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The Lower Cretaceous Hensel–Glen Rose Stratigraphic Couplet in the Llano Uplift, Central Texas

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ABSTRACT

The Lower Cretaceous Hensel Sandstone and Glen Rose Formation are lateral facies of the transgressive clastic/carbonate leg of the Trinity Division (or Group), whose stratigraphy in the area of the Llano Uplift is here mapped and characterized as a single depositional episode. The Hensel Formation represents alluvial-fan, fluvial, and coastal plain depositional settings, whereas mixed terrigenous and carbonate sediments of the overlying Glen Rose Formation represent peritidal and shallow-marine environments of deposition.

The Hensel–Glen Rose stratigraphic couplet (hence H–GR) thickens from the Llano Uplift eastward toward the Gulf of Mexico and southward toward the Rio Grande Embayment. The Glen Rose lithosome thins northward to zero across the southern and eastern margins of the Llano Uplift, primarily by facies change into Hensel arkosic clastics. Reciprocally, the Hensel lithosome thins eastward and southward by grading into Glen Rose strata, so that only thin terrigenous Hensel sandstones and mudstones are present at the base of the downdip H–GR.

At the start of H–GR deposition, the Llano Uplift was a hilly promontory projecting southeastward into the Late Aptian Gulf of Mexico and Rio Grande Embayment. Within the Uplift, the H–GR consists of poorly-consolidated arkosic conglomerates, sandstones and mudstones. Its thickness varies widely due to the paleotopography of the underlying Wichita Paleoplain (hence WPP). The H–GR is thin or absent over high-standing Early Paleozoic fault-blocks, and thick over low-standing Precambrian terranes and "minibasins." Hensel Sandstone thickness and configuration of the underlying WPP are mapped throughout the Llano Uplift based on such observed patterns around its margins.

The east-flowing precursor Llano River was the primary stream draining the interior of the promontory. The eastward course of the present Llano River coincides closely with its WPP valley, even though the WPP landscape had been completely filled-in and covered by the time of early Edwards deposition. The south-flowing Kimble valley drained the southwestern quadrant of the Llano Uplift, generating thick deposits of Hensel terrigenous clastics.

INTRODUCTION

Lower Cretaceous Transgressive Facies Tracts and the Llano Uplift

The Llano Uplift in Texas is a football-shaped domal uplift with a Precambrian core surrounded mainly by faulted Cambro-Ordo-vician carbonates and sandstones (Standen and Ruggiero, 2007). A rimrock of Lower Cretaceous formations (the Hensel Sandstone and Glen Rose Formation [H–GR] and overlying Edwards Limestone) lies adjacent on three sides—east, south, and west. These formations thicken to the east and south, across the Balcones-Ouachita Downwarp (Rose, 2016), which constitutes the updip margin of the Gulf of Mexico Basin. Only a few thin, isolated, remnant Hensel and Edwards outcrops remain in the northern Llano Uplift, scattered across the broad Cambro-Ordovician highland between the Llano and San Saba river valleys.

The earliest Cretaceous seas began their long and episodic encroachment from the evolving Gulf of Mexico northward onto the craton of south-central North America nearly 140 Ma (Phelps et al., 2014; Ewing, 2016). The basic pattern of this transgressive sedimentary record consists of coarse- to fine-grained terrigenous clastics derived from erosion of the subsiding coastal landscape, that grade laterally into shallow-marine carbonate sediments deposited offshore, in clearer warm tropical seas. The earliest example of such depositional couplets in south-central Texas is the Hosston-Sligo couplet (136–122 Ma), first recognized by Stricklin et al. (1971).

From 122 to 119 Ma, the transgressing seas moved farther northward across the subsiding craton, and the counterpart depositional sequence is the Sycamore Sandstone–Hammett Shale–Cow Creek Limestone succession (Loucks, 1977; Amsbury, 1996; Hull and Loucks, 2010). This sequence is preserved in

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outcrop only along the southeastern margin of the Llano Uplift, but is widely present in the subsurface downdip to the east and south.

On the southeastern flank of the Llano Uplift, the next cratonward pulse of the invading Cretaceous sea began about 115 Ma with the accumulation of the terrestrial to peritidal Hensel Sandstone. The Hensel was deposited on a faulted and deeply weathered hilly terrane of mostly Cambro-Ordovician carbonate and terrigenous strata, and Precambrian (Grenville) metamorphic and plutonic rocks, all of which had been deformed during the Ouachita orogeny (300–290 Ma). The Glen Rose Formation is the coeval offshore peritidal and shallow-marine carbonate facies of the Hensel Sandstone. The H–GR stratigraphic couplet was succeeded by the peritidal to shallow marine Edwards Limestone (104–98 Ma), which completely flooded the craton of central Texas. Across most of that area, a regional disconformity between the Edwards and underlying H–GR couplet represents a short period of broad areal exposure but little consequential erosion (Rose, 1972, 2016, 2019).

The land surface across which those successive transgressive terrigenous clastic sedimentary aprons gradually migrated—Hosston, Sycamore, and Hensel—is the Wichita Paleoplain (WPP) of Hill (1901) and Rose (2021), thus, it is also time-transgressive, older downdip and younger updip (i.e., farther north on the craton). In the Llano Uplift. the WPP represents a hiatus lasting roughly 190 m.y. (Pennsylvanian Desmoinesian to Cretaceous early Aptian).

Influence of WPP Topography on H–GR Stratigraphy, Llano Uplift

Previously, detailed mapping (Rose, 2021) in the southeast Llano Uplift treated the Hensel and Glen Rose as separate formations rather than lateral lithofacies within a single depositional unit. The present paper adopts and documents a revised, more regional approach, treating the Hensel and Glen Rose lithosomes as facies of a single transgressive stratigraphic couplet, the H–GR. Even so, it must be emphasized that the H–GR consists entirely of Hensel terrigenous clastic facies over most of the Llano Uplift and is dominated by Glen Rose carbonate facies only to the south and east, along the Balcones-Ouachita Downwarp.

In the Llano Uplift, additional stratigraphic variations in H–GR thickness and composition were caused by the substantial paleotopographic relief of the regional unconformity upon which the H–GR was deposited, the WPP. Such relief was mainly the result of differential weathering and erosion: areas underlain by Precambrian crystalline rocks, which had already undergone one long period of weathering in late Precambrian-early Cambrian time, were once more deeply weathered during the 190 m.y. that followed the Ouachita Orogeny, along with fault-juxtaposed Cambro-Ordovician dolomites and sandstones. The geomorphic result is the counterintuitive inverse structural topography so characteristic of the Llano Uplift today: high-standing grabens of Cambro-Ordovician carbonate and sandstone strata juxtaposed against lowland-horst blocks composed of Precambrian gneisses, schists, and granites as discussed by Rose et al. (2022). Such inverse geomorphology began to develop following the Ouachita Orogeny: Neogene uplift, erosion and weathering of the Llano Uplift area has only reinforced it.

H–GR sedimentation gradually and successively filled-in most WPP paleotopography in the southern Llano Uplift, leaving only a few high-standing Cambro-Ordovician graben blocks and small Precambrian exfoliation domes. Lower Edwards carbonate strata eventually covered the highest hills. Local paleotopographic relief of the WPP caused substantial and abrupt changes in thickness and composition—and thus stratigraphy—of the infilling H–GR sediments, as recognized by Campbell (1962). The central core of the Llano Uplift—especially the Llano River watershed—consists only of deeply-eroded Precambrian rocks: no H–GR or Edwards outcrops are present there. But outcrops of thin and relict Hensel Sandstone are present to the east, south, and north (as well as thick outcrops to the west), demonstrating the earlier presence of the Hensel across the entire Llano Uplift. Thus, one of the present research challenges was to project H–GR thickness and lithology from the margins of the Llano Uplift across the central core of the Uplift. Such interpretive mapping was guided by the areal distribution of underlying Precambrian and Paleozoic outcrops and major fault trends (as displayed on all maps) as well as adjacent isopachous gradients where H–GR strata were present.

PURPOSE AND PLAN

Purpose

This project intends to characterize and delineate the H–GR stratigraphic couplet as a transgressive depositional unit throughout the Llano Uplift and its surrounding areas, and to discuss any further attending geological implications.

Plan

Sequential construction of six related figures—maps and cross-sections—provided the geotechnical basis for the contemplated analysis. The principal work products of the project consist of:

(1) A base map derived from the Geological Atlas of Texas, Brownwood and Llano 1:250,000 sheets (Kier et al., 1976; Barnes, 1981) showing latitude and longitude, county lines, major streams, principal towns, and outcrop areas of Precambrian, Paleozoic, and Lower Cretaceous strata (Fig. 1);

(2) A paleotopographic map drafted on the base map, showing the present configuration of the WPP, derived partly from earlier (Rose, 2021) mapping, but also incorporating substantial, newly available, more detailed mapping (Fig. 2);

(3) A thickness map of the H–GR stratigraphic couplet drafted on the base map, projecting H–GR distribution and thickness throughout the Llano Uplift region, especially the Llano River Valley, where no Hensel outcrops are present (Fig. 3);

(4) A schematic cross-section showing main features of the H–GR stratigraphic couplet, Llano Uplift and adjacent areas, Central Texas (Fig. 4);

(5) Four regional geological cross-sections (Fig. 5), showing elevations, thickness, facies, and extent of the H–GR stratigraphic couplet, in relation to the WPP and the base of the overlying Edwards Limestone (bKed—important as the regional stratigraphic reference datum), major faults, and underlying formations; and

(6) a paleotopographic map drafted on the base map, showing the configuration of the WPP when first transgressed by the H–GR around 115 Ma (Fig. 6). This map was constructed by restoring the current paleotopographic map of the WPP surface (Fig. 2) to its configuration and elevations at the beginning of H–GR deposition by eliminating the northwestward-rising regional slope caused by Neogene Balcones faulting and uplift and regional elevation of the Colorado Plateau. Rose (2021) described this procedure.

