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Transition from Paleosols in the Cenomanian Woodbine Group to Carbonates in the Coniacian Lower Austin Chalk in East Texas Field: An Example of a Compressed Transgressive Succession from Subaerial Processes to Deepwater Deposition

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ABSTRACT

Cores in East Texas Field and adjacent areas in the East Texas Basin illustrate significant lithologic and facies variability above and below a regional, angular unconformity at the base of the Austin Chalk. Paleosols in the Woodbine Group below the unconformity record long-lived periods (at least 6 million years [Myr]) of subaerial exposure of delta-plain environments. The Woodbine sedimentary fabric below the unconformity is significantly modified by insect burrows and root traces, as well as by diagenetic clays. These paleosols throughout East Texas Field and adjacent areas suggest that subaerial environments in the Woodbine Group were more regionally extensive and persistent through time than previously documented.

Regional inundation and marine reworking of the Woodbine Group is represented by a basal (1 to 3 ft [0.3 to 0.9 m]) section of upward-fining, mixed clastics and carbonates with rip-up clasts, shell debris, and marine trace fossils. This basal section is overlain by deeper water (shelf), low-permeability chalk deposits that form a regional seal over the Woodbine succession. Over a span of less than 3 ft (<0.9 m) of preserved stratigraphy, Lower Austin Chalk strata display a change from a subaerial exposed system to one containing marine sediments deposited at 300 ft (91.5 m) depths or deeper. When relative sea level started to rise over the exposed Woodbine floodplain, the initial depositional environment was a shallow-marine system, with remnants of shallower water fauna (oysters and echinoderms), detrital chert and phosphate, and abundant reworked silt and sand from the Woodbine Group. However, original shallow-water sediments were subsequently reworked into deeper water (shelf) sediments. As transgression continued, Austin Chalk marine depositional environments became deeper and biota became exclusively deepwater in origin, with coccolithophore fragments, planktic foraminifers, and inoceramid clams. This stratigraphic section is an excellent example of deeper water sediments deposited over a subaerial exposure surface during a regionally extensive sea-level rise coupled with decreased accommodation during progressive rise of the tectonically active Sabine Uplift. This resulted in little evidence of intervening shallower water depositional processes.

Results from this study have implications for future exploration and development for oil and gas in the Woodbine Group in the East Texas Basin. Woodbine sandstones of shallow-marine origin may exist between the Woodbine paleosol succession and the base-of-Austin-Chalk unconformity where greater accommodation may have occurred in areas away from the Sabine Uplift. In addition, complex sedimentary fabrics and fine-grained, silty mudstones and clays in Woodbine paleosols may contribute locally to the main seal (base-of-Austin Chalk unconformity) in East Texas Field and adjacent areas in the East Texas Basin.

INTRODUCTION

Cores in East Texas Field (Figs. 1 and 2) and adjacent areas illustrate significant lithologic and facies variability above and below a regional, angular unconformity at the base of the Austin Chalk (Fig. 3). The Eagle Ford Formation, which overlies the Woodbine Group, is entirely missing in East Texas Field because it has been eroded by the base-of-Austin Chalk unconformity (Ambrose et al., 2009). The transition from siliciclastics into the Lower Austin Chalk carbonates that is marked by a well-

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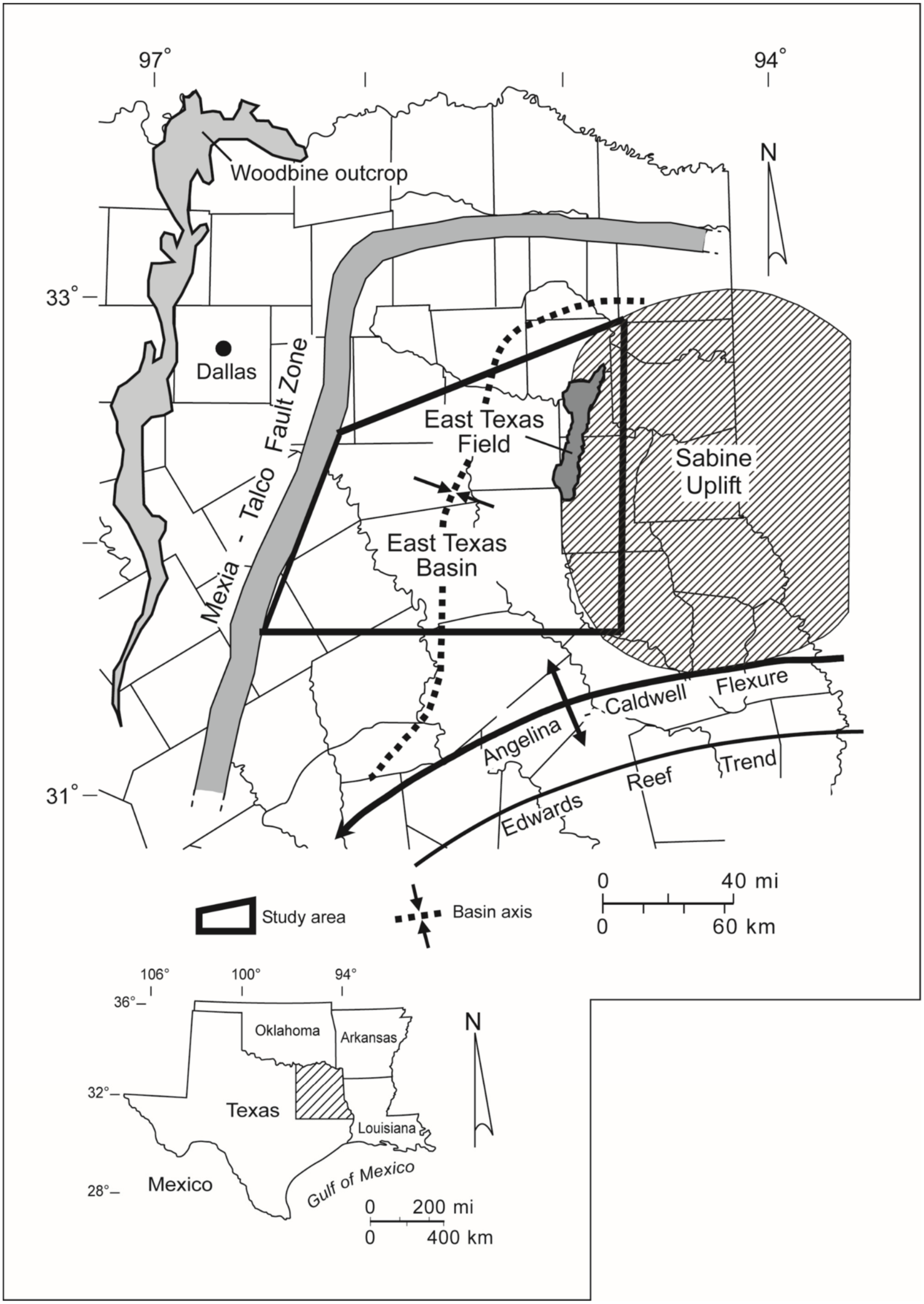


Figure 1. Geologic setting of the East Texas Field (modified after Ambrose et al., 2009).

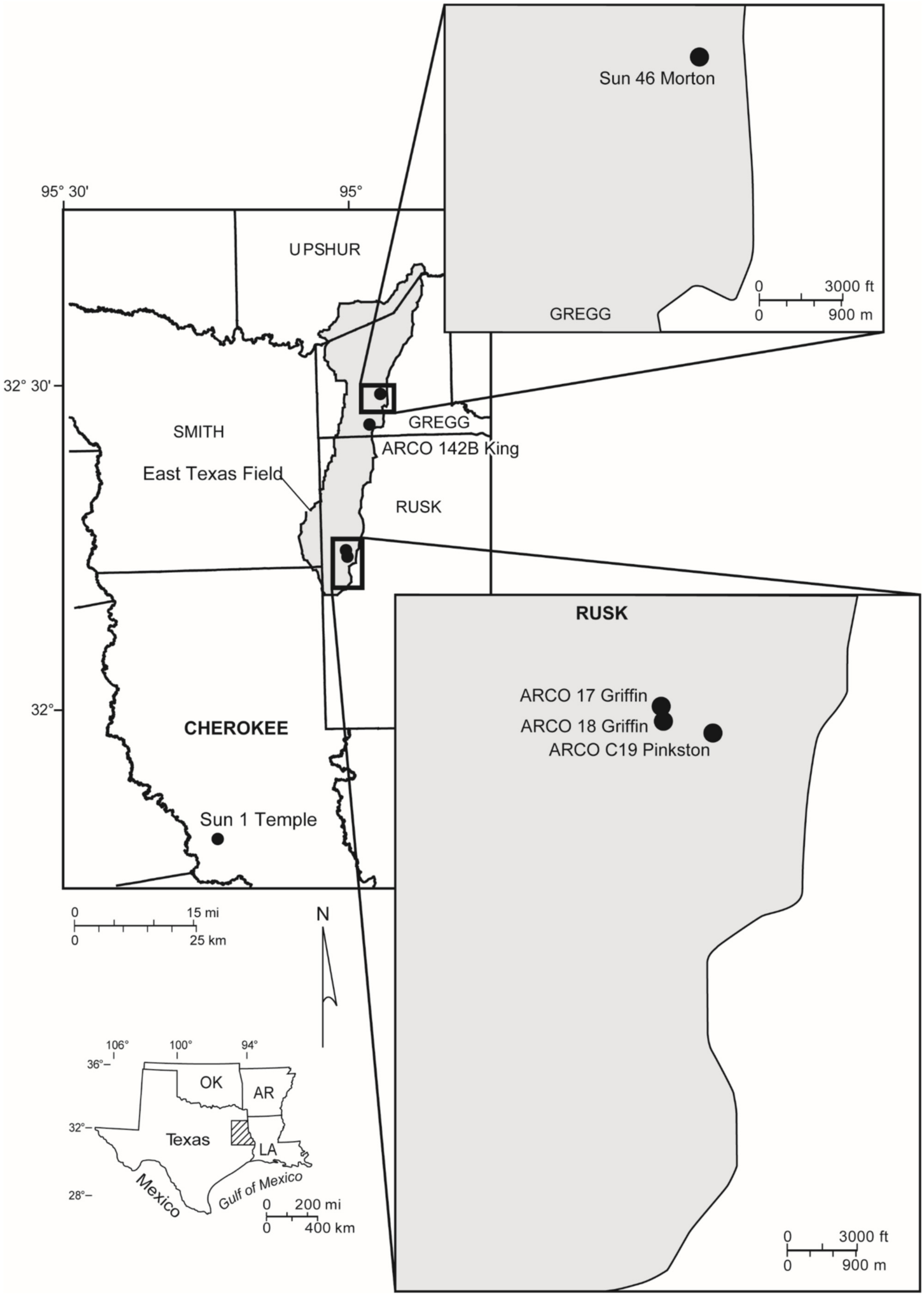


Figure 2. Location of the East Texas Field and six cores presented in this study, indicated by black dots (modified after Ambrose and Hentz, 2010).

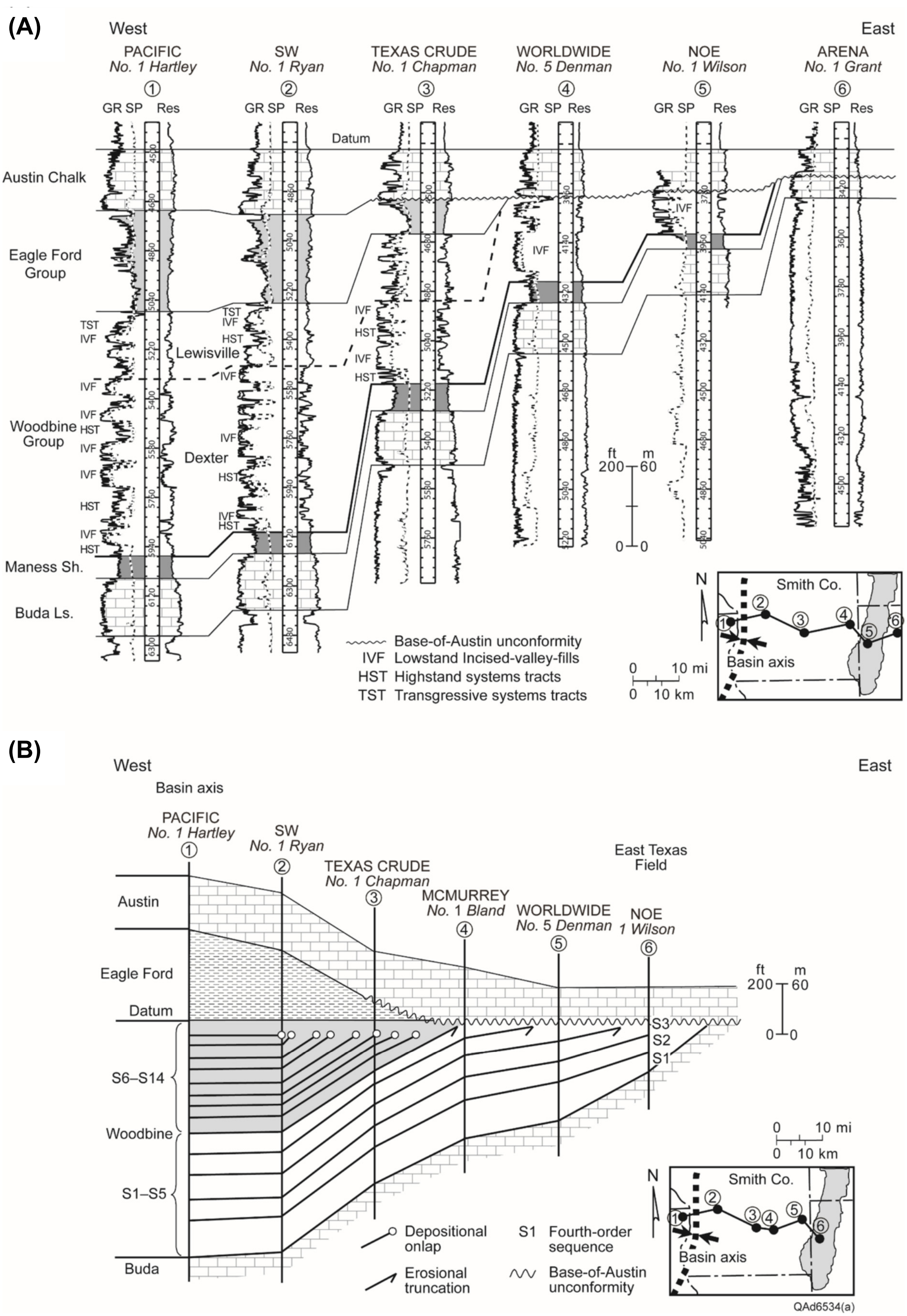


Figure 3. (A) Stratigraphic cross section displaying sequences in the Woodbine Group from the axis of the East Texas Basin to the southern part of the East Texas Field. Datum is the top of the Austin Chalk. (B) Same stratigraphic cross section displaying eastward pinchout and truncation of sub-Austin-Chalk stratigraphic units eastward toward East Texas Field. Modified after Ambrose and Hentz (2010).

