

Depositional system transitions and sequence stratigraphic evolution of the Tuscaloosa Group in the Mississippi Embayment, USA: Accommodation space and sediment supply controls

Husamaldeen Zubi^{a,b,*}, Brian F. Platt^a, Muneer Abdalla^b, Jennifer Gifford^a, Belkasim Khameiss^{c,d}

^a Department of Geology and Geological Engineering, The University of Mississippi, 120A Carrier Hall, University, Oxford, MS, USA

^b Department of Geology, Faculty of Science, Omar Al-Mukhtar University, P.O. Box 919, Al Bayda, Libya

^c Kansas Geological Survey, Lawrence, KS, USA

^d Department of Earth Science, University of Benghazi, Benghazi, Libya

ARTICLE INFO

Article history:

Received 24 June 2025

Received in revised form

12 August 2025

Accepted in revised form 12 September 2025

Available online 17 September 2025

Keywords:

Depositional sequence

Sediment supply

Global sea level

Systems tracts

Lithofacies

ABSTRACT

The Tuscaloosa Group (Grp), the basal unit of Upper Cretaceous strata in the northern Gulf of Mexico (GoM), formed during the late Cenomanian transgression across the southeastern United States. Despite its significance, comprehensive sequence stratigraphic analyses of the Tuscaloosa Grp within the south-central Mississippi Embayment (MSE) are limited. This study integrates core data, wireline logs, and field observations to characterize its depositional evolution and sequence stratigraphic architecture, delineating stratigraphic surfaces, systems tracts, and depositional sequences, and examining controlling factors. Four third-order sequences were identified from four sequence boundaries, two transgressive surfaces, and three maximum flooding surfaces. Sequence 1 (S1) includes a lowstand systems tract (LST), transgressive systems tract (TST), and highstand systems tract (HST); Sequence 2 (S2) has a TST and HST; Sequence 3 (S3) contains a LST, TST, and HST; and Sequence 4 (S4) includes a LST and TST. S1 comprises fluvial and incised valley deposits (LST), transitioned to deltaic TST during rising sea levels, and culminated in barrier island and shelf HST. S2 features distal shelf TST deposits followed by a prograding deltaic HST. S3 records a full cycle: fluvial LST, retrograding deltaic TST, and progradational deltaic HST. S4 is less developed, with fluvial LST and localized retrograding deltaic TST deposits. The Tuscaloosa's evolution was driven by accommodation space changes and sediment supply. Subsidence of the MSE in the Late Cretaceous may have increased accommodation and facilitated TST formation in the Upper Tuscaloosa. The Appalachian Highlands supplied most sediments, with the Ouachita Highlands as a secondary source.

© 2025 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

The Mississippi Embayment (MSE) is one of the regions of North America that was inundated by an overall transgressive trend during the Late Cretaceous. Throughout this time, there was a notable accumulation of sediments in the MSE, including the Tuscaloosa Group (Grp) (Cushing et al., 1964). The Tuscaloosa Grp in the subsurface of Mississippi and southwestern Alabama contains three major lithostratigraphic units: in ascending order, the

Lower Tuscaloosa, the Middle Tuscaloosa (known as Tuscaloosa Marine Shale in Louisiana), and the Upper Tuscaloosa (Mancini et al., 1987). Hydrocarbon exploration in the Lower Tuscaloosa massive sandstone at South Carlton Field and Pollard Field in southern Alabama began in the early 1950s, marking the first recognition of the Lower Tuscaloosa Group's economic significance in Alabama (Mancini et al., 1987). Additionally, the Middle Tuscaloosa was targeted for unconventional exploration in 1978 in Tangipahoa Parish, Louisiana (e.g., John et al., 1997; John et al., 2005). According to the USGS, the Tuscaloosa Marine Shale is estimated to contain recoverable unconventional resources of 1.5 billion barrels of oil and ~4.6 trillion cubic feet of gas (Hackley et al., 2018). The Middle Tuscaloosa also serves as a self-sourced reservoir in southern Mississippi (Hackley et al., 2020).

* Corresponding author. Department of Geology and Geological Engineering, The University of Mississippi, 120A Carrier Hall, University, Oxford, MS, USA.
E-mail address: husamaldeenubi@gmail.com (H. Zubi).

There has been limited investigation into the arrangement and development of the sequence stratigraphic hierarchy of the entire Tuscaloosa Grp within the south-central region of the MSE. Mancini and Puckett (2002) studied second-order transgressive-regressive cycles of Cretaceous rocks, including the Tuscaloosa Grp, in the northern GoM. Explicit definitions and mapping of third-order stratigraphic surfaces and systems tracts within the Tuscaloosa Grp, however, have not been conducted. Progress was made by other investigations that concentrated on the sequence stratigraphic structure and spatial distribution of the Lower Tuscaloosa in the southern MSE (e.g., Woolf, 2012; Ambrose et al., 2015). The detailed interpretation and discussion of the sequence stratigraphic architecture of the entire Tuscaloosa Grp in the south-central MSE, encompassing the identification of stratigraphic surfaces, system tracts, third-order stratigraphic sequences, as well as their lateral and vertical distribution, has yet to be undertaken. In consideration of the aforementioned research gaps, this study is conducted on the Upper Cretaceous Tuscaloosa Grp in the south-central MSE and aims to: (1) characterize the sequence stratigraphic framework of the Tuscaloosa Grp, including its depositional sequences, stratigraphic surfaces, and systems tracts; (2) reconstruct paleogeography to provide insights into the depositional evolution of the Tuscaloosa Grp over both space and time; and (3) interpret the possible factors that influenced the sedimentation of the Tuscaloosa's depositional sequences. Delineation of the stratigraphic architecture will improve understanding of the mechanism of sediment infilling in the MSE during the Late Cretaceous with respect to the factors that influenced the depositional basin. Moreover, the present study will offer valuable insights into the depositional patterns and sedimentary facies distributions within intracratonic basins. The established methodology will provide an effective approach that can be applied to sequence stratigraphic analysis and correlation of economically important strata in similar basins worldwide.

2. Geological background

2.1. The Mississippi Embayment (MSE)

The MSE forms a large, southwestward-plunging basin in North America, covering ~259,000 km² (Fig. 1A). The MSE extends across Texas, Louisiana, Alabama, Mississippi, Arkansas, Tennessee, Missouri, Illinois, and Kentucky (Cushing et al., 1964). The major structural features that define its boundaries are the Illinois Basin to the north, the Ozark Uplift to the northwest, the Nashville Dome and Cincinnati Arch to the northeast, the Appalachian Fold Belt to the east, and the Ouachita Belt to the southwest (Fig. 1A) (Mooney et al., 1983).

The MSE experienced major tectonic and depositional changes during its Cretaceous history that reflect a deep mantle control on the formation of this region. Cox and Van Arsdale (1997, 2002) suggested that the MSE was created by the movement of the Mississippi Valley graben system over a stationary Bermuda hotspot during the Cretaceous superplume event (~120 Ma). When the hotspot was under the Mississippi Valley Graben, decompression of the lithosphere led to the emplacement of molten rock reaching the surface, followed by a brief period of uplift and then erosion of the lithosphere. The eroded lithosphere subsided to produce accommodation space that enabled the deposition of nonmarine/marine sediments (Galloway and Hobday, 1983). This structural depression was influenced by marine transgression from the GoM (Mancini and Puckett, 2005). The marine transgression established an extensive seaway connecting the Gulf to the Western Interior Seaway, resulting in the deposition of marine chalk, marl, and shale formations (Dockery, 1996). The

embayment's structural framework continued to influence sediment distribution throughout the Cretaceous, with the most significant subsidence occurring during the subsequent Eocene (Ervin and McGinnis, 1975).

2.2. Stratigraphy of the Tuscaloosa Group

The Tuscaloosa Grp was named by Smith and Johnson (1887) for thick outcrops of clay and sand in Tuscaloosa, Tuscaloosa County, Alabama, and along the Black Warrior River, Hale County, Alabama. In the eastern GoM region, the Tuscaloosa Grp is divided into three formations, in ascending order: the Lower Tuscaloosa, the Middle Tuscaloosa (Marine Tuscaloosa), and the Upper Tuscaloosa (Fig. 1B) (Mancini and Puckett, 2002). The Lower Tuscaloosa and the Upper Tuscaloosa in the subsurface of southwestern Alabama were correlated to the Lower Coker and Upper Gordo formations at the surface of west-central Alabama (Mancini et al., 1987). Additionally, the Tuscaloosa Grp at the surface in Mississippi is also divided into the Coker and Gordo formations. According to the USGS, the Lower Tuscaloosa in southern Mississippi and Alabama comprises two members known as the Lower Massive Member and the Upper Stringer Member (Boswell and Lang, 1957). In southwestern Alabama, the Lower Tuscaloosa is divided into two major units, including the lower Massive Sand Member and the upper Pilot Sand Member (Mancini et al., 1987). Furthermore, the Massive Sand of the Lower Tuscaloosa is divided into three units, which are, in ascending order, a basal sandstone unit, an interbedded sandstone and claystone unit, and a massive sandstone unit. The Pilot Sandstone Member is divided into a lower claystone unit and an upper Pilot Sandstone unit. The Massive Sand Member of the Lower Tuscaloosa sits unconformably on Lower Cretaceous strata in southwestern Alabama (e.g., Mancini et al., 1987; Woolf and Wood 2010; Woolf, 2012).

The Middle Tuscaloosa contains gray, micaceous, fossiliferous calcareous claystone interbedded with glauconitic calcareous siltstone and very fine sandstone (e.g., Mancini et al., 1987; Mancini and Puckett, 2002). The Middle Tuscaloosa conformably overlies the Pilot Sand Member of the Lower Tuscaloosa, and it thickens downdip toward coastal and offshore Alabama (e.g., Mancini et al., 1987; Mancini and Puckett, 2002).

The Upper Tuscaloosa is situated above the Middle Tuscaloosa, and it has been described as glauconitic, fossiliferous fine to medium sandstone interbedded with shale and siltstone (e.g., Mancini et al., 1987; Zubi et al., 2025). In southern Mississippi, the Upper Tuscaloosa consists of red to dark gray, micaceous shale, purple to gray mudstone, as well as white, very fine to coarse, porous, and micaceous sandstone (Dinkins, 1969). In southwestern Alabama, it comprises greenish-gray, fossiliferous, fine to medium-grained sandstone that is interbedded with green shales and siltstone (Mancini et al., 1987). The Upper Tuscaloosa in southwestern Alabama has an average thickness of ~114 m (375 ft) (Mancini et al., 1987), whereas it ranges in thickness from 147 to 192 m (482–629.9 ft) along the Mississippi-Louisiana border (Dinkins, 1966).

2.3. Timing, cyclicity, and deposition of the Tuscaloosa Group

The Tuscaloosa Grp is late Cenomanian to late Turonian (~95–89.8 Ma) (e.g., Mancini et al., 1987; Mancini and Puckett, 2002). It has been suggested that the unconformity separating the Lower Tuscaloosa from older Lower Cretaceous rocks was due to subaerial erosion that was governed by tectonic uplift or global sea level fall (e.g., Mancini and Puckett, 2005; Salvador, 1991). During the beginning of the Late Cretaceous, global sea level rise (e.g., Miller et al., 2005; Haq, 2014) produced transgressive strata

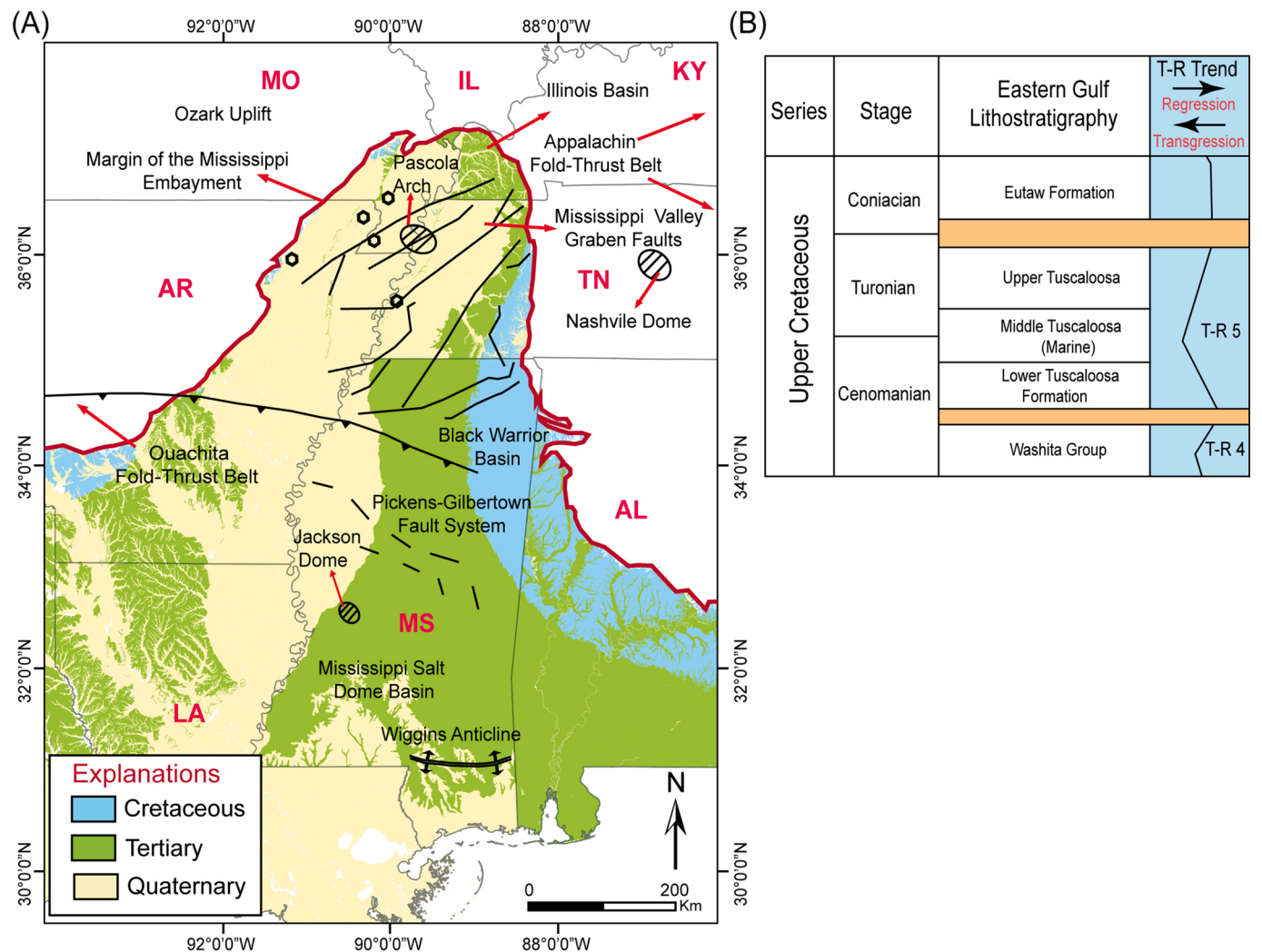


Fig. 1. A) The MSE with major structural elements. The Illinois Basin, Ozark Uplift, and Nashville Dome are sourced from [Ervin and McGinnis \(1975\)](#). The Appalachian Fold-Thrust Belt and Ouachita Fold-Thrust Belt are from [Hatcher \(1989\)](#). Thick lines represent the Mississippi Valley Graben faults ([Johnson et al., 1994](#)). Open polygons indicate Mesozoic alkalic plutons ([Hildenbrand et al., 1982](#)). The Pascola Arch and Jackson Dome are detailed by [Cox and Van Arsdale \(1997\)](#). The Pickens-Gilbertown Fault System and Wiggins Anticline are from [Dockery and Thompson \(2016\)](#). Note that the symbols used to represent the geological features are not to scale. Abbreviations: AR = Arkansas, MO = Missouri, IL = Illinois, KY = Kentucky, TN = Tennessee, AL = Alabama, MS = Mississippi, and LA = Louisiana. B) Stratigraphic column of the lower Upper Cretaceous in the eastern GoM region, modified from [Mancini and Puckett \(2002\)](#).

in the GoM Coast region and the MSE (e.g., [Chasteen, 1983](#); [Mancini et al., 1987](#)). This rise in global sea level was coeval with a warm climate (greenhouse) that persisted throughout the Early and Late Cretaceous ([Frakes, 1979](#)). Deposition of the Lower Tuscaloosa was initiated during the late Cenomanian with a transition in the depositional environment from fluvial and deltaic to marine (e.g., [Mancini et al., 1987](#); [Mancini and Puckett, 2002](#)). According to [Haq \(2014\)](#), global sea level rose from 220 to 240 m between 95 and 93.8 Ma, coincident with the deposition of the Lower Tuscaloosa. [Mancini and Puckett \(2002\)](#) documented that the Lower Tuscaloosa represents the beginning of the transgressive episode of the T-R 5 sequence (Fig. 1B) of the Eastern Gulf Coast region. It was believed that the Lower Tuscaloosa is probably sourced mostly from the Appalachian highland via ancient feeder valleys oriented north to south and northeast to southwest. Additionally, the Ouachita region may have served as a secondary source for the Lower Tuscaloosa, based on mineralogical evidence ([Woolf, 2012](#)). The Middle Tuscaloosa was deposited between the late Cenomanian and the early Turonian, ~93.8–92 Ma (e.g., [Dockery, 1996](#); [Mancini and Puckett, 2002](#); [Lowery et al., 2017](#)). According to their

findings, the lower interval of the Middle Tuscaloosa represents the final stage of the backstepping section and the completion of the T-R 5 sequence of the GoM Coast region, while the upper section of the Middle Tuscaloosa represents the beginning of the regressive cycle of the T-R 5 sequence (Fig. 1B). It is important to note that deposition of the Middle Tuscaloosa coincided with the highest peak of global sea level during the Late Cretaceous, which was ~250 m higher than the present-day sea level ([Haq, 2014](#)). The Middle Tuscaloosa was suggested to have originated in marginal to marine shelf settings (e.g., [Mancini et al., 1987](#); [Mancini and Puckett, 2002](#)). The Upper Tuscaloosa is middle and late Turonian (92–89.8 Ma) in age. During its deposition, global sea level dropped from 240 to 210 m relative to modern sea level ([Haq, 2014](#)). According to the global sea level model of [Miller et al. \(2005\)](#), the Tuscaloosa is associated with a slight increase in global sea level, with a drop and rise in the short-term sea level. The Upper Tuscaloosa was correlated to the regressive phase of the T-R 5 sequence of the Eastern Gulf Coast region, representing the infilling phase of the GoM (Fig. 1B) ([Mancini and Puckett, 2002](#)). The Upper Tuscaloosa

was probably deposited in fluvial, deltaic, and marine settings (e.g., Mancini et al., 1987; Ambrose et al., 2015).

