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The Wichita Paleoplain in Central Texas

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ABSTRACT

The Wichita Paleoplain (WPP) is the regional unconformity between Lower Cretaceous basal transgressive deposits and the Jurassic, Triassic, Paleozoic, and Precambrian rocks that lie immediately beneath them in the southwestern United States. This ancient buried erosion surface is here investigated and mapped in Central Texas at three levels of detail, applying principles derived from each phase to succeeding phases: (1) on the southeastern flank of the Llano Uplift in detail (phase one); (2) across the Llano Uplift and surroundings at intermediate detail (phase two); and (3) at regional scale throughout Central Texas, synthesizing work from many sources (phase three).

Over most of Central Texas, the WPP is a notably regular buried erosion surface with local relief of less than 100 feet. To the south, however, the Llano Uplift, which served as a structural buttress around which curved the Ouachita structural belt, experienced uplift and faulting related to the late Pennsylvanian Ouachita Orogeny, followed by a long period of weathering and erosion. There, vertical uplift of about 4500 feet and fault displacements of as much as 3000 feet characterize the tectonic effects of the Ouachita Orogeny. The WPP was present over all of that complex terrain. Local paleotopographic relief ranges up to about 400 feet in and around the Llano Uplift, mostly associated with high-standing fault blocks of Paleozoic carbonate and siliciclastic formations, and juxtaposed lowlands underlain by Precambrian crystalline rocks. Analogous paleotopographic relief was present on the WPP over faulted Paleozoic highs to the west, such as the Fort Chadbourne Fault Zone, Edwards Arch, Devils River Uplift, Ozona Arch, and Brown-Bassett structural complex.

Across most of the Llano Uplift, the Lower Cretaceous transgressive sequence of Hensel Sandstone, Glen Rose Formation and Edwards Limestone successively filled-in paleotopography on the WPP. Remarkably, present-day topography appears to have been influenced by WPP paleotopography: today's valleys and ridges commonly overlie corresponding valleys and ridges on the WPP, even though the thick regional blanket of Edwards Limestone lies (or once lay) between them. Also, outliers of Edwards Limestone around the Llano Uplift tend to overlie buried highs on the WPP. Differential compaction and/or isostatic adjustment were probably involved in this concomitance.

Elsewhere, distribution of some ridges and valleys on the buried WPP landscape bear little resemblance to today's stream drainage patterns. For example, the San Saba River may have drained northeastward into the East Texas Embayment, and the Colorado River may not have been a through-flowing stream. Three WPP valleys located in the southern Llano Uplift and related western terranes apparently drained southward into the Rio Grande Embayment.

When corrected for (1) regional northwest rise related to Neogene uplift of the Colorado Plateau; (2) Late Cretaceous and Paleogene regional dip into the Gulf Coast Basin; (3) the crescentic sedimentary wedge of Glen Rose sediments thickening gulfward from the Llano Uplift; and (4) Neogene Balcones uplift of the Edwards Plateau, the WPP appears as a vast, remarkably flat lowland broken only by scattered ranges of hills over the Llano and Devils River uplifts, and the Edwards and Ozona arches.

INTRODUCTION

The Wichita Paleoplain

R. T. Hill (1901, p. 363–367) defined the Wichita Paleoplain (WPP) as the unconformable regional contact between gently east-dipping Lower Cretaceous strata of Texas and Oklahoma, and the Jurassic, Triassic, Paleozoic, and Precambrian formations that lie immediately beneath them. Hill (1901) described the areal extent of the WPP as between the Ouachita Fold Belt on the north and east, the foothills of the Rocky Mountains on the west, and the Balcones Fault Zone on the south. He recognized, however, that the WPP extends eastward and southward into the subsurface, beneath the coastal plain of the Gulf of Mexico Basin. Hill (1901, p. 369) also understood that the basal Cretaceous sand formations that rest upon the WPP are time-transgressive, consisting of older formations lying to the east and south, succeeded westward and northward by younger terrigenous-clastic deposits. Although Hill (1901) recognized that the WPP represents an ancient, buried landscape having implicit paleotopographic relief, he tended to emphasize the remarkable regularity of this regional

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paleo surface. It fell to subsequent workers such as Cartwright (1932), Jager (1942), Boone (1968), Bain (1973), Atchley et al. (2001), and Sobehrad (2011) to describe substantial paleotopography of the WPP in different areas of its wide extent across Central Texas. Barker and Ardis (1996), however, tended to focus on the regional extent and configuration of the WPP in west-central Texas, and the geohydrology of the Edwards-Trinity Aquifer System that rested on it.

Purpose and Plan

This report (1) synthesizes previous geologic publications on the WPP; (2) characterizes its regional configuration at the present time as well as at the beginning of Hensel Sandstone deposition, in middle Aptian time (c. 110 Ma); and (3) describes and analyzes its influence on subsequent geologic features and events.

The investigation began on the southeast flank of the Llano Uplift, in eastern Gillespie, northern Blanco, and southernmost Burnet counties, Texas, utilizing detailed surface mapping by Virgil Barnes and others of 13 7.5–minute quadrangles (Barnes et al. (1947–1982). It resulted in a series of detailed oversized geologic maps presented here in more workable digital format (Digital Maps 1–7), showing the geometry of the WPP and the geological structure and thickness of the Lower Cretaceous formations that rest on that ancient erosional surface across almost all of the Llano Uplift: the Hensel Sandstone, the Glen Rose Formation, and the Edwards Limestone.[1]

Eight oversized regional geologic cross-sections aided in geological and stratigraphic correlations. Five are "dip" sections, oriented northwest-southeast, whereas three are "strike" sections, oriented west-east; all are presented on Digital Plates 1 and 2. Characteristic geological relationships and patterns that emerged from phase one were then utilized in phase two, expanding the investigation to the entire Llano Uplift area and surroundings. Phase three of the investigation further expanded the mapping to the region of the Edwards Plateau, north-central, and west-central Texas, utilizing previous publications. Manipulation of regional structure and isopach maps allowed reconstruction of WPP paleotopography at successively older times; the final map and block diagram show paleogeography of the ancient erosion surface at the start of the Hensel basal-transgression. Methods are described in the Appendix.

PHASE ONE: SOUTHEAST FLANK OF THE LLANO UPLIFT

Geologic History of the Llano Uplift

The Llano Uplift is the oval outcrop area in Central Texas of Precambrian crystalline rocks surrounded by faulted Paleozoic formations. A prominent rimrock of Lower Cretaceous sandstones and carbonates—the dissected edges of the Edwards Plateau—encircles the older core on the east, south, and west. A short summary of the geological history of the Llano Uplift is required, to convey how structural and stratigraphic events influenced the eventual erosional topography of the WPP. Central Texas experienced three separate and distinct regional episodes of subaerial exposure and erosion before the WPP was formed, transgressed, and buried by Cretaceous sedimentary formations.

The first erosional episode occurred during late Precambrian to middle Cambrian time, a period lasting somewhere between about 50 and 375 million years, depending on when a thick Precambrian ("Grenville") geological complex of metamorphic and intrusive granitic formations that formed 1300 to 1000 Ma, was uplifted and subaerially exposed, weathered, and eroded (Ewing, 2016). This weathered surface was transgressed by a northwesterly thinning, largely carbonate blanket of Cambro-Ordovician strata roughly 2800 feet thick; erosional relief of the buried Precambrian landscape at its base was as much as 800 feet (Barnes and Bell, 1977).

The area of the Llano Uplift was then exposed for a second time, eroded for about 140 million years (Middle Ordovician to Middle Mississippian), more deeply to the northwest than to the southeast. A few very thin remnant outcrops of Silurian and Devonian strata are preserved in karstic depressions on top of the regional unconformity developed mostly upon the Lower Ordovician Ellenburger carbonate succession. This erosional surface was next covered by about 750 feet of Middle Mississippian through Lower Pennsylvanian carbonate and shale strata—the Chappel Limestone, Barnett Shale, Marble Falls Limestone, and Smithwick Shale.

South and east of the Llano Uplift, formation of the Ouachita fold belt by collision of the ancient continents of Laurasia and Gondwana began in middle Pennsylvanian time (Des Moinesian = Strawn), and generated a complex series of near-vertical southwest-northeast faults that traversed the Llano Uplift, extending northeastward across the adjoining Fort Worth Basin (Fig. 1). Some of these faults are normal; some are transcurrent (Amsbury and Haenggi, 1993; Ewing, 2005). Many are complexly splayed at their terminations. Vertical displacements range up to about 3000 feet; many faults are 10 to more than 80 miles long. The Llano Uplift and surrounding area began to be uplifted simultaneous with this faulting, subaerially exposed, weathered, and eroded for the third time (Late Pennsylvanian to Early Cretaceous [Barremian]). Beginning in the Late Pennsylvanian, different tectonic trends also interacted gradually over the next 175 million years to shape the Llano area into a domal uplift centered around Llano County, Texas (Ewing, 2005). The Precambrian core of the Llano Dome was breached by erosion, deeply unroofed, and weathered again during this third period of regional exposure, which finally terminated as the WPP (Standen and Ruggiero, 2007).

By early Aptian time, the great Cretaceous transgression onto the North American Craton had encroached northwestward as far as the eastern edge of the Llano Uplift, where a basal onlapping succession of Sycamore Conglomerate, Hammett Shale, and Cow Creek Limestone was deposited on the WPP (Stricklin et al., 1971; Kerans et al., 2014). After being briefly exposed and eroded, it was then overstepped by the next transgressive leg, consisting of the Hensel Sandstone, Glen Rose Formation, and Edwards Limestone, which covered most of Central, North, and West Texas. Thus, the WPP itself was time-transgressive, becoming younger as it migrated northwestward onto the North American Craton. In the Late Cretaceous, the Llano Uplift was further inundated by the marine Austin Chalk and Taylor-Navarro formations (Rose, 2016), as the southern end of the Cretaceous Interior Seaway (Kauffman, 1977).

Beginning in the early Neogene, Central Texas was subaerially exposed, weathered, and eroded for the fourth time, now for about 65 million years. The present topography has been developed starting from the wide, almost horizontal plain of the blanketing Edwards Limestone, which once was continuous from the present area of the Edwards Plateau, southeastward across the Balcones Fault Zone into the subsurface beneath the Gulf Coastal Plain, and northwestward, beyond the Callahan Divide and the

[1]In the extreme southeastern sector of the Llano Uplift, along the Balcones-Ouachita Downwarp (Rose, 2016), a slightly older depositional triplet consisting of the Sycamore Sandstone, Hammett Shale and Cow Creek Limestone overlies the WPP, in turn being overstepped by the Hensel/Glen Rose/Edwards depositional triplet.

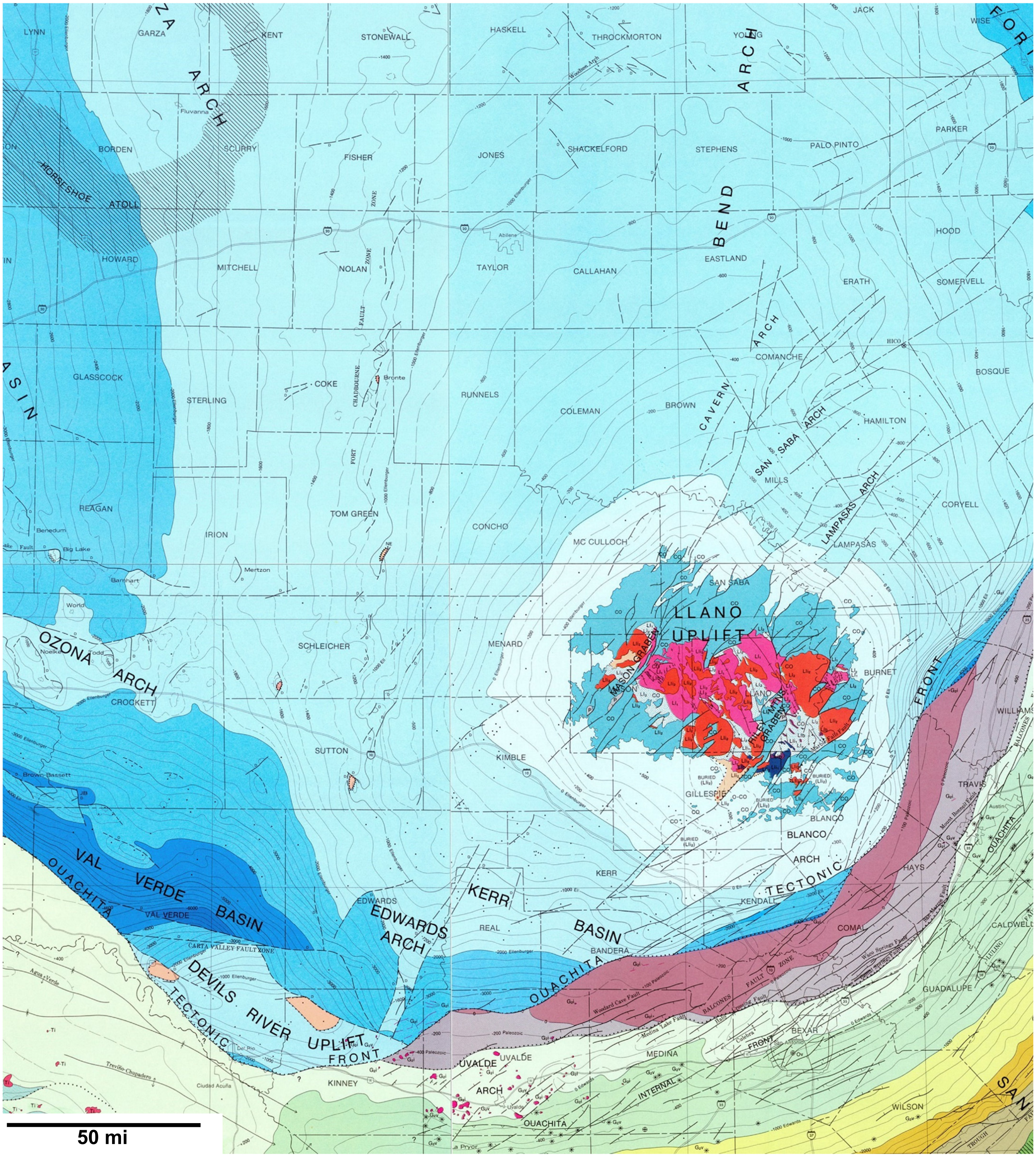

Figure 1. Tectonic map of Central Texas (modified after Ewing, 1991). Datum is mean sea level. Contour interval is 200 m with supplemental 100 m contours.

Mescalero Escarpment (Hill and Vaughan, 1898; Woodruff, 2002; Rose, 2016, 2017, 2019). The peritidal Edwards Limestone, which is a proxy for Early Cretaceous sea level, thus becomes a reference datum for the measurement of subsequent differential uplift. All present-day stream drainages have been cut into, or through, this ubiquitous, resistant carbonate mantle, especially since Balcones faulting (Rose, 2019), which further elevated the region beginning about 20 Ma (Balcones-related faulting in the Llano Uplift itself is thought to be minimal). The possible influence of isostatic adjustment is yet to be evaluated.

Review and Discussion of Digital Maps and Cross-Sections

The phase one base map, Digital Map 1, is a compilation showing the distribution and closely spaced elevations of the following outcropping geological contacts: the top of the WPP, base of the Glen Rose Formation, and base of the Edwards Limestone. Geologic features, map patterns, and relationships are identified, described, and interpreted for each of Digital Maps 2–7 in the following summaries. Contour interval for Digital Maps 2 and 4–7 is 20 feet. Reference to each map is recommended while reading. All digital maps may be accessed electronically. For convenience Figure 2 is an index map showing the location of 13 7.5–minute geological quadrangle maps used in the phase one investigation; these maps provide the basic ground truth for the subsequent restoration and interpretation.

Digital Map 2—Paleotopography of the Pre-Cretaceous Erosion Surface (= WPP)

It is important to emphasize that this map shows only the configuration of the old, buried erosion surface—not the identity or lithology of the underlying Paleozoic or Precambrian formations, or of the overlying Lower Cretaceous formations. The contour map is color-coded in 100 foot increments (dark blue = lowest > green > yellow > orange > dark brown = highest). The WPP is a rolling plain rising from less than +900 feet on the eastern edge of this map, to more than +1900 feet in the northwest, reflecting Neogene regional uplift of the Colorado Plateau. Local paleotopographic relief on the old unconformity increases northward, toward the present northern margin of the Pedernales River drainage basin (northern half of the Crabapple, Willow City, Blowout, Howell Mt. and Round Mt. quadrangles). Within the area of Digital Map 2, local relief of 100 to 300 feet is common on the WPP, but ranges up to more than 400 feet, which is broadly consistent with present-day topography.

Along the middle reaches of the Pedernales River, as well as its northern tributary, North Grape Creek (Hye, Rocky Creek and Johnson City quadrangles), the configuration of the WPP conforms strongly to the present valleys of those streams, posing questions concerning how an ancient buried landscape can influence the development of a much younger, modern landscape, especially when an intervening thick, resistant, near-horizontal succession (the Lower Cretaceous Edwards Limestone) covered the entire region before the onset of the present geomorphic cycle.

Digital Map 3—Distribution of Edwards Formation Outliers Relative to Paleotopography of the Underlying WPP

Areas of Edwards Limestone outcrop are colored light blue; paleotopography of the underlying WPP is shown by black contour lines. Visual inspection of Digital Map 3 indicates the common coincidence of closed topographic highs—ancient hills on the WPP—with overlying outliers of Edwards Limestone. This is most conspicuous in the northern part of the map area, in the northern edge of the Pedernales River drainage, where paleotopographic relief of the WPP is greatest. Such Edwards-capped promontories as (west to east) Mt. Nebo, Bell Mt., Andy Moore Mt., Hudson Mt., Smith Mt., Big Mts., Table Mt., Howell Mt., Rattlesnake Mt., Round Mt., and Shovel Mt. all coincide with high topographic closures on the underlying WPP. Other examples of Edwards outliers that coincide with underlying buried WPP hills are on the eastern reaches of the divide between North Grape Creek and the Pedernales River 6 miles north of Stonewall, Texas, and along the divide between Palo Alto Creek and North Grape Creek, 7 miles northeast of Fredericksburg. However, there are also a few exceptions, the most prominent being the closed, Y–shaped, 90-foot-deep depression on the WPP that underlies an Edwards outlier in the center of the Cave Creek School quadrangle 10 miles east of Fredericksburg. This depression is underlain by Lower Pennsylvanian Marble Falls limestone strata, rather than Lower Ordovician Ellenburger dolomitic strata (P. Tybor, 2020, personal communication). However, nonresistant Smithwick Shale, removed by pre-Cretaceous erosion, may have been present originally on top of the Marble Falls, leading to the development of the depression.

This is another aspect of the geological question posed in the previous discussion of Digital Map 2: how can a paleotopographic surface buried 110 Ma influence erosional topography developed during the last 20 million years, especially considering that the Lower Cretaceous Edwards Limestone covered the entire area, starting about 100 Ma?

Digital Map 4—Geologic Structure on the Base of the Glen Rose Formation

Each 100 foot contour on Digital Map 4 is color-coded (+1000 feet = blue-violet; +1100 feet = indigo blue; +1200 feet = dark blue; +1300 feet = true blue; +1400 feet = turquoise; +1500 feet = sea green; +1600 feet = chartreuse; +1700 feet = yellow; +1800 feet = orange; and +1900 feet = terra cotta). The base of the Glen Rose is an undulating surface that rises regularly from southeast to northwest with a dip rate of about 25 feet per mile, twice that of the overlying Edwards Limestone. This regional dip is most consistent in the southeastern part of the map area, but becomes increasingly irregular to the west and north, where domal Glen Rose outliers become more common, owing to the northwestward convergence of the basal Glen Rose onto the buried WPP. As with the overlying base of the Edwards Limestone, the base of the Glen Rose also drapes over (and sags under) paleotopographic highs and lows of the underlying WPP. Again, most WPP highs are underlain by high-standing Cambro-Ordovician graben-blocks, whereas most WPP lows overlie Precambrian crystalline rocks.

As noted by Barnes (1952a, 1952b), the Glen Rose Formation thins toward the Llano Uplift partly by grading laterally into terrigenous clastics characteristic of the underlying Hensel Sandstone. The zero line where this facies change is totally achieved is shown as a curving, west-to-northeast, serrated boundary in the northern part of the Palo Alto quadrangle and the central part of the Willow Creek quadrangle, where it terminates against the southeastern flank of the Riley Mt. fault-block.

V. Barnes also mapped the updip pinchout edge of the *Corbula* key bed (Lozo and Stricklin, 1956; Stricklin et al., 1971), marking the boundary between the lower and upper Glen Rose as a northeast-southwest line across the Round Mt., Johnson City, Rocky Creek, and Hye quadrangles, terminating near the northeast corner of the Stonewall quadrangle. This boundary is an excellent indicator of true depositional strike of the lower Glen Rose succession. Moreover, its regional decline, from about +1500 feet on the southwest, to about +1100 feet on the northeast, may be an accurate indicator of the amount of subsidence along this sector of the Balcones-Ouachita Downwarp (Rose, 2016) since early Albian time (~105 Ma).

Digital Map 5—Thickness of Hensel Sandstone

Petrology of the Hensel Sandstone indicates that it was sourced primarily from Precambrian crystalline rocks of the Llano Uplift (Payne and Scott, 1982; Jones and Kullman, 1997). Depositional environments range from alluvial and fluvial in the northwest part of the map area to shallow marine in the southeast. Hensel isopachous intervals range from >260 feet (blue-violet) in the western and southern quadrangles, to <20 feet (dark brown) in the northern and eastern quadrangles. Paleo highs—areas where the Hensel Sandstone is absent, and Glen Rose or basal Edwards strata rest on eroded Paleozoic and Precambrian rocks—are indicated by a right-sloping line pattern. Each of the

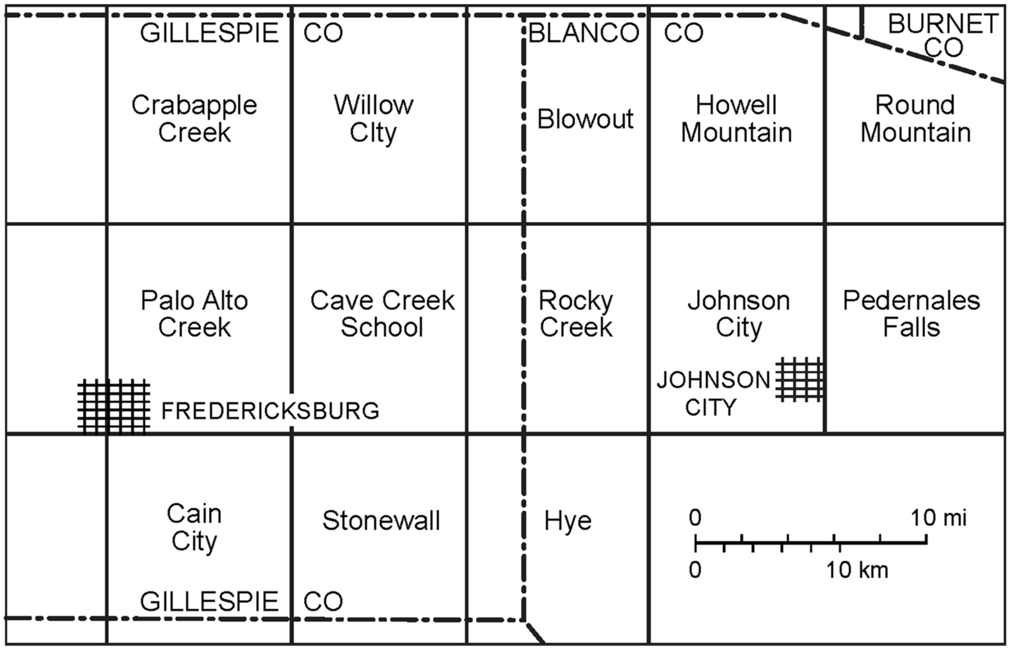

Figure 2. Index map for phase one mapping, southeastern flank of Llano Uplift, Texas.

ten northern and central quadrangles contains at least one such "baldheaded" structure; each of the southern three quadrangles contains at least one closed high structure on which the Hensel is less than 20 feet thick. There are two large areas covering 40–50 square miles in each of which the Hensel thins progressively to zero around the perimeter, showing that each was a topographically high area during Hensel deposition. Both of these large bald-headed areas are underlain primarily by faulted Cambro-Ordovician carbonate (mostly dolomite) strata. One area is in the southern Howell Mt. and adjoining northern Johnson City quadrangles (the Round Mt. Paleohigh); the other is in the western Rocky Creek and adjoining eastern Cave Creek quadrangles (the Cave Creek Paleohigh). Two high-standing fault-blocks lie to the north, along the southern rim of the Llano Uplift: the northeast-plunging Riley Mt. fault block (Willow City quadrangle) and the north-plunging Blowout Fault block (Blowout quadrangle). Both are underlain by Cambro-Ordovician carbonate (mostly dolomitic) formations. Both cover areas of 12–15 square miles. Smaller "bald-headed" structures covering < 2 square miles are present in the Round Mt. and Johnson City quadrangles (4 each), and the Crabapple and Palo Alto Creek quadrangles (one each). Only one is underlain by Precambrian crystalline rocks, Bear Mt., in the western Palo Alto Creek quadrangle.

