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Structural Control of Mesic Vegetation Communities within the Owl and Bear Creek Watersheds, Fort Hood Military Installation, Texas

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Abstract

The Fort Hood Military Installation is a karst landscape, dominated by Lower Cretaceous carbonates of the Trinity and Fredericksburg groups. The study area is the northeastern peninsula known as the Owl Mountain Province, utilized by the U.S. Army for troop maneuvers and training. The geomorphic evolution of the province has been controlled by the structural development of incised canyons in the Owl and Bear creek watersheds, following the deformational trend of the Balcones/Ouachita fault system and the transverse Belton High-Central Texas Reef Trend. These trends control cave development in the subsurface, karst manifestations at the surface, joints in outcrop, stream orientation, and vegetation associations. Previous transect vegetation surveys identified nine discrete areas of *Acer grandidentatum* habitat confined to mesic slot canyons in the watersheds. Traditional vegetation modeling has relied heavily on slope and aspect as key elements controlling ecological associations and soil moisture; in karst landscapes, permeability and solutional widening of conduits formed by local and regional deformation events can influence the location and ecological stability of these vegetation communities. Orientation trends derived from geologic mapping and spatial analyses of this karst landscape support the hypothesis that regional deformation events have exerted structural control on the relict mesic vegetation population.

Keywords: bigtooth maple, karst, geomorphology, carbonates, lineaments

1. Introduction

The Owl and Bear creek watersheds are located within the Owl Mountain Province, the northeastern section of the Fort Hood Military Installation in Central Texas (Figure 1).

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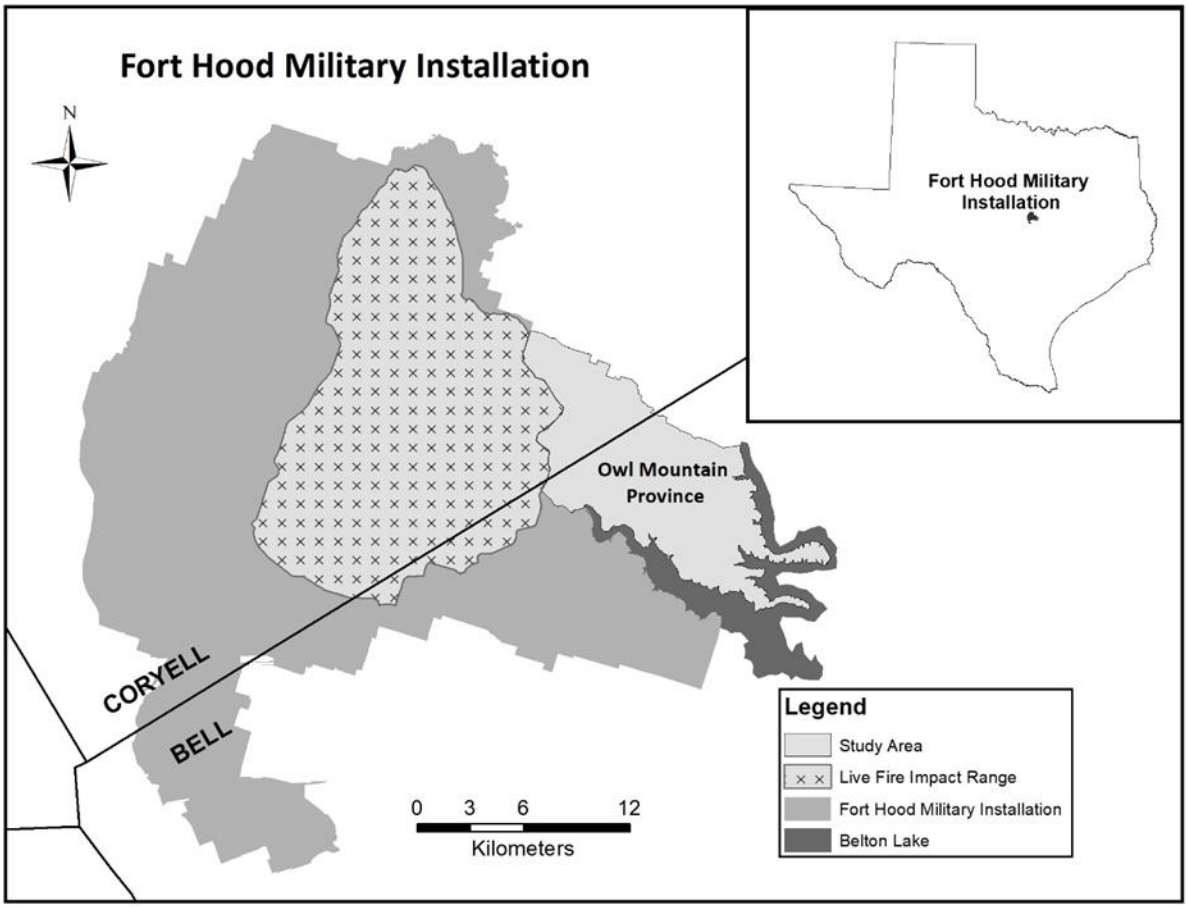

Figure 1. Owl Mountain Province is the northeastern peninsula of Fort Hood Military Installation. The area is used for troop maneuvers and training, as well as endangered species habitat and grazing acreage.

The landscape and its topography are largely controlled by the structural deformation and erosional behavior of the Lower Cretaceous limestones and marls of the Fredericksburg Group, namely the Comanche Peak and Edwards formations (Figure 2). The Edwards caps the plateaus while the lower permeability of the Comanche Peak forces ascending fluids to flow laterally and discharge as springs, incising slot canyons into the steep sided scarps. The creeks and their tributaries provide intermittent surface flow responsible for down cutting and incision of the karst plateau, with the Bear Creek watershed creating a solutionally-widened valley that dissects the uplands and the Owl Creek watershed defining the northern extent of the installation.

The structural evolution of the Owl Mountain Province has influenced the formation of the slot canyons that host mesic vegetation (Figure 2)that follow the major regional deformational trends from the Balcones/Ouachita lineaments, as well as transverse lineaments from the Belton High-Central Texas ReefTrend. These lineaments provide conduits for deep-seated fluids to rise along solutionally-widened flow paths to augment meteoric waters feeding surface streams and subaerial springs and seeps. Continued erosion along these deformational trends has created mesic slot canyons in varying orientations where forest species that grow best in cool, moist habitats continue to thrive. Within the Owl and Bear creek watersheds (Figure 2), disjunct populations of bigtooth maple (*Acer grandidentatum*), exist as Pleistocene relicts, isolated from larger populations by several hundred miles (Riskin and Diamond 1986). Bigtooth maple is a small, deciduous hardwood tree indigenous to North America existing as a continuous population in the intermountain regions of the western United States from southern Idaho through the Wasatch Mountains of Utah (Tollefson 2006).