3. Data and methods

3.1. Data collection

Geological and geophysical data, including wireline logs from nine wells (Fig. 2), core data from four wells (Table 1), well reports, and selected samples from Tuscaloosa outcrops (Fig. 2), were used in this study. These data sources were strategically selected to elucidate the spatial distribution of Tuscaloosa sequences along southeast-northwest and east-west transects. The Geological Survey of Alabama (GSA) and the Mississippi Oil and Gas Board provided well log data used in this study, including spontaneous potential (SP) and gamma-ray (GR) logs. Well reports for Alabama wells were obtained from the GSA; we do not have permission to reproduce them here, but they are available from the GSA. Well reports for Mississippi wells are publicly available through the Mississippi Oil and Gas Board (<https://www.ogb.state.ms.us/>). Furthermore, core data from four wells in southwestern Alabama was provided by the GSA for descriptive purposes and sampling. The core dataset contains partial core materials and chips. Core samples were systematically collected at ~3 m (10-foot) intervals across the four cored wells (Table 1). During this investigation, comprehensive examination of lithology of all available cores within each 10-foot interval was conducted. Hand samples were also collected from five exposures located in west-central Alabama and east-central Mississippi for lithologic description (Fig. 2).

3.2. Cores and measured sections

This study utilizes cores collected from four wells located in the southeastern region of Alabama (Fig. 2 and Table 1). The cores were analyzed to examine their lithologic characteristics, including bed thickness, average grain size, grain shape, sorting, color, and any visible sedimentary features. Field-based outcrop investigations were carried out at five different locations in west-central Alabama and east-central Mississippi. These sites were selected mainly because of their locations along the Tuscaloosa outcrop belt (Fig. 2 and Table 2). Fieldwork included a basic description of lithology, including sediment type, measuring bed thickness, and defining any sedimentary structures. A total of 12 samples were collected from the measured sections for lithological description, with a particular focus on average grain size, grain shape, and sorting. Once the lithologic properties were recorded from both the cores and the hand samples, lithofacies were then defined based on texture using three variables: average grain size, sorting, and mud content.

3.3. Sequence stratigraphic analysis

Wireline logs were used to interpret lithology such as sands or muds, log stacking patterns, depositional systems, stratigraphic surfaces, and systems tracts. Eight SP logs and one GR log from nine wells located in southwestern Alabama and southeastern central Mississippi (Fig. 2) were digitized using Log Evolve software. The digitized data were imported into Schlumberger Petrel software. Then, the wireline logs were calibrated with core descriptions and well reports (mud logs and cutting description) to establish a relationship between lithology and wireline log values. Once this relationship was established, the lithology of uncored intervals was interpreted. Following established methodologies, stacking patterns, stratigraphic surfaces, systems tracts, and sequences were systematically defined across all

studied wells according to the sequence stratigraphic principles of Mitchum et al. (1977) and Van Wagoner et al. (1990). Key stratigraphic surfaces identified from wireline log analysis include maximum flooding surfaces (MFSs), transgressive surfaces (TSs), and sequence boundaries (SBs). TSs are characterized in SP and GR logs by increased gamma-ray and spontaneous potential readings, where log motifs transition from funnel-shaped to bell-shaped patterns, indicating the onset of retrogradational stacking. MFSs are identified in wireline logs by peak gamma-ray readings and maximum negative deflections in SP logs, typically positioned near the zero baseline representing the shale reference level. SBs are recognized by abrupt transitions in log stacking patterns from retrogradational to progradational or aggradational architectures. These stratigraphic surfaces were utilized to delineate the extent and thickness of systems tracts, followed by definition of depositional sequences bounded by SBs. Depositional environment interpretations within each systems tract were conducted using wireline log characteristics following the methodologies of Cant (1992) and Rider (1996). This approach was implemented where core data and well reports were unavailable or provided insufficient detail for comprehensive analysis.

To quantify the coarse fraction within each systems tract, cumulative thicknesses of sand and gravel beds were calculated and divided by the total systems tract thickness to determine proportional values. For systems tracts lacking gravel deposits (such as HSTs), sand thickness alone represented the coarse fraction. This methodology adapts the sand fraction proxy approach of Ainsworth et al. (2018) from parasequence-scale to systems tract-scale analysis. Mean coarse fraction values were subsequently calculated for each systems tract across all wells to establish regional grain size distribution patterns reflective of relative sea-level fluctuations.

3.4. Isopach and depth maps

Depth and isopach maps were created using data from the nine wells to determine the lateral and vertical extent of the stratigraphic surfaces and systems tracts of the Tuscaloosa Grp. Initially, depth maps were created using Petrel Software for most stratigraphic surfaces identified from the wireline logs. Subsequently, isopach maps were generated for each systems tract by subtracting the depth of the upper surface from the depth of the lower surface of each systems tract. Following this, block diagrams of paleogeography were constructed, integrating information from both the depth maps and isopach maps. Additionally, details of the depositional environment interpretations from lithofacies and log facies were used to establish the paleogeographic maps.

3.5. Identification of systems tracts from the Tuscaloosa outcrops

To determine the extent of the identified systems tracts on the surface, the dip direction of each stratigraphic surface was determined on each depth map. After that, the dip amount was calculated using the following formula (Kehew, 2006):

$$\text{Dip angle } (\theta) = \tan^{-1}(\Delta h / D).$$

Where Δh is the elevation difference between two contour lines on the depth map, and D is the map distance between the two contour lines. Once the dip amount was determined from each stratigraphic depth map, a map distance was measured from the closest well to the outcrops to each of the five studied sections. Then, the following formula (Kehew, 2006) was used to find at

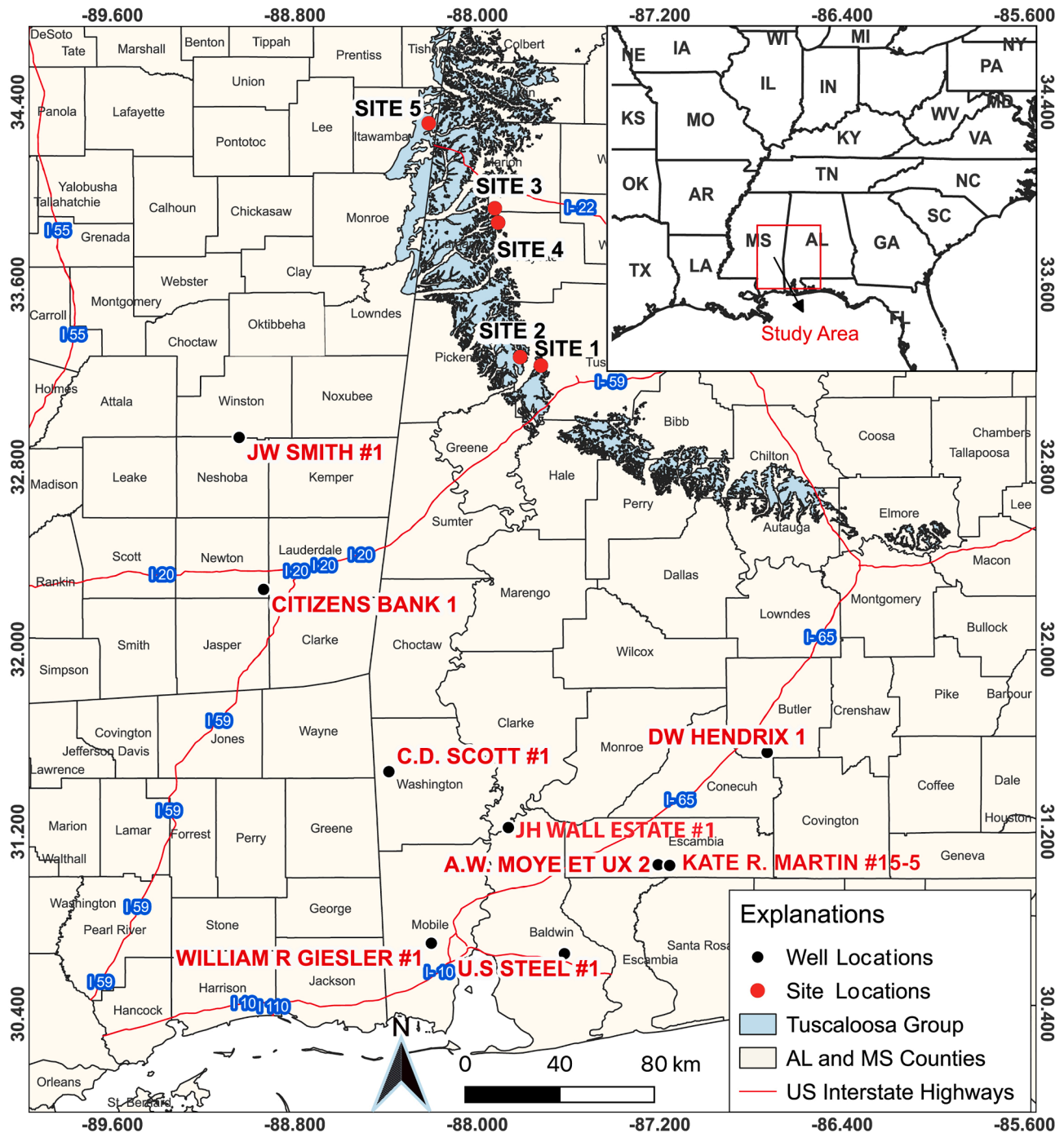


Fig. 2. A map displaying well locations and outcrop localities of measured sections.

what elevation each stratigraphic surface can be found on the surface:

$$\Delta h = D \times \tan^{-1}(\theta)$$

Where Δh represents the map distance from the projected strike line of each stratigraphic surface in the closest well to the outcrops to each of the measured sections. θ is the dip amount of

each stratigraphic surface. It is important to note that we attempted to correlate all identified stratigraphic surfaces within the Lower Tuscaloosa to the outcrops of the Coker Fm, which is equivalent to the Lower Tuscaloosa at the surface (Mancini et al., 1987). Stratigraphic surfaces of the Upper Tuscaloosa were correlated to the outcrops of the Gordo Fm, which is equivalent to the Upper Tuscaloosa on the surface (Mancini et al., 1987).

Table 1

Locations of wells with associated core data used in this study.

Well Name	Latitude	Longitude	Core Interval (m)	County and State
C.D. Scott #1	31.46312°N	88.38758°W	1675–1,795, 1848–1965	Washington, AL
William R. Giesler #1	30.71036°N	88.20137°W	2405–2,465, 2495–2,515, 2551–2566	Mobile, AL
JH Wall Estate #1	31.2177°N	87.86349°W	1375–1,445, 1585–1,680, 1735–1,743, 1747–1784	Clarke, AL
A.W.Moye Et Ux2	31.05469°N	87.20642°W	1805–1,815, 1817–1,826, 1857–1870	Escambia, AL

AL = Alabama and MS = Mississippi.

Table 2

Locations of the studied five measured sections.

Site	Nearest road	Latitude	Longitude	Vertical thickness (m)	County and State
1	Hillview Rd.	33.244499°N	87.720916°W	2.25	Tuscaloosa, AL
2	Highway 82	33.281676°N	87.811941°W	3.25	Tuscaloosa, AL
3	Bankhead Ave	33.934161°N	87.787147°W	4.80	Marion, AL
4	County Road 24	33.871436°N	87.772805°W	2.40	Fayette, AL
5	MS Highway 23	34.307135°N	88.212889°W	3.70	Itawamba, MS

AL = Alabama and MS = Mississippi.

Table 3

Lithofacies defined from cores and their SP log patterns. Only lithofacies identified from core analysis are included; outcrop-only lithofacies are excluded to limit the scope to core to log relationships.

Lithofacies	Log facies
CL1	Right blocky and serrated
CL2	Serrated right blocky and serrated
SH1	Right blocky and serrated right blocky
SH2	Right blocky and serrated right blocky
ST1	Right blocky and serrated
VFS1	Bell-shaped and left blocky
VFS2	Left blocky and serrated
FS1	Serrated, left blocky, and bell-shaped
FS2	Left blocky, serrated, and funnel-shaped
MS1	Left blocky
MS2	Left blocky
CS1	Left blocky
LS1	Right blocky
LS2	Left blocky

4. Results

4.1. Lithofacies and log facies

Six distinct lithofacies were identified within the Tuscaloosa Group based on comprehensive descriptions of partial cores, chips, and hand samples. This section focuses specifically on the lithofacies documented from cored intervals and measured sections, providing interpretations of their respective depositional environments. The lithofacies classification encompasses claystone (CL1 and CL2), shale (SH1 and SH2), siltstone (ST1), sandstone (VFS1, VFS2, FS1, FS2, MS1, MS2, MGS1, CS1, CSG1), gravel (G1), and carbonate (LS1, LS2). Table 3 provides a systematic summary of the log motif types correlated with each lithofacies (Fig. 3). In the subsequent section, we explain the lithofacies identified from cores associated with only four wells that are illustrated in Table 1, their associated log motifs, as well as the lithofacies defined from Tuscaloosa outcrops. For wells lacking core data, we relied on the diagnostic log motifs of defined lithofacies from cores, as presented in Table 3. Sandstone lithofacies typically exhibit leftward-trending blocky log motifs (Figs. 4A and 5A), while mudrock lithofacies, comprising claystone and shale, consistently display rightward-trending blocky signatures (Figs. 4A and 5A). Serrated log motifs are interpreted as representing sandstone interbedded with siltstone or mudrock lithofacies (Figs. 4A and 5A).

4.1.1. Claystone (CL) lithofacies

CL1 lithofacies: This lithofacies is characterized by gray to light brown claystone that is non-to slightly calcareous. It contains only clay-sized materials and does not show any sedimentary structures. The CL1 lithofacies is found only in the subsurface in three wells and tends to occur in the Upper, Middle, and Lower Tuscaloosa. It ranges in thickness from 2.4 to 9.1 m (8–30 ft). CL1 is typically bounded above and below by shale lithofacies and siltstone lithofacies, and it is rarely bounded above and below by sandstone lithofacies. According to the final well report, this lithofacies shows shell impressions near the top and bottom of the Lower Tuscaloosa and Middle Tuscaloosa, respectively.

The SP readings corresponding to this lithofacies range from –4 to –30 mV in well C.D. Scott #1 and from –10 to –30 mV in well JH Wall Estate #1. The log trend of the CL1 lithofacies predominantly displays a right-blocky to serrated-blocky shape, with a prevalence of a serrated trend, especially when the lithofacies is thin and situated between beds of siltstone and sandstone (Fig. 3D).

Interpretation: Claystone is found in low-energy areas within various depositional environments, such as deltaic, fluvial, estuarine, and shelf settings (McBride, 1974). In the Middle Tuscaloosa, this type of sediment is associated with distinct right-blocky log patterns, indicating continuous deposition of fine-grained materials and suggesting a shelf depositional environment (e.g., Cant, 1992; Radwan and Sen, 2020). In the Lower Tuscaloosa, this claystone lithofacies is bordered above and below by thick sandstone intervals of an incised valley setting (Figs. 4A and 5A). This suggests that the CL1 lithofacies may have been deposited in an estuary or prodelta, which is probably attributed to high-order sea-level fluctuations (Woolf and Wood, 2010).

CL2 lithofacies: This lithofacies primarily consists of massive, light to dark gray, and brown claystone. It contains ~5–10% sand-sized micas and a few glauconite grains. It is found in only two wells: JH Wall Estate #1 and C.D. Scott #1, with a thickness ranging from <1.52 to 5.4 m (5–18 ft). The CL2 lithofacies is present in the Upper and Middle Tuscaloosa and is typically bordered above and below by the shale (SH1, SH2) and siltstone (ST1) lithofacies.

The SP values for this lithofacies show variability, ranging from –2.28 to –37 mV in well JH Wall Estate #1 and from –26 to –40 mV in well C.D. Scott #1. In the SP log, this lithofacies is situated within a serrated right-blocky trend (Fig. 3D), frequently correlating with a serrated log trend when coarser sediments bound it.