STRATIGRAPHY OF THE H–GR COUPLET

Paleotopography Underlying the H–GR Stratigraphic Couplet

The base of the H–GR stratigraphic couplet—the WPP—ranges in elevation from more than 2100 ft in northwest Gillespie

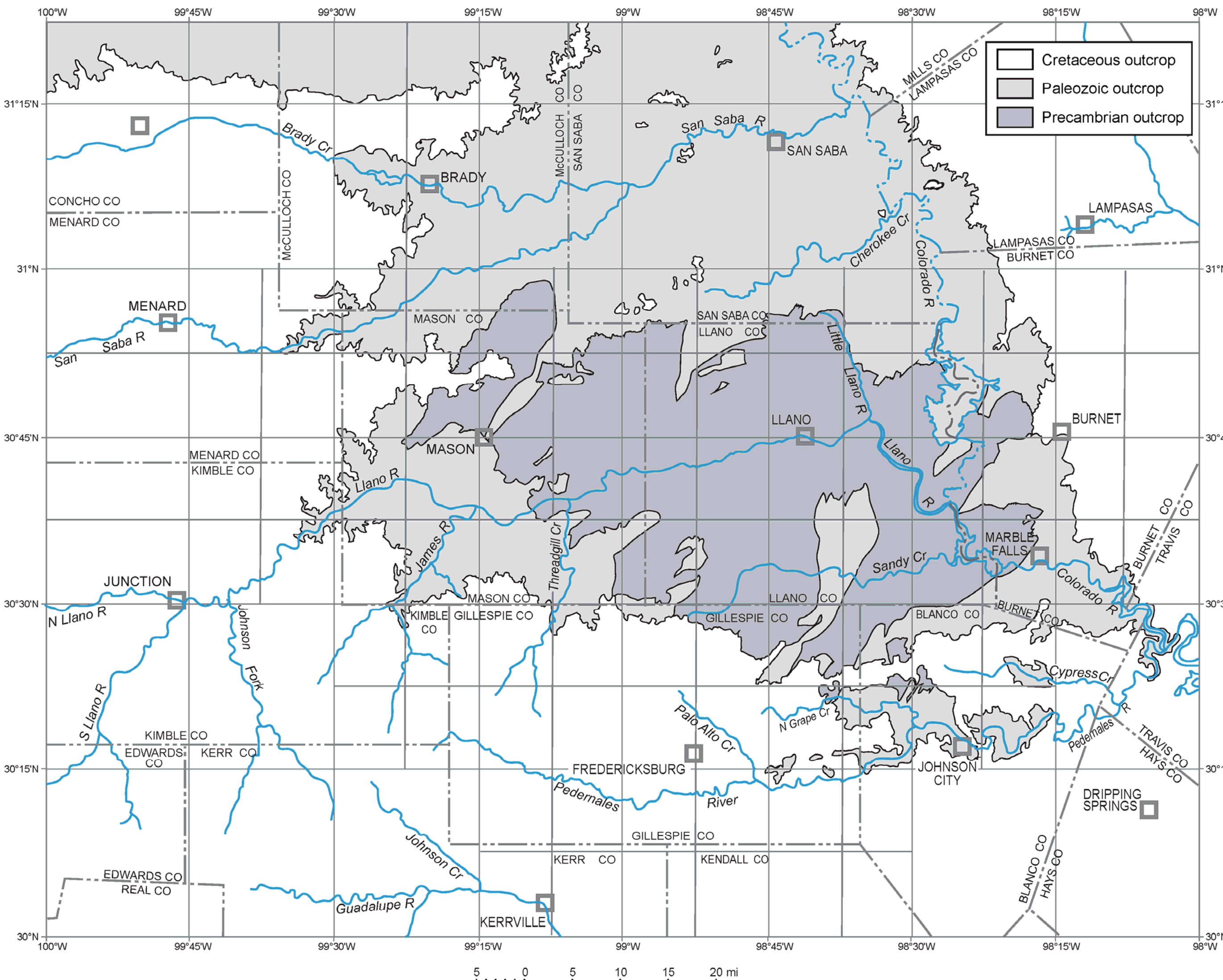

Figure 1. Base map showing outcrop areas of Precambrian, Paleozoic, and Cretaceous rocks, Llano Uplift, Texas (modified after Kier et al. [1976] and Barnes [1981]).

County (Fig. 2) southward to less than 1000 ft in northern Kerr and Kendall counties and eastward to less than 700 ft in western Travis County, in the Colorado River valley. In the southeastern part of the map area, south of Johnson City, west of Dripping Springs, and centered around Blanco, is a broad, low, southeast-trending ridge called the Blanco High, which is underlain by faulted Paleozoic strata.

The configuration of the WPP landscape in the Llano Uplift itself may be summarized as a broad, eastward-sloping upland dissected by two straight, parallel, east-sloping valleys, (the precursor Llano and San Saba rivers), with elongate, broad ridges to either side, whose divides stood 300 to 500 ft higher than the adjacent valleys (Fig. 2). A ridge to the north of the San Saba valley is lower and less well defined. All three ridges and valleys merge eastward into the eastward-steepening Balcones-Ouachita Downwarp. A gentle north-south divide in southwestern Mason County, elevation about 1650 ft, separates the east-flowing Llano Valley from the Kimble Valley, which flowed southward toward the Rio Grande Embayment.

All three ridges consist of faulted Cambro-Ordovician carbonate strata; the southern ridge stood highest (1600 to >2100 ft) and was radially dissected by tributary streams. The middle ridge (1600 to 1950 ft) was broader, less dissected, and extended farther east, across the present course of the Colorado River, into northwestern Burnet County.

Even a cursory inspection of WPP paleotopography (Fig. 2) shows that map areas underlain by Precambrian crystalline rocks are consistently low-lying, in contrast to consistently more elevated areas of Paleozoic rock outcrop. This phenomenon holds true for large areas, such as the central and eastern sectors of the Llano River valley, and also for local areas, especially where high-angle normal faults juxtapose Paleozoic outcrops and Precambrian granite, gneiss, or schist. Good examples are the Riley Mountain and Blowout fault blocks north of Fredericksburg, the Mason fault block southwest of Mason, and the Valley Spring fault block in northern Llano County. These localities demonstrate that such inverse topographic/structural relationships already existed on the WPP landscape before any Cretaceous deposition began.

High-standing granitic exfoliation domes are also present, scattered across the lowland Precambrian core of the Llano Uplift, such as House Mountain, Smoothing-Iron Mountain, and Enchanted Rock. These isolated, areally limited pinnacles all stand about 400 ft above adjacent crystalline terranes, terminat-