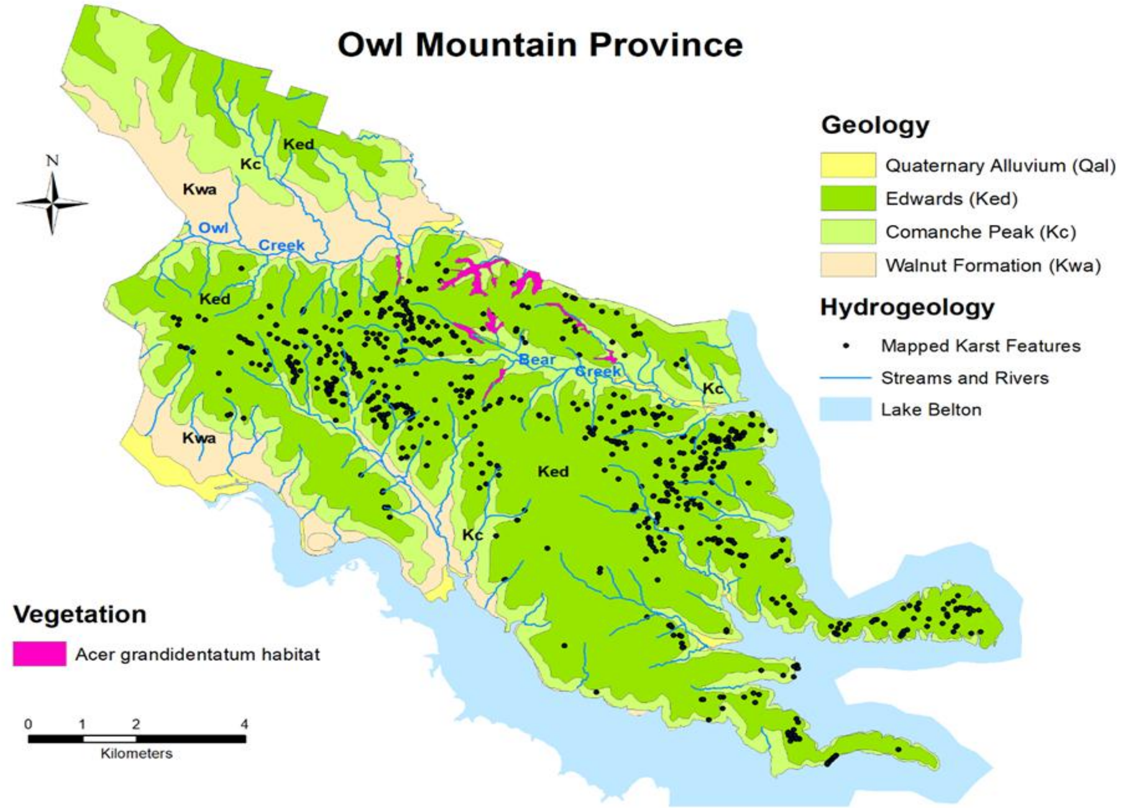

Figure 2. Geology and geomorphic features of the Owl Mountain Province. Ongoing geologic mapping and karst inventories provide information about caves, shelters, springs, seeps, and sinkholes (Geology from the Geologic Database of Texas, Texas Natural Resources Information System, accessed October 2018; karst features from Reddell *et al.* 2011; vegetation inventory from Fort Hood Natural Resources Management Branch Vegetation Survey by Hammer 2011.)

The geographic range spans almost 18° of latitude, varies greatly within elevation limits, and occurs on both xeric and mesic sites. Traditional vegetation modeling has relied heavily on slope and aspect as key elements of ecological associations and indicators of soil moisture. Within the Owl and Bear creek watersheds, the geomorphic evolution of the Owl Mountain Province has been controlled by the structural development along the Balcones/Ouachita deformation trend and the transverse Belton High-Central Texas Reef Trend (Figure 3). These trends control cave development in the subsurface, joints in outcrop, karst manifestations at the surface, stream segment orientation, and the general transmission of ascending fluids in the study area. While many of the springs in the study area are fed by meteoric waters (Faulkner *et al.* 2018), these incised canyons also receive fluids from deeper seated phreatic and/or hypogene fluids which emerge as ephemeral springs and seeps to augment soil moisture.

For the purposes of this paper, a lineament is defined as a surface expression of fracturing represented by alignments of topography and drainage, linear trends in vegetation associations, and the truncation of rock outcrops. Lineaments are often perceived in remotely-sensed images as reliable indicators of geologic structures, with patterns that are linear, continuous, reasonably well expressed, measurable, and related to natural earth features. In karst terrains, lineaments can also be indicative of secondary porosity, with the potential to supply reliable quantities of water from the subsurface in areas where surface water is limited. Lineaments can also be measured in outcrop associated with geologic mapping and in the subsurface by cave mapping.

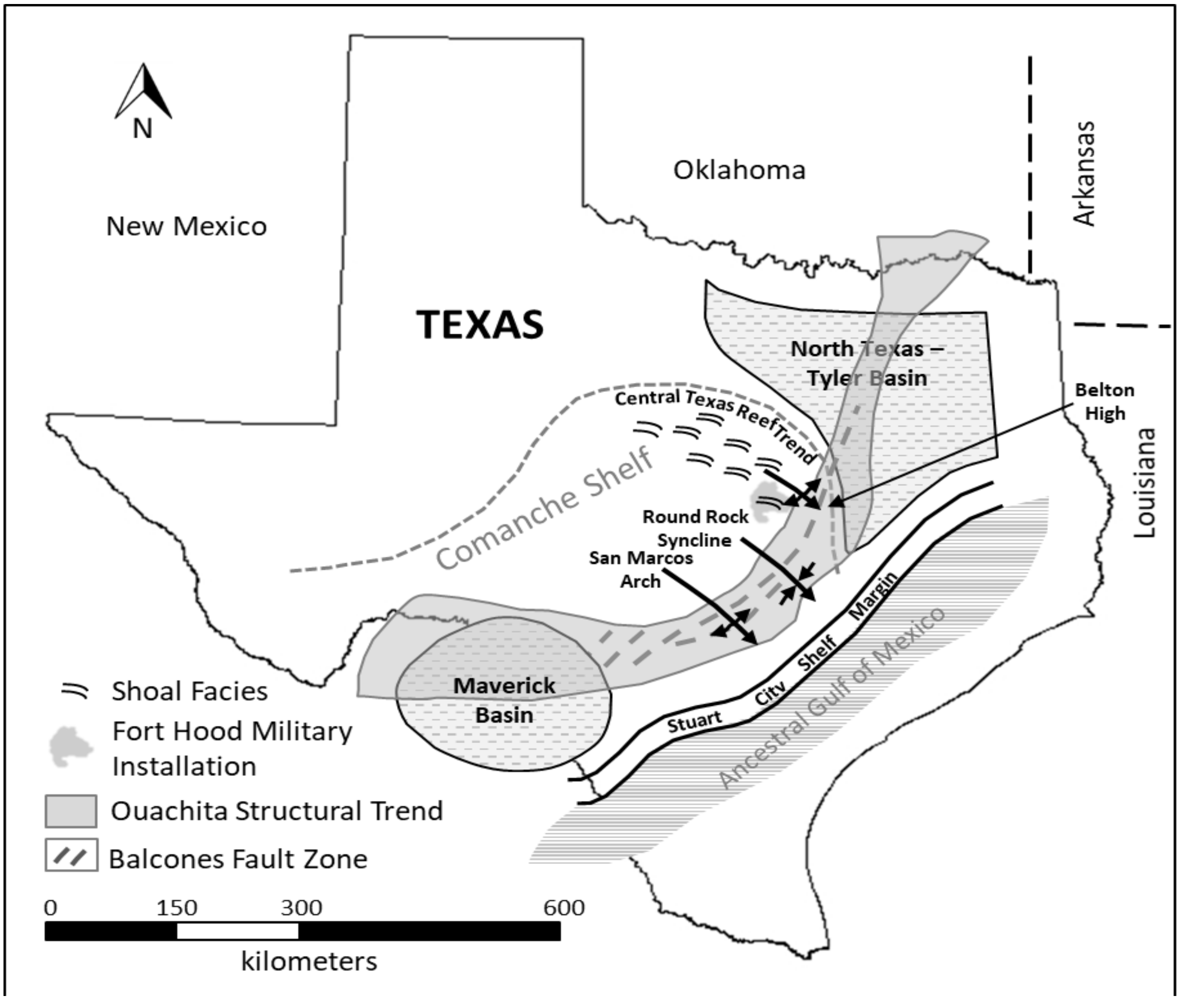

Figure 3. Location map showing major structural trends influencing strata in the Central Texas region. Shoal facies such as the Owl Mountain Province were formed south of the Central Texas Reef Trend across the axis of the Belton High (modified from Anaya and Jones 2009; Walker 1979; Fisher and Rodda 1969).

2. Study Area

The study area is the eastern peninsula of Fort Hood known as the Owl Mountain Province and is bounded by Owl Creek to the north, Belton Lake to the east, Cowhouse Creek to the south, and the Live Fire Impact Range to the west (Figure 1). The province is utilized by theU.S. Army for troop maneuvers and training; some parts have been extensively modified by training exercises and road construction, while more remote areas are set aside as grazing land, endangered species habitat, and recreational areas for military families (Pekins 2012; Hammer 2011; Hayden *et al.* 2001).

Within the study area, the Walnut, Comanche Peak, and Edwards carbonates crop out at the surface (Barnes 1970; Figure 2). The lower valleys along creeks and rivers have deeper soils and more dense vegetation with few prominent exposures of the Walnut; most are highly weathered and covered by thin veneers of soil (Faulkner and Bryant 2015). The Comanche Peak outcrops are exposed along the base of the plateaus, inter-fingering with exposures of the Edwards (Bryant 2012; Shaw 2012). Across the top of the plateaus, the Edwards forms the caprock and varies from rudistid-rich grainstone, oolitic and peloidal packstone, vuggy and porous wackestone, to mudstone outcrops. These strata, formed across the western flank of the Belton High (Figure 3), follow the model presented for shoaling facies associated with the Moffatt Mound model and the Central Texas Reef Trend (Faulkner and Bryant 2018; Bryant 2012; Amsbury *et al.* 1984; Brown 1975).

