavernous porosity, and local rudist reef accumulations characterize the Edwards Formation. The Edwards in the
intermediate area consists of rudistid biostromes and thin, hard, miliolid biosparite and biomicrite with associated nodular chert (Moore, Jr., 1964).

The Georgetown Formation overlies the Edwards Formation and is the top unit of the Northern Edwards Aquifer. It contains fossiliferous limestone, argillaceous limestone, and minor marl. Strata have wackestone, packstone, and grainstone textures. Rocks of the Georgetown Formation thicken northward from about 18 m to 34 m (Collins, 2005). The Georgetown contains bivalves and vuggy porosity but both are less common in the Georgetown Formation than in the Edwards Formation.

Balcones Fault Zone

Between 24 and 5 mya, faulting along the Balcones Fault Zone caused the Edwards Plateau, west of the fault zone, to be uplifted (Collins, 2005). Balcones Faulting produced normal en echelon faults that cut through Cretaceous rocks and generally follow the north-northwest regional strike of the Cretaceous rocks and structural grain of the buried Paleozoic Ouachita fold and thrust belt (Collins, 2005). Faults in this system are relatively consistent throughout the region, with an average strike of between 55° and 65° and are generally considered to be steep to nearly vertical based on local measurements (Ferrill and Morris, 2008). Monoclinal and anticlinal folds are uncommon but have been identified in the Balcones Fault Zone. Some faults have vertical
displacement gradients which diminish upwards into monoclinal folds in less competent strata (Ferrill and Morris, 2008). Most fracturing in the Balcones is thought to have occurred during the late Oligocene or early Miocene (Collins, 2005). The Balcones Fault zone formed due to a combination of factors but is unknown which played the most significant role. A combination of gulfward extension due to Basin and Range tectonism, tensional stress along the Ouachita fold and thrust belt from the accumulation of sediments in the Gulf of Mexico and downdip slippage on Jurassic salt all influenced the formation of this fault zone (Collins, 2005). Displacement of faults can alter hydraulic pathways, both increasing cross formational hydraulic connectivity and impeding lateral fluid migration.

Hydrogeology

The Northern Segment, the San Antonio Segment, and Barton Springs Segment are the three hydrogeologically distinct segments of the Edwards Aquifer. The Northern Segment of the Edwards Aquifer underlies parts of Bell, Travis, and Williamson counties and is bounded by the Colorado River to the south and Lampasas River to the north (Jones, 2003). Groundwater ion and isotope compositions indicate that young, fresh groundwater occurs in the unconfined aquifer strata to the west, while comparatively much older saline groundwater occurs in confined aquifer strata to the east (Jones, 2003).
The hydrogeology of the study area, including the Salado Creek watershed, is dominated by the Northern Segment of the Edwards Aquifer, which consists of Cretaceous strata of the Comanche Peak, Edwards, and Georgetown formations (Edwards Group) (Jones, 2003) (Figure 9). The confining units are the Walnut Formation below the aquifer and the Del Rio Formation above the aquifer; however, in some areas, the Walnut consists of semi-permeable beds. Due to varying degrees of karsting, water rapidly infiltrates and percolates through the aquifer system.

The main water-bearing unit in the aquifer is the Edwards Limestone. It is vuggy, with solution-collapse zones that occur parallel to bedding planes that are the result of dissolution of gypsum beds that formerly occurred in this unit (Jones, 2003). Cavernous, iron-stained strata, with brecciated limestone, chert, crystalline calcite, residual clays are characteristic of collapse-zones. These zones typically occur 18 m to 24 m above the base of the Edwards Limestone and are referred to as the Kirschberg Solution Zone (Jones, 2003). In addition to solution-collapse zones, groundwater in the Edwards Aquifer flows through a network of steeply dipping faults and joints (Jones, 2003). Field measurements indicate that effective porosity is greatest in the Comanche Peak and decreases in overlying units, with the Edwards and Georgetown formations being hydrologically connected (Jones, 2003).
Figure 9: Location and segmentation of the Edwards Aquifer (from Jones, 2003).
Regional dip and the Balcones Fault zone are the dominant structural features in the area (Figure 10). There is an angular unconformity between Cretaceous and Paleozoic rocks in the study area. The underlying Paleozoic rocks dip steeply to the west while the overlying Cretaceous rocks dip toward the southeast at rates varying from 3 m/km to 91 m/km that increase in dip with depth (Jones, 2003). In the Balcones Fault Zone, minor faults and joints occur adjacent to major faults with normal faulting common in aquifer strata. These minor faults exhibit displacement of less than two meters and tend to form fracture zones up to two kilometers wide with fracture densities ranging from 6 to 120 joints per 30 m (Jones, 2003). Many of these minor faults are partially filled by calcite; however, the joints generally have not been completely occluded with secondary minerals (Jones, 2003). These faults and fractures can alter groundwater flow in three ways: (1) fractures can provide planar surfaces that enhance fluid flow, (2) fractures act as physical barriers or (3) fractures hydrologically connect units as a result of fault displacement. Solution cavities are often the result of this groundwater flow along faults, joints and bedding planes.

In the Northern Segment of the aquifer, the potentiometric surface decreases toward the east and south. East of the main fault complex, hydraulic gradients decrease. In unconfined portions of the aquifer, the water table
Figure 10: Local geologic cross section of Cretaceous strata and the Balcones Fault Zone (from Jones, 2003).
occurs generally less than 30 m below the surface and may approach the surface along incised streams (Jones, 2003). Potentiometric surfaces of the Edwards Aquifer can exceed the land surface in confined portions of the Northern Segment of the aquifer system.

The Edwards Aquifer is anisotropic due to preferential vertical groundwater flow paths and restrictive west to east flows created by fracture boundaries (Jones, 2003). The Edwards Aquifer hydraulic properties are variable because of primary porosity associated with facies changes, fracture densities, and secondary porosity, including karst. Limestones deposited in subtidal environments exhibit lower porosities than carbonate sandstones or dolomites within the same strata (Jones, 2003). Fractures and solutional conduits make up one to three percent of the outcrop area, with karst features developed preferentially adjacent to faults and in dolomitized limestone (Jones, 2003). As a result, most flow through the aquifer is contributed by fractures and karst although it comprises a relatively small percentage of the total formational porosity; approximately one percent of total groundwater flow is attributed to matrix permeability (Jones, 2003). Transmissivity estimates for the Edwards Group range over seven orders of magnitude from $5 \times 10^{-2}$ to $4 \times 10^5$ m$^2$/day (Jones, 2003). High transmissivity is normal for cave systems and solution-enhanced fracture porosity systems, while low transmissivities are normal for regions dominated by intergranular or matrix porosity. Transmissivity is generally
higher in the central part of the aquifer due to higher fracture density, with hydraulic conductivity values ranging between 0.003 m/day to more than 9,000 m/day, median and geometric mean values are 3 m/day (Jones, 2003).

The Edwards Aquifer is recharged by two ways: (1) autogenic infiltration from precipitation that falls on the aquifer, and (2) allogenic recharge from runoff of areas upstream of the aquifer. In the study area, the recharge zone of the Northern Edwards Aquifer consists mainly of gently rolling terrain of the Lampasas Cutplain (Jones, 2003). The recharge sites in the study area are karst features including dissolution-enhanced fractures, sinkholes, and caves. Another way the aquifer is recharged is along faults and joints through direct infiltration when they are associated with losing streams. Water that infiltrates tends to collect within the Georgetown Formation because of low-permeability shale members and resultant lateral flow is discharged from seeps and springs (Jones, 2003). When Edwards and Comanche Peak formations are encountered, overland flow results in rapid recharge at the contact boundaries. Also, the underlying Trinity Aquifer can add to Edwards Aquifer recharge through cross-formational flow from below; models estimate that at least 500,000 hectare-meters (five trillion liters) are transmitted from the Trinity Aquifer into the Edwards Aquifer each year, mainly in lateral flow across faults (Stafford and Arens, 2014). Pumping, discharge to springs or seeps, and cross-formational flow all contribute to aquifer discharge. The Northern Segment is only slightly to moderately
developed anthropogenically, so natural discharge is much greater than pumping throughout the Salado Creek Watershed (Jones, 2003). Most pumping of the Northern Edwards Aquifer is associated with municipal and rural domestic withdrawals, primarily associated with the major municipalities of Salado, Georgetown, Pflugerville, and Round Rock (Jones, 2003).

Spring discharge rapidly increases as precipitation falls over the recharge zone. Lag time between precipitation events and spring response varies from nearly immediate to one or more weeks (Jones, 2003). Discharge from springs and seeps occurs adjacent or within unconfined parts of the aquifer. Spring discharge occurs through upward flow along faults where Del Rio Clay and Buda Limestone have been breached and a planar surface is created across confining layers. Discharge through cross-formational flow is most likely to occur within confined portions of the aquifer, as groundwater flows from the Edwards Aquifer through confining layers and into overlying strata (Jones, 2003).

The Colorado and Brazos river basins form a hydrological divide that splits the Northern Edwards Aquifer and corresponds with the boundary between Travis and Williamson counties. In Bell and Williamson counties, surface water flows to the north and east toward the Brazos River, in Travis county surface water flows toward the south to the Colorado River (Jones, 2003). Salado Creek is close to the study area and receives discharge from the aquifer, specifically associated with Salado Springs. Salado Creek is most likely spring fed
throughout the entire course of the creek because of the perennial spring flow throughout the year.

There are numerous springs that occur in the study area, although most of the minor springs are not significant enough to have been officially documented and studied. Known major springs in Bell County include: Hodge Place Spring, Groves Spring, Indian Camp Spring, Willingham Place Spring, and Willingham Church Spring (Jones, 2003). Known major springs in Williamson County include: Berry Springs, Brushy Springs, Cobbs Springs, and Georgetown Springs.

Geochemical composition defines the water quality of the groundwater (Figure 11). The downdip margin of the aquifer, referred to as the bad-water line, is defined as the easternmost extent of freshwater in the aquifer (Jones, 2003). East of the bad-water line, groundwater circulation is restricted due to fault displacement with TDS (Total Dissolved Solids) levels that are greater than 1,000 mg/L (Jones, 2003). As groundwater travels from the outcrop recharge zone to the downdip portions in the east, it gradually becomes more mineralized. TDS varies from 200 to 400 mg/L in the recharge zone and increases to more than 3,000 mg/L downdip (Jones, 2003). Saline groundwater occurs within two to three kilometers from the recharge zone in the south, and occurs more than sixteen kilometers from the recharge zone in the north where faulting is less intense (Jones, 2003). In addition to variations of TDS across the aquifer,
Figure 11: Distribution and variations in chemical composition of the Northern Edwards Aquifer (from Jones, 2003).
groundwater geochemical composition also varies downdip form Ca-HCO$_3$ to Na-
SO$_4$ type waters and Na-Cl type waters (Jones, 2003) (Figure 11). These
hydrochemical assemblages indicate hydrochemical evolution of groundwater
along flow paths, with hydrochemical zones that are much narrower in the south
than in the north because of fault density (Jones, 2003). Faults may also supply
ways for deep saline groundwater influx.

Two main flow systems control the spatial distribution of groundwater
having different geochemical compositions: (1) rapid circulation of fresh
groundwater from the recharge zone, and (2) slow influx of saline groundwater
from downdip (Jones, 2003). Groundwater geochemical compositions in the
north are influenced by hydrochemical evolution of fresh groundwater and the
south is influenced by updip movement of Na-Cl brines from the Gulf Coast Basin
(Jones, 2003).

Speleology
Karst principally develops in three broad genetic settings: (1) eogenetic
(coastal and oceanic) occurs in young rocks with high primary matrix porosity
and permeability and forms in the zones that have never been buried beyond the
range of meteoric diagenesis water; (2) hypogenic, occurs under confined to
semi-confined conditions where water enters a soluble formation from below; and
(3) epigenic (hypergenic), which occurs in unconfined conditions where
diagenetically-mature rocks are exposed directly to meteoric water that is recharged from the surface (Klimchouk, 2007). The above settings are the typical evolutionary sequence of a karst system. Historically, epigenic karst systems have been the focus of karst research and they currently dominate the karst paradigm, although the influence of hypogene phases in speleogenetic evolution are increasingly recognized (Klimchouk, 2007).