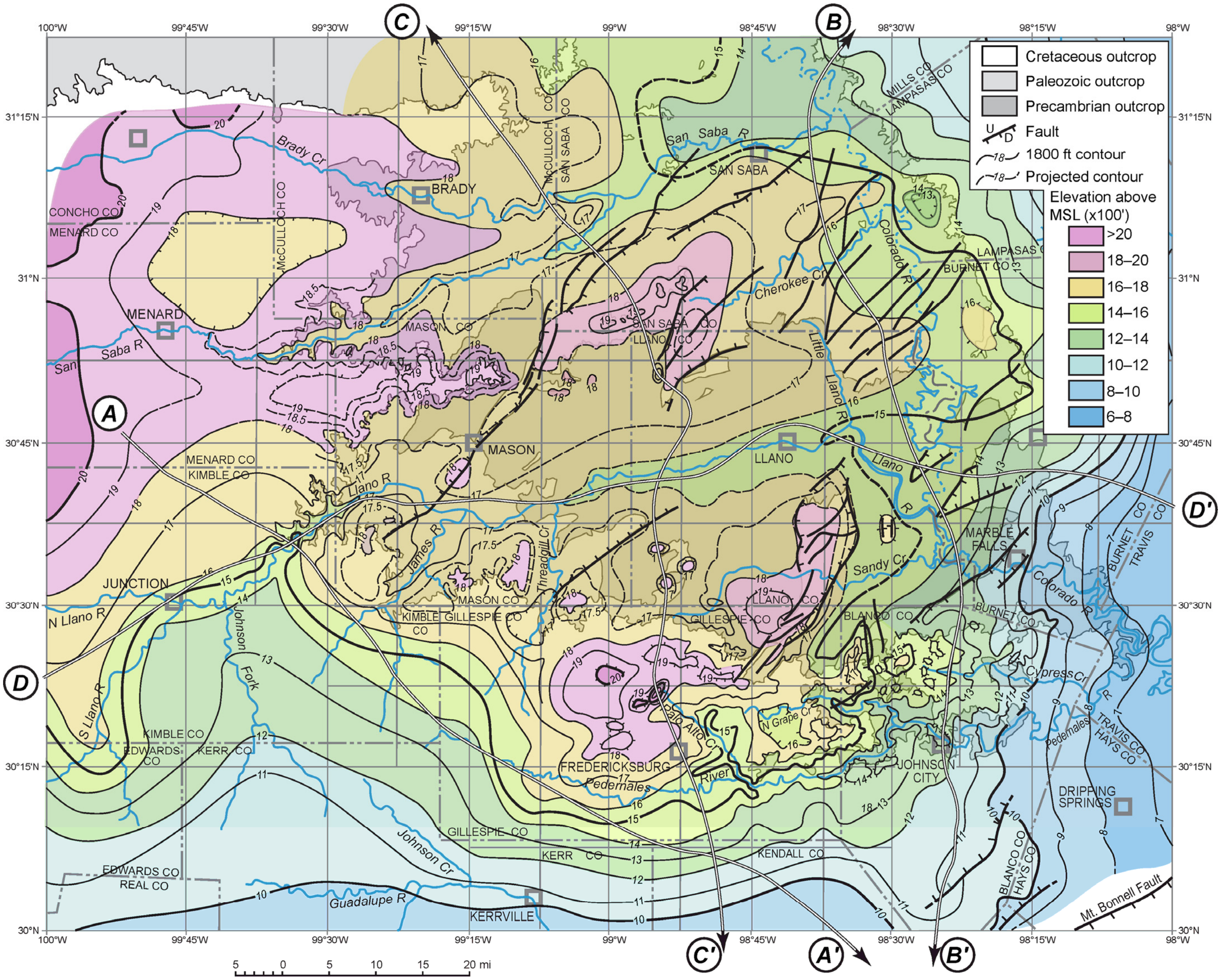

Figure 2. Configuration of the Wichita Paleoplain (WPP), Llano Uplift and adjacent areas, Central Texas, showing traces of geologic cross-sections A–A', B–B', C–C', and D–D' (Fig. 5). Note that local darkening of elevation colors exists due to the partial-transparent overlay of greyscale tones related to Paleozoic and Precambrian outcrop areas. Contour interval is 100 ft.

ing at or near the projected base of the Edwards Limestone (bKed). Any influence such domes may have had on H–GR sedimentation patterns has not yet been detected. Moreover, an explanation of their evident resistance to weathering and erosion, compared to the widespread deep weathering of adjacent granitic terranes, has yet to emerge.

H–GR Thickness and WPP Paleotopography

Generally, the Hensel lithosome is notably thinner in the eastern Llano Uplift (in the Burnet-Marble Falls-Johnson City sector) than in the central and western sectors. Total H–GR thickness (Fig. 3) ranges from zero over high-standing Paleozoic graben blocks and Precambrian exfoliation domes within the Llano Uplift, to more than 750 ft on the south flank of the Llano Uplift in northern Kerr and Kendall counties, and more than 400 ft in the Balcones-Ouachita Downwarp to the east. The regional pinchout edge of the *Corbula* key bed, which separates the Lower and Upper Glen Rose, trends northeast from east of Kerrville to west of Johnson City to east of Marble Falls. All Glen Rose strata northwest of the *Corbula* bed pinchout line lie within the Upper Glen Rose.

Abrupt local changes in H–GR thickness have been mapped peripheral to bounding fault-line scarps of the Riley Mountain, Blowout, and Marble Falls grabens (Rose, 2021). They are inferred in the vicinity of analogous structures, such as the Backbone Ridge, Long Mountain, Mason, and Valley Spring graben blocks. Over granitic terranes between some elevated graben blocks in the eastern Llano Uplift, the Hensel sand facies occurs as thick (>300 ft) accumulations in closed "minibasins" bounded by fault-line scarps. Analogous isopachous "thicks" exceeding 400 ft are also projected in the central and eastern sectors of the elongate precursor Llano River valley. Such inferred H–GR thicknesses are consistent with observed and mapped H–GR thicknesses in Gillespie, Llano, and Mason counties. The H–GR couplet is thin over large areas underlain by Cambro-Ordovician subcrops, such as the Round Mountain and Cave Creek paleohighs of northwestern Blanco and eastern Gillespie counties respectively, and the broad Cambro-Ordovician highland of southern San Saba County. Farther south, in the subsurface of Blanco, Hays, and Kendall counties, the Hensel facies is thin where it overlies Paleozoic formations, even though the overlying Glen Rose facies has thickened substantially, to more than 500 ft (Wierman et al., 2010; Broun et al., 2020).

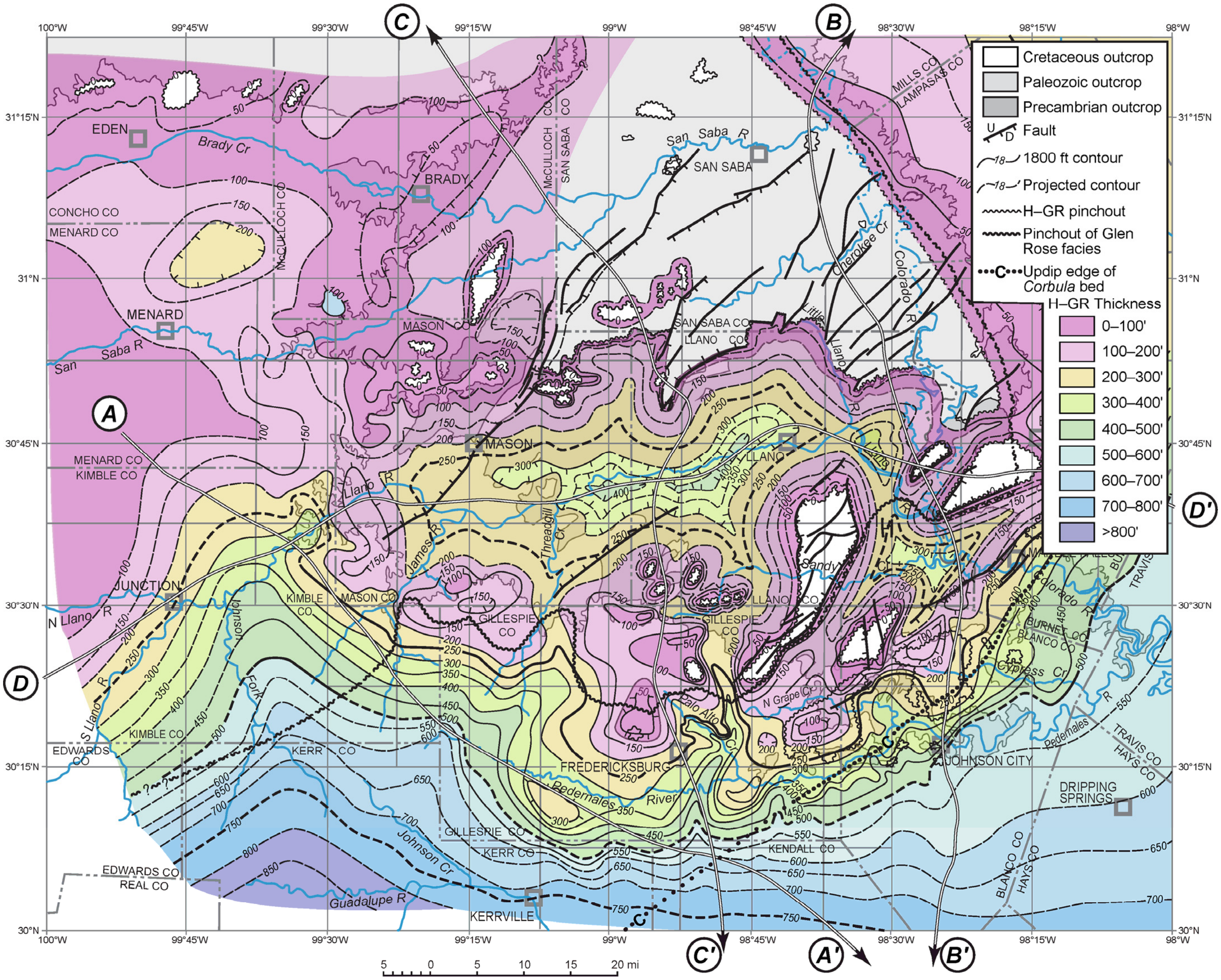

Figure 3. Thickness of the H–GR stratigraphic couplet, Llano Uplift and adjacent areas, Central Texas, showing traces of geologic cross-sections A–A', B–B', C–C', and D–D' (Fig. 5). Note that local darkening of thickness colors exists due to the partial-transparent overlay of greyscale tones related to Paleozoic and Precambrian outcrop areas. Contour interval is 50 ft.

