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Outcrop Evidence for Variations in Channel-Floodplain Facies and Stratal Architectures across the Simsboro to Calvert Bluff Transition, Wilcox Group, Butler, Texas

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ABSTRACT

Deposits of the uppermost Simsboro Formation and lowermost Calvert Bluff Formation of the Wilcox Group are exposed along outcrops in pits at the Acme Brick Company quarry, Butler, Texas. Because this is an active quarry, and the Simsboro and Calvert Bluff function as both an aquifer system and petroleum reservoirs, it was critical to document the characteristics of these rare, temporary exposures and preserve them digitally. An integrated sedimentologic and palynologic study coupled with high-resolution imagery and drone photogrammetry revealed complex facies relationships and stratal architectures.

Simsboro depositional environments include sand-rich channel thalweg, channel bar, point bar, and levee deposits of meandering channels, along with silt-rich abandoned-channel deposits. A low-diversity and low-abundance trace fossil assemblage, including diminutive *Planolites* and *Teichichnus*, indicates some marine-brackishwater influence during deposition. Abundant inclined heterolithic stratification, mud-draped sedimentary structures, common double mud-drapes, and mud rip-up clast lags suggest that these channels, although fluvial-distributive, repeatedly experienced tidal effects that drove mud out of suspension and forced mud deposition. Hence, Simsboro channels are interpreted as fluvial-tidal channels, which are rarely exposed in outcrops worldwide. High-resolution outcrop imagery reveals abundant erosional surfaces and complex cut-and-fill structures, point bars, and silt-rich channel-abandonment deposits of multistory channels. Abundant and recurrent incision and erosion, and the lack of preserved floodplain, indicates a low accommodation setting. Paleoflow was, on average, to the southwest during Simsboro deposition.

The Calvert Bluff comprises sand-rich channel deposits and levees isolated within floodplain deposits including lacustrine deposits, lignite, and paleosols, with fewer erosion surfaces and cut-fill structures than the Simsboro and no marine trace fossils. Lateral-accretion surfaces are a prominent component of sandbodies, which are also interpreted as deposits of meandering channels, although located further updip than those of the Simsboro. In contrast to the Simsboro, Calvert Bluff channel abandonment deposits are darker-colored, highly organic with abundant plant macrofossils, and are interbedded with paleosols containing rhizoliths and mottles. Mud drapes on sedimentary structures are less common. Paleosols are gleyed and likely immature (entisols and inceptisols) with some containing in-situ tree stumps. Calvert Bluff channel abandonment deposits indicate high-angle abandonment and probably represent oxbow lakes. Characteristics of outcrops indicate that accommodation and the water table were likely higher during Calvert Bluff deposition. Paleoflow indicators trend more toward the east-southeast.

Pollen assemblages for both the Simsboro and Calvert Bluff along with sparse in-situ dinoflagellates suggest a "middle" Thanetian age. Assemblage composition is consistent with a coastal-plain to delta-plain paleoenvironment dominated by fluvial channels and riparian to floodplain-wetland deposition, with limited marine influence.

Although well data are sparse in the area, outcrops can be correlated into the subsurface via wireline logs. Recent regional subsurface work to the northeast of the study area divided the Simsboro into 6 sequences and the Calvert Bluff into 6 sequences. Outcrops at Acme Brick are equivalent to

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deposits of the Simsboro 6 sequence and the Calvert Bluff 1 sequence. Net-sandstone maps of the Simsboro 6 and Calvert Bluff 1 sequences reveal the geometries of sand-rich fairways of fluvial systems such as those preserved in outcrops of the Acme Brick quarry. Ancient analogs for the Simsboro 6 and Calvert Bluff 1 sequences are proposed. This study provides a framework to predict the characteristics of similar deposits in frontier areas with poor well control.

INTRODUCTION

Outcrops and subsurface data from the Wilcox Group in Central Texas have received renewed attention because of several ongoing Paleocene-Eocene source-to-sink investigations of broad interest to both the petroleum industry and climate scientists (e.g., Demchuk et al., 2019; Ambrose et al., 2020). One member of the Wilcox Group, the Simsboro Formation (Fig. 1), is a regional aquifer (e.g., Thorkildson and Price, 1991; Mace and Smyth, 2003; Hutchison et al., 2009) and a hydrocarbon reservoir in the deeper subsurface. Many rural Texas residents and several large communities, including Bastrop and Bryan/College Station, rely on the Simsboro aquifer as their primary water source. Population expansion along the Interstate Highway 35 corridor from San Antonio to Georgetown is driving demand for additional potable water, with ever-increasing negative impacts on the water table and Simsboro aquifer. The overlying Calvert Bluff Formation (Fig. 1) is an aquitard, an oil and gas reservoir, and is also mined for lignite (Ayers and Lewis, 1985; Ayers et al., 1986).

During the past decade, revised sedimentology and high-resolution biostratigraphy combined with the application of sequence stratigraphic concepts has resulted in major revisions of interpretations for Wilcox depositional environments and regional correlations, with increased emphasis on marginal-marine to marine depositional environments and tidal influence on sedimentation (Demchuk et al., 2019; Ambrose et al., 2020). Fundamental aspects of the Simsboro and Calvert Bluff that include accurately identifying vertical and lateral facies trends, depositional settings (e.g., fluvial, marginal-marine, marine), and the evolution of depositional systems remain somewhat enigmatic. Optimal management and continued development of the Simsboro–Calvert Bluff aquifer-aquitard system will rely on refining regional correlations and developing 3D models that require a broad understanding of depositional systems. Important information will include detailed descriptions of facies, facies stacking, sandbody geometries and sand distribution, sandbody connectivity, shale barriers and baffles, and porosity-permeability trends.

We were afforded a unique opportunity to investigate the uppermost Simsboro and lowermost Calvert Bluff in pits at the Acme Brick Company in Butler near Elgin, Texas (Figs. 1–3). In this study, the term ‘quarry’ refers to the entire large-scale excavation area, the term ‘pit’ refers to individual excavations within the larger quarry, and the term ‘outcrop’ or ‘outcrop exposure’ refers to the relatively vertical, temporary face of the pit that has been described and photographed for documentation of facies trends and stratal architectures.

Brickworks, such as Acme Brick, have been exploiting resources in the uppermost Simsboro and lowermost part of the Calvert Bluff near the city of Elgin for decades. The economic value of the interval for brickmaking has been overshadowed more recently by the development of large open-pit lignite mines (e.g., Three Oaks lignite mine [Figs. 1, location 2, and 2B]). Fortuitously, Acme Brick pits provide several laterally extensive, accessible 3D exposures of the uppermost Simsboro (ELSTAN pit) and lowermost Calvert Bluff (TAN pit) (Fig. 2). These pits are actively excavated, however, and outcrops such as those detailed here are only temporary. Preserving such at-risk outcrops in digital format and archiving their data are critical for providing insight that might otherwise be lost, and for advancing the geological sciences discipline (Burnham et al., 2022). New technologies, software, and analysis techniques are continually being developed that also warrant digital preservation of key outcrops (Burnham et al., 2022).

The goals of this project are to (1) identify the type of depositional systems that generated these deposits, (2) document lateral and vertical facies changes and stratal architectures, and (3) provide age control. These factors will improve our understanding of the inter-related Simsboro and Calvert Bluff aquifer/reservoir system across the boundary between these formations and could be used to predict the characteristics of similar deposits in frontier areas that lack high-density well control.

STRATIGRAPHIC SETTING

Pioneering work on the Wilcox-Claiborne outcrop belt stratigraphy dates back to the late 19th century (e.g., Penrose, 1889; Dumble, 1894; Harris, 1897, 1899). Much of the stratigraphic succession, as currently understood, was established by the 1920s and 1930s (e.g., Deussen, 1924; Sellards, 1929; Plummer, 1933; Stenzel, 1938). Plummer (1933) summarized the development of stratigraphic terminology to that date. He proposed the name Rockdale Formation for what he considered to be a non-marine succession in the Wilcox, with sub-division into the Butler, Simsboro, and Calvert Bluff members in ascending order. Decades later, Sharp (1951, 1965) mapped an area in northern Bastrop County and established the Butler Clay as part of the basal Calvert Bluff, above the Simsboro. The Butler Clay is also known as the “BUFF” clay, at the Acme Brick pits (Fig. 2).

Stenzel (1951, 1953) suppressed the term Rockdale as a formation by elevating its three members to formation rank. He used the name Hooper Formation for the unit above the Seguin and below the Simsboro. Giannone (1951) mapped the Hooper, Simsboro, and Calvert Bluff in the informal Hooper type area of McKinney Roughs Nature Park (Fig. 1, location 5), where he estimated the Hooper thickness at 99 m [325 ft]. In southeastern Bastrop County, the Humble Oil and Refining Co. #1 E. W. Jones well penetrated approximately 396 m [1300 ft] of Hooper (re-interpreted from Kaiser [1974]).

Dips across Bastrop County are generally low, 1–2 degrees to the southeast. Faulting complicates outcrop relationships and subsurface correlations, but detection of faults in the generally subdued topography is difficult. Sharp (1951) mapped a fault west of the Acme Brick quarry with 64 m [210 ft] of downthrow to the northwest. A normal fault between the Acme Brick and Elgin-Butler pits (Fig. 2B), which causes a younger part of the Calvert Bluff, with thick lignites, to be exposed at Elgin-Butler was identified on borehole logs (Hunt, 2004). Resource evaluation drilling prior to development of the Three Oaks mine (Figs. 1, location 2, and 2B) on the Bastrop/Lee county border revealed previously unknown faulting (Williams, 2004).

Simsboro Formation

W. A. Reiter named the Simsboro member after the town of Simsboro in Freestone County, Texas, in a letter to F. B. Plummer in 1932. Plummer (1933) formally proposed the Simsboro sandstone with member status. In the northern part of Bastrop County, the Simsboro is 70 to 80% sandstone, but in the Three Oaks mine (Figs. 1 and 2) there is abundant silty sandstone and siltstone (Williams, 2004). According to Sharp (1965), the Simsboro in the Butler area is a coarse- to fine-grained, cross-bedded to featureless sandstone approximately 23 m [75 ft] thick, bioturbated in the lower part and containing siltstone clasts up to 1 m [3.3 ft] in size. It is probably of similar thickness at McKinney Roughs Nature Park (Fig. 1, location 5) where the base of the Simsboro is erosional, with coarser sandstone and siltstone clasts at the base (Giannone, 1951). Close to the base of the formation

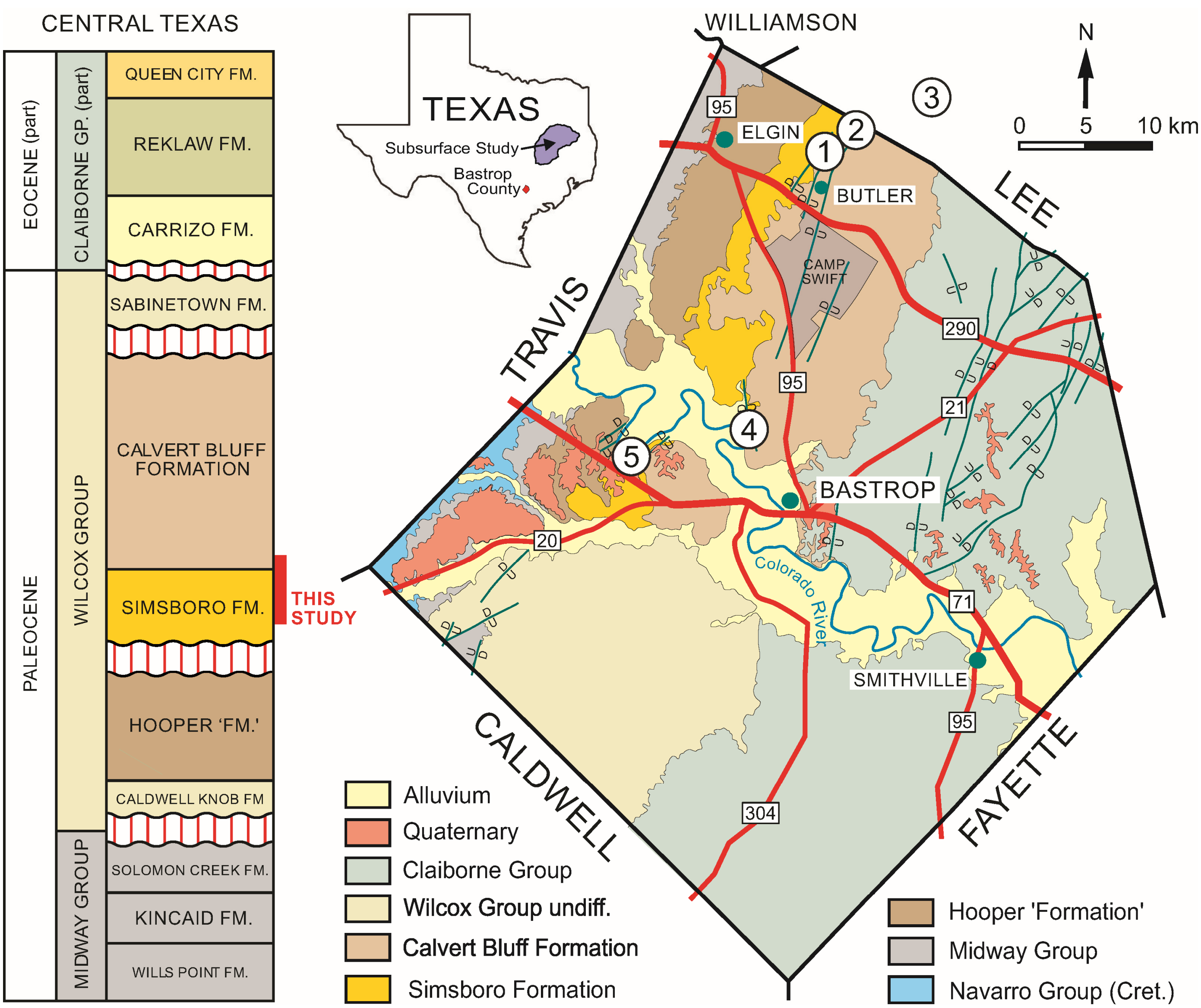

Figure 1. Bastrop County bedrock geology and outcrop distribution (modified after Barnes [1974], Gaylord [1985], and Giannone [1951]). Figure includes a generalized stratigraphic column as well as: Location 1—Acme Brick Company, location 2—Three Oaks mine, location 3—MPS Production Company Saunder IE #1 well, location 4—Powell Bend on Colorado River, and location 5—McKinney Roughs Nature Park. 10 km = ~6.2 mi.

in a borrow pit at McKinney Roughs Nature Park, a medium-grained sandstone with common mafic grains (salt-and-pepper texture) is exposed.