Surficial water sources dissolve soluble rocks at or near the surface and form epigene karst. The solutional aggressiveness of these waters in carbonate strata is derived from surface and subsurface processes, primarily associated with CO₂ production in the soil (Klimchouk, 2007). Epigenic karst systems are predominantly local systems where recharge occurs from the overlying or immediately adjacent surface (Klimchouk, 2007). Flow and development in epigene systems is driven largely by gravitational gradients and is typically lateral, although vertical shafts may exist in high-gradient regions (Klimchouk, 2007). Cave passages that are above the water table are referred to as vadose passages and passages that are below the water table are phreatic passages (Palmer, 2007). Vertical shafts and incised canyons are usually formed as vadose passages and phreatic passages commonly form laterally extensive and elliptical shaped passages. Epigenic speleogenesis is directly related to contemporary surface topography and commonly results in hierarchical dendritic conduit systems (Klimchouk, 2009).
Hypogene karst usually forms at deeper depths away from surficial processes. These karst systems are formed from the ascension of aggressive waters driven by hydrostatic pressure or other sources of energy, which establish density gradients that drive mixed convection, including components of free and forced flow (Klimchouk, 2007). Separated from surface or near-surface sources, fluid aggressivity in hypogene systems can be reached from depth or in soluble formations. Most hypogene speleogenesis occurs under confined conditions; however, there is an evolutionary trend for hypogenic karst systems to lose confinement from uplift and denudation related to the systems expansion (Klimchouk, 2007). Hypogene system development and flow are dominantly vertical but lateral components can develop; pervasive channeling and maze patterns form due to input and output restrictions in the system (Klimchouk, 2007).

Numerous cave types can be found in the Edwards Limestone coming from epigenic or hypogenic processes (Figure 12). Following deposition of the Trinity Group and Edwards carbonate sediments, regional uplift resulted in the exposure and partial erosion of Edwards sediments, increasing secondary porosity (Elliot and Veni, 1994). Fine-grained sediments trapped water in the Edwards units during a transgression and regional uplift fractured and tilted Cretaceous strata to the southeast during the Laramide Orogeny. Dissolution by surface or groundwater caused fractures to widen in upper Cretaceous strata.
Figure 12: Epigenic and hypogenic flow (from Klimchouk, 2007)
Balcones Faulting in the Miocene initiated rapid stream incision, exposing cavities and developing new discharge outlets (Elliot and Veni, 1994). Infiltration along Edwards outcrops west of the fault zone created a through-flowing aquifer system. Water began to flow down the potentiometric surface to discharge sites in the east by way of large phreatic passages (Elliot and Veni, 1994).
METHODOLOGY

Karst surveys, observation of outcrops for stratigraphic and petrographic analyses, GIS analyses, and the collection of geochemical data were conducted to study the Salado Creek Watershed. Karst surveys included traversing the Critchfield Ranch to locate karst features, surveying, and mapping any caves found. Observation of Edwards Limestone outcrops included measuring stratigraphic sections and describing packages of similar strata. Obtaining LiDAR data and converting it to DEMs, and then studying it through ArcMAP tools were conducted to study the hydrology and locate potential karst features within the entire Salado Creek Watershed. Collection of geochemistry data in the field with portable meters along with water samples from springs and surface water in the study area were taken for further laboratory analyses to study the groundwater.

Karst Survey

Knowing the density and distribution of karst features is helpful in interpreting the hydrogeologic framework of the subsurface. Field mapping of surficial karst features within the study area was completed to define and organize the different features found within the limits of the Critchfield Ranch property where land access was granted for this study. The first task completed...
was traversing and mapping of karst features on the 80 hectare ranch using a handheld GPS for navigation and to record feature locations. A series of transects were established across the study area for traverse-based mapping; however, different interval spacings were used to ensure all karst features were located and mapped within the focus area based on distance of unobstructed visual inspection. The densest vegetative areas were traversed in 10 m intervals and the less dense areas were traversed in 20 m intervals, which included approximately 69 kilometers of total surface survey traverse length (Figure 13). While the study area was systematically traversed, recognizable karst features such as sinkholes, caves, shelter caves, solutional conduits, and springs were recorded and described.

After surficial mapping of karst features, new caves discovered during surficial mapping were entered, mapped, and characterized. Cave mapping is the first step in obtaining quantitative data about caves as defined by Palmer (2007). During cave surveys, morphometric features and geology, including stratigraphy and structure, were documented to assist in interpretation of speleogenesis. A Leica Disto range finder and Suunto compass and clinometer were used in completing cave surveys. Survey data and cave maps were recorded and sketched in the field following the National Speleological Society standard protocol for cave mapping (Dasher, 2011). Cave maps and survey data were
Figure 13: Traverse lines for karst survey, 20 m for the farther apart lines, and 10 m for the closer together lines.
plotted using *Walls*, free software for the analyses of cave survey data, and then exported as line plots for drafting in *Xara Xtreme*, a drawing software program.

**Stratigraphy**

The Cretaceous Fredericksburg Group, and more specifically the Edwards Formation, was the main focus of this study; the Edwards Formation is the only unit of the Fredericksburg Group that crops out in the study area. The Cretaceous is extensively and rather fully developed in Texas (Sellards, 1990). Stratigraphic analyses were conducted within the study area to develop a suite of stratigraphic sections of the Edwards Formation cropping out in the Northern Edwards Aquifer to evaluate potential zones of greater and lesser potential for karst development. Seven outcrops were measured and described utilizing a measuring tape along high angle scarps (Figure 14). Each of the seven outcrops was also sampled starting at the base and working upward in correlation with discernable lithologic packages identified by macroscopic variability. Measurements included total thickness and thickness of each stratal zone, as well as descriptions of the corresponding lithology, fossil assemblages, porosity, bioturbation, and the assignment of Dunham (1962) classification. Hand samples taken from each stratal zone were labeled and packaged for more detailed laboratory analyses. A composite section was constructed utilizing scarp outcrops along Salado Creek where it bisects the study area and
Figure 14: Location of outcrops in study area that were studied for stratigraphic analyses.
supplemented with stratigraphic sections from caves mapped.

Billets were cut from the hand samples collected from each stratal zone of each outcrop were a stratigraphic section was measured. The billets were then analyzed under a binocular microscope and descriptions were more accurately compiled to enhance those made in the field. These data were subsequently used to identify similar facies within the study area in order to delineate variability within the depositional environment. Two representative billets from each facies were chosen for thin section preparation for more thorough analyses. Tulsa Sections prepared the thin sections, which included alizarin red staining and epoxy impregnation.

A three hundred point count of each thin section was completed in order to statistically determine composition of each of the facies identified. Allochem type, matrix composition, spar, porosity and any anomalous features were described within these point counts. Folk (1962) classifications were used to identify the facies using the percent compositions found during the point counts and a general diagenetic history was determined.

Geochemistry

Geochemical analyses of two springs and Salado Creek were conducted to provide a better understanding of the connections between groundwater and associated geologic formations. Geochemical analyses included physical
sampling for laboratory analyses as well as in-situ sampling of physico-chemical parameters. The composition of subsurface water are controlled by many variables including: composition of groundwater recharge, petrologic and mineralogical composition of subsurface rocks, and hydrogeologic properties of rocks which have a strong influence on the extent of water/rock reaction (Langmuir, 1997).

Critchfield Spring is located on the northwestern edge of the Critchfield Ranch study area and is underlain by the Edwards Formation, where it discharges into a minor tributary off of Salado Creek. Salado Creek runs through the western side of the Critchfield Ranch property and has eroded through the Edwards Formation (Figure 15). Salado Springs is located in Salado, Texas and is underlain by the Edwards Formation. Salado Springs discharges into the southern side of Salado Creek. All springs in Salado rise under artesian pressure through faults in the Edwards and associated limestones (Brune, 1981).

A 6920V2 Multi-Parameter Water Quality Sonde was used to measure chemical composition, temperature, pH, dissolved oxygen, turbidity, specific conductivity, and total dissolved solids. Water temperature is a primary factor affecting physical and chemical properties of water (Chang, 2013). Temperature has an accuracy of ± 0.15°C and resolution of 0.01°C. Water molecules are normally dissociated into hydrogen ions and hydroxyl ions (Chang, 2013). The pH has an accuracy of ±0.2 unit and a resolution of 0.01 unit. Dissolved oxygen
Figure 14: Location of Critchfield Spring within Critchfield Ranch Property.
for the percent saturation units, has a resolution of 0.1 %. The accuracy of turbidity is ±2 % or 0.3 NTU and the resolution is 0.1 NTU. Conductivity has an accuracy of ±0.5 % of reading plus 0.001 mS/cm and a resolution of 0.001-0.1 mS/cm. The total dissolved solids have an accuracy of ±1 % of reading or 0.1 ppt and resolution of 0.01 ppt.

Spring water samples were collected in the field for further laboratory analyses for better understanding between connections of groundwater and underlying geologic formations. Using sterile Nalgene bottles, water samples were collected from the springs, refrigerated until they could be examined, and analyzed at the Soil, Plant, and Water Analysis Lab. Analyses from the lab included pH, conductivity, bicarbonate, magnesium, sodium, fluoride, and chloride. Inductively Coupled Emission Spectroscopy was used to measure cations and an ion chromatography was used to measure anions. By titrating to a pH of 4.5 with 0.02072 N H₂SO₄, carbonates and bicarbonates were measured. In waters in which bicarbonate is the dominant anion, the total cation concentration will approximately equal the bicarbonate concentration, and hence pH and salinity in bicarbonate-rich waters are inversely related (Drever, 1997). The comparison of water quality in the three sites was used to assess the variability of sites within the Salado Creek Watershed. Stiff diagrams were prepared for chemical analyses; however, no statistics were calculated because of the low number of sample sites in the study area.
GIS

GIS (Geographic Information Systems) analyses were conducted across the study area, including the entire Salado Creek watershed. Analyses included interpolation of potential sinkholes from LIDAR data, geologic analyses of lithology and structure, and spatial analyses of known and predicted karst features. Sinkholes and depressions related to karst topography were delineated across the entire Salado Creek watershed and compared with physical land surveys conducted on the Critchfield Ranch property. This was done through spatial interpolation using terrain data to create Digital Elevation Models (DEMs), which were prepared to study the surface features in the study area and within Salado Creek Watershed. Many processes went into analyzing the raster data. DEM’s have to be made “hydrologically correct” before being used in hydrological models (Zhu, 2013).

LiDAR Analyses

Analyzing LiDAR data is a high resolution method for interpreting the terrain over a specific area. Airborne LiDAR is one of the most effective and reliable means of terrain data collection (Liu, 2008). The basic components of a LiDAR system include a laser scanner mounted in an aircraft, GPS, and an Inertial Measurement Unit (IMU) (Chang, 2014). Laser pulses are radiated over a particular area and distance is measured by the time lapse of the pulse while a GPS and IMU are recording the position and orientation of the laser source.
LiDAR has many advantages when working with elevation data including: vertical accuracy, fast data collection and processing, robust data sets with many possible products, and the ability to collect data in a wide range of conditions (Furgo Earthdata INC., 2011).

LiDAR data used for this study were acquired from Texas Natural Resource Information System (TNRIS). TNRIS is a division of the Texas Water Development Board (TWDB), and supplies geographic data to Texas. CAPCOG (Capital Area Council of Governments) is the source of the Williamson County LiDAR data with a resolution of 1.5 m. The source for Bell County is TNRIS with a resolution of 0.75 m. Because of the disparity in data resolution, all data was processed to 1.5 m.

The LiDAR data were processed using Esri ArcGIS for desktop. Using ArcMap 10.2, the LiDAR data were converted to DEMs though a three-step process: 1) LAS files were converted into multipoint shapefiles using the tool LAS to Multipoint, 2) multipoint shapefiles were then converted to a Triangulated Irregular Network (TIN), and 3) the TIN was converted into a Digital Elevation Model (DEM). When converting LiDAR data to a Multipoint shapefile, the 3D Analyst and Spatial Analyst extensions must be activated. After inserting the files to be processed, the average point spacing was set to 1.5 m in correlation with the minimum common reported data spacing of data collected for the study region. The input class code was set to 2 for bare earth, and input return values
were selected as *any returns* to analyze all data associated with earth surface returns. Due to the high number of elevation points from the LiDAR, a DTM (Digital Terrain Model) is recommended to make management of the data easier. To convert the TIN to a raster dataset, where cell-by-cell calculations can be made, tools in ArcGIS’s Spatial Analyst must be activated. A TIN approximates terrain with a set of non-overlapping triangles and is commonly used for terrain mapping and analyses (Chang, 2014). The second step in the process is to build a Digital Terrain Model or TIN from the multipoint shapefile. This was done using ArcMap 10.2 and using the tool *Create TIN* by inserting the multipoint files in the tool.