Physical Evidence for H–GR Facies Relationship

V. E. Barnes reported the first published evidence for a facies relationship between the H–GR in the earliest texts describing the geology of mapped quadrangles along the southern rim of the Llano Uplift (Barnes, 1952a [Crabapple Creek Quadrangle], 1952b [Willow City Quadrangle], 1952c [Blowout Quadrangle], 1952d [Palo Alto Creek Quadrangle]). The Glen Rose thins northward from 100 ft at Fredericksburg to zero over a distance of 3 to 6 mi, and also by grading laterally into Hensel arkosic sandstone. This Glen Rose pinchout edge wanders erratically from west to east across eastern Kimble, northern Gillespie, and southeastern Llano counties, where it is interpreted here to turn abruptly northwestward along the east side of the Colorado River, through western Lampasas and Mills counties (Fig. 3). Lozo and Stricklin (1956) also recognized the H–GR facies relationship, and Loucks (1977) recognized it in the subsurface of south Texas. Detailed mapping and stratigraphic cross-sections in the shallow subsurface of Blanco and Hays counties demonstrate lateral equivalency of upper Hensel sandstone and Lower Glen Rose carbonates (Wierman et al., 2010). Many other authorities also recognized the H–GR facies relationship (Campbell, 1962; Payne and Scott, 1982; Jones and Kullman, 1997; Amsbury, 1996; Barker and Ardis, 1996).

Later publications (Hull and Loucks, 2010; Phelps et al., 2014; Snedden and Galloway, 2019; Broun et al., 2020) focused on unravelling the complex sequence stratigraphy of the family of Aptian/lower Albian members that comprise the Pearsall Formation of the south-central Texas subsurface (Hammett Shale/Cow Creek Limestone/Bexar Shale/Hensel Sandstone) and the overlying Glen Rose Formation. By contrast, the present study focuses on H–GR stratigraphy in the Llano Uplift itself. In this area, most of the Hensel is in non-marine or coastal facies. The configuration and depositional settings of the H–GR couplet are significantly governed by the paleotopography of the underlying erosion surface—the WPP.

A schematic summary of the H–GR facies relationship is provided by Figure 4, which shows (1) the H–GR as a south-thickening sediment wedge composed of Hensel sandstone to the north, grading reciprocally southward to a progressively larger proportion of Glen Rose carbonate, culminating in 90% of the upper H–GR interval consisting of Glen Rose limestones and dolomites south of the Guadalupe River, where the H–GR interval is >600 ft thick; (2) the northward pinchout of Upper Glen

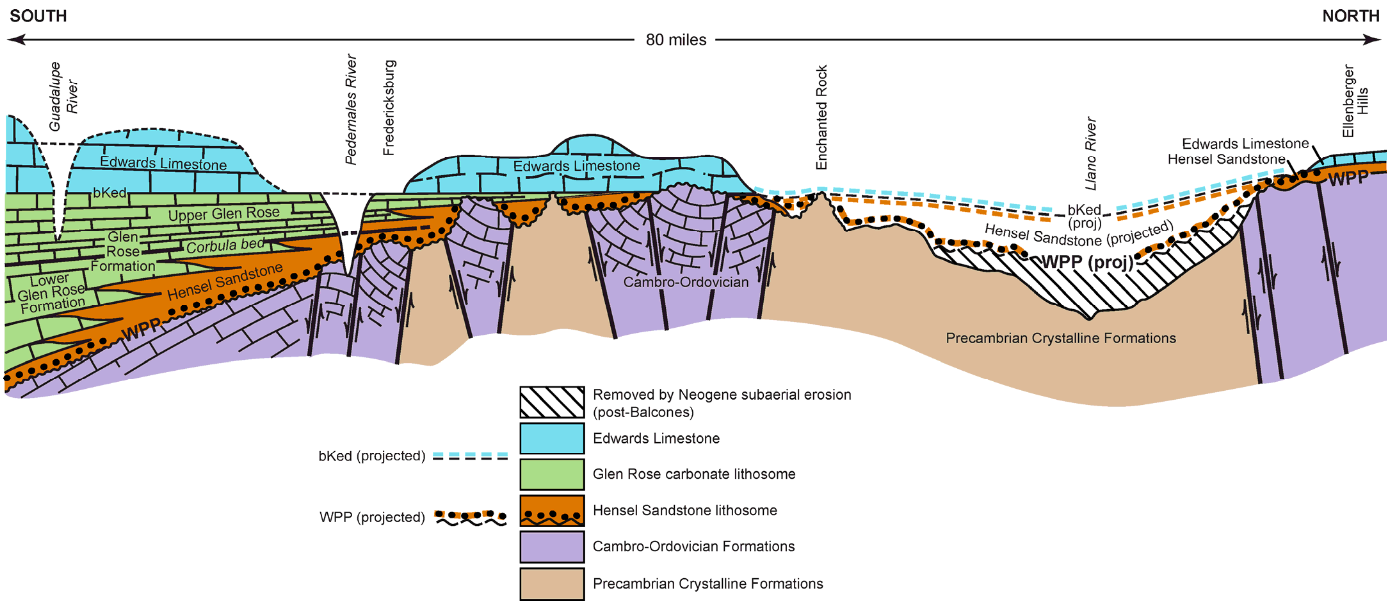

Figure 4. Schematic cross-section showing main features of the H–GR stratigraphic couplet, Llano Uplift and adjacent areas, Central Texas.

Rose facies into Hensel facies, so that the H–GR interval consists entirely of arkosic conglomerate and sandstone within the central core of the Llano Uplift, where it overlies terranes of Precambrian crystalline rocks; (3) the northward pinchout of the *Corbula* key bed, dividing the Glen Rose Formation into Lower and Upper members; (4) most of the Hensel coarse clastic facies of the central Llano Uplift to be younger than the *Corbula* key bed, commonly reaching upward through the Upper Glen Rose to the overlying Edwards Limestone[1]; (5) the close correspondence of abrupt and substantial thickening of Hensel sandstone into paleotopographic depressions of the WPP over Precambrian crystalline bedrock ("minibasins") in the interior of the Llano Uplift; and (6) the gentle decline of the overlying Edwards Limestone above Hensel minibasins, reflecting the basinward slope of Hensel alluvial fans that filled them. A prevailing (though not universal) upward fining of Hensel sediments above basal conglomerates is seen whether the Hensel is thick (>100 ft) or thin (<100 ft).

H–GR Lithology and Depositional Environments, Llano Uplift Area: Previous Work

Because the Hensel Sandstone is weakly indurated, extensive, well-exposed outcrops are rare. Consequently, Campbell (1962) and Payne and Scott (1982) based their analysis of Hensel petrography and depositional environments on 24 and 14 separate locations, respectively, scattered widely across the southern flank of the Llano Uplift; all their described deposits are compatible with the general terrestrial settings ascribed to them in this paper. Even though mapped thickness of the Hensel Sandstone at these locations ranges from 100 to >400 ft, none of the actual exposures spans continuous stratigraphic intervals thicker than about 20 ft; most are less than 10 ft thick. Unfortunately, no localities where the Hensel was thin—10 to 50 ft, commonly where it thins onto paleotopographic highs—were described or sampled, hence no published information is available as to what depositional environments characterize the Hensel in such settings, which are common around the margins of the Llano Uplift over high-standing Cambro-Ordovician graben blocks. Campbell (1962) described the petrography of the Hensel Sandstone as mostly immature to submature arkose, generally fining upwards.

Payne and Scott (1982) described the assemblage of Hensel depositional environments as scattered components of one general terrestrial setting comprising alluvial fan, fluvial, and coastal plain systems, including cross-bedded fluvial channel conglomerates and sandstones up to 6 ft thick, overbank sand splays, fine sand and mud levee deposits with root traces, and muddy playa and playa margin deposits. Paleosols, characterized by root traces and indurated pedocals (in situ and sedimentary fragments) are common in overbank deposits. Outcropping Hensel rocks are characteristically various shades of red and ochre. Basal Hensel sediments are dominated by alluvial-fan and valley-fill conglomerates; in contrast, upper Hensel intervals tend to be dominated by finer sand, silt, and mud, recording the Early Cretaceous invasion and eventual flooding of the Llano Uplift. Payne and Scott envisioned a semi-arid, seasonal climate. Upper Hensel fine-grained coastal plain sediments grade upward into peritidal muds and muddy carbonates, marking the gradational boundary between the Hensel and Glen Rose lithosomes. North and west of the Glen Rose pinchout, the H–GR interval—here equivalent only to the Upper Glen Rose—consists entirely of Hensel-type terrestrial deposits.

Rose (2021) identified a thick, narrow Hensel stream channel that originated in the general vicinity of Enchanted Rock, where it is >200 ft thick and passes southward along the Palo Alto Creek watershed east of Fredericksburg to intersect with the ancient valley of the Pedernales River, where it is >400 ft thick (Fig. 3). This isopachous "thick" coincides with a channel cut into the north bank of the Pedernales River (Fig. 2).