developed paleosol in the Woodbine Group overlain by a transgressive lag, in turn overlain by deeper water carbonates (chalk). Paleosols in the Woodbine Group below the unconformity record sustained periods of subaerial exposure of delta-plain sediments. Regional inundation and marine-reworking of the upper Woodbine Group is represented by a basal (1 to 3 ft [0.3 to 0.9 m]) section of upward-fining, mixed clastics and carbonates with abundant rip-up clasts, shell debris, marine trace fossils, and a coccolith-dominated matrix (Fig. 4). Grains too large to be transported far by shallow-marine processes (rather than deepwater debris-flow processes), such as oyster shells and lithoclasts, form a dispersed transgressive lag above the unconformity. This basal section is overlain abruptly by deeper water, low-permeability (less than 0.01 millidarcys [md]) chalk deposits that form a major, regional seal over the upper Woodbine succession in the northwestern Gulf Coast.

OBJECTIVE AND DATA

The main objective of this investigation is to describe the upper Woodbine through Lower Austin Chalk stratigraphic section and discuss major depositional and diagenetic processes within a section that displays an abrupt change from exposed paleosols to open-shelf carbonate deposits over a thin (commonly <3 ft [<0.9 m]) interval. Specific tasks are to: (1) describe the regional geologic setting from the upper 20 to 50 ft (6 to 15 m) of the Woodbine sandstones to the lower 10 to 40 ft (3 to 12 m) of section of the Austin Chalk, (2) define dominant lithofacies from

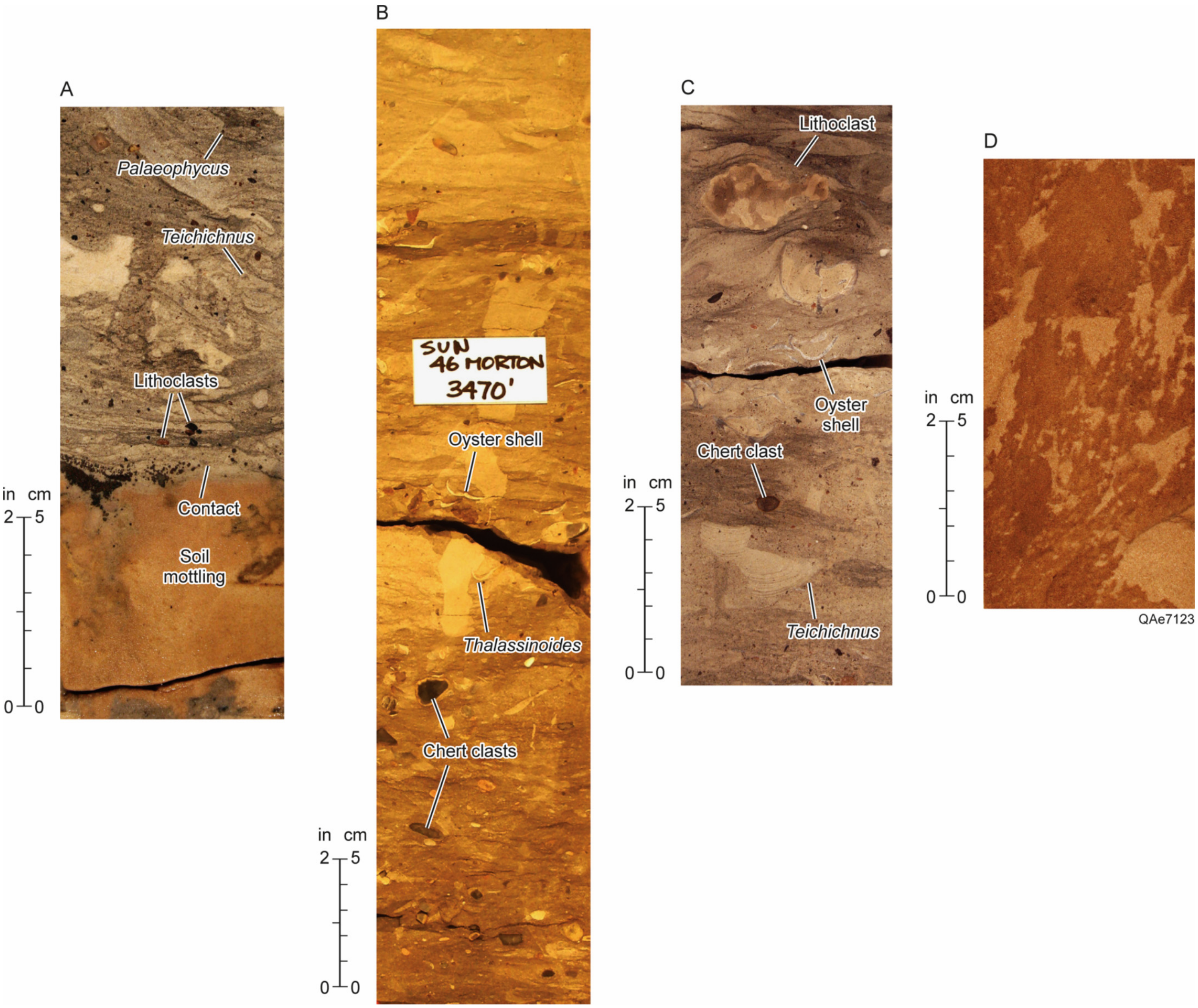


Figure 4. Photographs of the basal part of the Austin Chalk and upper Woodbine Group in the East Texas Field. (A) Contact between the Austin Chalk and Woodbine Group in the ARCO No. 18 Griffin core at 3573.6 ft (1089.5 m), showing soil mottling in the Woodbine Group. (B) The lower 1.2 ft (0.4 m) of the Austin Chalk in the Sun No. 46 Morton core at 3470 ft (1057.9 m), showing lithoclasts, oyster shell debris, and *Thalassinoides* burrow. (C) The lower part of the Austin Chalk in the ARCO No. 18 Griffin core at 3572.8 ft (1089.3 m), with a variety of lithoclasts, oyster shell debris, and *Teichichnus* burrow. (D) Fine-grained sandstone in the Woodbine Group in the ARCO No. 17 Griffin core at 3603.8 ft (1098.7 m), with angular and subangular mottling fabric. Descriptions of the ARCO No. 17 Griffin, ARCO No. 18 Griffin, and Sun No. 46 Morton cores are shown in Figures 5, 7, and 9, respectively.

whole-core data, (3) discuss variable depositional processes that affected this rapid transgression, and (4) explain the importance of understanding this type of transition. Insights about the results of rapid transgression from subaerial exposure into deeper water deposition can be obtained from investigating a series of whole cores in the transition from the Woodbine Group to the Austin Chalk.

This study is a portion of a larger investigation of the Woodbine Group and Austin Chalk based on description and interpretation of ~1600 ft (~490 m) of core from 31 wells and ~500 wireline logs in East Texas Field and adjacent areas (Ambrose et al., 2009; Ambrose and Hentz, 2010). Six cores, the ARCO No. 17 Griffin, ARCO No. 18 Griffin, ARCO No. B142 King, ARCO No. C19 Pinkston, Sun No. 1 Temple, and Sun No. 46 Morton illustrate the base-of-Austin-Chalk unconformity and underlying paleosols in the Woodbine Group (Figs. 2, 4, 5-9) without the intervening Eagle Ford Formation. These cores were described in detail to provide a context for interpretations of facies, depositional systems, and diagenesis in the Austin Chalk and Woodbine Group. These cores also demonstrate the flooding above the unconformity by Austin Chalk sediments and the transition from initial transgression into deeper water chalk deposition.

Thin-section analysis and scanning-electron microscopy (SEM) were performed on samples in both the upper Woodbine and Lower Austin Chalk section. Thin sections were described to characterize sandstone at the millimeter scale. Scanning-electron microscopy was employed because features in rock types such as chalks can only be defined by viewing the deposits at the micron scale.

REGIONAL SETTING

East Texas Field, the largest oil field in the lower 48 states in terms of original oil in place (OOIP) (Fig. 1), has produced more than 5.4 billion stock tank barrels of oil (BSTB) since its discovery in 1930 (Minor and Hanna, 1933; Alexander, 1951; Hudnall, 1951; Ambrose et al., 2007). The primary trapping mechanism is stratigraphic, with oil and gas in the Woodbine Group trapped along a vertical permeability barrier at an angular unconformity at the base of the Austin Chalk (East Texas Engineering Association, 1953; Adair, 1960; Halbouty and Halbouty, 1982). Mottled and variegated zones in the Woodbine Group subjacent to the base-of-Austin-Chalk unconformity are common, interpreted in Ambrose et al. (2009) as paleosols (Fig. 4).

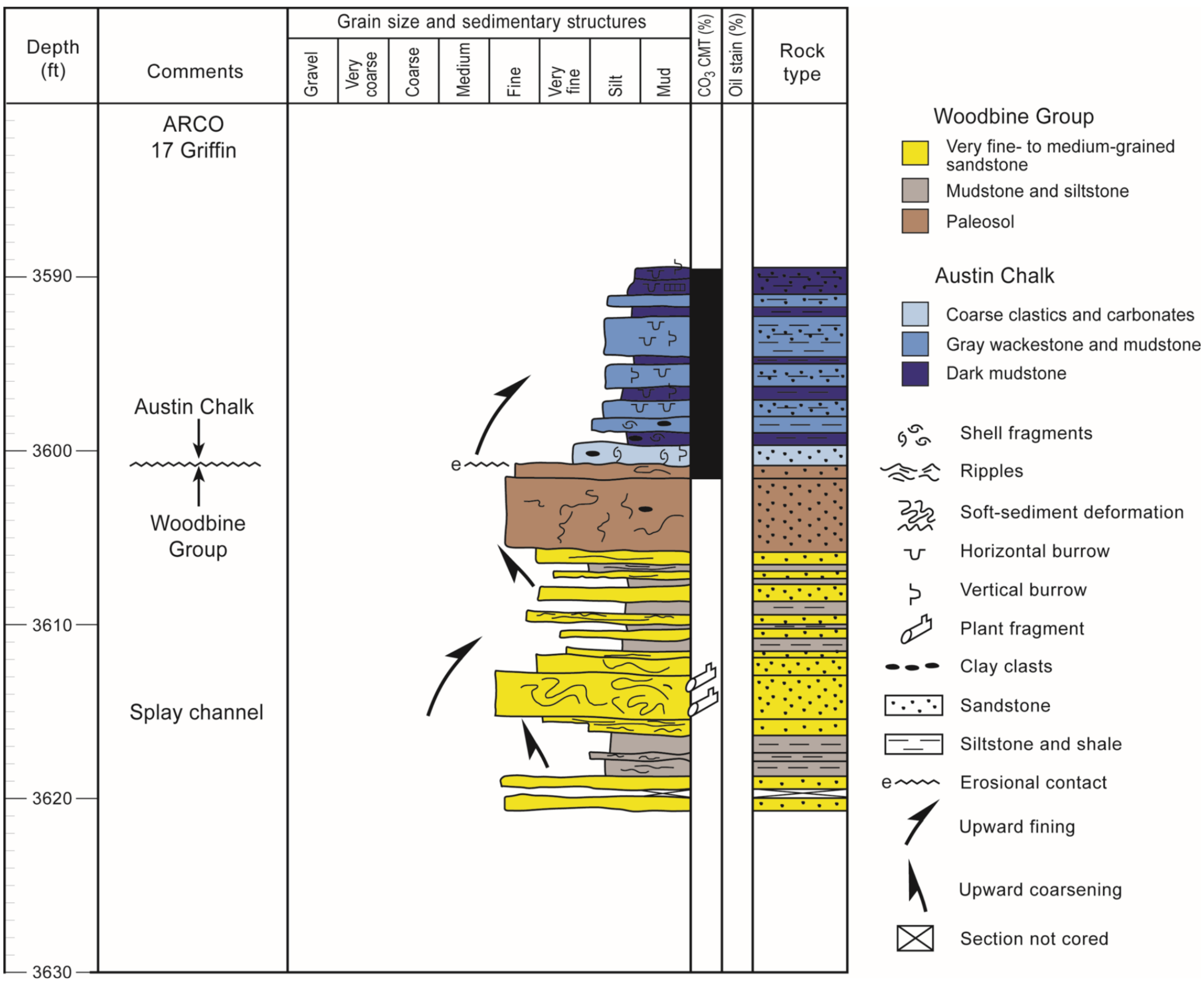


Figure 5. Description and interpretation of the ARCO No. 17 Griffin core in the southern part of the East Texas Field (modified after Ambrose and Hentz, 2010). Core location shown in Figure 2.