Plummer (1933) noted 73 m [23 ft] of Simsboro in eastern Milam County and western Robertson County, Texas. Bammel (1979) correlated the Simsboro in strike-oriented hydrocarbon exploration wells from Bastrop County to Freestone County, approximately 180 km [112 mi], with thicknesses varying from of 75–110 m [246–360 ft]. Kaiser (1974) interpreted about 110 m [360 ft] of Simsboro in the Humble Oil and Refining Co. #1 E. W. Jones well in northeastern Bastrop County. Bammel (1979) interpreted the same thickness in this well. Both authors included a heterolithic succession in the lower part of the Simsboro. However, a sharp-based sandstone at 725 m [2379 ft] could be the base of the Simsboro, making it only 43 m [141 ft] thick. Southeast of the Butler area, some 30 km [19 mi] downdip, Gaylord et al. (1985) interpreted 244 m [800 ft] of Simsboro in the Burford Oil Co. B. B. Sanders No. 1 well, with the Hooper being 70 m [230 ft] thick. From wireline logs, the Simsboro in this well can be re-interpreted as approximately 30.5 m [100 ft] thick, and the underlying succession with several well-developed sandstones attributable to the Hooper.

In his regional outcrop study Bammel (1979) identified sedimentary structures typical of a meandering channel system with point bars, scour pools, chute channels, overbank deposits, and abandoned channels. Ayers and Lewis (1985) mapped the Simsboro along the length of the outcrop belt and into the subsurface as a fluvial channel complex. In contrast, Adams (1957) noted bi-directional currents, possibly recording ebb and flood currents, and glauconite in the Simsboro of Bastrop County. Kohls (1963) acknowledged the marine nature of the Simsboro in Bastrop County, but between the Brazos and Trinity rivers he interpreted a continental environment of deposition. In a petrographic study of the Simsboro in Central Texas, Cast (1986) identified common to rare glauconite pellets in the Simsboro.

A river-cut cliff at Powell Bend on the Colorado River exposes the upper part of the Simsboro (Figs. 1, location 3, and 4). Although the cliff is vertical and mostly inaccessible, stacked

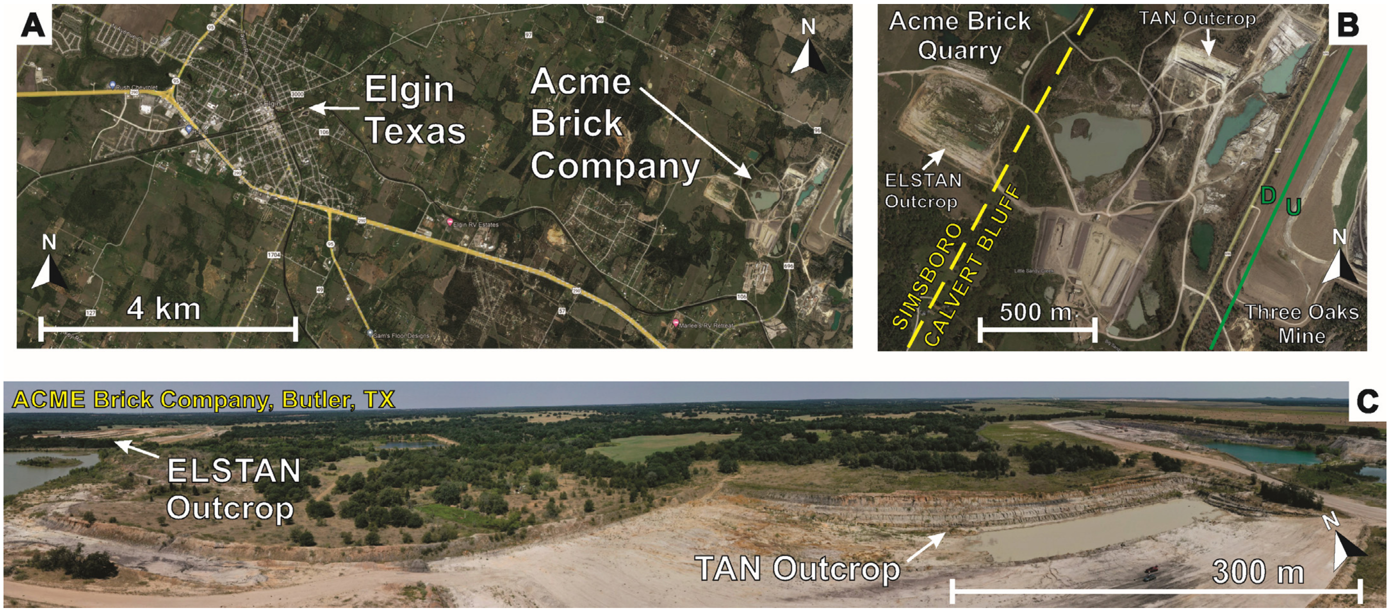

Figure 2. Figure shows (A) the location of Acme Brick Company relative to the city of Elgin, TX, (B) satellite image of the ELSTAN and TAN outcrop belts in the Acme Brick pits including the approximate location of the Simsboro–Calvert Bluff contact and fault along TX 696, and (C) drone panorama showing the relationship between the ELSTAN and TAN pits and outcrop belts.

sandbodies (barforms) with evident bounding surfaces and internal inclined bedding are visible in the lower two thirds of the cliff (12 m [40 ft] thick). The upper 5 m [15 ft] records a transition to horizontally bedded heterolithics.

Calvert Bluff Formation

Plummer (1933) designated the Calvert Bluff member, with the type locality at bluffs on the Brazos River, near Calvert, Robertson County, Texas, where about 21 m [69 ft] of mainly sandstone with lesser lignite beds is exposed. In the Humble Oil and Refining Co. #1 E. W. Jones well, Kaiser (1974) assigned 304 m [997 ft] to the Calvert Bluff, with lignite seams identified in the lower 73 m [240 ft], and a highly heterolithic succession of sandstones and shales above.

The value of lignites from the Calvert Bluff has been the focus of numerous publications, either through surface mining (e.g., English, 1988; Tewalt and Jackson, 1991; Hook et al., 2011; Warwick et al., 2011) or by subsurface gasification (e.g., Warwick et al., 2000; Swanson et al., 2015). However, these studies offer few, if any, details about the encasing sediments. Most of the Calvert Bluff stratigraphy between the major lignite-bearing successions at the top and base is only known from wireline logs and remains largely undescribed. A notable exception is the Letco TOH–2AO Settlemeyer well in Leon County of northeast Texas, where approximately 246 m [807 ft] of core is assigned to the Calvert Bluff (Ambrose et al., 2020). In the TOH–2AO core the basal Calvert Bluff includes coal and mudstone-siltstone with rhizoliths interbedded with very fine- to fine-grained sandstone. Upward-coarsening units that grade from mudstone into very fine-grained bioturbated sandstone, with lenticular bedding, mud-draped ripples, and abundant organic plant fragments overlie this coal and organic-rich interval (Ambrose et al., 2020). Marine dinocysts and bioturbation by marine organisms are common in the finer-grained lithologies overlying the coal. Ambrose et al. (2020) noted that the Simsboro to Calvert Bluff transition in the TOH–2AO core records a basinward-stepping of depositional systems, and a regressive cycle. The entire Calvert Bluff overlying this regression was deposited within a backstepping or retrogradational cycle (Ambrose et al., 2020).

Exposures of uppermost Calvert Bluff sandstones in the Tahitian Village area of Bastrop County contain the marine trace fossils *Ophiomorpha* and *Thalassinoides* as well as sedimentary structures that indicate tidal modification during deposition (Demchuk et al. 2019; Ambrose et al. 2020). A marine setting for sediments of the uppermost Calvert Bluff at Big Brown mine, Freestone County, Texas, and Martin Lake mine, Panola County, Texas, was proposed by Breyer (1986, 1987) who identified sedimentary structures in sandy channel-fill and muddy lateral-accretion deposits that indicate tidal influence on sedimentation. Klein (2000) documented additional examples of tidal sedimentary structures and marine dinocysts at Big Brown mine. Galloway (2002) described herringbone cross-stratification as well as flaser, wavy, and lenticular bedding in the upper Calvert Bluff at Mount Enterprise, Rusk County, Texas.

Plummer (1933) envisaged a complex, mostly continental paleoenvironment for deposition of the Calvert Bluff including river systems, levees, lakes, marshes, and swamps, only part of which was deltaic. For the lower part of the Calvert Bluff, Ayers (1989) interpreted a fluvio-deltaic setting at Sandow mine in Milam County, Texas, and in a brief overview of the Elgin-Butler pit, he interpreted floodplain muds and crevasse-splay channel sandstones. Hunt (2004) interpreted a similar setting for deposits in the Elgin-Butler pit. Early shaft and adit lignite mines, and the more recent large open-pit lignite mines along strike of the Calvert Bluff from the Three Oaks mine to the Dolet Hills and Oak Hills mines in northwest Louisiana, derived lignites from what are interpreted as primarily coastal-plain depositional settings. Similar interpretations exist for pits in the Sabine Uplift area of East Texas (Stenzel, 1951, 1953). Evidence of marine influence is somewhat rare in the lowermost Calvert Bluff. In the upper part, sedimentary structures and marine palynomorphs from along the outcrop belt show that deposition in a tidally affected marine environment was widespread (Nichols, 1970; Breyer and McCabe, 1986; Breyer, 1987, 1989; Galloway, 2002; Klein, 2000; O'Keefe et al., 2005; Sturdy, 2006; Ambrose et al., 2020).