The Hensel Sandstone is generally thin (<100 feet) in the eastern and northern part of the map area, aside from two small basins where the Hensel reaches thicknesses of >160 feet, in the northern Howell Mt. and northeastern Rocky Creek quadrangles. Both of these Hensel "thicks" are underlain by Precambrian crystalline rocks. However, the Hensel is thicker to the west and south of the map area, where it is commonly 140–280 feet thick. A notable area of thick Hensel Sandstone lies just east and north of Fredericksburg, roughly coincident with the present watershed of Palo Alto Creek, where the Hensel occupies a narrow, sinuous, north-south belt more than 240 feet thick, probably delineating the course of a south-flowing Hensel-age stream that almost certainly headed farther north, in southwestern Llano County.

Digital Map 6—Geologic Structure on Base of Edwards Limestone

Each 100 foot contour on Digital Map 6 is color-coded (+1500 feet = violet; +1600 feet = blue; +1700 feet = turquoise; +1800 feet = aqua; and +1900 feet = chartreuse). The base of the Edwards is an undulating surface that rises regularly from east to west with a dip rate of 12–15 feet per mile. This regional dip is most consistent in the southeastern part of the map area, but becomes increasingly irregular to the west and north, where domal Edwards outliers are more common. Eastward dip of the base-Edwards datum steepens to about 55 feet per mile on the northeast flank of the Riley Mt. fault block (eastern Willow City quadrangle) before flattening again eastwardly, through the northern Blowout and Howell Mt. quadrangles. Prominent along the south rim of the Llano Uplift is a west-east series of Edwards domal features overlying hills on the underlying WPP, as previously reviewed in the Digital Map 3 discussion. Especially notable over these features is the clearly mapped drape of the basal Edwards around the periphery of such domal highs as at Andy Moore Mt. and Hudson Mt. east of Willow City, and Smith Mt. and Big Mt. in the Blowout quadrangle. Analogous drape in the Glen Rose Formation, as reviewed in the Digital Map 4 discussion, is ascribed to differential compaction in the Hensel-Glen Rose section between the basal Edwards and the WPP, as first recognized by Cartwright (1932), but the role of isostatic adjustment is unknown. In the southwest corner of Digital Map 6, in the western Palo Alto Creek and central Cain City quadrangles, drape of the base Edwards mapping horizon around the margins of Edwards interfluves on both sides of the Pedernales River suggests the presence of underlying hills and ridges (presumably of high-standing Paleozoic fault blocks) on the WPP. This may be a southwestern extension of the Stonewall paleotopographic high (P. Tybor, 2020, personal communication).

Across the southeastern half of the mapped area, the Edwards Limestone rests mostly on the Glen Rose Formation. In the northwestern part of the area, however, especially over paleotopographic highs on the WPP, the base of the Edwards rests on Hensel Sandstone, upon Cambro-Ordovician strata, or even upon Precambrian granite. Examples include the high-standing southwest end of the Riley Mt. graben block (Willow City Quad), where basal Edwards strata rest directly upon Lower Ordovician Ellenburger dolomitic strata around Bell Mt. Eight miles west, on the headwaters of Crabapple Creek, basal Edwards beds rest directly on faulted Cambrian Cap Mountain Limestone, and at the aforementioned Bear Mt., eight miles south, in the western Palo Alto Creek quadrangle, a Precambrian granite pinnacle also terminates upward at the base of the Edwards.

Digital Map 7—Thickness of the Glen Rose Formation

As with the counterpart Hensel isopach map (Digital Map 5), the Glen Rose isopach map is color-coded, from gray (>500 feet) through blues, greens, yellows, reds, to dark brown (<20 feet). Downdip from the pinchout edge of the *Corbula* key bed marking the boundary between the lower and upper Glen Rose Formation, southeasterly thickening-rates are quite regular, and regional strike is consistently southwest-northeast, essentially parallel to the *Corbula* pinchout edge. To the northwest, however, the Glen Rose thins irregularly, by three different geological processes: (1) basal onlap; (2) internal convergence; and (3) facies change into Hensel arkosic clastics. Generally, Glen Rose isopach patterns are similar to Hensel isopach patterns—Glen Rose closed "thins" generally coincide with Hensel closed "thins," usually overlying high-standing Cambro-Ordovician fault blocks. Moreover, the Glen Rose is present but thin over the several large areas where the Hensel is absent.

A few exceptions are worth noting, however, such as the absence of any Glen Rose thickening corresponding to the aforementioned thick north-south sinuous stream channel in the Hensel Sandstone isopach map (Digital Map 5). Farther south, in the northern Cain City quadrangle, a boomerang-shaped Glen Rose "thick" seems to be reciprocal to an underlying Hensel "thin", and there is no analogous or reciprocal Hensel feature corresponding to the circular Glen Rose "thin" in the center of the Stonewall quadrangle.

Influence of WPP on Geology and Topography of the Southeastern Llano Uplift

The purpose of this section of the report is to identify and summarize important geological features, patterns, and relationships of the WPP on the southeast flank of the Llano Uplift that are likely to apply in the larger area of the greater Llano Uplift.

Configuration of the WPP

Along the extreme southeastern margin of the Llano Uplift, where the WPP lies beneath the Sycamore/Hammett/Cow Creek sequence at elevations of less than about +1200 feet, it is a regular southeast-steepening surface. To the northwest, it is a rolling plain rising northwestward from elevations of +1200 to more than +1900 feet, locally exposed as the unconformable contact between underlying faulted Lower Paleozoic and Precambrian formations, and the unfaulted Lower Cretaceous formations that rest upon them—the Hensel Sandstone, the Glen Rose Formation, and locally the Edwards Limestone (Digital Map 2). For convenient reference, a greatly reduced and simplified version has been placed in the text (Fig. 3). The Hensel Sandstone tends to be present (and thickest) over areas underlain by Precambrian metamorphic and igneous rocks, and thinnest (or absent) over areas underlain by Cambro-Ordovician carbonate or sandstone formations (Digital Map 5). Where the WPP is present as discrete hills or ridges, high-standing Paleozoic graben blocks tend to lie beneath; where it is present as swales or valleys, horst-blocks of Precambrian granite or gneissic terranes commonly lie below. In two large, elevated areas around which the Hensel has pinched out peripherally, strata of the Glen Rose Formation rest upon faulted Lower Paleozoic terranes. Where an underlying Lower Paleozoic hill stands higher than the adjacent subcrop, it is covered by relatively younger Glen Rose strata. In at least five localities in the map area, high-standing Lower Paleozoic beds lie directly beneath carbonate strata of the Edwards Limestone (Digital Maps 6 and 7).

Local paleotopographic relief on the WPP is typically 100–300 feet, ranging up to 400 feet, similar to present relief in the area (Digital Map 2). It is greatest in the northern part of the map area, along the southern rim of the Llano Uplift, and diminishes in magnitude and vertical relief southward and eastward (Fig. 3).

Paleotopographic Anomalies

The topographic configuration of the WPP (Digital Map 2) coincides closely with the middle reaches of the present Pedernales River valley, as well as with the valley of its northern tributary, North Grape Creek, which touches again on previously raised questions as to how a buried early Cretaceous landscape could influence Neogene geomorphology, especially since perhaps 1500 feet of middle and late Cretaceous strata lay between them (Rose, 2016, 2019).

Also noteworthy is the prevalent coincidence of erosional outliers of the Edwards Limestone with closed "highs" on the underlying WPP, as shown on Digital Map 3. The two geologic contacts are separated by 30 to 300 feet of Hensel and/or Glen Rose strata. The clear "drape" of the basal Edwards around the periphery of Edwards outliers that rest above discrete, high-standing Cambro-Ordovician fault-blocks, seems to be a related effect, probably related to differential compaction during the Late Cretaceous and Neogene.

This explanation assumes that the Hensel and Glen Rose strata intervening between the WPP and the overlying Edwards Limestone contain sufficient clay to produce more compaction on the flanks of Wichita hills than on the crest of such hills, hence the covering Edwards Limestone would drape gently over the buried hills. Additional compaction would be encouraged by the overburden of ~600 feet of Austin Chalk and Taylor-Navarro marls that were deposited above the Edwards during the 60 million years that followed Edwards deposition, but were removed by Tertiary erosion. Isostatic adjustments may also have contributed.

Thick Hensel Stream Channel

The Hensel Sandstone thickens in the western and northern part of the map area. A notable feature coinciding roughly with the present drainage of south-flowing Palo Alto Creek, east of Fredericksburg, is the narrow, sinuous belt of thick Hensel Sandstone (>240 feet thick), apparently heading south from the vicinity of Enchanted Rock, and splaying out south of the Pedernales River (Digital Map 5).

PHASE TWO: THE WPP IN THE LLANO UPLIFT AND SURROUNDINGS

The intent of this section of the report is to apply the geologic principles and relationships derived from the previous detailed study and reconstruction of the southeastern flank of the Llano Uplift to the area of the greater Llano Uplift, focusing mostly on the configuration of the WPP.

Geologic Structure of the Llano Uplift

The Llano Uplift is a football-shaped dome, elongated northwest-southeast, cut by a wide zone of long, subparallel northeast-southwest high-angle faults (Fig. 1). Precambrian gneisses, schists and intrusive granites predominate in the central core of the uplift, and roughly 2750 feet of faulted Paleozoic carbonate and terrigenous formations, some faulted against Precambrian crystalline rock, occupy the periphery, dipping radially away from the axis of the Llano Dome. Structural mapping by Standen and Ruggiero (2007) on the top of the Lower Ordovician Ellenburger Group (Fig. 4A) shows a domal feature breached by erosion from Early Permian through early Cretaceous (Aptian) time, and again from middle Paleocene through the present, especially since Balcones faulting and uplift began in the early Miocene (Rose, 2019). By projecting structural contours inward from the periphery, the maximum elevation of the youngest known resistant formation at the domal culmination (Morrowan Marble Falls Limestone), lying about 300 feet above the Ellenburger, may be estimated at about 4500 feet above present sea-level near

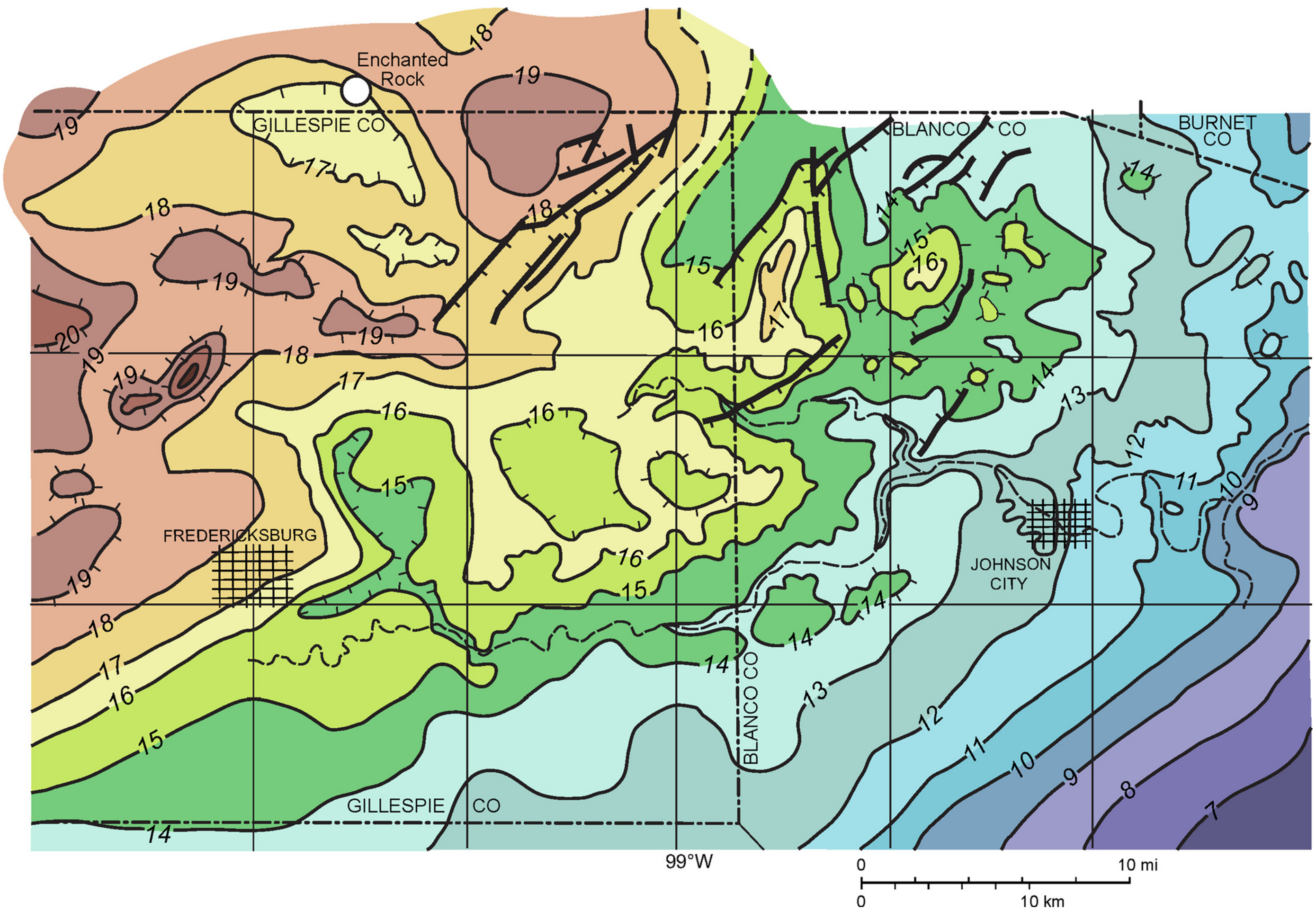

Figure 3. Simplified paleotopography of pre-Cretaceous erosion surface (= Wichita Paleoplain), Gillespie and Blanco counties, Texas.

the town of Llano.[2] Similarly, Standen and Ruggiero's (2007) map of the base of the Cambrian Hickory Sandstone (= top of Precambrian) supports the projection of an elevation of a little more than 2000 feet (Fig. 4b).

Standen and Ruggiero's (2007) structure maps allowed the construction of cross-sections J–J' and K–K' (Fig. 5), which depict the restoration of the Llano Uplift after uplift and faulting associated with the Ouachita Orogeny (Late Pennsylvanian), in comparison with the stratigraphic and structural position of the next depositional cycle, the Lower Cretaceous Hensel, Glen Rose and Edwards Formations, as well as projected thickness of the Upper Cretaceous units Austin and Taylor-Navarro groups from Rose (2016). Thus Figure 5 allows an appreciation of the substantial removal of Precambrian and Paleozoic rock by subaerial erosion during the hiatus between the end of Ouachita deformation and uplift and the arrival of the Early Cretaceous transgression (>3000 feet at the domal apex). It also shows the smaller volume of rock removed by subaerial erosion during the 66 million years of Tertiary time (about 2000 feet at the domal apex), especially during the Neogene, associated with Balcones faulting and uplift, about 21 Ma (Rose, 2019).

Subaerial erosion at this domal culmination probably began about 285 Ma, at the beginning of Virgil time (latest Pennsylvanian), and continued for the next 175 million years, when the entire Central Texas region was finally covered by transgressive fluvial and coastal deposits of the Lower Cretaceous Hensel and Glen Rose formations, and ending with the Maastrichtian Navarro marine marl and siltstone. A fourth period of subaerial erosion followed, throughout the Tertiary and Pleistocene (about 66 million years), accelerated during Miocene Balcones faulting and uplift (21 Ma), and continues, now diminishing, to the present day (Rose, 2016, 2019).

Development of the WPP

Elevation and topographic relief of what is now the Llano Uplift was greatest shortly after Ouachita-related faulting had ceased, in Late Pennsylvanian time. The area was surrounded by prairies and flatlands: arid plains sloped gently to the west, toward the Midland Basin. South and east, slopes fell away toward the curvilinear highlands of the Ouachita Fold Belt. The area north of the Llano Uplift was a prairie rising gently westward from the Fort Worth Basin and the Ouachita Fold Belt, cresting over the Bend Arch, then sloping westward.

The new Llano mountains created by the Ouachita Orogeny were long, linear, fault-bound ridges, oriented southwest-

[2]Actually, the Smithwick Shale, of variable thickness, is the youngest Pennsylvanian formation in the central Llano Uplift, but it is also highly nonresistant, thus an unreliable structural datum.

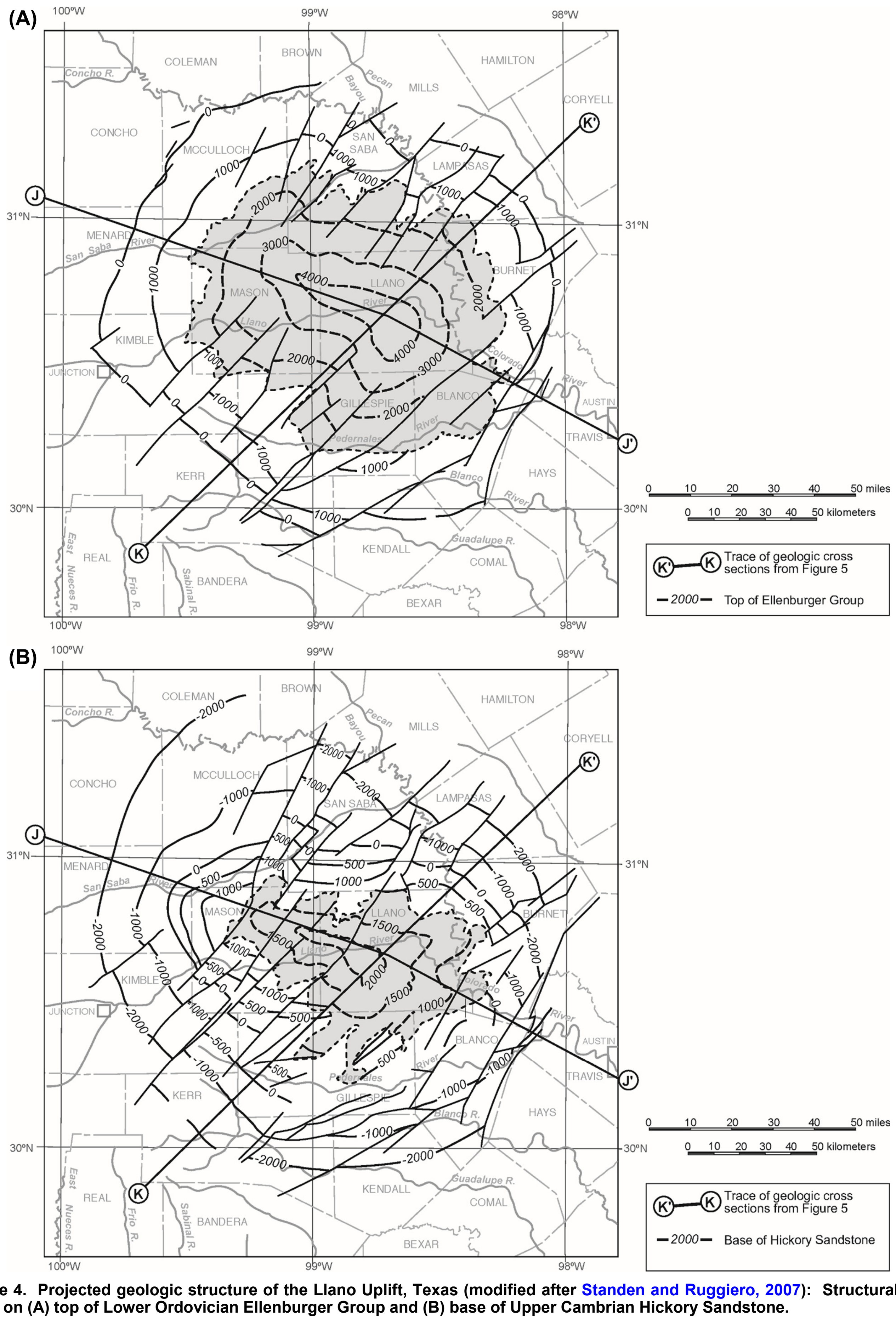

Figure 4. Projected geologic structure of the Llano Uplift, Texas (modified after Standen and Ruggiero, 2007): Structural contours on (A) top of Lower Ordovician Ellenburger Group and (B) base of Upper Cambrian Hickory Sandstone.

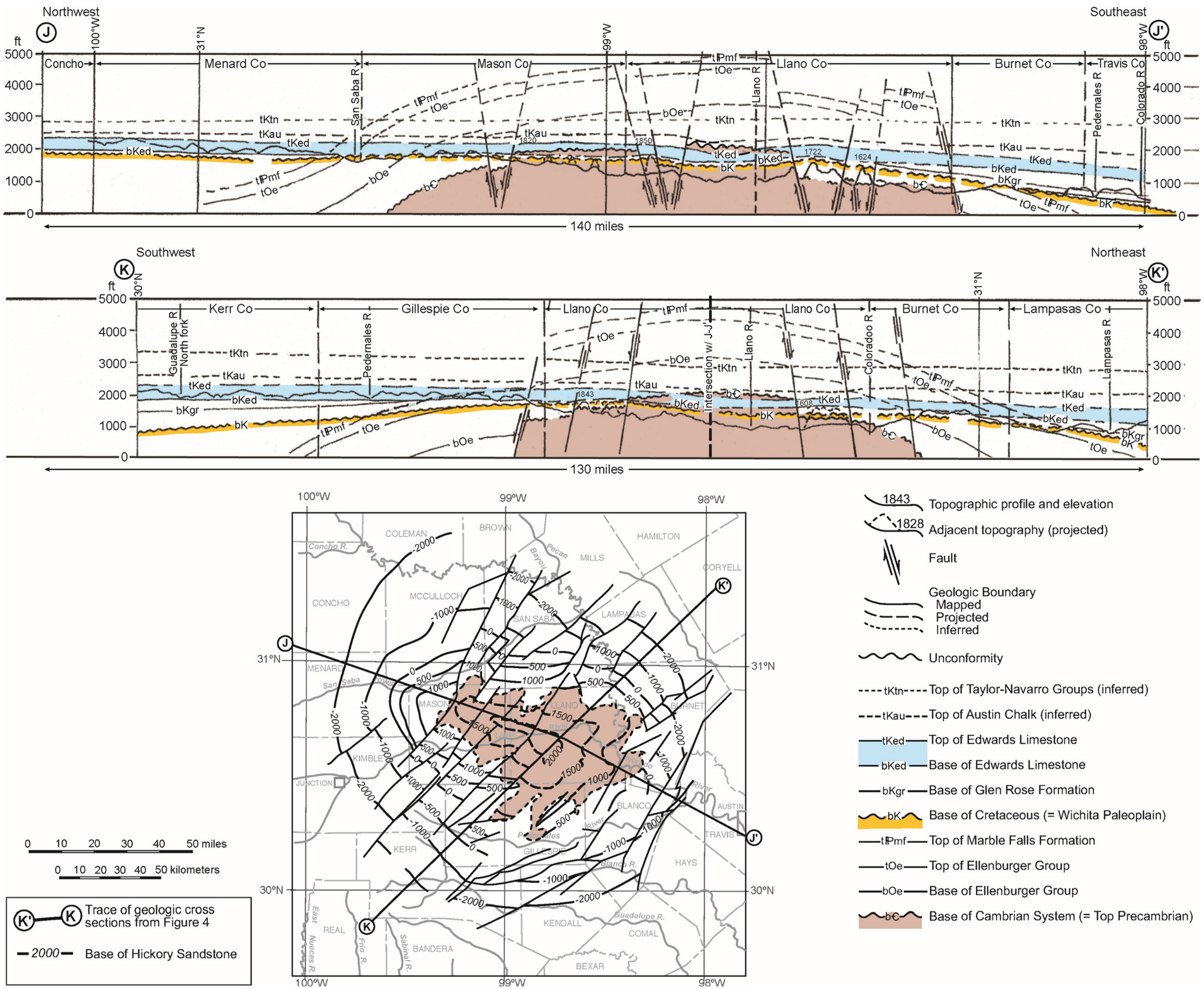

Figure 5. Geological cross-sections J–J' and K–K', across Llano Uplift, Texas, comparing restored post-Ouachita geologic structure in relation to present configuration of Wichita Paleoplain, base of Edwards Limestone (bKed), and present ground surface; after Standen and Ruggiero (2007).

northeast. The higher parts of the upthrown, rapidly eroding ridges consisted of Lower Paleozoic carbonates resting on Precambrian metamorphics and granites (Fig. 6). The adjacent graben-blocks consisted mostly of Lower Paleozoic carbonates and sandstones. Vertical displacement along these faults probably ranged upward to more than 3000 feet, but active erosion during and after the Ouachita Orogeny soon lowered the summits of the ridges substantially. After the Paleozoic strata in the upthrown ridges had been eroded down to expose the underlying Precambrian crystalline formations (which were more susceptible to erosion because they had been previously subjected to extended deep weathering during the late Precambrian and early Cambrian), further weathering and erosion of the faulted terrane generated valleys underlain by granite, gneiss, and schist, juxtaposed against higher fault-bound ridges composed of Paleozoic carbonate strata. Severe shearing related to transcurrent faulting, and preferential weathering related to climate also probably contributed to erosional susceptibility of weathered Precambrian granite and gneiss, in comparison with adjacent Lower Paleozoic carbonates. These processes of differential subaerial weathering and erosion persisted for about 175 million years (Late Pennsylvanian, Permian, Triassic, Jurassic, and earliest Cretaceous, eventually producing the inverted topography so characteristic of the Llano Uplift. This was the geological history that generated the Early Cretaceous landscape of the WPP in the area of the Llano Uplift area and its immediate surroundings.