The vector-based TIN was then converted to a raster-based data format in order to carry out spatial analyses. This was done using the tool *TIN to Raster*. Before inserting the TIN to be processed, enter the *environments settings and set the XY resolution and tolerance* type value to 1.5 meters for both. Under *raster analysis*, minimum inputs were selected and interpolation was calculated using *Natural Neighbor* methods with the *sampling distance* for cell size of 1.5 m. The natural neighbors’ interpolation method was selected because it is known to produce better results in terms of aesthetics and accuracy than the linear interpolation method (Esri, 2012). The cell size is determined by the resolution of the data. The resulting raster dataset or DEM provides a highly detailed model of
the topography that can then be used for detention of basins, river channels and other subtle topographical and hydrological features (Liu and Wang, 2008).

DEMs can be used for a wide variety of applications. It is decided to consider these as a selection of representative activities in the domains of: scientific applications, commercial applications, industrial applications, operational applications and military applications (Sulabak, 2000). With the 1.5 m resolution DEM, karst features such as sinkholes and depressions could be identified. A depression is a cell or cells surrounded by higher elevation values, thus representing an area of internal drainage (Chang, 2014). In order to identify depressions in the study area, the DEM must be run through the Flow Direction tool. The earliest and simplest method for specifying flow directions is to assign flow from each pixel to one of its eight neighbors, either adjacent or diagonal, in the direction with steepest downward slope (Tarboton, 1997). The Flow Direction tool is used to create a raster image of flow direction from each cell to its steepest downslope neighbor (ArcGIS Pro). Next, the raster created form the Flow Direction tool is put into the Sink tool and used to make a raster image that shows all of the depressions in the study area. The Sink tool makes a raster image that identifies all sinks or areas of internal drainage (ArcGIS Pro) (Figure 16).

For further analyses of spatial attributes, depressions must be delineated. The boundaries for the depression features were delineated by changing the
Figure 16: Model for finding sinks and sink depths.
depression raster to polygons, buffering the polygons with 0.5 m buffer, dissolving the buffers, smoothing the polygons, and finally simplifying the polygons. After this process is complete, filtering out those that are likely not related to karst can be done. Any depressions that are most likely not related to karst must be removed from the polygon database so the delineated depressions can be filtered and classified. The depression identification process identifies any depression features visible in the DEM, which means that depressions associated with river channels, roadways, and other man-made features will also be identified (Liu and Wang, 2008).

Lakes, roads, and quarries were used for classification factors to remove depressions that likely are attributable to anthropogenic processes. Small bodies of water, which were mostly stock ponds, within the Salado Creek watershed were delineated and digitized using aerial imagery from the Basemap feature in ArcMap. Any depression within 5 m of the small body of water was classified as a part of the body of water. Roads were digitized into three main types including paved, gravel, and dirt where paved roads were considered major roads and gravel and dirt roads were considered minor roads. Depressions within 20 m of the major roads and within 10 m of minor roads were assumed to be associated with road construction. Quarries are prominent throughout the study area and were also digitized using aerial imagery from the Basemap feature in ArcMap. Depressions within 20 m of any quarries were considered part of the quarry.
Cities in the watershed include Jarrell and Salado. These were buffered out to 200m.

Channel networks with arbitrary drainage density or resolution can be extracted from digital elevation data (Tarboton, 1991). In order to classify streams in the study area, first the Fill tool must be executed on the original DEM. This eliminates all the depressions in the DEM. Using the filled DEM as the input into the Flow Direction tool, the direction water will flow out of each cell of a filled elevation raster can be found, according to Chang (2014). To define streams and creeks, the raster that was found by utilizing the Flow Direction tool was used as input for the Flow Accumulation tool. This gave an output of a raster that tabulates for each cell the number of cells that will flow to it (Chang, 2014).

Digital Elevation Models (DEMs) of topography are widely used in Geographic Information Systems (GIS) to derive information for the modeling of hydrologic processes (Tarboton, 2009).

A flow accumulation raster is a raster image whose cell values represent the accumulated weight of all cells flowing into each downslope cell (ESRI, 2012). Cells with high flow accumulation values generally correspond to stream channels (Chang, 2014). After streams and creeks were defined with a Flow Accumulation raster, the Con tool was utilized to delineate streams with more than 100 cells contributing to it. The Con tool conducts an evaluation of input cells in an input raster (ESRI, 2012). To assign a more hierarchical
classification to the streams, the stream raster found from the *Flow Accumulation* tool and the *Flow Direction* raster were input into the *Stream Order* tool. When using the *Stream Order* tool, the method of stream order chosen was Strahler method. This method is where the stream order increases only when streams of the same order intersect (ArcMap tool help) (Figure 17). After streams were defined by a classification, they were filtered out by their stream order by using *Definition Query* under properties. Due to the vast quantity of streams in the study area, only streams with a stream order greater than 5 were kept in the raster image. Finally, the streams that were left with a classification greater than 5 were changed to vectors in order to utilize the buffers. Any depressions within the 10 m buffer of a stream or creek were considered a part of the stream or creek. After roads, quarries, streams, ponds, and cities were buffered, the *Select by Location* feature was used to quantify the number of sinks within those buffers. For a final “natural sink” count, sinks found from the original DEM were used for the input and the *erase features* was the merged buffered areas.

Along with removing sinks associated with man-made features, sinks that are not deeper than the vertical accuracy of the LiDAR must also be removed. The vertical accuracy of the LiDAR in this study was <15 cm. In order to account for error, anything below 20 cm was removed. To delineate sinks greater than 20 cm deep, first a minimum must be found by running *Zonal Statistics* with sink areas as the zone input and the original DEM as the raster input with minimum
Figure 17: Model for delineating streams in the study area.
as statistic field. *Zonal Statistics* calculates statistics on values of a raster within the zones of another dataset. Next, *Zonal Fill* was run to attain the maximum value of sink depths. Then subtractions of the minimum sink depth from the maximum sink depth were calculated using the *Minus* tool. To join sink depths to polygon sinks, *Zonal Statistics as Table* tool was applied where the input raster was the original sink polygon, zone field was object ID, input value raster was sink depths, and the statistics type was maximum. Once this table was made, it was joined back to the original sink polygon table.

Next, the underlying geology was used to classify depressions. The only karst forming geologic formations in the study area are the Edwards Formation and the Comanche Peak Formation. Other geologic formations in the study area were filtered out because depressions in them are not known to be associated with karst processes and are more likely to be the result of anthropogenic processes.

Finally, a slope analysis was implemented to find high-angle slopes that are likely areas for shelter cave development that would not be identified through depression analyses. Shelter caves are known to be associated with steep or near vertical slopes (Palmer, 2007), so a raster image representing the slope of each cell was created.
RESULTS

Karst surveys, stratigraphic and petrographic analyses, GIS analyses, and geochemical analyses were executed in order to determine speleogenesis and to study the hydrogeology within the Salado Creek Watershed. Karst surveys were completed in the Critchfield Ranch study area, where features associated with karst were identified and mapped. Stratigraphic analyses were completed in the Critchfield Ranch study area to determine if there were any stratigraphic controls on cave development and to examine porosity. Petrographic analyses were carried out for further inspection of the data from the outcrops. The entire Salado Creek Watershed was incorporated into the GIS analyses where LiDAR data was converted to DEMs and used to identify depressions or sinks in the area. To study hydrogeology in the Salado Creek Watershed, data from Critchfield Spring, Salado Spring, and Salado Creek were compared.

Karst Survey

Twenty five karst features were identified in the Critchfield Ranch study area from the traverse survey including caves, springs, sinks, and shelter caves. These include three caves, one spring, fourteen sinks, and seven shelter caves.
Two of the three caves are mainly horizontal, while the third is a vertical pit that turns into an area where there has been solutional widening along a bedding plane. The first cave has a sinkhole entrance that is oval in shape. The cave is approximately 91.4 m long and 6.5 m deep. The second cave is a circular pit entrance and is approximately 3.7 m deep. At the bottom of the pit, the cave trends to the east into a bedding plane. The third cave is a circular pit entrance that is approximately 3.0 m deep then trends east more than 6.0 m with a total depth of about 6.0 m.

Two of the fourteen sinks in the study area are entrances to caves. One sink, close to two of the caves, is approximately 1.5 m diameter and 0.5 m deep, with no clear drain for water and no airflow. Three sinks near the third cave area are all a part of the same complex. One sink in the complex is approximately 6.3 m x 4.0 m wide and 3.0 m deep. The second sink in the complex is approximately 6.2 m x 5.0 m wide and is 3.5 m deep. The third sink in the complex is approximately 3.2 m x 1.8 m wide and 1.5 m deep. All of these sinks in this complex have bedrock walls, a clear drain for water, and airflow. The remaining three sinks were in proximity of the previous mentioned complex. The first was a small sink approximately 1.0 m diameter and 0.3 m deep with meter size limestone blocks, a clear drain for water, and no airflow. The second was a small sink approximately 2.0 m diameter and 1.5 m deep, with meter size limestone blocks, clear drain for water, no airflow, and a solution hole
Figure 18: Locations of shelter caves on the Critchfield Ranch.
parallel to a bedding plane. The third was a sink approximately 2.5 m diameter and 0.2 m deep with meter size limestone blocks, clear drain for water, and no airflow.

Three caves, including the newly discovered Buzzard Roost Cave, and seven shelter caves were surveyed and drafted. Standard cave cartography symbology was used to assess their morphology, geology and speleogenesis.

Buzzard Roost Cave (Figure 19 and 20) has a survey length of approximately 6.0 m and depth of 6.0 m. Buzzard Roost Cave is developed in the Edwards Formation with three other sinkholes that are associated that could possibly be entrances into the cave system if excavated. The entrance to Buzzard Roost Cave is a pit with an opening of approximately 0.75 m diameter that descends about 3.0 m to an elliptical room that is composed of loose soil and dislocated bedrock, along with some rock breakdown and interrupted by small floor drops. Fractures are common throughout the passage with most the cave composed of breakdown collapse and only a partial solutional wall remaining on the northern side of the cave. At the end of the passage, the cave is mostly collapse material and soil. The three other sinks that make up the Buzzard Roost Cave Complex are approximately 6.3 m x 4.0 m wide and 3.0 m deep, 6.16 m x 5.0 m wide and is 3.5 m deep, and approximately 3.2 m x 1.8 m wide and 1.5 m deep.
Figure 19: Map of Buzzard Roost Cave Complex
Figure 20: Pictures of Buzzard Roost Cave.
Critchfield Bat Cave (Figure 21, 22, and 23) has a surveyed length of 91.4 m and a depth of 6.5 m. Critchfield Bat Cave is developed in the Edwards Formation. The entrance is in a sinkhole approximately 3.5 m diameter that has been breached by collapse based on the large accumulation of breakdown beneath the entrance. From the entrance, the cave splits off in east and west directions. The main passage contains collapse, great amounts of dirt, floor and ceiling drops, and flowstone along the walls. Critchfield Bat Cave has an undulating ceiling and lacks scallops. There are some fractures throughout the passage as seen in the ceiling. There are many vertical pits that are near the walls of the passage but are not enterable. At the farthest point in the westward direction that is humanly enterable, there are many secondary speleothems, including stalactites, stalagmites, and soda straws. The eastern end of the cave transitions into a small cavity that’s filled with very sponge-like, vuggy rocks.