The Moffatt Mound area and the Owl Mountain Province consist of thicker, more well-defined outcrops of Edwards Group strata that are lithologically distinct from the Edwards units to the south. These strata formed in more restricted circulation waters with variations in water depth as the main control for differences in lithology of outcrops (Bryant 2012; Faulkner 2016).

Vegetation in the study area is characterized as a mix of evergreen savanna, upland deciduous, and lowland riparian plant communities (Riskin and Diamond 1986; Figure 4). On the more xeric uplands, vegetation communities contain biotic contributions from the dry plateaus and massifs of northern Mexico and Trans-Pecos Texas (Mecke 1996). In more open areas, where disturbance to the landscape is severe and water potential is limited, *Juniperusashei* has encroached and dominates the floristic composition (Querejeta *et al.* 2007; Diamond 1997). Upland soils of the plateau and slopes are shallow (< 30 cm) and have generally developed in place, forming over limestone bedrock of the Edwards Group (Fowler and Simmons 2008).

Habitats of mesic, dissected portions of the study area are strongly influenced by floristic contributions from eastern deciduous forests. Steep slopes of the province support short-stature woodlands which vary from *J. ashei, Quercus sinuate,* and *Quercusbuckleyi* on xeric sites to deciduous mixed-oak hardwood woodlands on mesic sites, including isolated populations of *A. grandidentatum* (Ludeke *et al.* 2005; Gehlbach and Gardner 1983). Alluvial soils of the lower elevations developed over marls and clays, and become thicker proximal to streams and rivers (Picinich 2011). Climate of the Owl Mountain Province is sub-humid to sub-arid and historical precipitation averages fluctuate between 65 and 75 cm per year. Summer temperature highs and lows do not vary significantly and average 35° C and 22°C, respectively. Average minimum January temperatures range from approximately 4°C to 0°C (Larkin and Bomar 1983).

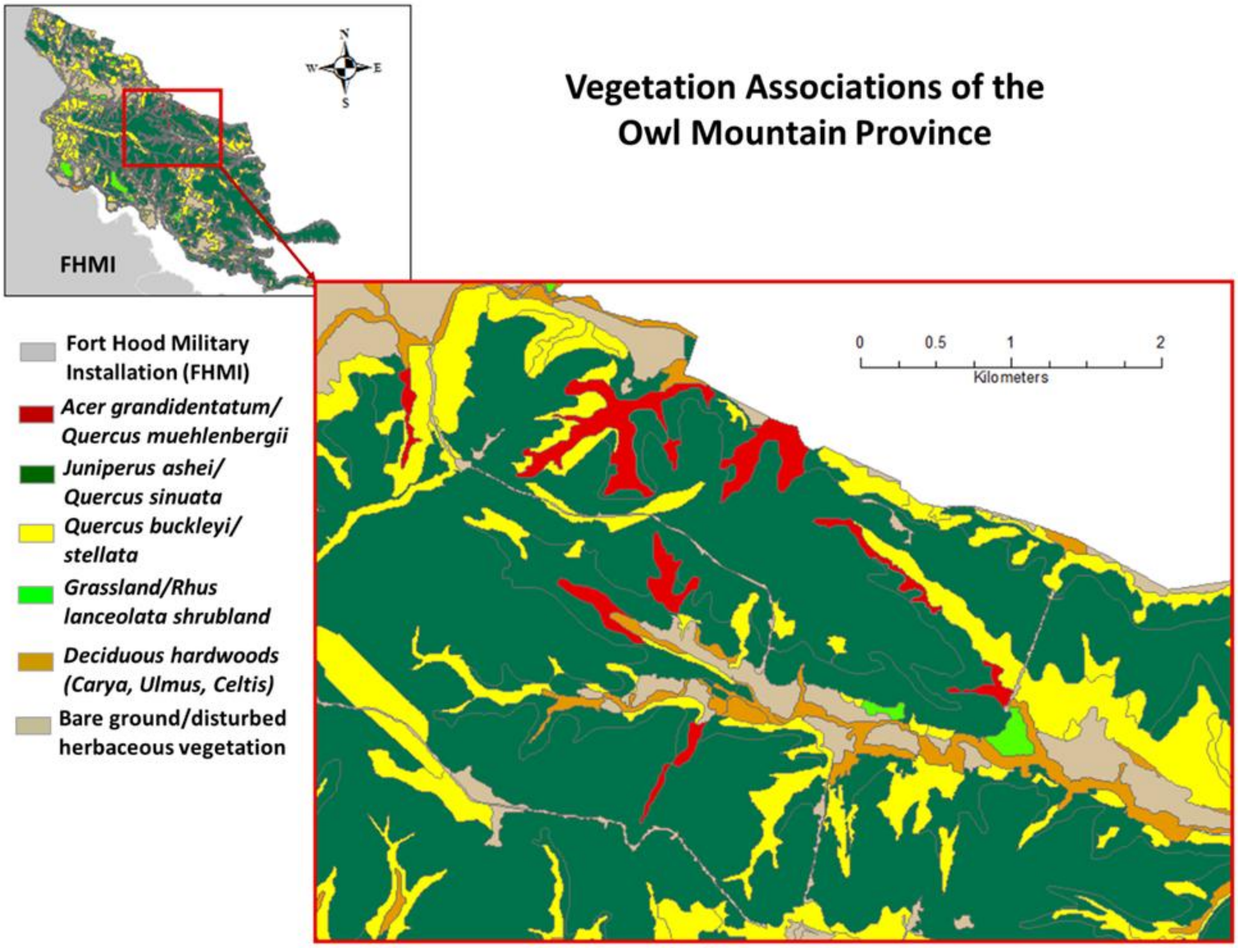

Figure 4. Generalized vegetation associations found in the Owl Mountain Province (modified from Hammer 2011; Teagueand Reemts2007).

3. Geologic and Structural Evolution of Owl Mountain Province

The Owl Mountain Province is dominated by thick sequences of Lower Cretaceous Comanchean Series carbonates fromthe Fredericksburg Group (Figure 2), deposited as part of major sedimentary sequences during the Zuni transgression. Edwards and Comanche Peak strata formed as shoal deposits on the northeastern Comanche Shelfsheltered by the Stuart City Shelf Marginto the southeast and the Central Texas Reef Trend to the north (Faulkner *et al.* 2013; Figure 3). The Comanche Platform was bounded on the east and south by a relatively deep-water oceanic basin, the ancestral Gulf of Mexico, and on the north and west by the North Texas-Tyler basin, an extensive marine basin which represents the deeper, back reef marine shelf facies (Nelson 1973; Fisher and Rodda 1969).

The Balcones/Ouachita structural trend is one of the major features influencing the Owl Mountain Province (Culotta *et al.* 1992; Caran *et al.* 1982; Figure 3). The Ouachita trend was the result of a major orogenic event as Gondwana and Laurentia collided during Mississippian and Pennsylvanian time, initiating the eventual formation of Pangaea near the end of the Paleozoic (Garrison 2005).Today, most geologic evidence of this trend lies in the subsurface of central and north Texas as part of the Ouachita fold-thrust belt. The belt is approximately 2100 kilometers and extends from the subsurface of Mississippi to the Marathon region of West Texas (Caran *et al.* 1982). The result of this collision was a suite of stacked, folded, and imbricated Paleozoic lithofacies that separated the North American craton on the north and west from the down warping Gulf of Mexico Basin on the south and east (Flawn*et al.*1961). This tectonic boundary has remained structurally active through most of the Phanerozoic, influencing deposition and structural deformation along most of the southern margin of the continental craton (Caran *et al.* 1982).

The Ouachita orogenic belt began to subside in Mesozoic time, coincident with the Zuni transgression that controlled deposition during the Cretaceous (McCann 2012; Rose 1972).By the end of the Cretaceous, a thick marine carbonate sequence covered most of the Ouachita System in Central Texas and the initial Gulf of Mexico basin existed to the southeast (Figure 3). Final shaping of the Gulf of Mexico occurred during the Laramide orogeny, as peninsular Mexico was transported eastward forming the Sierra Madres and constricting circulation in the Gulf (Caran *et al.* 1982). Uplift in the region provided clastic sediments from the interior of Texas for the extending Gulf Coastal plain (Hayward *et al.* 1990).