Geomorphology of the WPP in the Llano Uplift and Surroundings

Figure 7 shows the configuration of the WPP in relation to the domal outline of the Llano Uplift, as represented by the zero (= sea level) structural contour on top of the Ordovician Ellenburger Group (Ewing, 1991). Only over the northwest quadrant of the Llano Dome does the WPP not reflect the underlying Paleozoic domal structure. To the east, the WPP slopes consistently eastward toward the Balcones-Ouachita Downwarp at about 25 to 50 feet per mile; to the south and southwest, it dips toward the Rio Grande Embayment at similar dip rates. North of the buried Llano Uplift, from the axis of the Bend Arch through western San Saba and Brown counties, the WPP slopes consistently eastward even more gently, at about 10 feet per mile, gradually steepening eastward.

Over the Llano Uplift itself the WPP forms two large (>800 square mile), irregular, east-reaching ridges with elevations reaching above +1900 feet. The present Llano River closely fits the elongated lower area between these two ridges, indicating the presence of a pre-Cretaceous Llano valley. On the northern side of the northern ridge, the present San Saba River correspondingly occupies a counterpart east-trending valley. A slightly lower, broader, smaller (< 400 square miles) ridge lies north of the present San Saba River, forming the north side of the precursor San Saba River valley, and the south side of a segment of the Colorado River valley. Because Sobehrad (2011) did not utilize conventional contouring methods to depict WPP topography, comparison of her results with mine are less certain, but three of her four pre-Cretaceous ridges, all lying south of the Colorado River, seem to correspond to the three main ridges noted here.

The southernmost ridge lies on the present south flank of the Llano Uplift, mostly in the drainage area of the Pedernales River. Topography on top of the WPP appears to be more complex here than to the north, probably because of the detailed mapping made available by the aforementioned 7.5–minute quadrangles mapped by Barnes et al. (1947–1982). As defined by the +1800 foot contour, the southern ridge is an irregular oval with a small spherical depression in its center and four irregular +1900 foot closures lying east, south, and west. The WPP on this southern ridge area rests mostly, but not entirely, on faulted Paleozoic formations. Contours in the area to the east depict an irregular hilly topography with elevations of +1600 feet, declining eastward to about +1000 feet. The correspondence of parts of the present valleys of the Pedernales River and its tributary, North Grape Creek, with similar linear depressions of the underlying WPP, has been previously noted, as has been the narrow sinuous valley roughly coincident with the southward drainage of Palo Alto Creek. Also noted here again is the common association of outlying Edwards Limestone outcrops with topographic highs of the underlying WPP.

The next ridge to the north, lying on the north side of the present Llano River, is defined by the +1800 foot contour on the WPP; it is an elongated ridge about 15 miles wide, extending eastward about 50 miles from eastern Menard County, across northern Mason County into northwestern Llano County. The symmetrical location of this ridge between the two rivers is striking. Two closed highs, defined by the +1900 foot contour, mark the axis of this ridge. Aside from a 50 square mile oval pluton in north-central Mason County, this prominent ridge rests entirely on faulted Paleozoic formations. An east-reaching outcrop of Edwards Limestone, "Mason Mt.," extends from eastern Menard County into northwestern Mason County, yet another example of the correspondence of Edwards Limestone outliers with underlying "highs" of the WPP.

These two prominent east-reaching ridges are connected in southwestern Mason County by a sinuous isthmus, as defined by the +1800 foot contour. This winding ridge forms the northeastern side of a broad valley that appears to open southward, indicating a south-flowing drainage, here termed the Kimble valley, that follows the present course (but the opposite direction) of the northeast-flowing Llano River and its north-flowing tributary, Johnson Fork, that heads in northwestern Kerr County. The Kimble valley also appears approximately to underlie Rose's (1972) Junction Trough, as mapped on the base of the Edwards Limestone. Farther west, in western Concho and Menard counties, the WPP rises to elevations of more than +2000 feet.

The third, smaller, relatively broader, east-reaching ridge lies farther north, in southwestern McCulloch County. It forms the northern side of the San Saba river valley, as defined by the +1800 foot contour. A small indentation to the north appears to coincide with the valley of overlying Brady Creek, and the northern side of the broad ridge coincides with a short segment on the south side of the Colorado River valley. This third ridge on the WPP appears to be underlain by Pennsylvanian and Lower Permian strata that dip gently westward toward the Midland Basin. It is also overlain by two northeast-reaching Edwards interfluvial divides, between the San Saba River and Brady Creek, and between Brady Creek and the Colorado River.

Regional Thickness Variations in Hensel Sandstone

Another approach to detecting topography of the WPP has to do with thickness variations of the overlying Hensel Sandstone, based on documented significant topography on the pre-Cretaceous land surface, and to a lesser degree, on thickness changes within the overlying Glen Rose Formation. Such conclusions that may apply to the region of the Llano Uplift are hampered by the inevitable differences in estimating accuracy of the smaller contour intervals (20 foot) and larger scale of the 7.5–minute quadrangles on which phase one are based (1:24,000), compared with the 100 foot contour interval and 1:250,000 scale of the map shown in Figure 7. Nevertheless, a few basic observations are pertinent:

(1) The Hensel Sandstone is thinnest in Blanco, Hays, northern Kendall, and eastern Gillespie counties—typically 40 to 80 feet and commonly absent over high-standing Paleozoic terranes. This is the eastern sector of the large southern ridge of the WPP topographic high. Across this area, the Hensel grades eastward and southward from alluvial and fluvial sediments to coastal, peritidal and finally shal-

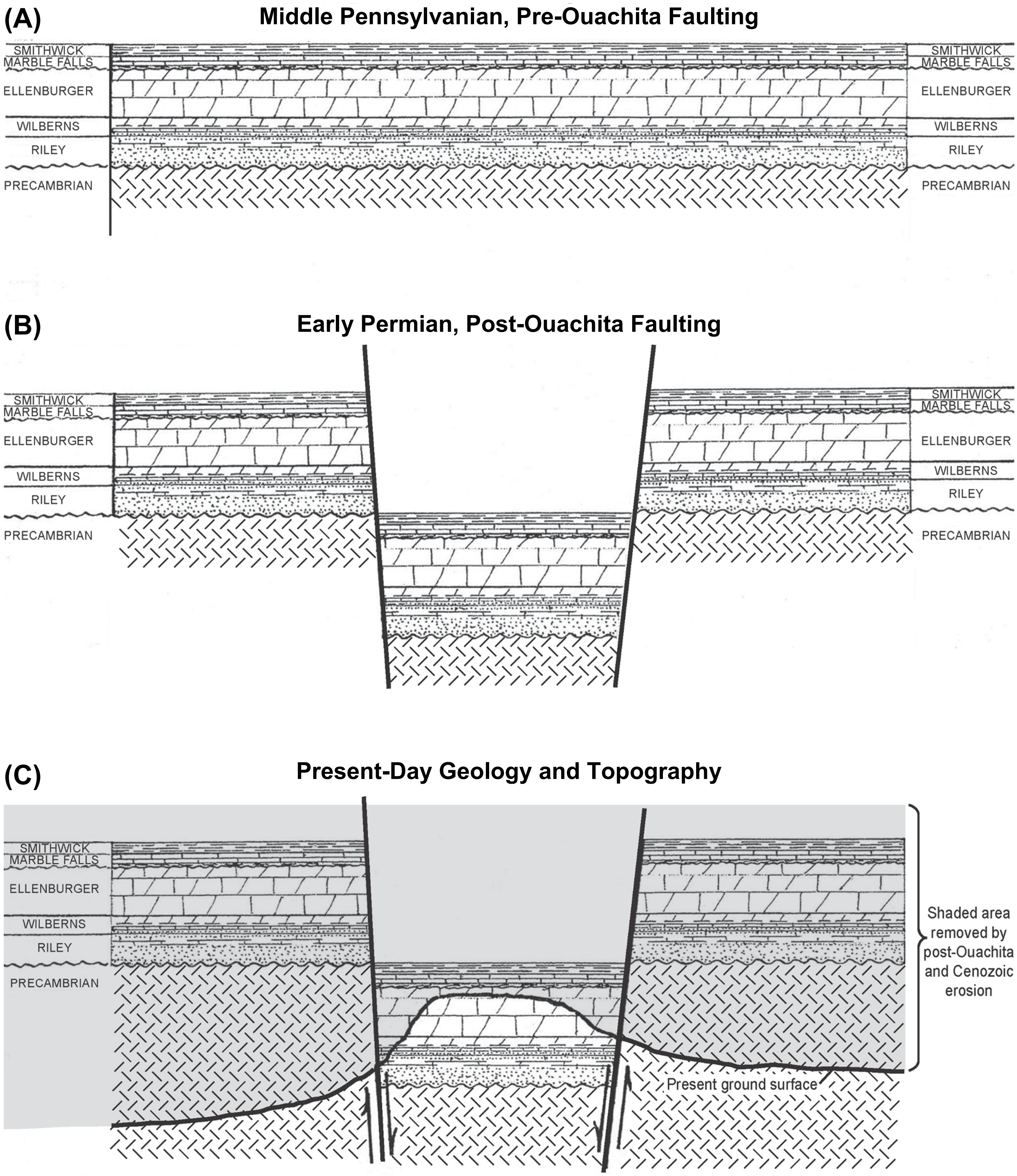

Figure 6. Schematic geologic cross-sections showing development of inverse structural topography: (A) Middle Pennsylvanian (300 Ma); (B) Early Permian; (275 Ma); and © Present-day geology and topography.

low marine carbonate deposits (A. S. Broun, 2020, personal communication).

(2) The Hensel is thicker to the west—commonly 100 to >300 feet thick in western Gillespie, eastern Kimble, and eastern Menard counties—although some of that increased thickness probably reflects a regional facies change wherein lower Glen Rose carbonates grade laterally westward to marls and calcareous siltstone originally assigned

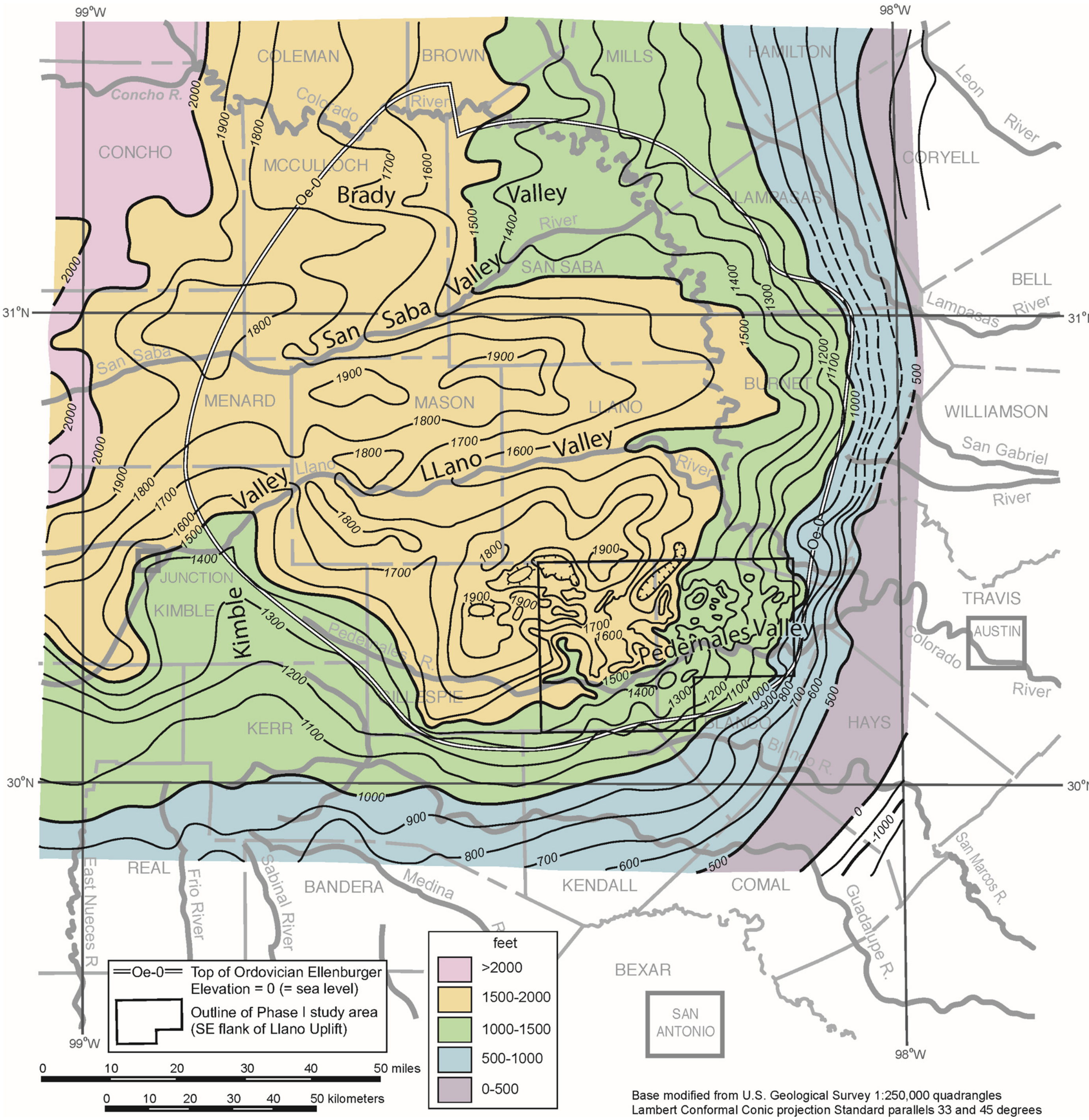

Figure 7. Present-day surface and subsurface configuration of the Wichita Paleoplain in the Llano Uplift and surroundings, Central Texas.

to the upper Hensel Sandstone (Barnes, 1952d; Rose, 1972; Jones and Kullman, 1997). It is also possible that some of the lower part of this clastic interval may be Hosston (= Sycamore) Sandstone, lithologically indistinguishable from the Hensel Sandstone (P. Tybor, 2020, personal communication).

(3) The Hensel is also thicker to the east, along the outcrop in central and southern Burnet County, where Hensel thicknesses of 100–200 feet are apparent on the Geologic Atlas of Texas (GAT) Llano sheet (Barnes, 1981), but it is absent over high-standing Cambro-Ordovician fault blocks in northern Burnet County.

(4) Farther north, in McCulloch and Concho counties, the Hensel appears to be thinner, typically 30 to 70 feet, perhaps reflecting greater distance north from the Llano Uplift sediment source.

If these thickness variations reflect underlying topography on the WPP, it would suggest that the Early Cretaceous structural apex of the Llano Uplift lay a few miles farther east than previously supposed, more in line with the domal culmination suggested by Standen and Ruggiero (2010), located near the town of Llano, due north of the thinner Hensel area of eastern Gillespie and Blanco counties.

Summary and Derived Principles

Based on patterns identified from detailed geologic mapping along the southeast flank of the Llano Uplift (phase one) as well as in the area of the greater Llano Uplift (phase two), the following geologic principles and relationships may be expected to apply to the regional area of the WPP throughout the greater Central Texas study area:

(1) There seems to be broad correspondence of WPP topography with present-day topography in the Llano Uplift area—present-day hills and ridges commonly overlie hills and ridges on the WPP, and present valleys commonly coincide with swales, sags, or troughs on the paleoplain. The relationship is, however, imperfect: although Brady Creek and the San Saba, Llano, and Pedernales rivers have their precursors on the WPP, there is little expression of their parent stream, the present Colorado River, on the topography of the underlying WPP. There are, however, indications of a possible valley roughly underlying a present 40 mile stretch of the Colorado River along the common boundaries of Coleman, Brown, Mills, and McCulloch counties, and easterly into northern San Saba County. Farther southeast, there is no indication of a Colorado River valley on the WPP. This question seems puzzling, inasmuch as present-day tributaries such as the San Saba, Llano and Pedernales seem to have their Early Cretaceous precursors on the WPP. For further perspective, Galloway et al. (2011) indicated the first appearance of a Colorado precursor stream in the Oligocene.

(2) The noted common correspondence of outliers of Edwards Limestone—isolated outcrops separated eastward and northward from the broad area of Edwards Limestone outcrop that covers the southwestern quadrant of the Llano Uplift and surroundings (Fig. 7)—with underlying ridges and hills on the underlying WPP, first noted in phase one of this report, is affirmed across the Llano Uplift and surroundings (phase two). Over a period of a few million years, the buried Wichita landscape was partially infilled by terrigenous clastic sediments of the Hensel Sandstone, followed by Glen Rose mudstones and marls that covered most of the remaining higher Wichita elevations, and finally by the thick, peritidal carbonate blanket of the Edwards Limestone. Roughly a thousand feet of Upper Cretaceous strata—Austin Chalk and Taylor-Navarro calcareous mudstones—accumulated above the Edwards blanket over the next 35 million years, before the region was exposed, uplifted, and eroded during the Tertiary and Pleistocene. This history allowed differential compaction of Glen Rose and Hensel strata to occur around the flanks of buried hills on the WPP. When the Edwards Limestone was subaerially exposed following Balcones faulting and regional uplift, gentle swales and slopes were uncovered on top of the vast carbonate blanket, which allowed surface runoff to be guided in broad pathways consistent with the topography of the underlying WPP. These early swales were then enlarged to form the initial drainage systems which eventually became the drainage basins of the Llano and San Saba rivers, and to a lesser extent, Brady Creek, and the Pedernales River. Regional isostatic adjustments may also have been involved.

(3) Assuming that those observations and the derived hypotheses apply more broadly, it would be expected that wherever discrete paleotopographic perturbations are observed on the WPP, they probably represent either erosional features, and/or underlying Ouachita-related faulting. Conversely, where the WPP appears to be fairly flat or gently sloping, the underlying strata would be expected to be regular and undeformed. Moreover, the overlying Edwards Limestone would reflect the same influences.

PHASE THREE: THE WPP IN WEST-CENTRAL TEXAS

This section of the report presents an expanded, more regional portrayal of the WPP across west-central Texas, employing geological principles and patterns derived from the previous two sections of the report, which were focused on and around the Llano Uplift. It integrates findings from the work of other geoscientists in areas north and west of the Llano Uplift in which the WPP was studied and mapped, as described below. Figure 8 shows the respective study areas of previously published work that is cited herein.

Regional Mapping

Figure 9 presents the regional synthesis of paleotopographic contouring of the WPP by Boone (1968), Bain (1973), Barker and Ardis (1996), Atchley et al. (2001), and Rose (1986), together with additional contour mapping by the author carried out as part of the present investigation. In addition, Boone (1968), Bain (1973), Barker and Ardis (1996), and Atchley et al. (2001) identified “valleys” and “divides” on the surface of the WPP, some of which are delineated diagrammatically on Figure 9, inasmuch as the relief of most of these paleogeomorphic features is less than the 100 foot contour interval.

Boone (1968) Mapping

Boone’s (1968) Ph.D. dissertation concerned the WPP and the stratigraphy of basal Cretaceous sandstone formations overlying it, in both the surface as well as the shallow subsurface aspects. Of interest here is the western part of Boone’s (1968) area.

The WPP across Callahan, Eastland, Erath, Brown, Comanche, Mills, Hamilton, Lampasas, and Coryell counties is a gently undulating surface that slopes consistently southeast, gradually increasing in dip-rate, from about 10 feet per mile on the west to about 20 feet per mile in Hamilton County, about 100 miles southeast. None of the gentle swales is distinct enough to qualify as a “valley” compared with the San Saba or Llano valleys of the Llano Uplift, as previously described. But Boone (1968) also carried out derivative mapping, which did identify several subtle southeast-trending swales, his Granbury, Twin Mt., Callahan, and Hamilton “valleys”, as shown on Figure 9. Boone’s (1968) Twin Mt. and Callahan valleys (which seem to coincide roughly with the present Bosque and Leon rivers respectively), are the only such features which may be precursors of a modern landform.

Boone found that alternating cuestas and troughs developed on gently tilted Pennsylvanian terranes were responsible for most fluctuations in the elevation of the WPP—highs over the crests of pre-Cretaceous cuestas, and lows over intervening linear swales. Such buried topography could generate as much as 100 feet of vertical relief locally on the WPP.

The prominent north-south zone of steepening eastward dip along the east margin of Figure 9 coincides with the Balcones-Ouachita Downwarp (Rose, 2016), marking the updip edge of the Mesozoic Gulf of Mexico Basin. This flexure swings around to the southeast and south of the Llano Uplift, where it marks the updip edge of the Rio Grande Embayment. Figure 9 shows that the WPP passes gulfward from the outcrop into the subsurface consistently along the +1500 to +1000 foot contour intervals.