The base-of-Austin-Chalk unconformity is overlain by large (0.5 to 2.0 in [1.3 to 5.1 cm]) chert and mudstone rip-up clasts from the underlying Woodbine section, as well as abundant shell fragments, reflecting marine transgression over a subaerially exposed Woodbine surface (Fig. 6E).

Woodbine Group

The Woodbine Group in the East Texas Basin was deposited during an early Cenomanian regressive event following a relative sea-level fall after deposition of the Buda Limestone (Salvador

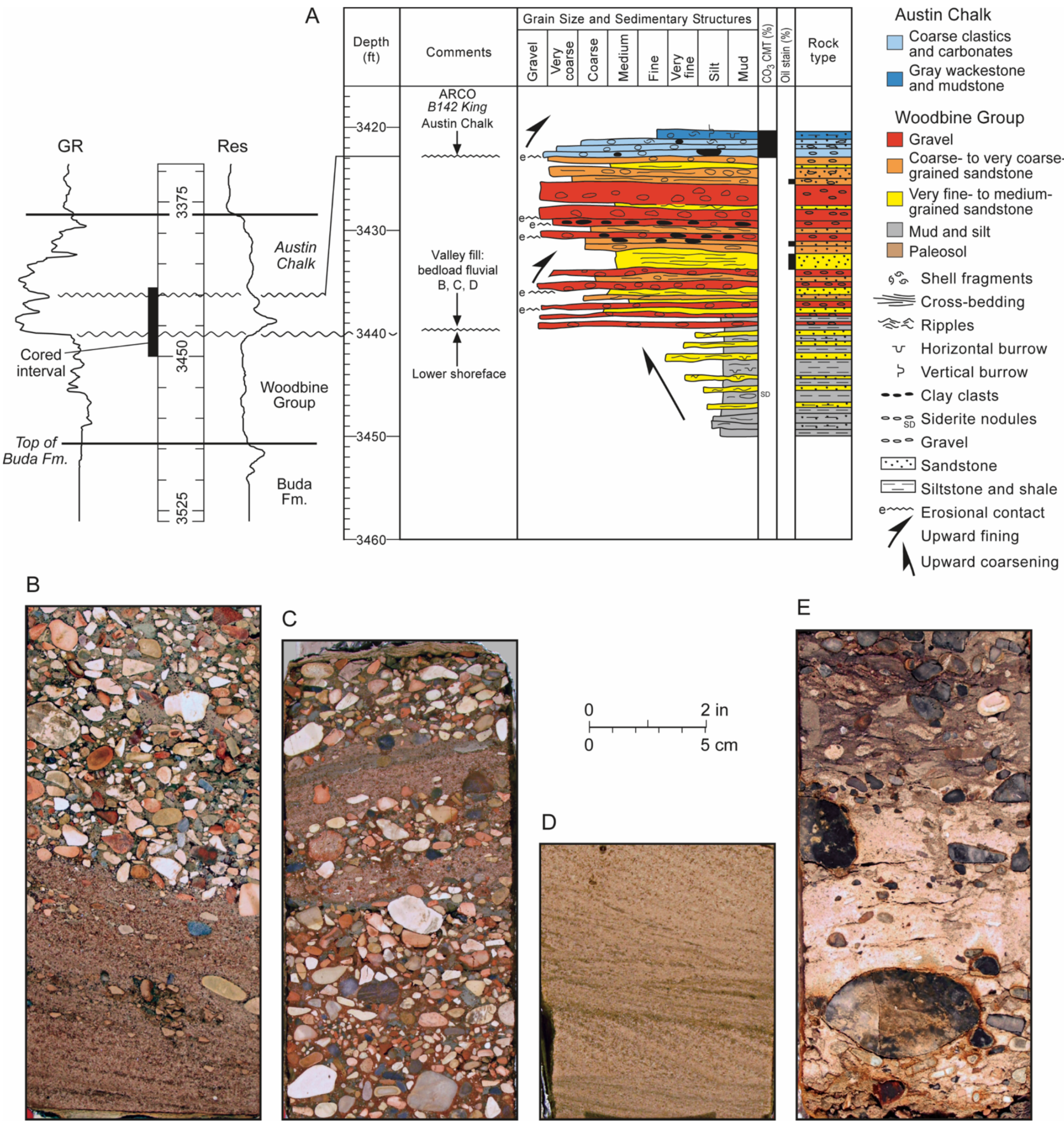


Figure 6. (A) Description and interpretation of the ARCO No. B142 King core in the East Texas Field. (B) Chert-gravel conglomerate in erosional contact with very coarse-grained sandstone with inclined planar stratification at 3437.4 ft (1047.9 m). (C) Chert-clast conglomerate, with alignment of some pebbles, interbedded with coarse-grained sandstone at 3438.6 ft (1048.4 m). (D) Cross-bedded, medium- to coarse-grained sandstone at 3437.0 ft (1047.8 m). Core location shown in Figure 2. Modified after Ambrose et al. (2009).

and Muñeton, 1989; Denne et al., 2016). The Woodbine Group is composed of a series of highstand deltaic wedges truncated by lowstand, valley-fill successions (Fig. 3A) (Ambrose et al., 2009). In East Texas Field, only the oldest of three fourth-order sequences (S1–S3) in the lower part of the Woodbine Group are preserved below the base-of-Austin Chalk unconformity (Fig. 3B) (Hentz and Bonnaffé, 2010).

Woodbine sediments were sourced from the north to northeast where they were eroded from the Mid-Continent area, Ouachita Mountains in southeastern Oklahoma, and a volcanic terrain in southcentral Arkansas (Stehli et al., 1972; Loucks et al., 2015). These valley-fill successions, having formed during periods of relative sea-level fall, are as much as 150 ft (45 m) thick in the East Texas Basin. Maximum flooding surfaces cap upward-fining successions (high-frequency transgressive systems tracts) as recognized by gamma-ray maxima on wireline logs above lowstand incised-valley-fill and highstand successions. As a result of the progressive rise of the Sabine Uplift on the eastern flank of East Texas Field, both the Woodbine Group and Eagle Ford Formation are progressively truncated by the base-of-Austin Chalk unconformity from west to east in the East Texas Basin (Fig. 3). The Sabine Uplift was periodically active during the Mesozoic and early Tertiary (Jackson and Laubach, 1991). Its present form is related to a Gulf-wide series of mid- to Late-Cretaceous disturbances and uplifts. Ewing (1991a, 1991b) and Halbouty and Halbouty (1982) described two episodes of uplift of the structure—just prior to Woodbine deposition and during late Woodbine and Eagle Ford sedimentation. As a result of movement along the Sabine Uplift, upper Woodbine strata become progressively thinner and pinch out eastward below the base-of-Austin Chalk unconformity (Fig. 3B).

Austin Chalk

Coniacian to lowermost Campanian Austin Chalk sediments were deposited during a global sea-level transgression and highstand (Vail et al., 1977). In Texas, the Austin Chalk was deposited on a south- and southeastward-dipping ramp in a flooded shelf

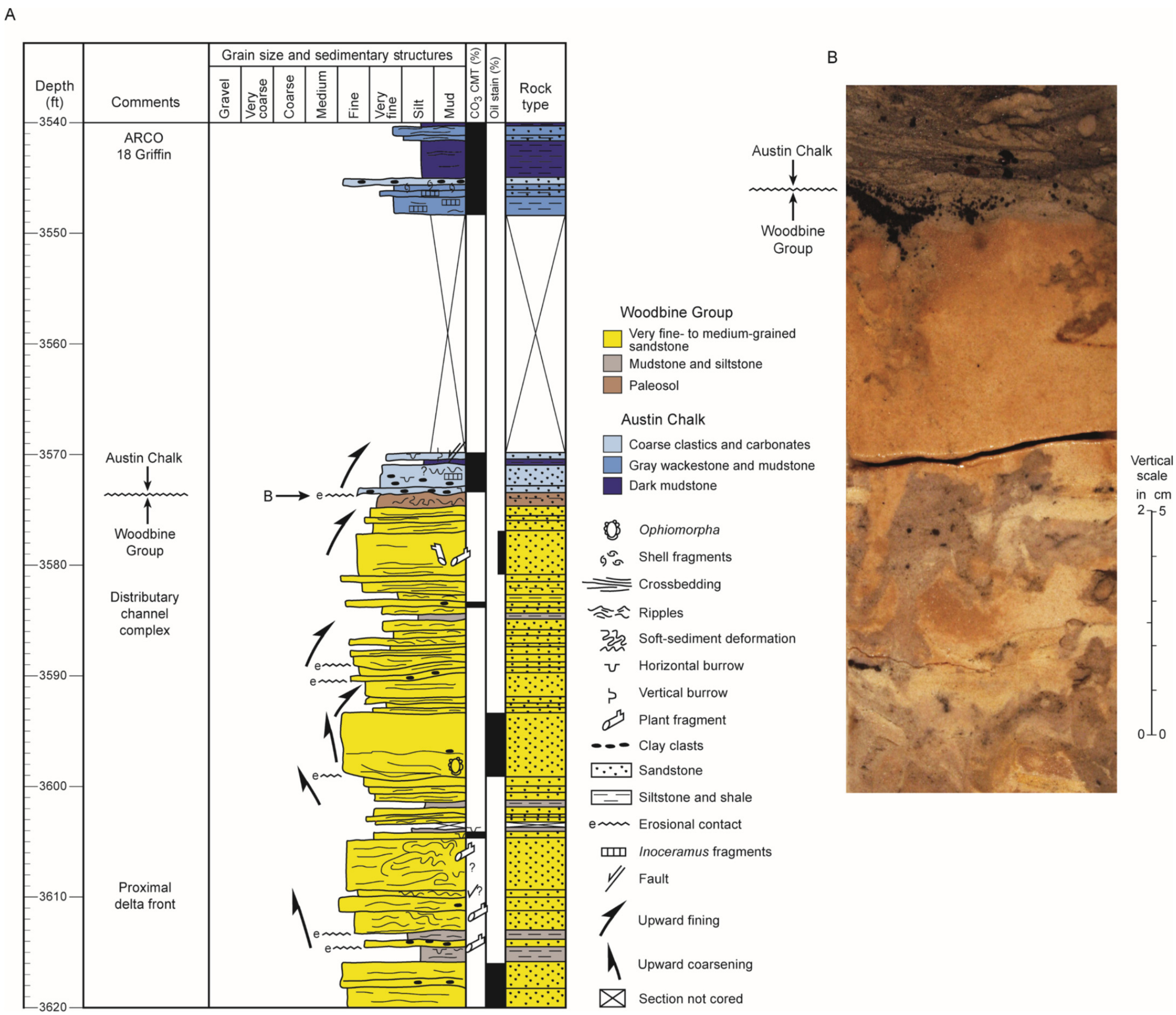


Figure 7. (A) Description and interpretation of the ARCO No. 18 Griffin core in the southern part of the East Texas Field. (B) Erosional contact between the Woodbine Group, exhibiting mottled texture, and the overlying Austin Chalk at 3574.5 ft (1089.8 m). Core location shown in Figure 2. Modified after Ambrose and Hentz (2010).