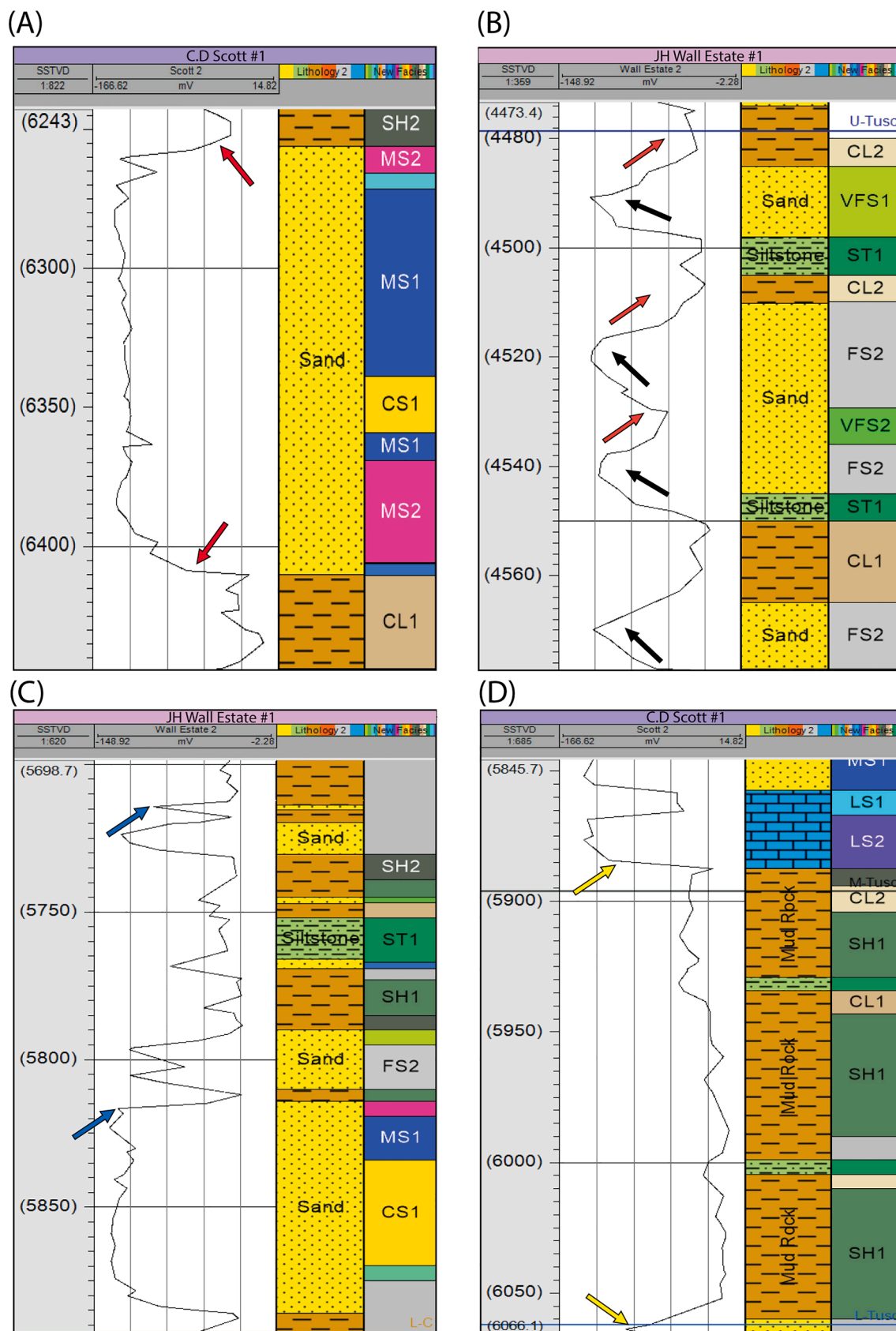


Fig. 3. SP log responses and log shapes of selected core lithofacies. A) A left-blocky log shape is associated with facies MS1, MS2, CS1, and LS2. Red arrows show the top and bottom sharp contacts that indicate sudden lithology shifts. B) A series of funnel (black arrows) and bell (orange arrows) shaped log trends. The funnel log motifs indicate a coarsening-upward trend (e.g., SL1 to FS2 and ST1 to VFS1). The bell log motifs show a fining-upward trend (e.g., FS2 to VFS2 and VFS1 to CL2). C) Blue arrows show the top and bottom of a serrated log shape that is correlated with the changes in lithofacies composition between sand, siltstone, claystone, and shale facies. D) Yellow arrows show the top

Interpretation: Claystone of this lithofacies likely represents deposition under low-energy conditions (e.g., McBride, 1974). The presence of mica flakes in claystone suggests periods of high salinity and slow sedimentation rates (Milne and Earley, 1958). Within the Middle Tuscaloosa interval, this lithofacies, which is similar to lithofacies CL1, is correlated with a thick, right-blocky log shape (Fig. 3D), which is typically interpreted as representing shelf deposits (e.g., McBride, 1974; Cant, 1992; Radwan and Sen, 2020). In the upper interval of the Upper Tuscaloosa in well JH Wall Estate #1, this lithofacies is associated with a succession that shows an overall coarsening-upward trend (Figs. 4A and 5A), which is consistent with a prodeltaic setting (Van Wagoner et al., 1990).

4.1.2. Shale (SH) lithofacies and log facies

SH1 lithofacies: This lithofacies primarily consists of light to dark gray and green shale that is slightly to highly calcareous. It often shows parallel laminations and shares similarities with the CL1 lithofacies in its low quantities of sand-sized grains. This lithofacies was only defined in the subsurface through the William R. Giesler #1, JH Wall Estate #1, and C.D. Scott #1 wells. According to the well reports, the Middle Tuscaloosa in well C.D. Scott #1 contains impressions of ammonites, gastropods, and other shell impressions within this lithofacies. The thickness of this lithofacies ranges from 0.6 to 16.7 m (2–55 ft), and it is primarily found in the Middle Tuscaloosa, where it tends to be associated with claystone and siltstone lithofacies. This lithofacies occurs in smaller quantities within the Upper and Lower Tuscaloosa.

The SP values of this lithofacies vary from –2 mV to –34 mV in C.D. Scott #1; –27 mV to –37 mV in well Wall Estate #1; and –8 mV to –24 mV in well William R. Giesler #1. It exhibits right-blocky to serrated right-blocky shapes in the well log (Fig. 3C and D).

Interpretation: Shale typically represents deposition from suspension in low-energy depositional environments. This lithofacies is found to be associated with other fine-grained lithofacies such as CL1, CL2, and SH2, which probably suggests deposition on a marine shelf, likely in the distal portion (Deconinck et al., 2021). The right blocky shape that is characteristic of the Middle Tuscaloosa (Fig. 3D) further supports the interpretation that this lithofacies originated in a marine shelf setting (Van Wagoner et al., 1990). In the Lower Tuscaloosa, particularly in the lower section, this lithofacies correlates with serrated-blocky log motifs in the lower section of the Lower Tuscaloosa, indicating variations in lithology that are probably associated with high-frequency sea-level fluctuations. Mancini et al. (1987) interpreted shales of the Lower Tuscaloosa, which here correlate with the SH1 lithofacies, to represent deposition in a shelf to deltaic setting.

SH2 lithofacies: This lithofacies is made up of shale that can range in color from light gray to dark gray. Additionally, the shale contains a small amount of sand-sized mica grains, making up ~3–10% of the total volume of the rock. Occasionally, this shale is slightly calcareous and shows trace amounts of green glauconitic grains. Well reports describe this lithofacies at the top of the middle Tuscaloosa as highly fossiliferous. The thickness of this lithofacies ranges from 1.2 to 8.2 m (4–27 ft), and it is found only in the Middle and Lower Tuscaloosa. It is bounded by the SH1 lithofacies of the Middle Tuscaloosa and the very fine to fine sand lithofacies of the Lower Tuscaloosa.

The SP values for this lithofacies range from –4 to –32 mV in well C.D. Scott #1 and –16 to –29.5 mV in well Wall Estate #1, and it corresponds to right-blocky and serrated right-blocky log motifs (Figs. 4A and 5A).

Interpretation: Within the Middle Tuscaloosa, this lithofacies, similar to lithofacies SH1, likely indicates a marine environment due to the presence of invertebrate fossils and glauconite grains. The presence of mica flakes in this lithofacies, particularly in the Middle Tuscaloosa interval, suggests deposition in calm waters with low sedimentation rates (e.g., Milne, 1958; Burke, 1985). When comparing this to the log shape associated with this lithofacies in the Middle Tuscaloosa interval (Figs. 4A and 5A), it is likely that this lithofacies represents deposition in a distal shelf environment (Galloway and Hobday, 1983).

4.1.3. Siltstone (ST) lithofacies and log facies

ST1 lithofacies: This lithofacies consists of dark to light gray siltstone that is massive and slightly micaceous. It is less dominant than the shale and claystone lithofacies and is found in all cored wells except well A.W. Moya Et Ux2. This lithofacies is mostly present within the Upper and Lower Tuscaloosa and rarely in the Middle Tuscaloosa. Well reports indicate that this lithofacies is often glauconitic and fossiliferous, with shell impressions observed in some intervals of the Upper and Lower Tuscaloosa in well William R. Giesler #1, as well as in the middle section of the Middle Tuscaloosa (Fig. 5) in well C.D. Scott #1. The thickness of this lithofacies is relatively thin compared to other lithofacies, ranging from 0.6 to 10 m (2–32.8 ft). This lithofacies mostly occurs with the CL1 and SH1 lithofacies and rarely with the CL2 and SH2 lithofacies.

The SP values for this lithofacies vary from –21 to –26 mV in well C.D. Scott #1 and from –41 to –49 mV in well JH Wall Estate #1. Similar to the claystone and shale lithofacies, this lithofacies exhibits mostly right-blocky to serrated right-blocky shapes in the corresponding SP log (Fig. 3C).

Interpretation: Siltstone can be associated with various depositional environments, including slope, shelf, and deltaic settings. This lithofacies is mainly associated with a right serrated-blocky pattern (Figs. 4A and 5A), which is consistent with a proximal shelf setting (e.g., Van Wagoner et al., 1990; Cant, 1992; Radwan and Sen, 2020). In well William R. Giesler #1, the ST1 lithofacies correlates with a funnel-shaped log motif, and it is bounded above by the MS2 lithofacies, suggesting a shallowing upward to an associated deltaic environment, where this lithofacies likely represents prodeltaic deposits (Parker, 1977; Galloway and Hobday, 1983).

4.1.4. Sandstone lithofacies and log facies

The sand lithofacies are divided by particle size into very fine sand (VFS), fine sand (FS), medium sand (MS), and coarse sand (CS). Interbedded coarse sand and gravel lithofacies are abbreviated as CSG.

VFS1 lithofacies: This lithofacies is characterized by very fine sand and sandstone with no to very low mud content. Sand grains are moderately well to well sorted, and grains vary from sub-rounded to angular. The sandstone of this lithofacies is light to dark gray and light yellow, massive to laminated, calcareous to non-calcareous, and often contains mica and glauconite grains. This lithofacies is present in all cored wells and in the measured section at site 2. The thickness of this lithofacies ranges from 0.8 m

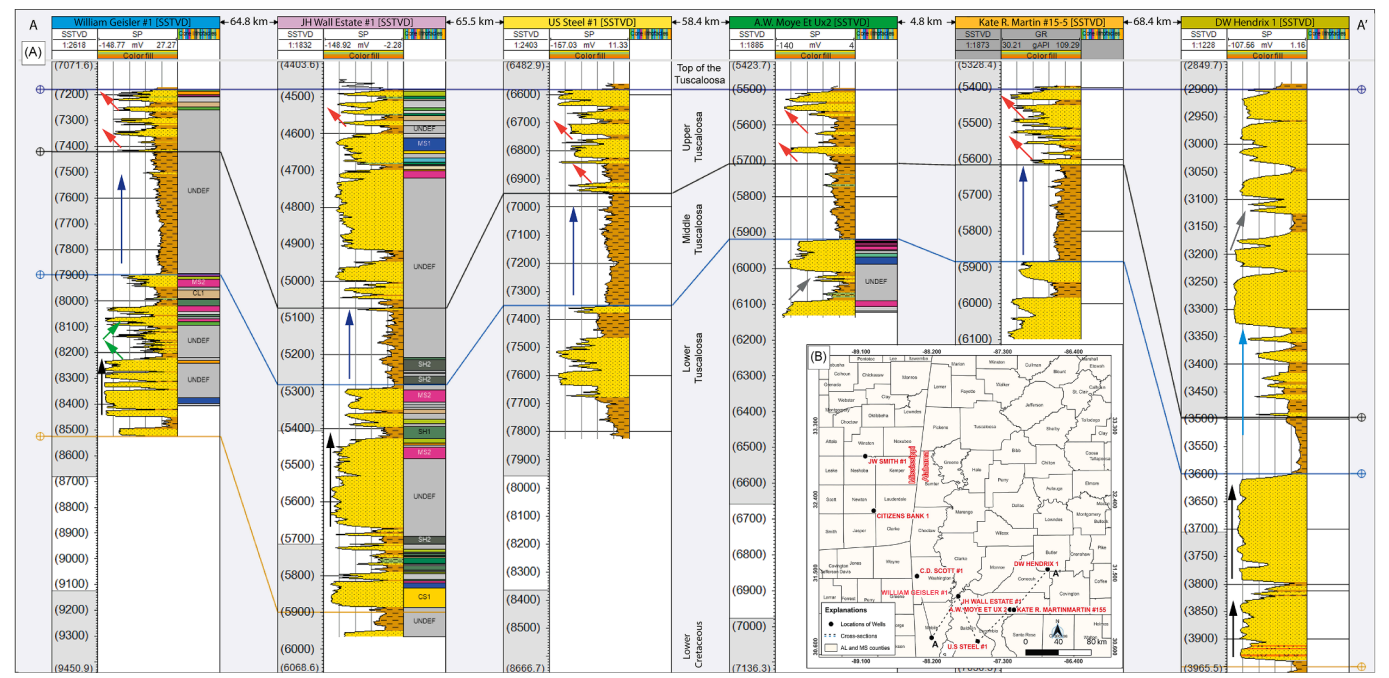


Fig. 4. (A) Stratigraphic cross-section (A-A') showing the lateral and vertical distributions of lithofacies and log facies of the Tuscaloosa Grp. Note that the top of the Upper Tuscaloosa is used as a datum. Black arrows show left-blocky to left-serrated-blocky log motifs. Dark blue arrows show right-blocky log motifs associated mostly with the mudrock facies of the Middle Tuscaloosa. Red arrows show funnel-shaped log motifs, which indicate changes in lithology from mudrock or siltstone facies to sandstone facies. A light blue arrow shows a serrated log trend, indicating variation in lithology. Gray arrows exhibit bell-shaped log motifs indicating fining-upward successions. See Fig. 5 for lithology symbol explanations. Vertical depth provided in feet. Datum = top of the Tuscaloosa Grp. (B) Reference map showing the trend of the A-A' cross-section illustrated in (A).

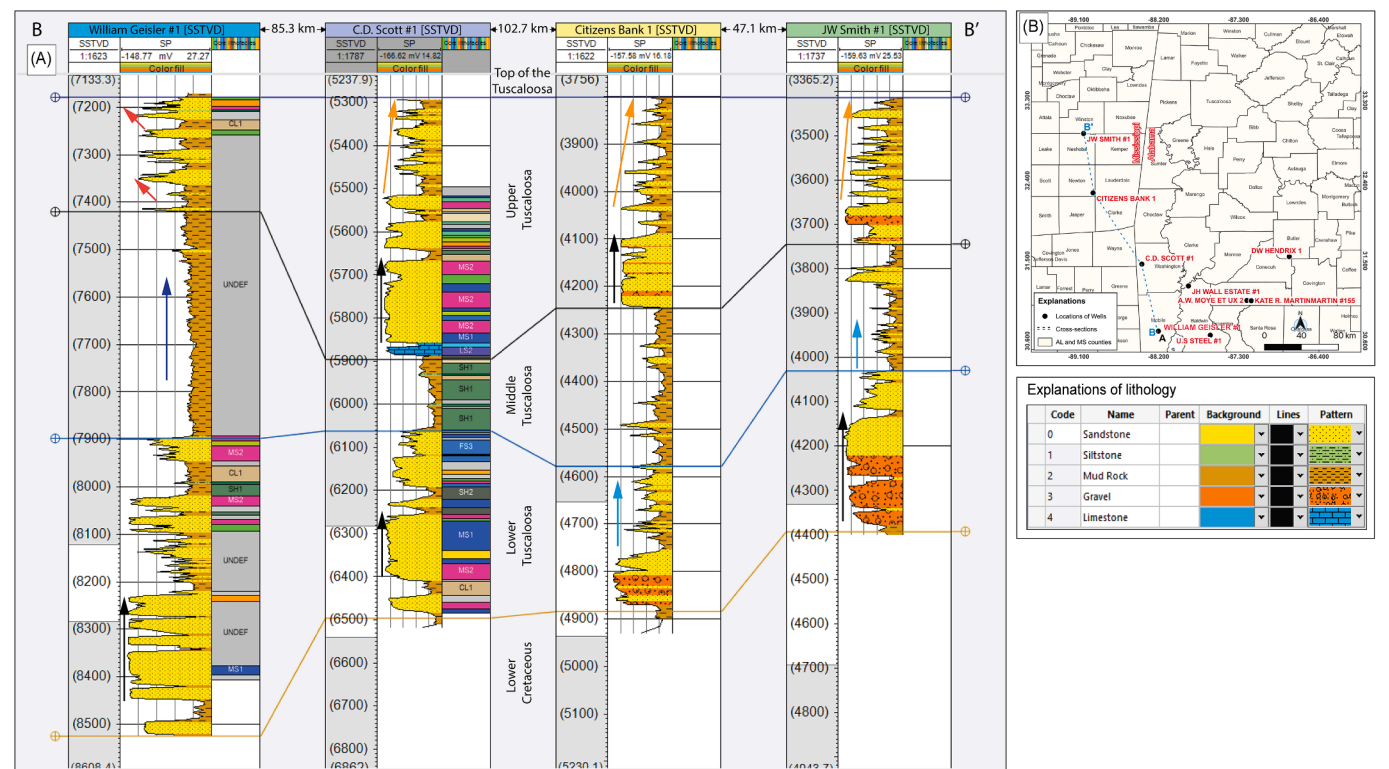


Fig. 5. (A) Stratigraphic cross-section (B-B') showing the lateral and vertical distributions of lithofacies and log facies of the Tuscaloosa Grp. Note that the top of the Upper Tuscaloosa is used as a datum. Black arrows show left-blocky to left-serrated-blocky log motifs. Dark blue arrows show right-blocky log motifs associated mostly with the mudrock facies of the Middle Tuscaloosa. Red arrows show funnel-shaped log motifs that indicate changes in lithology from mudrock or siltstone facies to sandstone facies. The light blue arrow shows serrated log motifs, suggesting variation in lithology. Gray arrows exhibit bell-shaped log motifs indicating fining-upward successions. The orange arrow shows an overall fining-upward trend. Vertical depth provided in feet. Datum = top of the Tuscaloosa Grp. (B) Reference map showing the trend of the B-B' cross-section illustrated in (A).

(2.6 ft) at the surface to ~3 m (10 ft) in wells C.D. Scott #1 and William R. Giesler #1.