Payne and Scott's (1982) measured section 'H' lies near the northern end of this stream channel, about 2 mi southwest of Enchanted Rock; Barnes (1952b) also measured a section of

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[2]Actually, this finding differs from the stratigraphic column of Hull and Loucks (2010, their figure 1), stratigraphic columns and cross-sections of Phelps et al. (2014, their figures 2, 5, and 15); and figures 4.2 and 4.11 of Snedden and Galloway (2019), which show Hensel sandstone facies equivalents limited to the updip Pearsall, Bexar, Lower Glen Rose and only the very lowest strata of the Upper Glen Rose.

Hensel Sandstone here. The Hensel is about 160 ft thick, although both Barnes (1952b) and Rose (2021) indicated an average Hensel thickness of about 210 ft in the area. This measured section begins with about 78 ft of mostly covered conglomerate and coarse sandstone (possibly alluvial fan deposits), overlain by about 82 ft of fluvial channel sediments, mostly as coarse to medium cross-bedded channel sand beds, each 2 to 4 ft thick, interbedded with red mudstone containing calcrete nodules and pipes, and root traces. Payne and Scott's (1982) measured section 'I,' at West Crabapple Creek, lies about 3 mi southwest. They describe a 12 ft section of overbank sands and muds overlain by a 4 ft bed of cross-bedded coarse-grained sand, representing a laterally accreting channel sand over calichified overbank deposits. Both measured sections are consistent with the alluvial fan to fluvial channel settings ascribed to them.

Wierman et al. (2010) presented detailed lithologic logs and cross-sections, including the H–GR interval, in the shallow subsurface southeast of the Llano Uplift, in Hays and southern Blanco counties. Here the Hensel lithosome is thinner than in areas farther west and north around the Llano Uplift—20 to 80 ft, consisting of transitional, finer-grained lithologies—sandstone, mudstone, dolomite, shale, and limestone. In contrast, the overlying Glen Rose lithosome is 500 to 700 ft thick. The Lower Glen Rose is a 200 to 300 ft- thick limestone unit constituting a classic shallow-marine seaward facies-succession thickening toward the southeast. The Upper Glen Rose is 300 to 400 ft thick, generally peritidal to shallow marine silty dolomitic strata, with common anhydrite/gypsum beds and nodules. The *Corbula* key bed divides the Upper from the Lower Glen Rose; its updip pinchout edge is shown on Fig. 3 as a dotted southwest-northeast line across the southeast corner of the Llano Uplift, representing Glen Rose depositional strike at that time.

Jones and Kullman (1997) analyzed Hensel Sandstone outcrops along the western margins of the Llano Uplift adjacent to the Llano River, in eastern Kimble County (Payne and Scott [1982] described a spectacular 40 ft section here of coarse-stratified pebble and cobble conglomerate succeeded upward by cross-bedded sandstone containing calcrete clasts, grading upward to laminated siltstone). Total Hensel thickness in this area ranges from 200 to 400 ft (Fig. 3). This area lies at the head of the south-flowing Kimble valley, a WPP valley eventually captured by the east-flowing Llano River during Neogene time (Rose, 2021). At the WPP level, the divide between the two drainages lay about 5 mi east of the Mason-Kimble county line (Fig. 2).

Jones and Kullman (1997) summarized the Hensel as comprising three distinct lithosomes, aggregating about 250 to 285 ft of total thickness:

(1) <u>Basal Conglomerates</u>, 0 to 50 ft thick, consisting of "vertically stacked and laterally lenticular clastic wedges." Thickness of individual conglomerate horizons is highly variable—the average thickness is four to seven ft; however, spectacular thicknesses that exceed 20 ft thick have been observed "in some areas." Clast size varies from boulders to pebbles, in a coarse to medium sand matrix. Most clasts have been derived from the underlying Ordovician Ellenburger and Pennsylvanian Marble Falls formations. Paleocurrents indicate a southwest paleoflow direction, consistent with the mapped southwest trend of the Kimble valley.

(2) <u>Middle Paleosols</u>, about 105 ft thick, consisting of a series of bright red paleo soil horizons and fluvial channel sandstones; the sandstone beds are typically 2 to 6 ft thick. The paleocaliches display prominent calcrete horizons and vertical root marks.

(3) <u>Upper Fines</u>, about 130 ft thick, consisting of fine-grained siliclastic sediments in the lower half of this interval, succeeded upward by predominantly tan calcareous siltstone with a few thin-bedded limestones near the top, interpreted as the distal ends of alluvial fans. The lower boundary is abrupt, representing the shift from subaerial to a subaqueous depositional setting. The upper boundary is the disconformable contact with the overlying Edwards Limestone.

Jones and Kullman (1997) interpreted the two lower lithosomes (basal conglomerates and middle paleosols) to represent one or more alluvial fan deposits. They interpreted the upper fines lithosome as distal alluvial fan deposits succeeded upward by peritidal fan-delta deposits.

Although Jones and Kullman (1997) may well be correct that their upper fines lithosome is laterally equivalent to the Upper Glen Rose Formation (i.e., above the *Corbula* key bed), their recommendation that this unit be formally assigned to the Glen Rose is inappropriate for three reasons: (1) both Hensel and Glen Rose are rock units (i.e., formations, not time-rock units); (2) the upper fines lithosome is dissimilar to classic Upper Glen Rose lithology; and (3) adoption of the conceptual stratigraphic couplet to apply to the two lithologic/facies members of the H–GR renders such a recommendation unnecessary. For perspective, Rose (1972) recognized the upper fines lithosome as intermediate between typical Hensel and Glen Rose lithology but made no recommendation regarding stratigraphic reassignment, and the 1:250,000 Llano Sheet of the Geologic Atlas of Texas (Barnes, 1981) followed then-established terminology, assigning the upper fines unit to the Hensel Formation.

In the northwestern Llano Uplift, the Hensel Sandstone crops out along the foot of Mason Mountain, an east-reaching interfluve of the Edwards Plateau in northwestern Mason County. Mutis-Duplat (1982) and Hunt et al. (2021) described thin (20 to 40 ft) red and yellow intervals of arkosic, dolomite-cemented clastics, some cross-bedded, fining upward from basal conglomerates to mudstones.

Northwest of the Llano Uplift, in Concho County, Hensel Sandstone equivalents are assigned to the Antlers Formation (Fisher and Rodda, 1966), which rests on a succession of Permian formations that dip gently westward across the eastern shelf of the Midland Basin. These formations consist of lightly indurated shales, limestones, and fine-grained sandstones. Although local erosional relief on the WPP ranges up to about 100 ft, the underlying strata are less disturbed by faulting than farther southeast, in the Llano Uplift. In the subsurface farther west, equivalent terrigenous clastic strata underlying the Edwards Limestone, are assigned to the "Basal Cretaceous Sand" (Smith and Brown, 1983). Barker and Ardis (1996), citing Romanak (1988), described the Basal Cretaceous Sand as a highly diverse succession of terrigenous clastics, commonly conglomeratic in the lower part, with finer-grained variegated sands in the middle, with some paleocaliche, and increasingly finer-grained sands, silts, and claystones toward the top. The conglomerates consist mainly of eroded fragments of underlying formations. Common paleocaliche indicates a semi-arid paleoclimate, which also implies that some of the finer-grained sands may be of aeolian origin. Romanak (1988) interpreted some fluvial deposits, primarily representing braided streams. Given the lightly indurated, flat-lying character of the underlying beds, and the long extent of the hiatus before deposition of the Antlers and Basal Cretaceous Sand (about 180 to 140 Ma), it seems likely that a deeply weathered, residual regolith was present, which was reworked and incorporated into the overlying transgressive terrigenous clastics of the Antlers and Basal Cretaceous Sand.

Atchley et al. (2001) studied the "Travis Peak Formation," comprising the Sycamore and Hensel sandstones, in the area northeast of the Llano Uplift, in San Saba, Lampasas, and Mills counties. They characterized the Sycamore as a "lower chert-pebble conglomerate derived mostly from the Ordovician Ellenburger Group, representing braided stream deposits formed as alluvial fans draining northeastward from Llano Uplift highlands" and the overlying Hensel as an "upper medium-grain sandstone," formed as meandering fluvial deposits draining northeastward across a sloping outwash plain north of the Llano Uplift. Both lithosomes contain abundant evidence of paleocaliche.

Regional Cross-Sections

Four interlocking regional cross-sections (A–A', B–B', C–C', and D–D' illustrated in Figure 5), document lateral thickness variations of the H–GR stratigraphic couplet in the Llano Uplift relative to paleotopography of the WPP, lithology of underlying formations, and H–GR depositional environments. Traces of all four cross-sections are mapped on Figures 2 and 3.