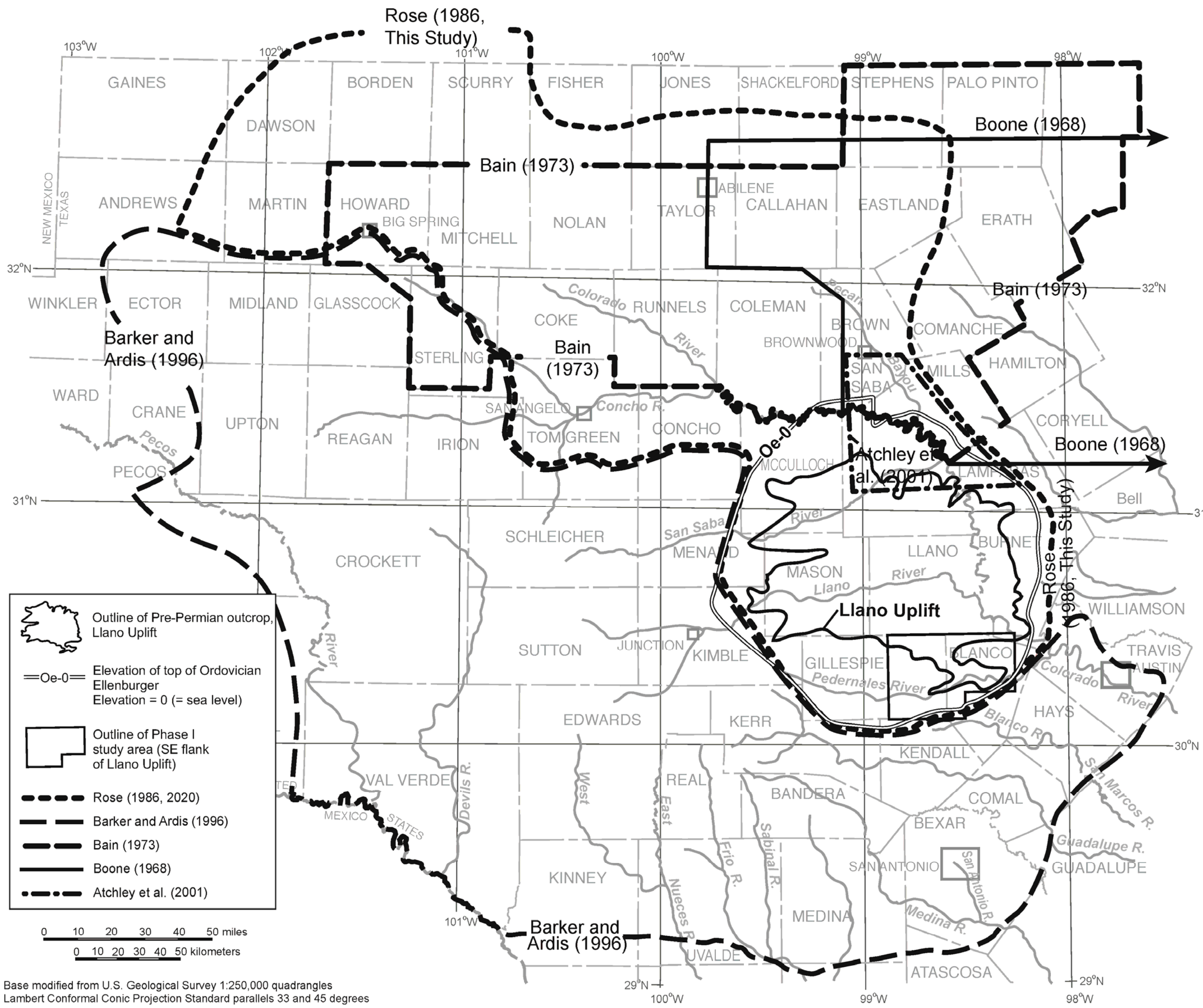

Figure 8. Areas of study by previous investigators of Wichita Paleoplain.

Bain (1973) Mapping

Working mostly west and north of Boone's (1967) project area (Fig. 8), Bain (1973) traced the contact between the Lower Cretaceous Antlers Sand and whatever formations lay immediately beneath it—in eastward succession, the Triassic, Permian, or uppermost Pennsylvanian—along the Callahan Divide, that series of Edwards Limestone outliers that caps and protects the underlying, less resistant Antlers Sand outcrops that rest on the WPP. Consistent with Boone's (1967) findings, Bain (1973) showed that the WPP was an undulating surface that dips gently E and ESE at about 12–15 feet per mile. In the western part of Bain's (1973) study area, in Mitchell, Sterling, Nolan, Coke, Taylor and Runnels counties, his derivative mapping suggested several very gentle, linear, subparallel troughs in the WPP bearing east-southeast across the area, some of which appear to line up roughly with segments of modern stream courses, such as Bain's (1973) "Sterling valley" with the lower segment of the North Concho River, in eastern Sterling County; his "Howard valley" with the Colorado River in Coke, Runnels and Coleman counties; and his "Taylor valley" with the upper drainage of Pecan Bayou, in Coleman and Brown counties. None of Bain's (1973) "valleys" compare in magnitude with analogous valleys of Boone's (1967), however, and certainly not with the precursor San Saba and Llano river valleys of the Llano Uplift area.

Atchley et al. (2001) Mapping

In this largely stratigraphic study, Atchley et al. (2001) followed outcrops of basal Cretaceous terrigenous clastic formations along the east side of the valleys of Pecan Bayou and Colorado River, through Brown, Mills, and Lampasas counties. Those formations rest unconformably upon alternating fluvial to coastal sandstones and shales of the Pennsylvanian (Des Moines) Strawn Group along that transect, which terminates southward where the basal Cretaceous sands pinch out, and the overlying Glen Rose Formation rests on the Paleozoic. The purpose of the Atchley et al. (2001) study was to measure the erosional relief and topographic orientation of basal Cretaceous channels and ridges on the WPP.

Based on closely spaced measurements along the outcrop of the WPP, they found that the paleotopography of the unconformity was shaped by differential erosion of northwest- dipping Strawn sandstones and shales, which generated a pre-Cretaceous trellis drainage dominated by northeast-trending ridges and swales. Troughs on the WPP are typically underlain by shale

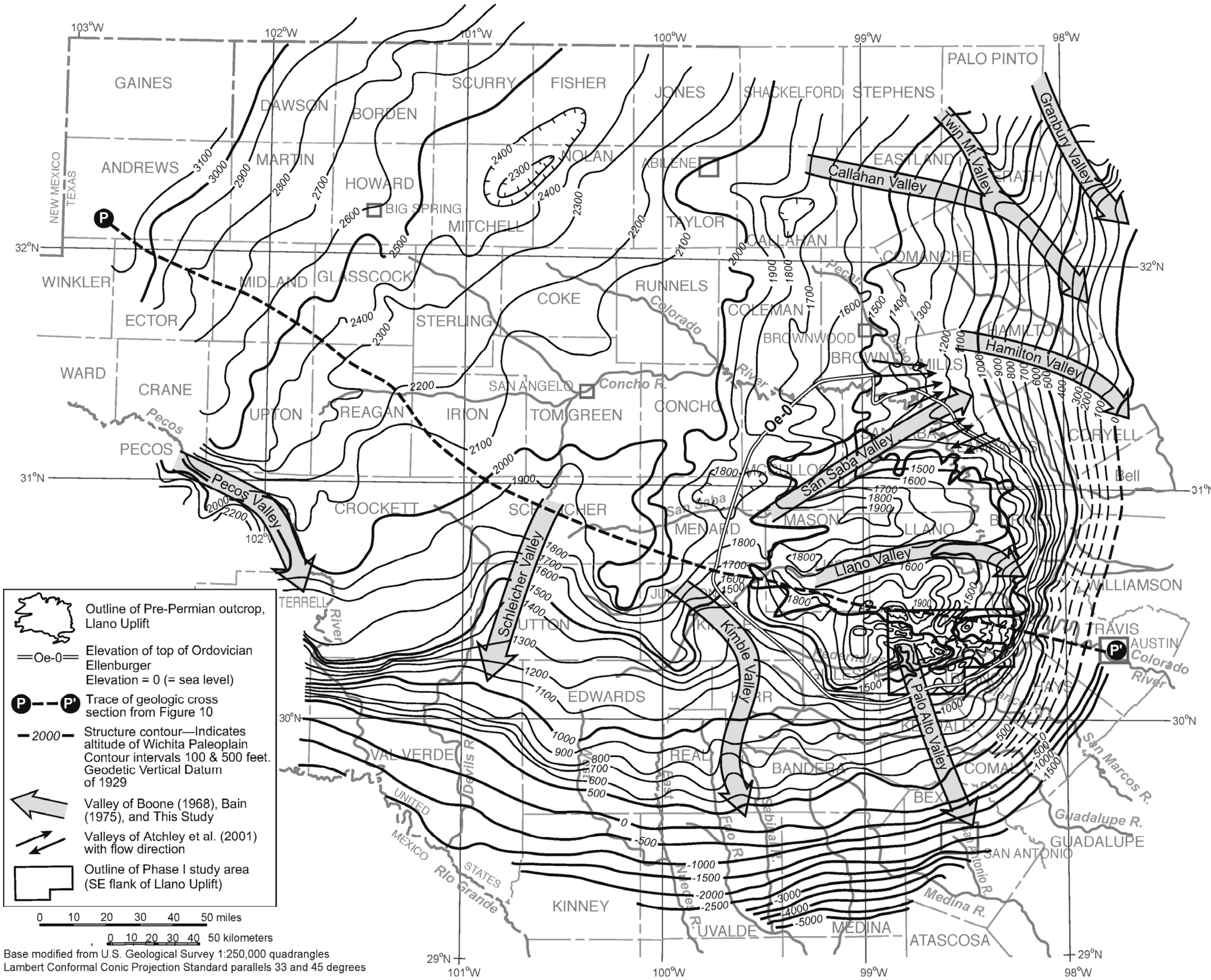

Figure 9. Regional paleotopographic map of present-day Wichita Paleoplain (surface and subsurface), Central Texas, showing trace of cross-section P–P', and apparent paleovalleys (modified after Barker and Ardis, 1996).

members of the Strawn Formation, whereas ridges are commonly underlain by sandstone members. For the most part, local paleotopographic relief on the WPP ranges up to about 100 feet, indicating "valleys" which all drain to the northeast. However, a low segment of the outcrop belt in southern Mills County is more than 150 feet lower than adjacent high WPP outcrops; this deeper valley lines up with the WPP precursor of the San Saba River valley. Further, a segment of the WPP outcrop 3–4 miles wide in western Lampasas County is 150 feet lower than adjacent outcrops. Two sets of paired troughs and ridges on the WPP in that sector appear to open up to the southwest, rather than the northeast, suggesting they may represent tributaries of a precursor Colorado River.

It should be emphasized that, with the two aforementioned exceptions, all of the ridges and troughs identified by Atchley et al. (2001) are much smaller features than the pre-Cretaceous Llano and San Saba valleys discussed in the previous section on the Llano Uplift, and resemble more closely those identified by Boone (1968).

Atchley et al. (2001) recognized two separate formations within the overall basal Cretaceous sandstones in their area of study: (1) a lower chert-pebble conglomerate derived mostly from Ordovician Ellenburger Group, which they assigned to the Sycamore Formation; and (2) an upper medium-grain sandstone which they assigned to the Travis Peak Formation, equivalent to and continuous with the Aptian Hensel Sandstone of the Llano Uplift. Both formations contain abundant evidence of in situ paleocaliche.

As initial deposits of the regional Lower Cretaceous transgression, the Sycamore Conglomerate was interpreted by Atchley et al. (2001) as braided-stream deposits formed as alluvial fans draining northeastward from highlands of the Llano Uplift, that partially filled valleys on the WPP. The "Travis Peak" sands that succeeded them—equivalent to and continuous with the Hensel Sandstone of the Llano Uplift—Atchley et al. perceived as meandering fluvial deposits draining northeastward across a sloping outwash plain north of the Llano Uplift, that filled valleys and finally capped low divides on that landscape. The Hensel grades upward and laterally into coastal Glen Rose strata.

Barker and Ardis (1996) Mapping

With respect to the WPP, by far the largest area of subsurface mapping west and north of the Llano Uplift was carried out by Barker and Ardis (1996) in connection with a U.S. Geological Survey Water Resources study of the Edwards-Trinity Aquifer of the Edwards Plateau. Figure 9 shows the WPP rising regularly from the Llano Uplift northwest over about 200 miles, from about +1900 feet to more than +3200 feet in Ector, Andrews, and Dawson counties, an average rise of 6.5 feet per mile. As also noted by Sobehrad (2011), this regular slope seems to be independent of whatever pre-Cretaceous strata underlie the WPP: the WPP subcrop consists of Pennsylvanian and older formations east of western Real, western Kerr, central Kimble, central Menard, and western McCulloch counties. To the west, the WPP is developed on Permian rocks. Farther northwest, it rests on Triassic strata. Thus, the hiatus between the WPP subcrop and the Lower Cretaceous strata that rest upon it is greatest in the center of the Llano Uplift and diminishes steadily northwestward. Clearly, the erosional vacuity represents more geologic time (Precambrian through Jurassic) than the period represented by the Early Cretaceous transgression (early Aptian through Albian).

As mentioned earlier, the WPP's extended northwesterly rise reflects Neogene uplift of the Colorado Plateau (Galloway et al., 2011; Ewing, 2016). The only substantial departure from this regular sloping surface is a prominent, narrow, sinuous ridge, delineated by the +2000 foot contour, that extends southward for about 50 miles, from central Concho County through western Menard, northwestern Kimble, and northeastern Sutton counties. Paleotopographic relief of this ridge is 100 to 200 feet. Northwestward from this ridge, the WPP rises consistently at about 6 feet per mile. This sinuous ridge lies on the east side of the Fort Chadbourne Fault Zone, a north-south trend of mostly right-lateral wrench faults that strike consistently north-northeast and involve Pennsylvanian and older Paleozoic formations. The Fort Chadbourne fault trend appears to be related genetically to the faults of the Llano Uplift, which have been shown here to affect paleotopography of the WPP.

On the west side of the aforementioned ridge, mostly in Schleicher and Sutton counties, is a broad sag that opens toward the south. The contour pattern here suggests four gentle drainage-ways on the WPP that converge in western Sutton County, flowing southward toward the Rio Grande Embayment. This drainage is here termed the Schleicher valley.

Other noteworthy features of the Barker and Ardis (1996) mapping, shown on Figure 9, include:

(1) an apparent valley on the WPP that coincides with the present course of the Pecos River for more than 50 miles in western Crockett County, originally noted by Jager (1942);
(2) a broad anticlinal nose overlying the Ozona Arch in northwestern Crockett County;
(3) a gentle southerly nose in northwestern Edwards County overlying the Edwards Arch; and
(4) abruptly steepening south dip to about 50 feet per mile over the Brown-Bassett anticlinal feature in northern Val Verde County, north of the Devils River Uplift.

Any smaller-scale topographic features of the WPP, such as erosional valleys or buried ridges, would seem to be beneath the scale of portrayal on this map.

Throughout the area of most of the Barker and Ardis (1996) mapping, the Basal Cretaceous Sand (Smith and Brown, 1983) is described as braided-stream and other related alluvial deposits ranging from zero to >300 feet thick, consisting of terrigenous rock material derived chiefly from formations upon which the WPP rests. The lower part of the succession is generally conglomeratic, fining upward to calcareous mudstones, the same general depositional sequence described by Atchley et al. (2001).

Rose (1986, 2020) Mapping

Rose (1986, 2020) generated geological structural mapping of the base of the Edwards Limestone as well as the base of the Cretaceous (= WPP) across much of North and West Texas, primarily from 1:250,000 GAT maps (Barnes, 1970–1983). Also, whenever previous mapping by different workers is synthesized into one interpretation, decisions and compromises are required. In that vein, a limited amount of additional mapping has been carried out by the author in the North Texas area.

WPP in Central Texas as Restored to Early Cretaceous Configuration

As previously noted, the present elevation and configuration of the WPP (Fig. 9) reflects past distortions introduced by different geological events and influences. Restoring it to its Hensel-age elevation and geometry requires sequential steps of graphical manipulation, as illustrated on a regional geological cross-section (Fig. 10). Three separate steps are required, as described in detail in the Appendix:

(1) correcting for Albian-through-Pleistocene regional tilting using the base of the peritidal Edwards Limestone (bKed) as a proxy for middle Albian sea level (Figs. 11 and 12);
(2) correcting for the crescent-shaped wedge of Glen Rose sediment that thickens gulfward from Central Texas into the Rio Grande and East Texas embayments (Figs. 13 and 14); and
(3) correcting for Balcones Uplift by returning the WPP to its regional early Hensel elevations (Figs. 15 and 16).

It is important to point out here that the trends of the various "valleys" shown on previous Fig. 9 may shift their positions slightly on subsequent maps as the WPP is restored to its Hensel configuration.

Effects of Restoration

The result of this restorative procedure is shown on Figure 12, which represents a reasonably close approximation of the configuration of the WPP at the beginning of Edwards Limestone deposition (Albian) over the northwestern half of the map area, in relation to its present elevation.

The overall effect of the restorative process is to "soften" the topography—to reduce the overall amount of topographic relief on the WPP. Above the zero subsurface contour, the total vertical relief on the mapped surface, across the entire map area, is about 3200 feet (Fig. 9), whereas the equivalent vertical relief on the restored map (Fig. 12) is a little less than 1400 feet. In the area of greatest local topographic relief, the Llano Uplift, maximum topographic relief is nearly 500 feet; on the restored map, it is about 300 feet.

But other topographic effects accompany restoration: the narrow, sinuous paleotopographic ridge winding southward from Concho County between Schleicher and Menard, thence between Kimble and Sutton counties (Fig. 9), appears as a broader, less prominent topographic high on the restored map (Fig. 12). The aforementioned nose over the Ozona Arch in Crockett County on Figure 9 appears as a low-relief closed domal feature on the restored Figure 12. The prominent belt of steep south dip along the Val Verde–Crockett County boundary on Figure 9 becomes an elongated east-west ridge on Figure 12, apparently overlying the Brown-Bassett structure north of the Devils River Uplift. The gentle south-plunging nose in northwestern Edwards County on Figure 9 appears as a domal hill closed by the +1500 foot contour on Figure 12.

Other significant differences include topographic features that suggest hitherto unsuspected ancient drainage systems on the restored map shown on Figure 12.

(1) No evidence of a south-flowing precursor Colorado River appears near its present-day location on the eastern flank of the Llano Uplift, but the previously mentioned San Saba precursor stream appears to continue eastward across

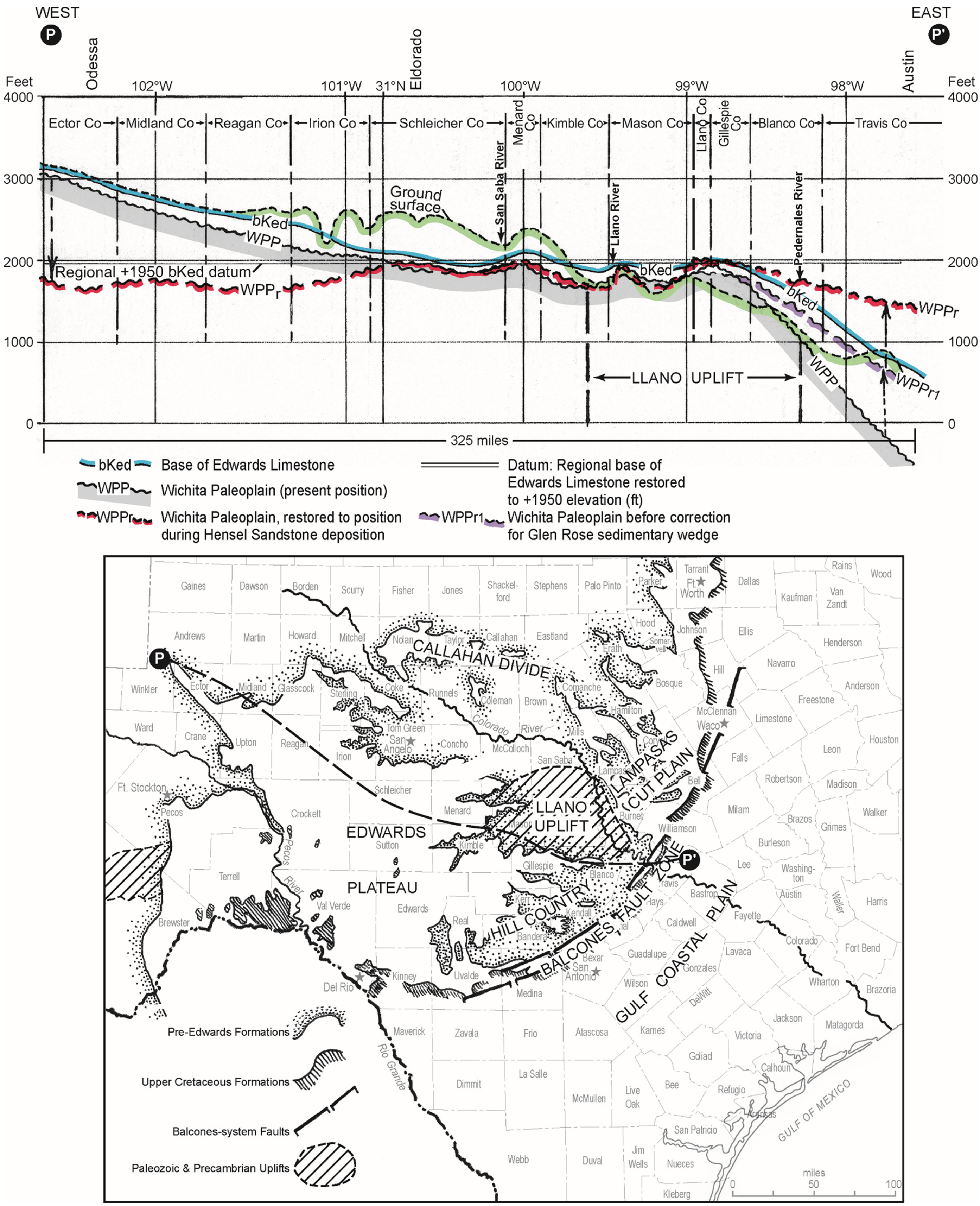

Figure 10. Regional geologic cross-section P–P', showing present (WPP) and restored (WPPr) topography of Wichita Paleoplain, in relation to present ground surface, base of Edwards Limestone (bKed), and position of datum (bKed + 1950) used for restoration of Wichita Paleoplain to earlier configurations.

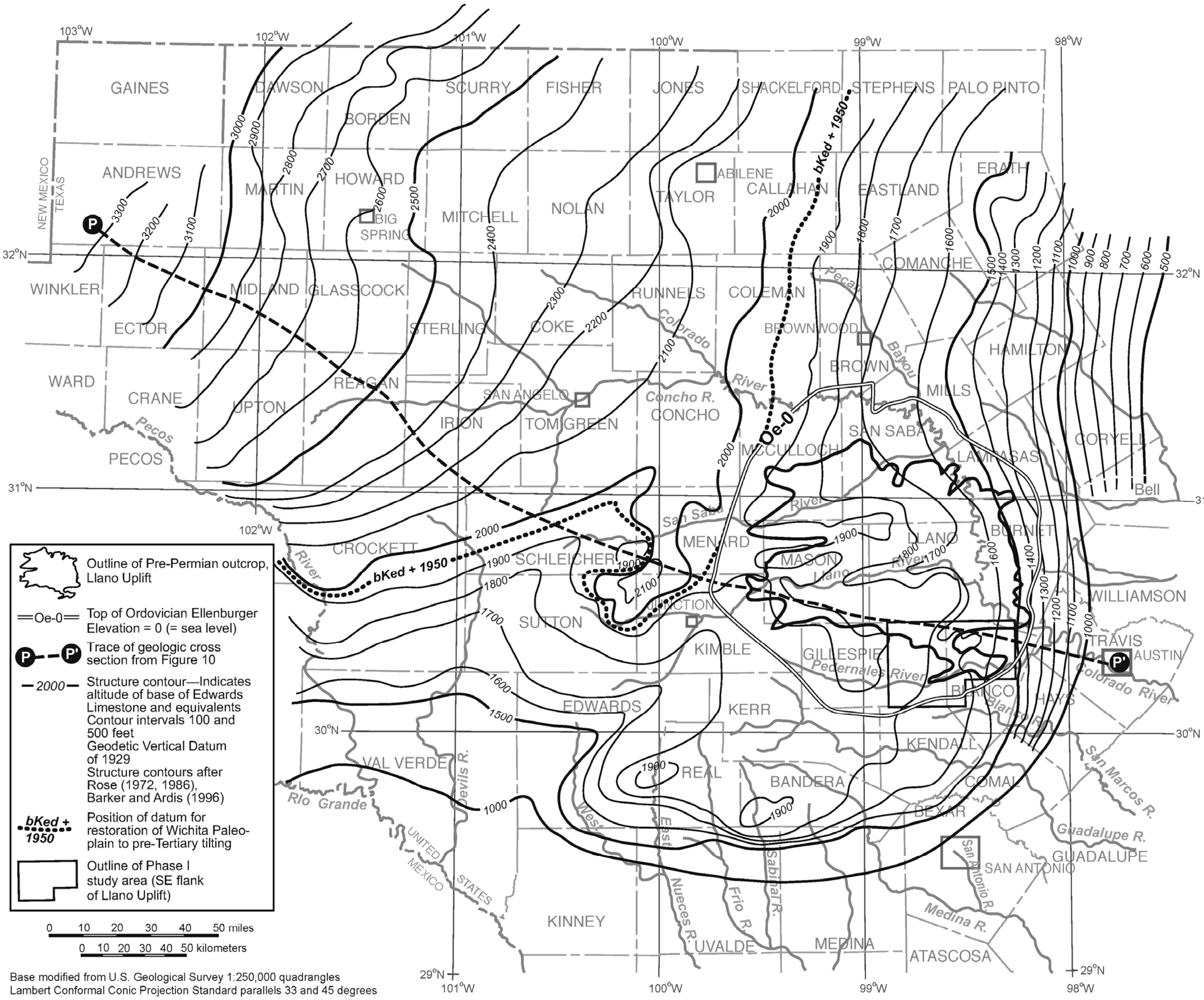

Figure 11. Regional geologic structure on base of Edwards Limestone and equivalents, Central and North Texas, showing trace of cross-section P–P' and position of datum (bKed + 1950) used for restoration of Wichita Paleoplain to configuration at beginning of Edwards deposition (modified after Rose, 1986).