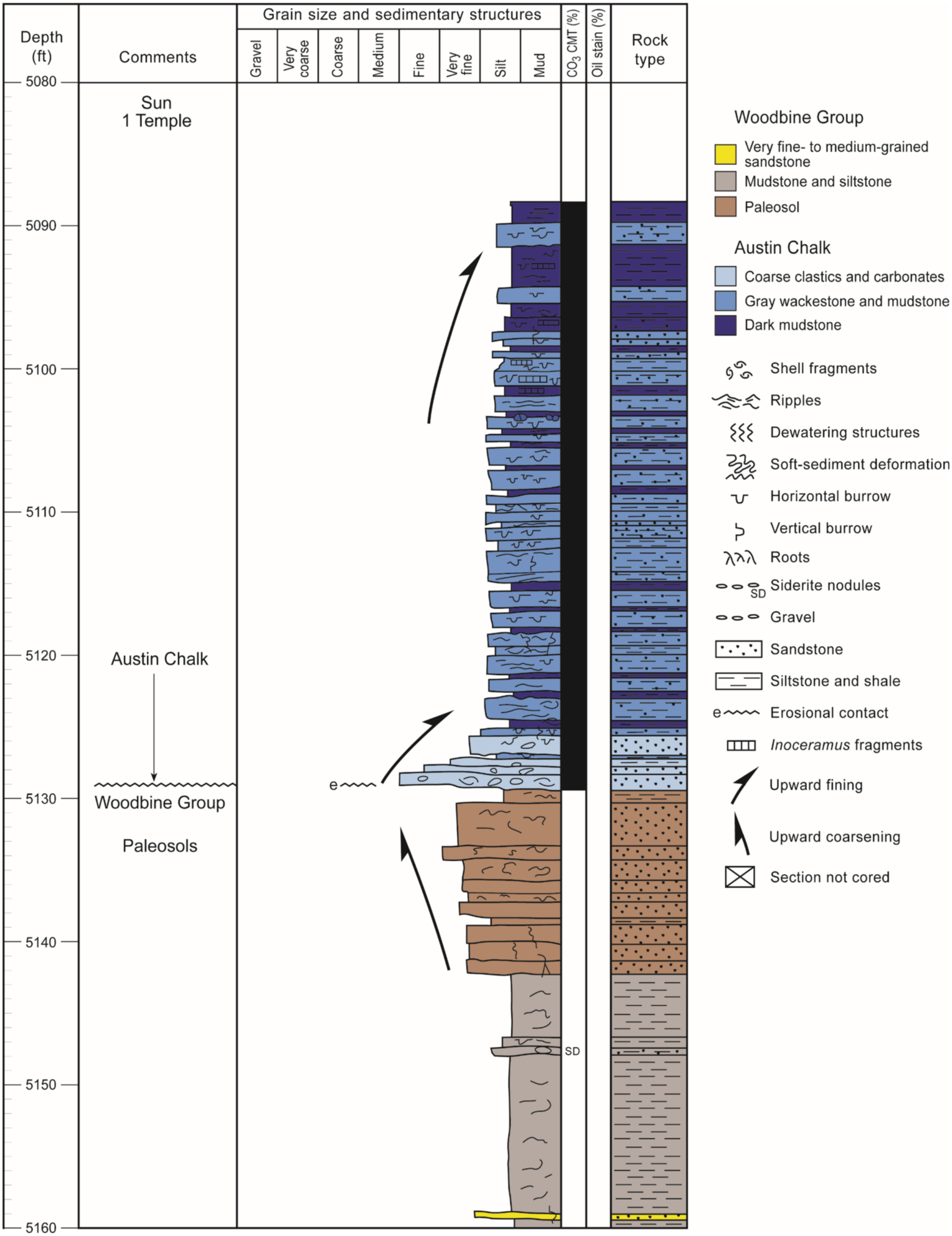


Figure 8. Description and interpretation of the Sun No. 1 Temple core in Cherokee County, southwest of the East Texas Field (modified after Ambrose and Hentz, 2010). Core location shown in Figure 2.

setting, with paleowater depths estimated to have exceeded 300 ft (~90 m) (Dravis, 1979; Dawson et al., 1995). Fossil assemblages in the study area of predominantly deeper water biotas (e.g., coccoliths, planktic foraminifers, and inoceramid clams) and trace-fossil assemblages indicate normal marine salinity in a dominantly open-marine, below storm-wave base, oxygenated shelf setting. In addition, no sedimentary structures that record reworking of sediments by storms are observed in cores in the study area, suggesting a depositional setting below wave base.

Austin Chalk reservoirs, elsewhere, have low porosity and low permeability and are dual-pore systems. They consist of a nano- to microporous matrix (interparticle pores between coccolith hash) and fractures. Diagenesis, including mechanical compaction, calcite cementation, and stylolitization has greatly modified pore systems in the Austin Chalk (Pearson, 2010).

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

Introduction

To understand the transition from the shallower water Woodbine siliciclastics into deeper water Austin Chalk carbonates, we divide the stratigraphic section into three units: (1) base-of-Austin-Chalk unconformity Woodbine Group, (2) basal Austin Chalk Group transition zone, and (3) Lower Austin Chalk Group. Each of these stratigraphic successions records distinctly different processes of sedimentation that change over thin (commonly less than 40 ft [<12 m]) depositional intervals.

Base-of-Austin-Chalk Unconformity: Woodbine Group

Macrodescription

The Woodbine Group in East Texas Field and adjacent areas, where it has not been affected by pedogenesis, commonly consists of crossbedded, planar- and ripple-stratified, mostly fine-grained sandstone with well-defined, vertical grain-size trends that record various deltaic and open-marine depositional environments such as delta-front, distributary-channel, crevasse-splay, and lower-shoreface (Figs. 6A, 7A, and 9). In contrast, stratification and grain-size fabrics in upper Woodbine zones in contact with and closely below the base-of-Austin-Chalk unconformity are commonly heavily mottled. These zones have a variety of

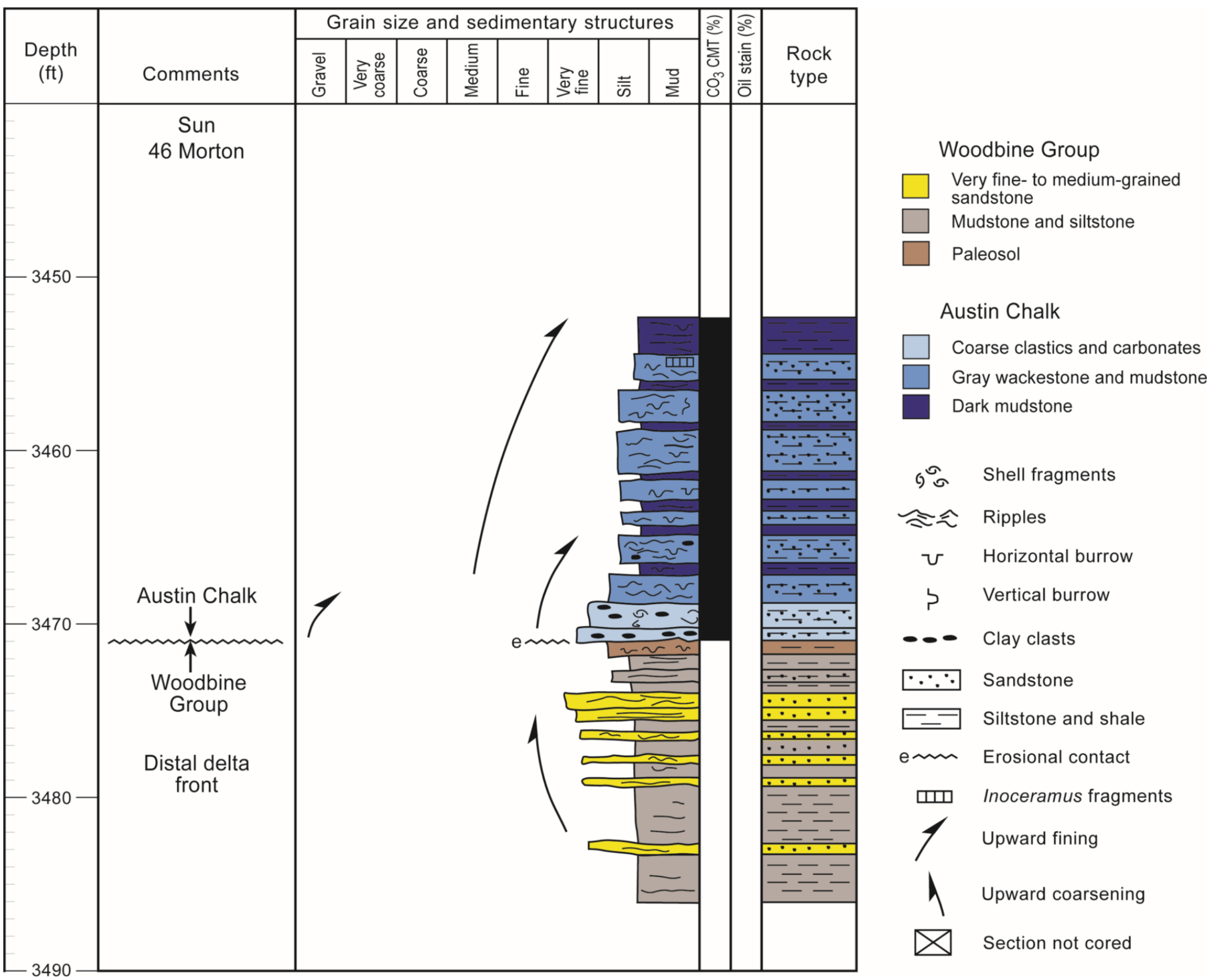


Figure 9. Description and interpretation of the Sun No. 46 Morton core in the northern part of the East Texas Field (modified after Ambrose and Hentz, 2010). Core location shown in Figure 2.

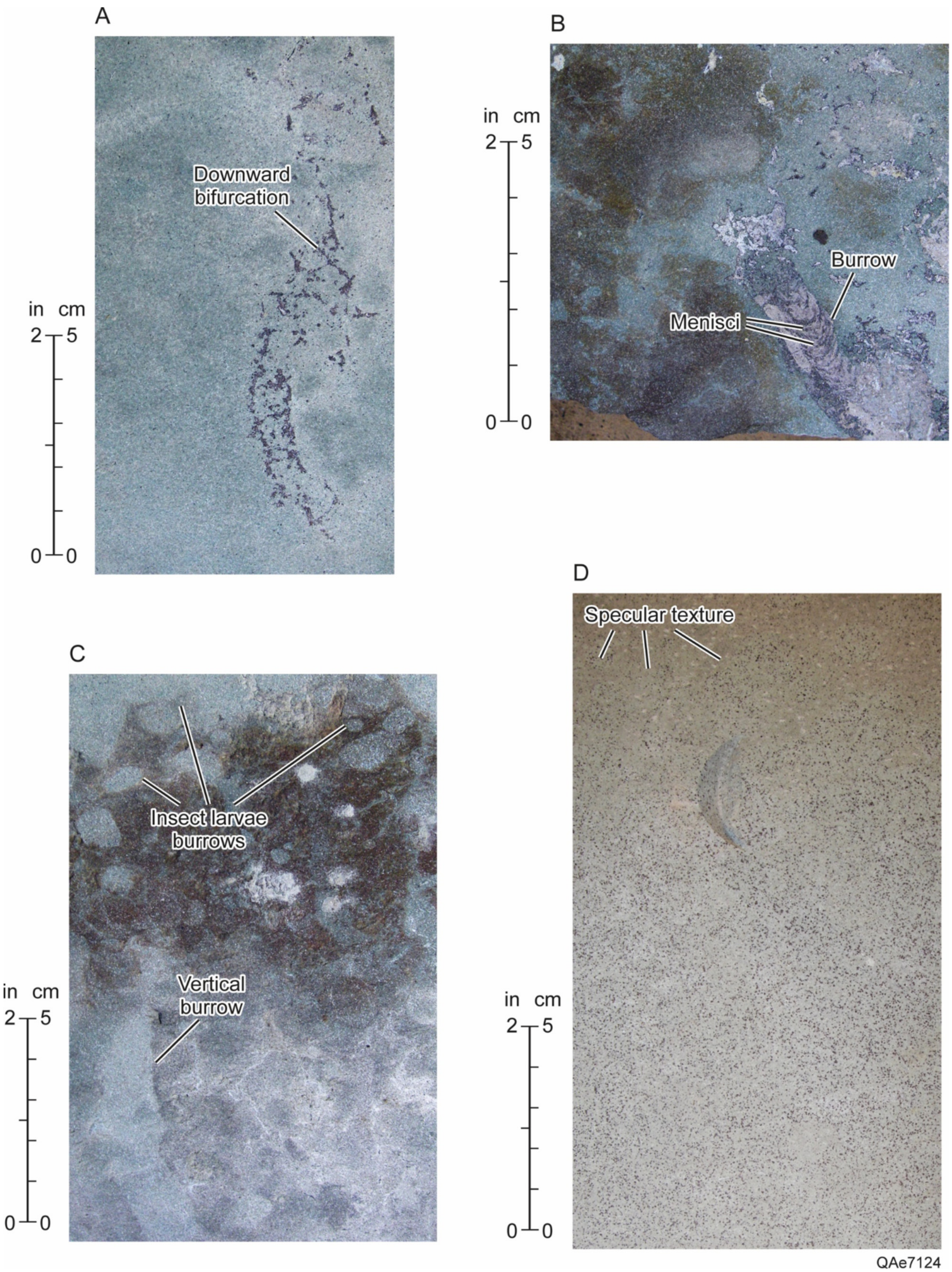


Figure 10. Photographs of paleosol fabrics in the upper Woodbine Group in the Sun No. 1 Temple core south of the East Texas Field. (A) Possible vertical root mottling or beetle burrow in greenish-gray, very fine-grained sandstone in the Woodbine Group at 5133.0 ft (1564.9 m). (B) Inclined beetle burrow with internal, arcuate menisci in variegated, very fine-grained sandstone in the Woodbine Group at 5131.4 ft (1564.5 m). (C) Intensely mottled, very fine- to fine-grained, predominantly gray-green sandstone in fine-grained sandstone in the Woodbine Group at 5133.5 ft (1565.1 m). (D) Very fine-grained, speckled sandstone in the Woodbine Group at 5137.5 ft (1566.3 m). Description of the Sun No. 1 Temple core is shown in Figure 8.

hues ranging from greenish-gray to reddish-brown and orange-brown (Figs. 4, 7, and 10). Five (5) main types of mottling occur in these sections: (1) irregular and subangular, subparallel light and dark patches (Fig. 4D), (2) vertical to subvertical, downward-bifurcating patterns, up to 0.4 in (1 cm) wide (Fig. 10A), (3) inclined to subvertical, elongate burrows with internal, arcuate menisci (Figs. 10B and 11B), (4) intensely deformed sections with dominantly horizontal, oval textures (burrows) (Fig. 10C), and (5) minute, dark (commonly brown-black) speckles in unstratified sections (Fig. 10D). Other textures include discrete, oval features, commonly white and gray, but also in varied hues such as purple to reddish-purple (Figs. 11A, 11C, and 11D). These oval features are at both millimeter and centimeter scales and commonly occur in clusters, although some are disseminated (Fig. 11D).