Critchfield Bat Cave #2 (Figure 21) is likely connected to Critchfield Bat Cave #1 because of a bedding plane extending 12 m toward the other cave. In Critchfield Bat Cave, there is a very thin passage or bedding plane at the bottom of one of the vertical pits that extends towards this cave. This cave has a depth of approximately 4.5 m and length of 14 m. Critchfield Bat Cave #2 is mostly collapse from the vertical pit entrance, floor drops, and flowstone along the cave walls. This cave has many localized features within the stratigraphy including grainstone nodules, collapse breccia, and a calcite layer.
Critchfield Bat Caves
Williamson County, Texas
Depth: 6.5 meters
Length: 91.4 meters

Suunto & Disto Survey (30 May 2014) by C. Fuls, K. Stafford & A. Vermeulen

Figure 21: Map of Critchfield Bat Caves.
Figure 22: Pictures of Critchfield Bat Cave.
Figure 23: Pictures of Critchfield Bat Cave.
There were seven shelter caves found and surveyed along Salado Creek in the Critchfield Ranch study area. Five shelter caves were found on the west side of the property along the Salado Creek scarp and the remaining two were found along the scarp near Critchfield Spring. The largest shelter cave found adjacent to Salado Creek, Critchfield Shelter Cave 1 (Figure 24 and 25), was approximately 10.0 m long and 5.0 m deep. This shelter cave was the biggest in size and contains sponge-like, vuggy rocks throughout the cave. Critchfield Shelter Cave 1 has fractures that extend back into the scarp which could be preferential flow paths for water. Others shelter caves found along this scarp were: 1) Critchfield Shelter Cave 2 (Figure 26) which is approximately 2 m long and 2.5 m deep; 2) Critchfield Shelter Cave 3 (Figure 27) which is approximately 3.5 m long and 3.0 m deep; 3) Critchfield Shelter Cave 4 (Figure 28) which is approximately 3.0 m long and 2.5 m deep; and 4) Critchfield Shelter Cave 7 (Figure 29) which is approximately 0.75 m long and 2.5 m deep. There are two shelter caves along the scarp near the spring: 1) Critchfield Shelter Cave 5 (Figure 30) which is approximately 2.0 m long and 1.75 m deep; and 2) Critchfield Shelter Cave 6 (Figure 31) which is approximately 3.5 m long and 4.0 m deep. These shelter caves are longer than they are deep with the exception of Critchfield Shelter Cave 7.

In the study area, there is only one spring on the western side of the property, Critchfield Spring. This spring is discharging at a lithologic boundary in
Figure 24: Map of Critchfield Shelter Cave 1.
Figure 25: Pictures of Critchfield Shelter Cave #1.
Figure 26: Map of Critchfield Shelter Cave 2.
Figure 27: Map of Critchfield Shelter Cave 3.
Figure 28: Map of Critchfield Shelter Cave 4.
Figure 29: Map of Critchfield Shelter Cave 7.
Figure 30: Map of Critchfield Shelter Cave 5.
Figure 31: Map of Critchfield Shelter Cave 6.
the Edwards Formation at the base of the scarp. Baseflow that dominates streamflow usually produces streams with minor flow-rate fluctuations. Groundwater and surface-water systems are closely related in recharge and discharge zones, where interchange occurs as a result of recharge and discharge processes, respectively (Baker et al., 1986). An example of this form of stream is Salado Creek, which is controlled by spring discharge. The water pooling up in Salado Creek on the Critchfield Ranch could potentially be from spring discharge. Creeks in the area such as Salado Creek cross the outcrop of the aquifer and are likely recipients of groundwater discharge, indicated by their perennial flow (Jones, 2003).

Stratigraphy

Representative stratigraphic columns were made using measurements and descriptions of seven outcrops of the Edwards Formation in the study area (Figure 14). In the field, these outcrops were divided into stratal packages according to similar lithologies for stratigraphic characterization (Figure 32). From the seven outcrops, eight Edwards Formation facies were determined, which include (Figure 33):
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<th>Allochems</th>
<th>Other Features</th>
<th>Weathering Profile</th>
<th>Porosity</th>
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<td>Calcite Spar</td>
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<td>Intergranular</td>
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<td>Gastropod</td>
<td>Iron Oxidation</td>
<td>5 - High Relief</td>
<td>Fracture</td>
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<td>Chert Nodules</td>
<td>10 - Cliff Former</td>
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Figure 32: Legend for stratigraphic columns 1-7.
Figure 33: Representative photographs of the eight stratigraphic facies.
• **Facies 1**: Mudstone with sub-mm size interparticle porosity (29.7%), and fracture porosity (<1%), with moderate iron stain (25%) and low bioturbation.

• **Facies 2**: Mudstone with mm-cm size calcite macrospar (20-40%), sub-mm size interparticle porosity (7-22%), vuggy porosity (2-4.3%), fracture porosity (<1-2%), with moderate iron stain (15%) and low bioturbation.

• **Facies 3**: Mudstone with sub-mm size interparticle porosity (25%), vuggy porosity (4.3 %), and fracture porosity (<1%) with localized foram fossiliferous grainstone nodules containing abundant allochems and heavy bioturbation.

• **Facies 4**: Peloidal fossiliferous packstone with sub-mm interparticle porosity (10.3 %), and moldic porosity (3%) with abundant sub – mm size allochems and moderate to heavy bioturbation and moderate iron stain (10%) with localized foram fossiliferous grainstone nodules containing abundant allochems and heavy bioturbation.

• **Facies 5**: Foram fossiliferous wackestone with sub-mm size interparticle porosity (1-3.3%), fracture porosity (4.7%), and vuggy porosity (12.7%) with sub-mm size allochems, moderate bioturbation and significant iron stain (40%).
• **Facies 6**: Foram fossiliferous grainstone with sub-mm size interparticle porosity (10.7-18%) and vuggy porosity (2%), with abundant sub-mm size allochems, moderate iron stain (10%), and heavy bioturbation.

• **Facies 7**: Bivalve fossiliferous wackestone with sub-mm size forams and ooids, sub-mm size interparticle porosity (16-18.3%), fracture porosity (1-8%), and vuggy porosity (1.7%), with moderate iron stain (10%), and moderate bioturbation.

• **Facies 8**: Foram fossiliferous packstone with sub-mm to 2 mm size bivalves, gastropods, and pelloids, with sub-mm interparticle porosity (11.3%) and moldic porosity (2%), with minor iron stain 5% and moderate to heavy bioturbation.

**Outcrop Descriptions**

Outcrop #1 (Critchfield Shelter Cave #1) is located on the west side of the property along Salado Creek and is 4.5 m thick (Figure 32 and 34). Three lithologic packages were described in the section, starting at the base of the outcrop. All lithologic packages are in the Edwards Formation.

• Package 1 is 0.3 m thick and contains 20% total porosity which includes intergranular porosity with extensive calcite spar in pores, bioturbation ichnofabric index of 2, and minor iron oxidation. Package 1 is a mudstone and is associated with Facies 2.
Figure 34: Outcrop #1 stratigraphic column.
• Package 2 is 1.3 m thick and contains very sparse ooids, 40% total porosity which includes vugs that are 2-5 mm in diameter, intergranular porosity, and fracture porosity with extensive calcite spar in pores, bioturbation ichnofabric index of 2, and minor iron oxidation. Package 2 is a mudstone and is associated with Facies 2.

• Package 3 is 2.9 m thick and contains very sparse pelloids and bivalves, 10% total porosity which includes intergranular and fracture porosity, extensive calcite spar in pores, and bioturbation ichnofabric index of 2. Package 3 is a mudstone and is associated with Facies 2.

Outcrop #2 (Buzzard Roost Cave) is located on the south side of the Critchfield Ranch property along the property boundary and is 2.06 m thick (Figure 35). Four lithologic packages were described, starting at the base of the outcrop. All lithologic packages are in the Edwards Formation.

• Package 1 is 0.85 m thick and contains bivalves and ooids, 15% total porosity which includes interparticle and fracture porosity, with extensive calcite spar in pores, minor iron oxidation, and bioturbation ichnofabric index of 2. Package 1 is a packstone and is associated with Facies 8.

• Package 2 is 0.46 m thick and contains bivalves and ooids, 15% total porosity which includes interparticle, fracture, and fenestral porosity, with minor iron oxidation, algal laminations, and bioturbation ichnofabric index
### Outcrop #2 Stratigraphic Column

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Location: Outcrop #2 - Buzzard Roost Cave

Figure 35: Outcrop #2 stratigraphic column.
of 2. Package 2 is a packstone associated with Facies 8.

- Package 3 is 0.55 m thick and contains bivalves and pelloids, 10% total porosity which includes interparticle porosity, with minor iron oxidation, algal laminations and bioturbation ichnofabric index of 2. Package 3 is a packstone and is associated with Facies 8.

- Package 4 is 0.2 m thick and contains bivalves, pelloids, and ooids, with a total porosity of 15% that includes 2-4 mm vugs, moldic and fenestral porosity, extensive calcite spar, minor iron oxidation and bioturbation ichnofabric index of 3. Package 4 is a packstone and is associated with Facies 8.

Outcrop #3 (Critchfield Bat Cave #1) is located on the north side of the property, along the property boundary, and is 5.81 m thick (Figure 36). Eleven lithologic packages were described, starting at the base of the outcrop. All lithologic packages are in the Edwards Formation.

- Package 1 is 0.53 m thick and contains 20% forams, 15% pelloids, 5% bivalves, and 5% gastropods with 5% total porosity that includes fracture porosity, extensive calcite spar, minor laminations, minor iron staining, and bioturbation ichnofabric index of 2. Package 1 is a packstone and is associated with Facies 4.

- Package 2 is 0.18 m thick and contains 5% forams and 3% bivalves, 25%
Figure 36: Outcrop #3 stratigraphic column.
total porosity that includes moldic, interparticle, 2-5 mm vugs, and fenestral porosity, with significant iron oxidation, extensive calcite spar in pores, and bioturbation ichnofabric index of 2. Package 2 is a wackestone and is associated with Facies 5.

- Package 3 is 1.07 m thick and contains 5% forams with 15% total porosity that includes interparticle, 2-5 mm vugs and fracture porosity with extensive calcite spar in pores, moderate iron oxidation, and bioturbation ichnofabric index of 1. Package 3 is a wackestone and is associated with Facies 5.

- Package 4 is 0.33 m thick and contains 3% bivalves, 6% total porosity that includes interparticle, moldic and fenestral porosity, with extensive calcite spar in pores, moderate iron oxidation and bioturbation ichnofabric index of 1. Package 4 is a wackestone and is associated with Facies 5.

- Package 5 is 0.11 m thick and contains 5% forams, 3% bivalves, and 5% pelloids with 15% total porosity that includes fenestral and 2-5 mm vuggy porosity, with significant iron oxidation, extensive calcite spar in pores and bioturbation ichnofabric index of 1. Package 5 is a wackestone and is associated with Facies 5.

- Package 6 is 0.56 m thick and contains 25% pelloids, 20% forams, 5% bivalves, and 5% gastropods, with 20% total porosity that includes interparticle, moldic, and fracture porosity with significant iron oxidation,
minor calcite spar in pores and bioturbation ichnofabric index of 1.

Package 6 is a grainstone and is associated with Facies 6.

- Package 7 is 0.52 m thick and contains 25% pelloids, 20% forams, 5% bivalves, and 5% gastropods with 20% total porosity which includes interparticle, fracture, fenestral, and vuggy (vugs 2-5 mm), with significant iron oxidation, minor calcite spar in pores and bioturbation ichnofabric index of 2. Package 7 is a grainstone and is associated with Facies 6.

- Package 8 is 0.85 m thick and contains 10% forams, 5% bivalves, and 3% echinoderms and 15% total porosity which includes moldic, and fracture porosity, with moderate iron oxidation, minor calcite spar in pores, and bioturbation ichnofabric index of 3. Package 8 is a wackestone and is associated with Facies 7.

- Package 9 is 0.35 m thick and contains 15% forams, 10% pelloids, 5% gastropods, and 5% bivalves with 5% total porosity which includes interparticle porosity, with minor iron oxidation, minor calcite spar in pores and bioturbation ichnofabric index of 2. Package 9 is a wackestone and is associated with Facies 7.

- Package 10 is 0.60 m thick and contains 15% forams, 10% pelloids, 5% gastropods, and 5% bivalves with 10% total porosity which includes interparticle and fenestral porosity, with minor calcite spar in pores and
bioturbation ichnofabric index of 2. Package 10 is a wackestone and is associated with Facies 7.