Mills, southern Hamilton, and Coryell counties toward the East Texas Embayment;

(2) The aforementioned Twin Mt. valley of Boone (1968) trends southeastward across Eastland and Erath counties into Bosque County;

(3) The Callahan valley of Boone (1968) bears southeastward across Callahan, northern Brown, and southern Comanche counties into Hamilton County where it appears to join the precursor San Saba drainage;

(4) A short segment of an east-flowing apparent Colorado River precursor is present between Coleman and McCulloch, and Brown and San Saba counties, which appears to join the San Saba valley in Mills County;

(5) Although the precursor Llano River valley is still present, restoration appears to have rendered it less conspicuous, and its eastward trend appears to deflect southeastward toward the present course of the modern Colorado River;

(6) Prominent valleys appear, flowing southeastward and southward:

   (a) from north-central Gillespie County across Kendall County, toward the Rio Grande Embayment; this valley may be a southward extension of a precursor of the Palo Alto Creek drainage (east of Fredericksburg) discussed previously;

   (b) from Menard County southward across Kimble, Kerr, and western Bandera counties toward the Rio Grande Embayment, described earlier as the Kimble valley; and

   (c) from northeastern Schleicher County southward across Sutton and central Edwards counties, toward the Rio Grande Embayment previously discussed as the Schleicher valley; and

(7) A broad, gentle, southwest-trending precursor valley of Live Oak Draw, an eastern tributary of the present Pecos River, in Sterling and Reagan counties, that probably terminates against the aforementioned Pecos River valley of Jager (1942).

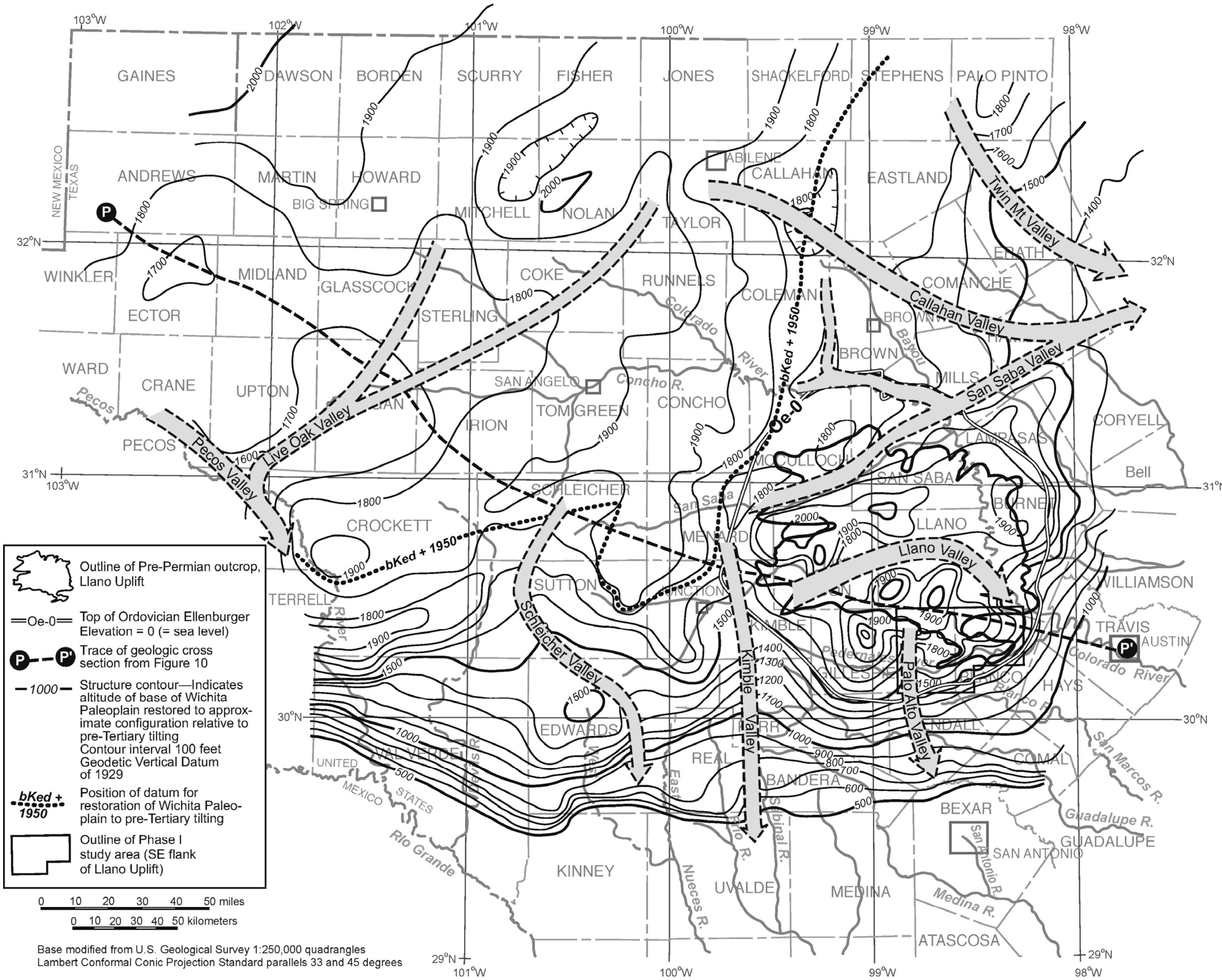

Figure 12. Regional paleotopography of Wichita Paleoplain, restored to configuration at beginning of Edwards deposition (Albian stage, 105 Ma), showing trace of cross-section P–P', position of datum (bKed + 1950) used for restoration of Wichita Paleoplain, and apparent valleys.

Conversion of WPP Configuration to Early Hensel Configuration

A second step in the restoration process entails the conversion of the map shown on Figure 12 to that on Figure 14, by eliminating the effect of the crescentic wedge of Glen Rose sediments that curves around the buttress of the Llano Uplift, beneath the Edward Limestone (Fig. 13).[3] The resulting map (Fig. 14) depicts the WPP as a remarkably flat, rolling plain having elevations ranging from 1500 to 2000 feet. It should be noted that these elevations still reflect the present elevation of the WPP, not its elevation with respect to Hensel sea-level.

Most of the valleys previously identified on Figure 12 are still apparent on Figure 14, in clockwise order: the Callahan, San Saba, Llano, Palo Alto, Kimble, and Live Oak valleys. The Schleicher valley, however, has shifted from a southerly course on Figure 12 to a southwesterly course, joining with the precursor Pecos River drainage on Figure 14, just north of the Rio Grande-Pecos junction. Other dramatic changes involve ranges of hills overlying high-standing Paleozoic structures, such as:

(1) the ridge attending the Fort Chadbourne Fault Zone, which bears south and southwest, culminating in the Edwards Arch and Devils River Uplift;
(2) a linear ridge trending southwest from western Schleicher County across southern Crockett County, where it seems to overlie the Brown-Bassett structure north of the Devils River Uplift; and
(3) a low domal feature in western Crockett County that overlies the Ozona Arch.

Conversion of WPP Elevations to Early Hensel Elevations

The final step in the restoration process involves the approximate location of the Hensel shoreline, the elevation that corre-

[3]Cartwright (1932) also recognized and mapped this Glen Rose wedge.

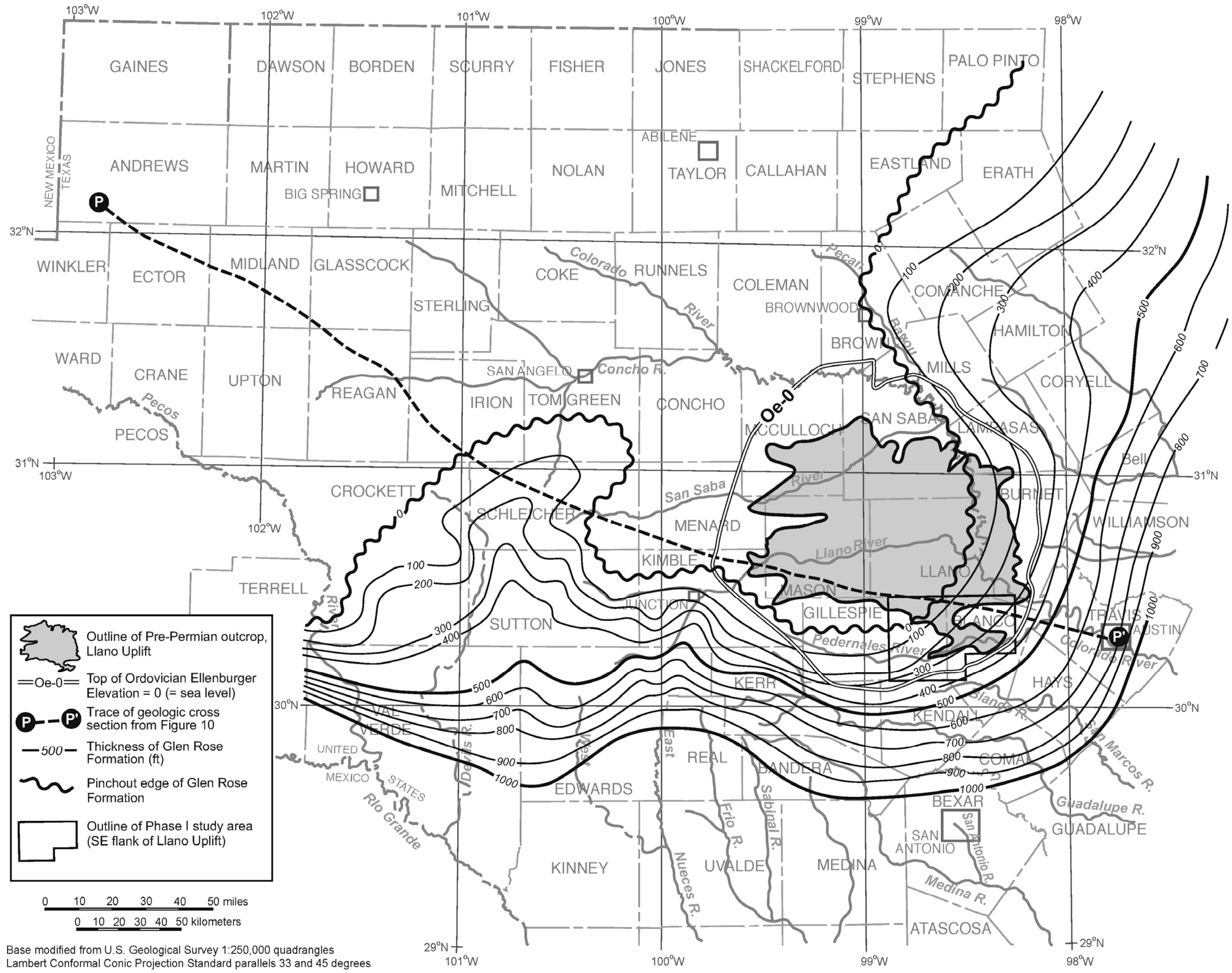

Figure 13. Thickness of Glen Rose and equivalent formations used in final restoration of Wichita Paleoplain to time of early Hensel deposition (Aptian, 115 Ma), and trace of cross-section P–P'.

sponds to that contour, the designation of that contour as approximate Hensel sea level, and the renumbering of higher contours consistent with the designated sea-level contour. The approximate position of depositional strike where the Hensel Formation grades laterally from alluvial and coastal-plain terrigenous clastics into peritidal and shallow-marine deposits (Wierman et al., 2010) coincides roughly with the 1600 foot contour of Figure 14, and also coincides approximately with the updip pinchout edges of the Cow Creek, Hammett and Sycamore formations along the steepening regional dip of the Balcones-Ouachita Downwarp. Renumbering the 1600 foot contour to zero, and renumbering higher contours accordingly, accomplishes the final step in the conversion process, and eliminates the effects of Balcones Uplift in the early Miocene (Fig. 15).

Topographic features such as valleys or ranges of hills are unchanged from Figure 14.

The Landscape of the WPP at the Beginning of Hensel Deposition

Like the time-transgressive terrigenous clastic sediments that migrated northwesterly across Central and North Texas at the base of the Lower Cretaceous invasion, the WPP is also of different ages: around the subsiding margins of Central Texas, the ancient landscape is slightly older than it is on the higher reaches of the Llano Uplift, where basal Cretaceous transgressive sands were last to be deposited. Figure 15 attempts to correct for that effect.

At a regional scale, the WPP was remarkably flat (Fig. 15), from a coastal plain fronting an arm of the East Texas Basin, rising almost imperceptibly westward over 250 miles across most of north-central and northwest Texas, to an elevation of about +400 feet, a slope of less than 2 feet per mile. In the northeastern sector of the outcrop area, a low-relief drainage system flowed eastward toward the East Texas Embayment.

Farther south, in the Llano Uplift and surroundings, local topography was greater, with eastward-flowing valleys and divides showing up to 100 feet of local erosional relief, and the San Saba and Llano precursor valleys each more than 150 feet deep. Southward, the lower Hensel shoreline swung steadily southwestward, then westward, creating a broad, dissected coastal promontory facing south. The terrain rose steadily northward toward a range of hills as much as 500 feet higher than the southern coastline. These hills were the surface expression of the Llano Uplift,

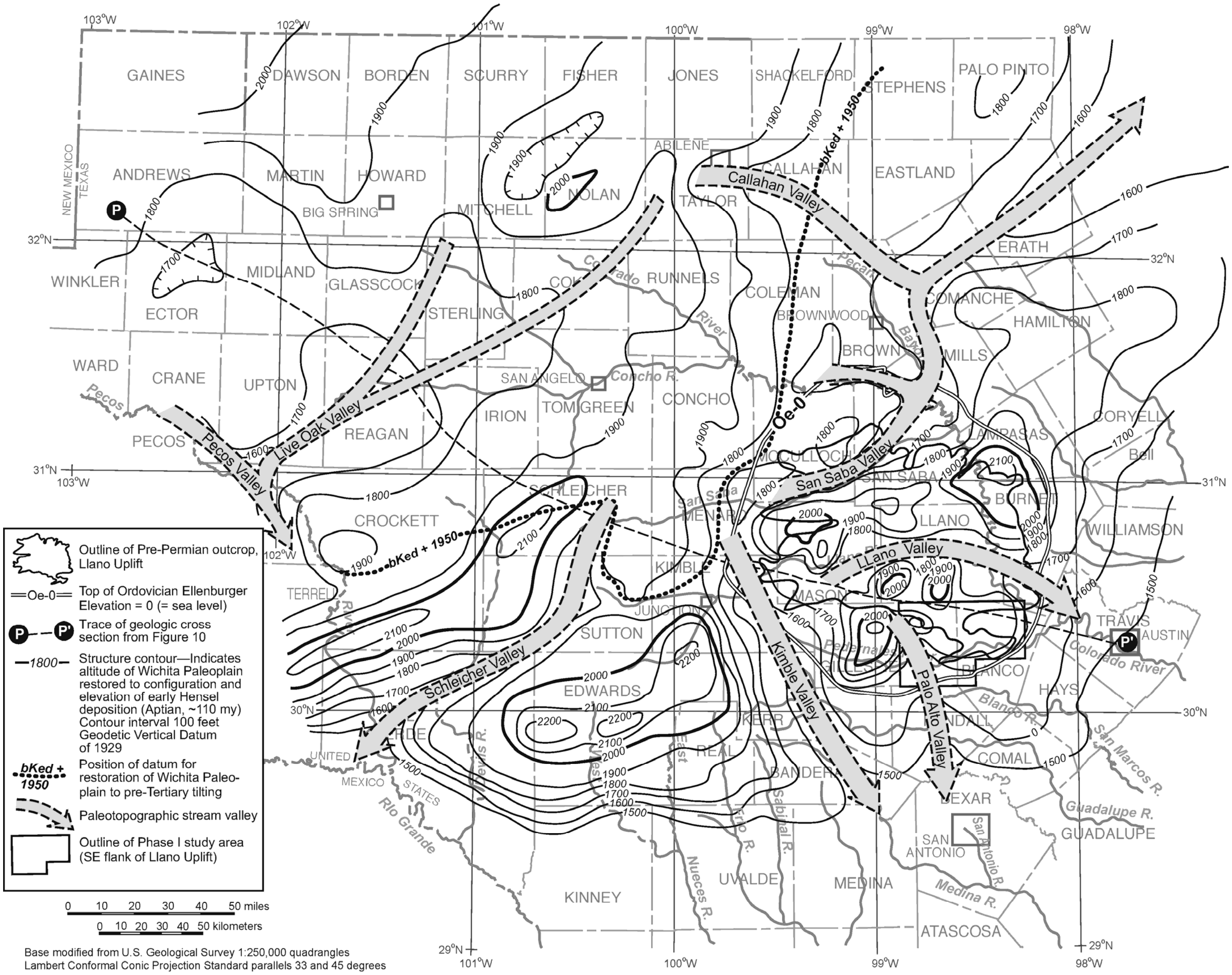

Figure 14. Paleotopography of Wichita Paleoplain, restored to configuration (but not elevations) existing at start of Hensel Sandstone deposition (Aptian, 115 Ma), showing trace of cross-section P–P', position of datum (bKed + 1950) used for restoration of Wichita Paleoplain, and apparent valleys.

a dissected domal uplift underlain by faulted Paleozoic carbonate strata and massive Precambrian crystalline rocks. Local topographic relief of 200–300 feet was common, characteristically adjacent to high-standing fault blocks of Paleozoic carbonate strata. Three closed highs on the WPP >+400 feet were present on the south side of the Llano valley; to the north, two larger closed highs >+400 feet lay along the divide between the Llano and San Saba valleys.

The slope of the WPP was consistently steeper all along the south Hensel coast, toward the Rio Grande Embayment, generally 15 to 25 feet per mile. Three short, high-gradient valleys trended southeastward and southward from the Llano hills toward the Rio Grande Embayment.

During early Hensel deposition, the Llano Uplift was bisected by the valley of the east-flowing precursor of the Llano River, and parallel on the north, the counterpart San Saba valley, each 100–300 feet lower than the divides on either side. North of the broad divide on the north side of the precursor San Saba valley, lay a short tributary valley, possibly a precursor segment of the Colorado River.

On the east side of the Fort Chadbourne Fault Zone, was an elongated closed high >300 feet above Hensel sea level. High-standing Paleozoic fault blocks underlay all such closed highs on the WPP.

West of the Llano Uplift, the WPP was a broad, gentle, rolling prairie 200 to 600 feet above Hensel sea level. Three low-relief topographic highs were present on this surface:

(1) A broad, undulating Y–shaped ridge defined by the 300 foot contour, stretching from eastern Runnels County southward and westward across Concho, southeastern Tom Green, eastern and western Schleicher, and eastern and western Sutton, and southern Crockett counties, related to the Fort Chadbourne Fault Zone and the Brown-Bassett Anticline. On the east side of the Fort Chadbourne Fault Zone was an elongated closed high >300 feet above Hensel sea level. High-standing Paleozoic fault blocks underlay all such closed highs on the WPP;

(2) A west-bearing ridge across Crockett County, culminating in a low domal closure on the +300 foot contour, reflecting the Ozona Arch; and

(3) A prominent east-west anticlinal ridge in southern Edwards County, defined by the +400 foot contour, coincident with the Medina Arch (Rose, 1972, 2016), and overlying the Paleozoic Edwards Arch.

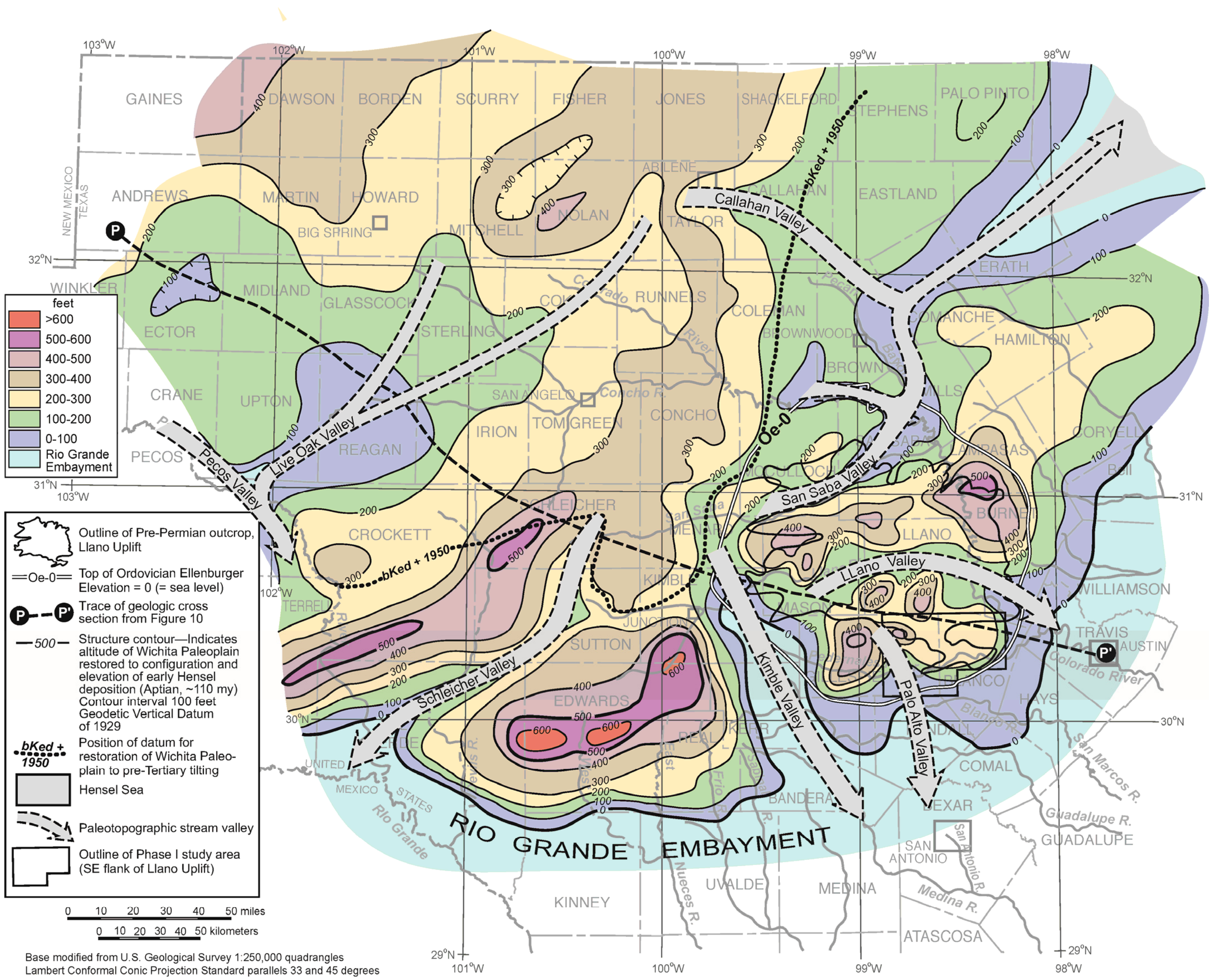

Figure 15. Paleogeography of Central Texas in Aptian time (115 Ma), showing topographic configuration and elevations then existing, trace of cross-section P–P’, position of datum (bKed + 1950) used for restoration of Wichita Paleoplain, apparent valleys, and location of Rio Grande Embayment shoreline.

SUMMARY

The WPP is a vast, early and middle Mesozoic relict landscape that covered most of Texas and southern Oklahoma. Much of it is buried deep in the subsurface of the Gulf Coast Basin. It is present at the outcrop across Central, West, and North Texas, and in the shallow subsurface beneath the Edwards Plateau. Across most of north-central Texas, the WPP is a long-evolving, remarkably flat paleosurface developed upon gently dipping, weakly indurated Permian and Triassic strata. Probably no more than 100–200 feet of rock debris was removed, by weathering, solution, and erosion, during the 170 million years represented by the Permian, Triassic, Jurassic, and first 30 million years of the Early Cretaceous periods (Fig. 9). Farther south, however, in the vicinity of the Llano Uplift, as much as 5000 feet of Paleozoic and Precambrian rock, uplifted during the Ouachita Orogeny (Fig. 5), were removed before the WPP was developed upon ancient terranes represented by a range of hills rising as much as 600 feet above Hensel sea level (Fig. 15). Local topographic relief of 100 to 300 feet was common. The WPP is similarly undulating in several analogous areas to the west, where it also overlies terranes deformed by Ouachita tectonics, such as the Fort Chadbourne Fault Zone, the Edwards Arch, the Devils River Uplift, the Brown-Bassett Anticline, and the Ozona Arch.