Micropetrography

Thin sections from the Sun No. 1 Temple well (Fig. 12) were described to characterize the sandstone at the millimeter scale for compositional analysis. Woodbine sandstones in the cored section are argillaceous and range in grain size from coarse silt to medium sand grained. Grain mineralogy is dominated by quartz with lesser sedimentary rock fragments and rare feldspar grains. Loucks et al. (2015) classified the Woodbine sandstones, using Folk's (1974) classification, as mainly quartzarenites and lesser sublitharenites by point counting thin sections. Figure 12F shows a meniscate burrow of the type described by Hasiotis (2004) and Hasiotis and Platt (2012).

Scanning electron microscope (SEM)–based x–ray energy dispersive maps of an argillaceous sandstone from the Sun No. 1 Temple are shown in Figures 13A and 13B. They display clay-rich matrix between quartz grains where interparticle pores are occulted by clay. The thin section in Figure 13B contains a chlorite-replaced rock fragment that may be an altered volcanic rock fragment.

Interpretation and Depositional Processes

Sandstones in the Woodbine Group were deposited in a variety of depositional environments that include bedload fluvial, fluvial-dominated deltaic, and open-marine (lower-shoreface to inner-shelf) (Ambrose et al., 2009). At the end of Woodbine deposition, the Sabine uplift was rising (Ewing, 2009) and the Woodbine section was extensively eroded. Long-term (up to 6 Myr [Denne and Breyer, 2016]) subaerial exposure occurred, allowing for the formation of locally thick soils. For example, the paleosols in the Sun No. 1 Temple core are 13 ft (4.0 m) thick (Fig. 8). Features that are diagnostic of paleosol formation at the top of Woodbine sandstones include terrestrial insect burrows, nodules, root traces, coloration of sediments consisting of various hues such as orange, tan, yellow, green, and greenish gray that correspond to different states of oxidation and reduction of iron, and mineralogical changes that include clays, argillaceous matrix, and cements. Diagnostic features for paleosols such as those observed in the Woodbine section are summarized and described by Retallack (1991), Kraus (1999), and Hasiotis (2004).

Some cores in the Woodbine Group in East Texas Field and adjacent areas feature meniscate and sand-filled burrows that are interpreted as those of beetles and insect-larvae. Burrows from soil-dwelling arthropods are common in continental deposits (Genise et al., 2004; Buatois and Mangano, 2004; Hasiotis, 2004). Beetle larvae in the Sun No. 1 Temple core (Fig. 10B) create backfilled, meniscate burrows that are distinct from backfilled burrows constructed by marine organisms (O'Geen and Busacca, 2001; Hasiotis and Bourke, 2006; Smith and Hasiotis, 2008; Hasiotis and Platt, 2012). Beetle larvae do not construct open burrow systems. Instead, they construct single, open cells that are twice body width and approximately equal to body length (Counts and Hasiotis, 2009). Beetle larvae burrows are made by scraping sediment with the head and mandibles, with sediment being consolidated and packed onto the back end of the cell, resulting in a meniscate internal fabric. These menisci are closely spaced, thin (<1 mm), and are subparallel to burrow margins. Average diameter is 0.4 in (1 cm), with grain size being the same as the surrounding matrix (Hasiotis and Platt, 2012). *Naktodemasis*, a common genus of burrowing beetles, is associated with moderately to well-drained soils within A and upper B horizons, although these burrows also occur in subaerial exposure surfaces associated with pedogenesis.

Basal Austin Chalk Group Transition Zone

Macrodescription

The basal section of the Austin Chalk in East Texas Field area overlies an erosional contact with mottled sandstone and siltstone beds of the Woodbine Group (Figs. 4A and 5–9). This section is upward-fining, composed of 1 to 3 ft (0.3 to 0.9 m) of phosphatic, shell-rich, clast-bearing, coarse-grained siliciclastics and carbonates grading upward into burrowed wackestone (Figs. 4A–4C, 5, 6E, and 7–9) with a matrix composed of coccolith-dominated carbonate mud. Soft-sediment deformation and scour surfaces are common throughout this basal section. Lithoclasts in the basal section of the Austin Chalk are dominated by chert pebbles and phosphate clasts. Mollusk fragments (commonly oysters), along with inoceramid fragments are also present. Burrows in the lowermost Austin Chalk section are identified as *Thalassinoides*, *Teichichnus*, *Palaeophycus*, and minor *Planolites* (Fig. 4) whereas those higher in the Austin Chalk section are commonly composed of *Thalassinoides*, *Chondrites*, and minor *Schaubcylindrichnus*.

Micropetrography

From thin sections and scanning electron microscopy, the mineralogy of the Woodbine Group below the base-of-Austin-Chalk unconformity includes argillaceous sandstone with rare, silt-sized calcite grains in a transition within a few feet to sandy, argillaceous marly chalk composed of coccolith hash with globigerinids, sand grains, and clay (chlorite and illite) (Figs. 13A and 13B).

Thin-section analysis (Fig. 14) of this transitional-lag zone at the base of the Austin Chalk shows a combination of shallower water allochems with deeper water planktic biotas (Fig. 14). Also, abundant reworked sand grains have been incorporated from the underlying Woodbine Group (Figs. 14B and 14C). The shallower water biota includes oyster and echinoderm fragments (Fig. 14B), whereas deeper water biota includes planktic foraminifers (Figs. 13C, 13D, 14B, 14C, and 14F), inoceramid fragments (Figs. 14B, 14C, 14E, and 14F), and coccoliths and coccolith hash (Figs. 13C, 13D, and 15). Transported phosphate clasts are also present (Figs. 14A and 14F). The matrix is composed of coccoliths and coccolith hash and shows a peloidal texture that may be the result of pellet production or marine snow (e.g., Figs. 16A, 16C, and 16D).

Interpretation and Depositional Processes

The basal section of the Austin Chalk records the marine transgression over Woodbine sandstones and associated paleosols. The initial depositional setting of the Austin Chalk during the early phase of transgression of the marine environment over Woodbine soil zones was a shallow-water system with abundant organisms such as oysters and echinoderms. These organisms were ultimately mixed together with relatively deeper-water organisms such as coccoliths, planktonic foraminifers, and inoceramids.

Coarse-grained lithoclasts such as chert pebbles and mollusk shells are the only remaining evidence of initial flooding over the

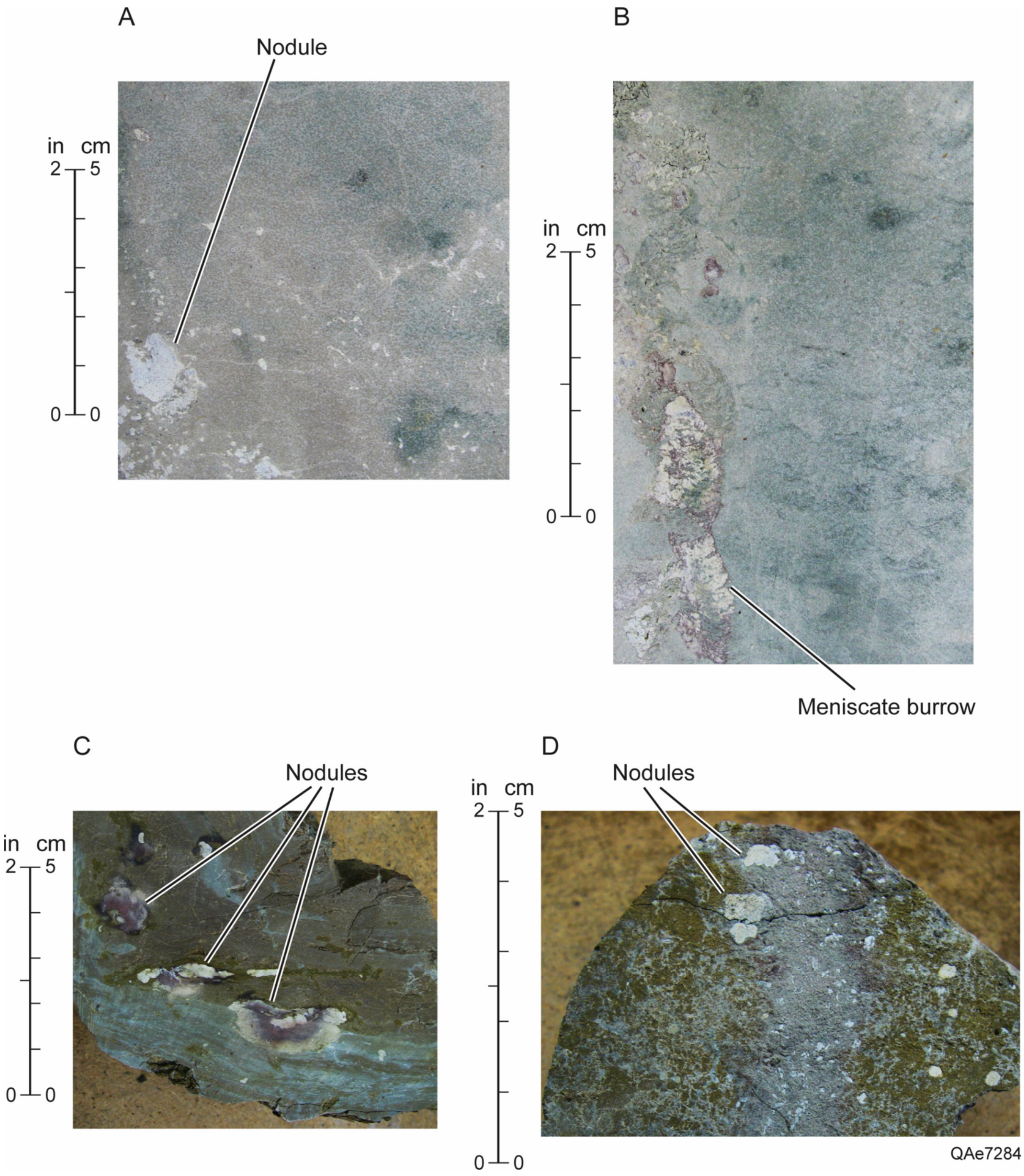


Figure 11. Photographs of paleosol fabrics in the upper Woodbine Group in the Sun No. 1 Temple core south of the East Texas Field. (A) Irregular nodules in very fine-grained sandstone at 5136.4 ft (1566.0 m). (B) Vertical beetle burrow with internal, arcuate menisci in variegated, very fine-grained sandstone and coarse-grained siltstone at 5139.7 ft (1567.0 m). (C) Purple and gray nodules in siltstone at 5,146.5 ft (1,569.1 m). (D) Disseminated, gray-white nodules in a green-gray siltstone matrix at 5157.7 ft (1572.5 m). Description of the Sun No. 1 Temple core is shown in Figure 8.