The SP values associated with this lithofacies exhibit a range of –66 to –93 mV in well William R. Giesler #1 and a range of –40 to –130 mV in well C.D. Scott #1. The shapes of the SP log for this lithofacies are predominantly funnel to bell and occasionally display left-blocky patterns (Fig. 3B).

Interpretation: Very fine sandstone alone is not diagnostic of a specific depositional environment. However, the presence of glauconite grains, which are often abundant in this lithofacies, may indicate deposition in a proximal shelf setting, likely a barrier island (Bhattacharyya and Chanda, 1970), as previously mentioned by Mancini et al. (1987).

VFS2 lithofacies: This lithofacies consists of very fine sand, which ranges in color from gray to brown. The sand grains are mostly angular to subangular, and there are also some mica and glauconite grains present. The sandstone is mostly massive, although planar laminations are visible in certain intervals. This lithofacies is found only in the subsurface and has a thickness ranging from 0.6 to 3.9 m (2–13 ft), with an average of 2.1 m (7 ft). This lithofacies is typically bounded above and below by other fine and medium-sized sandstone lithofacies (MS1, MS2, FS1), and it is rarely bounded by claystone and shale lithofacies.

The SP values associated with this lithofacies range from –26 to –84 mV in well William R. Giesler #1 and –49 to –122 mV in well Wall Estate #1. In wireline logs, this lithofacies primarily displays left-blocky to serrated log motifs, with funnel log motifs being rare.

Interpretation: The poor sorting and high mud matrix of this lithofacies may indicate deposition in a low-energy environment, where sedimentation occurs from saltation and suspension (Johansson and Stow, 1995). The occurrence of this lithofacies within serrated to funnel log motifs, as well as the presence of glauconite, is consistent with deposition in marine settings, specifically the proximal portion of the shelf (Galloway and Hobday, 1983). Mancini et al. (1987) also mentioned deposition in a shelf setting as a possible environment for the fine sandstones that occur at the top of the Lower Tuscaloosa in southwestern Alabama, which aligns with the stratigraphic position of this lithofacies.

FS1 lithofacies: This lithofacies consists of gray to dark gray fine sandstone. The sandstone is well to very well sorted and contains a low to very low amount of matrix. It is massive and often calcareous and slightly glauconitic. The majority of sand grains are subrounded to angular. The thickness of this lithofacies varies from 0.9 to 3 m (3–10 ft). This lithofacies is found between various lithologies, including very fine sandstone, medium sandstone, and sometimes shale lithofacies, and it is typically present in the Upper and Lower Tuscaloosa (Figs. 4 and 5).

The SP values associated with this lithofacies range from –40 to –146 mV in well C.D. Scott #1, –90 to –93 mV in well A.W. Moyer Et Ux2, and –67 to –102 mV in well William R. Geisler #1. The SP log patterns of this lithofacies are serrated, right-blocky, and bell-shaped.

Interpretation: The well-sorted nature of the sand and very low matrix content can indicate deposition with relatively higher energy. Within the Lower Tuscaloosa, this lithofacies correlates with thick, left-blocky log motifs, indicating deposition in an incised valley. Notably, this fine-grained lithofacies consistently overlies medium-grained sandstone lithofacies, suggesting a fining-upward succession typical of a fluvial environment (Galloway and Hobday, 1983).

FS2 lithofacies: This lithofacies is characterized by fine sandstone that is light to dark gray, angular to subangular, moderately to poorly sorted, and has moderate to high matrix content. Some beds are slightly calcareous, micaceous, and glauconitic. The

sandstone is mostly massive, except in some intervals where mud lenses and parallel laminations of dark grains, particularly micas and asymmetrical ripples, are present. The thickness of this lithofacies ranges from 1.5 to 6.7 m (5–22 ft), and, like lithofacies FS1, it occurs only within the Upper and Lower Tuscaloosa. According to the well reports, this lithofacies contains shell impressions, particularly at the top of the Lower Tuscaloosa in well William R. Geisler #1. This lithofacies is bounded above and below by various lithologies, including very fine sandstone lithofacies and medium sandstone lithofacies.

The SP values for this lithofacies fluctuate, ranging from –95 to –133 mV in well C.D. Scott #1 and –76 to –129 mV in well J.H. Wall Estate #1. This lithofacies shows various log motifs in the wireline logs, including left-blocky, serrated, and funnel-shaped (Fig. 3B and C).

Interpretation: The presence of poor sorting, a moderate amount of matrix, and shale lenses in this lithofacies suggests that it was deposited in a marginal marine environment with alternating periods of high and low energy. The presence of shale lenses, especially in the Upper Tuscaloosa, may indicate deposition influenced by tides (Dalrymple et al., 1992). This lithofacies in the Upper Tuscaloosa is correlated with log motifs that show a coarsening upward pattern (Figs. 4A and 5A), which we interpret as being associated with a tide-dominant delta (Galloway and Hobday, 1983).

MS1 lithofacies: The sandstone in this lithofacies is medium-sized, and the grains are subangular to subrounded. It is well to very well sorted and has little to no mud content. The color of the sandstone ranges from light gray to medium gray when found in the subsurface and from light yellow to orange when found at the surface. In some areas, the sandstone is slightly calcareous, moderately to highly glauconitic, and rarely micaceous. Sedimentary structures are not apparent in most cases, although cross and planar laminations can be seen in certain intervals. At site 1, the sandstone in this lithofacies is mostly massive, but horizontal laminations, cross laminations, and deformed bedding can occasionally be observed. The thickness of this lithofacies varies from 0.6 to 2.5 m (2–8.2 ft) on the surface and 0.6–3.7 m (2–12 ft) in the subsurface. This lithofacies is bounded by different lithologies, including the very fine sandstone lithofacies (VFS1), one other medium sandstone lithofacies (MS2), and, commonly, the coarse sandstone lithofacies (CS1).

In the wireline log, this lithofacies correlates with a left-blocky shape (Fig. 3A and C), and the SP values range from –66 to –133 mV in well C.D. Scott #1 and from –112 to –136 mV in well A.W. Moyer Et Ux 2.

Interpretation: This lithofacies is mostly correlated with left blocky motifs, particularly within the lower and middle portions of the Lower Tuscaloosa (e.g., well C.D. Scott #1 and JH Wall Estate) (Figs. 4A and 5B). This log trend for this lithofacies might indicate deposition in an incised valley, which agrees with a previous interpretation of sandstone lithofacies of the Lower Tuscaloosa in southwestern Alabama and southeastern Louisiana (e.g., Woolf and Wood, 2010; Ambrose et al., 2015). In the upper portion of the Lower Tuscaloosa, particularly evident in the C.D. Scott #1 and A.W. Moyer Et Ux2 wells, this lithofacies is characterized by abundant glauconites. Mancini et al. (1987) described sandstone with comparable characteristics, interpreting such lithofacies as indicative of a barrier island setting.

MS2 lithofacies: This lithofacies is characterized by light to dark gray, medium-sized, moderately to poorly sorted, and angular to subangular massive sandstone that exhibits a moderate matrix content. The sandstone is often calcareous, glauconitic, and micaceous. This lithofacies occurs both in the subsurface within the four cored wells and at the surface at sites 2 and 3. The

thickness of this lithofacies varies from 0.6 to 9.1 m (2–30 ft). This lithofacies is mainly bounded by the MS1 lithofacies, fine sandstone lithofacies (FS2), very fine sandstone lithofacies (VFS1, VFS2), and claystone lithofacies (CL1).

In the wireline log, this lithofacies shows a left-blocky trend (Fig. 3A), and the SP values associated with this lithofacies are > -130 mV in well C.D. Scott, -61 to -118 mV in well A.W. Moye Et Ux 2, and from -89 to -147 mV in well JH Wall Estate #1.

Interpretation: This lithofacies, like lithofacies MS1, is associated chiefly with left-blocky log motifs. Within the Lower Tuscaloosa, particularly the lower section, this lithofacies contains no glauconite, and it is found within a fining upward succession. This fining upward interval is found below 1949.5 m (6396 ft) in well C. D. Scott #1, and it is distinctive of a fluvial environment (Galloway and Hobday, 1983). The medium size of sand grains and moderate to poor sorting of this lithofacies in the lower section of the Lower Tuscaloosa might indicate variations in the energy regime (Heap and Nichol, 1997). This interpretation is similar to Mancini et al. (1987) and Woolf and Wood (2010), who described the medium sandstone of the lower section of the Lower Tuscaloosa as being deposited in a fluvial environment. In the upper portion of the Lower Tuscaloosa, specifically in well William R. Giesler #1 below -2407 m (-7900 ft) and well A.W. Moye Et Ux2 below -1804.4 m (-5920 ft), this lithofacies shows a significant amount of glauconite, and in certain sections, displays high fossil content, which indicates marine deposition for the upper section of the Lower Tuscaloosa.

MSG1 Lithofacies: This lithofacies occurs only at the surface, particularly at site 3, and it is composed of 3.5 m (11.4 ft) of friable orange sand interbedded with 3–30 cm thick gravel beds (Fig. 6B). The sand is medium-sized, moderately well-sorted, rounded to subrounded, and contains a very low matrix content ($>3\%$). The gravel is poorly sorted, and the size of the particles ranges from 4 to 60 mm. The sedimentary structures observed in this lithofacies include parallel laminations and trough cross-bedding, occasionally displaying gravel clasts mixed with medium-sized sands at the base of each cross-bed (Fig. 6B).

Interpretation: The grain properties and sedimentary structures in this lithofacies, such as trough cross-bedding, suggest that deposition likely occurred in fluvial environments, specifically braided streams (e.g., Cant and Walker, 1976; Seli and Finthan, 2022). The horizontal beds of gravel within this lithofacies are interpreted as lag deposits. The presence of both horizontal gravel beds and trough cross-bedding interbedded with medium sand can indicate deposition in longitudinal bars or minor channel fills (e.g., Miall 1985; Miall 1996). The presence of gravel lag deposits on the concave-up portion of each trough cross-bed (Fig. 6B) could be attributed to a decrease in flow energy, which allowed the gravel to settle on the riverbed.

CS1 Lithofacies: This lithofacies is characterized by medium to light gray, coarse, subrounded to subangular, well to very well sorted, and non to slightly calcareous sandstone that either lacks or contains a very low matrix content (0–10%). This lithofacies occurs only in the subsurface and is associated only with the Lower Tuscaloosa. This lithofacies is less dominant than the other sandstone lithofacies, and its thickness ranges from 6.1 to 8.8 m (20–29 ft). This lithofacies is bounded mostly by lithofacies MS1 and MS2.

The SP values for this lithofacies are > -98.3 mV in well JH Wall Estate #1 and > -129 mV in well C.D. Scott #1. In the wireline log, this lithofacies is correlated with a left-blocky shape (Fig. 3A).

Interpretation: This lithofacies is only found in the lower section of the Lower Tuscaloosa in wells C.D. Scott #1 and JH Wall Estate #1, near the contact between the Lower Tuscaloosa and the Lower Cretaceous. The absence of glauconite, the presence of well-

sorted grains, and the lithofacies's stratigraphic position may suggest that it was deposited in an incised valley by high-energy fluvial processes (e.g., Galloway and Hobday, 1983; Van Wagoner et al., 1990). This interpretation is further supported by the overall fining-upward trend observed above this lithofacies. Mancini et al. (1987) described similar sandstone beds with comparable textural properties in the lower section of the Lower Tuscaloosa in southwestern Alabama, attributing their origin to fluvial and deltaic settings.

CSG1 lithofacies: This lithofacies is composed mainly of orange friable sand interbedded with thin gravel beds. The thickness of these horizontal gravel beds ranges from 1.8 to 2.5 cm, and they occur every 15–30 cm (0.5–0.9 ft). The sand is coarse, angular to subangular, often pebbly, moderately sorted, and has no matrix content. The grain size of the gravel ranges from 7 to 45 mm, and the grains are rounded to well-rounded. The sand is characterized by horizontal laminations and low to medium-angle cross-laminations (Fig. 6C). This lithofacies occurs only at the surface at site 4, and it is bounded below by conglomerate lithofacies (G1).

Interpretation: The sedimentary structures and lithologic properties of this lithofacies suggest probable deposition in a fluvial environment. Characteristics such as horizontal laminations, planar cross-beds, and coarse sands are indicative of linguoid bars, which are commonly found in braided rivers (Miall, 1985). The existence of horizontal gravel beds suggests that these materials likely represent lag deposits left on the riverbed when the flow carried only the finer sediments. These deposits were linked to shallow braided streams. The horizontal lag deposits within this lithofacies can also be linked to longitudinal bars of braided streams, and their presence as interbedded beds with coarse sand that are often pebbly supports this interpretation (Miall, 1985, 1996).

4.1.5. Gravel (G) lithofacies

G1 lithofacies: The lithofacies is only found at the surface at site 4, immediately below lithofacies CSG1. Its thickness is ~ 0.9 m (2.9 ft), and it is primarily composed of gravel-sized materials, ranging in size from 3 to 40 mm. The gravel exhibits poor sorting, and the clasts are subrounded to rounded. Within this lithofacies, there is a moderate matrix content near the bottom and a low matrix content near the top. The matrix consists mainly of medium to coarse, angular to subangular sand. This lithofacies displays massive to normally graded bedding, as shown in Figure 6A.

Interpretation: The lithological characteristics of this lithofacies, along with its association and position below lithofacies CSG1, suggest that it was deposited in a fluvial setting, likely by meandering streams. The presence of massive to normally graded gravel beds may have originated from longitudinal bars, as discussed by Miall (1985, 1996). The upward decrease in the sand matrix within this lithofacies likely resulted from an increase in water energy that transported the finer sediments downstream (e.g., Rust, 1972; Hein and Walker, 1977; Miall, 1985, 1996).

4.1.6. Carbonate (LS) lithofacies

LS1 lithofacies: This lithofacies is composed of light gray carbonate mudstone that contains a few quartz and mica grains. It is slightly fossiliferous, with some *Pecten* sp. fragments. This lithofacies occurs only in well C.D. Scott #1 near the boundary between the Middle Tuscaloosa and the Upper Tuscaloosa. It has a thickness of ~ 3 m (10 ft) and is bounded below by carbonate lithofacies (LS2) and above by medium sandstone lithofacies (MS1).

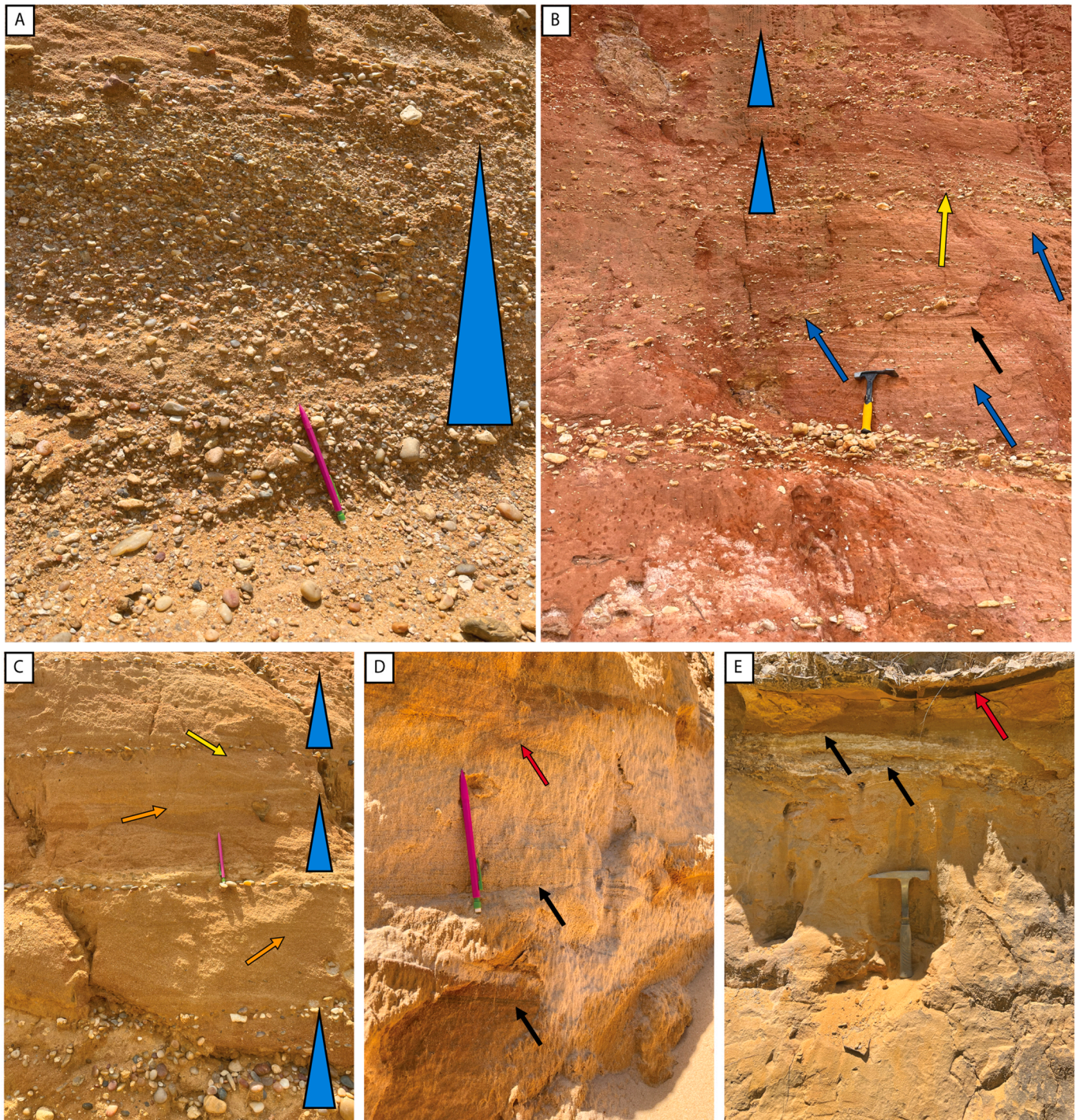


Fig. 6. Field photographs showing sedimentary structures in the five studied measured sections. A) The lower portion of measured section 3 shows normal graded bedding in lithofacies G1; the triangle head points to finer grains. B) MSG1 Lithofacies exhibits trough cross-bedding (blue arrows), parallel sand laminations (black arrow), and horizontal bedding of granule-sized gravel (yellow arrow). C) CSG1 lithofacies is characterized by decreasing grain size from granule/pebble-sized gravel to medium-sized sands (blue triangle). D) MS1 lithofacies displays low to medium-angle cross-laminations (red arrows) and parallel laminations of localized opaque mineral zones (black arrows). E) VFS1 lithofacies at site 2 shows well-cemented sandstone beds (red arrow) and interbedded mud layers in the middle portion (black arrows).