- Package 11 is 0.71 m thick and contains 15% forams, 10% pelloids, 5% gastropods, and 5% bivalves with 15% total porosity which includes vuggy (vugs 2-3 mm), interparticle, and fracture porosity, with minor calcite spar in pores and bioturbation ichnofabric index of 3. Package 11 is a wackestone and is associated with Facies 7.

Outcrop #4 (Critchfield Bat Cave #2) is located on the north side of the property along the property boundary and is 3.71 m thick (Figure 37). Eight lithologic packages were described, starting at the base of the outcrop. All packages are the Edwards Formation.

- Package 1 is 0.98 m thick and contains 30% total porosity which includes interparticle, fracture, and vuggy (vugs 1 cm) porosity, minor iron oxidation and minor calcite spar in pores, bioturbation ichnofabric index of 1. Within this section are grainstone nodules that contain ooids, bivalves, gastropods, 5% total porosity which includes interparticle porosity, with some iron oxidation, extensive calcite spar and bioturbation ichnofabric index of 5. Package 1 is a mudstone and is associated with Facies 3.

- Package 2 is 0.22 m thick and contains 20% forams, 15% pelloids, 5%
Figure 37: Outcrop #4 stratigraphic column.
bivalves, and 5% gastropods with 13% total porosity which includes interparticle and moldic porosity, with significant iron oxidation, extensive calcite spar and bioturbation ichnofabric index of 2. Within this section are grainstone nodules that contain bivalves, gastropods, and ooids, 9% total porosity which includes interparticle porosity, with significant iron oxidation and extensive calcite spar and bioturbation ichnofabric index of 5.

Package 2 is a packstone and is associated with Facies 4.

- Package 3 is 0.55 m thick and contains 5% forams, 3% bivalves, and 5% peloids with 15% total porosity which includes fracture, moldic, and vuggy (vugs 2-5 mm) porosity, with moderate iron oxidation, extensive calcite spar laminations and bioturbation ichnofabric index of 1. Package 3 is a wackestone associated with Facies 5.

- Package 4 is 0.37 m thick and contains 25% peloids, 20% forams, 5% bivalves, and 5% gastropods with 10% total porosity which includes fracture and interparticle porosity, with significant iron oxidation, minor calcite spar in pores and bioturbation ichnofabric index of 2. Package 4 is a grainstone and is associated with Facies 6.

- Package 5 is 0.19 m thick and contains collapse breccia with extensive calcite spar and some vuggy porosity (vugs 3mm) (5%).

- Package 6 is 0.49 m thick and contains 25% peloids, 20% forams, 5% bivalves, and 5% gastropods with 17% total porosity which includes
interparticle, moldic, fenestral, and fracture porosity with a bioturbation ichnofabric index of 1. Package 6 is a grainstone and is associated with Facies 6.

- Package 7 is 0.11 m thick and contains localized calcite macrospar or flowstone.
- Package 8 is 0.80 m thick and contains bivalves, 10% total porosity which includes fracture and moldic porosity, some iron oxidation and calcite spar, bands of nodular chert 15 cm wide by 6 mm tall, and a bioturbation ichnofabric index of 2. Top of Package 8 contains bivalves, gastropods, ooids, and pelloids with calcite spar, some iron stain and bioturbation ichnofabric index of 4. Package 8 is a grainstone and is associated with Facies 6.

Outcrop #5 (spring) is located on the west side of the property and is 8.63 m thick (Figure 38). Five packages were described, starting at the base of the outcrop. All packages are the Edwards Formation.

- Package 1 is 0.83 m thick and contains 40% total porosity which includes moldic, vuggy (vugs cm size), conduit (up to 20 cm diameter), and interparticle porosity, with moderate iron oxidation, extensive calcite spar, chert nodules, bottom of section is heavily leached, bioturbation ichnofabric index of 2. Package 1 is a mudstone associated with Facies 2.
Figure 38: Outcrop #5 stratigraphic column.
• Package 2 is 0.88 m thick and contains 25% total porosity which includes moldic, vuggy (vugs up to 2 mm), and conduit (up to 40 cm), with moderate iron oxidation, extensive calcite spar and bioturbation ichnofabric index of 2. Package 2 is a mudstone and is associated with Facies 2.

• Package 3 is 1.16 m thick and contains 30% total porosity which includes fracture, vuggy (vugs up to 2 cm), and fenestral porosity, with chert nodules, bioturbation ichnofabric index of 2 and extensive calcite spar. Package 3 is a mudstone and is associated with Facies 2.

• Package 4 is 4.76 m thick and contains 30% total porosity which includes interparticle and vuggy (vugs 0.5-2 mm), with extensive calcite spar, chert nodules and bioturbation ichnofabric index of 2. Package 4 is a mudstone associated with Facies 2.

• Package 5 is 0.9 m thick and contains 45% total porosity which includes vuggy (vugs 2-5 mm) and interparticle porosity, with moderate iron oxidation, extensive calcite spar and bioturbation ichnofabric index of 2. Package 5 is a mudstone associated with Facies 2.

Outcrop #6 (Cistern) is located on the west side of the property and is 6.75 m thick (Figure 39). Six packages were described, starting at the base of the outcrop. All packages are the Edwards Formation.
Figure 39: Outcrop #6 stratigraphic column.
• Package 1 is 0.9 m thick and contains 30% total porosity as interparticle porosity, with extensive calcite spar and bioturbation ichnofabric index of 1. Package 1 is a mudstone and is associated with Facies 2.

• Package 2 is 0.50 m thick and contains very sparse bivalves and 25% total porosity which includes interparticle, fracture, moldic, and vuggy (vugs up to 1cm), with moderate iron oxidation, extensive calcite spar and bioturbation ichnofabric index of 2. Package 2 is a mudstone and is associated with Facies 2.

• Package 3 is 0.90 m thick and contains 12% total porosity which includes vuggy (vugs 2-5 mm), fracture, and interparticle porosity, with moderate iron oxidation, extensive calcite spar and bioturbation ichnofabric index of 3. Package 3 is a mudstone and is associated with Facies 2.

• Package 4 is 1.65 m thick and contains 40% total porosity which includes interparticle, moldic, and vuggy porosity, with moderate iron oxidation and extensive calcite spar, bioturbation ichnofabric index of 1 and a leached top section. Package 4 is a mudstone and is associated with Facies 2.

• Package 5 is 0.80 m thick and contains 25% total porosity which includes vuggy (vugs 5mm), interparticle, and fracture porosity, with moderate iron oxidation, extensive calcite spar and bioturbation of 2. Package 5 is a mudstone and is associated with Facies 2.
Outcrop #7 (Barn) is located on the northwest side of the property and is 5.23 m thick (Figure 40). Six sections were described, starting at the base of the outcrop. All sections are the Edwards Formation.

- Package 1 is 1.05 m thick and is a highly-fissile marl that contains 5% total porosity which includes fracture porosity with moderate iron oxidation, minor calcite spar and bioturbation ichnofabric index of 2. Package 1 is a mudstone and is associated with Facies 1.

- Package 2 is 0.83 m thick and contains 30% total porosity which includes interparticle, moldic, and fracture porosity, with extensive calcite spar and bioturbation ichnofabric index of 2. Package 2 is a mudstone and is associated with Facies 2.

- Package 3 is 0.60 m thick and contains 17% total porosity which includes moldic, vuggy (vugs up to 2 cm), and interparticle porosity, with extensive calcite spar that has been recrystallized into calcite rhombs, moderate iron oxidation and bioturbation ichnofabric index of 3. Package 3 is a wackestone associated with Facies 2.

- Package 4 is 0.30 m thick and contains 25% total porosity which includes vuggy, fenestral, and fracture porosity, with moderate iron oxidation, extensive calcite spar and bioturbation ichnofabric index of 1. Package 4 is a mudstone and is associated with Facies 2.

- Package 5 is 1.80 m thick and contains a total porosity of 45% which
Figure 40: Outcrop #7 stratigraphic column.
includes vuggy (vugs cm scale), interparticle, fracture, and moldic porosity, with moderate iron oxidation, extensive calcite spar, non-continuous chert horizons, and bioturbation ichnofabric index of 2.

Package 4 is a mudstone and is associated with Facies 2.

- Package 6 is 0.65 m thick and contains rare gastropods up to 3 cm in size, 11% total porosity which includes moldic and vuggy (vugs cm scale) porosity, with moderate iron stain, extensive calcite spar and bioturbation ichnofabric index of 3. Package 6 is a mudstone and is associated with Facies 2.

**Petrography**

After completion of stratigraphic analyses, representative thin sections of each of the identified facies were analyzed to refine facies definitions and analyze the diagenetic evolution of strata. Thin sections from seventeen different stratigraphic horizons representing the eight facies identified in the study area were analyzed under a petrographic microscope, including 300-point, point counts that documented allochem, porosity, cement and matrix variability. These point counts were subsequently used to provide a relevant Folk (1962) classification of each facies. Each of these thin section analyses are summarized below with corresponding representative figures.
• Facies 1 (Outcrop 7, Barn 2 sample from middle package) (Figure 41) is a micrite or mudstone that is comprised of micrite matrix (69.7%) with significant interparticle porosity (29.7%) and rare fracture porosity (<1%). Significant iron staining (25%) occurs throughout.

• Facies 2 (Outcrop 1, Critchfield Shelter Cave 1 sample A1) (Figure 41) is a dismicrite or mudstone comprised of micrite matrix (66.3%) with significant mm-cm size calcite spar (21.7%), common interparticle porosity (9%) and uncommon vuggy porosity (3%). Calcite spar largely fills interparticle and vuggy porosity and iron staining (15%) is common.

• Facies 2 (Outcrop 7, Barn 3 sample from bottom package) (Figure 41) is a dismicrite or mudstone that is mostly comprised of micrite matrix (66.3%), with significant mm-cm size calcite spar (17%), and interparticle porosity (11.3%). Vuggy porosity (4%), and fracture porosity (1.7%) are rare. Calcite spar largely fills interparticle and vuggy porosity and iron staining (15%) is common.

• Facies 2 (Outcrop 5, Cistern 3) (Figure 42) is a dismicrite or mudstone that is mostly comprised of micrite matrix (60.7%), significant mm-cm size calcite spar (28%) and common interparticle porosity (7%). Fracture porosity (4.7%), and vuggy porosity (<1%) are rare. Calcite spar largely fills interparticle and vuggy porosity and iron staining is common (15%) throughout.
Figure 41: Representative photographs of thin sections Barn 2 Middle, Critchfield Shelter Cave A1, and Barn 3 Bottom.
Figure 42: Representative photographs of thin sections Cistern 3, Barn 6, Spring A Base, and Critchfield Bat Cave #2 sample 1.
Facies 2 (Outcrop 7, Barn 6) (Figure 42) is a dismicrite or mudstone that is mostly comprised of micrite matrix (70.7%), significant mm-cm size calcite spar (18%), and interparticle porosity (7.3%). Fracture (2%), vuggy (1.3%), and moldic porosity (<1%) are rare. Calcite spar largely fills interparticle and vuggy porosity and iron staining is common (15%) throughout.

Facies 2 (Outcrop 5, Spring A sample from bottom package) (Figure 42) is a dismicrite or mudstone that is mostly comprised of micrite matrix (39.4%), significant mm-cm size calcite spar (31%), with common interparticle porosity (22%) and iron staining (15%). Vuggy porosity (4.3%), fenestral porosity (2.7%), and fracture porosity (<1%) rare. Calcite spar largely fills interparticle and vuggy porosity.

Facies 3 (Outcrop 4, Critchfield Bat Cave #2 sample 1) (Figure 42) is a micrite or mudstone that is mostly comprised of micrite matrix (66.7%), and common interparticle porosity (25%). Vuggy porosity (4.3%), calcite spar (3.3%), and fracture porosity (<1%) are rare, while iron staining (5%) is uncommon. Included in Facies 3 (Outcrop 4, Critchfield Bat Cave #2 sample 1 Nod) (Figure 42) is a nodule that is a oolitic, peloidal, bivalve, gastropodal, foram, unsorted biosparite or a foram fossiliferous grainstone that is mostly comprised of forams (55.7%), gastropods (20%), bivalves (10%), with common interparticle porosity (8.7%), calcite spar (4.7%), pelloids (3%), and rare ooids (<1%).
• Facies 4 (Outcrop 4, Critchfield Bat Cave #2 sample 2) (Figure 43) is a pelloidal, gastropodal, bivalve, foram packed biomicrite or pelloidal fossiliferous packstone that is mostly comprised of pelloids (15%), gastropods (10%), bivalves (11%), and forams (25%), with significant micrite matrix (29.7%), common calcite spar (11%), interparticle porosity (10.3%) and rare moldic porosity (3%). Iron staining is common (10%).

