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A Reevaluation of the Lithostratigraphy and Facies of the Lower Cretaceous Hensel Sand–Lower Glen Rose Transition, Comanchean Shelf, Blanco and Hays Counties, Central Texas

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ABSTRACT

The identification and delineation of the Hensel Sand–Lower Glen Rose lithostratigraphic transition is important to the reconstruction of Early Cretaceous depositional history in Central Texas and has implications for the hydrostratigraphy of the region. The Hensel transition from a "thick" (>40 feet) siliciclastic dominant alluvial plain-supratidal facies in the west (Blanco County) to a "thin" (<40 feet) dolomitic siltstone peritidal-interior platform facies in the east is abrupt in western Hays County. This facies change is coincident and partially time equivalent with a north-south trend of basal Lower Glen Rose shallow shelf carbonates with build-ups of coral-rudistid patch reefs/mounds. The transition is subparallel to Cretaceous strandplains along the southern flank of the Llano Uplift and generally tracks the trend of the subsurface Paleozoic Ouachita Front and the related Balcones/Ouachita Downwarp. These major tectonic elements define the depositional and structural history of the Cretaceous Comanche Shelf and the eastern edge of the Gulf of Mexico Basin in Central Texas. The basin margin position of the Middle Trinity stratigraphic section in the study area can be tied to the early Aptian and late Aptian–early Albian oceanic anoxic events (OAE) identified in the deep basin. The Hensel is equated to OAE 1b and the scleractinian coral dominated, basal Lower Glen Rose patch reefs (such as the classic Narrows of the Blanco River) are correlated with the early recovery phase of OAE 1b. This study characterizes this lithologic and facies transition using outcrops and borehole geophysical logs, cuttings and rock core. We suggest that this facies change may be structurally controlled and can be mapped locally. The flexure/"hinge line" or downwarp (Balcones/Ouachita Downwarp) that influenced sedimentation is related to the subsurface Ouachita Front. The delineation of the Hensel Sand–Lower Glen Rose lithologic transition also marks a hydrogeologic transition from the Hensel as an aquifer unit to the west, becoming an aquitard unit to the east. This understanding has hydrologic implications for projects analyzing the groundwater availability of Central Texas.

INTRODUCTION

The study area is located along the eastern margin of the Edwards Plateau within Central Texas between the Llano Uplift and the Balcones Fault Zone (Fig. 1). Geographically, it occupies a portion of the eroded eastern margin of the Edwards Plateau and is outside the boundaries of major oil and gas plays of Texas. The study area includes portions of Hays and Blanco counties and minor areas in Comal and Travis counties. It straddles two major drainage basins that contribute to Trinity Aquifer recharge: the Colorado River basin (with major drainages including Onion Creek and Barton Creek) to the north and the Guadalupe River basin (Blanco River) to the south.

The focus of this paper is on the Hensel Formation (also sometimes referred to as the "Hensell Sand") in western Hays County, Texas, close to the Hays/Blanco county line (Fig. 2). In this area, the Hensel transitions from a "thick" sandy, fluvial-

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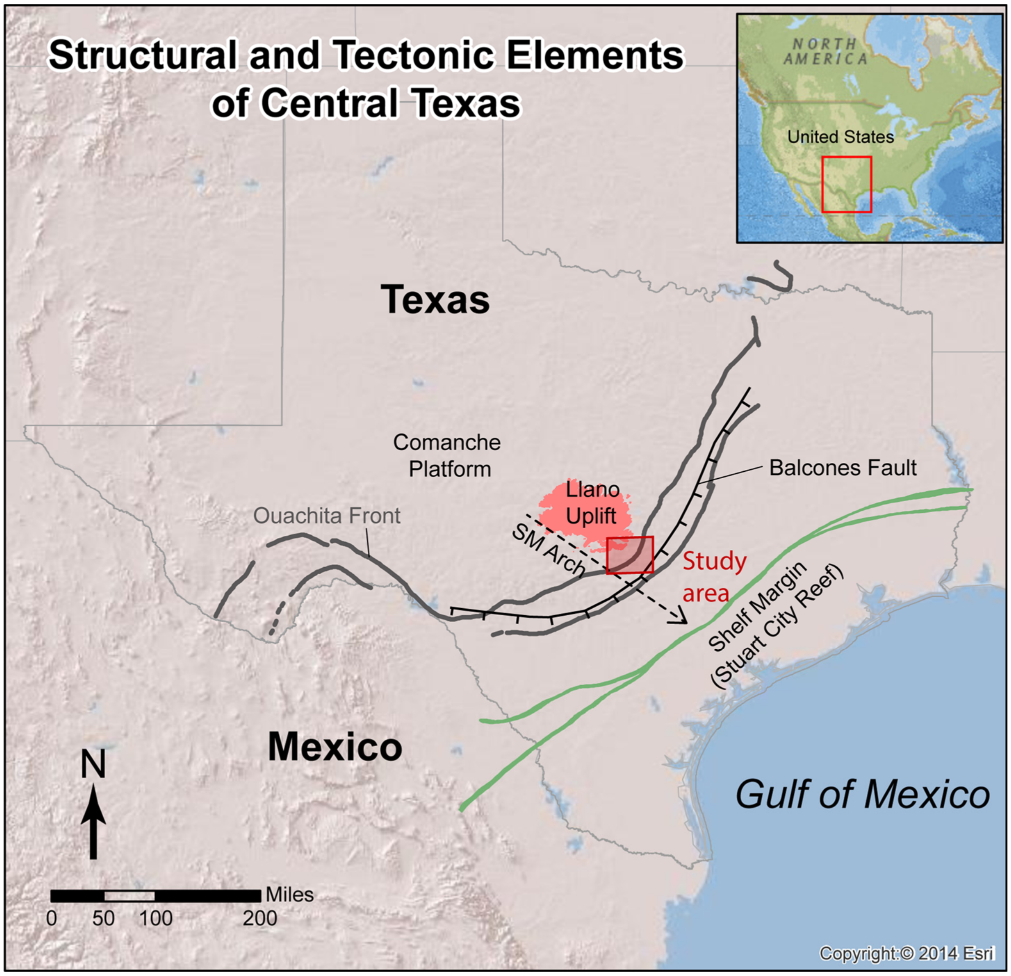

Figure 1. Regional map identifying study area and key structural and tectonic elements of Central Texas. Features modified after Ewing (1991).

supratidal facies in the west to a "thin" silty, dolomitic, subtidal-interior shelf facies to the east. This change in lithology and depositional environment has been recognized by many authors in a number of publications (Lozo and Stricklin, 1956; Perkins, 1974; Amsbury, 1974; Scott, 2007; Wierman et al., 2010; Kerans, 2017). The transition was depicted with either the entire western Hensel Formation equated to the eastern marine facies or as a facies change with the Lower Glen Rose carbonate. Increasing availability of geologic models from detailed borehole logs, cuttings, and rock core suggested the depositional and stratigraphic models needed to be refined to explain and predict the nature and location of the facies change of these important geologic and hydrogeologic units.

STRATIGRAPHIC FRAMEWORK

Lithostratigraphy

The study area is located in Central Texas along the western margin of the Early Cretaceous transgressive wedge of sediment that abuts the Proterozoic/Paleozoic Llano Uplift (Figs. 1 and 2). The buried western edge of the northeast-trending, Late Paleozoic Ouachita Thrust Front runs through the middle of the study area and lies just north of the San Marcos Arch. Stratigraphically the focus is on the primarily carbonate section that includes rocks of the Trinity Group that range in age from the Valenginian-Hauterivian Sycamore and Hosston formations in the lower interval through the uppermost Aptian to Albian Glen Rose Formation (Fig. 3). The outcropping strata dip gently to the southeast until intersected and down-dropped by the Balcones Fault Zone (Fig. 4).

The Lower Cretaceous Trinity Group has been subdivided into three hydrostratigraphic units which correspond with the following lithostratigraphic units: Lower Trinity Aquifer (Sycamore/Hosston and Sligo), Middle Trinity Aquifer (Hammett, Cow Creek, Hensel and Lower Glen Rose), and Upper Trinity Aquifer (Upper Glen Rose) (Fig. 3). The section was deposited on a broad platform by a shallow sea that transgressed the Paleozoic unconformable surface from east to west. The wedge of sediment onlapped and pinched out against the stable Llano Uplift (Wierman et al., 2010).

The study area occupies a small portion of the western edge of the onlap from the transgression (Fig. 2). Coarse siliciclastics and silty mudstone and carbonate were deposited in an alluvial-shallow marine environmental setting building southeastward into the gradually subsiding shelf (Sycamore/Hosston). The basal section onlaps the Paleozoic and can be seen in outcrop along the Pedernales River in western Travis and northern Hays counties. The Hosston typically produces water from a pea gravel-conglomerate in western Hays County. Sligo Formation skeletal-peloidal carbonate grainstone transgressed the basal section and pinches out in the subsurface in eastern Blanco and western Hays County but does not crop out (Fig. 2). When fractured, the Sligo limestone produces a minor amount of groundwater that is included with Lower Trinity Aquifer production.

The widespread Hammett Formation is a dark colored dolomitic mudstone/clay and is an important aquitard between aquifer units in the region (Fig. 3). The Hammett is equated to the Pine