Infill of WPP Topography by Lower Cretaceous Formations

Over most the southern half of the area (Fig. 15), the transgressive Hensel\Glen Rose\Edwards succession filled in valleys on the WPP, first with Hensel fluvial terrigenous clastic sediments, then with Glen Rose coastal-plain mudstones and peritidal marls. Eastward and northeastward, over the Balcones-Ouachita Downwarp, a slightly older succession, the Sycamore Conglomerate, rests on the eroded WPP. Farther northeast, basal Cretaceous sandstones assigned to the Travis Peak or Antlers formations fill in erosional topography on the old paleosurface. The thick regional blanket provided by the Edwards Limestone, consisting of peritidal and shallow marine carbonate sediments, finally obliterated the underlying topography, so that the top of the Edwards Group is today mostly a regular surface sloping very gently eastward from the Edwards Plateau, arching gently over

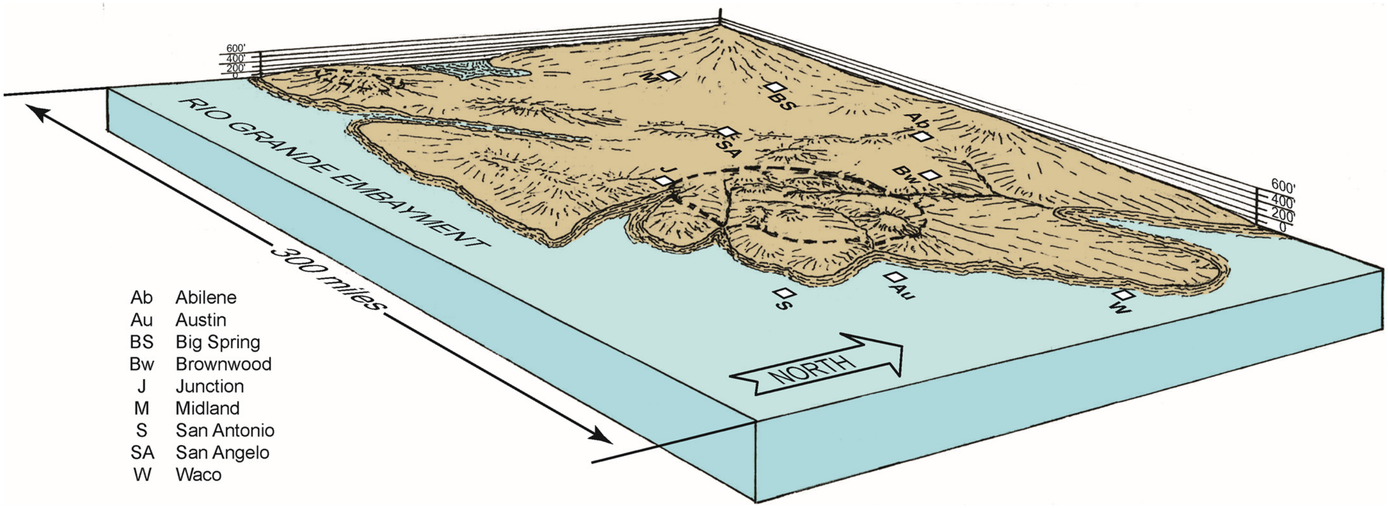

Figure 16. Block diagram showing Wichita Paleoplain landscape at start of Hensel deposition and shoreline of Rio Grande Embayment. Dashed ovals indicate Llano Uplift and Brown-Bassett structure; lettered squares indicate approximate locations of towns for purposes of orientation.

the Llano Uplift, then resuming its eastward dip, steepening gulfward over the Balcones-Ouachita Downwarp.

Hensel Sandstone Thickness as an Indication of Topographic Elevation of WPP

In the Llano Uplift, the Hensel Sandstone is thickest where the underlying WPP occurs in valleys, which are commonly developed on deeply weathered Precambrian granites, gneisses, and schists. The Hensel is thinnest (or absent) where it overlies (or onlaps) high-standing Paleozoic fault blocks, as discussed previously. In the mapped area on the southeast flank of the Llano Uplift (phase one), "bald-headed" structures—areas where Glen Rose Formation or even Edwards Limestone rest directly upon eroded Paleozoic strata, with Hensel Sandstone missing—are common (Digital Map 5). The area where the two largest bald-headed structures are located—the Round Mt. and Cave Creek "highs"—in eastern Gillespie and western Blanco counties, may represent the topographic apex of the Llano Uplift during Hensel deposition.

Examination of Figure 15 indicates that the Hensel Sandstone must have transgressed the WPP northwestward from the ancestral gulf toward the crest of the southern lobe of the Llano Uplift, rising about 500 feet in about 30 miles, or about 15 feet per mile. North of the Llano Uplift, however, the elevation of the WPP remained remarkably level, at elevations of 200–400 feet above Hensel sea level.

Coincidence of Topographic Features

The influence of the WPP on the subsequent Cretaceous depositional cycle, as well as its effects on the succeeding Tertiary erosional cycle, have been widespread, substantial, and often surprising, especially considering the thick regional blankets of peritidal and marine- shelf carbonate sediments—the Lower Cretaceous (Albian) Edwards Group and the Upper Cretaceous (Coniacian-Santonian) Austin Chalk—that covered the entire region. The erosional landscape that developed after Balcones faulting and uplift was probably developed mostly upon the widespread resistant carbonate sheet of Edwards Limestone that mantled the area now known as the Hill Country and eastern Edwards Plateau (Rose, 2019).

The most striking examples of the influence of WPP topography on the modern landscape of Central and North Texas is the correspondence of the present-day Llano and San Saba river valleys with remarkably similar valleys on the underlying WPP (Figs. 7, 9, 12, and 14). A related phenomenon is the prevailing association of outlying Edwards Limestone outcrops with underlying high-standing Paleozoic fault blocks.

The obvious question is, "how did such topographic features redevelop over their buried paleotopographic counterparts, given that a consistently thick (>400 feet) regional blanket of subhorizontal Edwards Group peritidal carbonate strata intervened between the WPP and the evolving ground surface of the region throughout the 65 million years of Tertiary subaerial exposure and erosion?" One clue is the observed "drape" of Edwards outliers around the edges of underlying highs on the Glen Rose, Hensel, Paleozoic, or even Precambrian.

The offered explanation, first advanced by Cartwright (1932) and here augmented, involves differential compaction of Hensel and Glen Rose strata that thin toward the crest of such buried hills: more compaction where such formations are thicker, less where they are thinner. The historical sequence is important:

(1) Approximately 600 feet of Upper Cretaceous Austin Chalk and Taylor-Navarro marine marl that was deposited above Edwards Group carbonates (and with them, contributed to Hensel and Glen Rose compaction), was eroded away from the Hill Country and Edwards Plateau mostly during the Paleogene, exposing the regional Edwards carbonate blanket.

(2) This was followed by Balcones faulting and uplift, immediately initiating major regional erosion, characterized by westward and northward erosional retreat of Edwards Plateau margins during the Neogene (Rose, 2016, 2019).

(3) When resistant Edwards carbonates were widely exposed after Balcones faulting and uplift (Rose, 2019), low-amplitude swales and swells were exposed on resistant limestone strata, the consequence of previous differential compaction. Such gentle undulations served as precursors of future valleys and hills, and eventually modern drainage basins that reflected underlying WPP drainage basins. Such differential compaction also explains the remarkable coincidence of outliers of outcropping Edwards Limestone with underlying high-standing fault blocks. The additional contribution of isostatic adjustment to such geological patterns needs further investigation.

Regional Stream Drainage on WPP

Based upon the restored paleotopographic map of the WPP at the onset of Hensel deposition (Fig. 15) and the counterpart block diagram (Fig. 16), the restored landscape of Central and North Texas, and especially the stream drainage patterns associated with the WPP, was very different from the stream pattern of today, which has evolved after Balcones faulting and uplift (Rose, 2019).

First, the position of the Hensel shoreline fixed the destination for all streams in the map area. The Hensel shoreline described a giant arc 400 miles long, trending south from the western margin of the East Texas Embayment into Central Texas, then veering southwest and west, forming the northern coastline of the Rio Grande Embayment, before finally veering northwest approaching the present Rio Grande River. The dissected uplands of the Llano Uplift provided a topographic buttress around which the Hensel shoreline curved symmetrically, at a consistent distance of 15–20 miles.

Second, the Hensel stream drainage system was different from the stream drainage system that developed after Balcones faulting and uplift (Rose, 2019). Low-volume, low-gradient streams in the Twin Mt. and Callahan valleys flowed southeasterly into the East Texas Embayment. Farther south, the precursor San Saba River flowed northeasterly in its valley, counterpart of its modern course, across McCulloch and San Saba counties, where it was joined by an attenuated segment of the future Colorado River. The conjoined streams apparently continued eastward across Mills and Hamilton counties, where they joined the Callahan valley in Comanche County, near the shoreline of the East Texas Embayment. This interpretation implies that the present Colorado River did not assume its present course until after Hensel deposition, and before Balcones faulting (Rose, 2019). The precursor stream to the present Llano River followed the same course it does today, eastward across Mason and Llano counties, turning south and possibly following a short southward course to empty into the ancestral Gulf of Mexico near the mouth of the precursor Pedernales River. Four short streams flowed southeast and south from the hills of the Llano Uplift and faulted Paleozoic terranes farther west, into the Rio Grande Embayment:

(1) the Palo Alto Creek precursor;
(2) the Kimble valley;
(3) the Schleicher valley; and
(4) the Live Oak valley and ancestral Pecos valley.

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I thank all these friends for their suggestions. Any errors of fact or omission are, however, entirely my own responsibility.

This paper is dedicated to the memory of the late Dennis Trombatore, Chief Librarian of the Walter Geological Library at the Jackson School of Geoscience, University of Texas at Austin, and to recently departed members of the Austin Geological Society, all victims of Covid 19: Gerry Wermund, Dwight Cassell, and Jim Sansom.

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APPENDIX—METHODS

Phase One: WPP on the Southeastern Flank of the Llano Uplift

The first phase of the project was to map the paleotopography of the WPP, where existing high-quality geological and topographic mapping enabled detailed contour maps to be constructed of geological structure, thickness, and stratigraphy of formations overlying the WPP—the Hensel Sandstone, and the Glen Rose Formation (including its contact with the overlying Edwards Limestone). A suite of 13 7.5–minute geologic quadrangle maps by Virgil Barnes and others of the Texas Bureau of Economic Geology (Barnes et al., 1947–1982), along the southeast flank of the Llano Uplift, provided the basic data (Blowout [1947], Willow City [1952], Cain City [1952], Crabapple Creek [1952], Palo Alto Creek [1952], Johnson City [1963], Rocky Creek [1965], Hye [1965], Stonewall [1966)], Cave Creek School [1967], Howell Mountain [1978], Round Mountain [1978], and Pedernales Falls [1982]). The first five geologic maps were planimetric, so had to be "fitted" to more recent counterpart U.S. Geological Survey topographic quadrangle maps. A base map of each quadrangle was first constructed showing distribution and elevation of geologic boundaries between pre-Cretaceous (Lower Paleozoic and Precambrian) formations, and overlying Cretaceous formations, the Hensel Sandstone, the Glen Rose Formation, and the Edwards Limestone. Each of the 13 quadrangle maps was then reduced to 50% of original size and combined to make a composite base map (Digital Map 1). This base map was used to make all six additional maps. An interlocking network of eight geologic cross-sections (A–A', B–B', C–C', D–D', E–E', X–X', Y–Y', and Z–Z') documented lateral changes in formation thickness and lateral extent, in relation to the geology underlying the WPP, and supported detailed structure and isopach mapping. Subsurface control was provided by water well data, maps and cross-sections compiled by Paul Tybor, Hill Country Ground Water Conservation District Manager.[4] The resulting seven maps and all eight cross-sections were again reduced to 50% (Digital Maps 1–7 and Digital Plates 1 and 2) presented via electronic access because of their size:

- Digital Map 1: Base Map—Surface and Subsurface Elevations of Formation Boundaries
- Digital Map 2: Paleotopography of Pre-Cretaceous Erosion Surface (= Wichita Paleoplain)
- Digital Map 3: Distribution of Edwards Limestone Outliers in relation to Paleotopography of Pre-Cretaceous Unconformity (= the WPP)
- Digital Map 4: Geologic Structure on Base of Glen Rose Formation (= top of Hensel Sandstone)
- Digital Map 5: Thickness of Hensel Sandstone
- Digital Map 6: Geologic Structure on Base of Edwards Limestone (= top of Glen Rose Fm.)
- Digital Map 7: Thickness of Glen Rose Formation
- Digital Plate 1 and Digital Plate 2: Geologic Cross-Sections, Southeast Flank of Llano Uplift, Gillespie and Blanco Counties, Texas

Phase Two: WPP in the Llano Uplift and Surroundings

After completion of detailed structural and stratigraphic mapping (phase one) documenting geologic relationships along the southeast flank of the Llano Uplift, the second phase of the project was to map the paleotopography of the WPP in the greater Llano Uplift. First, a regional tectonic map from Ewing (1991) provided a broad-scale perspective on faulting associated with the Ouachita Orogeny (Fig. 1). Next, previous work by Standen and Ruggiero (2007) provided the basis for reconstructing the configuration of structural arching of Paleozoic formations across the Llano Dome (Figs. 4A and 4B). Integrating that work with the 1:250,000 GAT Brownwood (1976) and adjoining Llano (1982) sheets (Barnes, 1970–1983), allowed construction of two regional geologic cross-sections (Fig. 5, J–J' and K–K') that show restored post-Ouachita structure in comparison with the present configuration of the WPP, the base-Edwards regional mapping datum, and the present ground surface.

Elevations of the WPP contact on pre-Cretaceous formations were posted on the Brownwood and Llano GAT sheets (Barnes, 1970–1983), which were then combined on a base map reduced 50% to a scale of 1:500,000. These elevations were than contoured, so as to depict the configuration of the WPP. Detailed mapping of the southeastern flank of the Llano Uplift (phase one) was further reduced in scale, integrated into the phase two map (Fig. 7), "Paleotopography of the Wichita Paleoplain in the Llano Uplift and surrounding areas," and reduced again.

Phase Three: WPP in West-Central Texas

The final phase of the project involved integrating phase two mapping with published geological structure mapping of the WPP in the subsurface beneath the Edwards Plateau of west-central Texas by Barker and Ardis (1992), plus mapping by Boone (1967), Bain (1973), Atchley et al. (2001), and Rose (1986, 1990) in north-central Texas (Fig. 8). The result is a regional synthesis showing the present surface and subsurface configuration of the WPP in Central Texas (Fig. 9), and an interpretation of the geologic processes involved in its subsequent development

Barker and Ardis's (1992) base map of the WPP was used as the base map for construction of the phase three synthesis. But the present regional attitude of the original WPP has been distorted, first by increasing gulfward subsidence on the east and south, beginning in the early Cretaceous, then by the crescentic wedge of Glen Rose Formation around the Llano Uplift, by increasing regional northwestward elevation during the Neogene, related to the rise of the Colorado Plateau, as shown by the steady northwesterly rise of the WPP in the Edwards Plateau area (Fig. 9), and finally by Balcones faulting and uplift in the early Miocene. Accordingly, if the geometric effects of these four geologic warpings can be eliminated, the configuration and elevation of the WPP at the time of Hensel Sandstone deposition may be approximated.

Using the overlying base of the peritidal Edwards Limestone as a proxy for Early Cretaceous sea-level, simple geometry allows the restoration of the WPP to its approximate original topography, as shown by Figure 10, which depicts geological cross-section P–P', showing both the present and restored early-Cretaceous attitudes of the base-of-Edwards mapping datum and the WPP, northwest to southeast, across the regional map area. This cross-section also shows the present ground surface as well as the +1950 foot Edwards reference datum, used to adjust both the base-of-Edwards and the WPP mapping surfaces for subsequent elevation and subsidence.

The geometric corrections shown graphically in Figure 10 are carried out using Figure 11, showing the structural configuration of the base of the Edwards Limestone rising steadily northwestward across the areas, and Figure 12, showing the WPP restored to its geometry at the beginning of Edwards Limestone deposition. The actual procedure is described below:

(1) The regional map showing the base of the Edwards Limestone (Fig. 11) was overlain with the regional paleotopographic map of the WPP (Fig. 9).

(2) The +1950 foot base-Edwards (bKed) contour was selected as the neutral value, and plotted on Figure 11.

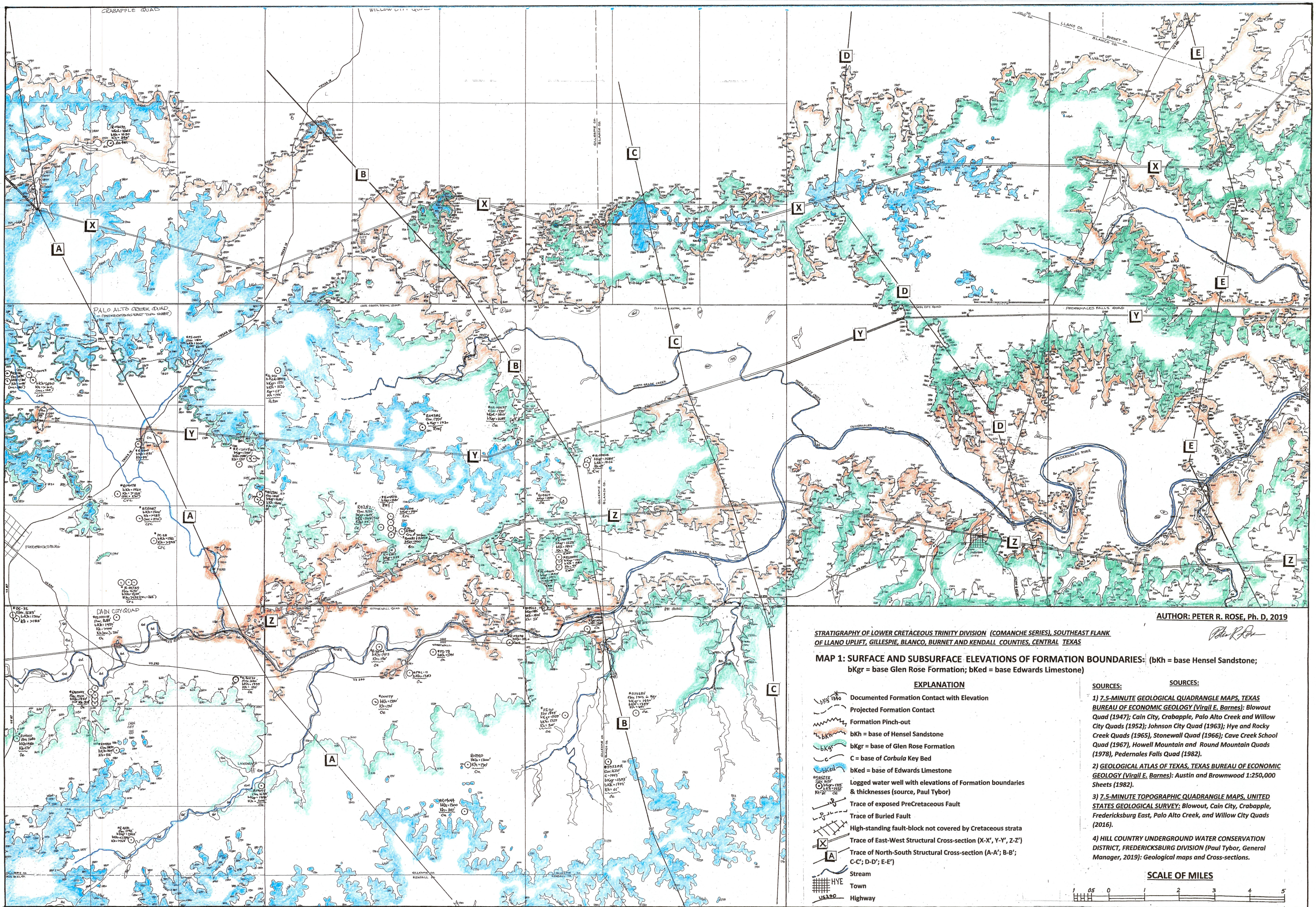
(3) In areas north and west of the +1950 foot bKed contour, wherever a WPP (wpp) contour crosses the bKed contour, the wpp value was reduced by the difference between the value of the bKed contour and +1950 feet. Example—where the 2800 foot bKed contour crosses the 2500 foot wpp contour, the restored wpp value of +1650 feet was posted: [2500 – (2800 – 1950)] = +1650 feet.

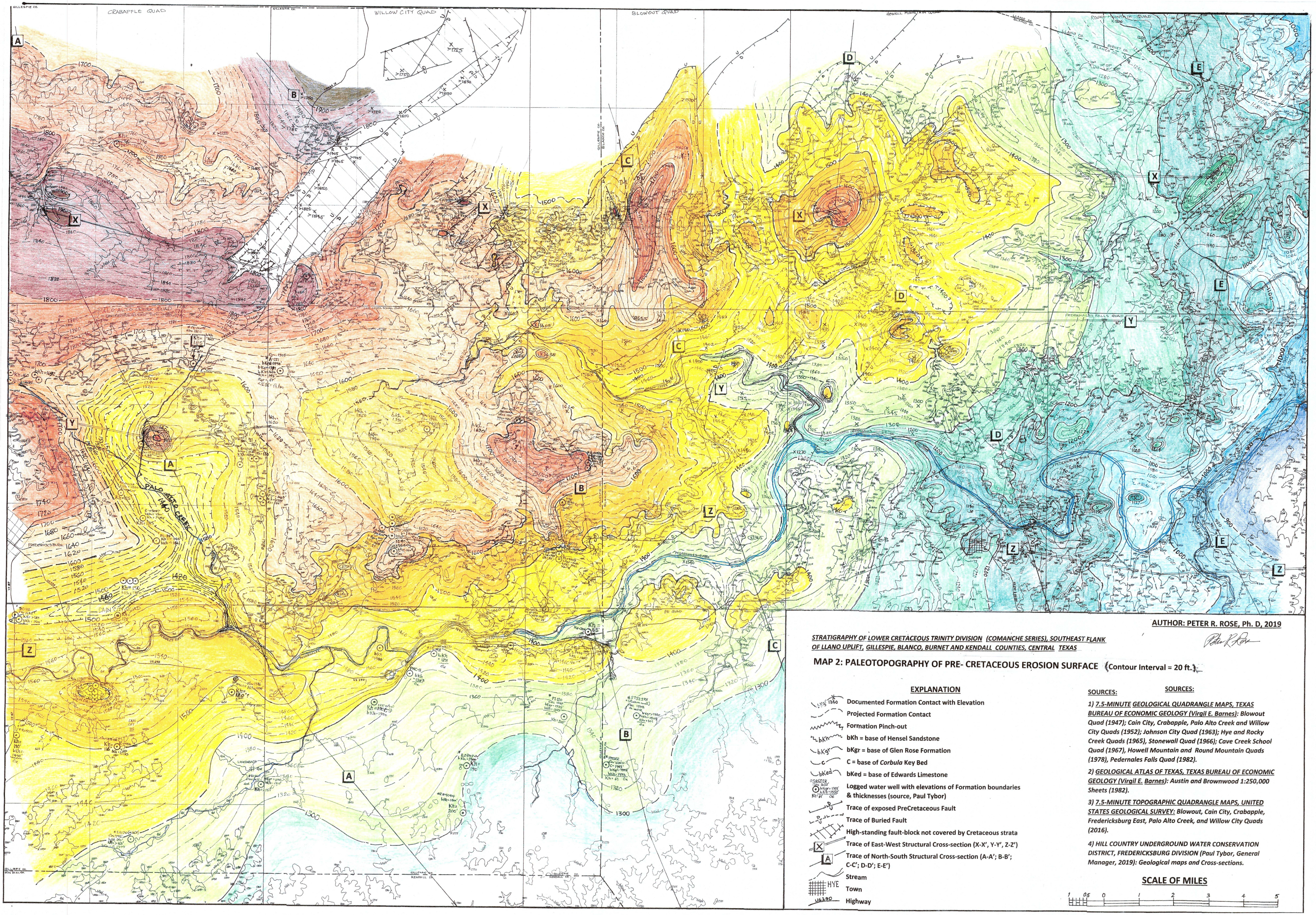
(4) In areas south and east of the +1950 foot bKed contour, wherever a wpp crosses a bKed contour, the wpp value was increased by the difference between 1950 feet and the value of the bKed contour. Example—where the 1500' bKed contour crosses the 1100' wpp contour, the restored wpp value of +1550 feet was posted: [1100 + (1950 – 1500) = +1550 feet.