METHODS

Standard stratigraphic techniques were used during outcrop analysis with a focus on identifying sedimentary structures, faci-

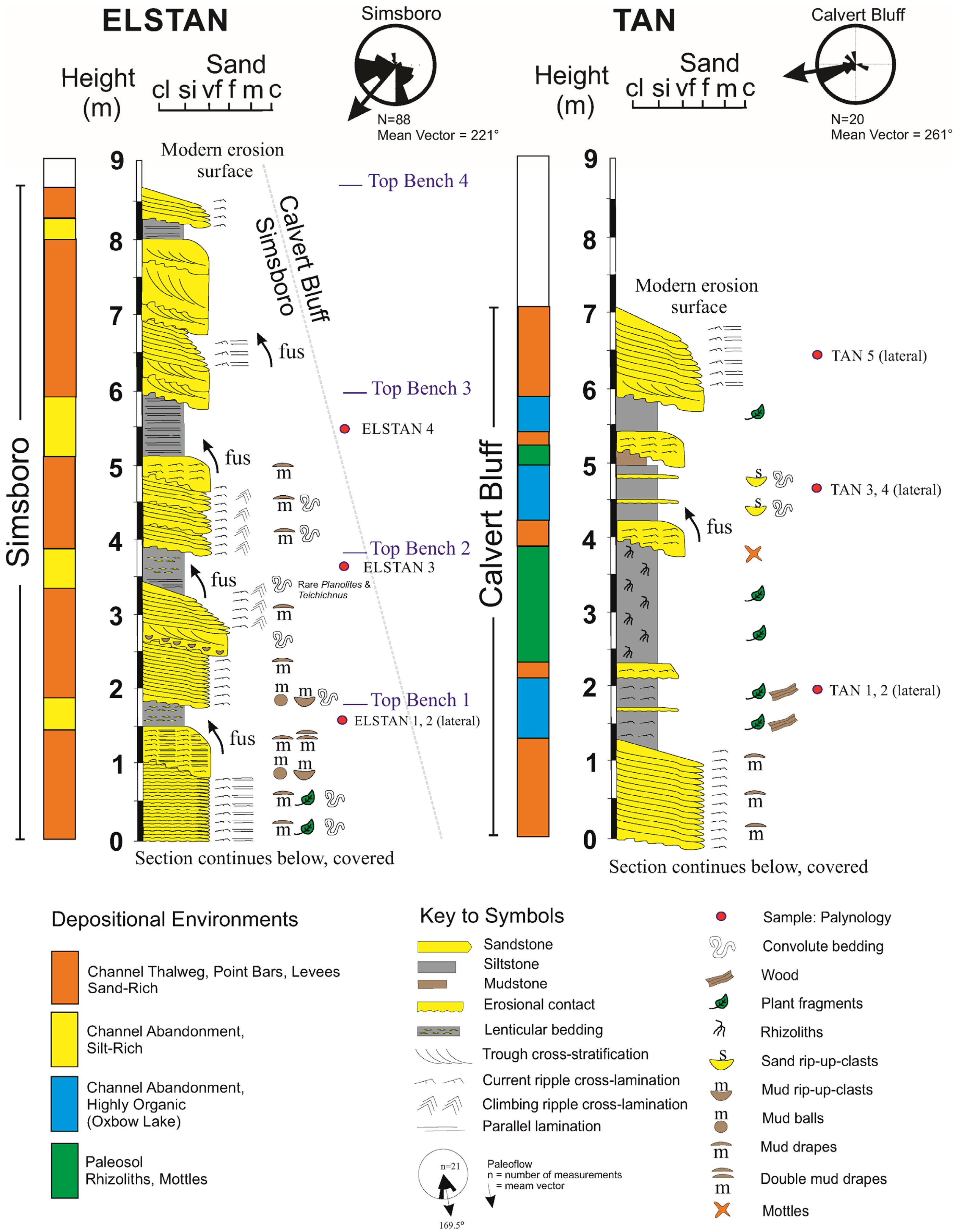

Figure 3. Measured stratigraphic succession through the ELSTAN and TAN outcrops including the location of samples taken for palynology, paleocurrent orientations, and depositional environment interpretations. 1 m = 3.28 ft.

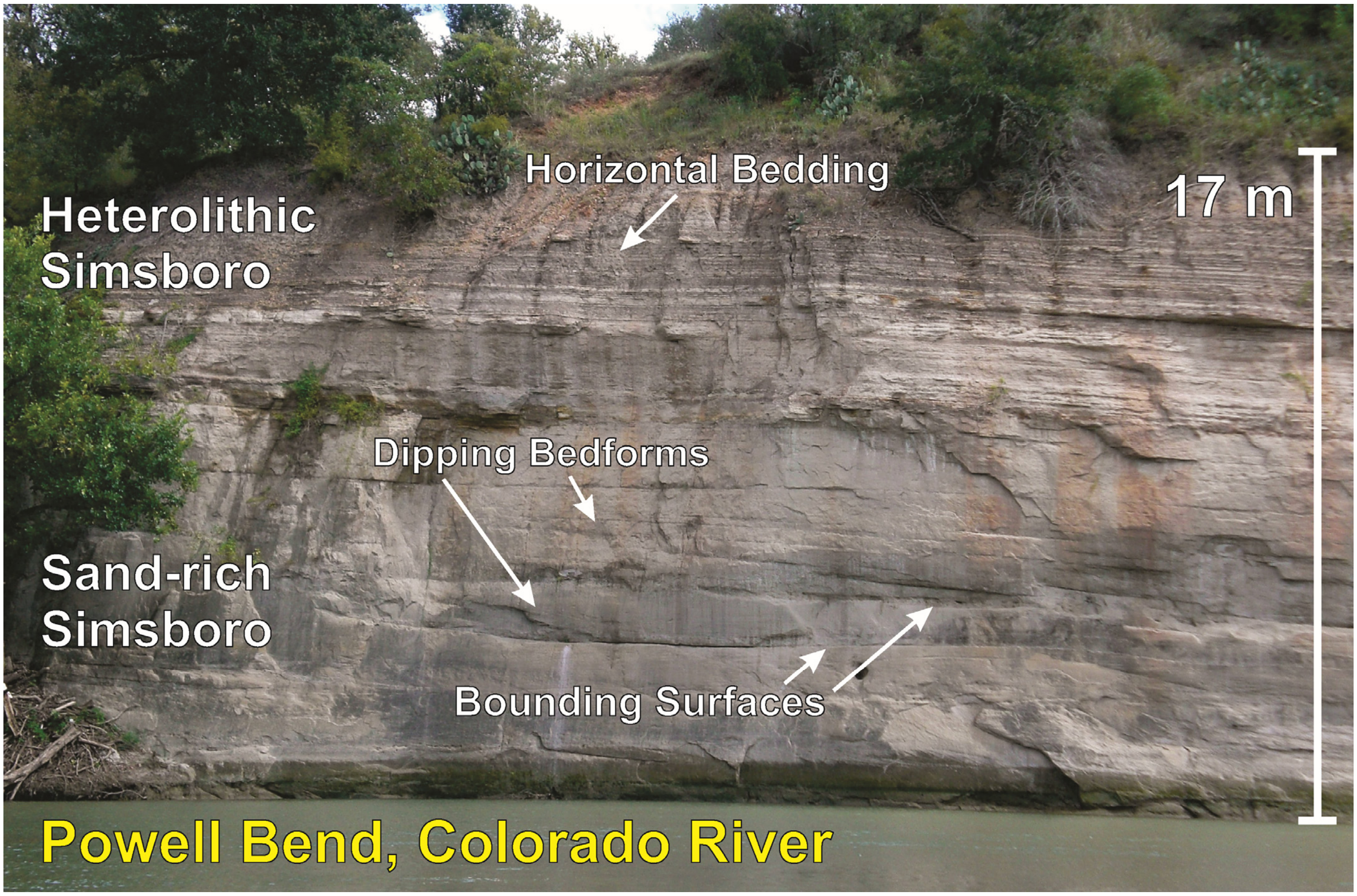

Figure 4. Upper part of the Simsboro exposed at Powell Bend on the Colorado River (see Figure 1, location 3). Image shows a vertical sandstone cliff in lower part (c. 12 m [39 ft] thick) with bounding surfaces and inclined surfaces. Image also shows the transition to heterolithics in upper part (c. 5 m [16 ft] thick). Quaternary gravels cap the cliff. 1 m = 3.28 ft.

es, facies stacking, and key surfaces. For this study two vertical successions along accessible laterally extensive outcrop exposures (Figs. 2 and 3, and Appendix) within the ELSTAN and TAN pits in the Acme Brick quarry were recorded that document grain size, sedimentary structures, and facies stacking (Fig. 3).

One hundred and eight (108) paleocurrent measurements were recorded and plotted as rose diagrams (Fig. 3). Paleocurrent measurements were recorded separately from the Simsboro and Calvert Bluff from large-scale and small-scale trough cross-stratification, imported into GEOrient software, and exported as polar lines in 20° classes to identify the overall mean vector of paleoflow for each formation.

A combination of high-resolution GigaPan photopanoramic imagery and drone photogrammetry was developed into qualitative photomosaics (GigaPans) and quantitative 3D models and orthomosaics (drone photogrammetry) to capture vertical and lateral facies variability and architectural elements exposed in the quarry (Appendix).

High-resolution photomosaics were recorded using a Nikon D 810 SLR camera, 200–400 mm ED Nikkor lens, and GigaPan Epic Pro robotic panhead mounted on a surveyor's tripod. Photomosaics were assembled in GigaPan Stitch EFX software, exported as high-resolution JPEGs, and used in conjunction with drone photogrammetry and measured stratigraphy for correlation of facies and stratal architecture analysis across the outcrop belts. All GigaPan imagery was uploaded to the GigaPan website. Links to the high-resolution photomosaics archived on the GigaPan website are available in the supplemental Appendix. Drone photogrammetry was recorded using a DJI Mavic 2 Pro Quadcopter. Drone images were aligned and developed into high density 3D point clouds, 3D models (triangular mesh and photographic texture), and orthomosaics using Agisoft Metashape and Meshlab software. Links to 3D models archived on the V3Geo website can also be found in the supplemental Appendix. CorelDRAW was used for image interpretation.

Wireline logs from wells nearest to the Acme Brick quarry were examined in Petra and compared to a template and regional correlations available in Ayers and Lewis (1985). Ayers and Lewis provided wireline log characteristics for identifying the Midway Group, Hooper, Simsboro, Calvert Bluff, Sabinetown, Carrizo, and Reklaw using resistivity, conductivity, and spontaneous-potential logs. Exposures in the Acme Brick pits were correlated into the subsurface using the MPS Production Company Saunders IE #1 wireline log 13 km [8 mi] to the northeast of Acme Brick in Lee County, and compared to logs from the Letco TOH–2A Settlemeyer well drilled adjacent to the Letco TOH–2AO well and core (Ambrose et al., 2002) 75 km [47 mi] to the northeast. Ambrose et al. (2020) developed a series of net-sandstone and gross-sandstone maps of the Simsboro and Calvert Bluff from wireline logs, two of which are presented here. Net-sandstone from wireline logs was defined from a cutoff value of ~30% from a baseline of gamma-ray deflection to a consistent leftward deflection that indicates minimum clay content. This ~30% value was determined by calibrating wireline-log response to net-sandstone values measured in core descriptions. If wells lacked a gamma-ray curve, the spontaneous-potential curve was used to determine net-sandstone values with a cutoff value of 25%. The resistivity curve was also used in zones with poor gamma-ray and spontaneous-potential responses. Net-sandstone maps are isopach maps rather than isochore maps. Values of net sandstone were posted on maps and hand-contoured, with wireline-log responses used as a guide for contours.

Both the Simsboro (ELSTAN) and Calvert Bluff (TAN) pits were sampled for palynology. Samples in the ELSTAN pit were selected from siltstones exposed in each bench along the outcrop belt (Fig. 3). Four samples (ELSTAN#1 through ELSTAN#4) were collected, one from each bench (Fig. 3). Four samples were also collected in the TAN pit. TAN#1 was sampled from a siltstone in the lowest part of the pit which contained abundant macroplant material (Fig. 3). TAN#2 through TAN#4 were collected from different siltstone units to reveal any differences in palynomorph abundance and diversity. Palynological samples were prepared by PetroStrat Ltd. using HCl and HF acid-digestion techniques. Residues were lightly oxidized. Slides were made of the 10 to 30 micron sieved fraction, which consists of small palynomorphs, mainly pollen, and of the 30+ micron fraction, which consists of large pollen and spores, dinocysts, other large algal cysts, cuticle, and organic particles. Only ELSTAN#1 and TAN#1 samples produced rich and diverse palynomorph assemblages. Slides were scanned for a visual estimation of palynomorph populations.

FACIES ANALYSIS

Deposits exposed in the Acme Brick pits display complex, interbedded sand-rich facies and silt- to mud-rich facies with a variety of erosion surfaces, scours, and cut-fill structures. Characteristics of deposits of the Simsboro along the ELSTAN outcrop belt and the Calvert Bluff along the TAN outcrop belt differ considerably (Figs. 3, 5, and 6, and Appendix), and they are therefore discussed separately. Facies are combined into four different depositional environments (Fig. 3).

Simsboro: ELSTAN Outcrop

Simsboro deposits in the ELSTAN pit are dominated by very fine- to fine-grained large-scale to small-scale trough cross-stratified sandstone and modified current-ripple cross-stratified very fine- to fine-grained sandstone (Fig. 5). Parallel-laminated sandstone and climbing ripple cross-stratified sandstone are also common (Fig. 5). Inclined heterolithic stratification (Thomas et al., 1987) is common throughout the outcrop belt. Almost all identifiable sedimentary structures in sandstones have thin (~1 mm) mudstone drapes on them (Fig. 5), with some intervals containing double mud drapes or thicker mud drapes, and what appears to be rhythmically repetitious bedding (Fig. 5H). Mud-clast breccias (lags) overlying erosion surfaces are found at several locations along the outcrop belt (Figs. 6A and 6B) and scouring from the small scale to the large scale is common. Interbedded with the sand-rich facies and mud-clast breccias are finer-grained siltstone-rich intervals (Figs. 6A, 6C, and 6D) that may be parallel-laminated to structureless and rarely contain a low-abundance, low-diversity trace fossil assemblage that includes diminutive *Planolites* and *Teichichnus* (Fig. 6D). Rhizoliths, mottles, and ped structures that signify paleosol development along with lignite are absent.