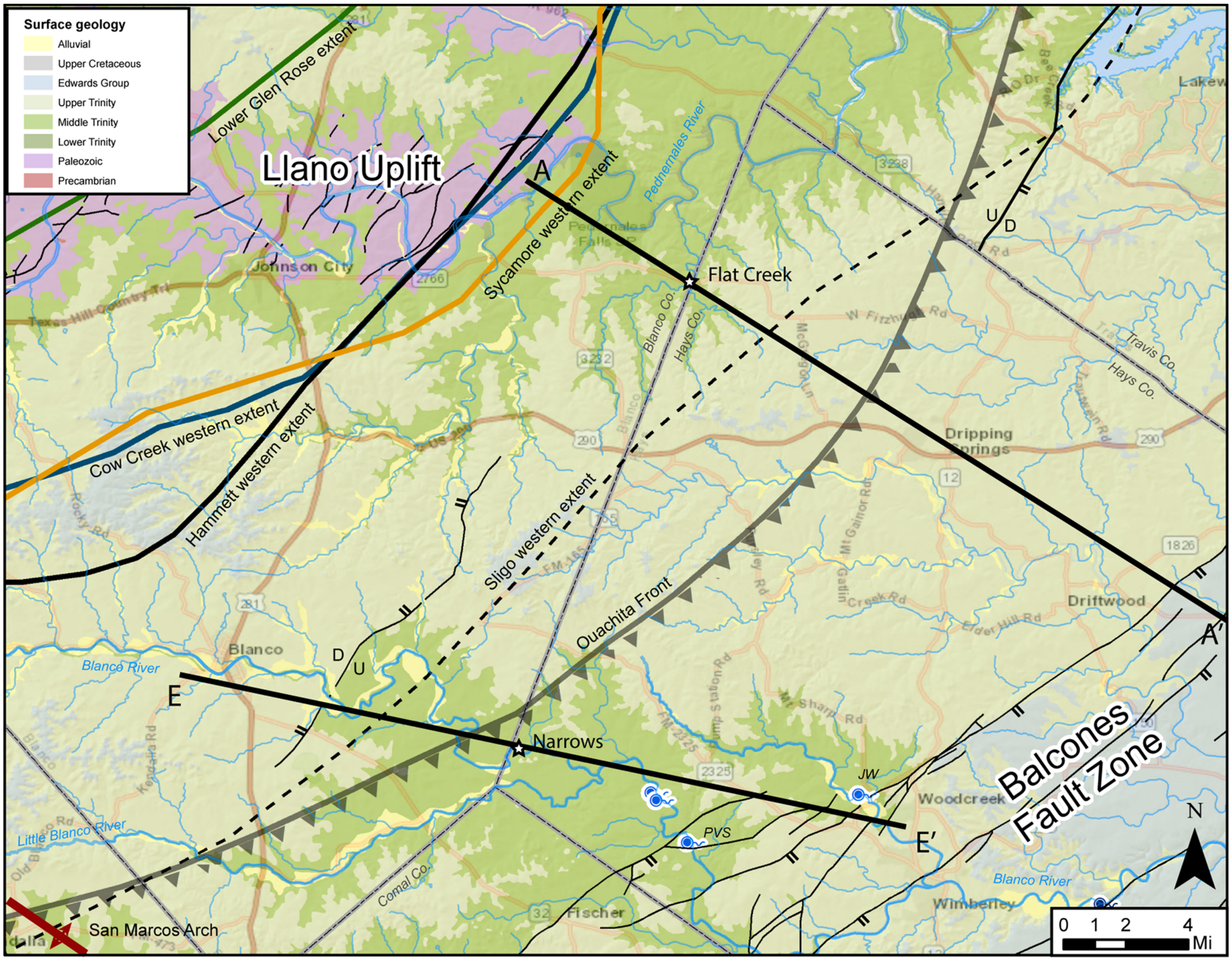

Figure 2. Study area geologic and structural framework map. Geologic map and faults from the Geologic Atlas of Texas. Ouachita Front modified after Ewing (1991). San Marcos Arch after Rose (1972) and stratigraphic extents modified after Wierman et al. (2010). Two important outcrop and measured sections are indicated by stars at the Narrows and Flat Creek.

Island Shale (well developed in South Texas subsurface). These clays signal the end of the Sligo carbonate "factory" during the Cretaceous within the basin attributed to the Oceanic Anoxic Event 1a (OAE 1a; Phelps et al., 2014, 2015). In a partial recovery of carbonate deposition, the overlying Cow Creek skeletal limestone and dolomite facies are well developed and define a large Cretaceous strandplain (Owens and Kerans, 2010). The Cow Creek is one of the most productive aquifer units of the Middle Trinity in the region. The unit varies between 70–90 feet thick and is transitional with the underlying Hammett. A relative drop in sea level introduced a paleosol of varying thickness (caliche/calcrete) at the top of the Cow Creek. This interval can be observed in outcrop to the northwest along the Pedernales and Colorado river exposures and has been cored at several localities in Hays County (Broun and Watson, 2017, 2018a, 2018b). Where present, the paleosol unit is 0–20 feet thick and represents a sharp, unconformable transition with the overlying Hensel Formation; this transition marks the end of the partial recovery of the carbonate "factory" and is equated with the onset of OAE 1b (Phelps et al., 2014, 2015).

The Hensel formation is correlated with the relatively thicker Bexar Shale, which is prominent and well developed in South Texas (Loucks, 1977). The transition from a "thick" sandy fluvial-supratidal deposit in the west (Blanco County) to a "thin" silty, dolomitic shallow shelf-subtidal deposit to the east (Hays County) is the primary focus of this paper.

The Lower Glen Rose limestone thickens from 140 feet in the west to 250 feet along the Balcones Fault Zone. There are two "reefal" zones developed in the formation. The basal, coral-rudistid patch reef interval was identified from the outcrop at the Narrows of the Blanco River (Figs. 5 and 6) and nearby surface locations (Stricklin et al., 1971). In the subsurface the unit's presence was interpreted from core, cutting samples and wireline logs in a number of local water wells. Through correlation with logs in Blanco County the reef interval is correlative to the "upper" sandy facies of the Hensel. The deeper, "lower" Hensel strata are correlative to the eastern "thin" Hensel silty dolomitic facies. The upper reef interval of the Lower Glen Rose (Pipe Creek/Red Bluff Creek) is dominated by Caprinid Rudists and represents the full recovery from the lower Albian OAE 1b (Phelps et al., 2014, 2015).

The Upper Glen Rose is 350 feet thick in eastern Blanco County and thickens to the southeast reaching 450 feet thick in the Balcones Fault Zone. It outcrops in the north and west of the

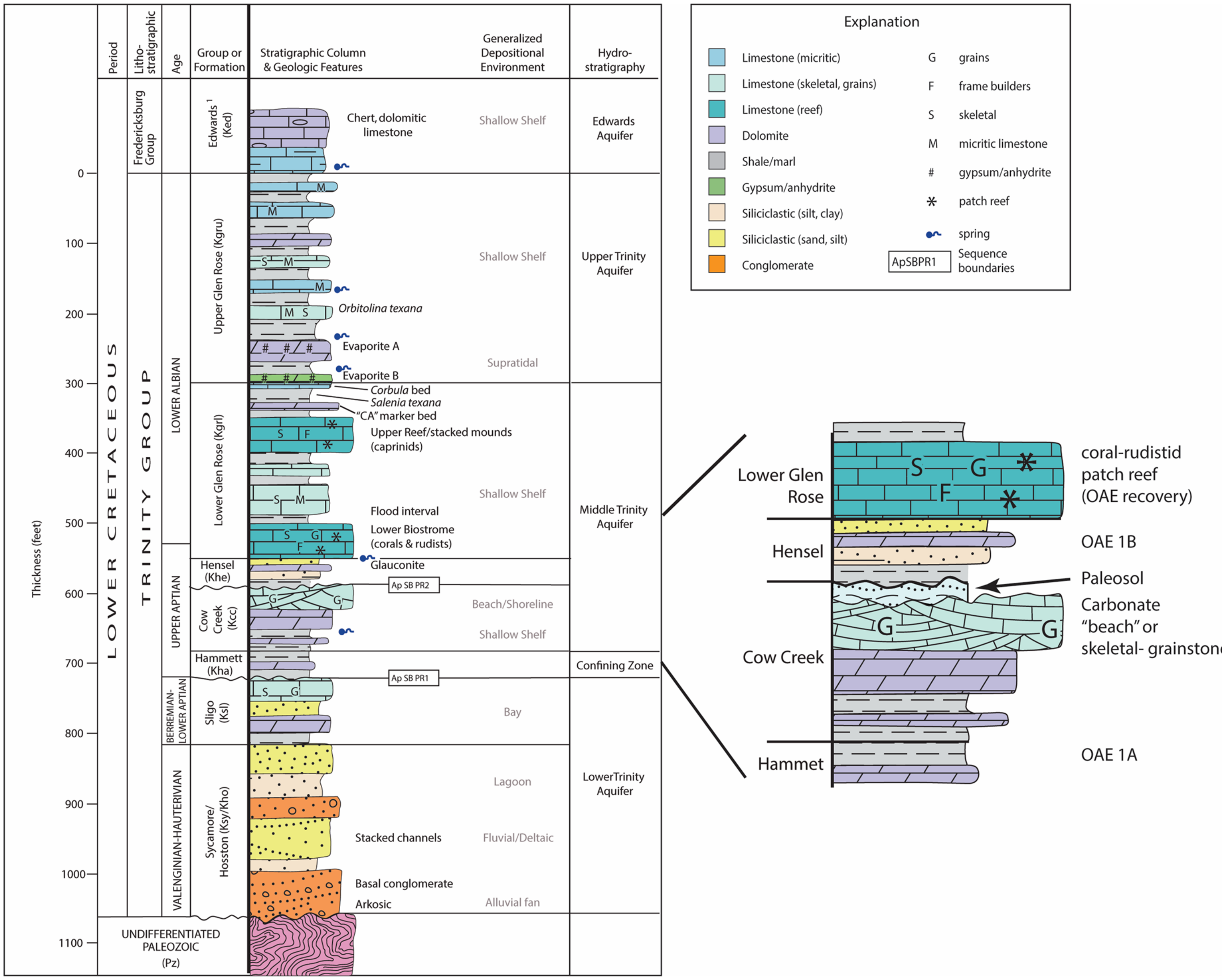

Figure 3. Stratigraphic/hydrostratigraphic column of Central Texas. Inset diagram emphasizes the Middle Trinity Aquifer units composed of the Cow Creek, Hensel, and Lower Glen Rose. Figure modified after Stricklin and Lozo (1971) and Wierman et al. (2010). Edwards Group defined by Rose (1972); ages and sequence boundaries from Scott (2007), and oceanic anoxic events (OAE 1A, 1B) approximated from Kerans et al. (2019).

study area but has been fully incised in much of the Blanco River Valley area in the south. The Upper Glen Rose consists of thin interbedded, nodular limestone and dolomite with interlayered mudstones and clay. However, to the west the Upper Glen Rose transitions laterally into upper Hensel sand approaching the Llano Uplift. There is an anhydrite unit near the base of the section over most of western Hays County.

Hydrostratigraphy

The hydrostratigraphic framework of the region is presented in detail in Wierman et al. (2010) and Hunt et al. (2017) and generally shown in Figure 3. The focus of this study is on the Hensel and Lower Glen Rose lithostratigraphic units, which are important units of the Middle Trinity Aquifer. The change in facies described in this paper has hydrogeologic implications for recharge, groundwater flow, and groundwater availability.

The Cow Creek is the primary aquifer unit of the Middle Trinity Aquifer (Wierman et al., 2010). However, caliper logs run in local water wells often show voids or washouts in the basal Hensel, the upper Cow Creek paleosol and/or the upper Cow Creek carbonate.

The Hensel in Blanco County is dominantly a clastic unit with higher primary porosity and permeability and serves as an aquifer or readily allows recharge at the surface. However, where the Hensel becomes a thin silty carbonate, it has low primary porosity and permeability and behaves as a semi-confining unit within the Middle Trinity Aquifer in Hays County.

Although the Cow Creek limestone and dolomite facies are the primary groundwater producing units of the Middle Trinity, there is often water in the reef mound facies of the basal Lower Glen Rose are also productive. Thus, the presence of the Lower Glen Rose reef facies influences groundwater availability due to the high primary porosity and permeability (Soto-Kerans et al., 2018).

Groundwater flow in the Middle Trinity Aquifer is generally from west to east in the study area, approximately the same direction as regional stratigraphic dip (Wierman et al., 2010).