By Miocene time, the second principal component of the trend, the Balcones Fault Zone, had been superimposed on the Ouachita deformation zone (Faulkner and Bryant 2018; Ferrill and Morris 2008; Caran *et al.* 1982; Figure 3). Balcones (also the Luling,Mexia, and Talco) fault zones extend as an arcuate belt of *en echelon* normal faults from Del Rio to Dallaswith the Mexia/Talco fault zone extending into eastern Texas, displacing the Mesozoic to lower Paleocene section above the Ouachita System subcrop. Recent faulting (between 24 and 5 mya) initiated the uplift and subsequent dissection of the Lower Cretaceous strata (Caran *et al.* 1982).Most of the displacement is believed to have occurred in the late Oligocene or early Miocene as evidenced by the abundance of reworked Cretaceous fossils and limestone fragments in the fluvial sandstones created down-dip of the major fault trends (Adkins and Arick 1930; Ferrill and Morris 2008). There is some evidence for both earlier movement (late Cretaceous) along faults within this zone and perhaps later movement during the Pliocene, but the evidence is inconclusive at present. These major normal faults generally strike N/NE parallel to the Ouachita structural grain and dip from 40^0 to 80^0 (Ferrill and Morris 2008). The net throw across the fault zone is down toward the southeast, although faults dip both east and west (Senger*et al.* 1990). The subsurface Ouachita structures acted as a hinge for downwarping into the ancestral Gulf of Mexico (Caran *et al* 1982). This downwarping, along with upward flexing of the continental interior west of the Balcones/Ouachita trend, continued throughout the Cenozoic.

Structural deformation transverse to the Balcones/Ouachita trend appears to coincide with structural features known primarily from subsurface data such as platforms and undulations in the strata that mimic anticlinal and synclinal structures. The San Marcos Arch, Round Rock Syncline, and Belton High trend are three such features that represent undulation and thickening in Cretaceous lithofacies (Culotta *et al.* 1992; Caran *et al.* 1982; Figure 3).Shoal facies of the Owl Mountain Province are northwesterly trending areas on the flank of the Belton High in which the Edwards exhibits increased thickness and lithology changes; these areas indicate local, high-energy shoaling adjacent to a shallow marine shelf sequence (Faulkner and Bryant 2018; Bryant 2012; Amsbury *et al.* 1984; Brown 1975).

4. Hydrogeology

The Fort Hood Military Installation is underlain by the Trinity and Edwards aquifers, with both receiving surficial recharge from meteoric water (Anaya and Jones 2009; Jones 2003) within the installation boundary. Aerial exposure of the Glen Rose occurs across the western portion of the base, where the Trinity Aquifer receives direct recharge from precipitation (Faulkner *et al.* 2018; Faulkner and Bryant 2015). In the Owl Mountain Province, exposures of the Fredericksburg Group limestones and marls receive direct recharge from meteoric waters via sinkholes, joints, and other karst manifestations exposed by surface denudation and dissolution (Faulkner *et al.* 2013). Both aquifers are instrumental in providing base flow for perennial and intermittent streams, as well as springs and seeps in the study area.

Topography is dominated by plateaued drainage divides capped by resistant Edwards limestone and bordered by steep scarps exposing the interfingering relationship of the Comanche Peak and Edwards (Faulkner and Bryant 2018; Bryant 2012; Amsbury *et al.* 1984; Brown 1975; Figure 5). As a result, permeability varies greatly across the study area with regions where these units interfinger typically having lower permeabilities than areas dominated by only Edwardsstrata(Walker 1979). Groundwater discharges at the surface where Edwards strata crops out or where a gradational facies between Edwards and Comanche Peak formations has sufficient permeability to transmit fluids (Faulkner *et al.* 2018). Surface drainage of the Owl Mountain inland is performed by numerous unnamed ephemeral creeks and streams; larger streams such as Owl and Bear creeks flow directly into Belton Lake when sufficient surface water is available (Figure 2). As is common in this type of topography and climate, many stream segments will flow intermittently as water transmits between the surface and subsurface.

5. Karst Manifestations

The level of karst development within the study area is controlled primarily by lithology; where the Edwards Group is exposed to meteoric influences, surficial karst manifestations are more pronounced. Many of the sub-surface karst features are fracture controlled, correlating well with both local and regional tectonic trends, with macro porosity development controlled by lithologic and permeability boundaries within and between contacts of the Comanche Peak and Edwards units (Faulkner and Bryant 2018; Bryant 2012).

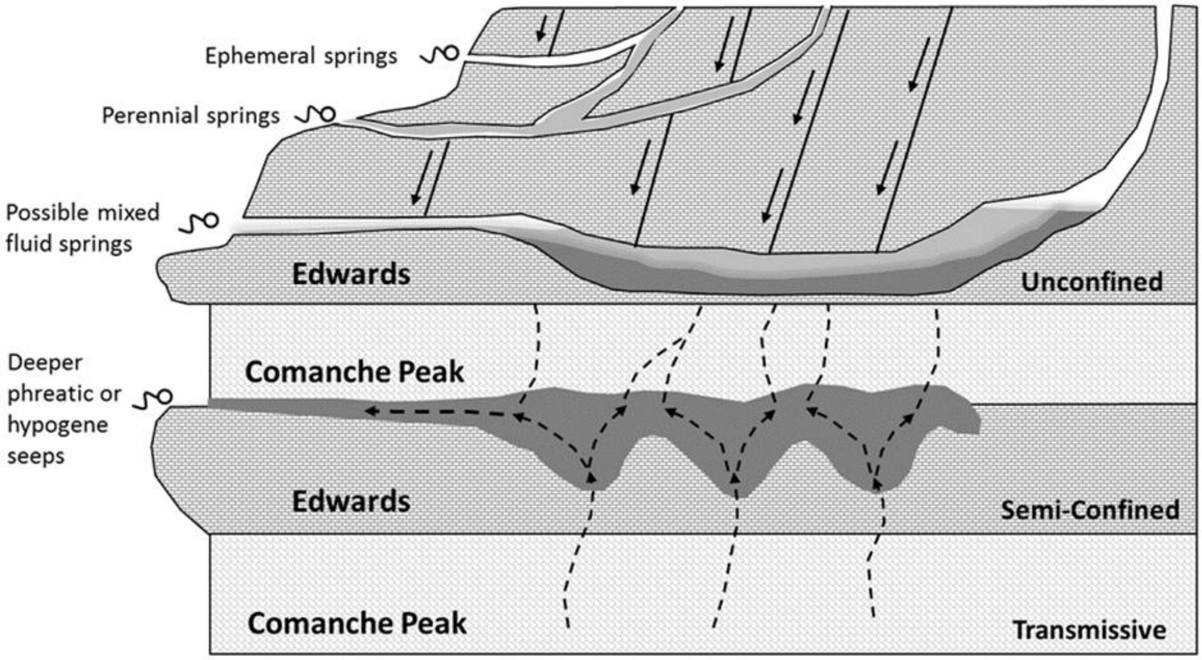

Figure 5. Hydrogeologic model of Owl Mountain Province. Many mesic vegetation sites exhibit no surface flow; these sites are maintained by phreatic and/or hypogenic water resources that maintain soil moisture (Faulkner 2016).

Regional uplift of the Edwards Group associated with the Laramide orogeny resulted in exposure and partial erosion of these units, increasing secondary porosity and tilting strata to the southeast. During the Miocene, faulting and subsequent uplift along the Balcones initiated development of incised drainage systems and as erosion exposed the Lower Cretaceous strata, the intersection of fracture conduits with stream base level helped widen cavities and develop spring discharge outlets. Some karst development is controlled by bedding planes with springs, seeps, and rock shelters developing along the interface of lithological contacts between the Comanche Peak and Edwards units. To date, surface mapping by the Fort Hood Natural Resources Management Branch, Faulkner (2013), Bryant (2012), Reddell *et al.* (2011) and others have identified over 300 caves, 80 springs, 803 sinks and 491 shelter caves across the entire military installation (Figure 2).

Most of the karst features identified within Fort Hood are coupled to the surface and exhibit solutional widening and overprinting by meteoric waters. Sinkholes and cave entrances are often small and associated drainage basins are spatially limited, generally covering less than one hundred square meters in area. In the study area, many sinkholes and cave entrances appear to have formed as upward stoping collapse structures and/or features that have been breached by surficial denudation (Faulkner and Bryant 2018; Faulkner *et al.* 2013; Bryant 2012). Cave development is commonly associated with high-angle scarps truncated by abrupt, eroded edges of the plateaus in the eastern portion.