It is important to understand how these cross-sections were constructed:

(1) First, the profile of the ground surface was configured along the trace of each cross-section from topographic maps, with the underlying formation listed below the profile (Precambrian, Cambro-Ordovician, Pennsylvanian) as derived from the 1:250,000 Brownwood and Llano sheets of the Geologic Atlas of Texas (Kier et al., 1976; Barnes, 1981);

(2) Next, the elevation of the base of the Edwards Limestone (bKed), as derived (or interpreted) from geologic/topographic maps, was entered on each cross-section;

(3) Third, the thickness of the H–GR succession was entered, as derived from Figure 3; in areas south of the Glen Rose pinchout line, both the Hensel and Glen Rose facies thicknesses were shown on the cross-sections. North of the Glen Rose pinchout line, the H–GR couplet consists solely of Hensel terrigenous clastic sediments;

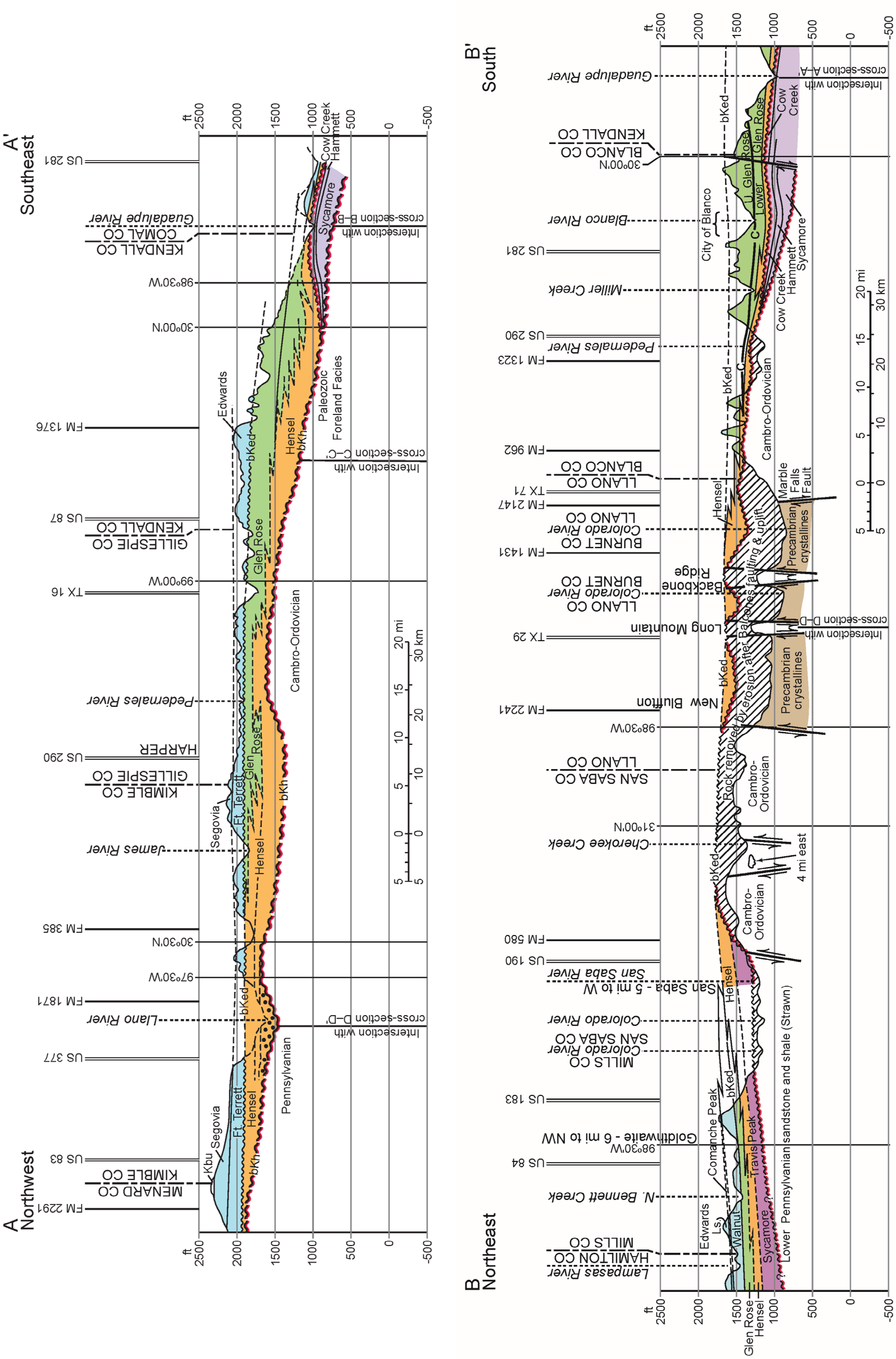
(4) Finally, where cross-sections B–B', C–C' and D–D' (Fig. 5) traverse the valleys of the Llano, San Saba, and Pedernales rivers, the base of the H–GR (the WPP) lies above the present ground surface, by intervals of 0 to 600 ft. Such intervals, shown by a right-sloping diagonal-line pattern, are believed to represent the thickness of rocks eroded from these river valleys during the Neogene, after Balcones faulting and uplift. It should be acknowledged, however, that projected thicknesses of the Hensel lithosome from Figure 3 are interpretations, involving application of observed stratigraphic patterns and projection of observed thickening rates in contouring. The accuracy of such interpretations is supported by the consistently increased thickening of the removed section in the downstream segment of the Llano River. This topic will be further discussed in summaries of cross-sections B–B', C–C', and D–D'.

Cross-section A–A' (Fig. 5) passes southeasterly from the Edwards Plateau of central Menard County across the valley of the Llano River of northeastern Kimble County back up onto the Edwards Plateau of southern Gillespie and northern Kendall County, thence into the valley of the Guadalupe River about 4 mi west of the town of Spring Branch. It intersects cross-section D–D' at their joint crossing of the Llano River in northeast Kimble County, cross-section C–C' in northwestern Kendall County, and cross-section B–B' at their joint crossing of the Guadalupe River in northern Kendall County. Cross-section A–A' demonstrates the reciprocal thickness relationship of the Hensel and Glen Rose lithosomes, previously noted, within the H–GR stratigraphic couplet, where the Hensel facies dominates to the north, and the Glen Rose dominates to the south. It also illustrates the sequence of the thick Hensel section in the western Llano valley, described by Jones and Kullman (1997), indicating that their "upper fines" member of the Hensel does appear to be laterally equivalent to the Upper Glen Rose Formation (above the *Corbula* key bed). No Upper Glen Rose carbonate facies have been identified west of western Gillespie County. At the southeastern end of A–A', the Cow Creek/Hammett/Sycamore succession is present beneath the H–GR couplet in the Guadalupe River valley.

Cross-section B–B' (Fig. 5) trends from south to north across the eastern end of the Llano Uplift, from the end of cross-section A–A' on the Guadalupe River through Johnson City, Marble Falls, across the Ellenburger Hills of San Saba County to about 5 mi east of San Saba, ending in southwestern Mills County. Cross-section B–B' intersects cross-section D–D' on Long Mountain in eastern Llano County. It shows a thin Hensel section overlying the Round Mountain paleohigh, and dramatic thickness changes northward, where the Hensel overlies Precambrian granitic lowlands adjacent to high-standing Cambro-Ordovician fault blocks. Neogene erosional removal of 100 to 300 ft of Paleozoic strata is indicated where cross-section B–B' crosses the Ellenburger Hills in southern San Saba County, suggesting that H–GR strata may have once been present there. However, thin remnant intervals of Hensel beneath the overlying Edwards Limestone are present 20 mi west (see cross-section C–C', Fig. 5), suggesting that if the Hensel was present above the WPP, it was probably thin. Farther northward, cross-section B–B' crosses over faulted Lower Pennsylvanian rocks before passing onto middle Pennsylvanian Strawn sandstone and shales, and thence onto Lower Cretaceous Travis Peak, Glen Rose, and Edwards strata east of the Colorado River. Cross-section B–B' is noteworthy for showing robust thickness changes in Hensel facies passing from high-standing Cambro-Ordovician fault blocks onto low-lying Precambrian crystalline terranes in Llano County, as well as thick, laterally extensive sectors of inferred Neogene erosion of Precambrian rocks, denoted by the right-sloping linework pattern.

Cross-section C–C' (Fig. 5) is a south-to-north cross-section that lies 20 to 30 mi west of cross-section B–B'. It begins in the Guadalupe River valley in northwestern Kendall County near the village of Waring, bearing north across the Edwards Plateau into Gillespie County, crossing the Pedernales River south of Fredericksburg, continuing northward across the Pedernales-Llano divide in northern Gillespie County, onto the Precambrian terrane of the Llano River valley. In northern Llano County, cross-section C–C' crosses onto Cambro-Ordovician highlands near Smoothing-iron Mountain, then veers northwest across southwestern San Saba County, crossing the San Saba River and Brady Creek, then into eastern McCulloch County, where it crosses a narrow eastern extension of the Edwards Plateau, thence down into the wide valley of the Colorado River. Cross-section C–C' is noteworthy in showing: (1) the southward thickening of the H–GR stratigraphic couplet toward the Rio Grande Embayment; (2) the association of thin Hensel sandstone intervals with high-standing Cambro-Ordovician subcrops, and thick Hensel intervals with low-lying Precambrian subcrops; and (3) the substantial thickness of Neogene erosional removal in the Llano, San Saba, and Colorado river valleys (the right-sloping linework pattern between the Precambrian subcrop and the base of Hensel, as defined from Hensel isopachous mapping).