PREVIOUS WORK

Geologic studies of the Trinity Group/Division in Central Texas began late in the 19th century with field work and interpretation by Taff and Hill. Many of the structural features and some

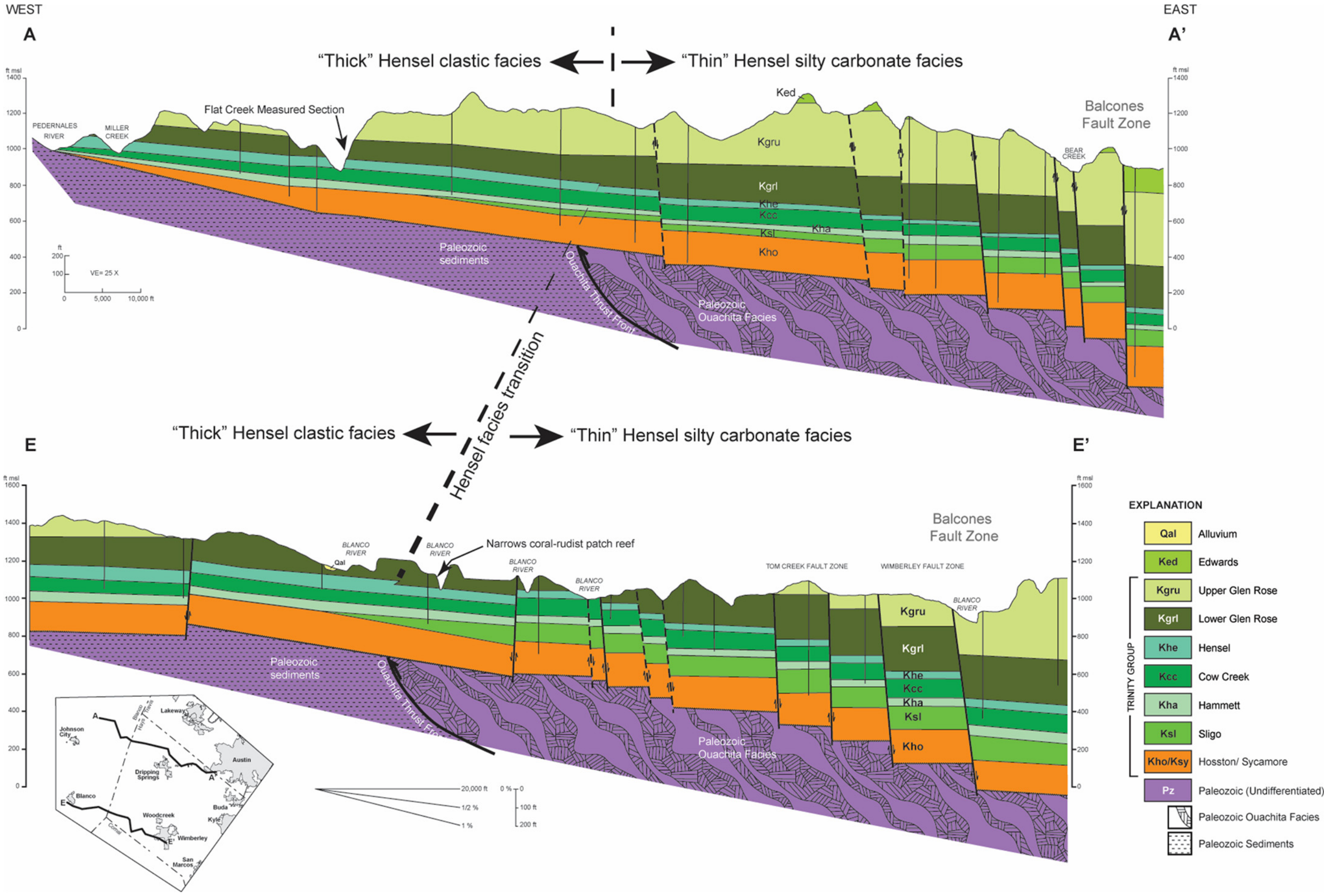

Figure 4. Regional dip cross sections showing location of Hensel facies transition. Geologic cross sections modified after Wierman et al. (2010).

of the basic stratigraphic nomenclature was proposed at that time including the Glen Rose, Hensel, Cow Creek, and Sycamore formations (Hill, 1901). Wells (1932) published on the corals of the Trinity Group and included plates illustrating corals that had been collected from the Narrows of the Blanco River (Stricklin et al., 1971).

In the 1950s through the 1960s, several major oil companies used Gulf Coast geology as a field laboratory for domestic and worldwide petroleum exploration and training. Shell carried out detailed lithostratigraphic, petrographic, and paleontological analyses and interpretation of the outcropping Trinity Group in Central Texas. Their in-depth field and laboratory analyses were tied to a series of measured sections, stratigraphic core holes, and wireline logs (Lozo and Stricklin, 1956; Stricklin, et al., 1971); Amsbury, 1974; Perkins, 1974). These publications have direct application to this study area. Much of the early Lower Cretaceous stratigraphy in these publications was derived from exposures along the Colorado, Pedernales, Blanco, and Guadalupe Rivers. Field mapping by Virgil and Barnes (1982) and later by Collins (2000) added further knowledge to stratigraphic understanding of the area. Additional research by Inden (1974) and by Achauer (1977) added to the Early Cretaceous depositional interpretations. Detailed stratigraphic analysis by Kerans et al. (2017), along the Colorado River and correlation to the subsurface has further refined the understanding of this interval (Phelps et al., 2014 and 2015). Work by Rose (1972, 2017, 2019), Scott (2007), Kerans (2019), Clark et al. (2016), and others have contributed to the current stratigraphic framework.

The initial focus for the present report began at the classic Lower Glen Rose reef outcrop at the Narrows of the Blanco River (Fig. 5). Lozo and Stricklin (1956) described the outcrop location as a well-known scenic gorge of the Blanco River on the Craft Ranch in westernmost Hays County. The reef occurs within the basal 100 feet of the Lower Glen Rose section and is comprised predominantly of corals. The authors noted that the reef is exposed over a distance of one quarter mile along the river channel and that coral debris was seen in bluffs downstream. The outcrop was also measured by Achauer (1977). He described facies from bottom to top as a massive coral boundstone overlain by a very thin rudistid boundstone and a transitional zone of interbedded coral boundstone and reef-derived skeletal grainstone. Near the top of the section is a bedded, reef-derived skeletal grainstone. Above this layer is a thin calcrete zone (a Lower Glen Rose paleocaliche about 1 foot thick). His interpretation was that the vertical facies sequence implies a gradual emergence of the reef from subtidal to exposure which was marked by the paleocaliche zone (Fig. 6).

Stratigraphic studies of the area identified both the basal Lower Glen Rose coral-rudist reef and an upper caprinid rudistid reef (Perkins, 1974). Amsbury (1996) noted that the coral and rudistid beds at the Narrows are substantially older than the rudist reef interval in the upper part of the Lower Glen Rose (such as Pipe Creek). He further mentioned that a rig was set up on top of the grainstone flat a couple of hundred meters from the gorge to core the coral-bearing section. This core, No. 2 Craft Ranch, has been described in detail by Kerans et al. (2019) including an

Figure 5. Overview photograph of classic Lower Glen Rose Narrows section above the Blanco River.

analysis of the Narrows outcrop. However, the precise location where the core was collected is unknown.

Scott (2007) described two types of biotic accumulations that are well developed in the Lower Glen Rose: coral-rudistid assemblages (Narrows outcrop) in the basal portion of the Lower Glen Rose and caprinid-dominated assemblages in the upper portion represented by the reef complex at Pipe Creek. His in-depth study at the Narrows divided the section into a lower, thick bedded coral-rudist packstone facies and an upper wackestone facies separated by a thin caliche. His interpretation of the reef however, differs from other studies in that he considered the outcrop an example of multiple stacked biostromes. Kerans et al. (2017, 2019) described the outcrop as a mid-shelf patch reef, 16 feet thick and roughly 1300 feet in diameter—including reef core and flank debris beds. Kerans et al. (2019) further noted that the significance of this example is that the first reef builders following the OAE–driven crisis are coral reefs. It is not until higher in the Lower Glen Rose that the more typical caprinid carbonate factory returns to dominance.

Wierman et al. (2010) showed a schematic geologic section of the Narrows outcrop that synthesizes our current stratigraphic interpretation of the Narrows. The section from bottom up contains a recrystallized dolomitic mudstone and brown sucrosic dolomite at the base that is interpreted as Hensel. The overlying Lower Glen Rose is about 90 feet thick and includes a basal coral-rudistid "reef" (boundstone) that is locally cavernous and shows large vug porosity. A July 2018 field visit of the Narrows outcrop added a thin paleosol unit about halfway up the section (Fig. 6D).

Figure 6. (A) Outcrop of Hensel terrigenous sand facies from Flat Creek measured section, Hays County. (B) Photograph of the Narrows at the Blanco River. Height of patch reef is about 5 feet. (C) Photograph of the coral-rudist patch reef in the Lower Glen Rose at the Narrows. Note pocket knife for scale. (D) Photograph of the paleosol/caliche interval overlying shallow water shoals and patch reef at the Narrows.

METHODS

Much of the data for this report comes from subsurface data such as core, wireline geophysical logs, and cutting samples recovered from area water wells. In addition, field work involving measured sections and reconnaissance geologic mapping provided critical stratigraphic interpretation.

Formation cuttings samples were generally collected at 10 foot intervals. Selected wells were cored at key intervals, including the contact between the Hensel and Lower Glen Rose. Samples were described petrographically with a binocular microscope. A downhole video camera was often run, revealing close up images of the rock formation including bedding details, fossils, and porosity. Natural gamma ray and four-point resistivity logs were used to identify formation intervals and rock types and to estimate fluid content. In a separate run, the caliper log clearly identified cavities (voids).

A significant source of data used in this evaluation was provided in Wierman et al. (2010). Since that report, new data from recently drilled wells and core analyses from monitor wells drilled by the Hays Trinity Groundwater Conservation District in 2017–2018 have been made available: the Skipton DSISD and ESD wells (Broun and Watson, 2017, 2018a, 2018b). Thus, the combined data from Wierman et al. (2010) and data from new wells consisting of core, geophysical logs, and cuttings provide the foundation for the lithostratigraphic analysis presented in this report.

The combined geophysical logs, cutting samples, and cores made it possible to correlate with some confidence from the outcrop to the subsurface with information that was not available to past stratigraphic studies. An interval within the Hensel contained locally high gamma ray readings (450 counts per second) on the natural gamma ray curve as evidenced at the ESD monitor well (Broun and Watson, 2018b). The interval was also correlated to high gamma ray counts in nearby wells and is shown on the stratigraphic cross sections.