6. Methodology

For the purposes of this study, a 1m Digital Elevation Model derived from LiDAR captured in March of 2009 was used as a base map (Pekins 2012). These data, and the color infrared image (Figure 6A), were obtained from the Fort Hood Natural Resource Management Branch.

The bare earth LAS files were used to build adigital terrain model and converted into raster format to perform cell-by-cell calculations. The horizontal (1.1 m) and vertical accuracy (27.52 cm) of the DEM were derived in accordance with the ASPRS Guidelines for Vertical Accuracy Reporting for LiDAR Data (Flood, 2004). The DEM was used to derive a hillshade (Figure 6B) and slope raster (Figure 6C)for lineament analysis. The fill-difference method from the hydrology tool was used to create a shape file of karst depression which were then filtered and classified by their spatial attributes to remove depressions associated with natural (stream channels, water bodies) and anthropogenic (road building, engineered drainage, military training sites) activities, providing an initial database of 1,539 potential karst sinks. Sinks that exhibited circularity were removed from the databases as their orientation could not be determined; after filtering, the major and minor axes of the remaining 718 elliptical sinks (Figure 6D) were used to determine their orientation relationship to regional structural features. Stream segments were delineated for the study area through the creation and classification of a flow accumulation raster and the zonal geometry tool was used to determine stream segment orientation in 5m increments, yielding 755 measurements.

Because the land surface in the Owl Mountain Province has been heavily modified by road building and troop maneuvers, satellite imagery and terrain models were not as useful for determining some lineament patterns and trends. In order to augment the lineament trends derived by the digitized surface, three additional data sets were analyzed: 1) joint trends in outcrop from geologic mapping; 2) subsurface joint measurements from Texas Speleological Society cave surveys from Bell and Coryell counties; and 3) the orientation of established mesic vegetation communities, using the presence of bigtooth maple as a proxy for subsurface lineaments and potential water resources.

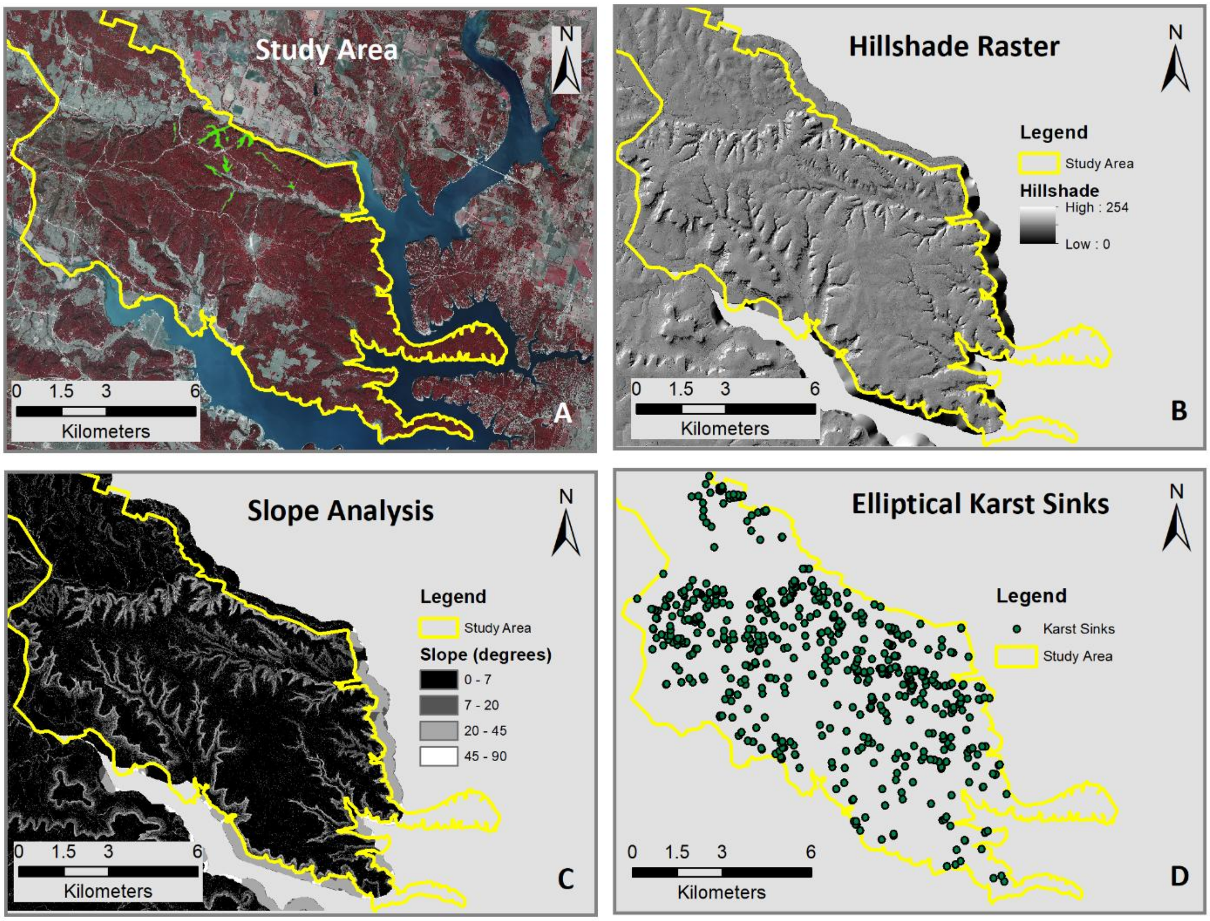

Figure 6. ArcGIS models of the study area were processed to determine structural features: the color infrared image (A) was provided by the Fort Hood Natural Resources Management Branch; the 1m DEM derived from LiDAR was used to calculate a hillshade raster at azimuth 315 and inclination of 45 degrees above the horizon (B); slope analysis (C); and delineate potential elliptical karst sinks (D). The landscape has been heavily modified by military activities; therefore, it was difficult to filter some anthropogenic modifications. The eastern peninsulas of the Owl Mountain Province are in a no-fly zone; therefore, no LiDAR data was collected or processed for this area.

Geologic mapping in the study area yielded 619 joint trends measured in outcrop and along the shoreline of Belton Lake. These measurements were collected from September 2011 through February 2015 during sample collection and facies analyses (Faulkner 2017).The Texas Speleological Survey(2014) cave survey data base was mined for joint trends recorded from cave mapping in Bell and Coryell counties. These measurements were weighted according to length in 5m increments, with greater weight being assigned to longer and more extensive subsurface jointing, yielding 1,267 joint measurements. Finally, the vegetation map provided by the Fort Hood Natural Resources Management Branch was used to isolate the vegetation polygons designated as *A. grandidentatum* habitat (Pekins 2012; Hammer 2011; Hayden *et al.* 2001; Figures 2 and 4). Major orientations of each polygon were measured, yielding 43 measurements. Rose diagrams were created for each data set to determine the similarities and differences between lineament orientations. Finally, lineament trends were compared to known regional trends from the Balcones/Ouachita deformation events and the Belton High-Central Texas Reef Trend.

7. Lineament Analyses

The nearest surficial expression of the Balcones/Ouachita trend occurs seven kilometers east of the study area; at present there are no mapped faults in the Owl Mountain Province. The strike of these normal faults ranges from N0° to N40°Ewith the general trend of N22°E and net throw to the southeast (McCann 2012; Senger *et al.* 1990; Rose 1972; Figure 7).

The Belton High is a topographic positive that follows the Central Texas Reef Trend along the western edge of the North Texas/Tyler basin and separates the basin from the interior of the Comanche Shelf(Figure 3). Along this trend, thickened sequences of the Edwards formed isolated shoals of oolitic and peloidal packstones and grainstones indicative of local high energy environments (Faulkner 2016; Bryant 2012; Shaw 2012; Caran *et al.* 1982). The Belton High, Round Rock Syncline, and San Marcos Arch are mostly known through subsurface mapping and are thought to be topographic undulations on the Comanche Platform representing a more stable part of the shelf than the adjacent, rapidly subsiding areas of the Fort Worth-Tyler and Marathon basins (Caran *et al.* 1982). Following the general dip trend of the lithologies in the area, these structures plunge to the southeast.