Calvert Bluff: TAN Outcrop

Calvert Bluff deposits in the TAN pit also include abundant large-scale to small-scale trough cross-stratified fine- to medium-grained sandstones (Fig. 6E) along with current-ripple cross-stratified and parallel-laminated fine-grained sandstone. However, in contrast to the ELSTAN Simsboro deposits, mud-drapes on sedimentary structures are not common and mud-clast breccias are rare. Intervals of organic-rich siltstone to mudstone make up a higher percentage of the TAN sediments (Figs. 6E–6H). Highly carbonaceous siltstone with faint current-ripples to parallel-lamination and abundant leaves and carbonized woody material occurs near the base of the TAN outcrop belt (Figs. 6E, 6G, and 6H). Lignite is present but somewhat rare in the exposed interval, although it is typically common near the base of the Calvert Bluff and is mined locally. Also found in the TAN pit is an interval of mottled siltstone and mudstone with abundant carbonaceous rhizoliths and internal structures resembling soil peds (Fig. 6F). Circular- to oval-shaped dark-colored carbonaceous features can be seen on the uppermost flat surfaces alongside reddish to yellow-green mottles (Fig. 6F).

PALEOCURRENTS

Eighty-eight (88) paleocurrent measurements were recorded from large-scale and small-scale trough cross-stratification along the ELSTAN Simsboro outcrop belt (Fig. 3). Paleocurrent directions fluctuate across the entire range of 360° but are most concentrated within a range of 100–300°, with a mean vector of 221°. Twenty (20) paleocurrent measurements were recorded from similar large-scale and small-scale trough cross-stratification along the TAN Calvert Bluff outcrop belt (Fig. 3). Paleocurrent directions also fluctuate across the entire range of 360° but are most concentrated within a range of 220–320°, with a mean vector of 261°.

PALYNOLOGY

Most of the eight palynology samples collected from the ELSTAN and TAN pits (Fig. 3) did not provide abundant assemblages; however, one sample from each of the pits (ELSTAN#1–Simsboro, TAN#1–Calvert Bluff) produced diverse and abundant pollen characteristic of an upper Paleocene assemblage (Fig. 7). Assemblages are dominated by species of *Momipites* (Fig. 7), including *M. wyomingensis* and abundant *M. anellus* and *M. actinus* (Figs. 7A and 7B). *Caryapollenites* species are also present but in lower numbers; species include mostly *C. imparalis* and *C. prodromus*, with lesser numbers of *C. inelegans* and *C. veripites* (Figs. 7C–7E). Also abundant are species of *Intratriporollenites* spp. (Fig. 7F), and various species of *Tiliaepollenites*-like pollen. Assemblages are consistent with the upper Paleocene P5 biozone of Nichols and Ott (1978) which would likely equate to a mid-Thanetian age. Dinocysts were also recovered from ELSTAN#1, most of them having been reworked. The only specimens assignable to the Paleogene (Danian-Selandian?) are two examples of *Hafniasphaera*, neither of which are well preserved, attributed to *H.* cf. *fluens*, and *H.* aff. *delicata*.

ELSTAN#1 is unusual in producing numerous and diverse dinocysts, but the great majority of these are reworked from Cretaceous deposits. *Chatangiella* spp. and *Isabelidinium* spp. are probably Santonian-Maastrichtian (although the absence of *Dinogymnium* and allied genera potentially excludes the Maastrichtian). *Ovoidinium verrucosum* is probably Cenomanian. *Odontochitina operculata*, *Aptea* spp., *Florentinia* spp., and *Paleoperidinium* spp. indicate a more general Late Cretaceous age. Cretaceous reworking is also evident in the spore/spore assemblages, with several *Callialasporites dampieri*, a few *Aquilapollenites* spp., rare *Appendicisporites* spp., and rare *Gleicheniidites senonicus* occurring. Many bisaccate pollen grains and smooth trilete spores are also probably reworked; some have darker coloration, indicating a higher thermal maturity than in situ specimens.

OUTCROP ARCHITECTURES AND DEPOSITIONAL SYSTEM INTERPRETATIONS

The Simsboro outcrop belt in the ELSTAN pit (Appendix) is dominated by very fine- to fine-grained sandstone comprising stacked barforms and abundant cut-and-fill structures along with inclined heterolithic stratification. Bars are primarily represented by large-scale dunes (large-scale trough cross-stratification) over-

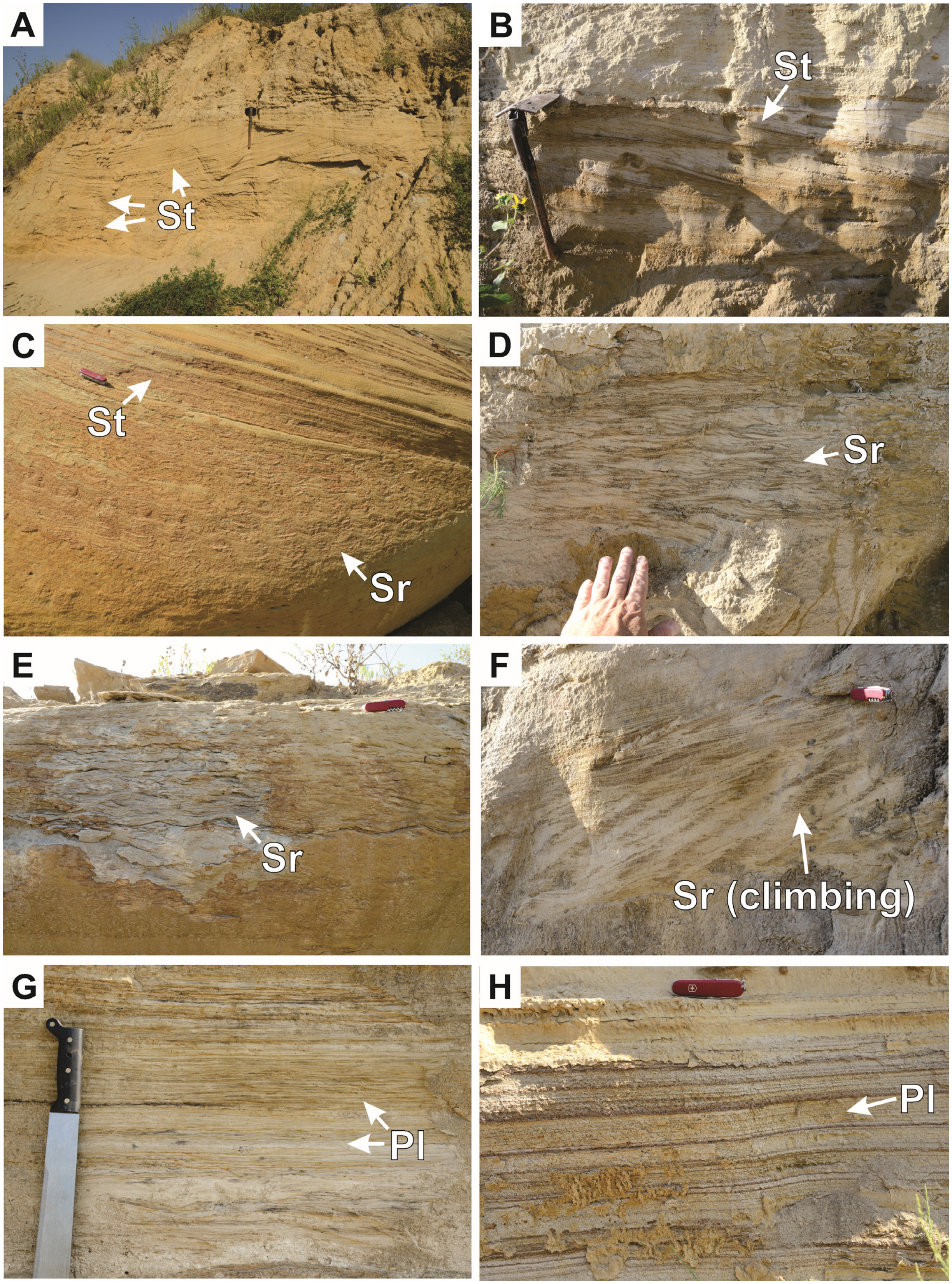

Figure 5. Example of sandy facies of the Simsboro found along the outcrop belt in the ELSTAN pit. Figure includes (A) large-scale trough cross-stratified (St) sandstone, (B) small-scale trough cross-stratification (St), (C) large-scale trough cross-stratification (St) overlying modified current ripple cross-stratification (Sr), (D) modified current ripple cross-stratification with mud-drapes on ripple surfaces, (E) quartz-cemented modified current ripple cross-stratification with mud-drapes on ripple surfaces, (F) climbing current ripple cross-stratification with mud-drapes on ripple surfaces, (G) Parallel lamination mud-drapes on bedding surfaces, and (H) single and double mud-drapes on bedding surfaces. Shovel is 53 cm (21 in) long. Machete blade is 38 cm (15 in) long. Pocket knife is 9 cm (3.5 in) long.

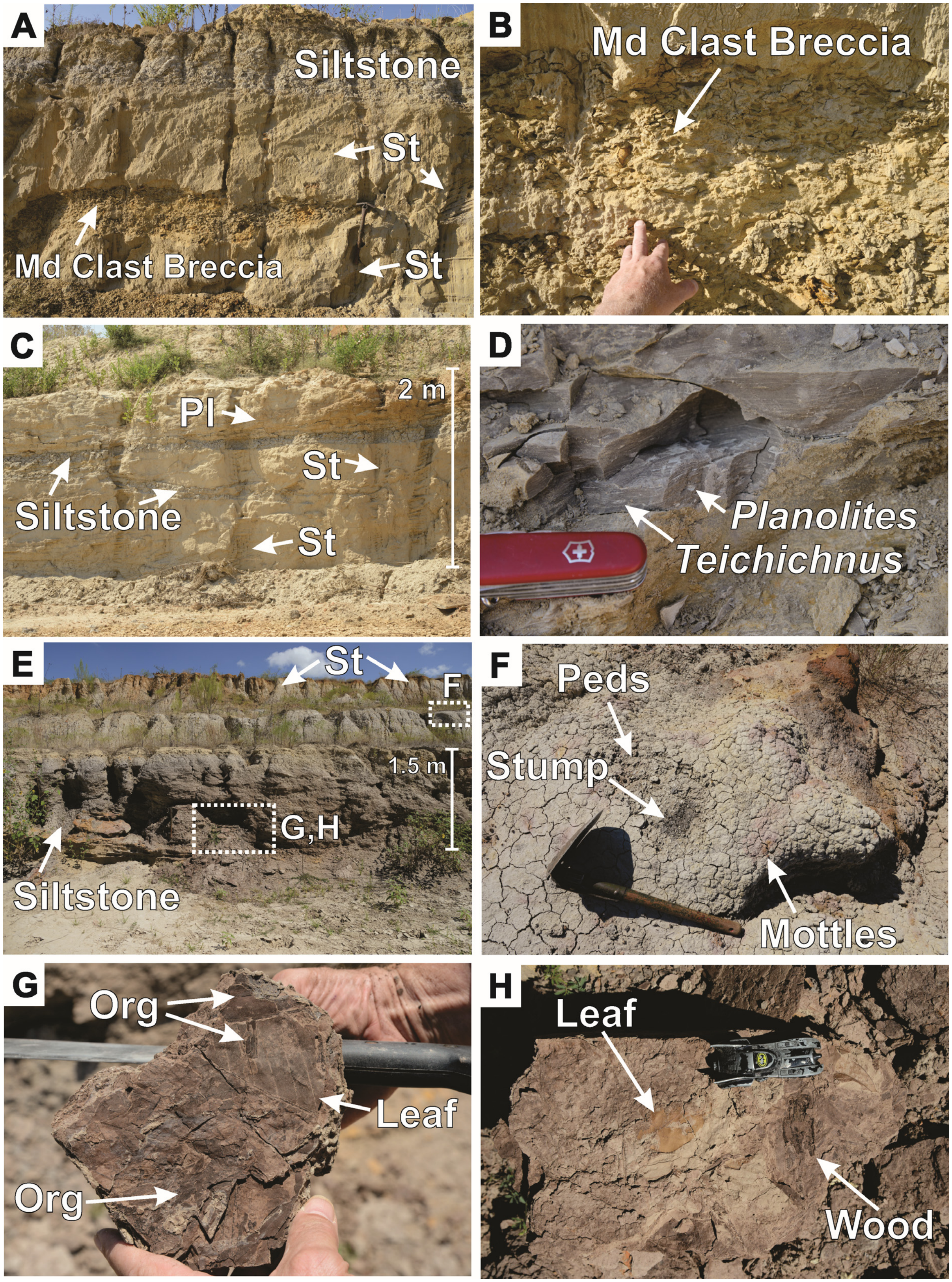

Figure 6. Example of interbedded sandy facies and silt- to mud-rich facies of the Simsboro and Calvert Bluff formations found along the outcrop belts in the ELSTAN and TAN pits. Figure includes (A) interbedded siltstone, trough cross-stratified sandstone (St) and mud-clast (Md) breccia along the ELSTAN (Simsboro) outcrop belt, (B) close-up of mud-clast breccia in "A" overlying an erosion surface, (C) interbedded trough cross-stratified sandstone (St), parallel-laminated sandstone (Pl), and siltstone along the ELSTAN outcrop belt, (D) the trace fossils *Planolites* and *Teichichnus* in a siltstone along the ELSTAN outcrop belt, (E) highly organic siltstone, paleosol (see inset F), and trough cross-stratified sandstone in the TAN (Calvert Bluff) outcrop belt, (F) peds, red and yellow mottles, and carbonaceous circular to oval structures (stumps) in the in the TAN outcrop belt, (G) leaf fossil and abundant organic material in the TAN outcrop belt, and (H) leaf fossils and wood from the TAN outcrop belt. Shovel is 53 cm (21 in) long. Pocket knife is 9 cm (3.5 in) long. Batman is 7 cm (2.7 in) long. 1 m = 3.28 ft.