In the wireline log, this lithofacies shows a right-blocky trend (Fig. 3D), with SP readings ranging from -45 to -51 mV.

Interpretation: Carbonate mudstone can be associated with a depositional environment characterized by calm and light current activity, such as the bottom of a lagoon or subtidal settings (e.g., Scrutton, 2000; Masuda, 2017). *Pecten* impressions in this lithofacies support the interpretation of deposition in a lagoon (e.g.,

Makurath, 1977; Fujita et al., 2006). The presence of a few quartz and mica grains within this lithofacies suggests terrestrial input, and their presence within this lithofacies is another indicator of deposition in a near-shore setting, probably lagoon (e.g., Braithwaite, 1967; Blair, 1978; Carannante et al., 2000).

LS2 lithofacies: This lithofacies is composed of light gray rudstone that contains large *Pecten* fragments and some quartz grains.

The thickness of this lithofacies is ~6.1 m (20 ft), and it occurs only in well C.D. Scott #1, a few meters above the contact between the Middle Tuscaloosa and the Upper Tuscaloosa. It is bounded above by lithofacies LS1 and below by shale lithofacies SH2.

The SP values of the lithofacies range from –118 to –139 mV, and in the wireline log, the lithofacies shows a serrated left-blocky shape (Fig. 3D).

Interpretation: Rudstone is associated with various depositional environments, including shallow marine and internal lagoonal-tidal environments (e.g., Stefano and Ruberti, 2000; Brandano and Ronca, 2014). The presence of detrital grains in this lithofacies suggests an influx of terrigenous sediment, and its occurrence within the rudstone has been linked to a mixed siliciclastic-carbonate environment (Sanders and Pons, 1999). The absence of micrite in this lithofacies, when compared with lithofacies LS1, supports deposition in a high-energy shallow marine environment rather than in a lagoon setting where calm water conditions would be more prevalent (Ruberti, 1997). The presence of this lithofacies above lithofacies SH1 and the sand content within the rudstone could be attributed to high-frequency sea-level fluctuations (Martinuš et al., 2012).

4.2. Tuscaloosa sequence architecture and internal organization

Four depositional sequences have been identified from the studied wells across the study area. The spatial distribution, systems tract configuration, and key stratigraphic surfaces of each depositional sequence were defined following the principles of Mitchum et al. (1977) and Van Wagoner et al. (1990), and they are described below.

4.2.1. Sequence 1

Sequence 1 (S1) is the lowermost sequence, and it contains a LST, a TST, and a HST. Sequence boundary 1 (SB1) occurs at the boundary between the base of the LST, which is found at the base of the Lower Tuscaloosa, and the upper contact of the Lower Cretaceous. This marks an erosional unconformity correlated to the one described by Mancini et al. (1987), which marks the base of the T-R 5 sequence of the Eastern GoM region. In the wireline log, SB1 is characterized by a sharp base, signifying abrupt shifts in stacking patterns from retrograding below to prograding above. SB1 was delineated mostly across the entire study area, where it can be traced from well William R. Giesler #1 in the south to well JW Smith #1 in the northeastern part of the study area (Figs. 7 and 8). The results also reveal that SB1 on the isopach map exhibits a gradual increase in depth towards the southwestern region of the study area. In contrast, in the northeastern portion, it tends to show a shallowing trend (Fig. 9A).

Overlying SB1, the LST occurs at the base of the Lower Tuscaloosa and represents the first systems tract of S1 (Figs. 7A and 8A). It is bounded below by SB1 and above by TS1. This systems tract was defined in most of the studied wells (Figs. 7 and 8), except for wells A.W. Moye Et Ux2, Kate R. Martin #155, and U.S. Steel Co #1, where the lower portion of the Lower Tuscaloosa is not covered in the wireline logs. In the wireline logs, the LST is characterized mostly by left blocky to left serrated blocky log motifs with mostly sharp base contacts (Figs. 7 and 8). The LST in the southern part of the study area is composed of thick sand bodies that are often interbedded with thin mudrocks (Figs. 7 and 8). In the northernmost and northeastern parts of the study area, the LST is composed mainly of thick gravel and sand deposits. The average proportion of the coarse fraction in the LST of S1 is ~96.7%. The thickness of the

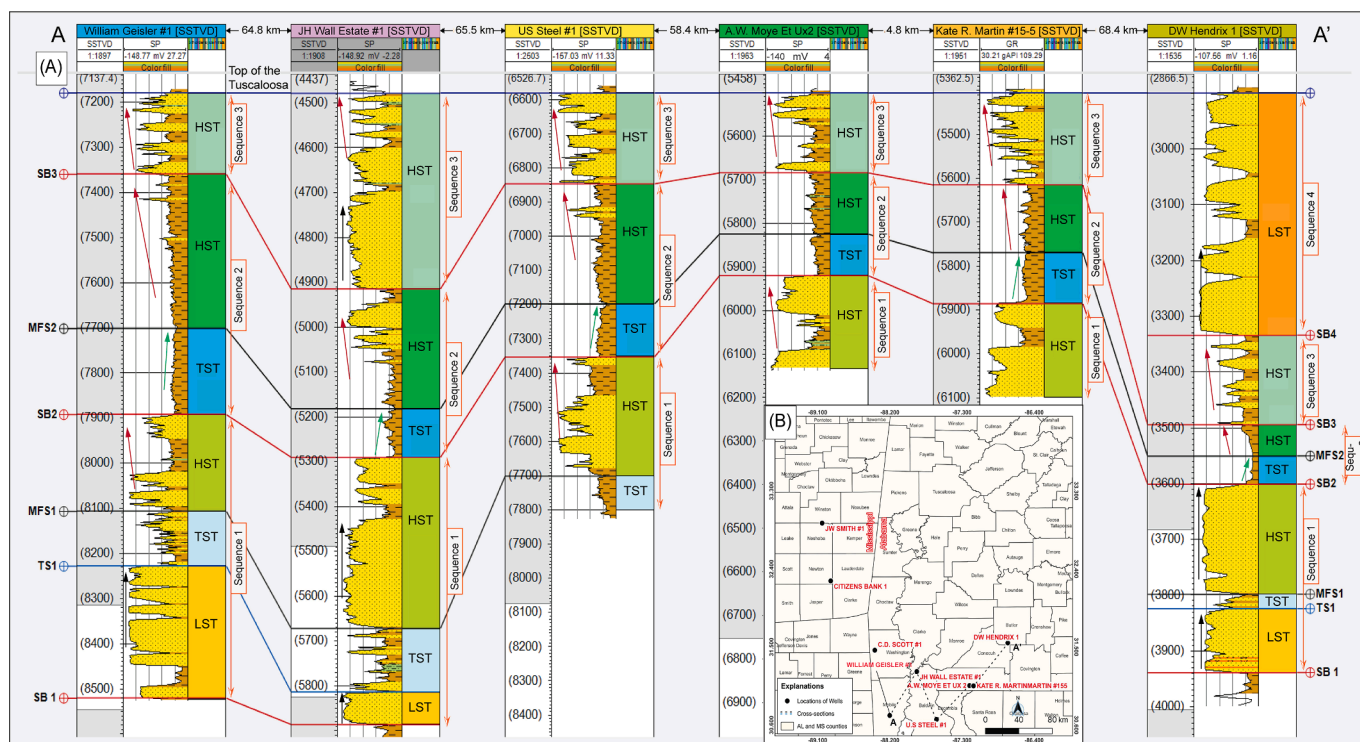


Fig. 7. (A) Stratigraphic cross-section A-A' shows the identified stratigraphic surfaces, systems tracts, and sequences. SB1, SB2, SB3, and SB4 are sequence boundaries 1, 2, 3, and 4; TS1 is transgressive surface 1; MFS1 and MFS2 are maximum flooding surfaces; LSTs are lowstand systems tracts; TSTs are transgressive systems tracts; HSTs are highstand systems tracts; S1, S2, S3, and S4 are depositional sequences 1, 2, 3, and 4. Red arrows show funnel-shaped log motifs; green arrows show bell-shaped log motifs; black arrows show left-blocky log motifs. The top of the Tuscaloosa Grp is used as the datum. Vertical depth provided in feet. (B) Reference map displaying the trend of the A-A' cross-section illustrated in (A).

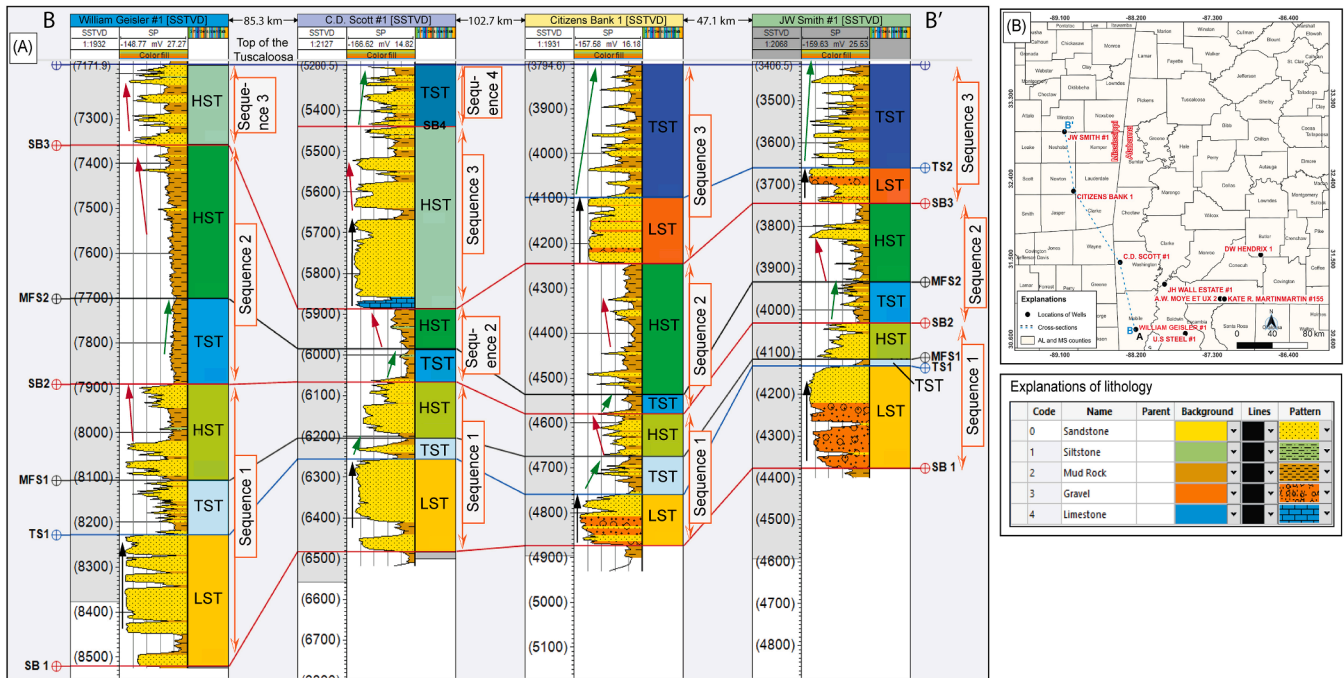


Fig. 8. (A) Stratigraphic cross-section B-B' shows the identified stratigraphic surfaces, systems tracts, and sequences. SB1, SB2, SB3, and SB4 are sequence boundaries 1, 2, 3, and 4; TS1 and TS2 are transgressive surfaces 1 and 2; MFS1 and MFS2 are maximum flooding surfaces 1 and 2; LSTs are lowstand systems tracts; TSTs are transgressive systems tracts; HSTs are highstand systems tracts; S1, S2, S3, and S4 are depositional sequences 1, 2, 3, and 4. Red arrows show funnel-shaped log motifs; green arrows show bell-shaped log motifs; and black arrows show left-blocky log motifs. The top of the Tuscaloosa Grp is used as a datum. Vertical depth provided in feet. (B) Reference map displaying the trend of the B-B' cross-section illustrated in (A).

LST ranges from 22.5 to 89.9 m (74–295.2 ft) (Figs. 7 and 8). On the isopach map, the LST appears to be decreasing in thickness towards the northern and northeastern parts of the study area, while it shows greater thickness on the southwestern side of the study area (Fig. 11A).

Subsequently, the LST of S1 is bounded above by the lowermost transgressive surface (TS). This surface occurs mostly throughout the entire study area, and it is bounded above by the TST of S1 (Figs. 7A and 8A). In the wireline logs, it is expressed as a change in stacking patterns from prograding to retrograding, which indicates a basinward shift of depositional strata (Catuneanu et al., 2011). On the isopach map, the TS exhibits a comparable pattern when compared to the lower SB, wherein it gradually deepens towards the southwest and gradually becomes shallower towards the northeast (Fig. 11B).

A TST occurs above the TS of S1, forming the second component of S1. This systems tract is separated from the overlying HST by a MFS (Figs. 7 and 8). In the wireline logs, the systems tract is identified by bell to serrated log motifs, indicating an overall trend of fining-upward strata. This systems tract predominantly consists of mudrocks that are often interbedded with sandstones and siltstones. The TST of S1 exhibits a relatively thin thickness, ranging from 8.8 to 43.3 m (29–142.1 ft). The average coarse fraction of this TST is ~24.2%, and it is consistently present in all wells. The TST can be traced both in a SE-NW and in a SW-NE direction (Figs. 7 and 8).

The lowermost maximum flooding surface (MFS 1 of S1), which occurs within the upper section of the Lower Tuscaloosa, can be traced across the entire study area. MFS 1 separates the underlying TST from the overlying HST of S1 (Figs. 7A and 8A). It is distinguished by changes in log stacking patterns from bell-shaped and right-blocky to an overall funnel shape. On the isopach map, this surface deepens towards the southwestern and south-central

regions of the study area, while it becomes shallower towards the north and northeast, reaching a depth of ~ -1097 m (–3600 ft) (Fig. 9C).

HST1 of S1 occurs within the upper section of the Lower Tuscaloosa, and it forms the last component of this sequence. This systems tract is separated from the overlying TST of depositional sequence 2 (S2) by SB2 (Figs. 7A and 8A). HST1 is traceable across the entire study area, and its thickness ranges between 26.5 and 116.3 m (87.2–381.7 ft). In the wireline logs, the HST of S1 often correlates with serrated left-blocky and overall funnel log motifs, indicating aggradational and progradational stacking patterns (Figs. 7A and 8A). The HST is composed predominantly of thick sandstone beds, which are commonly interbedded with mudrocks and siltstones. The average proportion of the coarse fraction of this system tract is ~80.2%. On the isopach map, the HST is thickest in the south-central portion of the study area, and it thins gradually toward the northeast and northwest portions of the study area (Fig. 11B).

4.2.2. Sequence 2

Sequence 2 (S2) occurs at the boundary between the Lower Tuscaloosa and Middle Tuscaloosa, and it is separated from S1 by SB2. A HST is the lower component of S2, and it correlates with transitions from progradational and aggradational to retrogradational stacking patterns (Figs. 7 and 8). Similar to SB1, SB2 is found at a shallower depth toward the northeastern part of the study area, and it deepens toward the southwestern portion of the study area (Fig. 9D).