RESULTS

The distribution of water wells (data points) with wireline logs and interpreted thicknesses is shown in Figure 7. Detailed notes and analysis of individual well data is presented in the Appendix at the end of this report. Ten of the wells are shown on the figure as schematic sections (strip logs) derived from cuttings samples and core (Skipton and DSISD monitor wells). The map further identifies the Ouachita Thrust Front and key outcrop areas such as the Narrows. Photos of the Narrows Lower Glen Rose reef outcrop are shown in Figure 6. Field photographs and pho-

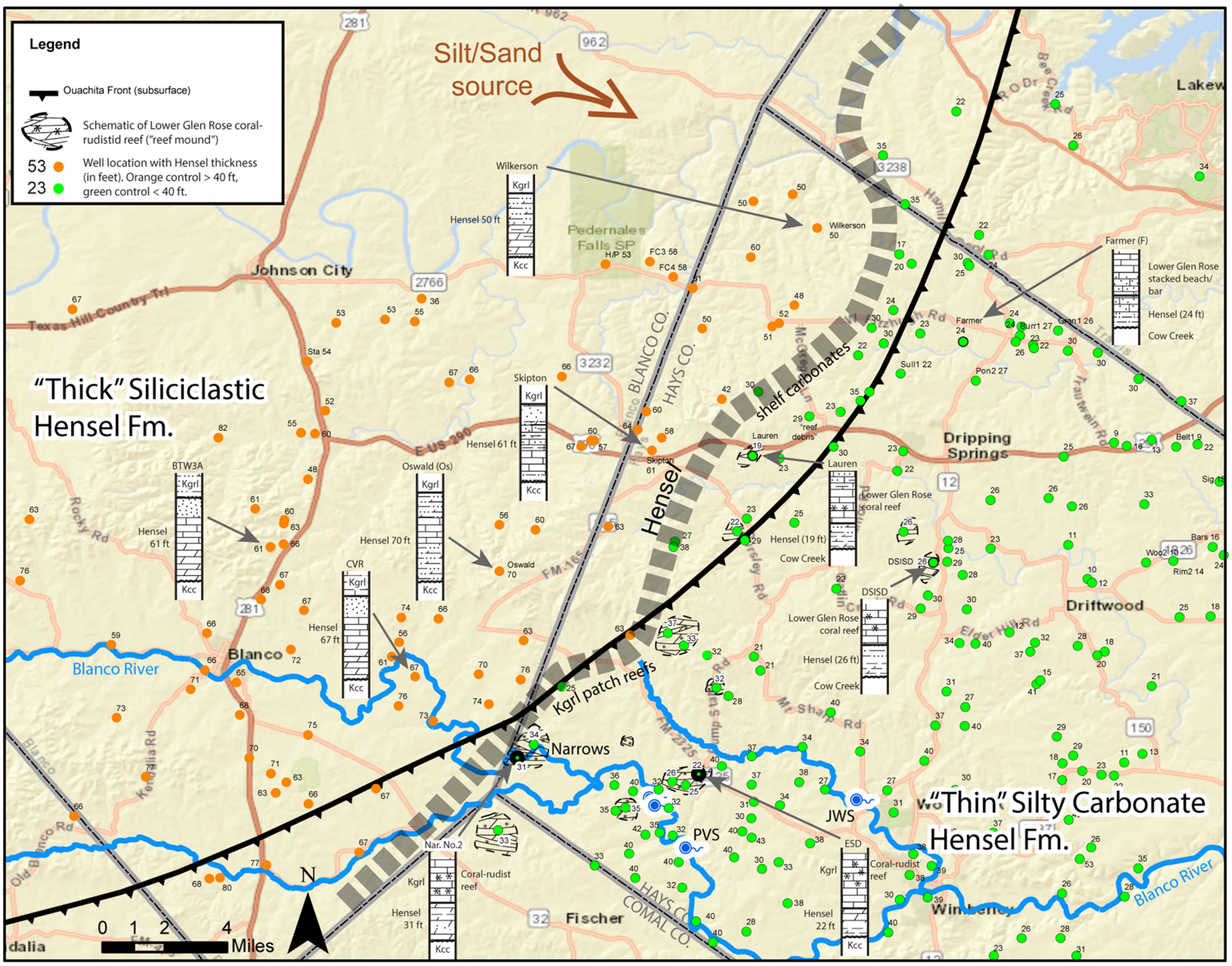

Figure 7. Map showing Hensel thicknesses from well-data control points and the transition separating thick siliciclastic Hensel to the west and thin silty carbonate Hensel to the east. Representative lithologic strip logs are indicated for selected wells and the areal distribution of basal Lower Glen Rose coral-rudist patch reefs are indicated. Subsurface location of the Ouachita Front modified after Ewing (1991).

tomicrographs of cores and driller's cuttings are presented in Figures 8 and 9. The mapped boundary between the thick (>40 feet) and thin (<40 feet) Hensel is a sharp boundary delineated in Figure 7 by the gray dotted line. In the Blanco River Valley the "thick" Hensel sand facies to the northwest (primarily in Blanco County) is about 70 feet thick. Southeast of the indicated "transition," the Hensel is reduced to less than 30 feet and there are well defined locations of basal Lower Glen Rose patch reef.

The Lower Glen Rose coral-rudistid patch reefs occupy the early recovery phase of OAE 1b (Kerans, 2019). The reefal fauna has been described at the Narrows outcrop (Stricklin et al., 1971; Amsbury, 1974; Scott, 2007; Achauer, 1974; Kerans, 2017), and by the authors (Wierman, 2010). Scleractinian (hexacorals) corals were observed in cuttings samples and cores (Figs. 9A and 8C). There are rudistids, coralline algae and microbial growth present in the patch reefs and mounds but not until the upper Lower Glen Rose reefal unit are the rudistid caprinids dominant.

Roughly south of U.S. Highway 290, the basal Lower Glen Rose patch-reef trend is indicated at several wells from cuttings samples and wireline log signature. The coral-rudistid buildups in the Lower Glen Rose have been identified in outcrop at the Narrows (Figs. 6B and 6C); with subsurface control provided by core data at the Narrows (No. 2 Craft Ranch core) and in the ESD monitor well (Fig. 8C). The other patch reef locations are interpreted from wells with cutting samples and geophysical logs. The facies change is relatively sharp and roughly correlates with the subsurface Ouachita Thrust Front (Flawn, 1961). The "transition" is approximately 15 miles southeast of the interpreted Middle Trinity paleo-shoreline. Other than the interpreted "reef debris" at the Bleakley well (Fig. 7, just north of Hwy. 290), there were no patch reefs found in the area north of the Hwy. 290. The Lower Glen Rose section is primarily carbonate; high energy shoals and associated subtidal–intermediate shelf deposits. As in the south, the "transition" is roughly parallel to the buried Ouachita Front. As indicated from well samples and outcrop, there is a source of terrigenous siliciclastic sediment from the northwest (and outside of the mapped area); possibly from rivers draining the Llano Uplift. It is probable that the scleractinian corals, prominent further the south, were unable to survive in this environment.

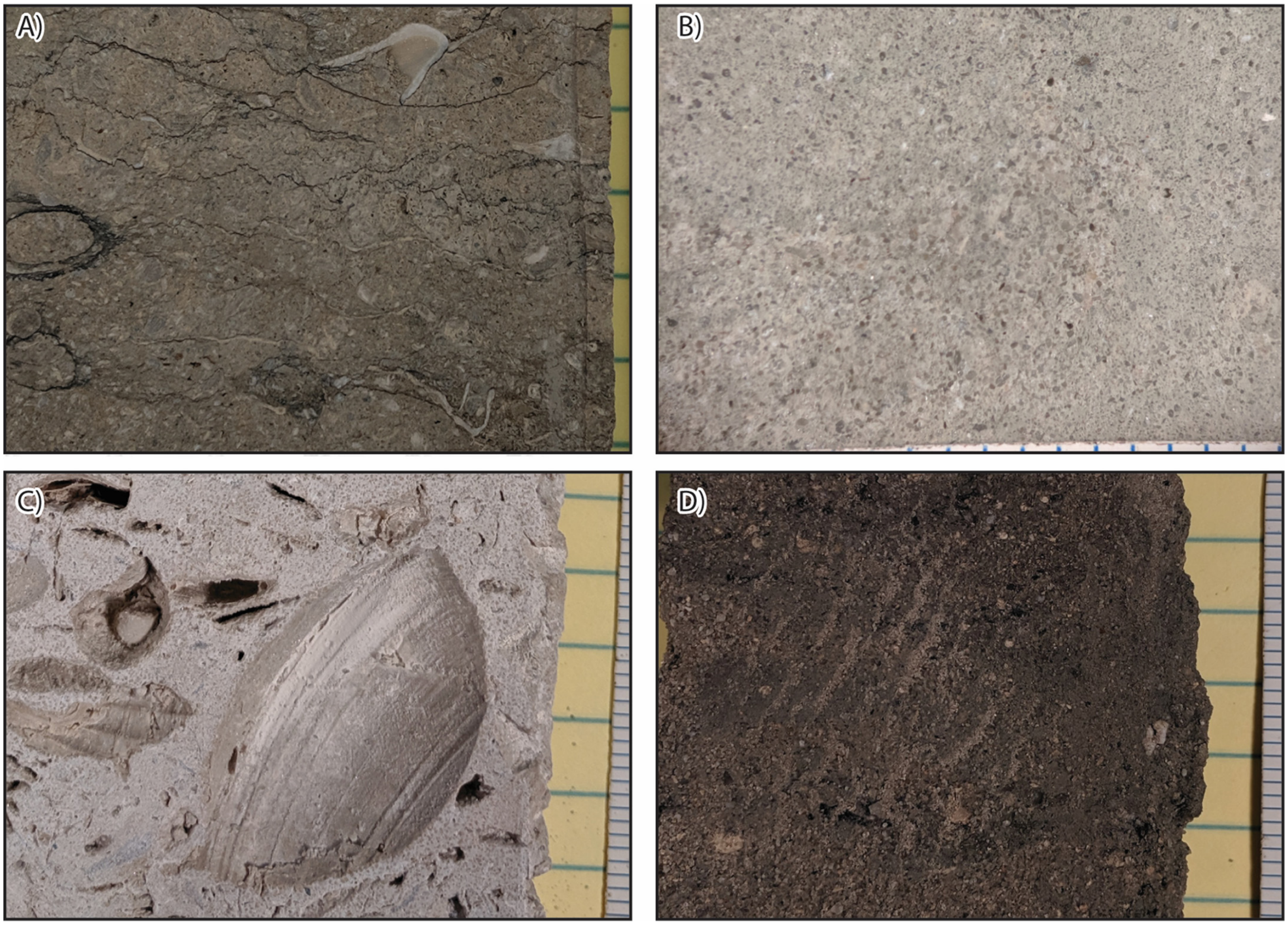

Figure 8. Skipton monitor well: (A) slabbed core photo (346 to 347 feet), Lower Glen Rose skeletal-micritic packstone, fine to medium skeletal grains with scattered coarse mollusks, monoplurid, wispy irregular stylolites, fine crystalline dolomitic matrix, burrowed; scale divisions are 1/16 inch. (B) Photomicrograph of slabbed core (377 feet) Hensel sandstone, fine crystalline dolomitic matrix, fine to medium grained quartz, tight; scale divisions are 1/16 inch. (C) Slabbed core photo (412 feet), Hensel, skeletal packstone, bimodal, coarse mollusks in very fine to fine grained skeletal hash matrix, good moldic and vuggy porosity; scale divisions are 1/16 inch. (D) Slabbed core photo (430 feet) base Hensel, carbonaceous siltstone, sandy, detrital grains, supratidal marsh; scale divisions are 1/16 inch.