Within the study area, development of joint sets in concert with regional deformation events is well documented from outcrop measurements and cave mapping performed as part of karst inventory of the Fort Hood Military Installation (Reddell *et al.* 2011). Other research such as sinkhole delineation (Faulkner *et al.* 2013) and facies analyses (Faulkner 2016; Bryant 2012) have provided a wealth of information about the evolution of the carbonate platform upon which the shoals of the Owl Mountain Province were deposited. Analyses of lineament measurements for each data set revealed two dominant trends; joint measurements, major sinkhole axes, and stream channel segments presented with a primary northeast/southwest trend concomitant with the regional Balcones/Ouachita trend (Figure 7). Caves and vegetation polygons followed a northwest/southeast trend associated with the Belton High-Central Texas Reef Trend (Figure 3). Each data set also reflected a secondary trend sub-perpendicular to their primary orientation. Joint measurements in outcrop appear to be more directly influenced by Balcones/Ouachita deformation, exhibiting a 0° to 25° azimuth trend, although the overall trends for this data set are more evenly distributed than many of the others (Figure 8A). Joints can form as a result of tensional movement perpendicular to the resultant fracture plane, or by unloading associated with erosional processes near the surface.

As this area was uplifted by initiation of Balcones faulting, the subsequent removal of Washita Group formations (Georgetown, Austin Chalk) and extension of the Gulf of Mexico could have created stress along the previously fractured Ouachita sediments, inducing joint creation along the Balcones/Ouachita trend. Even though the study area is to the west of the Balcones/ Ouachita trend (Figure 7) and no faults are known in the immediate study area, tensional stresses associated with sediment transport to the southeast and regional stress could have induced fractures in the Edwards and Comanche Peak. Today, these joints are also associated with karst features such as shelter caves, tafoni, tufa, sinks, and springs; indicating they function as a primary mechanism for fluid transport. Since the study area is underlain by both the Trinity and Edwards aquifers, ascending fluid pressure resulting from Balcones deformation could also provide a mechanism for joint trends seen at the surface (Faulkner *et al.* 2018).Secondary joint development along the Belton High-Central Texas Reef Trend indicates an azimuth trend of 285°, with most measurements falling between 270° and 295° (Figure 8A).

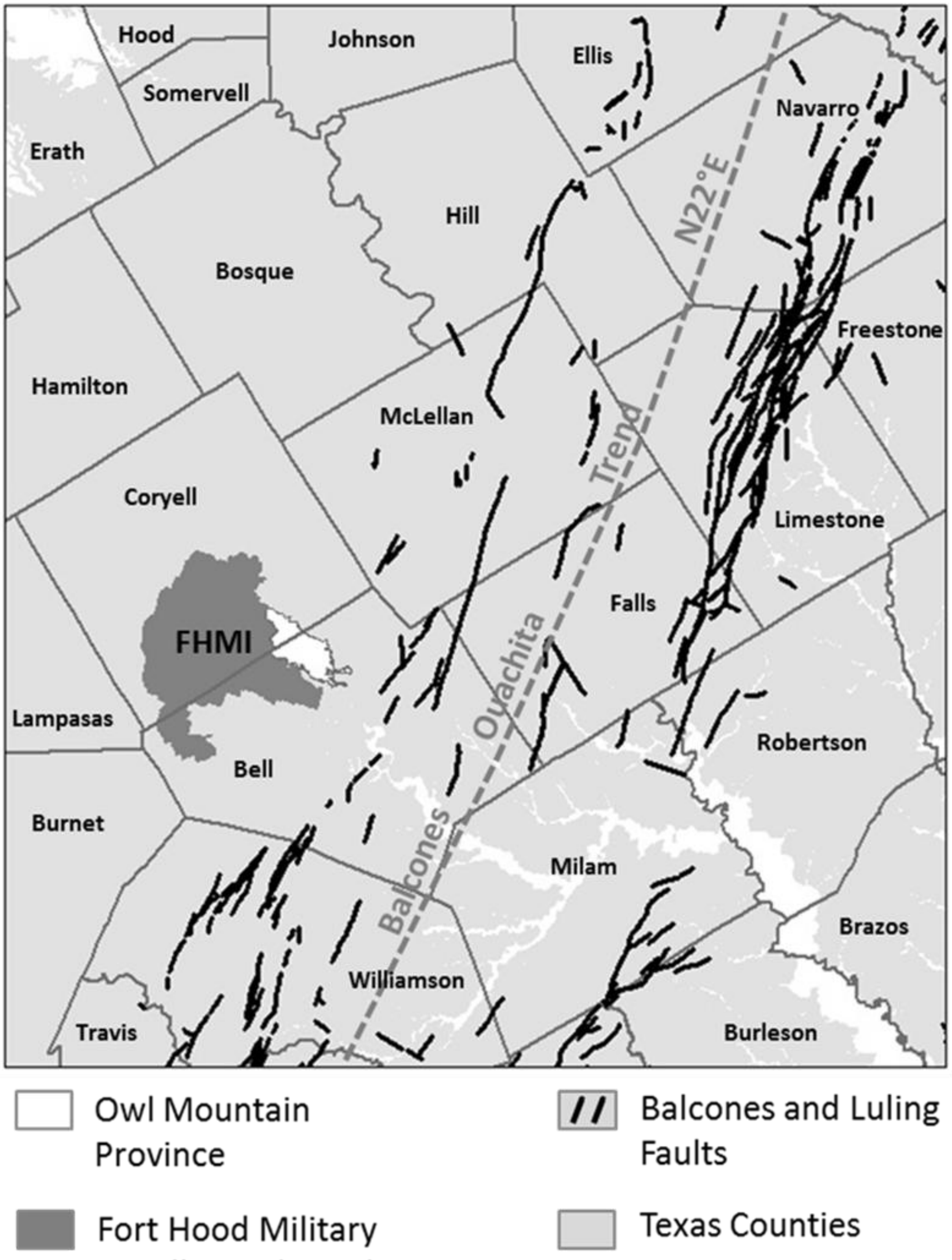

Figure 7. Balcones/Ouachita trend in North Central Texas. Balcones and Luling fault data from the Geologic Database of Texas, Texas Natural Resources Information System, accessed January 2016.