The TST of S2 occurs in the lower section of the Middle Tuscaloosa and represents the basal component of S2. This systems tract predominantly consists of thick mudstone deposits, exhibiting substantial thickness across the southern region of the study area. In contrast, in the far northern part of the study area,

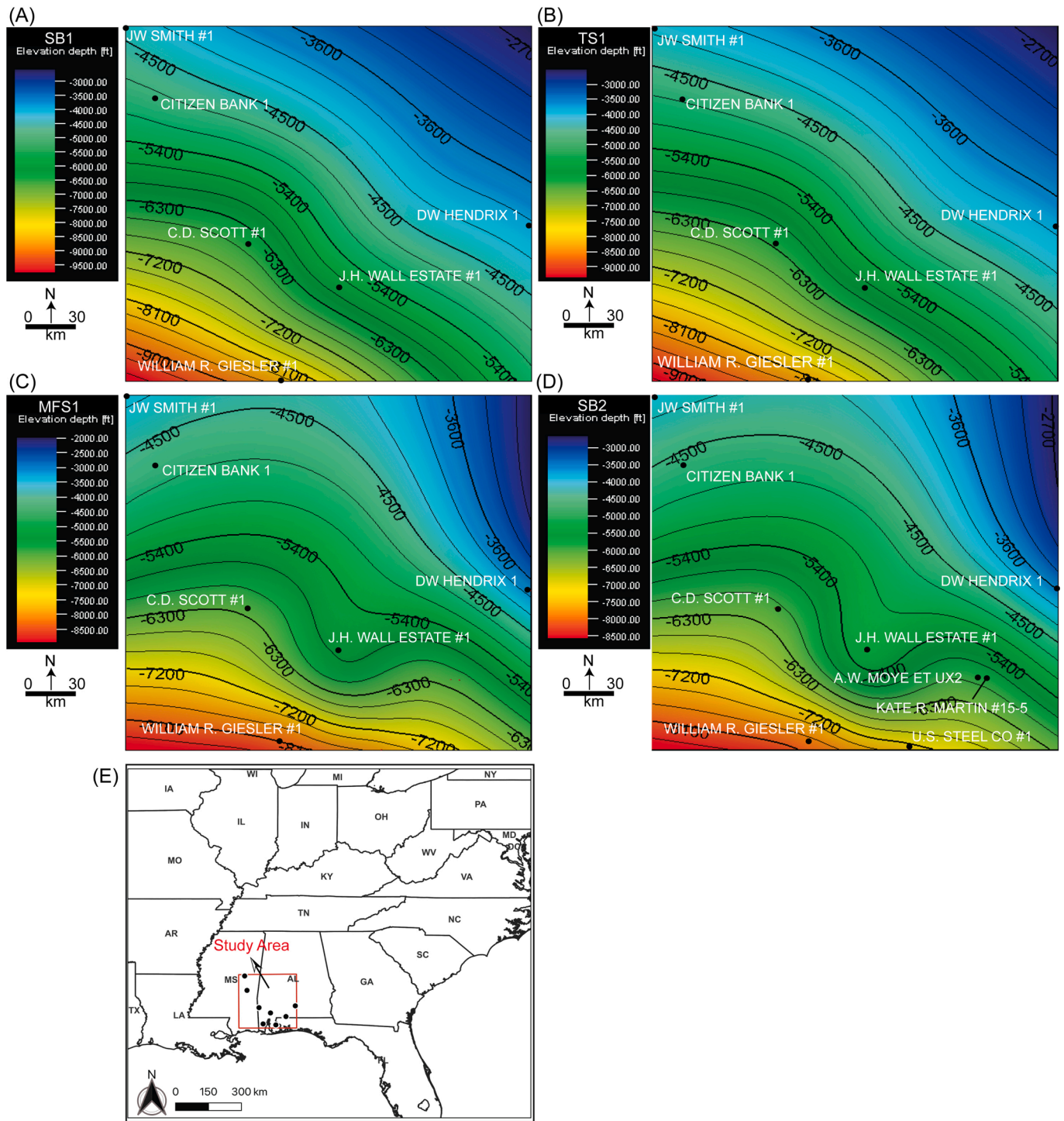


Fig. 9. Structure depth maps for selected stratigraphic surfaces: (A) A depth map for SB1; (B) A depth map for TS1; (C) A depth map for MFS1; and (D) A depth map for SB2. Note that SB1, TS1, and MFS1 are not observed in wells A.W. Moye Et Ux2 and Kate R. Martin #15-5; therefore, they are not shown in (A), (B), and (C). Vertical depth in A, B, C, and D is given in feet. (E) Reference map of the mapped area.

it comprises mudrocks interbedded with sandstone beds (Fig. 7A). With an average coarse fraction proportion of ~2.6%, this represents the finest-grained systems tract among all identified units. The TST thickness ranges from 14.9 to 60.2 m (49–197.6 ft). In the wireline logs, it exhibits right-blocky and overall bell-shaped log motifs. The isopach map reveals that TST thickness decreases from the southwestern to the central region of the

study area and then increases toward the northeastern section (Fig. 9C).

Maximum flooding surface 2 (MFS2), which is present within the Middle Tuscaloosa, separates the underlying TST from the overlying HST of S2 (Figs. 7A and 8A). MFS2 is observed in all studied wells (Figs. 7 and 8) and can be distinguished by the changes in stacking patterns from retrogradation to aggradation.

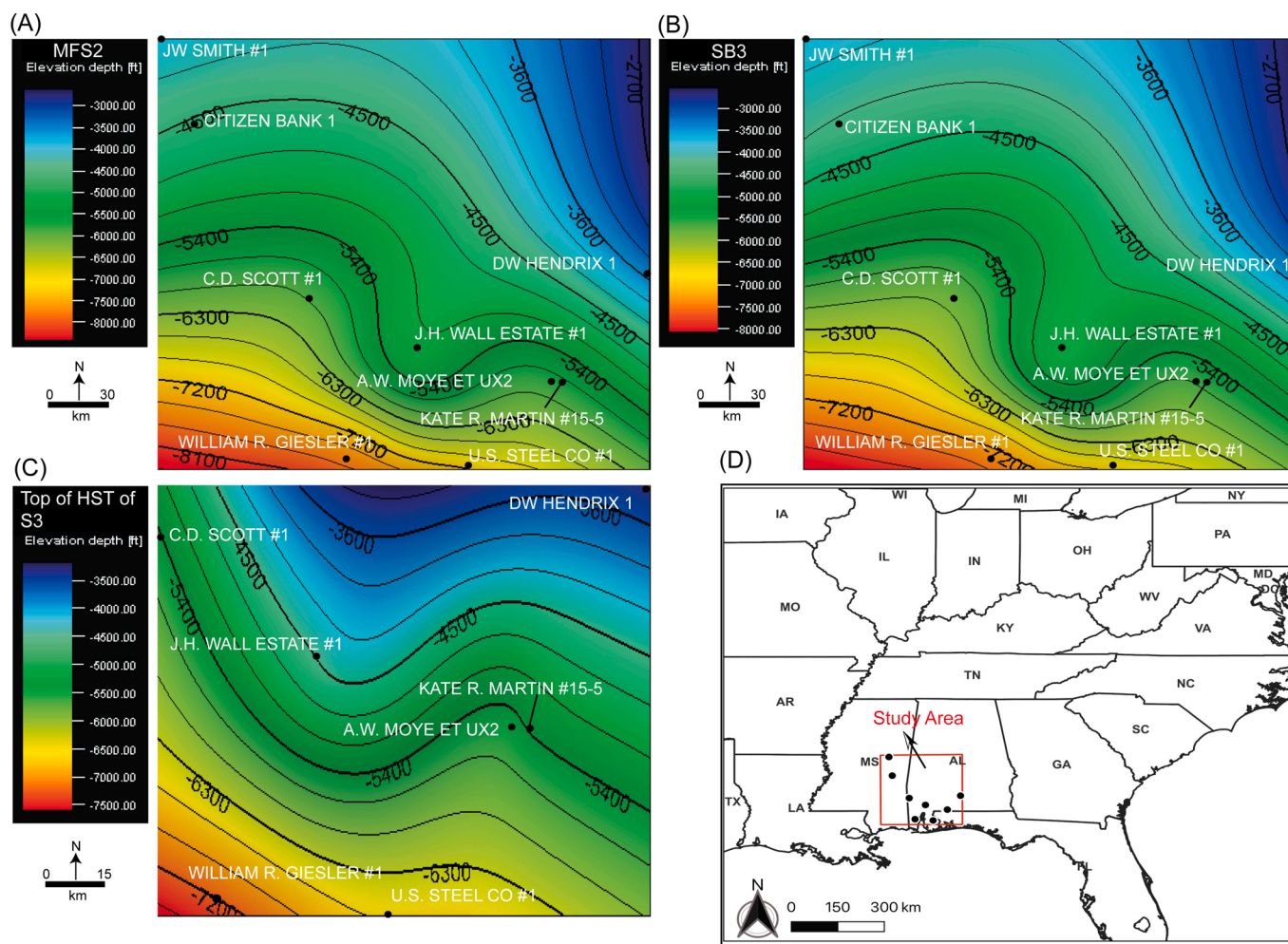


Fig. 10. Structure depth maps for selected stratigraphic surfaces: (A) A depth map for MFS1; (B) A depth map for SB3; and (C) A depth map for the top of HST of S3, which marks the upper boundary of the Tuscaloosa Grp in most of the studied wells, except for JW Smith 1 and Citizen Bank 1, where HST3 is not present. Vertical depth in A, B, C, and D is provided in feet. (D) Reference map of the mapped area.

This systems tract exhibits a varying depth distribution across the study area, as shown on the isopach map. It ranges in depth from ~ 822 m (-2700 ft) in the northeastern portion of the study area, deepening toward the southern and southwestern portions of the study area, reaching a maximum depth of ~ 2468 m (-8100 ft) (Fig. 10A).

A HST occurs between the upper section of the Middle Tuscaloosa and the lower section of the Upper Tuscaloosa, forming the last component of S2 (Figs. 7A and 8A). This systems tract is separated from the HST and LST of sequence 3 (S3) by SB3. The HST ranges in thickness from 17.2 to 105.1 m (56.4–345 ft). In the wireline logs, this systems tract exhibits an overall funnel-shaped log trend, indicating an overall coarsening upward trend (Figs. 7A and 8A). This systems tract is composed mostly of mudrocks in the lower portion and mudrocks and sandstones in the upper section that thicken toward the northern part of the study area (Figs. 7A and 8A). The average proportion of the coarse fraction in this HST is $\sim 9.14\%$. On the isopach map, HST2 is thickest in the south-central part of the study area. Toward the eastern side of the study area, HST2's thickness decreases slightly, whereas its thickness drops dramatically toward the northeastern portion of the study area (Fig. 11D).

4.2.3. Sequence 3

Sequence 3 (S3) sits on SB3, which stratigraphically occurs at the boundary between the Middle Tuscaloosa and Upper Tuscaloosa. The nature of the overlying systems tract above SB3 varies spatially across the study area. In the southern and central parts of the study area (Figs. 7B and 8B), SB3 separates the underlying HST of S2 from the overlying HST of S3. In these areas, the wireline logs show shifts from progradational stacking patterns dominated by mud to aggradational and progradational stacking patterns dominated by sand (Figs. 7A and 7B). However, in the northern portion of the study area (Fig. 8B), particularly in wells Citizen Bank 1 and JW Smith #1, SB3 separates the underlying HST of S2 from the overlying LST of S3, as defined by abrupt shifts from fine-grained mud to coarse sand and gravel (Fig. 8A). SB3 on the isopach map decreases in depth from ~ 2195 m (-7200 ft) in the southwestern part of the study area to ~ 822 m (-2700 ft) toward the northeastern part of the study area (Fig. 10B). The projection of SB3 at the Tuscaloosa outcrop belt is ~ 115 m (378 ft) above sea level and 50 m (165 ft) below the surface at site 3 (Fig. 14). SB3 occurs stratigraphically below the gravel of the Gordo Fm of the Tuscaloosa Grp. This is the only stratigraphic surface of the Tuscaloosa Grp present near the surface of the Tuscaloosa outcrop belt.

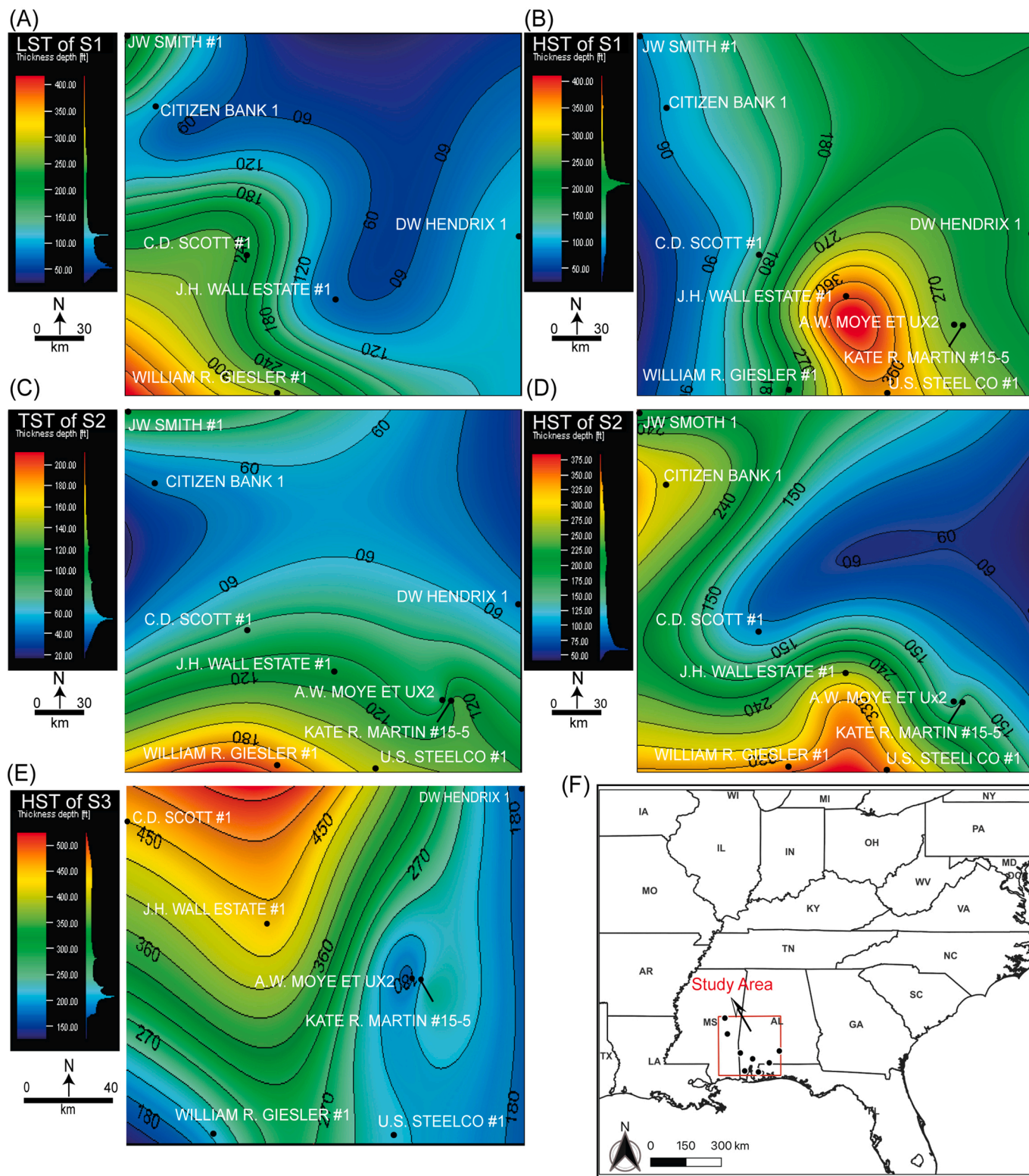


Fig. 11. Isopach maps of selected systems tracts that tend to be observed in most of the study area: (A) Isopach map for LST of S1; (B) Isopach map for HST of S1; (C) Isopach map for TST of S2; (D) Isopach map for HST of S2; and (E) Isopach map for HST of S3. Each isopach map was created by subtracting the top from the bottom contact of each systems tract. The red color on each map refers to the area of high thickness. Vertical depth in A, B, and C is provided in feet. (F) Reference map for the mapped area.

A LST of sequence S3 exhibits limited spatial distribution, occurring only at a local scale and forming the basal component of S3 (Figs. 8A and B). This systems tract is identified in only two studied wells: Citizen Bank 1 and JW Smith #1. It is bounded above

by the TST of S3. This LST displays characteristic thick left-blocky to serrated left-blocky log motifs in the wireline logs. This systems tract consists predominantly of gravel and sand deposits, with thicknesses ranging from 24.9 to 44.8 m (82.2–147.8 ft). The mean

coarse fraction proportion reaches 100%, indicating an entirely coarse-grained composition.

In contrast, across the central and southern portions of the study area (Figs. 7A and B), the HST of S3 directly overlies SB3 of S3 (Fig. 7A), extending from the middle to the upper intervals of the Upper Tuscaloosa. In these areas, the HST is underlain by the HST of S2 and overlain by the Eutaw Fm in all of the studied wells except for well C.D. Scott #1, where it is overlain by the TST of sequence 4 (S4) (Fig. 8A). In well DW Hendrix, this HST is overlain by the LST of sequence 4 (S4) (Fig. 7A). In the northern part of the study area, this HST is not identified. The HST of S3 is relatively thick, ranging from 54.7 to 136.3 m (179.6–447.2 ft). In the wireline logs, the HST of S3 shows blocky and overall funnel log motifs, which indicate aggradational and progradational stacking patterns, respectively. This systems tract is composed of sand beds that are interbedded with mudrocks and siltstones. Within this systems tract, there is a set of parasequences that can be traced across the entire study area (Figs. 7 and 8), and we attribute them to high-frequency fluctuations in base sea level (e.g., Van Wagoner et al., 1990). The mean proportion of the coarse fraction of this systems tract is ~64.3%.

A TST, which marks the last component of S3, was identified in only two of the studied wells: Citizen Bank 1 and JW Smith #1 (Fig. 7A), where it is overlain by the Eutaw Fm. In the wireline logs, it is characterized by an overall bell-shaped pattern. Along this trend, there are small fining-upward log motifs, and each one of them likely represents a high-order sequence (Fig. 7A). This TST ranges in thickness from 45.5 to 90.2 m (149.5–296.1 ft) and is composed of sandstones interbedded with mudrocks. The mean coarse fraction of this systems tract is ~41.4%.

4.2.4. Sequence 4

S4 is identified exclusively in two wells within the study area. In DW Hendrix and C.D. Scott #1 wells, S4 is demarcated from the underlying S3 by SB4 (Fig. 7A).

In well DW Hendrix 1, S4 contains a LST in its basal portion (Fig. 7A). This systems tract exhibits distinctive thick, repeated left-blocky and serrated left-blocky log motifs characteristic of sandstone, which are interspersed with thin bell-shaped log patterns characteristic of mudrock beds (Fig. 7). These log pattern variations reflect systematic changes in lithology from coarse-grained sandstone to fine-grained mudstone. This LST exhibits a total thickness of approximately 131 m (430 ft) and is stratigraphically bounded by HST3 below and the overlying Eutaw Formation above. The average coarse fraction proportion within this LST is ~82%, reflecting the predominantly sandy nature of this depositional unit.

In the central study area (Fig. 8B), S4 contains a TST that occurs exclusively within well C.D. Scott #1 (Fig. 8A). It is stratigraphically positioned between the HST of S3 below and the Eutaw Formation above, and it exhibits a distinctive fining-upward profile in wireline logs. The upward transition from sand-dominated to mud-rich lithofacies reflects the retrogradational stacking pattern of this systems tract.

5. Discussion

5.1. Correlation between wireline logs data and surface data

The projection of SB3, defined in the JW Smith #1 well, to the Tuscaloosa outcrop belt yields a position of ~50 m (164 ft) below the surface exposure of the Gordo Fm at site 3. This correlation successfully facilitates linking the gravel and sand of the Gordo Fm to the gravel and sand of the LST of S3, which is observed within the Upper Tuscaloosa in the subsurface (Figs. 12 A and B). However,

the attempt to correlate other subsurface stratigraphic surfaces and systems tracts identified from wireline logs with surface outcrops of the Tuscaloosa Grp revealed results contrary to what was expected. The projection of the Lower Tuscaloosa top to the Coker Fm outcrop site exhibited considerable vertical disparity, positioning the projected surface ~330–352 m (1085–1155 ft) lower than the base of the outcrop's elevation. Note that the base of the outcrop is not the base of the Coker Fm. Therefore, this mismatch complicates linking Lower Tuscaloosa systems tracts identified from wireline logs to the Coker Fm at sites 1, 2, and 5 (Figs. 12 A and B).