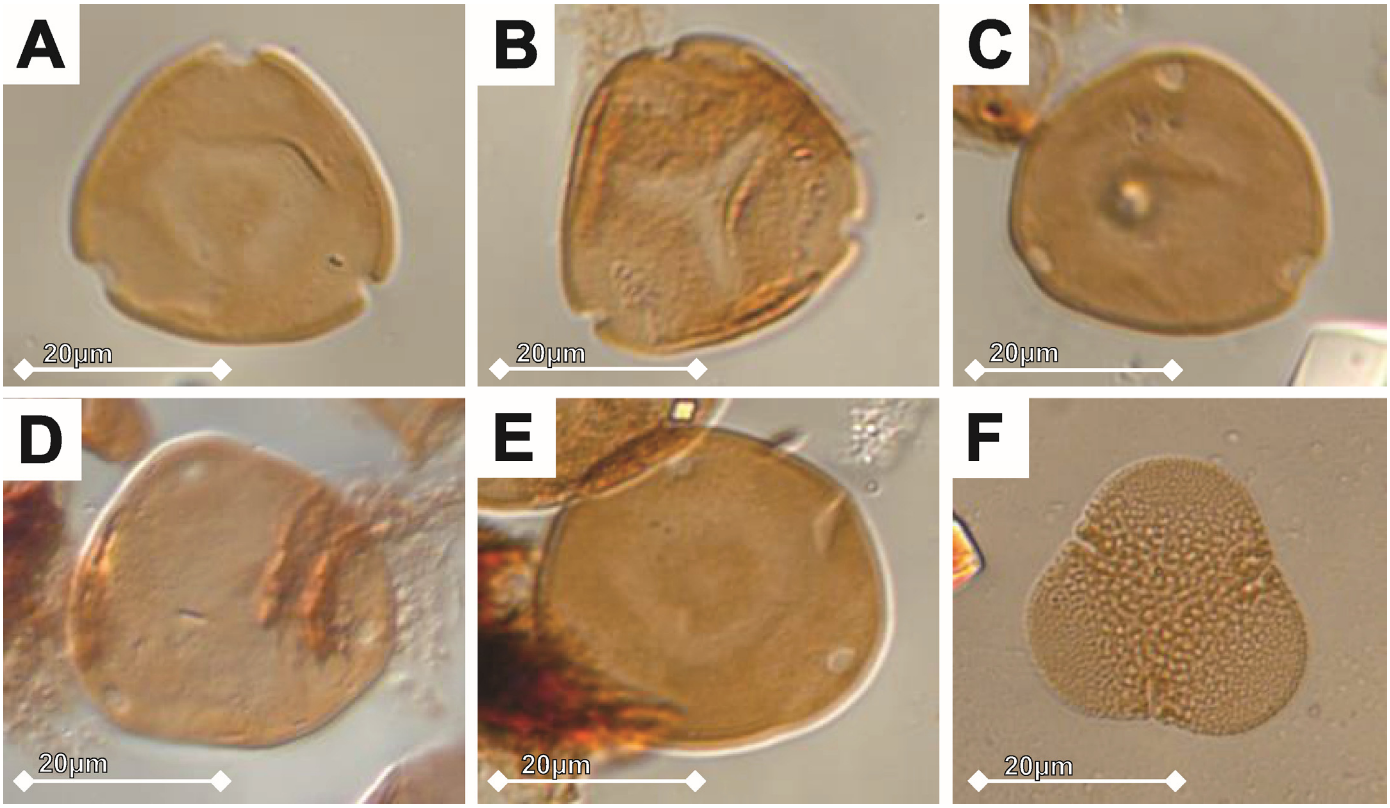

Figure 7. Palynologic assemblage recovered from the ELSTAN and TAN pits. Figure includes (A) *Momipites anellus*, (B) *Momipites actinus*, (C) *Caryapollenites imparalis*, (D) *Caryapollenites inelegans*, (E) *Caryapollenites veripites*, and (F) *Intratriporopollenites* sp. Scale bars = 20 microns.

lying concave-up scour surfaces (Figs. 5A–5C and 8A–8C). Some barforms are best described as compound bars, composed of a combination of stacked large-scale dunes, small-scale dunes, and modified current ripple cross-laminated sandstone or climbing ripple cross-laminated sandstone (Fig. 5). Mud-clast breccias overlie numerous scour surfaces (Fig. 6A). These scour surfaces, mud-chip breccias, and barforms record multistory channel thalweg and channel bar deposits (Fig. 3) of sand-rich coastal distributary river systems that also transported abundant mud (Dalrymple and Choi 2007; Ethridge, 2011). Parallel-laminated to ripple cross-stratified tabular sandstones (Fig. 5G) are likely associated levee deposits (Michaelsen et al., 2000; Flaig et al., 2011). Laterally extensive planar surfaces that dip downward at several degrees from horizontal typically at a high-angle relative to paleoflow and continue across the outcrop belt for tens of meters (tens to hundreds of feet) are abundant (Fig. 3 and Appendix). These surfaces are commonly overlain by siltstone or mudstone and record lateral accretion of point bars typical of meandering river systems (Smith, 1987; Flaig et al., 2011 and references therein). The vertical relationship of major scour surfaces along with the thickness of most fining up-ward successions (Fig. 3) suggest that channels were likely 2–3 m [6–10 ft] deep. The wide spread of paleocurrent directions recorded from dunes and bars in the Simsboro (Fig. 3) is consistent with deposits of meandering river systems (Flaig et al., 2011). Interbedded laterally extensive tabular siltstones (Figs. 6A, 6C, and 8B-8C) record fine-grained point bar deposits. Some siltstones overlie concave-up scour surfaces and thicken into the scour (Fig. 8A and Appendix) recording high-angle channel abandonment and subsequent fine-grained fill of abandoned channels (Collinson 1978; Miall 1996; Flaig et al., 2011). Organics are relatively rare except as drapes on sedimentary structures, most commonly near the base of channels. Ubiquitous mud-draped sedimentary structures (Fig. 5) along with inclined heterolithic stratification indicate that these fluvial distributaries had a significant fine-grained suspended sediment load and likely occupied the most distal part of the coastal plain or delta plain, where tidal effects allowed mud to recurrently settle out of suspension (Nio and Yang, 1991; Dalrymple and Choi, 2007). Mudstone-clast breccias are similar to those interpreted as channel lag and bank collapse features that commonly form in channels in tidal settings (Kitazawa, 2007; Musial et al., 2012). Although uncommon, some bi-directionality is also recorded in paleocurrent directions that plot to the northeast and northwest (Fig. 3), which is typical of tidally-modified distributary channel deposits. Rare, diminutive *Planolites* and *Teichichnus* found in siltstones indicate that, although the environment was stressed and primarily freshwater-dominated, salinities were high enough at times for bioturbation by organisms common to marine or brackishwater environments (Olariu et al., 2015; Flaig et al., 2019).

The Calvert Bluff outcrop belt in the TAN pit (Appendix) exposes laterally extensive, current ripple cross-stratified to parallel-laminated fine- to medium-grained sandstones with internal lateral-accretion surfaces (Figs. 3 and 8E). Sandbodies may be coarser-grained than those of the Simsboro, fine upward, and are separated from each other by finer-grained siltstone-rich to mudstone-rich intervals that are commonly highly carbonaceous (Figs. 6E–6H and 8D–8F). Channels appear similar in depth (2–4 m [6–13 ft]) or slightly deeper than those of the Simsboro (Figs. 3 and 8, and Appendix). Highly organic siltstones with abundant carbonaceous plant and leaf matter may overlie scour surfaces (Figs. 8D and 8F). An interval of siltstone and potential carbonaceous tree stumps (circular/oval carbonaceous features) is pedogenically modified at the top as evidenced by rhizoliths, ped structures, and mottles (Fig. 6F), indicating that a paleosol horizon developed there (Flaig et al., 2013). This combination of

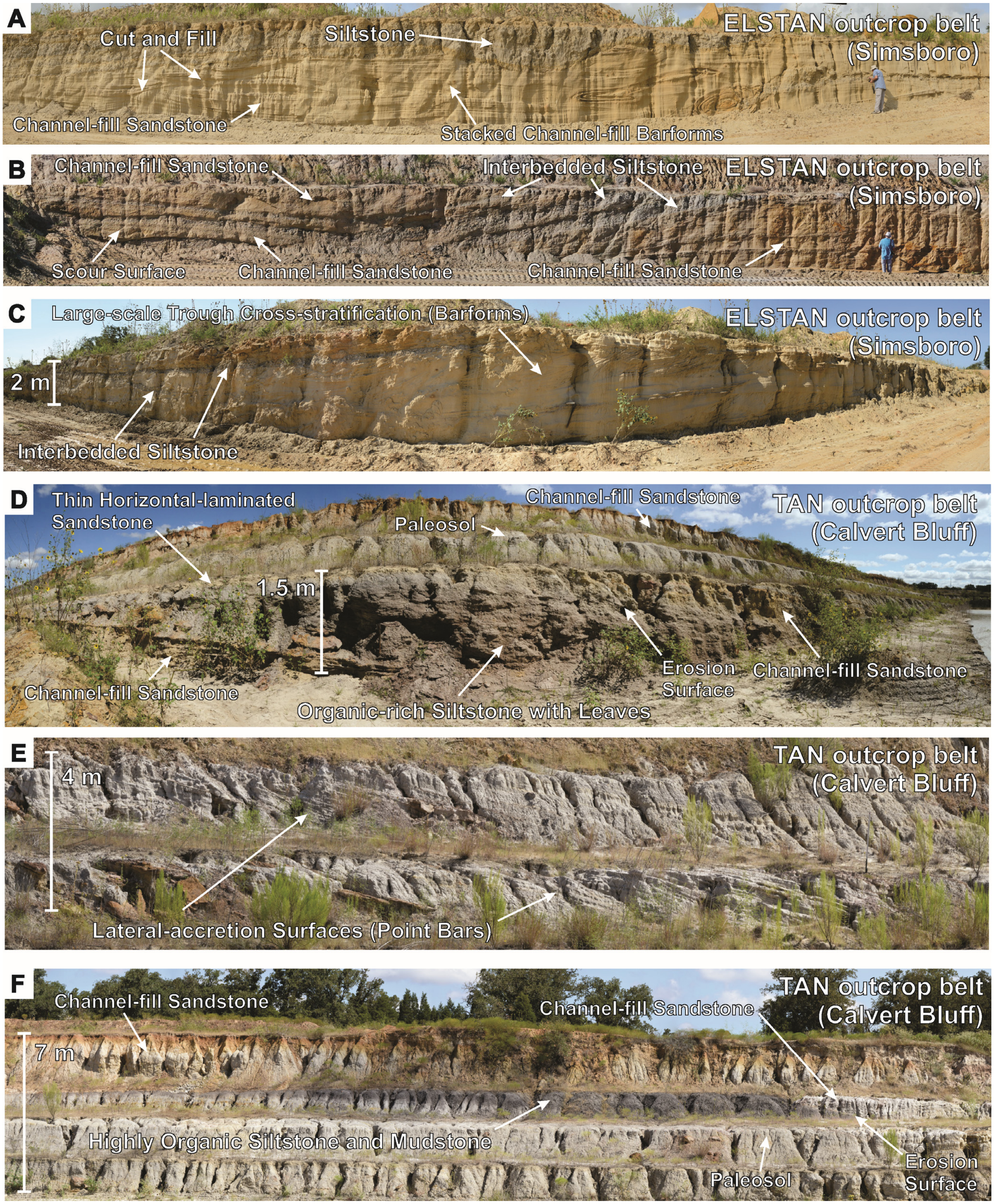

Figure 8. Key surfaces and stratal architectures in the ELSTAN Simsboro (A–C) and TAN Calvert Bluff (D–F) outcrop belts. Figure includes (A) channel-fill sandstone, channel barforms, cut and fill structures, and a siltstone-filled abandoned channel, (B) channel-fill including the basal scour surface and interbedded siltstone and sandstone within the fill, (C) large-scale trough cross-stratification (channel-bars) and interbedded siltstone (finer-grained point bar deposits), (D) organic-rich siltstone with abundant plant material incised-into by the basal surface of a sand-filled channel along with a paleosol horizon and additional channel at the top of the outcrop, (E) lateral-accretion surfaces in sandstone, and (F) highly organic siltstone and mudstone that transitions laterally into sandstone to the left of the image and is incised into by a channel sandstone to the right. Shovel is 53 cm (21 in) long. Parts A, C, and D were recorded with a handheld SLR camera near the outcrop, and exhibit some level of distortion. Part B is a relatively small image clip from a larger orthomosaic exported from a 3D model of the ELSTAN outcrop. Parts E and F are clips from larger GigaPan images. 1 m = 3.28 ft.

sedimentary structures, lateral-accretion surfaces, and stratigraphic relationships across the outcrop belt (Appendix) indicate that these are deposits of meandering river systems, levees, and associated organic-rich floodplains (Flaig et al., 2011). Highly organic siltstones that overlie scour surfaces are likely abandoned channel-fills akin to deposits of oxbow lakes (high-angle abandoned channels) that captured an extensive array of organics. Pedogenic modification likely occurred on levees and on floodplains adjacent to channels (Flaig et al., 2013). The absence of tidal modification of sediments or marine trace fossils combined with the abundance of leaves, plant matter, and wood suggest that these Calvert Bluff deposits represent more updip, continental fluvial-alluvial environments further from the continental-marine transition than those of the Simsboro.