Stratigraphic cross-sections correlating wireline logs and cuttings data are presented in Figures 10 and 11. These wells show the detailed stratigraphy and facies of the rock units and the basis for interpretations of the Hensel–Lower Glen Rose transition.

A structure contour map of the top of the Cow Creek (Fig. 12) shows the relatively gentle dip to the east. Schematic dip and strike sections are shown on Figures 13 and 14 and illustrate the abrupt transition of the unit facies and thicknesses

DISCUSSION

A schematic synthesis of the results is presented in Figure 15. The transition of the Hensel "thick" sandy facies to a "thin" silty dolomitic facies occurs along a well-defined north-south trend in western Hays County (Figs. 7, 13, and 14). The transition aligns roughly with the subsurface Ouachita Front (Flawn, 1961) and the associated Balcones/Ouachita Downwarp (Rose, 2016, 2019).

Scleractinian corals observed in cuttings were originally aragonitic and they are commonly preserved encased in microcrystalline calcite (Fig. 9A). These corals have a low tolerance for suspended sediment but are able to grow in high-energy areas (Scholle, 2003). It is hypothesized that the streams draining the Llano Uplift (Fig. 15) were the source of fine-sediment and inhibited coral and carbonate production. In the northern portion of the study area (north of Hwy. 290 to the Travis County line) there appears to have been a significant influx of siliciclastic sand and silt (streams draining the main Llano Uplift). This is indicated by increased terrigenous sand content in well samples and in the outcrop. In this study, no reef development was encountered, which supports the findings of Hunt et al. (2020) in western Travis County.

A trend of basal Lower Glen Rose coral-rudistid patch reefs can be mapped from outcrop and subsurface data (Figs. 7 and 15). The reefs and reefal mounds are time-equivalent to the "upper" Hensel sandy facies and establishes the western facies contact between the onlapping Lower Glen Rose shallow-shelf carbonates and the Hensel, non-marine-supratidal sediments. The Balcones/Ouachita Downwarp is sub-parallel to the Middle Trinity strandline that was extant along the eastern margin of the emergent Llano Uplift and the patch reef trend. It is likely that minor variation in sea floor topography along the "hinge line" (structural influence on subsequent deposition) cre-

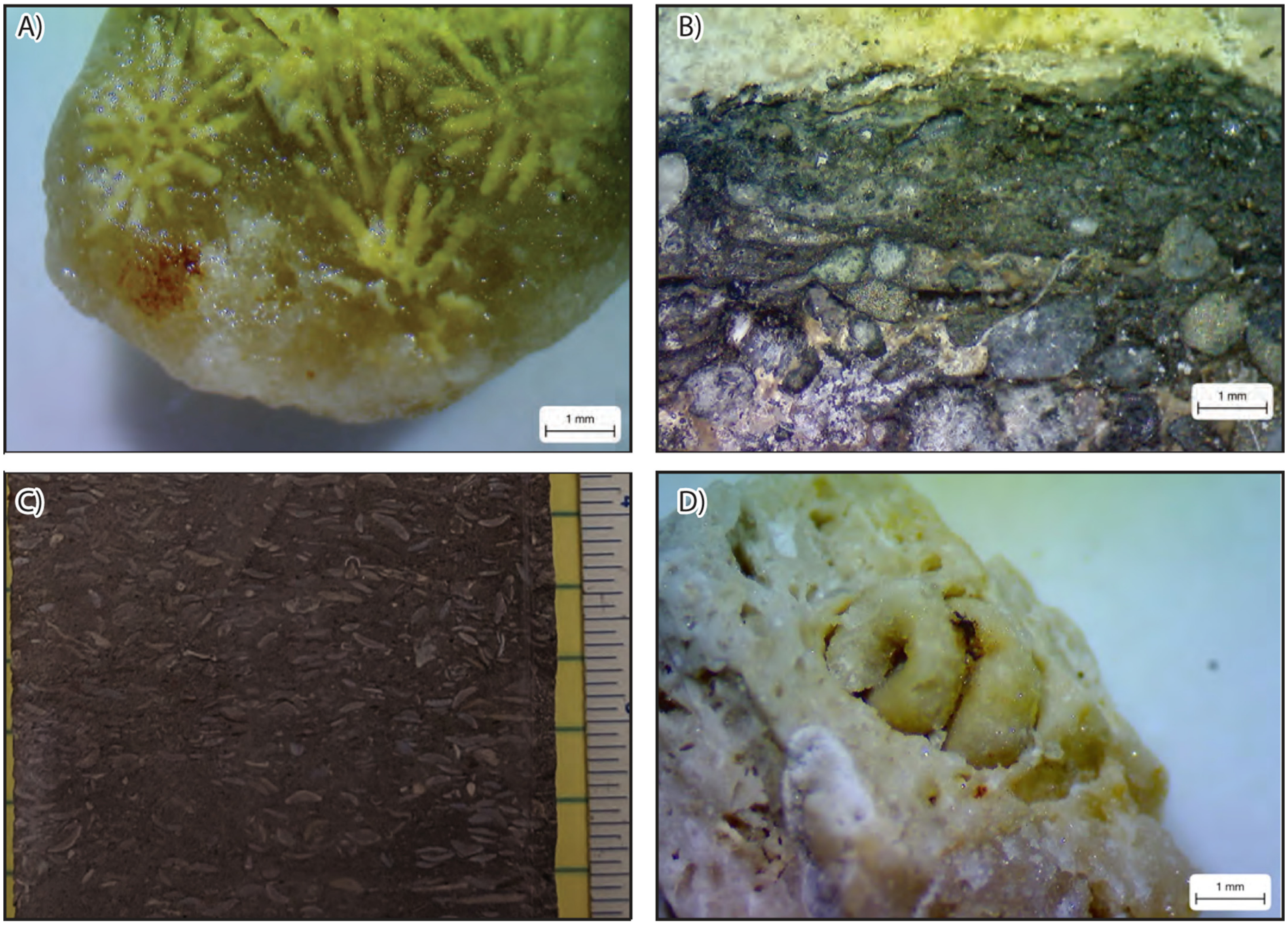

Figure 9. (A) Lauren Concrete well: cuttings (430–440 feet) Lower Glen Rose, framebuilder, coralline limestone, scleractinian (hexacoral), colonial, in crystalline calcite; photomicrograph. (B) ESD well: slabbed core (250–252 feet), interval containing dark green/black clasts of glauconite and pyrite. (C) Skipton well: slabbed core photo (356–357 feet), Lower Glen Rose, Orbitolina packstone, skeletal-micritic, fine crystalline matrix; scale divisions are 1/16 inch. (D) Lauren Concrete well: cuttings (430–440 feet) Lower Glen Rose, gastropod in fine crystalline coral matrix, photomicrograph.

ated the necessary environment for reef development along the front of the transgressive Lower Glen Rose sea. The regional Balcones/Ouachita Downwarp flexure or "hinge line" represents the northern margin of the paleo–Gulf of Mexico Basin (Rose, 2019).

The early Aptian (Selli event, ~120 Ma) and early Albian (Paquier event, ~111 Ma) oceanic anoxic events are at least partially represented in this shelf margin area by the Hammett (Pine Island Shale) and the Hensel/Lower Glen Rose (Bexar Shale) formations (Kerans, 2019). Although of different depositional environments and lithology, both act as important aquitards in the Hays County Trinity Aquifer. The widespread gray-green, dark-colored Hammett dolomitic mudstones/clays provide the bottom seal for the Middle Trinity aquifer and the top seal for the underlying Lower Trinity aquifer. The Hensel acts as the semi-confining aquitard for the Cow Creek sub-aquifer (Wierman, 2010). The lithologic signature of a "hot shale" unit (150-450 cps) mapped within the Hensel can be correlated on the gamma ray curve between local well logs and confirmed with cutting samples and cores (Figure 9B). It is interpreted as representative of the OAE 1b dark carbonaceous shales. Jenkyns (2010) noted organic carbon as the key sedimentary signature of oceanic anoxic events.

The observed transition in the Hensel from sandy facies in the west to dolomitic facies in the east has important implications for groundwater flow and storage in the Middle Trinity Aquifer. The Lower Glen Rose, Hensel, and Cow Creek have conventionally been grouped together as a single aquifer. However, the observed facies change in the Hensel may allow it to act as a more effective seal for the Cow Creek east of the facies transition. This could potentially cause significant differences in hydraulic head and geochemistry between groundwater in the basal Lower Glen Rose and Cow Creek. Additional studies are needed to determine the implications of the Hensel facies transition on the Middle Trinity Aquifer. The Hays Trinity Groundwater Conservation District installed nested piezometer wells (ESD well and DSISD well, Fig. 7) in 2018; and the Barton Springs/Edwards Aquifer Conservation District has installed multiport wells in the study area. Hydraulic head data and geochemical data from these wells could provide valuable insights on variations in the aquifer across the Hensel facies transition.

CONCLUSIONS

In the Blanco/Hays county area, the change in thickness and lithology of the Middle Trinity Hensel ("Hensel Sand") For-