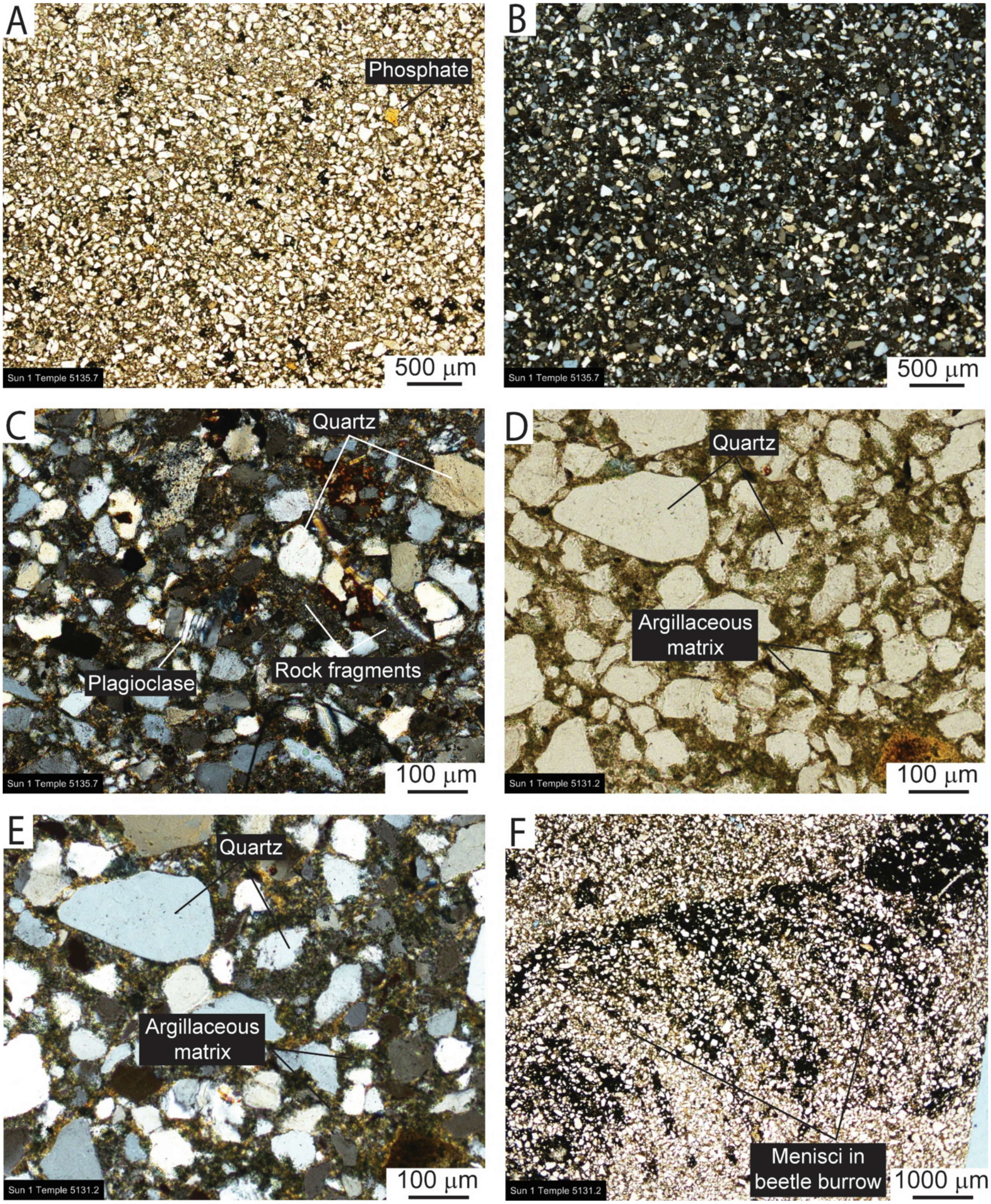


Figure 12. Paleosol interval in the upper Woodbine Group. (A) Argillaceous coarse silt to very fine-grained sandstone with rare phosphate. Grains are composed of predominantly quartz and lesser rock fragments and feldspars. Sun No. 1 Temple core at 5135.7 ft (1565.4 m). (B) Same as A, but under cross-polarized light. (C) Close up of argillaceous sandstone shown in A and B. The sandstone contains abundant sedimentary rock fragments. Sun No. 1 Temple core at 5135.7 ft (1565.4 m). (D) Argillaceous, very fine- to medium-grained sandstone. Clay may be related to pedogenic processes. Sun No. 1 Temple core at 5131.2 ft (1563.0 m). (E) Same as A, but under cross-polarized light. All primary interparticle pores are occulted by argillaceous material. (F) Possible beetle burrow in paleosol, showing spreiten. Sun No. 1 Temple core at 5131.2 ft (1563.0 m). Description of the Sun No. 1 Temple core is shown in Figure 8.

exposed Woodbine terrestrial surface. Following deposition of the basal Austin Chalk, the depositional setting was transformed into a deeper water setting below storm-wave base. As water depth increased, the environmental setting favored deeper water (shelf) organisms. However, bioturbation remained a dominant process at the same scale, resulting in the mixing together of shallower and deeper marine biotas. At the large scale, the overall upward-fining grain-size profile of lower part of the Austin Chalk succession, as well as in the lag section resulted from diminished depositional energy (lesser degree of wave reworking) with increasing water depth. No hydrodynamic structures resulting from wave oscillation are observed. The bottom waters and sediments were aerobic as noted by abundant bioturbation.

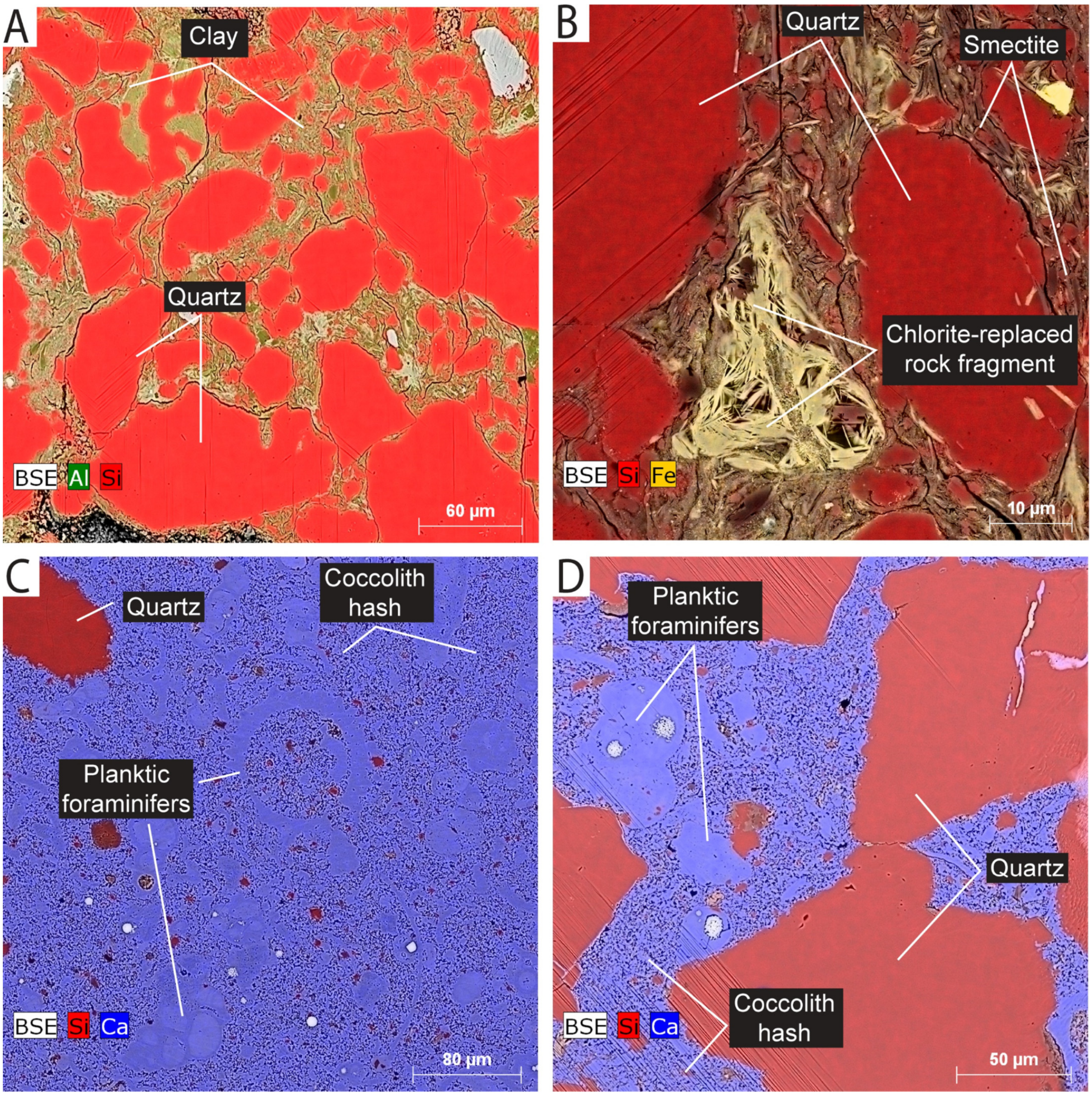
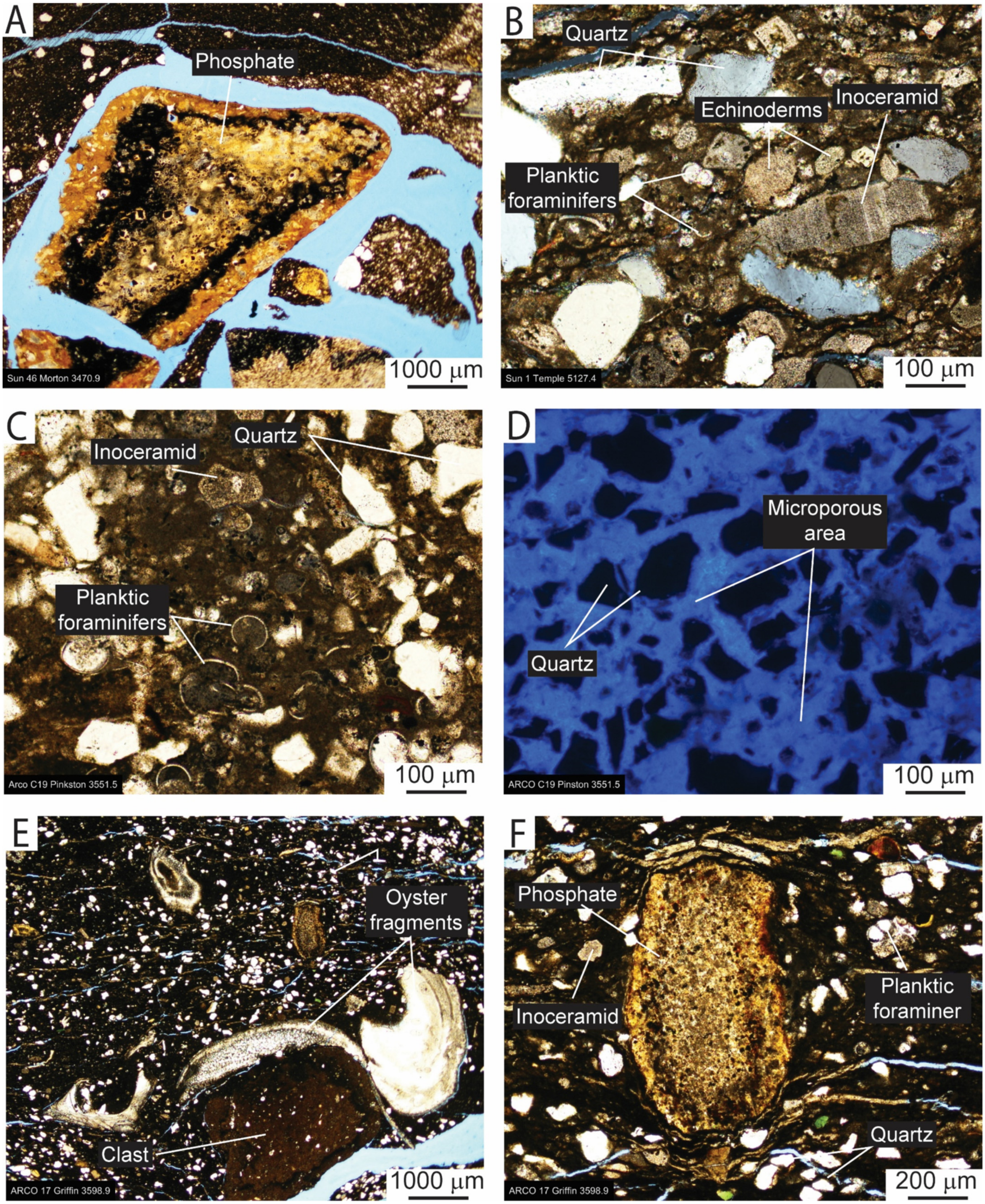


Figure 13. Scanning electron microscope energy dispersive x–ray element maps. Back-scattered images overlain by element maps. (A) Woodbine argillaceous sandstone less than 2 ft (<0.6 m) beneath the base-of-Austin-Chalk unconformity. The silt to fine-grained sand has clay matrix. Sun No. 1 Temple core at 5131.2 ft (1564.0 m). (B) Close up of clay matrix composed of illite and clay-size quartz. A silt-size, chlorite-replaced rock fragment is present. Sun No. 1 Temple core at 5131.2 ft (1564.0 m). (C) Austin Chalk composed of globigerinid grains in a coccolith-hash matrix <3 in (<7.6 cm) above unconformity. A few quartz grains are present. Sun No. 1 Temple core at 5129 ft (1563.3 m). (D) Quartz grains in a matrix of coccolith hash and globigerinids 1 ft (0.3 m) above unconformity. Sun No. 1 Temple core at 5128 ft (1563.0 m). Description of the Sun No. 1 Temple core is shown in Figure 8.


A
Phosphate
Sun 46 Morton 3470.9
1000 μm
B
Quartz
Echinoderms
Inoceramid
Planktic foraminifers
Sun 1 Temple 5127.4
100 μm
C
Inoceramid
Quartz
Planktic foraminifers
Arco C19 Pinkston 3551.5
100 μm
D
Microporous area
Quartz
ARCO C19 Pinston 3551.5
100 μm
E
Oyster fragments
Clast
ARCO 17 Griffin 3598.9
1000 μm
F
Phosphate
Inoceramid
Planktic foraminer
Quartz
ARCO 17 Griffin 3598.9
200 μm

(FACING PAGE) Figure 14. Austin Chalk Group transition zone. Lag deposits directly above unconformity. (A) Large phosphate clast in sandy wackestone. Sun No. 46 Morton core at 3470.9 ft (1057.9 m). (B) Very sandy, argillaceous, lime wackestone to packstone with planktic foraminifers, echinoderms, and inoceramid fragments. Sand grains are fine to medium grained. Sun No. 1 Temple core at 5127.4 ft (1562.8 m). (C) Very sandy, argillaceous, lime wackestone with planktic foraminifers and inoceramid fragments. Very fine- to fine-grained sand. Planktic foraminifers indicate deeper water deposition. ARCO No. C19 Pinkston core at 3551.5 ft (1082.5 m). (D) A thin section photographed under ultraviolet light showing microporous areas as blue haze. Dark grains are quartz-sand grains. ARCO No. C19 Pinkston core (description not presented in this study) at 3551.5 ft (1082.5m). (E) Sandy lag contains clasts and oyster fragments. ARCO No. 17 Griffin core at 3598.9 ft (1096.9 m). (F) Large phosphate clast in sandy argillaceous lime wackestone. Fossils include planktic foraminifers and inoceramid fragments. ARCO No. 17 Griffin core at 3598.9 ft (1096.9 m). Descriptions of the ARCO No. 17 Griffin, Sun No. 1 Temple, and Sun No. 46 Morton cores are shown in Figures 5, 8, and 9, respectively.