(5) When calculations of all such contour-crossings have been posted, contour the restored values (Fig. 12).

Analogous procedure was used to account for the crescentic Glen Rose sedimentary wedge (Fig. 13), so as to restore the WPP to its configuration (but not its elevation) as of the start of Hensel Sandstone deposition (Fig. 14). The final adjustment was to restore the WPP to its estimated sea-level and topographic elevations that existed at the start of Hensel Sandstone deposition, including the configuration of the Hensel shoreline (Fig. 15). Regionally the Hensel stratigraphic transition from coastal to shallow marine deposition coincides approximately with the 1600 foot paleotopographic contour, so the 1600 foot contour is lowered to zero, with all higher contours reduced by 1600 feet. Figure 16 is a block diagram derived from Fig. 15, showing regional topography of the WPP landscape at the beginning of Hensel deposition.

[4]From 2017 to 2019, Tybor generated a series of ten geologic cross-sections based on gamma-ray logs of water-well control, a base map of Gillespie County, and at least seven geologic maps for use by his HCGWCD office. They are not formally published.


CRABAPPLE QUAD
WILLOW CITY QUAD
PALO ALTO CREEK QUAD
CAIN CITY QUAD
FREDERICKSBURG
PEDERNALES FALLS QUAD
PEDERNALES RIVER
LLANO CO.
BURNET CO.
BLANCO CO.
GILLESPIE CO.
KENDALL CO.
US 290
AUTHOR: PETER R. ROSE, Ph. D, 2019
STRATIGRAPHY OF LOWER CRETACEOUS TRINITY DIVISION (COMANCHE SERIES), SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE, BLANCO, BURNET AND KENDALL COUNTIES, CENTRAL TEXAS
MAP 1: SURFACE AND SUBSURFACE ELEVATIONS OF FORMATION BOUNDARIES: (bKh = base Hensel Sandstone; bKgr = base Glen Rose Formation; bKed = base Edwards Limestone)
EXPLANATION
Documented Formation Contact with Elevation
Projected Formation Contact
Formation Pinch-out
bKh = base of Hensel Sandstone
bKgr = base of Glen Rose Formation
C = base of Corbula Key Bed
bKed = base of Edwards Limestone
Logged water well with elevations of Formation boundaries & thicknesses (source, Paul Tybor)
Trace of exposed PreCretaceous Fault
Trace of Buried Fault
High-standing fault-block not covered by Cretaceous strata
Trace of East-West Structural Cross-section (X-X', Y-Y', Z-Z')
Trace of North-South Structural Cross-section (A-A'; B-B'; C-C'; D-D'; E-E')
Stream
Town
Highway
SOURCES:
1) 7.5-MINUTE GEOLOGICAL QUADRANGLE MAPS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Blowout Quad (1947); Cain City, Crabapple, Palo Alto Creek and Willow City Quads (1952); Johnson City Quad (1963); Hye and Rocky Creek Quads (1965), Stonewall Quad (1966); Cave Creek School Quad (1967), Howell Mountain and Round Mountain Quads (1978), Pedernales Falls Quad (1982).
2) GEOLOGICAL ATLAS OF TEXAS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Austin and Brownwood 1:250,000 Sheets (1982).
3) 7.5-MINUTE TOPOGRAPHIC QUADRANGLE MAPS, UNITED STATES GEOLOGICAL SURVEY: Blowout, Cain City, Crabapple, Fredericksburg East, Palo Alto Creek, and Willow City Quads (2016).
4) HILL COUNTRY UNDERGROUND WATER CONSERVATION DISTRICT, FREDERICKSBURG DIVISION (Paul Tybor, General Manager, 2019): Geological maps and Cross-sections.
SCALE OF MILES
1 0.5 0 1 2 3 4 5



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STRATIGRAPHY OF LOWER CRETACEOUS TRINITY DIVISION (COMANCHE SERIES), SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE, BLANCO, BURNET AND KENDALL COUNTIES, CENTRAL TEXAS

MAP 2: PALEOTOPOGRAPHY OF PRE- CRETACEOUS EROSION SURFACE (Contour Interval = 20 ft.)

EXPLANATION

Documented Formation Contact with Elevation
Projected Formation Contact
Formation Pinch-out
bKh = base of Hensel Sandstone
bKgr = base of Glen Rose Formation
C = base of *Corbula* Key Bed
bKed = base of Edwards Limestone
Logged water well with elevations of Formation boundaries & thicknesses (source, Paul Tybor)
Trace of exposed PreCretaceous Fault
Trace of Buried Fault
High-standing fault-block not covered by Cretaceous strata
Trace of East-West Structural Cross-section (X-X', Y-Y', Z-Z')
Trace of North-South Structural Cross-section (A-A'; B-B'; C-C'; D-D'; E-E')
Stream
Town
Highway

SOURCES:

SOURCES:

1) 7.5-MINUTE GEOLOGICAL QUADRANGLE MAPS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Blowout Quad (1947); Cain City, Crabapple, Palo Alto Creek and Willow City Quads (1952); Johnson City Quad (1963); Hye and Rocky Creek Quads (1965), Stonewall Quad (1966); Cave Creek School Quad (1967), Howell Mountain and Round Mountain Quads (1978), Pedernales Falls Quad (1982).

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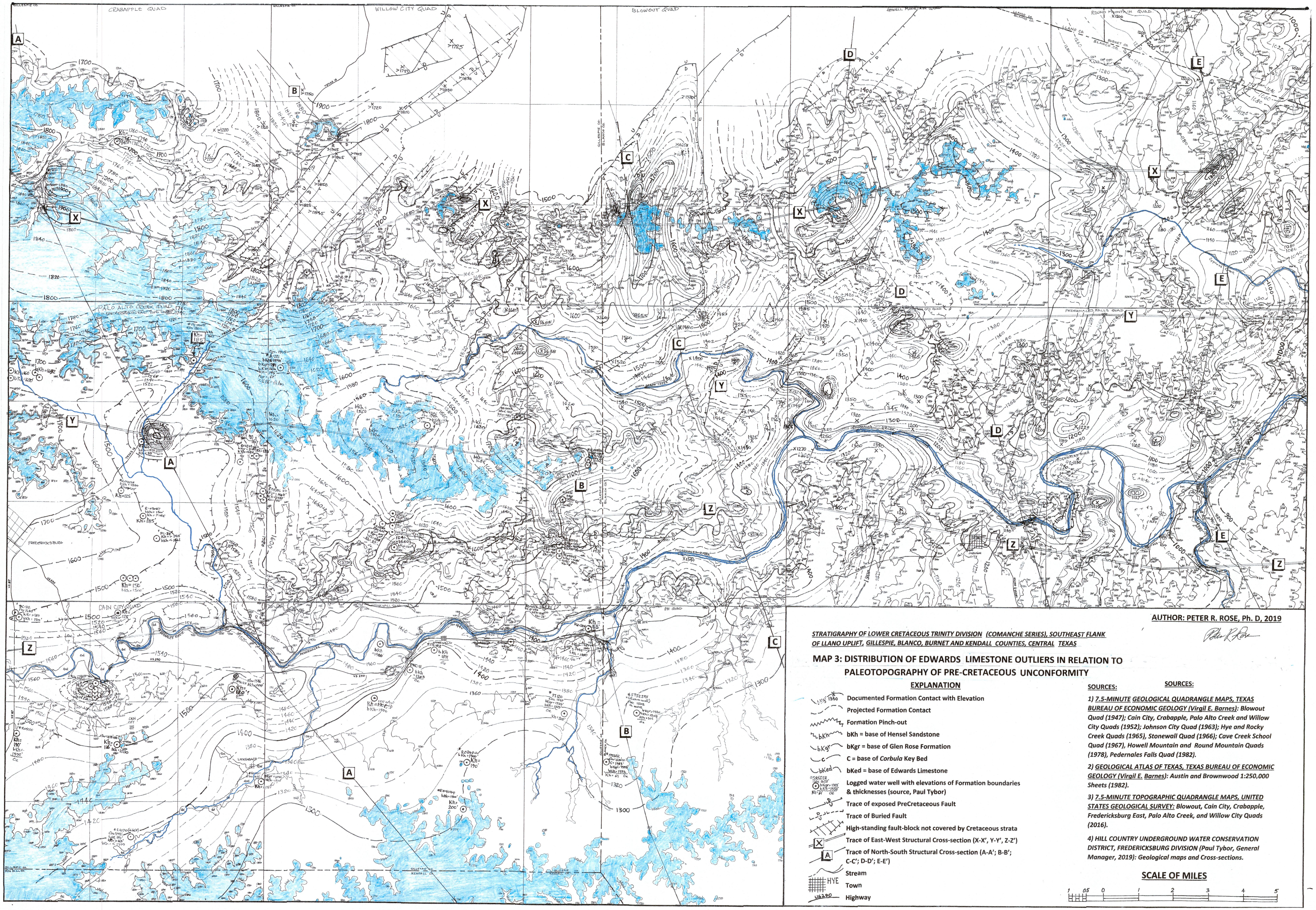
3) 7.5-MINUTE TOPOGRAPHIC QUADRANGLE MAPS, UNITED STATES GEOLOGICAL SURVEY: Blowout, Cain City, Crabapple, Fredericksburg East, Palo Alto Creek, and Willow City Quads (2016).

4) HILL COUNTRY UNDERGROUND WATER CONSERVATION DISTRICT, FREDERICKSBURG DIVISION (Paul Tybor, General Manager, 2019): Geological maps and Cross-sections.

SCALE OF MILES

1 0.5 0 1 2 3 4 5


CRABAPPLE QUAD
WILLOW CITY QUAD
BLOWOUT QUAD
PALO ALTO CREEK QUAD
CAIN CITY QUAD
PEDERNALES FALLS QUAD
FREDERICKSBURG
AUTHOR: PETER R. ROSE, Ph. D, 2019
STRATIGRAPHY OF LOWER CRETACEOUS TRINITY DIVISION (COMANCHE SERIES), SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE, BLANCO, BURNET AND KENDALL COUNTIES, CENTRAL TEXAS
MAP 3: DISTRIBUTION OF EDWARDS LIMESTONE OUTLIERS IN RELATION TO PALEOTOPOGRAPHY OF PRE-CRETACEOUS UNCONFORMITY
EXPLANATION
Documented Formation Contact with Elevation
Projected Formation Contact
Formation Pinch-out
bKh = base of Hensel Sandstone
bKgr = base of Glen Rose Formation
C = base of Corbula Key Bed
bKed = base of Edwards Limestone
Logged water well with elevations of Formation boundaries & thicknesses (source, Paul Tybor)
Trace of exposed PreCretaceous Fault
Trace of Buried Fault
High-standing fault-block not covered by Cretaceous strata
Trace of East-West Structural Cross-section (X-X', Y-Y', Z-Z')
Trace of North-South Structural Cross-section (A-A'; B-B'; C-C'; D-D'; E-E')
Stream
Town
Highway
SOURCES:
SOURCES:
1) 7.5-MINUTE GEOLOGICAL QUADRANGLE MAPS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Blowout Quad (1947); Cain City, Crabapple, Palo Alto Creek and Willow City Quads (1952); Johnson City Quad (1963); Hye and Rocky Creek Quads (1965), Stonewall Quad (1966); Cave Creek School Quad (1967), Howell Mountain and Round Mountain Quads (1978), Pedernales Falls Quad (1982).
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4) HILL COUNTRY UNDERGROUND WATER CONSERVATION DISTRICT, FREDERICKSBURG DIVISION (Paul Tybor, General Manager, 2019): Geological maps and Cross-sections.
SCALE OF MILES
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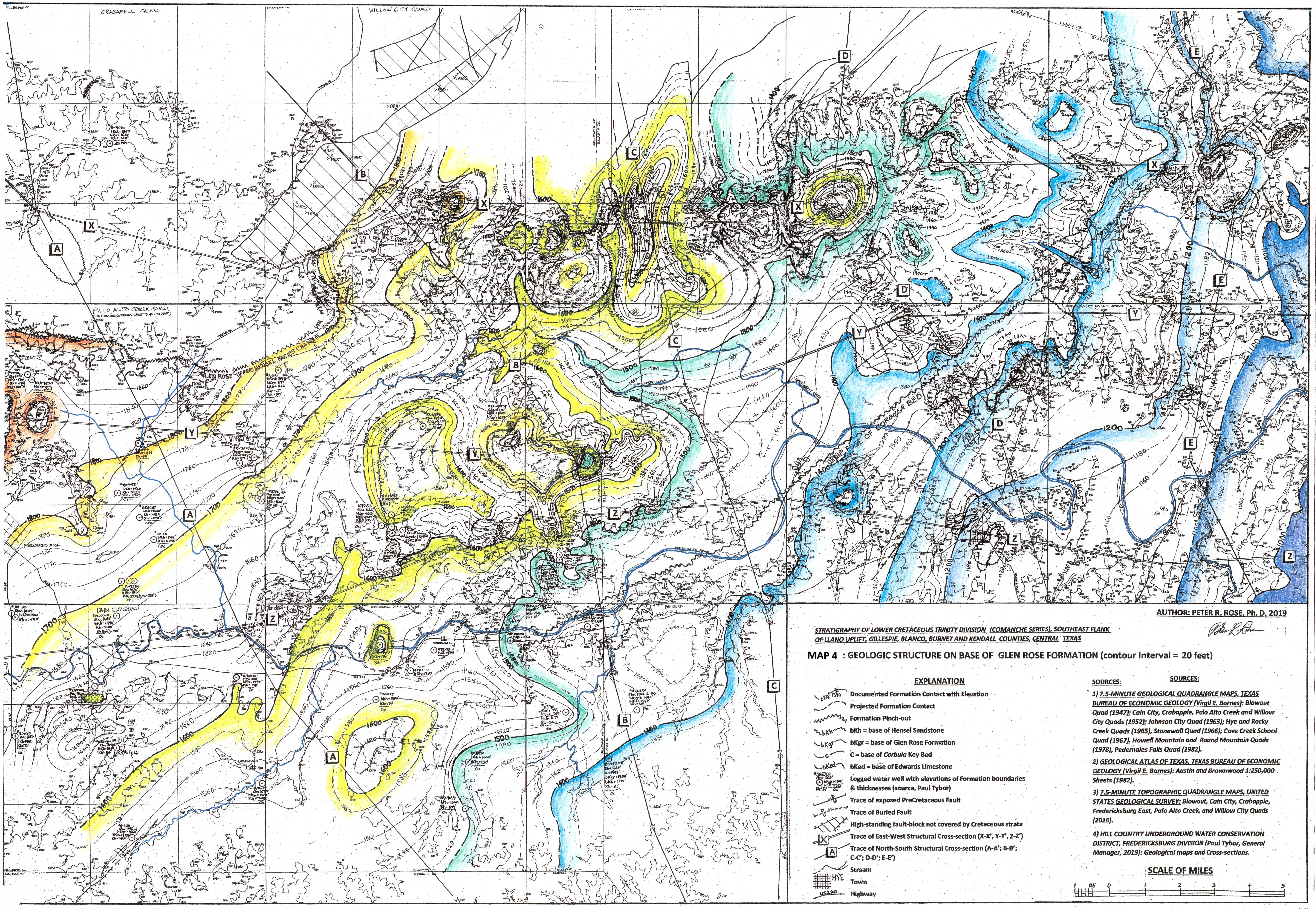
CRABAPPLE QUAD
WILLOW CITY QUAD
PALO ALTO CREEK QUAD
CAIN CITY QUAD
GLEN ROSE - UPPER HENSEL FACIES CHANGE
UPPER BASE OF CORBULA BED
AUTHOR: PETER R. ROSE, Ph. D, 2019
STRATIGRAPHY OF LOWER CRETACEOUS TRINITY DIVISION (COMANCHE SERIES), SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE, BLANCO, BURNET AND KENDALL COUNTIES, CENTRAL TEXAS
MAP 4 : GEOLOGIC STRUCTURE ON BASE OF GLEN ROSE FORMATION (contour Interval = 20 feet)
EXPLANATION
Documented Formation Contact with Elevation
Projected Formation Contact
Formation Pinch-out
bKh = base of Hensel Sandstone
bKgr = base of Glen Rose Formation
C = base of Corbula Key Bed
bKed = base of Edwards Limestone
Logged water well with elevations of Formation boundaries & thicknesses (source, Paul Tybor)
Trace of exposed PreCretaceous Fault
Trace of Buried Fault
High-standing fault-block not covered by Cretaceous strata
Trace of East-West Structural Cross-section (X-X', Y-Y', Z-Z')
Trace of North-South Structural Cross-section (A-A'; B-B'; C-C'; D-D'; E-E')
Stream
HYE
Town
US290
Highway
SOURCES:
SOURCES:
1) 7.5-MINUTE GEOLOGICAL QUADRANGLE MAPS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Blowout Quad (1947); Cain City, Crabapple, Palo Alto Creek and Willow City Quads (1952); Johnson City Quad (1963); Hye and Rocky Creek Quads (1965), Stonewall Quad (1966); Cave Creek School Quad (1967), Howell Mountain and Round Mountain Quads (1978), Pedernales Falls Quad (1982).
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4) HILL COUNTRY UNDERGROUND WATER CONSERVATION DISTRICT, FREDERICKSBURG DIVISION (Paul Tybor, General Manager, 2019): Geological maps and Cross-sections.
SCALE OF MILES
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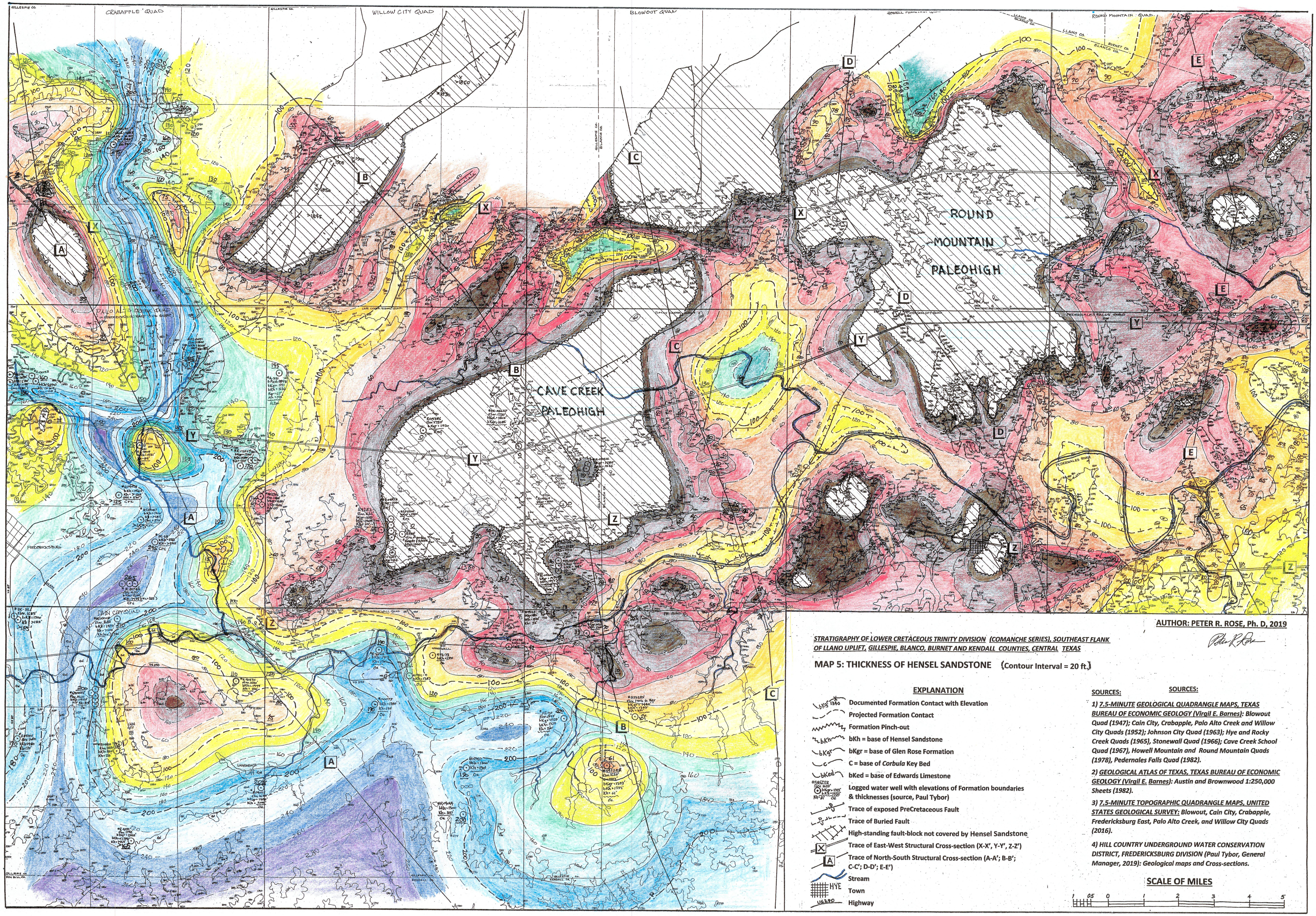
CRABAPPLE QUAD
WILLOW CITY QUAD
BLOWOUT QUAD
ROUND MOUNTAIN QUAD
ROUND MOUNTAIN PALEOHIGH
CAVE CREEK PALEOHIGH
AUTHOR: PETER R. ROSE, Ph. D, 2019
STRATIGRAPHY OF LOWER CRETACEOUS TRINITY DIVISION (COMANCHE SERIES), SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE, BLANCO, BURNET AND KENDALL COUNTIES, CENTRAL TEXAS
MAP 5: THICKNESS OF HENSEL SANDSTONE (Contour Interval = 20 ft.)
EXPLANATION
Documented Formation Contact with Elevation
Projected Formation Contact
Formation Pinch-out
bKh = base of Hensel Sandstone
bKgr = base of Glen Rose Formation
C = base of Corbula Key Bed
bKed = base of Edwards Limestone
Logged water well with elevations of Formation boundaries & thicknesses (source, Paul Tybor)
Trace of exposed PreCretaceous Fault
Trace of Buried Fault
High-standing fault-block not covered by Hensel Sandstone
Trace of East-West Structural Cross-section (X-X', Y-Y', Z-Z')
Trace of North-South Structural Cross-section (A-A'; B-B'; C-C'; D-D'; E-E')
Stream
HYE
Town
US290
Highway
SOURCES:
SOURCES:
1) 7.5-MINUTE GEOLOGICAL QUADRANGLE MAPS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Blowout Quad (1947); Cain City, Crabapple, Palo Alto Creek and Willow City Quads (1952); Johnson City Quad (1963); Hye and Rocky Creek Quads (1965), Stonewall Quad (1966); Cave Creek School Quad (1967), Howell Mountain and Round Mountain Quads (1978), Pedernales Falls Quad (1982).
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4) HILL COUNTRY UNDERGROUND WATER CONSERVATION DISTRICT, FREDERICKSBURG DIVISION (Paul Tybor, General Manager, 2019): Geological maps and Cross-sections.
SCALE OF MILES
1 .05 0 1 2 3 4 5

AUTHOR: PETER R. ROSE, Ph. D, 2019

STRATIGRAPHY OF LOWER CRETACEOUS TRINITY DIVISION (COMANCHE SERIES), SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE, BLANCO, BURNET AND KENDALL COUNTIES, CENTRAL TEXAS

MAP 6: GEOLOGIC STRUCTURE ON BASE, EDWARDS LIMESTONE (Contour Interval = 20 ft.)

EXPLANATION

- Documented Formation Contact with Elevation
- Projected Formation Contact
- Formation Pinch-out
- bKh = base of Hensel Sandstone
- bKgr = base of Glen Rose Formation
- C = base of *Corbula* Key Bed
- bKed = base of Edwards Limestone
- Logged water well with elevations of Formation boundaries & thicknesses (source, Paul Tybor)
- Trace of exposed PreCretaceous Fault
- Trace of Buried Fault
- High-standing fault-block not covered by Cretaceous strata
- Trace of East-West Structural Cross-section (X-X', Y-Y', Z-Z')
- Trace of North-South Structural Cross-section (A-A'; B-B'; C-C'; D-D'; E-E')
- Stream
- Town
- Highway

SOURCES:

SOURCES:

1) 7.5-MINUTE GEOLOGICAL QUADRANGLE MAPS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Blowout Quad (1947); Cain City, Crabapple, Palo Alto Creek and Willow City Quads (1952); Johnson City Quad (1963); Hye and Rocky Creek Quads (1965), Stonewall Quad (1966); Cave Creek School Quad (1967), Howell Mountain and Round Mountain Quads (1978), Pedernales Falls Quad (1982).