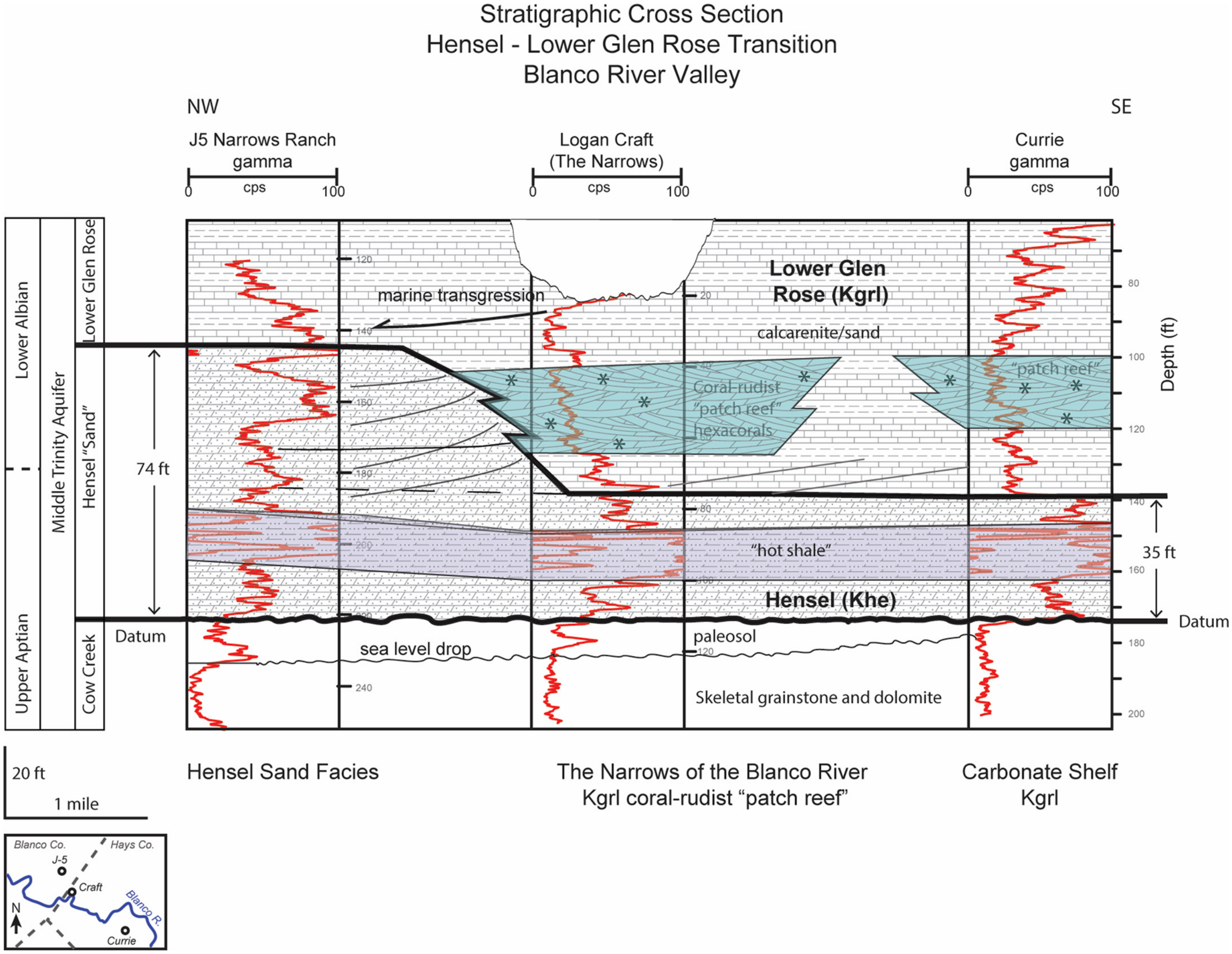

Figure 10. Stratigraphic cross section, Blanco River Valley, J–5 to Currie well (see Figure 12 for map view of cross-section line). Section shows thick Hensel sand facies transition and location of Lower Glen Rose coral-rudist patch reef at the Narrows.

mation from west to east has been noted in several publications. The interpretation was based on detailed field work along the creeks and rivers draining the Edwards Plateau and from shallow subsurface core studies. With newly acquired subsurface data from recently drilled water wells and monitor wells (some of which were cored through the critical interval) it is now possible to define the transition zone between the Hensel and Lower Glen Rose and to postulate its significance for basin analysis and hydrostratigraphic relationships.

The "upper" siliciclastic western facies of the Hensel formation is time-equivalent with the basal Lower Glen Rose coral-rudistid patch reef trend in western Hays County. The lower supratidal Hensel strata are equivalent to the "thin" eastern silty dolomite and siltstone facies. The "transition" is fairly sharp and follows a north-south trend from Comal to Travis counties (Fig. 15). The reefal trend is subparallel to the Trinity paleo-strand line and approximates the buried Ouachita Thrust Front and the associated Balcones/Ouachita Downwarp. It is postulated that the reef development is positioned along minor sea floor irregularities caused by the subsurface hinge line or flexure which forms the northern edge of the Gulf of Mexico Basin.

Stratigraphically the Middle Trinity in western Hays County can be correlated with a regional basin hinge line, and also influenced by the Late Aptian OAE 1a and Early Albian OAE 1b oceanic anoxic events. The Hammett dolomitic mudstone/claystone correlates to OAE 1a as documented in the Pine Island Shale (Phelps et al., 2015). The Cow Creek equates to the partial recovery of the carbonate factory and the OAE 1b occurs early in the lower Glen Rose (Kerans. 2019). The basal Lower Glen Rose patch reefs with dominant scleractinian corals signifies early recovery of the carbonate "factory." The caprinid reefs in the upper part of the Lower Glen Rose reflect the full cycle of a return to more normal marine conditions.

The delineation of the Hensel Sand–Lower Glen Rose lithologic transition also marks a hydrogeologic transition from the Hensel as an aquifer unit to the west, becoming an aquitard unit to the east. This study characterizes this lithologic transition with hydrologic implications for ongoing projects analyzing the groundwater availability of one of the fastest developing regions in Texas. Hydrologic implications, to list a few, include:

(1) the transition from unconfined to confined aquifer condition that should be considered in future groundwater modeling efforts,
(2) identification and study of recharge zones to the Cow Creek member of the Middle Trinity aquifer, and
(3) further understanding of surface water/groundwater interactions with the Blanco River in the vicinity of the Narrows.

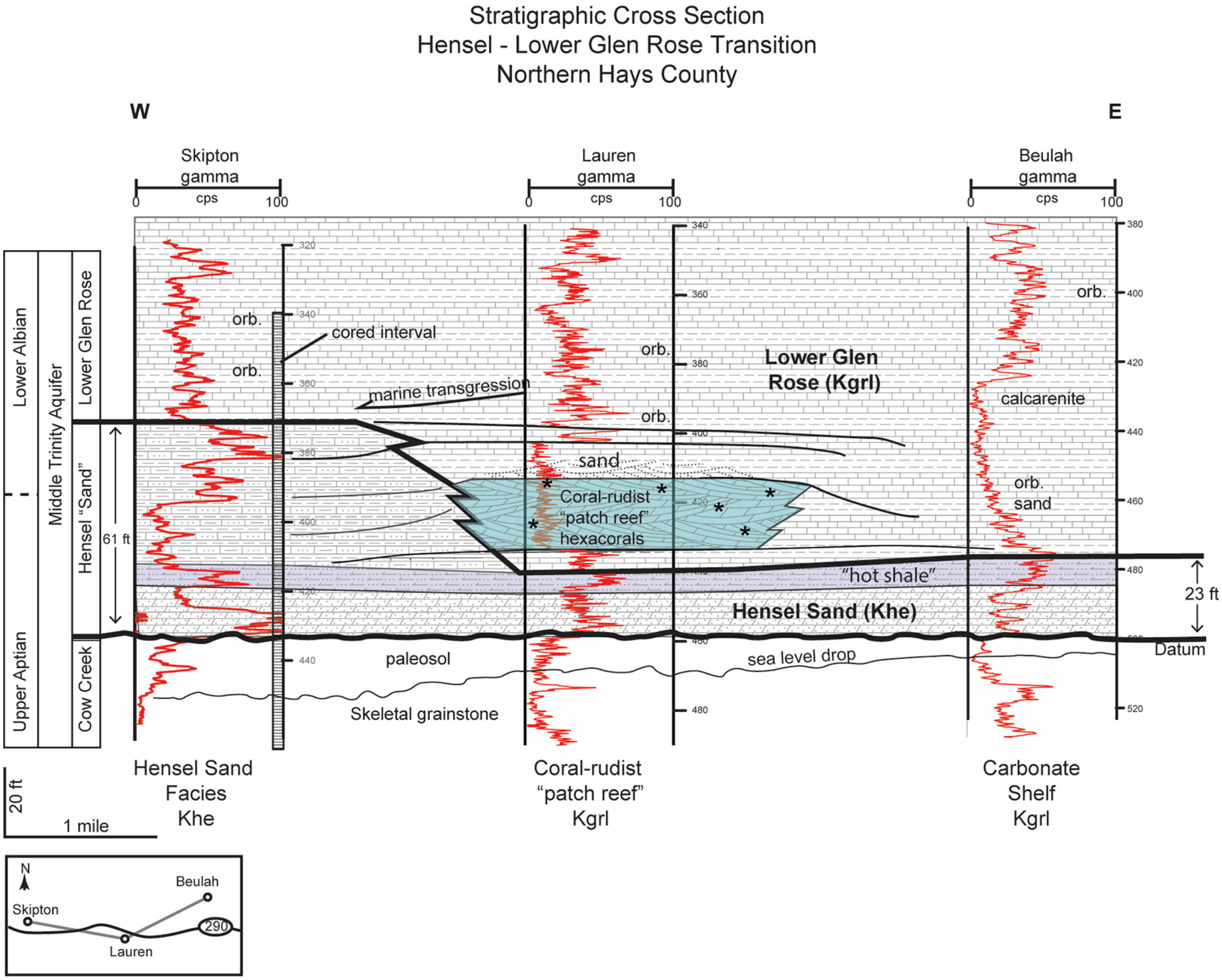

Figure 11. Stratigraphic cross section, northern Hays County, Skipton monitor well to Beulah. See Figure 12 for map view of cross-section line. Of note is cored interval at Skipton well through thick Hensel sand facies and sharp contrast with Lower Glen Rose coral-rudist patch reef and thin Hensel at Lauren (cutting samples and geophysical log).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contribution of the Hays Trinity Groundwater Conservation District, Barton Springs/Edwards Aquifer Conservation District, and Blanco Pedenernales Groundwater Conservation District in their ongoing acquisition of geotechnical data from local water wells and hydrostratigraphic evaluation in the study area and their willingness to share this information with the geotechnical community.