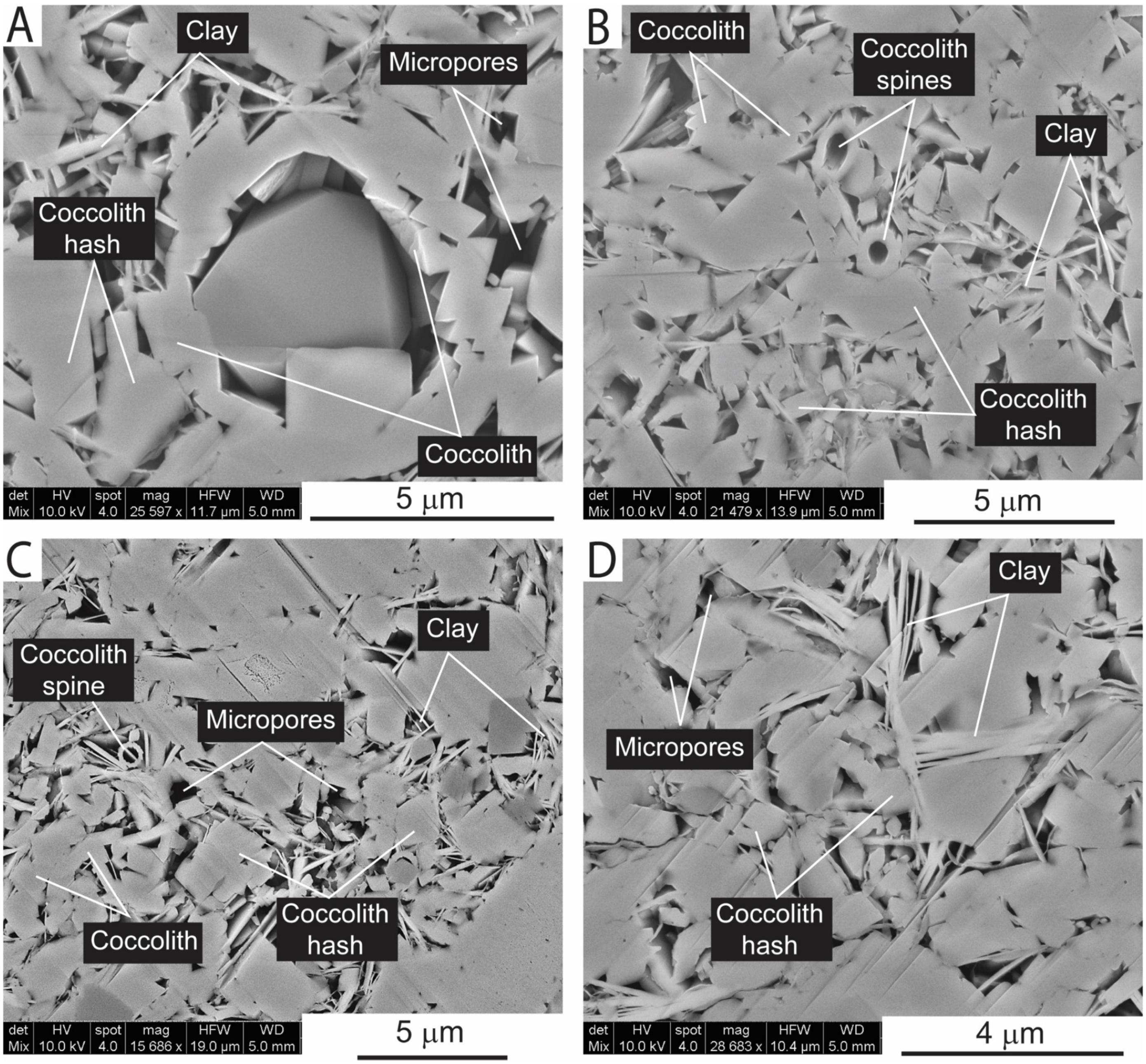
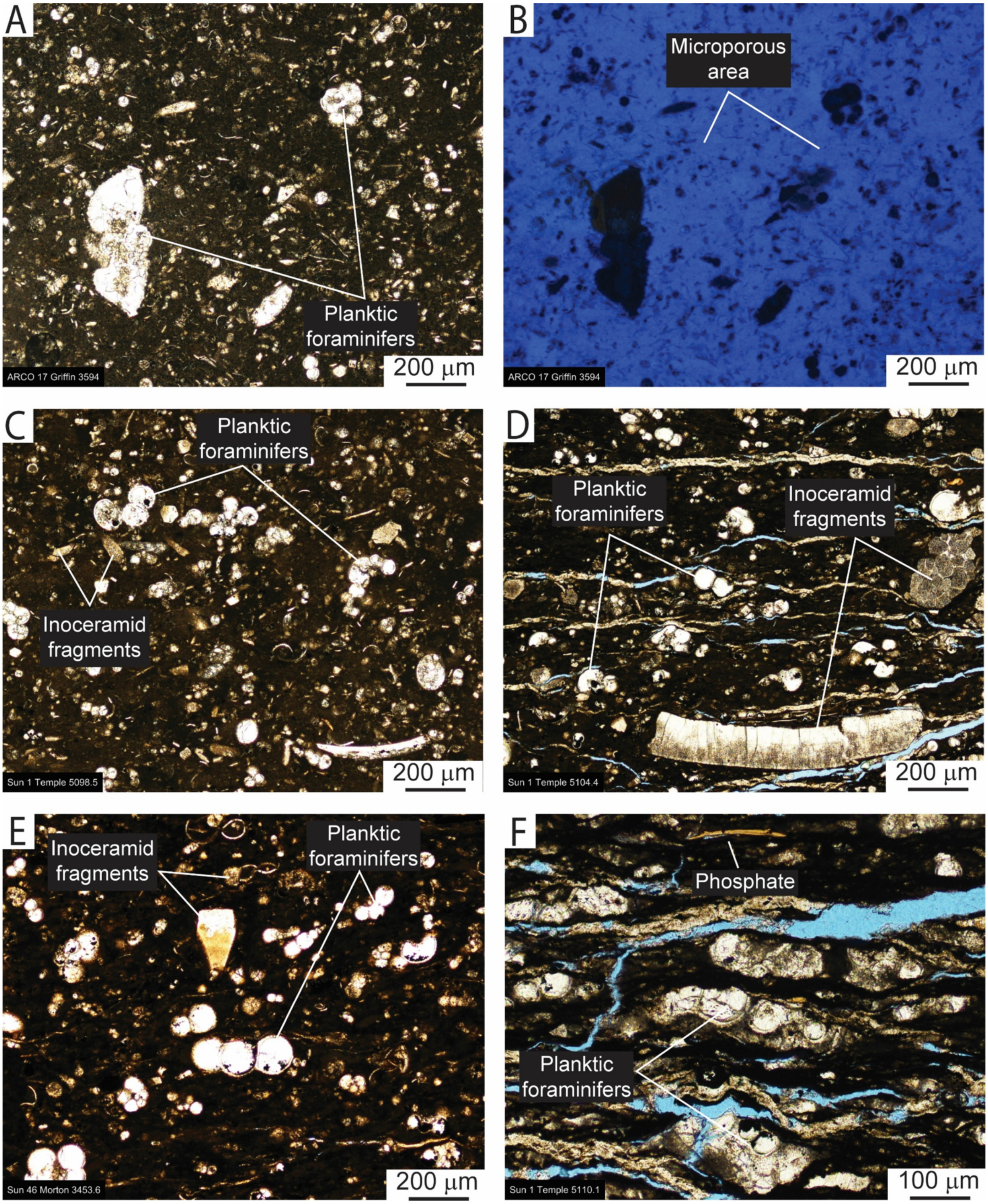


Figure 15. SEM Ar–ion-milled images of Austin Chalk Group in lag zone. (A) Coccolith mixed with coccolith hash and clay. Sun No. 1 Temple core at 5126 ft (1562.4 m). (B) Coccolith hash with coccolith spines and clay. Sun No. 1 Temple core at 5128 ft (1563 m). (C) Coccolith hash with coccolith spines and clay. Sun No. 1 Temple core at 5128 ft (1563 m). (D) Coccolith hash with clay. Sun No. 1 Temple core at 5128 ft (1563 m). Micropores are common in all illustrations. Description of the Sun No. 1 Temple core is shown in Figure 8.


A
Planktic foraminifers
ARCO 17 Griffin 3594
200 μm
B
Microporous area
ARCO 17 Griffin 3594
200 μm
C
Planktic foraminifers
Inoceramid fragments
Sun 1 Temple 5098.5
200 μm
D
Planktic foraminifers
Inoceramid fragments
Sun 1 Temple 5104.4
200 μm
E
Inoceramid fragments
Planktic foraminifers
Sun 46 Morton 3453.6
200 μm
F
Phosphate
Planktic foraminifers
Sun 1 Temple 5110.1
100 μm

(FACING PAGE) Figure 16. Lower Austin Chalk Group. Argillaceous chalk (wackestone). (A) Argillaceous planktic foraminifer lime wackestone. Matrix is composed of coccolith-rich peloids. ARCO No. 17 Griffin core at 3594 ft (1095 m). (B) Same as A, but under ultraviolet light showing microporous areas as blue haze. (C) Argillaceous planktic foraminifer lime wackestone with inoceramid fragments. Matrix is composed of peloids rich in coccoliths. Sun No. 1 Temple core at 5098.5 ft (1554 m). (D) Argillaceous planktic foraminifer lime wackestone with larger inoceramid fragments. Matrix is composed of coccolith-rich peloids. Sun No. 1 Temple core at 5104.4 ft (1555.8 m). (E) Argillaceous planktic foraminifer lime wackestone with inoceramid fragments. Matrix is composed of coccolith-rich peloids. Sun No. 46 Morton core at 3453.6 ft (1053.6 m). (F) Planktic foraminifer terrigenous mudstone with phosphate fish scale. The foraminifers show strong pressure solution. Sun No. 1 Temple core at 5110.1 ft (1557.6 m). ARCO No. 17 Griffin, Sun No. 1 Temple, and Sun No. 46 Morton cores are shown in Figures 5, 8, and 9, respectively.

Inoceramid clams suggest that some bottom conditions were soupy and may have been dysaerobic as these bivalves could live in low-oxygen settings on unstable substrates. The planktic foraminifers and coccolithophores lived in the shallower water column and upon death settled to the bottom.

DISCUSSION

Transition from Paleosol to Deeper Water Deposition

This study provides an example of a thin (<3 ft [(<0.9 m]) transition from clastic deposits in a subaerially exposed deltaic floodplain section to outer-shelf (approximately 300 ft [91.5 m] of water depth), chalk deposits with little preservation of intervening transgressive-shoreline and deltaic deposits. This abrupt facies transition may have resulted from a combination of relatively rapid sea-level rise associated with the regional Austin Chalk transgression and reduced accommodation on the western flank of the tectonically active Sabine Uplift. This transition took place in several steps that lasted ~6 Myr (Denne and Breyer, 2016). Following the deposition of the Woodbine sands, a relative sea-level fall occurred that was related in part to the Sabine Uplift. During this drop in sea level, extensive erosion, resulting in the formation of valleys occurred in the East Texas Field area (Ambrose et al., 2009). As a result of this erosion and subsequent subaerial exposure of fluvial channel-fill and floodplain deposits, thick (locally >10 ft [>3 m]) paleosols in the Woodbine Group developed (Fig. 8), indicating long-term subaerial exposure. According to biostratigraphic data in Denne and Breyer (2016), ~6 Myr are missing between the Woodbine and the Austin Chalk sections in the area of East Texas Field.

When sea-level began to rise, Woodbine paleosols were flooded by marine waters. Initially the depositional environment was likely characterized by a shallow marine depositional system, indicated only by remnants of shallower water fauna (oysters and echinoderms), detrital fragments of chert and phosphate, and abundant reworked Woodbine silt and sand. However, original deposits of shallow water depositional systems that might be expected including deltaic and shorezone facies were not preserved intact, with transgressive-lag deposits (oyster shells and coarse-grained lithoclasts) being the only preserved deposits. They appear to have been reworked into younger, deeper water sediments. This reworking and absence of shallow marine facies was probably related to both a lack of accommodation and sediment mixing from bioturbation. Even though the shallower and deeper water sediments were mixed, a distinct transitional lag section is evident in all cores in this study because larger grains resisted significant transport by marine-reworking currents. As transgression continued, Austin Chalk depositional environments became deeper and the biota became exclusively of deepwater origin, consisting of coccolithophore fragments, planktic foraminifers, and inoceramid clams. Even though the transition from Woodbine section and hypothesized overlying shallow water succession into the deepwater Austin Chalk appears to have been rapid because it occurs over a very short stratigraphic section (commonly less than 3 ft [<0.9 m]), it actually represents several millions of years in length. Much of this time is accounted for by erosion and nondeposition.