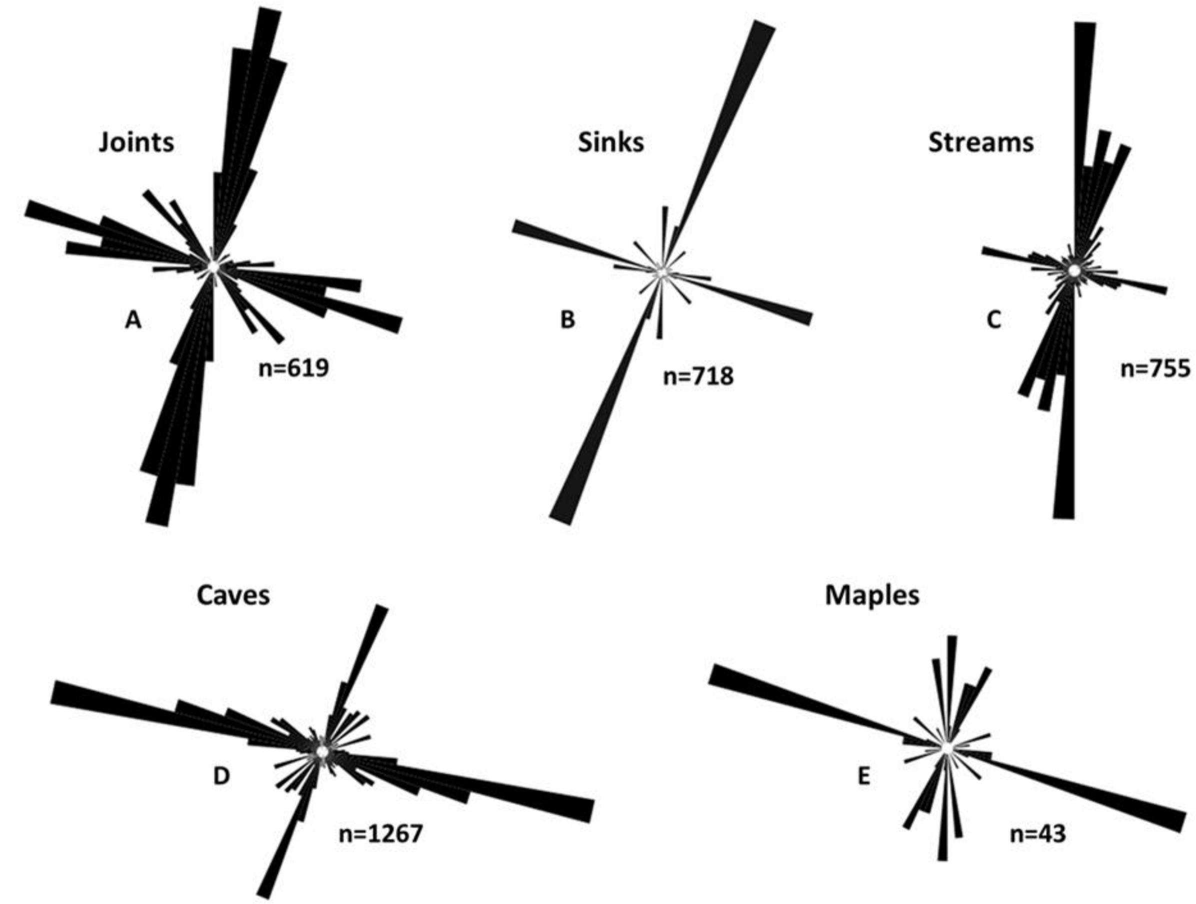

Figure 8. Major lineament trends for surface and subsurface deformation in the Owl Mountain Province. Joint measurements (A) were derived from geologic surface mapping; elliptical sink orientations (B) were derived from a 1m DEM used to delineate karst features in the study area; stream orientations (C) were derived from the flow accumulation raster processed in ArcGIS; cave measurements of major and minor axes (D) were mined from the Texas Speleological Survey database; and major orientation trends in established maple habitat (E) were measured from vegetation maps provided by the Fort Hood Natural Resources Management Branch.

Potential karst sinks were classified by geoanalytical methods and the orientation and asymmetry of each sink was calculated to determine their relationship to regional structural trends. Asymmetry calculations showed that 53.4% (n=821) of the depressions were symmetric; since their geometry does not support characterization of their primary orientation, these sinks were removed from consideration. The remaining 46.6% (n=718) exhibited an asymmetrical, elliptical geometry and may be associated with fracture controlled solutional widening and epikarstal processes (Figure 8B). The major and minoraxes orientations of these sinks appear to have been controlled by development of transmissive conduits along the deformational trend of the Balcones/Ouachita fault system (22°) and transverse Belton High-Central Texas Reef Trend (285°). These sinks also act as conduits for meteoric fluid into the subsurface, which can augment cave development in the subsurface and soil moisture in mesic vegetation communities.

Analyses of stream segment orientation within the study area shows that Balcones/Oauchita deformation also appears to exert a greater influence on channel orientation (Figure 8C), although their orientation may be influenced as much by the topography as regional deformation trends. Within the study area, incised valleys are created to the north and south of the plateaus capped by the resistant Edwards by short stream segments that flow into the Owl and Bear creek watersheds (Figure 2). These valleys are drained by larger creeks and streams that flow generally east and southeast, eventually draining into Belton Lake. These streams, with their tributaries, are responsible for most of the slope retreat and incision that has created the unique topography of the Owl Mountain Province.

The Owl and Bear creek watersheds are separated by drainage divides and characterized by steep slopes and scarps with interbedded exposures of the Edwards and Comanche Peak formations. Joints act as focal points for water ascending from below and descending from above, and as slope retreat intersects with ascending fluids, joints became solutionally-widened and began to function as ephemeral surface drainage (Klimchouk *et al.* 2012; Klimchouk and Ford 2009; Figure 9). The communication between the Trinity and Edwards aquifers and the surface also serves as a potentiometric driver for ascending fluids. Geochemical analyses of springs within the Owl Mountain Province indicate that most meteoric water transmits directly to the subsurface; today, many of these stream segments are mostly dry and experience intermittent flow for a few hours or days after precipitation events (Faulkner *et al.* 2018).

Cave measurements were determined to be more directly influenced by the Belton High-Central Texas Reef Trend, with many of cave maps showing a regional lineament trend between275° and 285° (Figure 8D). All of the known caves within the Fort Hood Military Installation occur in the Edwards Formation, or along permeability boundaries in the interbedded Comanche Peak and Edwards formations (Faulkner and Bryant 2018). Many of the caves in this area formed along conjugate joint sets in a semi-confined environment, both laterally and vertically. While the northwest lineament trend was dominant, many of the caves exhibited secondary development along the Balcones/Ouachita trend. Joints along this trend provided a planar surface for ascending fluids with solutional widening along these fractures continuing cave development along transmissive zones or bedding planes. Tensional stresses associated with faulting and focused along the axes of folds can have a similar effect by opening multiple conduits such that fluid migration is dispersed along various pathways as dissolution commences along the fracture planes (McCann 2012). Today, many karst features within the study area are predominantly surficial expressions of collapse features or features resulting from vadose entrenchment, creating windows into karst conduits. Slope retreat along scarps, stream incision, and surface denudation have exposed karst features formed along dissolution surfaces associated with fluid transmission (Faulkner *et al.*, 2013; Bryant, 2012, Figure 9). Secondary transmissivity along the Belton High-Central Texas Reef Trend probably exists as matrix porosity, particularly within interbedded Comanche Peak and Edwards carbonates as differences in permeability force ascending fluid laterally along the contacts (Figure 5). As shoals accumulated along this northwestern trend, restricted circulation along the Comanche Shelf would control facies development. As evidenced in oolitic and peloidal packstones and wackestones in the interfingering units, transmissivity between facies would be controlled by the shoaling trend to the northwest. This trend would in turn control subsurface porosity in the form of solutionally-widened conduits and cave development.

Lineament analyses of *A. grandidentatum* vegetation associations determined that the results were mixed. Twenty-one of the 43 lineaments (49%) aligned along the Balcones/Ouachita trend, 30% (13 of 43) were associated with the Belton High-Central Texas Reef Trend (Figure 8E). Based on transect vegetation surveys, designated maple habitat covers 71 hectares in the Owl Mountain Province, and is found within nine vegetation polygons mapped by the Nature Conservancy and Fort Hood Natural Resources Management Branch. These trees exist in sheltered,incised canyons and along the edges of the scarps in the Owl and Bear creek watersheds. Within these watersheds, bigtooth maple exists in regions of the installation that have been set aside as environmentally sensitive areas for wildlife habitat and nature preserves. Even though these populations exist within training areas for military exercises,