Cross-section D–D' (Fig. 5) bears eastward across the Llano Uplift, following the general trend of the modern Llano River from southwest of Junction to the eastern boundary of Paleozoic formations, midway between Burnet and Marble Falls in Burnet County. It intersects cross-section A–A' at their joint crossing of the Llano River in northeastern Kimble County, cross-section C–C' in western Llano County just south of the Llano River, and cross-section B–B' on the Long Mountain fault block in eastern Llano County. The H–GR couplet consists entirely of coarse-to-fine arkosic clastics, even though there are no Hensel outcrops within the Llano valley itself. As previously described, Hensel thickness is inferred from isopachous mapping, ranging from zero over high-standing Precambrian granitic domes or Paleozoic fault blocks to >400 ft along the medial valley of the precursor Llano River (Fig. 3). Cross-section D–D' also shows the abrupt thinning of Hensel arkosic clastics adjacent to high-standing



A Northwest
A' Southeast
B Northeast
B' South
ft
2500
2000
1500
1000
500
0
-500
MENARD CO
KIMBLE CO
GILLESPIE CO
KENDALL CO
COMAL CO
HARPER
Llano River
James River
Pedernales River
Guadalupe River
Intersection with cross-section D–D'
Intersection with cross-section C–C'
Intersection with cross-section B–B'
Kbu
Segovia
Ft. Terrett
Hensel
bKh
bKed
Edwards
Glen Rose
Pennsylvanian
Cambro-Ordovician
Paleozoic Foreland Facies
Sycamore
Cow Creek
Hammett
HAMILTON CO
MILLS CO
SAN SABA CO
LLANO CO
BURNET CO
BLANCO CO
Lampasas River
N. Bennett Creek
Goldthwaite - 6 mi to NW
Colorado River
San Saba - 5 mi to W
San Saba River
Cherokee Creek
New Bluffton
Long Mountain
Backbone Ridge
Miller Creek
Blanco River
City of Blanco
Edwards Ls.
Walnut
Comanche Peak
Travis Peak
Lower Pennsylvanian sandstone and shale (Strawn)
Rock removed by erosion after Balcones faulting & uplift
Precambrian crystallines
Marble Falls Fault
4 mi east
Intersection with cross-section A–A'
Intersection with cross-section D–D'
U. Glen Rose
Lower Glen Rose
20 mi
30 km

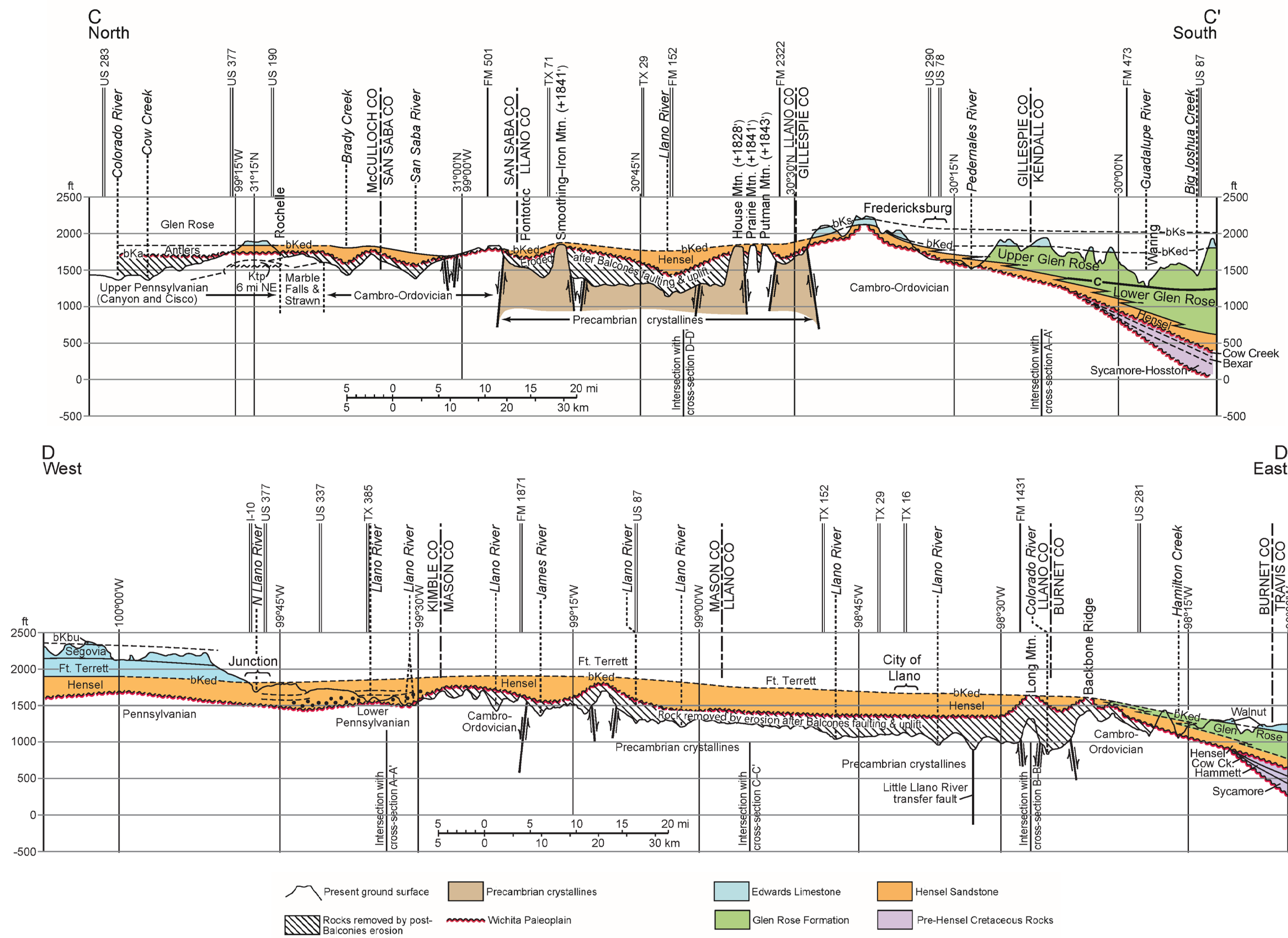


Figure 5. Regional geologic cross-sections A–A', B–B', C–C', and D–D', showing physical relationships of Edwards Limestone, H–GR stratigraphic couplet (Glen Rose Formation and Hensel Sandstone), Paleozoic formations, and Precambrian crystalline formations. Traces of all cross-sections are shown on Figures 2 and 3.

Paleozoic fault blocks such as Long Mountain and Backbone Ridge. Hensel lithologies are inferred from nearest adjacent outcrops, such as sections 'H' and 'I' of Payne and Scott (1982). Within the precursor Llano Valley, Hensel lithology is interpreted to be dominated by arkosic conglomerates and sandstones deposited as alluvial fans feeding into the Llano Valley from adjacent highlands to both north and south. Cross-section D–D' also demonstrates the association of thick Hensel clastic deposits with underlying paleotopographic lows, as previously described, and Hensel "thins" overlying high-standing Cambro-Ordovician fault blocks. Finally, the steady eastward thickening of the interval of inferred removal of (mostly) Precambrian granitic rock (east-sloping line-work pattern) is consistent with increasingly deep erosion along the eastern axis of the present Llano Valley during the Neogene.

SYNTHESIS: H–GR PALEOGEOGRAPHY, LLANO UPLIFT AREA

After a brief regression following Cow Creek deposition, the Late Aptian sea began its last inexorable northward advance across the Wichita Paleoplain, onto the southern and eastern flanks of the Llano Uplift, then a dissected promontory projecting southeastward into the ancestral Gulf of Mexico, where it merges westward with the Rio Grande Embayment. Figure 6 shows the topographic configuration of the WPP at the start of H–GR deposition, restored to its elevations at that time. The main features of the Late Aptian landscape, represented by modifying the present surface (Fig. 2), are still apparent in Fig. 6, though somewhat suppressed and softened (the northern, lowest ridge, which separated the precursor San Saba River from precursor Brady Creek on Figure 2 is suppressed on Figure 6). Two irregular east-west ridges now dominate Figure 6: the southernmost ridge, which separates the precursor Pedernales and Llano rivers, reflects an underlying faulted terrane of resistant Cambro-Ordovician formations, mostly dolomitic. It rises 500 to 700 ft above the Late Aptian sea level. Both ridges rise 300 to 500 ft above the intervening precursor Llano River. The northern ridge separates the precursor Llano and San Saba rivers. It rises 500 to 600 ft above Late Aptian sea level, and widens eastward to form a large, lobate highland in southern San Saba County which is also underlain by Cambro-Ordovician carbonate formations. H–GR thickness varies substantially and inversely in response to underlying WPP topography—thin over underlying highs, thick over underlying depressions (Fig. 3). Scattered across the Precambrian outcrop area, small, isolated high-standing graben-blocks, such as Putman and Prairie mountains, and granitic exfoliation domes such as House and Smoothing-Iron mountains and Enchanted Rock, stood as much as 400 ft above basal Hensel sedimentation, up to and slightly above the base of the Edwards Limestone (bKed). The most prominent early Cretaceous valley coincides with the present Llano River, and the Precambrian axis of the Llano Uplift.