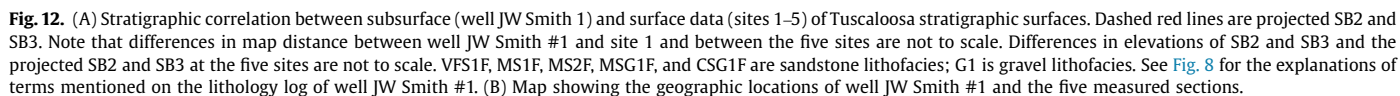
The mismatched correlations between systems tracts in the subsurface and surface units may be the result of structural complexity and variations in dip. This could be taken into account if seismic data were available. There is a possibility that the area has undergone significant structural deformation, such as faulting and folding, which could not be incorporated into the dip projections. Another possible reason for the mismatch would be that the dip measurements obtained from the depth map of the Lower Tuscaloosa may not accurately represent the entire region, which could be due to the limited number of wireline log data or the presence of local structural heterogeneities. In addition, it is also possible that the strata of the Coker Fm could be younger than those in the subsurface of the Lower Tuscaloosa.

5.2. Paleogeography

5.2.1. Sequence 1

Paleogeographic reconstructions (Fig. 13) were created for the systems tracts of the Tuscaloosa Grp in order to illustrate the evolution of depositional sequences. During the mid-Cenomanian, a major unconformity developed in the GoM Coast region due to a global drop in sea level (Salvador, 1991). This unconformity can be observed at the lower contact of the Lower Tuscaloosa, which represents the base of S1's LST. Prior to the deposition of this LST, the entire study area remained exposed. The LST of S1 originated on the shelf, landward of the shelf edge, a concept supported by the studies of Woolf and Wood (2010) and Woolf (2012). The formation of the LST of S1 likely occurred within a fluvial environment in an incised valley (Fig. 13A). In the southern part of the study area, the basal section of this LST consists of fluvial deposits that are immediately overlain by deltaic to estuarine deposits. In well William R. Geisler #1, it is probable that the LST of S1 was formed in an incised valley that was filled by shallow marine deposits during a later stage, probably governed by sea level rise (e.g., Van Wagoner et al., 1990; Catuneanu, 2006). The great thickness of this LST on the southwestern side of the study area (Fig. 13A) is likely due to the significant accommodation space resulting from ancient river incisions in older strata that provided sediments to the deep water (e.g., Woolf and Wood, 2010; Ambrose et al., 2015). Toward the northeastern and northwestern sides of the study area, the LST of S1 only contains gravel and coarse sandstone lithofacies (Fig. 8), and there are no marine deposits. These coarse deposits of this LST were likely deposited by braided rivers that flowed from the north and northeast (Woolf and Wood, 2010). This suggests that marine deposition of the LST of S1 was only dominant in the southern portion of the study area, and the ancient shoreline during the formation of this LST may not have advanced northward.

The formation of the LST of S1 ended with the development of TS1, which is present in most of the studied wells (Figs. 7 and 8). The development of this surface marks the beginning of the TST of S1 deposition. When comparing the depth map of TS1 with the depth map of SB1, there are slight changes in the distance between the contours (Fig. 9A and B), indicating minimal structural



mudrocks likely indicates deposition on the shelf as a result of a rise in sea level that occurred after the formation of the former LST. The distribution of this systems tract across the entire study area suggests that the shoreline migrated landward, potentially

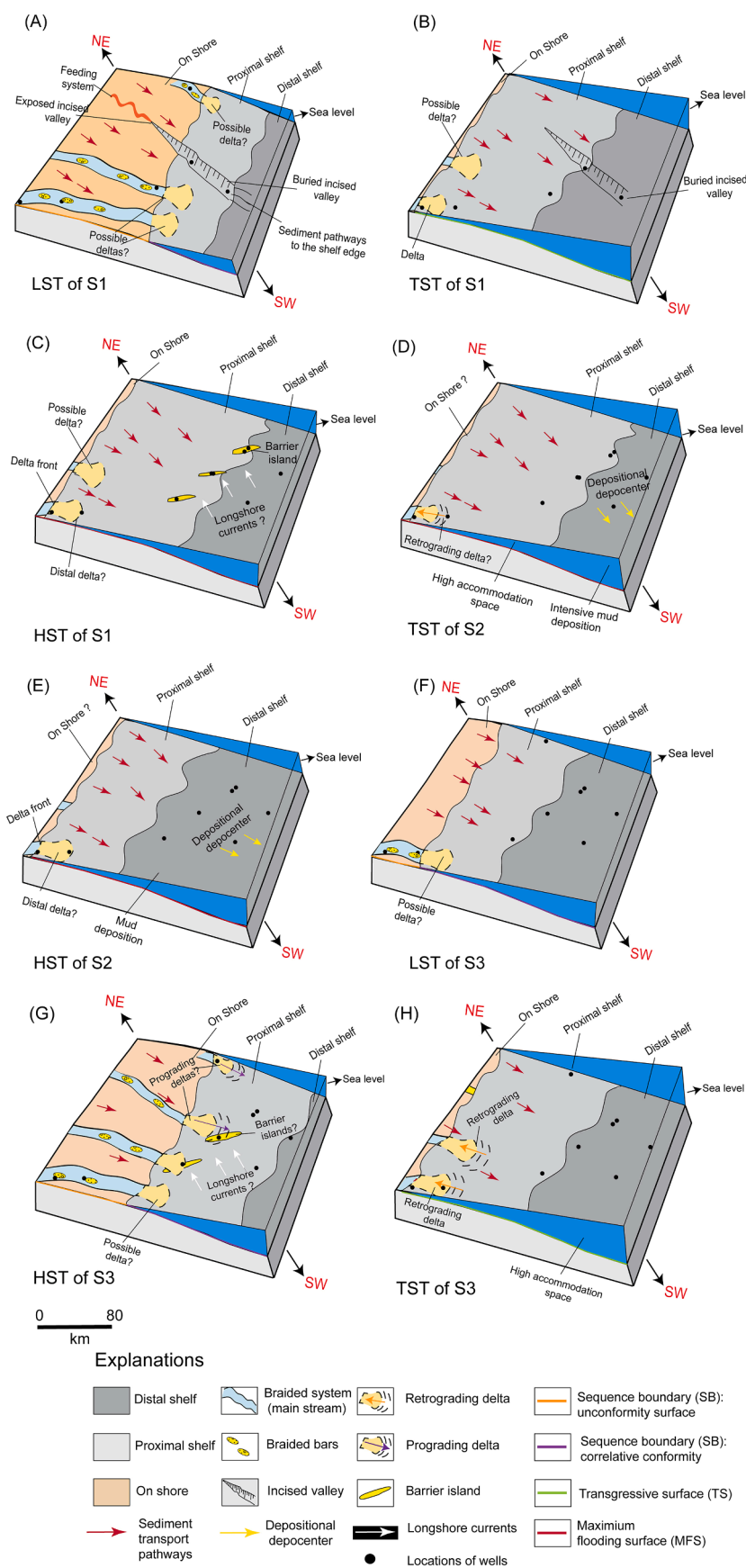


Fig. 13. Paleogeographic maps reconstructed for each systems tract by integrating surface depth maps, isopach maps, and depositional environment interpretations. (A) LST of S1 formation showing fluvial systems and an incised valley, suggesting shelf erosion prior to LST of S1 formation. (B) Development of a thin TST in S1 on former LST, indicating sea

resulting in renewed delta building directly on top of the fluvial deposits of the lower LST (Fig. 13B). This interval within the Lower Tuscaloosa is well recognized in many wells across Mississippi and Alabama, and it has been interpreted as a deltaic-to-shelf setting (Mancini et al., 1987). The formation of MFS1 marks the end stage of the TST of S1 formation, indicating changes in accommodation space and sediment supply (Catuneanu et al., 2011).

Following the formation of the MFS1, which marked the end of the lower TST deposition, the HST of S1 started to develop in most of the study area (Fig. 13C). In the wireline logs, there are notable changes in the mud and sand ratio compared with the lower TST (Figs. 9 and 10). In the southern part of the study area, particularly in well J.H. Wall Estate #1, the HST is thick, indicating an increase in sediment supply. According to the isopach map of this HST, the depocenter migrated toward the south-central part of the study area (Fig. 10B). Based on the lithologic properties of the sandstone and mudrock lithofacies of this systems tract, proximal shelf deposition might have been dominant during the initial stage of this systems tract formation. Such deposition on the proximal shelf might be related to the evolution of barrier islands (Swift, 1975). The presence of barrier island deposits is supported by the elongate, west-to-east trending, thick sand bodies that are present at the top of the HST of S1. This is also supported by the laterally distributed blocky log motifs associated with sandstone lithofacies in cross-section A-A' (Fig. 7A). Deposition on an inner shelf was previously mentioned by Mancini et al. (1987) as a possible depositional environment for the upper sand section of the Lower Tuscaloosa, which correlates here with the HST of S1. The presence of mudrock lithofacies (e.g., CL 1, SH1) between the thick blocky sandstone lithofacies (e.g., MS1, MS2) likely indicates a middle to distal shelf setting influenced by high-frequency sea level fluctuations, as mentioned by Mancini et al. (1987). Following depositional dip, as indicated by the slope of SB2 in the isopach map (Fig. 9D), the HST of S1 appears to have been fed from the north and northeast, with the thickest deposits accumulating along the eastern and south-central portions of the study area where accommodation space was greatest.

5.2.2. Sequence 2

S2 began to develop with the formation of TS2, which occurred after the cessation of the formation of the HST of S1. The absence of a lowstand systems tract within this sequence likely indicates that the study area remained submerged and was not exposed during the formation of S2 (e.g., Catuneanu, 2006). The TST of S2, which is present in the Middle Tuscaloosa, corresponds to the end of the backstepping phase of the T-R 5 sequence described by Mancini and Puckett (2002). The TST of S2, which is present throughout the study area (Figs. 7 and 8), is primarily composed of the mudrock lithofacies including CL1, SH1, and SH2. However, in the northwestern portion of the study area, it is interbedded with thin sand beds (Fig. 8A). As indicated on the depth maps, sea level continued to rise toward the north-northeast (Figs. 10D and 13D), increasing accommodation space, which allowed for the deposition of the thick mud deposits of the TST of S2. The depocenter shifted compared to the previously formed HST of S1 and became dominant in the southwestern and central parts of the study area (Fig. 11C). This likely indicates deposition in a distal shelf environment (Fig. 13D), except in the northwestern portion, where a

possible deltaic system may have developed on the shelf in a northward direction, as indicated by the wireline log pattern of well JW Smith #1 (Fig. 8A). This interpretation is also supported by Mancini and Puckett (2002), who described the lower portion of the Middle Tuscaloosa, which correlates here with TST2, as representing an open marine shelf.

The deposition of the TST of S2 concluded with the formation of MFS2, indicating the end of the ancient shoreline's movement inland and the initiation of the HST of S2, where sediment supply exceeded the rate of sea level rise. According to the depth maps, there were no major changes in the structure of the study area between the previously formed TST and this HST (Fig. 13A and B). The depocenter of the HST of S2 was mainly located in the south-central part of the study area, with a slight shift from the former TST2 (Fig. 13D). This systems tract likely represents deposition in the distal to proximal portion of the shelf (Fig. 13E) based on the abundance of mudrock lithofacies identified from wireline logs (Figs. 7 and 8). The prominent funnel-shaped log pattern observed in the HST of S2 across most wells, coupled with the presence of sandstone and siltstone lithofacies at the top of this systems tract, indicates a deceleration in the rate of sea level rise. This depositional pattern corresponds to the upper section of the Middle Tuscaloosa, which Mancini and Puckett (2002) previously interpreted as a deltaic system representing the early regressive phase of the T-R 5 sequence. The presence of interbedded sandstone and mudrock lithofacies, as observed in the well logs (e.g., Citizen Bank 1 and JW Smith #1) (Figs. 7A and 8A), here suggests probable deposition in shallower portions of the shelf, which is consistent with previous studies (e.g., Mancini et al., 1987; Mancini and Puckett, 2002).

5.2.3. Sequence 3

This sequence lacks an LST in the central and southern regions of the study area, with the LST development restricted to the northern portion (Fig. 8A). This spatial distribution indicates that the central and southern areas remained continuously submerged during the lowstand phase, precluding the formation of a subaerial unconformity and subsequent LST deposition (e.g., Vail, 1987; Van Wagoner et al., 1990; Catuneanu, 2006). Based on lithological characteristics and distinctive wireline log motifs, the LST of S3 was deposited within fluvial environments, most likely representing a braided stream system. This interpretation is supported by the presence of thick conglomeratic and sandy intervals that are characteristic of high-energy, coarse-grained fluvial deposition typical of braided stream environments (Miall, 1996).

In the central and southern parts of the study area, the HST of S3 is positioned on SB3, which is considered a correlative conformity that indicates changes in stratal stacking patterns (Catuneanu, 2006; Catuneanu et al., 2011). The presence of this surface in wells in the central and southern parts of the study area suggests that these areas remained inundated, as supported by the lack of a subaerial unconformity (e.g., Van Wagoner et al., 1990; Catuneanu, 2006; Catuneanu et al., 2011). The depocenter during the formation of the HST of S3 was mainly located in the central part of the study area, as indicated by its thickness in wells C.D. Scott #1 and J. H. Wall Estate #1 (Figs. 7A and 8A). The presence of rudstone and mudstone at the bottom of this HST in well C.D. Scott #1, which lies directly on mudrocks of the HST of S2 (Fig. 8A), suggests a transition likely from a proximal shelf to shallow marine and lagoon

level rise. (C) HST of S1 formation coeval with continued sea level rise but high sedimentation rates; barrier islands suggest the contribution of longshore currents. (D) TST of S2 evolution associated with the highest accommodation space, resulting in thick mud deposits. (E) HST of S2 formation; progradational stacking patterns indicate sedimentation outpaced accommodation space. (F) LST of S3 formation in the northernmost portion of the study area, suggesting a sea level drop and fluvial environment evolution. LST = Lowstand Systems Tract, TST = Transgressive Systems Tract, HST = Highstand Systems Tract. (G) HST of S3 evolution following former LST of S3, observed only in central and southern portions; barrier islands were later covered, likely by prograding deltaic deposits. (H) TST of S3 formation indicates sea level rise after HST formation. LST = Lowstand Systems Tract, TST = Transgressive Systems Tract, HST = Highstand Systems Tract.

depositional environments. The thick sand units overlying the carbonate section in well C.D. Scott #1 (Fig. 8A), which can be correlated to a thick sand unit at the base of the same systems tract in well J.H. Wall Estate #1, indicate deposition on the proximal shelf. The high glauconite content, relatively small grain sizes, and good sorting of these sand deposits, along with wireline log motifs, suggest deposition on barrier islands (Fig. 13G), as noted in previous studies (e.g., Penland et al., 1981; Penland and Suter, 1983; Oertel, 1985). The upper part of the HST of S3 is correlated with aggradational to progradational stacking patterns, characterized by a coarsening upward trend. This likely represents the development of a prograding deltaic system, marking the end of the HST of S3 and the Upper Tuscaloosa in most of the wells studied. This HST corresponds to the end of the regressive phase of the T-R 5 sequence described as deltaic to fluvial in origin by Mancini and Puckett (2002).

S3 ended with the development of a TST (Fig. 13H), which is only observed in the northwestern part of the study area. This systems tract represents the upper section of the Upper Tuscaloosa in wells Citizen Bank 1 and JW Smith #1. The absence of this TST in the southern, more basinward areas is likely due to the thinning and eventual pinching out of transgressive systems tracts against the underlying highstand systems tract (Catuneanu, 2006). The transition from the aggradational and progradational patterns of the LST and HST of S3 to the retrogradational stacking patterns of the TST of the same sequence (Fig. 8A) is likely associated with an increase in accommodation space at the end of the Turonian (Mancini and Pickett, 2002), potentially coupled with a decrease in sediment supply (e.g., Catuneanu, 2006; Catuneanu et al., 2011). The log motifs attributed to the TST of S3 (Fig. 8A) are potentially linked to an upward increase in the proportion of mud compared to sand, which is a characteristic feature of a retrograding deltaic system (e.g., Galloway and Hobday, 1983; Catuneanu, 2006; Catuneanu et al., 2011).

5.2.4. Sequence 4

This sequence is characterized by the development of a LST, which is observed only in well DW Hendrix 1 that occurs in the eastern part of the study area (Fig. 7A). The development of this LST may indicate a basinward movement of the shoreline following the formation of the below TST of S3. The LST of S4 is correlated with multiple left-blocky to serrated left-blocky log motifs associated with sandstone lithofacies. The occurrence of the SB4 below this LST, which likely represents a subaerial unconformity, indicates that the sea level fell and a fluvial depositional environment developed. The lithologic properties of the LST of S4 show fining upward trends within left-blocky log motifs, which represent multiple cycles of deposition in a fluvial environment. The presence of mudrock lithofacies between the sandstone lithofacies probably indicates floodplain deposition (e.g., Galloway and Hobday, 1983; Serra, 1985).

In well C.D. Scott #1, S4 lacks a LST but instead preserves a TST that is characterized in the wireline log by an overall fining-upward trend with systematically increasing mudrock content upward. This fining-upward pattern (Fig. 8A), which exhibits small-scale fining-upward cycles may have been formed by the development of a retrograding deltaic system (e.g., Galloway and Hobday, 1983; Abdalla et al., 2025) prior to the termination of Upper Tuscaloosa deposition.