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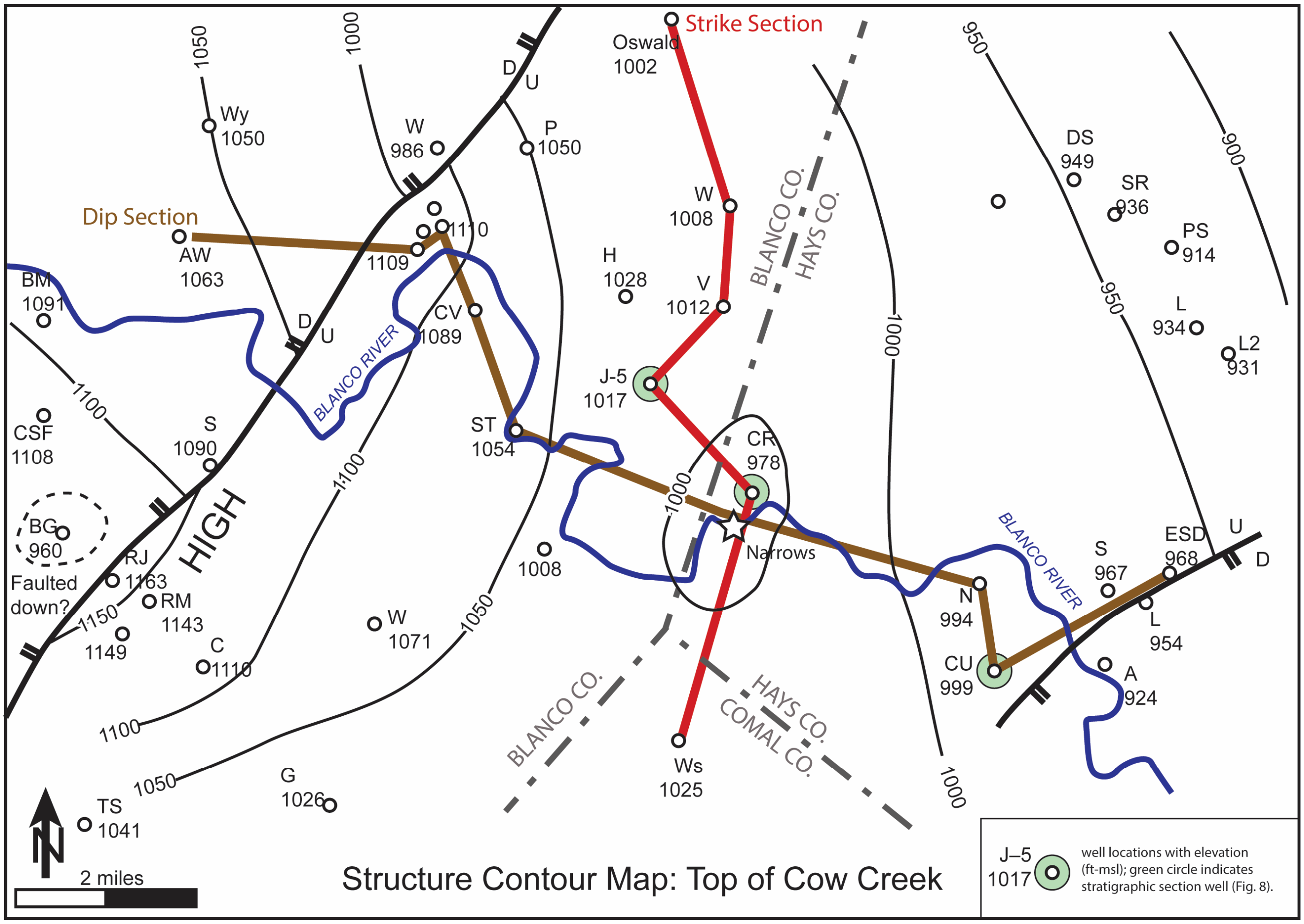

Figure 12. Cow Creek structure contour map, Blanco River Valley. Figure shows location of strike and dip cross-sections, and wells used in stratigraphic cross section (J–5 well, CR Craft Ranch well, and CU Currie well).

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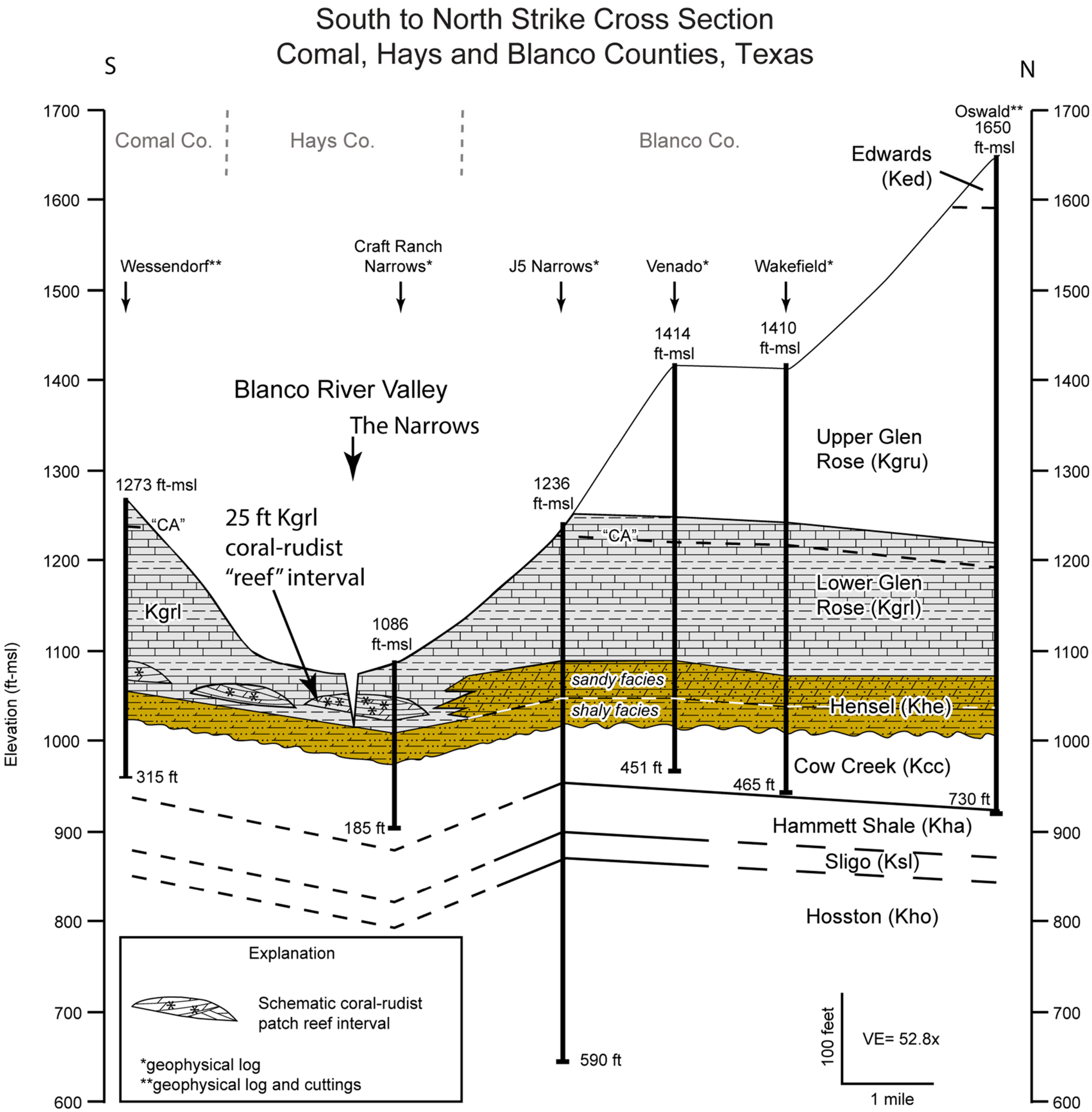

Figure 13. Regional strike structural cross section (north to south): Oswald to Wessendorf well.

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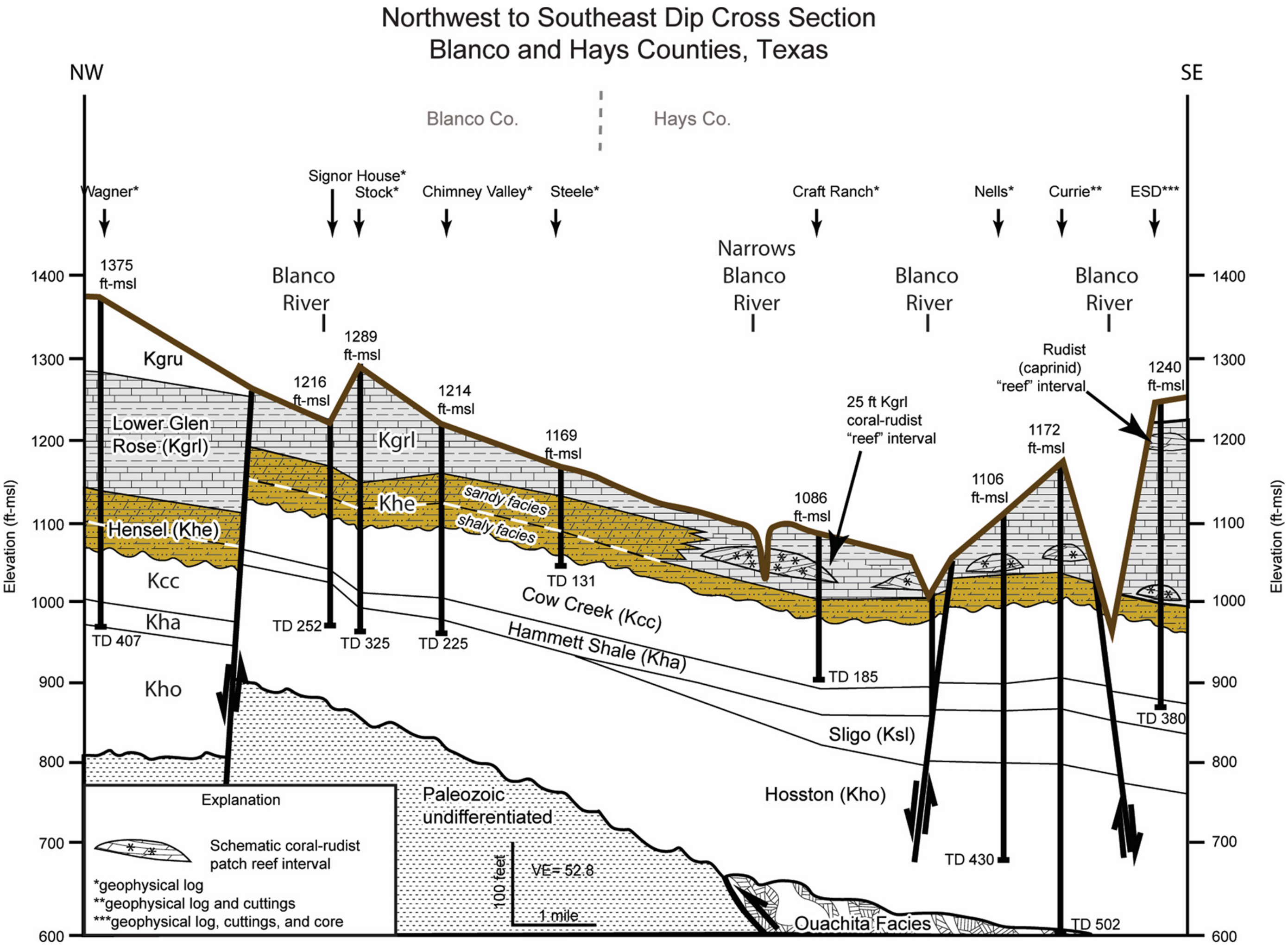

Figure 14. Regional dip structural cross section (northwest to southeast): Wagner to ESD well.