The sinuous divide along the western edge of the Llano Uplift separates the two dominant ridges from the south-reaching Kimble valley that flowed from eastern Kimble County southward across western Kerr County toward the ancestral Rio Grande Embayment. The divide between the two watersheds lies in westernmost Mason County, at an elevation of about 250 ft (Fig. 6). Southeastward, the Palo Alto valley is still prominent, extending from the Enchanted Rock area southward out of the Llano Basin just east of present Fredericksburg, toward the Rio Grande Embayment. The Kimble, Palo Alto, and Llano valleys all end in estuaries. There is no evidence of a precursor Colorado River in the map area; this is consistent with the interpretation of Galloway et al. (2011), that the Colorado River drainage system originated in the Paleocene (62 Ma), eroding headward northwesterly across the Gulf Coastal plain through the Paleogene.

Within the interior of the Llano Uplift, especially along the margins of fault-line scarps, "minibasins" up to ~300 ft deep overlay deeply eroded Precambrian crystalline rocks. They were filled by alluvial fans transmitting coarse dolomitic and arkosic sedimentary debris basinward from adjacent high-standing fault blocks. The earliest-derived clasts were primarily fragments of Cambro-Ordovician dolomite, chert, and sandy limestone. Later, as the Precambrian basement was uncovered, the counterpart coarse alluvium increasingly consisted of arkosic conglomerates and coarse sands. Because the surfaces of such fans sloped basinward, the base of the overlying Edwards Limestone (bKed) also slopes gently toward the center of such topographic depressions. For example, (Figs. 5A, 5B, and 5C), basal Edwards strata decline gently into the granitic valley of the precursor Llano River—northward from the southern ridge, southward from the northern ridge.

Inverse fault topography began to form during the long erosional period that followed Ouachita faulting; further erosion following Balcones faulting and uplift (early Miocene, about 21 Ma) only augmented this earlier geomorphic development. Accumulations of arkosic Hensel conglomerates and sandstones are inferred to reach >400 ft thick in the elongate basin of the precursor Llano River (Fig. 3). Hensel deposits on the northern divide are thin to absent. Where present, the Hensel consists of fluvial and distal-fan arkosic conglomerates, sandstones, and mudstones <~50 ft thick, which thicken abruptly southward into the Llano valley.

South and west of the Llano Uplift, dominated by the estuary of the Kimble valley, the sedimentary record of the H–GR transgression consists primarily of:

(1) relatively thick (>200 ft) terrigenous arkosic clastics eroded from the nearby Llano Uplift, deposited to the south and west, primarily as distal ends of alluvial fans; and
(2) a variety of fluvial deposits, succeeded upward by finer-grained coastal/peritidal deposits, all assigned to the Hensel lithofacies.

The Kimble valley, which underlies the Junction trough of Rose (1972), appears to have been the conduit by which these thicker Hensel successions were deposited in the southwestern Llano Uplift, as Snedden and Galloway (2019) speculated. Along the south coast of the Llano Uplift, Alluvial fans sloped down toward the south coast to merge with fringing beaches and tidal flats. Streams of the Palo Alto, North Grape Creek, and Llano valleys generated Hensel fluvial deposits.

The northernmost presence of Glen Rose carbonate strata in the Llano Uplift is limited to the coastal flank of the southern ridge and the southeast corner of the Llano Uplift, near what may have been the mouth of the precursor Llano River. Southeast of the Llano Uplift, the total H–GR succession consists of a thin (<100 ft thick) fine-grained terrigenous clastic interval assigned to the Hensel Formation, overlain by 150 to 300 ft of Lower Glen Rose shallow marine carbonates and 200 to 400 ft of peritidal carbonates, mudstones, and evaporites assigned to the Upper Glen Rose lithofacies (Wierman et al., 2010). Thin intervals of finer-grained H–GR terrigenous sediments mapped as Hensel that were deposited along the linear northwest-southeast shoreline east and northeast of the Llano Uplift may have been sourced from farther north and east via input from rivers flowing into the ancestral East Texas Basin or reworked from Appalachian sources even farther east (Snedden and Galloway, 2019). They are overlain by thin intervals of Glen Rose carbonates.

Low rolling plains lay north of the Llano Uplift, at elevations of 200 to 300 ft above Aptian sea level, where H–GR deposits consisted of terrigenous clastic sediments deposited by braided streams on outwash plains draining the northern sides of the Llano Uplift (Atchley et al., 2001).

Higher plains lay to the west and northwest of the Llano Uplift, in the area of the Fort Chadbourne Arch, demonstrating

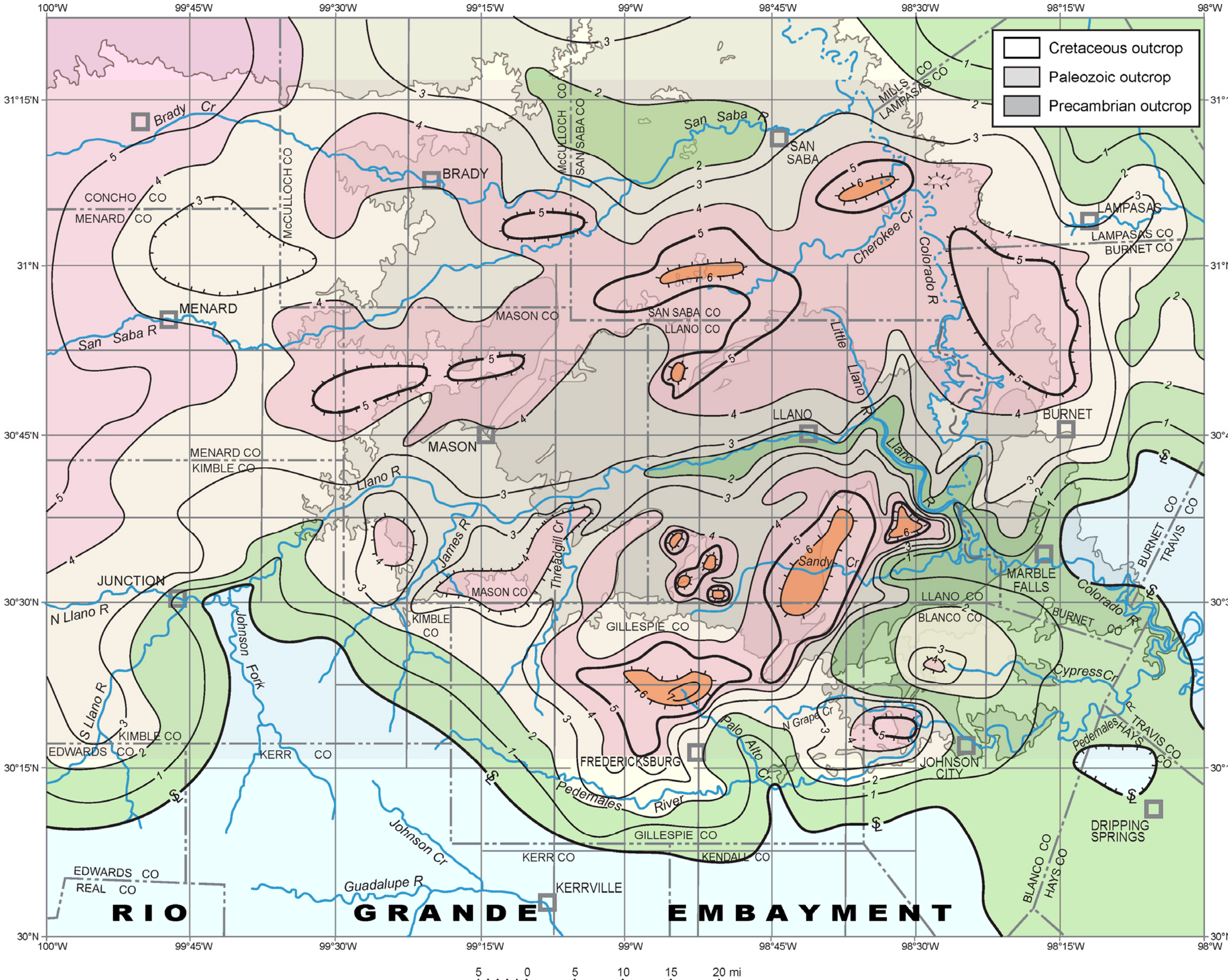


Figure 6. Paleotopography of WPP, restored to configuration and elevations that existed at the beginning of H–GR deposition, ~115 Ma, Llano Uplift area, Central Texas; restored contour interval is 100 ft.

that at least some of the present regional westward rise across western Texas existed long before Balcones and Colorado Plateau uplift during the Neogene. Here, directly underlying the Edwards Limestone, the Hensel-equivalent "Basal Cretaceous sand" forms a thin mantle consisting largely of residual terrestrial sands and silts, derived from weathering of underlying upper Pennsylvanian and lower Permian sediments. Some are probably modified through aeolian processes, and some are deeply calichified. There are also some indications of low-energy braided streams (Smith and Brown, 1983; Barker and Ardis, 1996).

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