The overall Paleocene pollen assemblage is indicative of plant communities that are common to a coastal-plain to delta-plain paleoenvironment containing fluvial channels and a riparian to floodplain-wetland. Predominantly terrestrial palynomorphs from the Calvert Bluff, with some examples of *Ovoidites* sp., a freshwater algal cyst, also suggest a coastal- to delta-plain paleoenvironment with associated fluvial channels and riparian to floodplain-wetlands.

SUBSURFACE CORRELATION AND DATA

Although publicly available well data is relatively sparse and widely spaced in the area around the Acme Brick quarry, transition from the outcrop belt into the subsurface can be accomplished using nearby wireline logs (Fig. 9). The best and most complete wireline log suite through the Wilcox Group, including the Simsboro to Calvert Bluff transition is from the MPS Production Company Saunder IE #1 well located 13 km (8.0 mi) northeast of Acme Brick (Figs. 1, location 5, and 9). Resistivity and spontaneous-potential logs capture the Simsboro–Calvert Bluff boundary at approximately 167.5 m [550 ft] depth (Fig. 9). The boundary is recorded as a transition from a blocky log signature in the resistivity curve of the Simsboro that records the thick, sand-rich interval that lacks organic-rich floodplain deposits in the ELSTAN pit to a "ratty" resistivity log signature overlain by a decreasing resistivity curve that records the organic-rich fine-grained sediments and lignite of the basal Calvert Bluff overlain by channel and floodplain deposits like those seen in the TAN outcrop belt (Appendix).

Ambrose et al. (2020) in a recent regional subsurface study located approximately 75 km [47 mi] northeast of the Acme Brick quarry divided the Simsboro into 6 sequences and the Calvert Bluff into 6 sequences, providing the most recent, regional context for interpreting the depositional setting of outcrops in Bastrop County (Fig. 10). They produced net-sandstone maps from wireline log data for all sequences. Exposures at Acme Brick are correlative with a portion of the deposits of the Simsboro 6 sequence and the Calvert Bluff 1 sequence (Figs. 10 and 11). Ambrose et al.'s (2020) net-sandstone maps of the Simsboro 6 and Calvert Bluff 1 sequences are consistent with deposits of fluvial systems such as those described at Acme Brick (Fig. 11).

The Simsboro 6 sequence is the youngest sequence in the Simsboro (Fig. 10). It exhibits overall blocky wireline-log responses within sand-rich depositional axes evident in net-sandstone maps (Fig. 11A). The Simsboro 6 sequence is composed of dip-elongate 6.4–9.6 km [4–6 mi] wide, south- and southeast-trending belts of 45–90 m [150–300 ft] of net sandstone (Fig. 11A). Depositional axes are wider and sandier in areas southeast and downdip of Bastrop County, where they contain > 76 m [>250 ft] of net sandstone in belts that are almost 16 km [10 mi] across. There, they feature anastomosing patterns, whereas depositional axes in the eastern part of the study area are isolated by areas of low net-sandstone values of <45.7 m [<150 ft]. Many of these dip-elongate belts pinch out southward, downdip. The organization of Simsboro 6 sequence sandbodies reflect an overall distributive pattern common to more distal, coastal fluvial-distributive systems.

The Simsboro 6 sequence represents a transitional zone from fluvial and upper-delta-plain depositional systems to shallow-marine systems in which channel systems are defined by narrow (commonly < 6.4 km [<4-mi]), south- and southeast-trending belts that pinch out and bifurcate southward (Fig. 11A). The lowest part of the Simsboro 6 sequence may also include lowstand incised valley-fill deposits, suggested by local and deep (almost 30.5 m [100 ft]) incision into the Simsboro 5 sequence in Burleson County (Ambrose et al., 2020) where there are dip-elongate net-sandstone trends with >76.2 m [>250 ft] of net sandstone (Fig. 11A). Basal sandstone bodies in the Simsboro 6 sequence in Burleson County have a blocky wireline-log response, consistent with aggradational fluvial deposits that commonly exceed the thickness of individual distributary-channel deposits, similar to those in the Woodbine Group in East Texas Field (Ambrose et al., 2009) and the Upper Wilcox succession in Bee County (Ambrose et al., 2018). Aggradational fluvial deposits of lowstand valley-fill origin in the Woodbine Group in East Texas field are locally >45.7 m [>150 ft] thick (Hentz and Bonnaffé, 2010), whereas those in the Upper Wilcox Group in northern Bee County are locally >24.4 m [>80 ft] thick (Ambrose and Zeng, 2016). In the Letco TOH–2AO core the uppermost Simsboro contains stacked coarsening-upward successions, some of which contain marine trace fossils suggesting a fluvial-deltaic setting for these deposits (Ambrose et al., 2020).

The Calvert Bluff 1 sequence is the basal sequence in the Calvert Bluff (Fig. 10). This sequence exhibits abrupt changes in wireline-log responses and net-sandstone thickness over short distances along depositional strike. Although dominated by southeast-trending, dip-elongate net-sandstone elements, the Calvert Bluff 1 sequence, locally, has a complex sandstone distribution pattern (Fig. 11B). From Houston to Angelina counties, the Calvert Bluff 1 sequence displays tributary patterns, where belts of 30–45 m [100–150 ft] of net-sandstone thickness merge southeastward in Trinity and Angelina counties. In contrast, sandstone patterns in Leon and Madison counties are complex, having anastomosing net-sandstone patterns, with some individual belts that continue for only 8 km [5 mi] between points of merging with other sandstone belts.

The Calvert Bluff 1 sequence is composed of tidally influenced, upper-delta-plain and lower-fluvial-alluvial plain deposits in the subsurface southeast of Bastrop County (Ambrose et al., 2020). Sandy framework facies, interpreted to be fluvial- and distributary-channel deposits, have both anastomosing and tributary patterns (Fig. 11B). Deposits of the Calvert Bluff 1 sequence in the Letco TOH–2AO core include coal, mudstone and siltstone with rhizoliths, and very fine- to fine-grained sandstone in both upward-fining and upward-coarsening successions (Fig. 10 and additional data in Ambrose et al. [2020]), recording deposits of both fluvial-distributive systems and those of shallow-marine, tidally modified environments (Ambrose et al., 2020). Net-sandstone maps of Ambrose et al. (2020) are consistent with major-sand isolith maps of the Simsboro and Calvert Bluff presented by Ayers and Lewis (1985) to the south and basinward of the study area, which show similar bifurcation and elongate sandstone bodies oriented predominantly north-south. Overall, the Calvert Bluff 1 sequence sandbodies exhibit more tributary patterns common to more proximal fluvial-alluvial systems.

DISCUSSION

Accessible outcrop exposures of this quality and lateral extent containing the uppermost Simsboro and lowermost Calvert Bluff formations of the Wilcox Group are rare. The exposures of outcrops found in brick pits described here are only temporary, hence, this is their only documentation. Characteristics and stratal architectures of these vertically and laterally heterogeneous,

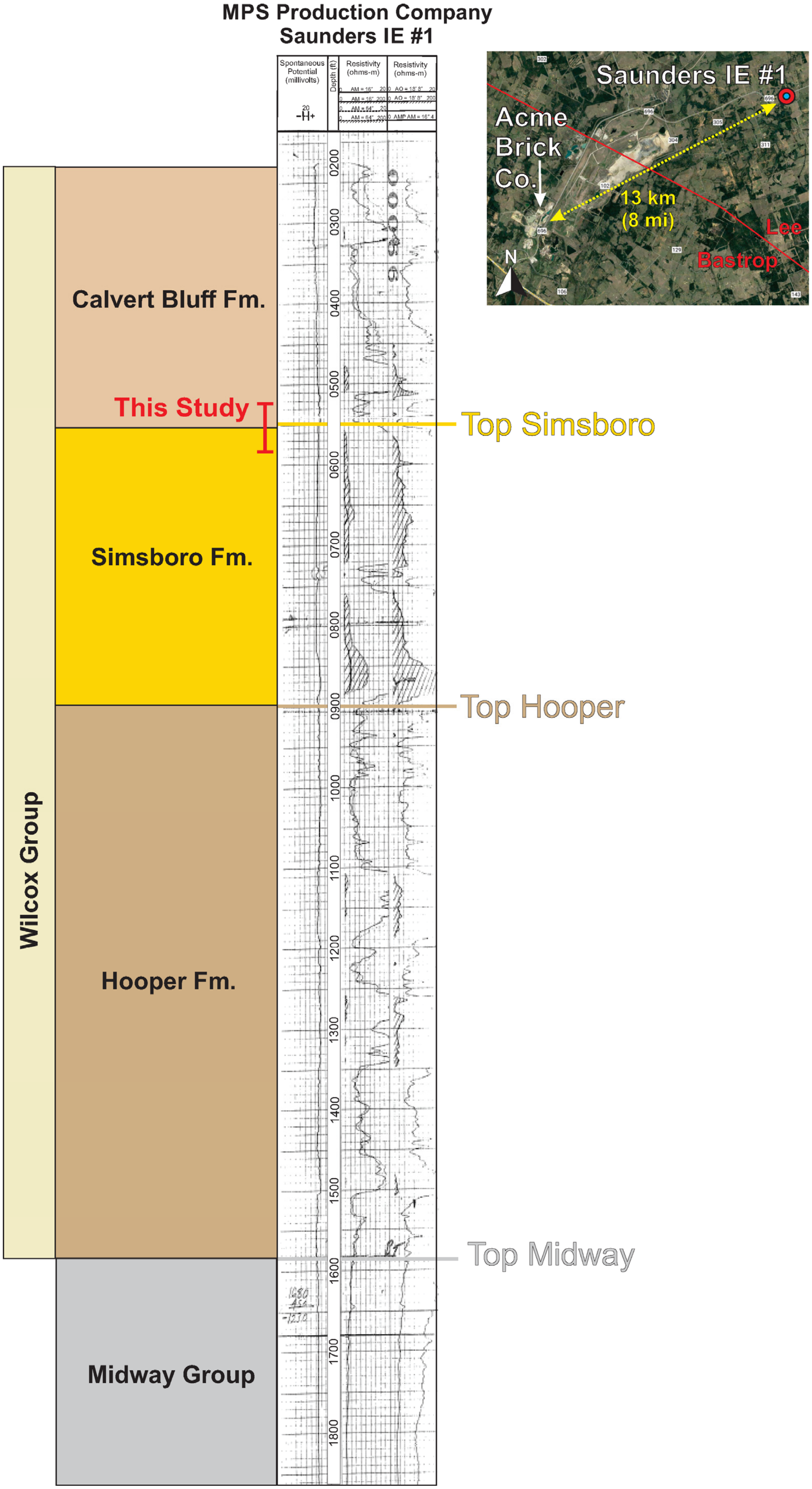

Figure 9. Wireline log for the MPS Production Company Saunders IE #1 well in Lee County located 13.0 km [8.0 mi] northeast of the Acme Brick Company. Log includes resistivity and spontaneous-potential logs. Intervals for the Midway, Hooper, Simsboro, and Calvert Bluff are identified based on wireline log signature.