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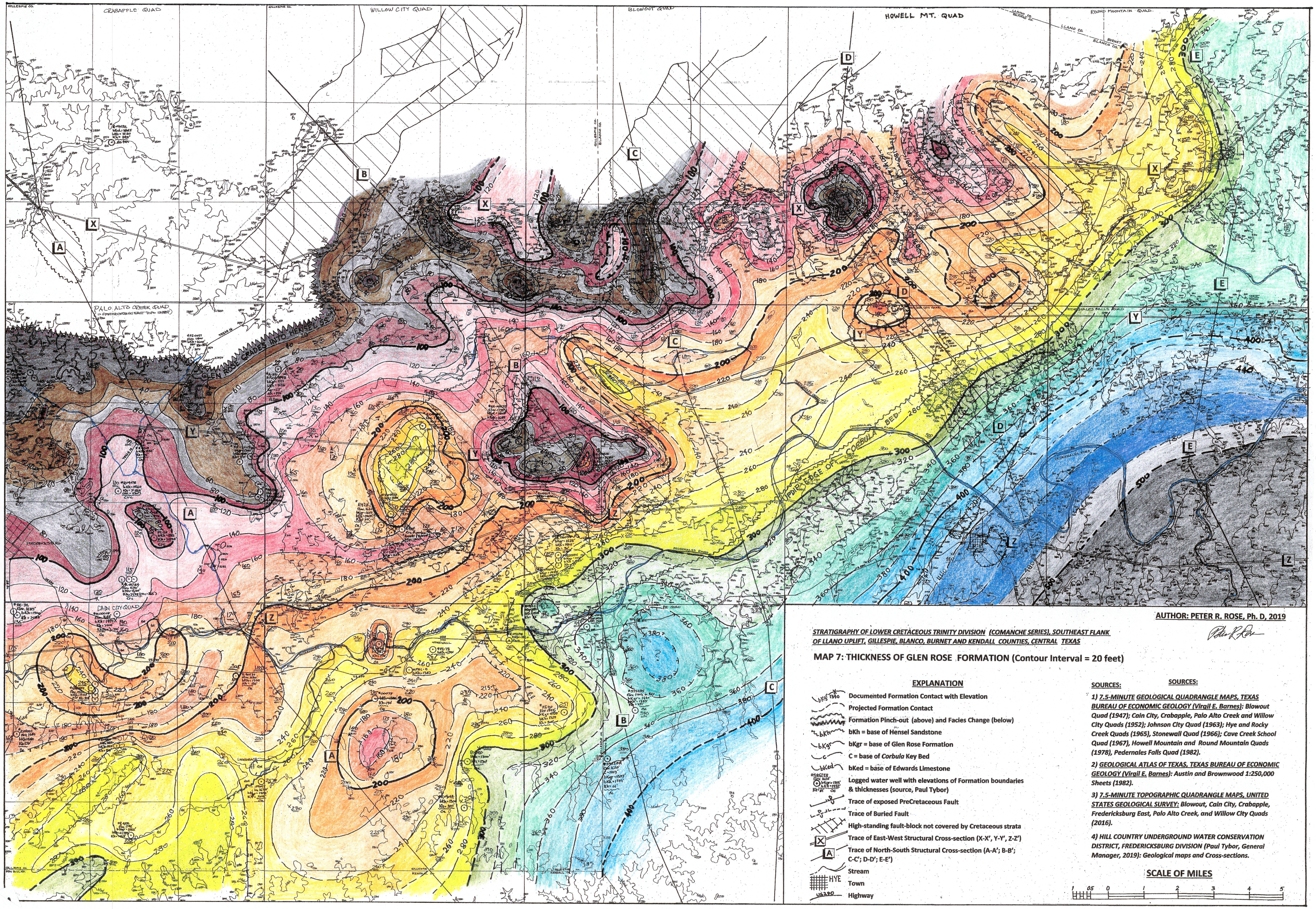
4) HILL COUNTRY UNDERGROUND WATER CONSERVATION DISTRICT, FREDERICKSBURG DIVISION (Paul Tybor, General Manager, 2019): Geological maps and Cross-sections.

SCALE OF MILES

1 .05 0 1 2 3 4 5



AUTHOR: PETER R. ROSE, Ph. D, 2019

STRATIGRAPHY OF LOWER CRETACEOUS TRINITY DIVISION (COMANCHE SERIES), SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE, BLANCO, BURNET AND KENDALL COUNTIES, CENTRAL TEXAS

MAP 7: THICKNESS OF GLEN ROSE FORMATION (Contour Interval = 20 feet)

EXPLANATION

- Documented Formation Contact with Elevation
- Projected Formation Contact
- Formation Pinch-out (above) and Facies Change (below)
- bKh = base of Hensel Sandstone
- bKgr = base of Glen Rose Formation
- C = base of *Corbula* Key Bed
- bKed = base of Edwards Limestone
- Logged water well with elevations of Formation boundaries & thicknesses (source, Paul Tybor)
- Trace of exposed PreCretaceous Fault
- Trace of Buried Fault
- High-standing fault-block not covered by Cretaceous strata
- Trace of East-West Structural Cross-section (X-X', Y-Y', Z-Z')
- Trace of North-South Structural Cross-section (A-A'; B-B'; C-C'; D-D'; E-E')
- Stream
- HYE Town
- US290 Highway

SOURCES:

1) *7.5-MINUTE GEOLOGICAL QUADRANGLE MAPS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Blowout Quad (1947); Cain City, Crabapple, Palo Alto Creek and Willow City Quads (1952); Johnson City Quad (1963); Hye and Rocky Creek Quads (1965), Stonewall Quad (1966); Cave Creek School Quad (1967), Howell Mountain and Round Mountain Quads (1978), Pedernales Falls Quad (1982).*

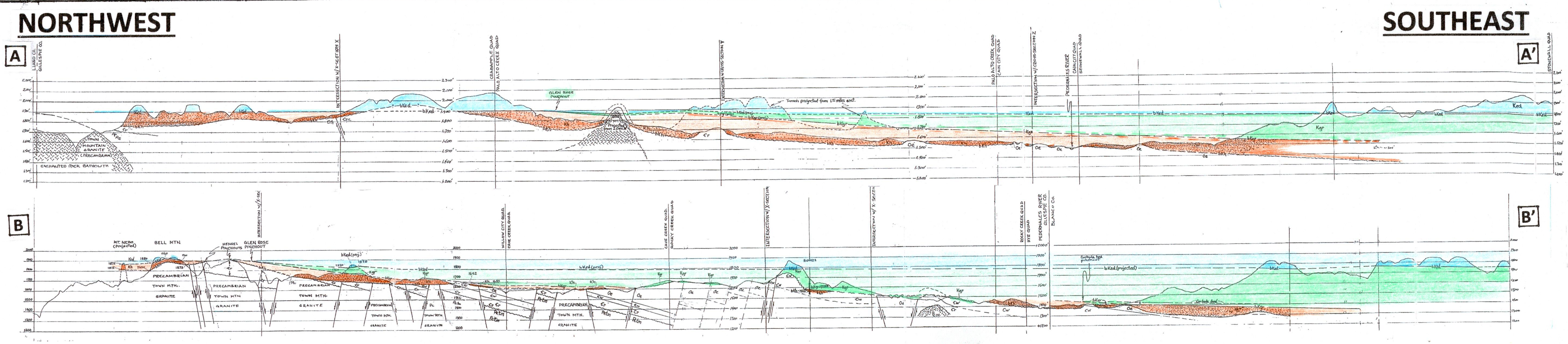
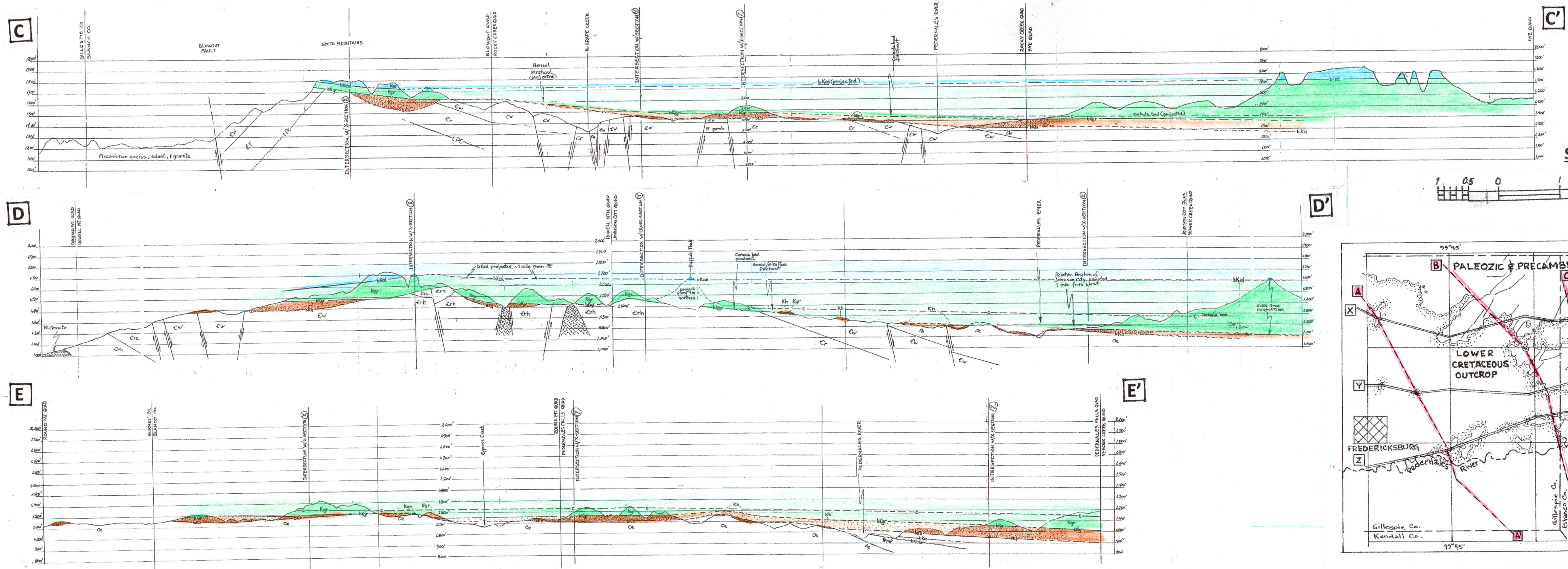
2) *GEOLOGICAL ATLAS OF TEXAS, TEXAS BUREAU OF ECONOMIC GEOLOGY (Virgil E. Barnes): Austin and Brownwood 1:250,000 Sheets (1982).*

3) *7.5-MINUTE TOPOGRAPHIC QUADRANGLE MAPS, UNITED STATES GEOLOGICAL SURVEY: Blowout, Cain City, Crabapple, Fredericksburg East, Palo Alto Creek, and Willow City Quads (2016).*

4) *HILL COUNTRY UNDERGROUND WATER CONSERVATION DISTRICT, FREDERICKSBURG DIVISION (Paul Tybor, General Manager, 2019): Geological maps and Cross-sections.*

SCALE OF MILES

1 .05 0 1 2 3 4 5

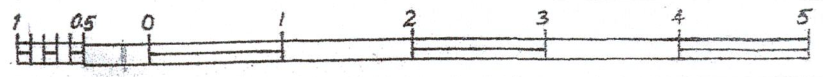
GEOLOGIC CROSS-SECTIONS, SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE & BLANCO COUNTIES, TEXAS

Peter R. Rose, 2020

SYMBOLS:

bKed	base of Edwards Group
C	Corbula bed of Glen Rose Fm.
Kgr	Glen Rose Fm.
bKgr	base of Glen Rose Fm. K
Kh	Hensel Sandstone
bKh	base of Hensel Sandstone
bKcc	base of Cow Creek Limestone
Kha	base of Hammett Shale
Pmf	Pennsylvanian Marble Falls Fm.
Oe	Ordovician Ellenburger Fm.
Cw	Cambrian Wilberns Fm.
Cr	Cambrian Riley Fm.
pCtm	Precambrian Town Mtn. Granite
pCps	Precambrian Packsaddle Schist

SCALE OF MILES



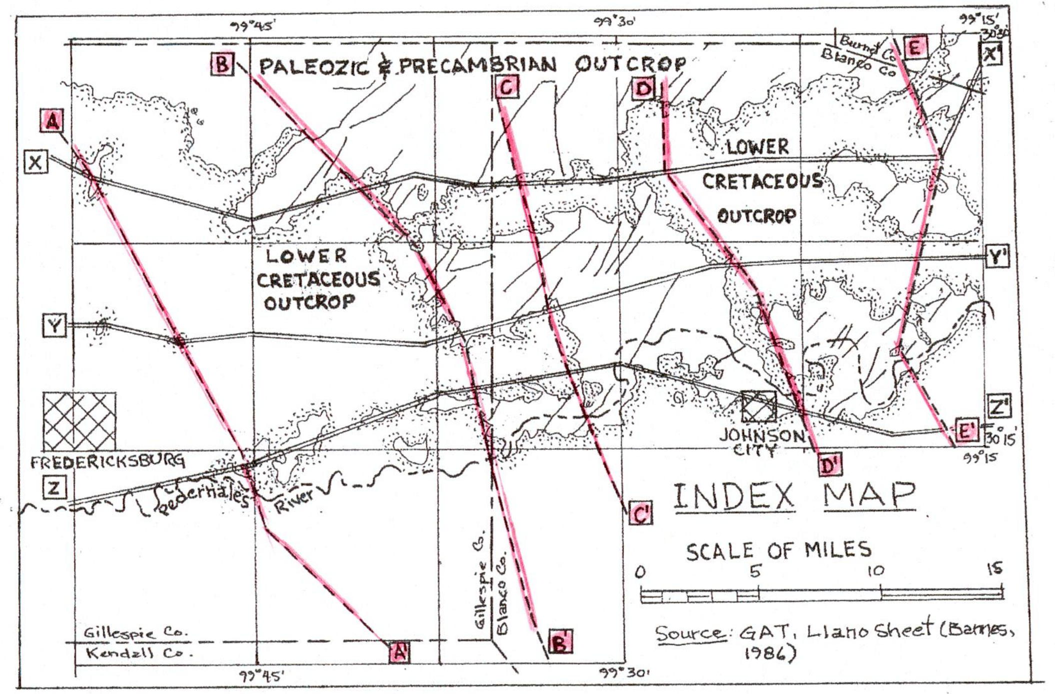


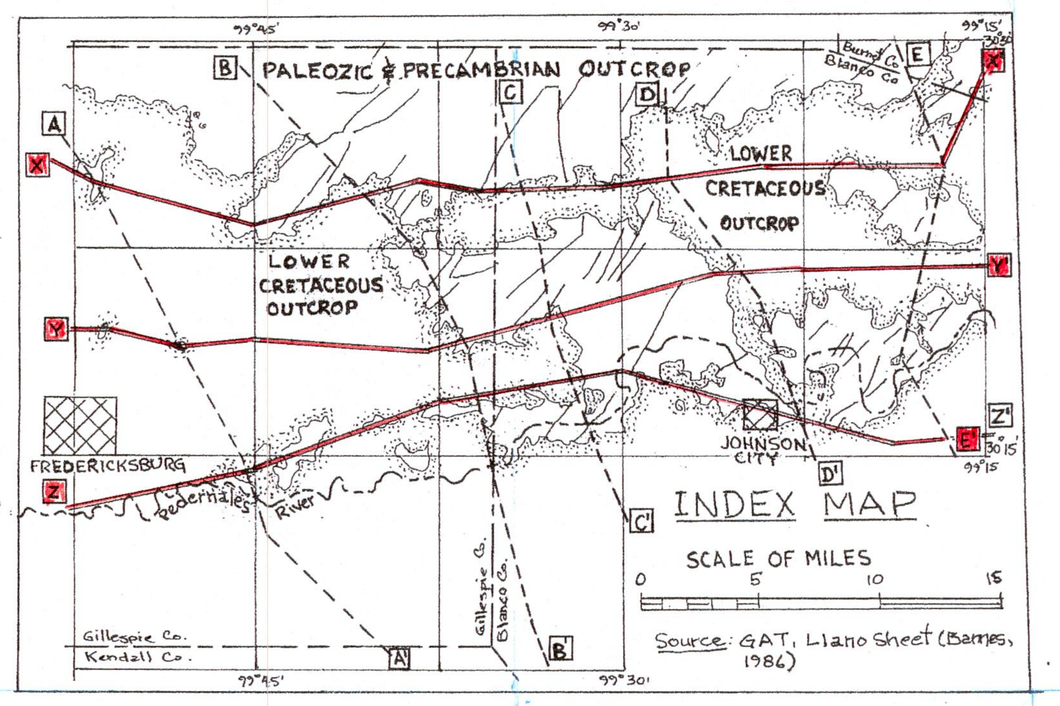
PLATE ONE

GEOLOGIC CROSS-SECTIONS, SOUTHEAST FLANK OF LLANO UPLIFT, GILLESPIE & BLANCO COUNTIES, TEXAS

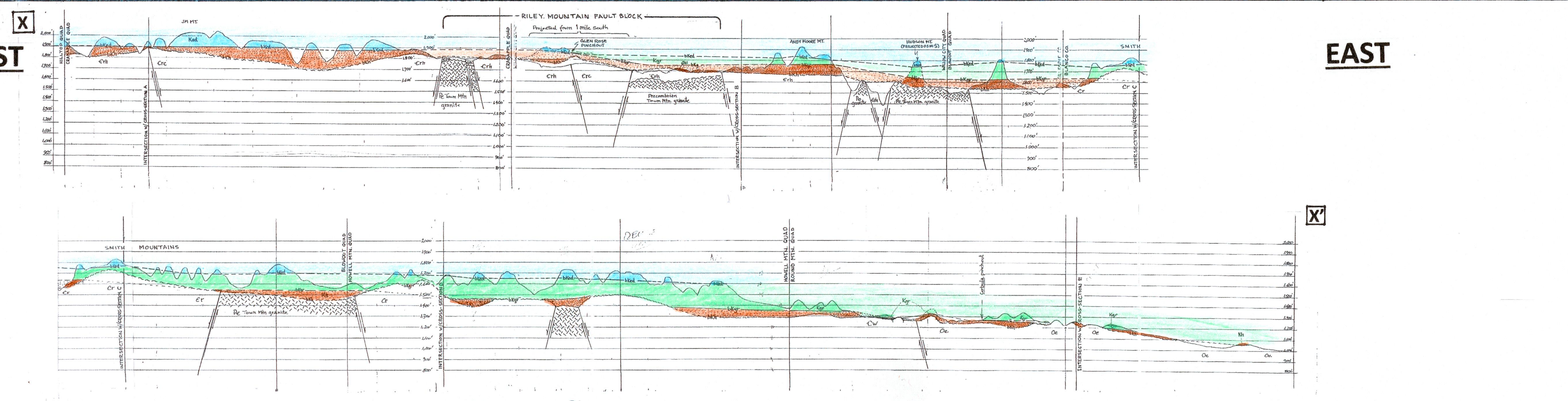
Peter R. Rose, 2020

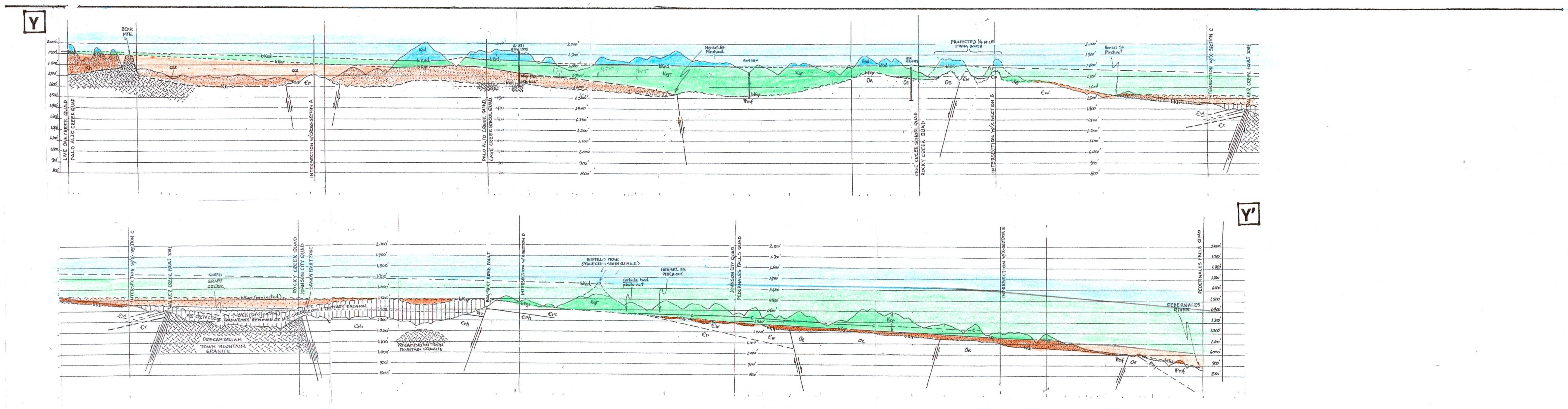
SYMBOLS:

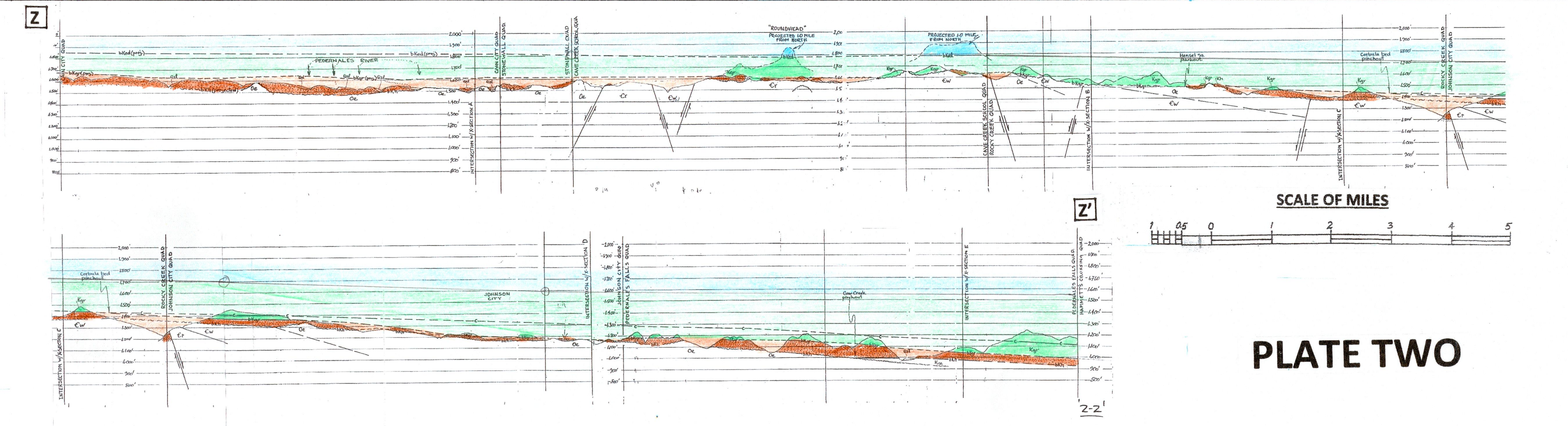
bKed	base of Edwards Group
C	Corbula bed of Glen Rose Fm.
Kgr	Glen Rose Fm.
bKgr	base of Glen Rose Fm.
Kh	Hensel Sandstone
bKh	base of Hensel Sandstone
bKcc	base of Cow Creek Limestone
bKha	base of Hammett Shale
Pmf	Pennsylvanian Marble Falls Fm.
Oe	Ordovician Ellenburger Fm.
Cw	Cambrian Wilberns Fm.
Cr	Cambrian Riley Fm.
pCtm	Precambrian Town Mtn. Granite
pCps	Precambrian Packsaddle Schist



WEST **EAST**







SCALE OF MILES

PLATE TWO