• Included in Facies 4 (Outcrop 4, Critchfield Bat Cave #2 sample 2 Nod) (Figure 43) is a nodule that is a oolitic, gastropodal, bivalve, foram, unsorted biosparite or foram fossiliferous grainstone that is mostly comprised of forams (45.3%), bivalves (22.4%), and gastropods (15%), and calcite spar (8.7%), with interparticle porosity (7.7%) common and rare ooids (1%).

• Facies 5 (Outcrop 4, Critchfield Bat Cave #2 sample 3) (Figure 44) is a pelloidal, foram, fossiliferous biomicrite or a foram fossiliferous wackestone that is mostly comprised of significant micrite matrix (76.7 %) with calcite spar (10%), pelloids (3%), forams (3%), bivalves (1.7%) common. Fracture porosity (4.7%), and interparticle porosity (1%) are rare with iron staining common (40%).
Figure 43: Representative photographs of thin sections Critchfield Bat Cave #2 sample 1 Nod, Critchfield Bat Cave #2 sample 2, and Critchfield Bat Cave #2 sample 2 Nod.
Figure 44: Representative photographs of thin sections Critchfield Bat Cave #2 sample 3, Critchfield Bat Cave F Bottom, Critchfield Bat Cave B Bottom, and Critchfield Bat Cave #2 sample 8 Top.
- Facies 5 (Outcrop 3, Critchfield Bat Cave sample F from bottom package) (Figure 44) is an unsorted pelmicrite or pelloidal wackestone that is mostly comprised of significant micrite matrix (74.7%), with vuggy porosity (12.7%) and calcite spar (9%). Pelloids (3%), forams (3%), bivalves (1.7%), and interparticle porosity (3%) are rare with iron stain (40%) common.

- Facies 6 (Outcrop 3, Critchfield Bat Cave sample B from bottom package) (Figure 44) is a gastropodal, bivalve, foram unsorted biosparite or foram fossiliferous grainstone that is mostly comprised of significant micrite matrix (37.3%), forams (40%), bivalves (25%), and pelloids (20%), with gastropods (13%), interparticle porosity (18%) and calcite spar (7.3%) common, rare vuggy porosity (2%) and common iron staining (10%).

- Facies 6 (Outcrop 4, Critchfield Bat Cave #2 sample 8 from top package) (Figure 44) is a bivalve, foram, unsorted biosparite or foram fossiliferous grainstone that is comprised mostly of forams (40%), bivalves (25%), and pelloids (20%), with common gastropods (13%), interparticle porosity (10.7%), and calcite spar (7%). Micrite matrix (4.3%) is rare and iron staining (20%) is common throughout.

- Facies 7 (Outcrop 3, Critchfield Bat Cave sample A1) (Figure 45) is an echinoderm, foram, bivalve, fossiliferous biomicrite or bivalve fossiliferous wackestone that is comprised mostly of micrite matrix (64.3%),
Figure 45: Representative photographs of thin sections Critchfield Bat Cave A1, Critchfield Bat Cave A2, and Buzzard Roost Cave A4.
interparticle porosity (18.3%), and calcite spar (9.3%), with uncommon to rare forams (2.4%), bivalves (2.3%), echinoderms (1%). Vuggy porosity (1.7%) and fracture porosity (1%) are rare with common iron staining (10%).

- Facies 7 (Outcrop 7, Critchfield Bat Cave sample A2) (Figure 45) is a bivalve, sparse biomicrite or bivalve fossiliferous wackestone that is comprised mostly of micrite matrix (55.7%), with uncommon forams (2.4%), bivalves (2.3%), and echinoderms (1%). Significant interparticle porosity (16%) present with common fracture porosity (8%) and rare calcite spar (<1%). Iron staining (10%) is common.

- Facies 8 (Outcrop 2, Buzzard Roost Cave sample A4) (Figure 45) is a gastropod, bivalve, foram, packed biomicrite or foram fossiliferous packstone that is comprised mostly of micrite matrix (30.7%), forams (21%), and gastropods (20%), with common pelloids (10%), bivalves (15%), and interparticle porosity (11.3%). Iron staining (5%) is uncommon and moldic porosity (2%) is rare.

Geochemistry

Two springs, Critchfield and Salado Springs, and Salado Creek were measured in the study area with portable water quality field meters at the same time samples were taken in sterile bottles for more detailed laboratory analyses
(Table 1). Critchfield Spring and Salado Creek are located south of Salado within the Critchfield Ranch study area and Salado Springs is located in Salado, Texas. All occur in the Edwards Formation and were actively flowing at the time of sampling.

Critchfield Spring’s physical parameters measured in the field were as follows: temperature of 21.21 °C, pH of 7.88, dissolved oxygen (DO) of 17.4 %, and total dissolved solids (TDS) of 0.268 mg/L. Chemical parameters that were found in a more detailed laboratory analysis were as follows: bicarbonate of 199.58 ppm, calcium of 88.64 ppm, potassium of 0.72 ppm, magnesium of 19.39 ppm, sodium of 4.68 ppm, fluoride of 0.14 ppm, chloride of 5.25 ppm, nitrate of 11.92, and sulfate of 7.33 ppm (Figure 46a).

Salado Creek’s physical parameters measured in the field were as follows: temperature of 27.57 °C, pH of 7.38, dissolved oxygen (DO) of 87.6 %, and total dissolved solids (TDS) of 0.273 mg/L. Chemical parameters that were found in more detailed laboratory analyses were as follows: bicarbonate of 22.83 ppm, calcium of 89.86 ppm, potassium of 1.69 ppm, magnesium of 10.35 ppm, sodium of 9.76 ppm, fluoride of 0.16 ppm, chloride of 6.79 ppm, nitrate of 0.11, and sulfate of 8.79 ppm (Figure 46b).

Salado Spring’s physical parameters measured in the field were as follows: temperature of 17.41 °C, pH of 7.70, dissolved oxygen (DO) of 80.90 %, and total dissolved solids (TDS) of 0.389 mg/L. Chemical parameters that were found in a more detailed laboratory analyses were as follows: bicarbonate of
Table 1: Geochemistry data from Critchfield Spring, Salado Creek, and Salado Spring.

<table>
<thead>
<tr>
<th>Geochemistry Data</th>
<th>Critchfield Spring</th>
<th>Salado Creek</th>
<th>Salado Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature °C</td>
<td>21.21</td>
<td>27.57</td>
<td>17.41</td>
</tr>
<tr>
<td>pH</td>
<td>7.88</td>
<td>7.38</td>
<td>7.7</td>
</tr>
<tr>
<td>HDO %Sat</td>
<td>17.4</td>
<td>87.6</td>
<td>80.9</td>
</tr>
<tr>
<td>TDS mg/L</td>
<td>0.268</td>
<td>0.273</td>
<td>0.389</td>
</tr>
</tbody>
</table>
Figure 46: Stiff diagrams of Critchfield Spring, Salado Creek, and Salado Spring.
189.00 ppm, calcium of 92.05 ppm, potassium of 1.15 ppm, magnesium of 16.42 ppm, sodium of 12.94 ppm, fluoride of 0.35 ppm, chloride of 11.65 ppm, nitrate of 31.35 ppm, and sulfate of 15.20 ppm (Figure 46c).

LiDAR

Depression Delineation and Classification

To identify depression features within the study area, a 1.5 m DEM was generated from LiDAR data. Using the Sink tool, depressions were found on the DEM and were delineated with polygons by converting raster to vector. Each depression feature found was shown with a single polygon. The method of finding polygons recognized a total of 1,698,358 depressions in the Salado Creek Watershed study area.

Depressions in the study area could be related to man-made structures or the naturally occurring karst in the area. These depressions were classified whether they relate to man-made or natural feature. Interference between classification and depression features were filtered out and removed from the results. By using the Select by Location feature, polygons associated with roads, quarries, streams, ponds, and cities were removed (Table 2). Roads, quarries, streams, and cities were buffered to a certain extent in order to eliminate any
<table>
<thead>
<tr>
<th>Feature</th>
<th>Buffer</th>
<th>Total Sink Features</th>
<th>Value after Select by Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Roads - Paved</td>
<td>20 m</td>
<td>1693858</td>
<td>89964</td>
</tr>
<tr>
<td>Minor Roads - Gravel and Dirt</td>
<td>10 m</td>
<td>1693858</td>
<td>55398</td>
</tr>
<tr>
<td>Streams</td>
<td>10 m</td>
<td>1693858</td>
<td>57652</td>
</tr>
<tr>
<td>Quarries</td>
<td>20 m</td>
<td>1693858</td>
<td>42326</td>
</tr>
<tr>
<td>Ponds</td>
<td>5 m</td>
<td>1693858</td>
<td>7584</td>
</tr>
<tr>
<td>Cities</td>
<td>200 m</td>
<td>1693858</td>
<td>105838</td>
</tr>
<tr>
<td>Vertical - &lt;20 cm</td>
<td></td>
<td>1693858</td>
<td>5748</td>
</tr>
</tbody>
</table>

Table 2: Number of sinks after filtering of features.
depression feature that could possibly be associated with them. Roads in the study area were split into paved, gravel, and dirt. Paved roads were considered major roads and buffered to 20 m and 89,964 sinks were removed within these buffers. Gravel and dirt roads were considered minor roads and buffered to 10 m and 55,398 sinks were removed within these buffers. Limestone mining is dominant in the study area, so quarries have to be taken into account and were buffered to 20 m. A total of 42,326 sinks were removed within the quarry buffers.

After streams were found and classified with the Flow Accumulation tool, they were also buffered for the filtering process. Streams were buffered to 10 m and 57,652 sinks were removed from within the stream buffers. Stock ponds in the study area are common because of the high number of ranches. These ponds were buffered to 5 m and 7,584 sinks associated with these ponds were removed from within the buffers. Cities in the Salado Creek Watershed were buffered to 200 m and 105,838 sinks were removed from within these buffers.

Vertical accuracy is the principal criterion in specifying the quality of elevation data (Flood, 2004). Vertical accuracy of the LiDAR was considered because any sinks not deeper than this value cannot be differentiated as true features from data errors. The vertical accuracy is <15 cm for this study and the value used to filter out sinks was 20 cm. After the Select by Location feature and Definition Query feature were implemented to attain these results, the total number of natural sinks was 3,395 in the Salado Creek Watershed. The density

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of the features before being filtered shows the heaviest areas of sinks in the northern portion of the Salado Creek Watershed (Figure 47).

After sinks were filtered and only the natural sinks were left, the density still seemed to dominate the northern portion of the study area (Figure 48). There were some trends in the central area of the watershed and along the watershed boundary. A processing artifact appears to exist between the northeastern and southwestern portions of the Salado Creek watershed; however, there are areas of likely karst development throughout the watershed. Localized high density regions occur in the northwest and the far eastern portions of Bell County.

**Slope Analysis**

A raster image showing slope in each cell was created of the study area to show slope analyses (Figure 49). Areas with higher slopes, generally larger than 45 degrees, usually represent areas prone to host shelter caves. Scarpas along waterways were the main areas where slope are greater than 45 degrees. Other areas where the slope is greater than 45 degrees were small and not associated with waterways in the study area.

Shelter cave development is related to near vertical slopes. A slope analysis was conducted to determine where high angle slopes were located in the Salado Creek Watershed. The slope analysis revealed that most high angle slopes were associated with Salado Creek stream segments. On the Critchfield
Figure 47: Density of all sinks before filtering.
Figure 48: Density map of natural sinks in the Salado Creek Watershed after buffers were done.
Figure 49: Slope analysis of Salado Creek Watershed and Critchfield Ranch.
Ranch, where Salado Creek runs through the western portion of the property, were the higher angle slopes and is the area where all shelter caves were found. There is a feature shown on the slope raster in the southeastern corner of the Critchfield Ranch that is man-made berm.