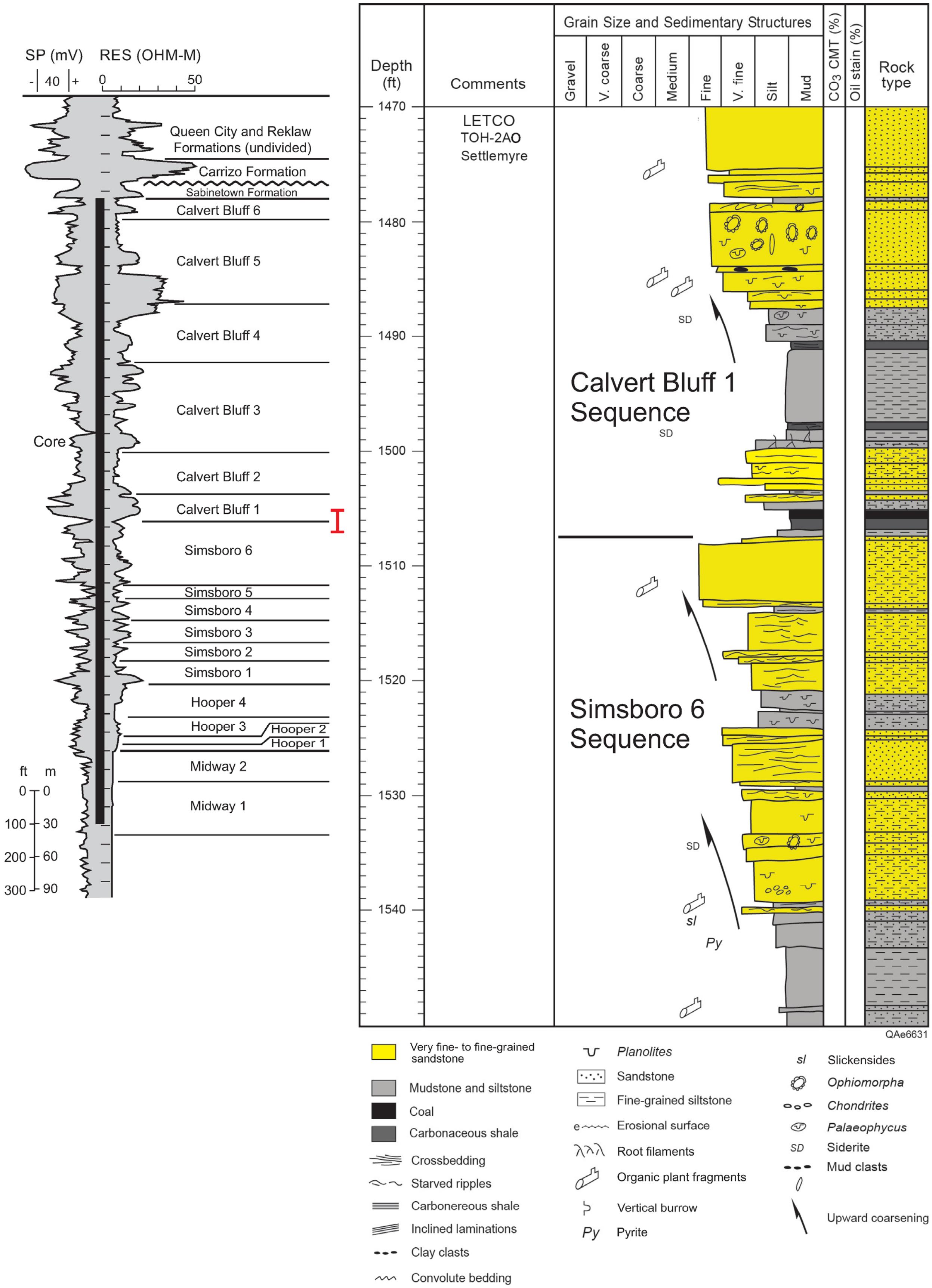

Figure 10. Wireline log (from Ambrose et al., 2020), including both gamma-ray and resistivity logs for the Letco TOH–2A well in Leon County (see Figure 11 for well location), including the divisions of the Midway, Hooper, Calvert Bluff, Sabinetown, Carrizo, and Queen City/Reklaw. Red line marks the location of the core description across the Simsboro 6 sequence and Calvert Bluff 1 sequence transition from core in the Letco TOH–2AO well adjacent to the Letco TOH–2A well. Interval is partially equivalent to the Simsboro and Calvert Bluff stratigraphy seen in the Acme Brick Company pits.

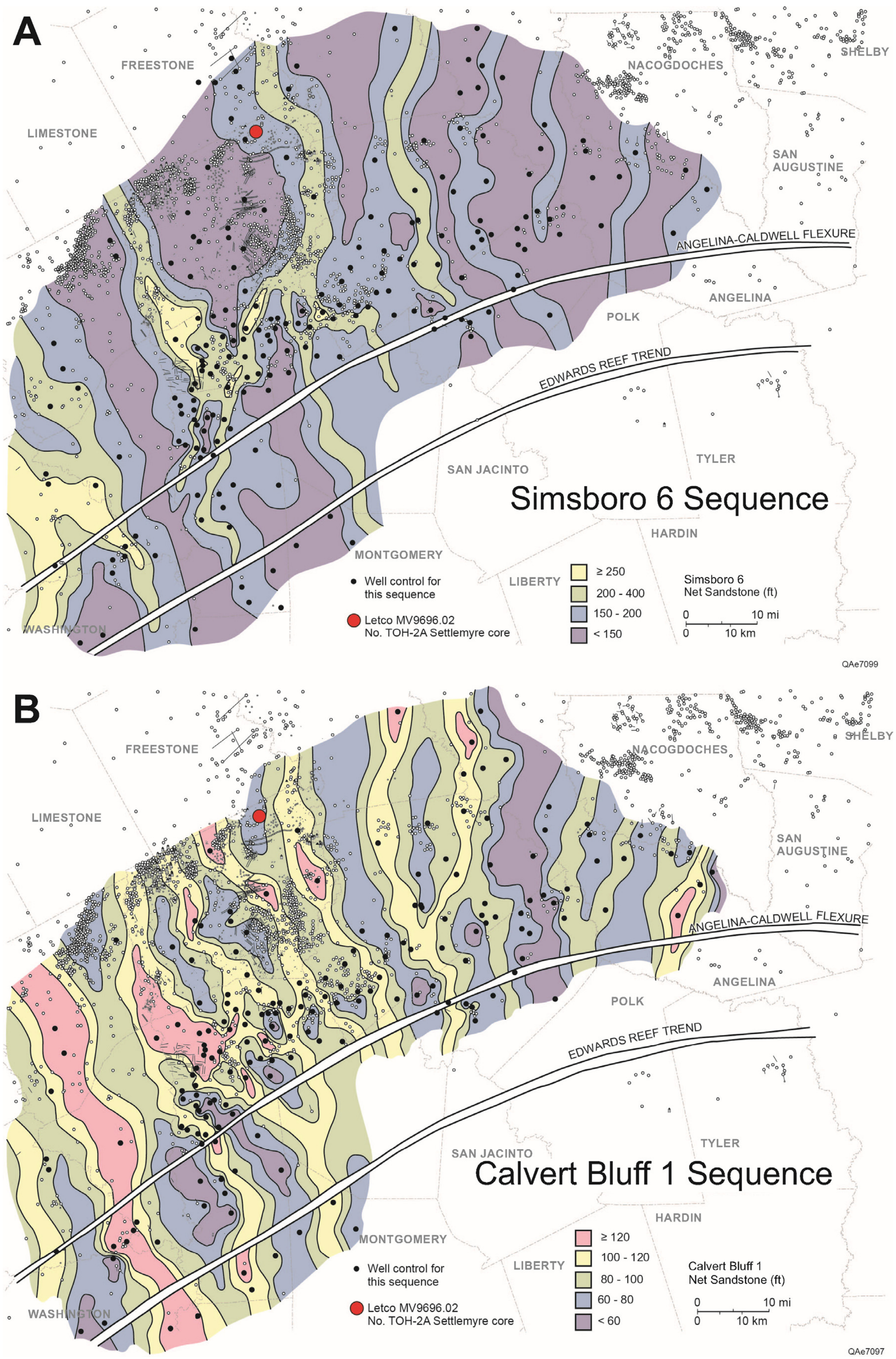

Figure 11. Net-sandstone maps of (A) the Simsboro 6 sequence and (B) the Calvert Bluff 1 sequence in the Limestone to Washington County region (from Ambrose et al. [2020]) located approximately 75 km [47 mi] northeast of the Acme Brick quarry. See Figure 1 for location of subsurface study and Figure 10 for placement of sequences within the overall Wilcox Group stratigraphy.

heterolithic deposits are best seen in extensive exposures such as these and could not possibly be recorded in such detail from even closely spaced core or wireline logs. Acme Brick Company outcrops are especially significant because they offer a fleeting glimpse into the lithofacies and stratal architectures of the Simsboro and Calvert Bluff aquifer system and as oil and gas reservoirs. Exposures like these are also ideal to record and curate high-resolution photomosaics and build quantitative 3D models and orthomosaics from drone photogrammetry. Digital preservation of these continually changing and temporary key outcrops is imperative (c.f. Burnham et al., 2022).

Quarrying activities created 4 stacked benches in the ELSTAN pit that exposed approximately 9 m [30 ft] of Simsboro stratigraphy (Fig. 3 and Appendix). Facies and architectural analyses revealed that Simsboro depositional environments include sand-rich fluvial-tidal meandering channel thalweg, channel bar, point bar, and levee deposits along with silt-rich point bar and abandoned-channel deposits. Paleoflow was, on average, to the southwest during deposition of the uppermost Simsboro (Fig. 3). Accommodation during upper Simsboro deposition appears to have been low because active channels commonly reoccupied previous channel locations, as evidenced by frequent scouring and erosion of underlying channel deposits by overlying channels. Floodplain deposits are not preserved, which is common in low accommodation settings (Heller et al. 1988; Dalrymple et al., 1998). A rare, low-diversity, low-abundance trace fossil assemblage in the Simsboro indicates a distal delta-plain or distal coastal-plain depositional setting with some influx of marine-brackish waters into channels. Nearly ubiquitous mud-draped sedimentary structures, along with double mud-drapes and mud-clast breccias (mud clast lags) suggest that these channels, although fluvial-distributive, repeatedly experienced tidal effects that flocculated mud out of suspension and deposited that mud in channels. Hence, these channels are best described as fluvial-tidal channels.

A proposed ancient analog for the Simsboro is the basal part of the Neslen Formation (Fig. 12). Channels of the lowermost Neslen like to those of the Simsboro have been described from laterally extensive outcrop belts near Floy Canyon, Utah (Olariu et al., 2015) and in East Canyon, Utah (Murphy, 2017). Basal Neslen multistory channels, interpreted as meandering fluvial-tidal channels, are preserved in tens of meters (tens to hundreds of feet) high cliffs and contain abundant inclined heterolithic stratification, common scouring, trough cross-stratified and current ripple cross-laminated sandstone with rare paleocurrent bi-directionality, mud-draped sedimentary structures, and trace fossils indicative of some marine-brackishwater influence. Simsboro channels do contain "mud plugs" which differentiate them from some of these Neslen channel deposits, suggesting that Simsboro channels may have transported more mud in suspension. Individual Neslen channel deposits are also thicker (5–8 m [16–26 ft] thick) that those of the Simsboro (2–3 m [6–10] thick).

Although the Simsboro and Calvert Bluff contact is not currently exposed in the quarry, it is located within a covered interval between the ELSTAN and TAN pits. Excavation at the TAN pit 1.2 km (0.75 mi) to the east of the ELSTAN pit exposed 4 stacked benches that comprise approximately 7 m [23 ft] of Calvert Bluff stratigraphy (Fig. 3; Appendix). The Calvert Bluff also consists of sand-rich channel deposits, albeit with fewer incisional reoccupation surfaces and cut-fill structures than those in the Simsboro. Lateral-accretion surfaces (point bar deposits) are a prominent component of Calvert Bluff sandbodies (Fig. 8E). In contrast to the Simsboro, Calvert Bluff channel abandonment deposits are darker-colored and highly organic, with abundant plant macrofossils, and are interbedded with paleosols containing peds, rhizoliths, mottles, and in-situ tree stumps. Paleosols appear gleyed and are likely immature (entisols and inceptisols), suggesting weak soil development and a high water table (Flaig et al., 2013). Characteristics of Calvert Bluff channel abandonment deposits indicate high-angle abandonment, and probably record deposits of oxbow lakes. Accommodation appears greater during Calvert Bluff deposition based on the preservation of floodplain sediments and organics, the isolation of channels from one another, and less frequent internal scouring (Heller et al. 1988; Dalrymple et al., 1998). Paleoflow shows a trend more toward the east-southeast during deposition of the lowermost Calvert Bluff (Fig. 3). No marine trace fossils were observed in the Calvert Bluff.

A proposed ancient analog for the Calvert Bluff is the Prince Creek Formation (Flaig et al., 2011, 2013; van der Kolk et al., 2015) described from outcrops in the Colville Basin on the North Slope of Alaska (Fig. 12). The Prince Creek deposits are similar to those of the Calvert Bluff because of evidence for channel-fill, lateral-accretion surfaces (point bars) and organic-rich, high-angle, abandonment deposits (oxbow lakes) of meandering channels, levees, small lakes, coal (swamps), and paleosols (Fig. 12). Weakly-developed and gleyed paleosols evidenced by mottling and rhizoliths, trees, stumps, abundant plant macrofossils, and organic-rich floodplains are common. Prince Creek deposits are those of distributary channels and associated floodplains typically found in a more updip position relative to the coastline compared to those of the basal Neslen or Simsboro. First-order trunk channel deposits of the Prince Creek Formation are considerably thicker (13–17 m [43–56 ft] thick) than those of the Calvert Bluff at the Acme Brick Company quarry (2–4 m [6–13 ft] thick). Second-order meandering distributary channels (2–6 m [6–20 ft] thick) of the Prince Creek are more analogous to Calvert Bluff channels.