The absence of a deltaic or shoreface succession above the Woodbine floodplain succession with subaerially exposed paleosols, coupled with the abrupt superposition of outer-shelf, open-marine chalk facies in the overlying Austin Chalk has implications for possible sandstone-reservoir facies of shallow-marine origin in East Texas Field and adjacent areas. Other Woodbine sandstones of shallow-marine origin may exist between the Woodbine paleosol succession and the base-of-Austin-Chalk unconformity where relatively greater accommodation may been present in areas more distant from the Sabine Uplift, where subsidence may have been greater.

Complex sedimentary fabrics and fine-grained material (silty mudstones and clays in Woodbine paleosols may also contribute to the main seal (base of Austin Chalk) in East Texas Field. The majority of whole cores of the Woodbine-to-Austin-Chalk transition in East Texas Field exhibit various degrees of paleosol development at the top of the Woodbine section (Ambrose and Hentz, 2010). Permeability and capillary-pressure data would be needed to test this hypothesis.

CONCLUSIONS

Cores in East Texas Field and adjacent areas illustrate significant lithologic and facies variability above and below a regional, angular unconformity at the base of the Austin Chalk. Paleosols in the Woodbine Group below the unconformity record long-term subaerial exposure (at least 6 Myr) of delta-plain environments.

Regional inundation and marine-reworking of the upper Woodbine Group is represented by a basal (1 to 3-ft [0.3 to 0.9-m]) section of upward-fining, mixed clastics and carbonates with abundant rip-up clasts, shell debris, and marine trace fossils above an unconformity at the base of the Austin Chalk. This basal section grades upward into deeper water, tight chalk deposits that form a major, regional seal overlying the upper Woodbine succession.

Major findings from this study include:

The transition from shallow marine to deeper water (shelf) depositional environments is more abrupt over a shorter interval (commonly <3 ft [<0.9 m]) than previously documented for the Woodbine Group to the Austin Chalk in East Texas Field and other areas in the East Texas Basin.

Well-developed paleosols in the uppermost Woodbine section in multiple cores in East Texas Field and adjacent areas suggests that subaerial environments in the Woodbine Group were more regionally extensive and persistent through time than previously documented (Oliver, 1971; Halbouty and Halbouty, 1982). In addition, paleosols may exist in other (sub-Woodbine) stratigraphic intervals in East Texas and other areas in proximity to the Sabine Uplift, where the base-of-Austin-Chalk unconformity has incised into older stratigraphic intervals.

Paleosols in the uppermost part of the Woodbine stratigraphic section are inferred to have an adverse effect on reservoir quality, as a result of bioturbation and clays disrupting the sandy framework, as well as the introduction of clays into the sandy matrix. These factors should be taken into account in reservoir-development strategies in the Woodbine Group in the East Texas Basin.

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REFERENCES CITED

Adair, J. K., 1960, East Texas Oil Field, Gregg, Rusk, Upshur, Smith, and Cherokee counties, Texas: Compass, v. 37, no. 3, p. 174–181.

Alexander, C. I., 1951, History of discovery and development of Woodbine oil fields in East Texas, *in* F. E. Lozo, ed., The Woodbine and adjacent strata: History of discovery and development of Woodbine oil fields in East Texas: Southern Methodist University Press Fondren Science Series 4, Dallas, Texas, p. 12–20.

Ambrose, W. A., T. F. Hentz, F. P. Wang, F. Bonnaffé, R. G. Loucks, E. C. Potter, and S. Clift, 2007, Pilot study of East Texas Field: Geology, engineering, and potential exploitation workshop: Bureau of Economic Geology, State of Texas Advanced Resource Recovery and Petroleum Technology Transfer Council Workshop SW0017, Austin, variously paginated.

Ambrose, W. A., T. F. Hentz, F. Bonnaffé, R. G. Loucks, L. F. Brown, Jr., F. P. Wang, and E. C. Potter, 2009, Sequence stratigraphic controls on complex reservoir architecture of highstand fluvial-dominated deltaic and lowstand valley-fill deposits in the Woodbine Group, East Texas Field: Regional and local perspectives: American Association of Petroleum Geologists Bulletin, v. 93, p. 231–269, <https://doi.org/10.1306/09180808053>.

Ambrose, W. A., and T. F. Hentz, 2010, Depositional systems and facies variability in highstand fluvial-dominated deltaic and lowstand valley-fill systems in the Lower Cretaceous (Cenomanian) Woodbine Group, East Texas Field, *in* T. F. Hentz, ed., Sequence stratigraphy, depositional facies, and reservoir attributes of the Upper Cretaceous Woodbine Group, East Texas Field: Bureau of Economic Geology Report of Investigations 274, Austin, Texas, p. 17–81, <https://doi.org/10.23867/RI0274D>.

Buatois, L. A., and M. G. Mangano, 2004, Animal-substrate interactions in freshwater environments: Applications of ichnology in facies and sequence stratigraphic analysis of fluvio-lacustrine successions, *in* D. McIlroy, ed., The Application of ichnology to palaeoenvironmental and stratigraphic analysis: Geological Society (London) Special Publications, v. 228, U.K., p. 311–333.

Counts, J. W., and S. T. Hasiotis, 2009, Neoichnological experiments with masked chafer beetles (Coleoptera: Scarabaeidae): implications for backfilled continental trace fossils: *Palaios*, v. 24, p. 74–91, <https://doi.org/10.2110/palo.2008.p08-026r>.

Dawson, W. C., B. Katz, and V. D. Robison, 1995, Austin Chalk (!) petroleum system, upper Cretaceous, southeastern Texas: A case study: Gulf Coast Association of Geological Societies Transactions, v. 45, p. 157–163.

Denne, R., and J. Breyer, 2016, Relationship between the deposition episodes of the Woodbine/Eagle Ford of East Texas and the Eagle ford of South Texas, *in* C. M. Lowery, J. W. Snedden, and N. C. Rosen, eds., Mesozoic of the Gulf Rim and beyond: New progress in science and exploration of the Gulf of Mexico Basin: Proceedings of the 36th Gulf Coast Section of the Society of Economic Paleontologists and Mineralogists Foundation Research Conference, p. 173–204, <https://doi.org/10.5724/gcs.15.35.0173>.

Denne, R. A., J. A. Breyer, T. H. Kosanke, J. M. Spaw, A. D. Callender, R. E. Hinote, M. Kariminia, N. Tur, Z. Kita, J. A. Lees, and H. Rowe, 2016, Biostratigraphic and geochemical constraints on the stratigraphy and depositional environments of the Eagle Ford and Woodbine groups of Texas, *in* J. A. Breyer, ed., The Eagle Ford Shale—A renaissance in U.S. oil production: American Association of Association of Petroleum Geologists Memoir 110, Tulsa, Oklahoma, p. 1–86, <https://doi.org/10.1306/13541957M1103660>.

Dravis, J. J., 1979, Sedimentology and diagenesis of Upper Cretaceous Austin Chalk Formation, South Texas and northern Mexico: Ph.D. Dissertation, Rice University, Houston, Texas, 513 p.

East Texas Engineering Association, 1953, The East Texas Oil Field, 1930–1950: East Texas Engineering Association, Kilgore, 644 p.

Ewing, T. E., 1991a, The tectonic framework of Texas: Bureau of Economic Geology, text accompanying the Tectonic Map of Texas, Publication SM0001, Austin, 36 p.

Ewing, T. E., 1991b, Structural framework, *in* A. Salvador, ed., The geology of North America, v. J: The Gulf of Mexico Basin: Geological Society of America, Boulder, Colorado, p. 37–52, <https://doi.org/10.1130/DNAG-GNA-J.31>.

Ewing, T. E., 2009, The ups and downs of the Sabine Uplift and the northern Gulf of Mexico Basin: Jurassic basement blocks, Cretaceous thermal uplifts, and Cenozoic flexure: Gulf Coast Association of Geological Societies Transactions, v. 59, p. 253–269.

Folk, R. L., 1974, Petrology of sedimentary rocks: Hemphill, Austin, Texas, 182 p.

Genise, J. F., E. S. Bellosi, and M. G. Gonzalez, 2004, An approach to the description and interpretation of ichnofabrics in paleosols, *in* D. McIlroy, ed., The application of ichnology to palaeoenvironmental and stratigraphic analysis: Geological Society (London) Special Publications, v. 228, U.K., p. 355–382.

Halbouty, M. T., and J. J. Halbouty, 1982, Relationships between East Texas Field region and Sabine Uplift in Texas: American Association of Petroleum Geologists Bulletin, v. 66, p. 1042–1054.

Hasiotis, S. T., 2004, Reconnaissance of Upper Jurassic Morrison Formation ichnofossils, Rocky Mountain Region, USA: Paleoenvironmental, stratigraphic, and paleoclimatic significance of terrestrial and freshwater ichnocoenoses: Sedimentary Geology, v. 167, p. 177–268, <https://doi.org/10.1016/j.sedgeo.2004.01.006>.

Hasiotis, S. T., and M. C. Bourke, 2006, Continental trace fossils and museum exhibits: displaying organism behavior frozen in time: The Geological Curator, v. 8, no. 5, p. 211– 226.

Hasiotis, S. T., and B. F. Platt, 2012, Exploring the sedimentary, pedogenic, and hydrologic factors that control the occurrence and role of bioturbation in soil formation and horizonation in continental deposits: and integrative approach: The Sedimentary Record, v. 10, no. 3, p. 4–9, <https://doi.org/10.2110/sedred.2012.3.4>.

Hentz, T. F., and F. Bonnaffé, 2010, Sequence stratigraphy of the Upper Cretaceous (Cenomanian) Woodbine Group: Chronostratigraphic integration of the East Texas Basin and East Texas Field, *in* T. F. Hentz, ed., Bureau of Economic Geology Report of Investigations 274, Austin, Texas, p. 1–16, <https://doi.org/10.23867/RI0274D>.

Hudnall, J. S., 1951, East Texas Field, *in* F. A. Herald, ed., Occurrence of oil and gas in northeast Texas: University of Texas Publication 5116, Austin, p. 113–118.

Jackson, M. L. W., and S. E. Laubach, 1991, Structural history and origin of the Sabine Arch, East Texas and northwest Louisiana: Bureau of Economic Geology Geological Circular 91–3, Austin, Texas, 47 p.

Kraus, M. J., 1999, Paleosols in clastic sedimentary rocks: Their geologic applications: Earth-Science Reviews, v. 47, p. 41–70, <https://doi.org/10.1016/S0012-8252(99)00026-4>.

Loucks R. G., R. M. Reed, and W. A. Ambrose, 2015, Analysis of pore networks and reservoir quality of the Upper Cretaceous Woodbine Sandstone in the high-recovery-efficiency, giant East Texas Field: Gulf Coast Association of Geological Societies Journal, v. 4, p. 88–108, <https://www.gcags.org/Journal/2015.GCAGS.Journal/2015.Journal.v4.6.p88-108.Loucks.et.al.press.pdf>.

Minor, H. E., and M. A. Hanna, 1933, East Texas Oil Field: American Association of Petroleum Geologists Bulletin, v. 17, p. 757–792.

O'Geen, A. T., and A. J. Busacca, 2001, Faunal burrows as indicators of paleo-vegetation in eastern Washington, USA: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 169, p. 23–37, <https://doi.org/10.1016/S0031-0182(01)00213-9>.

Oliver, W. B., 1971, Depositional systems in the Woodbine Formation (Upper Cretaceous), northeast Texas: Bureau of Economic Geology Report of Investigations 73, Austin, Texas, 28 p.

Pearson, K., 2010, Geologic controls on Austin Chalk oil and gas production: Understanding a dual conventional-continuous accumulation: Gulf Coast Association of Geological Societies Transactions, v. 50, p. 557–570.

Retallack, C. J., 1991, Untangling the effects of burial alteration and ancient soil formation: Annual Reviews Earth Planetary Science, v. 19, p. 183–206, <https://doi.org/10.1146/annurev.ea.19.050191.001151>.

Salvador, A., and J. M. Q. Muñeton, compilers, 1989, Stratigraphic correlation chart, Gulf of Mexico Basin, the Gulf Coast Basin, *in* A. Salvador, ed., The geology of North America, v. J: Geological Society of America, Boulder, Colorado, plate 5.

Smith, J. J., and S. T. Hasiotis, 2008, Traces and burrowing behaviours of the cicada nymph *Cicadetta calliope*; Neoichnology and paleoecological significance of extant soil-dwelling insects: *Palaios*, v. 23, p. 503–513, <https://doi.org/10.2110/palo.2007.p07-063r>.

Stehli, F. G., W. B. Creath, C. F. Upshaw, and J. M. Forgotson, Jr., 1972, Depositional history of Gulfian Cretaceous of East Texas Embayment: American Association of Petroleum Geologists Bulletin, v. 56, p. 38–67.

Vail, P. R., R. M. Mitchum, Jr., and S. Thompson, III, 1977, Seismic stratigraphy and global changes of sea level, part 4: Global cycles of relative changes of sea level, *in* C. E. Payton, ed., Seismic stratigraphy—Applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, Tulsa, Oklahoma, p. 83–97.