Field Verification of LiDAR Analyses

Field verification was necessary in order to confirm the results of the LiDAR analyses. Depressions associated with roads, quarries, streams, and natural features were explored in the field. After delineating sinkholes in the study area, a comparison of the sinks found on Critchfield Ranch was made. With surficial mapping, fourteen likely sinks were identified. LiDAR analyses showed more than fourteen sinks on the ranch. They also showed sinks at different locations on the ranch than those found with the ground survey. After the buffers for creeks, major and minor roads, and quarries were added, many sinks were removed (Figure 50). Many sinks on the property correlate with man-made depressions as the landowner has used excavating equipment within the area of study. The LiDAR did pick up two of the cave entrances and showed them as depressions. The LiDAR analysis found many more sinks in the study area than was found traversing the area. The entrance to Critchfield Bat Cave #2 is small so it did not
Figure 50: Close-up of Critchfield Ranch with creek buffers, major and minor road buffers, and quarry buffers along with sinks found from LiDAR and ground surveys.
find it. The slope analysis revealed that all high angle slopes were adjacent to Salado Creek where all shelter caves on the property were found also.
DISCUSSION

Stratigraphy, geochemistry, GIS, and cave analyses were studied in order to determine speleogenesis of Critchfield Bat Caves, Buzzard Roost Cave, and shelter caves located on the Critchfield Ranch in Central Texas. These analyses were also conducted to gain more insight into the hydrogeology of the Northern Edwards Aquifer and more specifically the Salado Creek Watershed.

Stratigraphic analyses determined that rocks on the Critchfield Ranch can be divided into eight facies with various depositional environments from low-energy to high-energy shelf environments. The geochemical analyses concluded that groundwaters from two springs were similar with each other except higher amounts of sodium, sulphate, calcium, chloride, and nitrates found at Salado Springs.

GIS analyses determined that there are many sinks in the study area but these sinks may or may not be related to karst in the area. After filtering of sinks within a close proximity to man-made features, only natural sinks were left, which suggest geologic control on spatial distribution of karst. Specific interest in caves on Critchfield Ranch was due to it being an analog for caves in the entire Salado Creek Watershed. Cave studies indicated that the caves on Critchfield Ranch
are epigene caves with a combination of vadose and phreatic morphologies and have limited lateral extent due to the facies that do not promote uniform porosity development.

Stratigraphy

Depositional environments of strata in the study area represent low-energy environments with some high-energy environments throughout. Cretaceous sedimentation of the study area began approximately 110 mya on the Comanche Shelf in lee of the Stuart City Reef (Collins, 2005). Most strata in the study area are either lagoonal or open platform depositional environments due to the range of deposits found in the study area being mudstones to grainstones. The strata in the study area are primarily composed of mudstones, wackestones, packstones, and grainstones with fossils, ooids, and pelloids being common within most strata, but in generally in low abundance. Also observed in various lithologic packages are calcite spar and iron oxidation. Chert nodules were also found within some areas of strata. Much porosity is found throughout the strata in the study area including interparticle, vuggy, moldic, fenestral, and fracture. Porosity of the Edwards Aquifer is controlled by interactions among depositional porosity formed in the sedimentary environment, early and burial diagenetic alteration, and late diagenetic alteration (Hovorka et al., 1996).
At the bottom of the stratigraphic sequence found on the Critchfield Ranch, the first facies are mudstones. Facies 1, found in outcrop 7, is equivalent to Collins (2005) facies description “facies 3” of the Edwards Formation. Collins (2005) states that facies 3 is a unit of nodular, fossiliferous, burrowed, argillaceous limestone and marl. The facies found in the study area is a mudstone with characteristics of highly fissile marl and is most likely a lagoonal mud (Figure 51). The depositional environment of facies 1 is representative of a restricted lagoonal facies with the highly fissile nature associated with dispersed evaporite minerals and potential terrigenous influx into a low-energy inland lagoon. An older reef or rudist reef to the east would have caused the restriction allowing these lagoonal facies to accumulate. The higher salinity in a lagoon prohibited significant fauna from flourishing. The lack of allochems indicates a low-energy, restricted environment of a lagoon where these mudstones would have accumulated.

Facies 2, found in outcrops 1, 5, 6, and 7, is the transition zone between Collins (2005) “facies 3” and “facies 4” as sea level adjusted and marine circulation became slightly higher-energy and less restrictive. This facies is a mudstone with abundant recrystallized calcite macrospar, an indication of higher
Figure 51: Conceptual figure of facies found on Critchfield Ranch.
original permeability that has been secondarily infilled. The unit lacks allochems and bioturbation and the presence of abundant mud indicates a low-energy, shallow-water, likely subtidal, environment of deposition within a transition from lagoon to open platform.

Facies 3 through 8, found in outcrops 2, 3, 4, and 8 are equivalent to Collins (2005) “facies 4” description of the Edwards Formation. Collins (2005) states that “facies 4” is an upper interval of thin- to thick-bedded limestone, dolomitic limestone, and dolomite.

Facies 3 is a mudstone with localized grainstone nodules and is representative of an isolated mudflat within a platform environment that is protected by a nearby shoal environment. The nodules within the mudstone facies represent higher energy lenses, likely associated with higher-energy channel regions. No allochems or bioturbation are present in this facies except in the nodules. The nodules contain abundant allochems and high bioturbation with no mud representing a close proximity to a high-energy, depositional environment (Figure 52). These nodules contain a high percentage of fossils, ooids, and pelloids.

Facies 4 is a packestone with localized grainstone nodules. These were deposited in an intermediate-energy environment proximal to a channel environment where nutrient supply was more abundant, increasing bioturbation.
Figure 52: Conceptual of facies found on Critchfield Ranch with topography and caves.
The packstone contains pelloids and fossils, moderate to heavy bioturbation, and some mud, indicating a medium to high-energy depositional environment. This was deposited in an open platform environment within proximity of grainstone shoals.

Facies 5 is a wackestone, a transitional facies between shoal deposits and mudstones which would have been deposited in an open platform environment. This facies is interfingering between the grainstone/packstone facies.

Facies 6, found is a grainstone. The presence of abundant fossil allochems and lack of mud indicates a high-energy, shallow-water depositional environment, possibly a shoal environment within a more high-energy, open-shelf environment. The fossils, pelloids, algal laminations, and heavy bioturbation suggest grainstone shoals.

Facies 7 is a wackestone that represents a transitional facies between mudstones and channel environments of facies 4. The presence of fossil and ooid allochems suggests the depositional environment between the mudstones and channels on an open platform environment.

Facies 8 is a packstone that was likely developed on the flanks of facies 6 in an intermediate-energy environment within an open shelf depositional environment. The presence of fossil and pelloid allochems and some mud indicate a medium-high energy depositional environment.
Two springs and Salado Creek were sampled and analyzed to determine if they are related hydrogeologically. Field data from Critchfield and Salado Springs had slight variations between each other. Critchfield Spring has a higher temperature and pH than Salado Spring. Data collected in the field at the two springs suggest different origins because the dissolved oxygen (DO) content varies greatly between the two springs with the DO at Salado Spring being higher than Critchfield Spring. The total dissolved solids (TDS) measured at each spring was similar, but the TDS at Critchfield Spring is lower than Salado.

When data were analyzed in the lab, the two springs varied in results. Cation metals found in the spring water from Salado Spring were generally higher than those found in the water at Critchfield Spring. Calcium and sodium were higher at Salado Springs while magnesium was found at higher levels in Critchfield Spring. Anion metals between the two springs were significantly different. Fluoride, chloride, nitrate, and sulfate were all much higher at Salado Springs. The increase of sodium, sulphate, calcium, and chloride indicate longer circulation paths that are more in contact with evaporite minerals. Differences between mineral composition in the layers may result in considerable variation in water composition with depth at any given site (Hem, 1985). Nitrates at Salado Springs were significantly higher, likely due to greater anthropogenic influences such as fertilizers; nitrate found at Critchfield spring were at least one third of that.
found at Salado Springs. Bicarbonates found in both springs were close to the same value.

The Edwards aquifer generally contains consistent calcium bicarbonate water (Senger and Kreitler, 1984). The higher values of field parameters and metals in Salado Springs indicate a longer residence time of groundwater in the aquifer. Critchfield Spring is closer to the recharge zone of the Edwards Aquifer so it travels a shorter distance, before discharging on the Critchfield’s property, than the more eastward Salado Springs and likely represents local portioning of the Edwards Aquifer. The observed hydrochemical patterns of Edwards’ groundwater indicate hydrochemical evolution of groundwater along its downdip, easterly flow path (Senger et al., 1990).

In order to obtain more data and improve depth study of the geochemistry in the Salado Creek Watershed, more data need to be collected from a larger sampling size throughout the study area. Discharge at Salado Springs suggests a higher anthropogenic influence with higher values of anion metals than those found at Critchfield Spring; however, limitations of this study provide very limited results and indicated that a dedicated spring hydrogeochemical study should be conducted of the Salado Creek watershed.
GIS

Using LiDAR data, a 1.5 meter digital elevation model was produced and depression features were identified in the Salado Creek Watershed. With the growing availability of high-resolution DEMs produced by airborne LiDAR, GIS-based hydrologic applications often need to handle larger geographic areas at finer resolutions (Wang and Liu, 2006). The total number of sinks found when the data was processed was 1,693,858. After sinks or depressions were filtered out from the buffered man-made features, 3,395 sinks remained. These remaining sinks likely represent the natural sinks in the study area; however, it must be assumed that some minor error exists in filtering where some natural features were likely removed and some anthropogenic features likely remain within the filtered data. Two density maps were made to show the density of karst features per square kilometer within the watershed. The “before” density map depicts all the sinks in the watershed that were found before the filtering was conducted. This showed more features in the northern part of the study area. The northern part of the study area is also the areas in Bell County which was acquired with a higher resolution LiDAR data collection, thus the higher density reflects the significantly greater detail of data from this region. This unfiltered karst density map correlates well with fluvial bodies throughout the Salado Creek watershed, indicating that most small depressions are natural occurrences associated with minor erosional variations within stream beds.
The “after” density map depicts all sinks left in the watershed after buffering of features was conducted. This showed more features in the northern portions of the study area as well, but not as many as the “before” density map. Also, noticeable in the “after” map is the natural sinks trending in the central area of the watershed. These are the effect of the resolution of the LiDAR data. Some karst within that area could be real and some probably is not. The higher density areas along the northwestern and northeastern portions of the watershed boundary are likely karst features. On the northwestern edge, any karst features are formed by the water table divide where water is flowing in two directions and causing much dissolution. The high density cluster on the northeastern boundary, which also coincides with the town of Salado and Salado Springs, karst features are formed by spring discharge and springs along the Balcones Fault. The small cluster within the remaining watershed is likely the packstone facies identified on Critchfield Ranch where there is more cave development. These packstones are near surface and reflect greater solutional development.

When slope analysis was conducted, scarps along Salado Creek were shown to have higher angles, which is a good indicator of locations favorable for shelter cave development. Shelter caves are more predominant along these high angle scarps because fluctuations in stream flow in Salado Creek likely induce shelter cave development as water can be forced into and drained back out of adjacent strata to help dissolve specific horizons through repeated intervals of
high flow and persistent stream down-cutting. High angle slope areas occur along the creek with greater frequency in the northern portion of the study area where additional tributaries of Salado Creek converge. These areas indicate potential areas where shelter caves are likely to develop or areas of where existing shelter caves are most probable.

Speleogenesis

Three caves, Critchfield Bat Cave, Critchfield Bat Cave #2, and Buzzard Roost Cave, were found and surveyed on Critchfield Ranch along with eight shelter caves adjacent to Salado Creek. Porosity and permeability constantly evolve as seen in the speleogenetic evolution of Edwards strata in the study area. Early phases of speleogenetic development include vuggy porosity with secondary emplacement of dogtooth spar that likely occurred in deep-seated conditions prior to Balcones faulting and significant karst development.

In the mid-tertiary, Balcones faulting changed the hydraulic gradient and heavily fractured strata, adding fracture porosity and establishing preferential flow paths; today, cave development within region is focused on planar surfaces, including fractures and bedding planes that create zones of preferential dissolution. Most caves follow joints, which are more numerous and generally more permeable (Palmer and Palmer, 2009), which is consistent with trends
observed in the study area. Lithologic variability dictates vertical and lateral extent of cavernous porosity development.