Palynological analysis is critical to place the stratigraphy within a regional biostratigraphic and depositional-systems framework. Pollen assemblages (Fig. 7) indicate that deposits fall within the upper Paleocene ("middle" Thanetian) P5 biozone of Nichols and Ott (1978) and are consistent with deposition in a coastal-plain to delta-plain environment.

Although the height/thickness of each outcrop exposure is limited, these laterally extensive windows provide a unique, high-resolution, comparative glimpse into the substantially different internal characteristics of the uppermost Simsboro and lowermost Calvert Bluff. Connectivity between sandbodies in the Simsboro is high due to scouring. Scours occur in cut-and-fill structures, at the base of barforms, and at the base of channels, increasing overall connectivity and providing overall good aquifer/reservoir properties. Barriers and baffles to flow in the Simsboro include mud-drapes on sedimentary structures, silt drapes on point bars, and abandoned silt-filled channels. Some of these barriers and baffles are breached through scouring. Even along this 400 m [1330 ft] window, exposures have highly variable lithologies and stratal architecture (Figs. 5 and 6; Appendix). Aquifer draw-down studies and hydrocarbon exploration and production should incorporate this variability as part of resource management strategies.

The Calvert Bluff likely functions as an aquitard because of the increased amount of floodplain fines, organic-rich intervals, paleosols, and lignite that are preserved. Deposits are also highly variable lithologically along the 288 m [950 ft] outcrop belt. Scouring within and between channels in the TAN outcrop belt is generally absent, and there are no tidally controlled mud-drapes. Under the right conditions isolated channels of the Calvert Bluff encased within floodplain fines can be aquifers or reservoirs.

Evidence from the Acme Brick pits shows that the change from the Simsboro to the Calvert Bluff is from tidally influenced distal distributary channels to more updip fluvial systems and organic-rich floodplains. This indicates that the system was overall progradational, which is consistent with interpretations by Ambrose et al. (2020) of a regressive cycle at the Simsboro/Calvert Bluff transition. Net sand maps of the Simsboro 6 and Calvert Bluff 1 sequence reveal larger-scale, elongate, northwest

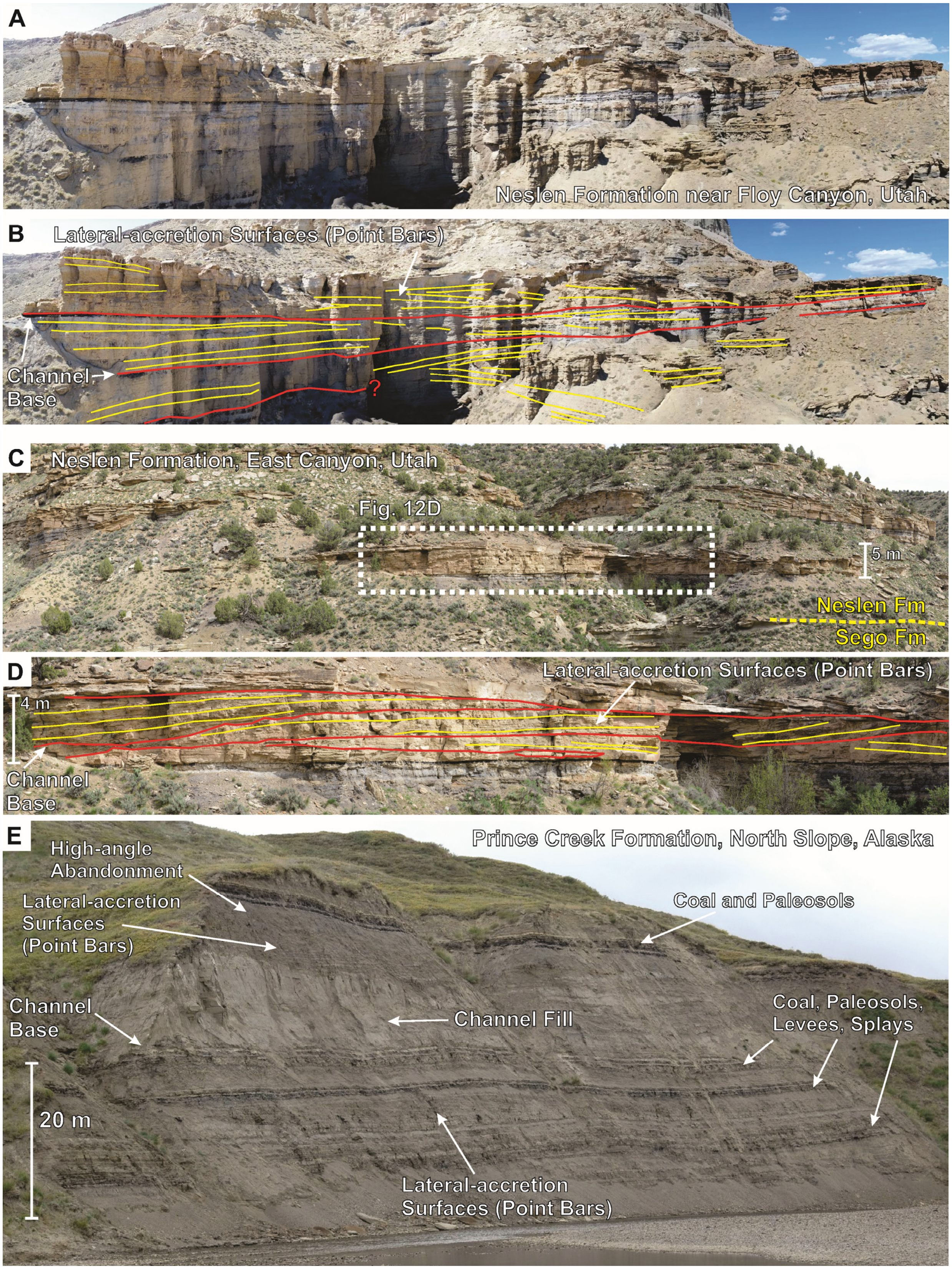

Figure 12. Outcrop images of possible analogs for the Simsboro and Calvert Bluff, including (A) uninterpreted drone panorama of channel deposits of the Neslen Formation (Upper Campanian) near Floy, Utah, (B) interpreted Neslen drone panorama proposed as an analog for the Simsboro deposits in the Acme Brick Company quarry, (C) outcrop image of the Sego-Neslen formation contact in outcrops in East Canyon, Book Cliffs, Utah, including the location of the interpreted outcrop image in part D, (D) interpreted Neslen GigaPan image of Neslen Channel systems proposed as an analog for the Simsboro deposits in the Acme Brick Company quarry, and (E) outcrop image of the Prince Creek Formation (Maastrichtian) including channel deposits, lateral-accretion surfaces, coal, and paleosols proposed as an analog for the Calvert Bluff deposits in the Acme Brick Company quarry. 1 m = 3.28 ft.

to southeast trending sand-rich fairways interspersed within less sand-rich intervals. Both sequences show thick sandstone fairways that can act as reservoirs or aquifers. This study provides additional detail on the internal characteristics of those reservoirs and encasing sediments and could provide predictability for frontier areas with poor well control, core data, and/or outcrop control.

CONCLUSIONS

Deposits of the uppermost Simsboro and lowermost Calvert Bluff formations of the Wilcox Group are exposed along outcrops in pits at the Acme Brick Company quarry, Butler, Texas. These outcrops are temporary, and it is critical to document their features and preserve them digitally. This study provides a highly-detailed framework for characterization of similar deposits in frontier areas with poor well control.

Simsboro deposits are those of meandering channel thalwegs, channel bars, point bars and silt-rich abandoned-channels. Abundant mud-drapes, mud clast breccias and a low-diversity and low-abundance marine trace fossil assemblage suggest that these channels experienced tidal effects and some marine influence. Simsboro channels are interpreted as fluvial-tidal channels. Abundant erosional surfaces, complex cut-and-fill structures and incision, and the lack of preserved floodplain indicates a low accommodation setting. Paleoflow was to the southwest during Simsboro deposition.

Calvert Bluff sand-rich channel deposits are isolated within floodplain deposits, have fewer erosion surfaces and cut-fill structures, and contain no marine trace fossils. Lateral-accretion surfaces are prominent, indicating meandering channels. Channel abandonment deposits are darker-colored, highly organic with abundant plant macrofossils, and are interbedded with paleosols containing rhizoliths and mottles. These deposits indicate high-angle abandonment and probably represent oxbow lakes. Paleosols are gleyed and likely immature (entisols and inceptisols) with some containing in-situ tree stumps. Accommodation and the water table were likely higher during Calvert Bluff deposition. Paleoflow shows a trend more toward the east-southeast.

Pollen assemblages indicate a "middle" Thanetian age. Assemblage composition is consistent with a coastal to delta-plain paleoenvironment dominated by fluvial channels and riparian to floodplain-wetland deposition with limited marine influence.

Outcrops are correlated into the subsurface using the wireline logs of the MPS Production Company Saunder IE #1 well located 13 km (8.0 mi) northeast of Acme Brick. Recent regional subsurface work to the northeast of the study area divided the Simsboro into 6 sequences and the Calvert Bluff into 6 sequences. Outcrops at Acme Brick are equivalent to deposits of the Simsboro 6 and Calvert Bluff 1 sequences. Net-sandstone maps of both the Simsboro 6 and Calvert Bluff 1 sequences reveal the larger-scale geometries of sand-rich fairways of fluvial systems such as those preserved in outcrops of the Acme Brick quarry. Simsboro 6 sequence sandbodies reflect an overall distributive pattern common to distal, coastal fluvial-distributive systems. Calvert Bluff 1 sequence sandbodies exhibit more tributary patterns common to more proximal fluvial-alluvial systems. The transition from the Simsboro to Calvert Bluff in the Acme Brick quarry records progradation, consistent with interpretations from subsurface datasets. The characteristics of both of these depositional systems should be taken into consideration when modelling petroleum reservoirs or aquifers.

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APPENDIX

GigaPan Capture, Curation, and Accessibility

Images for the development of high-resolution photomosaics were recorded using a Nikon D 810 SLR camera, 200–400 mm ED Nikkor lens (at 400 mm), and GigaPan Epic Pro robotic panhead mounted on a surveyor's tripod. Photomosaics were assembled in GigaPan Stitch EFX software, uploaded to the GigaPan website (http://gigapan.com/) where they are publicly available. The GigaPan website is privately owned, so we cannot guarantee the longevity of these links. No special viewing software is needed to access these GigaPans. Links to three GigaPans from the study area (ELSTAN and TAN pits) are given below.

Acme Brick Company: ELSTAN pit (Simsboro Formation) Outcrop Image #1

Link: http://gigapan.com/gigapans/840fdfbf8f5de52a3eca616393314283
Input images: 104 (26 columns by 4 rows)
Field of view: 145.8 degrees by 13.4 degrees high
Focal length (35 mm equiv.): 400.0 mm
Aperture: f/29
Exposure time: 0.0125 sec
ISO: 400

Acme Brick Company: ELSTAN pit (Simsboro Formation) Outcrop Image #2

Link: http://gigapan.com/gigapans/fa0ed830e50b23d74d58a477994300cd
Input images: 135 (27 columns by 5 rows)
Field of view: 142.5 degrees wide by 17.2 degrees high
Focal length (35 mm equiv.): 400.0 mm
Aperture: f/29
Exposure time: 0.0125 sec
ISO: 400

Acme Brick Company: TAN pit (Calvert Bluff Formation) Outcrop Image #3

Link: http://gigapan.com/gigapans/227174
Input images: 130 (26 columns by 5 rows)
Field of view: 152.0 degrees wide by 17.1 degrees high
Focal length (35 mm equiv.): 400.0 mm
Aperture: f/29
Exposure time: 0.0125 sec
ISO: 400

3D Model from Drone Photogrammetry Capture, Curation, and Accessibility

Drone photogrammetry was recorded using a DJI Mavic 2 Pro Quadcopter. Drone images were aligned and developed into 3D point clouds, 3D models, and orthomosaics using a combination of Agisoft Metashape and Meshlab software. Links to 3D models archived on the V3Geo website. The V3Geo site purpose is for sharing virtual 3D models. Models are georeferenced and searchable using geological metadata. All public models are available under Creative Commons licenses and can be used in classrooms, publications, research, or as the basis of virtual field courses and excursions.

Links

ELSTAN pit (Simsboro Formation)
https://v3geo.com/model/460

TAN pit (Calvert Bluff Formation)
https://v3geo.com/model/407

Additional References

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Digital Plates (High-Resolution Orthomosaics)

Digital Plate 1. Orthomosaic developed from drone photogrammetry of the ELSTAN outcrop belt. Figure includes the locations of interpreted figures provided in the manuscript text and the location of palynology sample ELSTAN#1.

Digital Plate 2. Orthomosaic developed from drone photogrammetry of the TAN outcrop belt. Figure includes the locations of interpreted figures provided in the manuscript text and the location of palynology sample TAN#1.

Acme Brick Company ELSTAN Outcrop Belt

Acme Brick Company TAN Outcrop Belt