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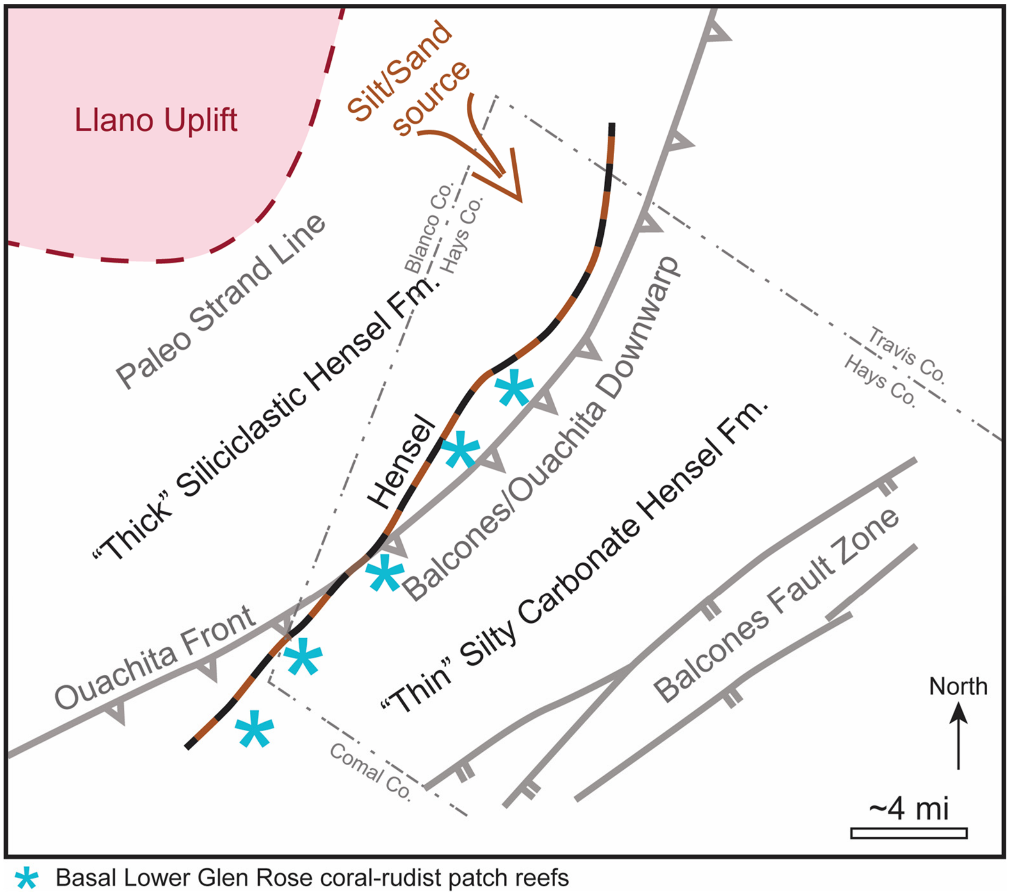

Figure 15. Summary map indicating the mapped extent of the Hensel transition relative to critical structural elements in the study area. Features modified after Ewing (1991) and Rose (2019).

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APPENDIX—NOTES AND COMMENTARY ON STRATIGRAPHIC ANALYSIS OF WELL DATA BY ALEX BROUN

Northern Sector: Northwestern Hays County and Lithostratigraphic Database

The Skipton monitor well, drilled in Hays County in 2017, is well documented and provides the western base for subsurface correlation (Fig. 11). Data include a geophysical log, cutting samples and core. The Hensel is 61 feet thick and represents the "thick" sandy lithofacies. It directly overlies a well-developed Cow Creek paleosol. The basal 8 feet is a dark gray, carbonaceous, silty mudstone with coal intraclasts and pyrite. The overlying section is 25 feet thick and consists of micritic and skeletal-detrital limestone with mollusks and calcareous algae. The upper 28 feet of Hensel is made up of dolomitic siltstone, mudstone and fine grained quartz sandstone (Fig. 8B–8D). The basal Lower Glen Rose interval is micritic-skeletal limestone with calcareous mudstone. The section contains *Orbitolina texana* (Figs. 8A and 9C), gastropods, and monoplurid fragments and is stromatolitic. It represents those sediments deposited on a shallow water, carbonate shelf that is transgressive over the fluvial-supratidal Hensel. There is no evidence of the basal Lower Glen Rose reef interval at this location.

In 2019, the Lauren Concrete borehole (Fig. 7) was drilled some 2.8 miles east of Skipton. It has both cutting samples and a geophysical log. The Hensel formation is 19 feet thick at this location and rests directly over the Cow Creek paleosol. It consists of sandy dolomite with oysters. The basal Lower Glen Rose section is interpreted to be a coral-rudistid reef mound (Figs. 6B and 6C) that is equated to the Narrows patch reef and is time equivalent to the "upper" Hensel supratidal sediments cored in the Skipton well. Cutting samples from the Bleakley well drilled about 2 miles east-northeast of the Lauren Concrete location had samples with hexacorals below 500 feet. The corals were encased in micritic calcite and any porosity was plugged with a dense, off-white micrite. The abraded skeletal grains may be reef debris.

At the Beulah well (geophysical log and cuttings) (Fig. 11), the Hensel is 23 feet thick and overlies the interpreted Cow Creek paleosol. The Hensel is very fine crystalline dolomite overlain by dolomitic claystone and dolomite. The basal Lower Glen Rose is comprised of dolomite and sandstone with quartz grains and dolomitic cement with pyrite; there is a skeletal-micritic-detrital fractured limestone with very fine to fine grained sandstone with abundant coarse skeletal clasts; above this unit is 15 feet of fine to very fine argillaceous calcareous sandstone with *Orbitolina texana* and skeletal fragments overlain by 25 feet of dolomitic calcarenite and coated grain-skeletal-pellet limestone. The basal Lower Glen Rose buildup is interpreted as a beach/bar over a lagoon or shallow shelf. There is no evidence of the coral-rudistid patch reef facies (Fig. 11).

In 2011, a detailed surface section was measured at Flat Creek (Fig. 2) on the Blanco-Hays county line by Hunt and Smith (Hunt et al., 2011). The Hensel Sand is 81 feet thick at this location although the lower beds may be the paleosol included with the Cow Creek in this report. There is a sandy, lithic pebble conglomerate near the base of the section that contains fossil fragments of oysters, gastropods, and clams. Overlying this bed the Hensel includes fine to medium grained sandstone with calcareous cement that becomes muddier upsection. At the top is a fine to medium grained silty sandstone with rounded to sub-angular grains. The overlying Lower Glen Rose is comprised of a basal unit of wackestone-packstone with Orbitolina texana. Above this is a 10–12 foot thick toucasid-chrondrodontid biostrome with a very fine grain pelloid matrix that is interpreted as an estuarine deposit.

Southern Sector: The Blanco River Basin and Lithostratigraphic Database

There are multiple reports and field-trip guide books on the geology of the Blanco River Basin and there is good geophysical log coverage from water wells in Blanco and Hays counties that allowed reliable correlation from the outcrop to the subsurface (Amsbury and Jones, 1996; Kerans et al., 2017, 2019). Structural control at the top of the Cow Creek formation is a sharp, reliable pick on logs (Wierman, 2010) and the Cow Creek surface provides a firm datum to build a stratigraphic interpretation of the overlying strata. Figure 12 illustrates a gently dipping surface from a high in Blanco County to the east with minor faulting and a flattening or broad contour interval over the Narrows.

To the north, the Oswald well in Blanco County (Fig. 14) has good cutting samples and logs; there is core from the No. 2 Craft Ranch well (Kerans, 2017), and cuttings and log data from the Narrows location; and geophysical logs and samples from multiple wells in Hays County to the southeast. The ESD monitor well (Fig. 7) (Broun and Watson, 2018b) drilled in 2018 was selected as the southern anchor for the project because of good geophysical logs, cutting samples and core. The thickness and lithofacies changes in the Hensel from west to east occurs immediately west of the coral-rudistid reef outcrop (Fig. 7).

In the ESD monitor well (Fig. 7), the top of the Cow Creek is marked by a paleosol interval 13 feet thick as identified in core. Hensel sediments overlying the paleosol are dark gray dolomitic mudstone and fine crystalline dolomite. The interval contains common dark green/black clasts of glauconite and pyrite. From 250–252 feet depth, the top of the Hensel as seen in core is a disturbed zone comprised of thinly laminated, contorted, black, carbonaceous silty mudstone with abundant clasts of glauconite, pyrite, and quartz; and with coarse extra-clasts of skeletal packstone (Fig. 9B). This interval recorded abnormally high (450 counts per second) readings on the natural gamma ray log and is referenced as "hot shale" on the cross section. The transition with the Lower Glen Rose is relatively sharp and consists of skeletal-micritic packstone (gastropods, oysters) and wackestone with scattered skeletal fragments and stylolites. The overlying unit, which forms the base of the reefal mound, is brecciated, with very coarse skeletal fragments and solution features. The reefal limestone (10–15 feet thick) contains hexacorals and rudists. The interpreted patch reef is overlain by a skeletal-grain limestone with very coarse skeletal clasts in a medium to coarse grained skeletal-pellet-coated grain (ooid) matrix.

The natural gamma ray logging tool has been active in the oil and gas industry since the 1930s. It was used to identify relative shalynesse and in constructing sand/shale ratio maps. In 1955 the U.S. Geological Survey (Tourtelot, 1955) demonstrated the use of gamma ray logs for the identification of organic rich shales. Organic rich shales have higher radioactivity responses than typical shales because the organic matter tends to concentrate uranium ions that otherwise would be scattered throughout the sediment. Doveton (2016) noted that black shales are marked by much higher and variable radioactivity which is controlled by their uranium content.

At the Currie well (Figs. 10 and 12), the interpreted Cow Creek paleosol interval is 16 feet thick. The overlying Hensel is primarily a dark gray-green fine grained crystalline dolomite with glauconite clasts and quartz grains. (There is also basal fine grained quartz sandstone.) The top 10 feet of Hensel contains fine to very coarse coral and rudistid fragments with glauconite and quartz grains that is above the "hot shale" interval and may be reworked reef debris. The basal 18 feet of Lower Glen Rose is a medium to coarse grained calcarenite of coated skeletal clasts in a fine, coated-grain matrix with coarse skeletal fragments that is interpreted as a sand shoal. The overlying 20 feet of section contain both coral and rudistid framebuilders overlain by calcarenite and sandstone with skeletal fragments (Fig. 8).

Cutting samples and a geophysical log were collected from the Craft water well located ½ mile to the northeast of the Narrows outcrop. (Fig. 10) The Hensel is interpreted to be 38 feet thick at this location and the "hot shale" interval is well developed (10 feet thick). The Lower Glen Rose reef is about 25 feet thick from the log signature and is correlated with the patch-reef outcrop at the Narrows and core from the No. 2 Craft Ranch stratigraphic borehole. The transition from the Lower Glen Rose patch-reef to the Hensel sand lithofacies is identified between the Logan Craft well and the J–5 Narrows Ranch well (Fig. 10).

The J–5 Narrows well, located 6 miles to the northeast, (Fig. 10) was logged but no cutting samples were available. The borehole is interpreted to have a 74 foot thick Hensel section with the basal 40 feet correlated to the Hensel section at the Narrows, including a 10 foot thick "hot shale" interval. The overlying "upper" Hensel is within the "thick" sandy facies. There is no indication of reefal buildup from the geophysical log. The Oswald well (Fig. 11) with very good cutting samples and a geophysical log anchors the strike cross section to the northwest. There is no Lower Glen Rose reef development indicated in the samples from Oswald.