Cavernous porosity in the study area is largely limited to packstone facies; however, facies 5, a wackestone, which exhibits high vuggy porosity and permeability where water cannot be concentrated through one area, but instead is more dispersed. Other mudstone and wackestone facies do not appear to promote cave development but do promote shelter cave development. Grainstone facies do not promote cave development nor significant solutional enhancement because high interparticle porosity in these regions promotes uniform high permeability.

Within the facies that do promote cave development, phreatic porosity development occurred when water tables were higher; however, as water levels lowered vadose morphologies overprinted these abandoned phreatic horizons, including characteristics of vadose caves. Surveyed caves in the study area are epigene cave and show both vadose and phreatic morphologies with initial karst porosity formed in phreatic environments with subsequent vadose overprinting. Epigene caves are formed by the movement of water from overlying or immediately adjacent recharge surfaces to springs in nearby valleys (Palmer, 1991). The evolution of these caves are guided by the early networks of phreatic primary tubes as commonly described in classic epigene karst systems described globally (Ford and Williams, 2007). Caves are dominantly oriented
along fractures near-perpendicular to the north-northwest strike of the Balcones Fault Zone with lateral widening along bedding planes that are more susceptible to differential dissolution.

Critchfield Bat Cave has a tube- or elliptical-shaped passage which indicates a phreatic origin that initially formed when the Edwards Aquifer water table was higher and under phreatic conditions. There are thin layers within the cave that exhibit solutional widening along bedding planes that extend laterally into walls. When water table levels declined in aquifer because of stream entrenchment and evolution of the Balcones Fault Zone region, Critchfield Bat Cave was removed from phreatic conditions and placed in vadose conditions. During vadose conditions, secondary mineralization occurred including calcite macrospar (flowstone) and significant speleothem development in the western end of the cave. As surface denudation continued, breaching of the caves occurred. The main phreatic passage of Critchfield Bat Caves developed in packstone facies; however, in down-gradient regions the cave transitions into vuggy zones developed in facies 5. These facies limit the lateral extent of Critchfield Bat Cave because facies 5 is a wackestone that promotes sponge-like, vuggy porosity and extremely high permeability flow zones.

Critchfield Bat Cave #2 shows vadose morphologies with a vertical shaft entrance and solutional widening along a bedding plane at the bottom. This cave
is primarily a vadose pit that developed as recharge features connected surface to subsurface flow regimes in the area.

Similar to Critchfield Bat Cave, Buzzard Roost Cave contains vertical shafts and fractures that have been solutionally-widened. This implies both vadose and phreatic morphologies. When the water table was higher, the majority of the cave formed under phreatic conditions, but as the water table fell and transitioned into vadose conditions, secondary mineralization occurred. Buzzard Roost Cave is similar to Critchfield Bat Cave but there is extensive, near complete collapse and breakdown throughout the known extent of the cave due to more intense local surface denudation. It is probable that there are many unexplored portions of Buzzard Roost Cave that do exist with evidence suggested by a large flowstone accumulation in line with the cave at Salado Creek, approximately 400 meters to the west, northwest.

Shelter caves in the study area appear to be related to stream incision. They developed in relation to entrenchment of Salado Creek in study area and appear to be limited facies 5 strata. As the creek entrenched, facies 5 was intercepted and water was injected into strata as groundwater recharge, which promoted local dissolution. As stream entrenchment continued, facies 5 was left above the base level of Salado Creek; however, flood events continue to inject water into these porous zones increasing dissolution as recharge occurs and further increasing dissolution as discharge from this soluble zone when stream
conditions return to baseflow. Effectively, shelter caves within the study area have formed and continue to form by backflooding processes.

On the western edge of Critchfield Property, two additional shelter caves and Critchfield Spring occurs. Critchfield Spring is currently discharging at the upper contact of facies 1 due to permeability variations. Shelter caves proximal to the spring appear to have formed through a different process and instead likely represent paleo discharge features when the Edwards Aquifer water table was higher than it is current level. These paleo-discharge features are now relict features and do not appear to be hydrologically active in the current speleogenetic system.

Cavernous porosity in northern Williamson and southern Bell counties rely on fractures and bedding planes for the groundwater flow. Karst exhibits preferential dissolution along stratigraphic horizons that dip gently towards the Balcones Fault Zone, including highly porous, vuggy zones and brecciated zones. Current data analyses indicate epigene karst development within the Salado Creek Watershed is tied to the geomorphic evolution of Salado Creek and primary local system discharge through Salado Springs. Surface denudation coupled with stream incision has partially partitioned this shallow epigene karst system within the watershed. To the west of Salado Creek, shallow spring discharge occurs along the entrenched stream channels while well-developed paleo-phreatic tubes are now abandoned to the east; vadose pit development
and sinkhole collapse have created direct recharge conduits into the system. Karst along entrenched scarps of Salado Creek indicates that in the past Salado Creek provided significant groundwater recharge to eastern dipping portions of the watershed; however, these horizons are now abandoned. These shallow components are all coupled with deeper groundwater flow paths that discharge at Salado Springs.
CONCLUSIONS

Karst development is extensive throughout the Salado Creek watershed but is limited to specific lithologies that are favorable for dissolution. Cave development primarily occurs in packstone facies and shelter cave development occurs in mudstone facies along high-angle scarps of Salado Creek and its tributaries. These packstone and mudstone facies interfinger with a highly vuggy, wackestone facies that does not promote cave development, but instead promotes the development of spongework porosity and thus restricts the lateral continuity of caves. Three caves and seven shelter caves were found on Critchfield Ranch along with fourteen sinks and one spring, which provide the basis for extrapolating the general speleology of the Salado Creek watershed.

The accumulation of Edwards Formation facies on the Comanche Shelf was controlled by the Stuart City Reef which enabled carbonate sediment deposition in an open platform or lagoonal environment. This allowed for mudstones, wackestones, packstones, and grainstones to be deposited as sea level increased and decreased. The study area is limited to the upper Edwards Formation and is very similar to Collins (2005) description of the Edwards Formation “facies 3” and “facies 4.” The facies in the study area are interfingering representing many environments. Facies 1, equivalent to Collins (2005) “facies
3," was deposited in a low-energy, inland lagoon which is highly fissile and does not promote cave development. Facies 2 is a probable transitional facies between Collins (2005) description of “facies 3" and “ facies 4." This facies has some shelter cave development within it in the study area, but does not appear to promote significant lateral cave development.

Collins (2005) description of “facies 4" is equivalent to the remaining facies 3-8 in the study area. Mudstone and wackestone facies (facies 3, 5, and 7, respectively) do not appear to promote cave development in the study area. Facies 5 exhibits a very vuggy porosity due to preferential dissolution of the highly-bioturbated rocks and which does not allow water focused through a narrow region needed for cave development, but instead water flow is more dispersed creating significant porosity and “spongework" pore system through dissolution. This facies is found at the ends of Critchfield Bat Caves and in Critchfield Shelter Cave #1 where human exploration cannot be continued because secondary porosity structure changed form from isolated cavernous porosity to highly-connected, touching-vug porosity. Grainstone facies (facies 6) do not appear to promote cave development likely due to the interparticle porosity making them highly transmissive. Packstone facies (facies 4 and 8) appear to promote cave development more than other facies within the study area. Packstone facies comprise the entire phreatic tube region of Critchfield Bat Cave and were found in Buzzard Roost Cave, although more difficult to
recognize there exact correlation due to the significant extent of collapse material.

The packstones (facies 4 and 8) and grainstones (faces 6) represent high-energy environments of deposition while the mudstones (facies 1, 2, and 3) and wackestones (facies 5 and 7) represent a low-energy depositional environments. The lagoonal mud facies (facies 1) were deposited in a low-energy, shallow environment restricted from wave action. Above the lagoonal mud is a facies (facies 2) that is in the transition zone between the lagoonal sediment to an open shelf environment with various other environments including mudflats and shoals observed in the upper strata of the study area (facies 3-8). A typical vertical sequence is a low-energy, shoaling-upward cycle consisting of a basal transgressive unit, muddy carbonate with impoverished fauna, and capped by intertidal and/or supratidal deposits (Enos, 1983).

Geochemistry of two springs indicates that the groundwater from both springs is coming from the same aquifer system, but with minor to moderate variations. Data suggest that discharge from Salado Springs is associated with longer flow paths and greater residence time, including contact with more evaporite strata than spring discharge from Critchfield Spring. Salado springs also has a higher anthropogenic influence as seen from the much higher value of nitrates found in the water as compared to Critchfield Spring.
When LiDAR data was converted to DEMs and depressions in the study area were identified using various tools, not all known depressions were identified. To get more accurate data points, LiDAR should be shot at lower elevations with a higher density of points. For the study area, LiDAR was converted to 1.5 m resolution DEMs so anything smaller than 1.5 m could not be seen with the data. After all sinks in the watershed were found, two density maps were made to show the distribution of karst features in the study area. The “before” density map showed a higher density of sinks in the northern area of the Salado Creek Watershed which closely correlated with streams. Before the second density map was made, sinks had to be removed that correlated with man-made features like roads, quarries, stock ponds, etc. These were digitized and buffered to a certain extent and sinks that fell within these buffers were removed. The “after” density map also showed a higher density in the northern area of the watershed. There were also some density trends in the central portion of the watershed and along the watershed boundary. The central trend is possibly due to the difference in resolution of LiDAR between Bell and Williamson Counties. The clusters along the watershed boundary are likely related to karst. On the northwestern boundary dissolution and karst is related to the water table divide where there are two directions of flowing water. The northeastern cluster correlates with the town of Salado and Salado Springs and karst development is due to the spring discharge and Balcones Faulting. The
smaller areas of likely development within the watershed could be the packstone facies that promoted cave development and are near surface so they reflect greater solutional development.

The slope tool was used to determine areas where slope exceeds 45° which would be areas of possible shelter cave development. Areas found with higher slopes tend to correlate with the streams running through the watershed and there were no unusual patterns found in the study area.

Three caves and seven shelter caves on Critchfield Ranch were entered and surveyed. Speleogenetic history began pre-Balcones faulting, with early vuggy porosity infilled with dogtooth spar that occurred during deep-seated, mesogenetic diagenesis. With the onset of Balcones faulting, fractures in the rock and fracture porosity developed throughout Edwards strata during telogenetic diagenesis, which was coupled with change in local and regional hydraulic gradient. This established new flow paths within the Edwards Formation which facilitated karst development. Within the Salado Creek watershed, cavernous and touching-vug porosity were primarily developed in phreatic conditions when the Edwards Aquifer water table was higher. As lowering of base level took place, caves investigated in this study were placed above the water table and speleogenesis transitioned into vadose conditions as observed with shaft development, void collapse and secondary mineralization. With the incision of Salado Creek, shelter caves formed by backflooding
processes and the lowering of spring discharge points. As surface denudation continues, void collapse and soil infilling continue resulting in near-complete destruction of cavernous zones as seen in Buzzard Roost Cave. It is probable that new horizons of phreatic caves are currently developing beneath the water table in the contemporaneous environment in conjunction with long flow paths coupled to Salado Spring discharge. As the region continues to evolve, the karst of the Salado Creek Watershed will continue to evolve with it.

Future Studies

To better understand the speleogenetic evolution of the Salado Creek Watershed, more data within the extent of the watershed are needed, specifically more detailed studies like this one on additional private ranches throughout the area. Additional stratigraphic analyses should be conducted to better correlate the stratigraphy of the area and attain a more thorough understanding of the facies and depositional environments in the northern extent of the Edwards Aquifer system. More in-depth geochemical analyses of springs in the watershed, including sampling from spatially distributed springs with temporal monitoring should be conducted to provide a better understanding the hydrogeochemistry. A study should be conducted that correlates the accuracy of LiDAR analyses within the watershed beyond Critchfield Ranch to evaluate the accuracy of the LiDAR. Finally, expansion of mapping of karst features to the entire Salado Creek
Watershed would be useful in understanding not only the karst but their relationship with the groundwater in the aquifer. These recommended future studies will require access and permission to conduct research on private properties throughout the Salado Creek watershed; therefore, it is probable that the most efficient way to expand this study into future projects is to continue to conduct additional site-specific karst studies throughout the region where land access can be attained. Over time, these projects would provide data that could be combined to refine the speleogenetic and hydrogeochemical models of the Salado Creek watershed.
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