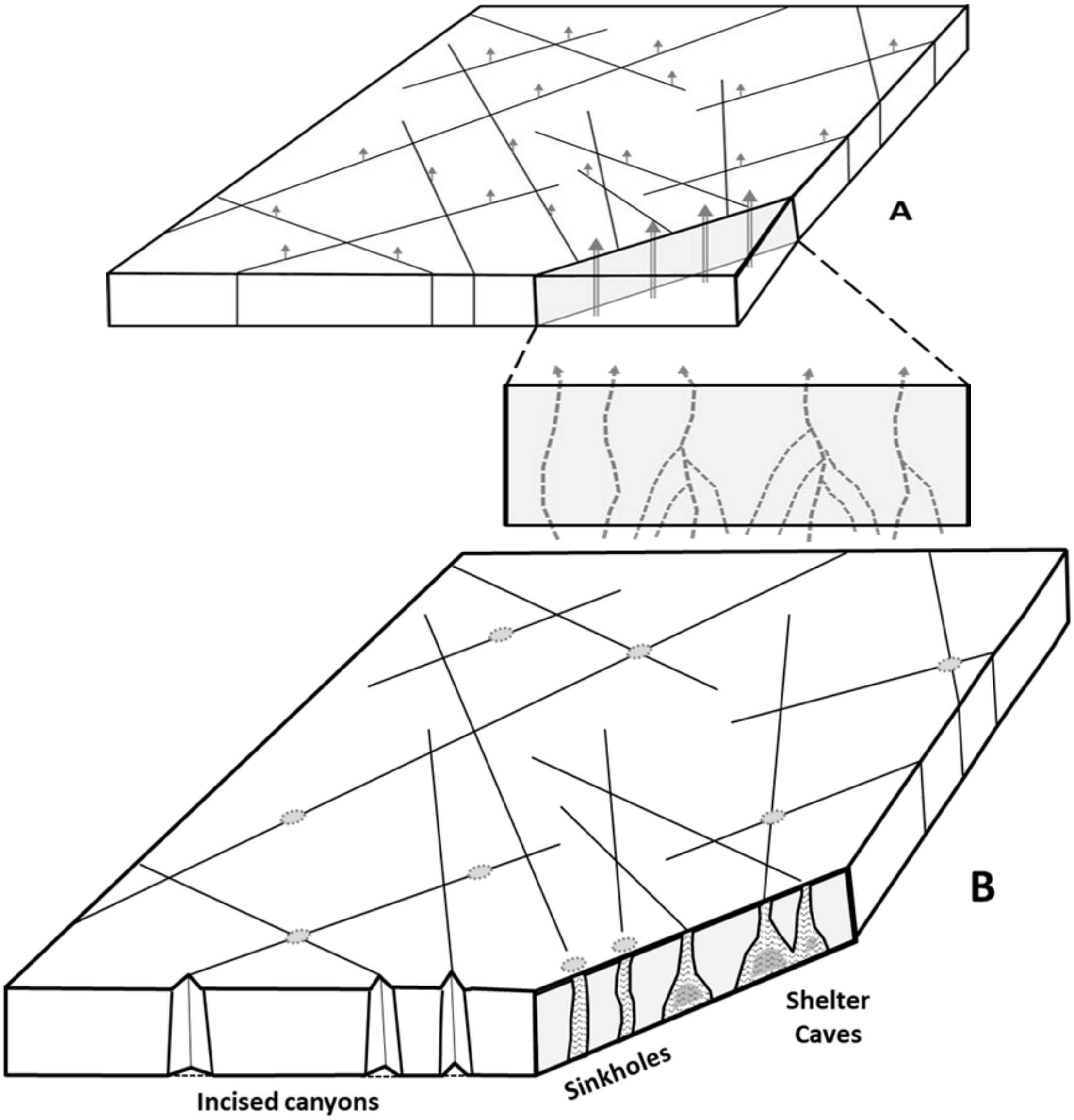

Figure 9. A conceptual model of phreatic/hypogenic fluid transport through conjugate joint sets in a semi-confined aquifer. Karst features develop along solutionally-widened conduits, influencing development of incised canyons for mesic vegetation and surficial karst features (modified from Klimchouk and Ford 2009).

The terrain is rugged and most of these populations are in remote areas of the base not generally visited by wheeled or tracked vehicles, or used for training exercises.

8. Mesic Vegetation Communities in the Owl Mountain Province

Bigtooth maple's life form in its continuous range is dependent upon moisture regime and varies greatly within elevation limits, occurring on both xeric and mesic sites. In canyon bottoms and along streams, trees with single or multiple trunks can grow up to 15m tall and 30cm in diameter (Tollefson 2006; Phillips and Ehleringer 1995). On dry canyon slopes, it grows primarily as a shrub with two or more stems reaching 8m tall. It often grows with Gambel oak (*Quercusgambelii*) either as co-dominant, or replacing Gambel oak in canyon bottoms and moister areas. On cooler sites, bigtooth maple may replace Gambel oak entirely, but further succession could lead to dominance by white fir (Tollefson 2006). Bigtooth maple can also be found as isolated populations at lower latitudes throughout the southwestern United States and into northern Mexico, including incised canyons within Fort Hood Military Installation (Tollefson 2006; Riskin and Diamond 1986; Gehlbach and Gardner 1983).

Some of these canyons are fed by short, ephemeral stream segments flowing north and south off plateaus, and by ascending fluids along joints following the Balcones/Ouachita trend (Figures 5 and 10). These fluids migrate through lower permeability zones of the Comanche Peak and are forced to flow laterally by confining units.

In the Owl Mountain Province, vegetation polygons have been mapped with Comanche Peak as the underlying lithology; at present, no springs or creeks flow through the incised canyons hosting maple vegetation (Figure 2). The Comanche Peak formation consists of nodular, fossiliferous limestone that has a dull chalky texture; porosity typically ranges from 1 to 8%, much less than the overlying Edwards. The lower permeability of the strata supports a deeper phreatic and/or hypogene source for moisture within these incised canyons, as meteoric water that falls on uplands is directed into the subsurface through karst features and emerges within the Edwards or along the Edwards and Comanche Peak boundary (Faulkner *et al.* 2018; Figure 5). Geochemical analyses of karst springs sampled from December 2012 through February 2015 support this hypothesis, spring chemistry showed a residence time between three and six months with water in the subsurface long enough to equilibrate with rock temperature (Faulkner *et al.* 2018). Calcium is enriched with respect to magnesium, indicating a shorter residence time and reflective of the lithology through which the water flows. Permeabilities within the Edwards favor discharge within the unit along scarps in Owl and Bear creek watersheds. Water discharging from the Comanche Peak at lower elevations within canyons is probably emerging from below along solutionally widened flow paths to augment soil moisture and support mesic vegetation (Figure 9).

Canyons with maple populations are oriented in a variety of aspects: north, northeast, southeast, and south, indicating that canyon aspect cannot be the only determining factor in maple survival. Most stream channels in these canyons do not exhibit base flow, rather they are fed by occasional precipitation events and springs and seeps that provide moisture to maintain these mesic sites. The springs and seeps follow the trend of dominant joint sets, which then exert structural control on the location and continued existence of these maple populations.

This species develops an extensive root system during the first growing season, with both lateral roots and a deep tap root (Alder *et al.* 1996). It is relatively tolerant of low soil water potentials, and can grow with oaks on drier, open slopes (Tollefson 2006; Correll and Johnston 1970). Roots are distributed throughout the soil profile but active sites of water absorption are in the deeper soil horizons. Recent studies (Phillips and Ehleringer 1995; Flanagan *et al.* 1992; Ehleringer *et al.* 1991; Donovan and Ehleringer 1991) indicate that a number of perennial plant species do not significantly utilize summer precipitation, rather these species, including bigtooth maple, rely on deep soil water that originates from winter recharge of the soil profile. Many species with large geographic ranges exhibit adaptations to local environments, including variations in morphology, gas exchange, and plant-water relations (Bsoulet et al. 2006). In Central Texas, where winter recharge from snowpack is non-existent, these trees likely rely on ascending fluids from deeper seated water tables and aquifers (Faulkner 2016).

Literature is somewhat lacking on the physiological attributes of these disjunct populations, but some parallels may be drawn between the stand dynamics of continuous and isolated populations. As they do in their continuous range, isolated populations of bigtooth maples within the Owl Mountain Province can exist on xeric and mesic sites as a shade tolerant, seral understory tree or shrub beneath Ashe juniper or a variety of oak species, and/or as co-dominant with other hardwoods such as pecan, sugarberry, elm, and oaks, particularly *Quercusmuehlenbergii* and *Quercusbuckleyi* (Hammer 2011; Teague and Reemts 2007) if sufficient water resources are available.

9. Summary and Conclusion

This study utilized a variety of methods to determine major structural deformation trends and their influence on the evolution of topography and mesic vegetation communities in the study area. Within the Owl and Bear creek watersheds, the geomorphic evolution of the Owl Mountain Province has been controlled by structural development of incised canyons along the Balcones/Ouachita deformation trend and the transverse Belton High-Central Texas Reef Trend. These trends control cave development, joints in outcrop, stream segment orientation, and general transmission of ascending fluids in the study area. While many springs in the study area are fed by meteoric waters, incised canyons also receive fluids from deeper seated phreatic and/or hypogene fluids which emerge as ephemeral springs and seeps to augment soil moisture.

Access to water in karst landscapes is often controlled by subsurface structural trends, and the Balcones/Ouachita trend appears to be the major conduit by which these mesic vegetation communities gain access to water resources.

In some cases, transverse, sub-vertical conduits have forced fluid flow between units, connecting ascending fluids with vadose waters. These features are exposed today along the scarps associated with the Edwards and Comanche Peak, often with several zones of karst features exposed along these cliff faces with interbedded exposures of these units (Figure 9).

Due to the multi-purpose land use of the Owl Mountain Province, the study area has been extensively modified by past and current military use, thus lineaments and other surface features related to military use cover most of the study area and must be taken into consideration when interpreting results. The combination of heavy military use and high resolution elevation data make it extremely difficult to discern between natural and anthropogenic lineaments; therefore models developed from LiDAR analyses at Fort Hood are assumed to have errors, both in the inclusion of anthropogenic lineaments and the exclusion of true structural features.

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