5.3. Factors controlling the evolution of the depositional sequences

5.3.1. Accommodation space

The relationship between sequence boundaries and stacking patterns can be used to determine whether sediment supply, basin

tectonism, or global sea-level fluctuations are the dominant factors controlling accommodation space (e.g., Schlager, 1993; Catuneanu et al., 2011). Several lines of evidence within the studied Tuscaloosa Grp suggest that sea-level fluctuations are the dominant control on the evolution of the studied sequences. The cyclicity of the interpreted sequences is continuous along the entire study area, and the LST, TST, and HST units and their bounding surfaces are traceable and extend over a few hundred kilometers in both dip and strike directions (Figs. 7 and 8). The stacking patterns of the delineated log facies also suggest changes in sea level (i.e., alternating fining- and coarsening-upward units shown by the funnel and bell log motifs) (Fig. 3B). The lithofacies shift from marine shales at the base (HST of S2) to continental sandstones at the top (LST of S3) may have resulted from a sea-level fall. On the contrary, the lithology changes from the continental sandstones (LST of S3) to overlying shale-dominant units may indicated a sea-level rise (Figs. 7 and 8). Additionally, a correlation of long-term changes in accommodation space, determined from cycle stacking patterns and sequence boundaries in the studied sequences, with the global eustatic charts of Haq et al. (1987) and Miller et al. (2005) has proved that sea-level oscillations are the major control on the deposition of the Tuscaloosa Grp sequences.

The presence of fluvial deposits at the base of the LST of S1 in the basinward part of the study area, along with the thick fluvial intervals in the LST of S1, indicates a decrease in marine accommodation space (Zecchin, 2007). This reduction in accommodation space was likely attributed to a decrease in global sea level (Miller et al., 2005) (Fig. 14A). Just above the fluvial section of the LST of S1 in the basinward area, there are well-developed marine mudrocks and sandstones, which can be attributed to the initial increase in marine accommodation space. The enhanced accommodation space during the initial deposition of the Tuscaloosa Grp resulted from a transgressive event affecting the GoM Coast Region in the early Late Cretaceous (Mancini et al., 1987). This transgression likely originated from both short-term and long-term sea-level rises occurring in the late Cenomanian (Fig. 14). The available accommodation space continued to expand, as indicated by the presence of the thin TST of S1 throughout the entire study area (Figs. 7, 8, and 11B). TST1's lithological features, characterized by a limited presence of coarse fractions (Fig. 14C), likely reflect a scenario where the rate of accommodation space creation exceeded sediment supply (Catuneanu et al., 2011). Haq et al. (1987) noted fluctuations in the short-term sea-level curve between 93 and 95 Ma (Fig. 14), which coincided with the time of deposition of the Lower Tuscaloosa, including the TST of S1 (Figs. 14B and C). These fluctuations may have contributed to the creation of the necessary accommodation space for the formation of this TST. The development of the HST of S1, which exhibits a higher coarse fraction compared to the lower TST, supports the ongoing increase in accommodation space, possibly with higher sedimentation rates compared to the lower TST (Fig. 14). The long-term global sea-level curves published by Miller et al. (2005) and Haq et al. (1987) demonstrate a consistent rise in eustatic sea level, which aligns with the timing of the formation of the HST of S1 and marks the final stage of deposition for the Lower Tuscaloosa (Fig. 14). This indicates that global sea-level fluctuations influenced the continuous development of accommodation amplitude during HST formation (Fig. 14).

The formation of the TST of S2, which corresponds to the lower section of the Middle Tuscaloosa (Figs. 7A and 8A), indicates a continued increase in accommodation space. This is supported by the presence of extensive and widespread mud deposits and minimal coarse fraction values throughout the study area. The substantial thickness of this TST interval is likely

a result of a prolonged period of increasing water depth across a large geographical region (Zecchin, 2007). The enhanced accommodation space during the formation of the TST of S2 (Fig. 14C) likely corresponds to coincident maxima in both long-term and short-term eustatic cycles of the Haq et al. (1987) sea-level curve during the early Turonian (Fig. 14B). This interpretation contrasts with the Miller et al. (2005) global sea-level model, which indicates an overall decline in eustatic sea level throughout the Turonian. However, Miller et al.'s (2005) curve also documents a minor positive excursion during the early Turonian that may have provided sufficient accommodation space to facilitate TST deposition within S2 during this interval. Mancini and Puckett (2002) also attributed the transgressive interval of the Middle Tuscaloosa to the increase in global sea level. The slight increase in the coarse fraction in the HST of S2, compared to the lower TST of S1 (Fig. 14C), indicates a slight decrease in accommodation space combined with higher sedimentation rates (Catuneanu et al., 2011). The increase in the coarse fraction (Fig. 14C) and the decrease in marine accommodation space during the deposition of the HST of S2 are highly correlated with the decline in the long-term and fluctuations of short-term global sea level curves (Haq et al., 1987). Between the mid- and late Turonian, corresponding to the deposition of the HST of S2 and the upper section of the Middle Tuscaloosa, global sea level is estimated to have dropped by ~90–110 m compared with the early and mid-late Turonian, as shown in Haq et al., (1987)'s model (Fig. 14B) (Haq et al., 1987). The Miller et al. (2005) sea-level model further supports our interpretation of accommodation space reduction being driven by eustatic fall. According to this model, global sea level continued declining through the late Turonian (Fig. 14A), corresponding to the interval when S2's HST deposition terminated.

During the deposition of the Upper Tuscaloosa, there was a decrease in accommodation space. This decrease was accompanied by an increase in the coarse fraction of the LST and HST of S3 (Fig. 14C), suggesting that the change in accommodation space was likely due to a sediment supply rate that exceeded the available

space for deposition (Catuneanu et al., 2011). The presence of the LST of S3 in the northern part of the study area and the HST of the same sequence in the central and southern parts indicates that the ancient shoreline likely migrated basinward. A comparison of the LST and HST of sequence 3 with the long-term and short-term eustatic curves of Haq et al. (1987) reveals that their formation coincided with a declining global sea level during the mid to late Turonian (Fig. 14B). This interpretation is corroborated by the Miller et al. (2005) sea-level model, which similarly documents a decreasing eustatic trend during LST and HST deposition within S3 (Fig. 14A). Conversely, evidence for renewed accommodation space creation is observed during subsequent TST development within the upper portion of the same sequence.

Tectonic subsidence, along with variations in eustatic sea levels, has a significant impact on the stratigraphic framework by providing space for sediment deposition (Catuneanu et al., 2011). It has been reported that the MSE region, where the Tuscaloosa Grp was deposited, experienced subsidence during the Late Cretaceous (90–85 Ma) (e.g., Cox and Van Arsdale, 1996; Cox and Van Arsdale, 2002). This subsidence occurred at the final stage of deposition of the Upper Tuscaloosa in the MSE, which is believed to have taken place during the middle to late Turonian (92–89.8 Ma) (Mancini and Puckett, 2002). If this is the case, the subsidence may have increased the accommodation space, even if there was no global sea level rise (Zecchin, 2007). Toward the end of the late Turonian (90–89.8 Ma), there was a decline in global sea level compared to the lower late Turonian (Fig. 14B) (Haq et al., 1987). This decline in global sea level could have led to a decrease in accommodation space and the development of progradational strata (e.g., Helland-Hansen and Gjelberg, 1994; Helland-Hansen and Martinsen, 1996; Zecchin, 2007; Catuneanu et al., 2011). However, a well-defined retrogradational pattern is seen in the upper portion of the Upper Tuscaloosa, specifically in the TST of S3 (Fig. 8A). This trend is observed in two of the studied wells, including Citizens Bank 1 and JW Smith #1 (Fig. 8A). We speculate that the subsidence of the MSE at the beginning of the Late Cretaceous (Cox and Van Arsdale, 1997) played a crucial role in increasing accommodation space,

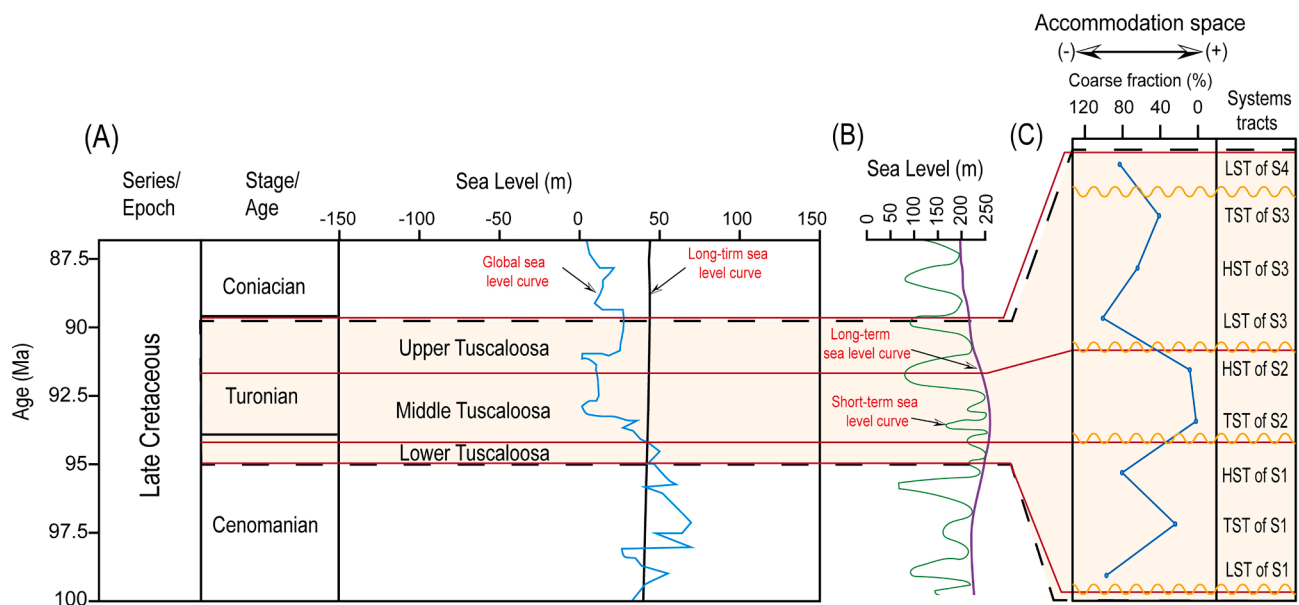


Fig. 14. Comparison between the identified systems tracts and published sea-level curves. (A) Short-term (blue line) and long-term (dark line) global sea level curves of the Late Cretaceous, modified from Miller et al. (2005). (B) Long-term (purple line) and short-term (green line) sea level curves of the Late Cretaceous, modified from Haq et al. (1987). (C) Coarse fraction proportion of the identified systems tracts within the Tuscaloosa Grp. Note that the coarse fraction includes sands of the TSTs and HSTs and sand and gravel of LSTs. The term accommodation here refers to marine accommodation. The dashed black lines represent the top and bottom contacts of the Tuscaloosa Grp, while the red solid lines represent the top and bottom contacts of the Tuscaloosa fms.

leading to the development of retrogradational stacking strata within the TST of S3 that is stratigraphically observed within the Upper Tuscaloosa (Fig. 8A).

5.3.2. Sediment supply

Sediments delivered to a sedimentary basin are greatly influenced by the chemical and mechanical weathering of the source area (Einsele, 2000). Periods of increased seasonal precipitation and wet climates are typically associated with a higher influx of siliciclastic materials into a basin and a decrease in carbonate production (Einsele, 2000). Conversely, wet or dry climates encourage the input or reduction of siliciclastic material into a basin, leading to the formation of chemical rocks (e.g., Cecil, 1990; Feldman et al., 2005; Catuneanu et al., 2011). The tectonism of the source area, as well as the lithology, also affects the amount and grain size of sediment carried by rivers or winds (e.g., Blum, 1991; Miall, 1996). Potential sediment directions for the systems tracts of the Lower and Upper Tuscaloosa can be interpreted by their coarse fraction proportions. In this study, we focus exclusively on interpreting the potential sources of delineated systems tracts within the Lower and Upper Tuscaloosa, as these units contain significantly higher proportions of coarse-grained sediments compared to the Middle Tuscaloosa.

The presence of coarse materials, particularly in the LSTs and HSTs of the Tuscaloosa Grp (Figs. 7, 8, and 12C), can be attributed to periods of intense weathering in the source area and a high influx of sediment into the MSE. In contrast, the presence of fine-grained rocks, particularly mudrocks of the TSTs and thin carbonate sediments in some of the HSTs of the Tuscaloosa Grp, indicates a decrease in sediment supply from the hinterland (Yang et al., 1995). The isopach maps of LST and HST of S1 (Figs. 11A and B) show particularly thick accumulations of sediments, suggesting that sediment originated from the north and northeast during Lower Tuscaloosa deposition; this agrees with Woolf and Wood (2010) and Woolf (2010). The dominant north to northeast source direction is consistent with the ancient Appalachian highlands as the primary region supplying sediment to the MSE, while the Ouachita highland region played a secondary role as a source area for Lower Tuscaloosa sediments (e.g., Woolf and Wood, 2010). Woolf and Wood (2010) associated the high quantities of quartz and sedimentary fragments as evidence of sourcing from recycled orogeny and craton interiors. Additionally, Zubi et al. (2025) also found high quantities of quartz grains and low quantities of feldspars in Lower Tuscaloosa rocks, supporting the interpretation of Woolf and Wood (2010) that these systems tracts were probably sourced from recycled orogeny source, most likely the Appalachians.

By the time of deposition of the HST of S3, the southeasterly thinning isopach geometry (Fig. 10E) indicates likely a shift to a more dominant northwesterly source, showing an increase in sediment supply from the Ouachita region (e.g., Woolf and Wood, 2010). This particular source was mentioned as an additional source for the Lower Tuscaloosa coarse sediments, and it is possible that it may have played a significant role during certain periods in the upper Turonian when the HST of S3, observed within the Upper Tuscaloosa, was being deposited. We hypothesize that this shift in provenance indicates the development of a drainage divide within the ancestral Mississippi River system that resulted in a Gulf-directed branch of the drainage system located to the east of the study area, which captured much of the Appalachian-derived sediments.

6. Conclusion

This study aimed to investigate the sequence stratigraphic framework of the Tuscaloosa Grp in the south-central MSE. The

research provided insights into the evolutionary patterns of the Tuscaloosa depositional sequences over vertical and lateral scales. From lithologic observations and wireline logs, five main lithofacies were defined: sandstone, mudrock (claystone and shale), siltstone, gravel, and carbonate. Four third-order depositional sequences are delineated based on four SBs, two TSs, and three MFSs. The sequences show varying systems tract assemblages: S1 with a LST, HST, and TST; S2 comprises a HST and TST; S3 contains a LST, HST, and TST; and S4 preserves a locally distributed LST and TST.

The depositional evolution of the Tuscaloosa Grp sequences reflects systematic changes in accommodation space and depositional environments controlled by relative sea-level fluctuations. During Sequence 1 development, the LST of S1 initially originated within fluvial and incised valley environments. Subsequently, the TS1 of S1 marked a critical transition from fluvial and incised valley sedimentation to deltaic depositional regimes that formed the TST of S1 as relative sea level began to rise. Following this transgressive phase, the HST of S1 developed in coastal environments characterized by barrier island formation and proximal shelf deposition during continued sea-level rise. S2 evolution demonstrates a different architectural pattern, where the TST of S2 developed within distal shelf environments. This transgressive phase was subsequently followed by the deposition of the HST of S2, which represents the transition from transgressive to regressive conditions through the establishment of a prograding deltaic system as accommodation space decreased relative to sediment supply. Similarly, S3 exhibits a complete depositional cycle beginning with the LST of S3, which developed within fluvial environments during relative sea-level fall. Additionally, the TST of S3 reflects retrograding deltaic system evolution, demonstrated by retrogradational stacking patterns observed in the northernmost portion of the study area. This was followed by the formation of the HST of S3, characterized by prograding deltaic system development as evidenced by progradational stacking patterns indicating sediment supply exceeding accommodation space. S4 shows limited development, where the LST may have been deposited in fluvial depositional environments during sea-level fall. This was followed by the initiation of the TST of S4 during the development of a retrograding deltaic system.

This work also demonstrated the influence of both accommodation space and sediment supply on the evolution of Tuscaloosa depositional sequences. The high marine accommodation space played a crucial role in influencing the formation of TSTs, HSTs, and the marine portions of LSTs. This accommodation space was primarily driven by the rise in global sea level, evident in the systems tracts associated with S1 and S2. Conversely, the impact of subsidence on accommodation space evolution was relatively moderate and observed only in the northern portion of our study area, as indicated by the retrogradational stacking patterns seen in the TST of S3. Based on the depocenter of the recognized systems tracts on the isopach maps, it appears that the Tuscaloosa Grp was primarily sourced from the north and northeast, likely from the Appalachians. The increasing thickness of the HST of S3, which is stratigraphically found in the Upper Tuscaloosa, toward the northwest of the study area suggests a shift to an increase in the volume of sediment input derived from the ancient Ouachita highlands, possibly due to alteration of the drainage system.

CRedit authorship contribution statement

Husamaldeen Zubi: Writing – original draft, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Brian F. Platt:** Writing – review & editing, Visualization, Supervision, Project administration, Investigation.

Muneer Abdalla: Writing – review & editing, Software, Methodology, Data curation. **Jennifer Gifford:** Writing – review & editing, Methodology. **Belkasim Khameiss:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this scientific article.

Acknowledgments

We thank the Geological Survey of Alabama for providing the core samples used in this study. We also gratefully acknowledge the financial support from the American Association of Petroleum Geologists to the first author during his Ph.D. research. Additionally, we extend our appreciation to Drs. Hakan Yasarer and Lance Yarbrough for their roles on the dissertation committee that included this research.

Data availability

The data that has been used is confidential.

References

- Abdalla, M., Zubi, H., Abdelnabi, A., 2025. Characterization and evolution of a retrograding-prograding deltaic system, NE Sirte Basin, north-central Libya — Sequence stratigraphic architecture and controlling factors. *Journal of African Earth Sciences* 224, 105558. <https://doi.org/10.1016/j.jafrearsci.2025.105558>.
- Ainsworth, R.B., McArthur, J.B., Lang, S.C., Vonk, A.J., 2018. Quantitative sequence stratigraphy. *AAPG Bulletin* 102 (10), 1913–1939. <https://doi.org/10.1306/02201817271>.
- Ambrose, W.A., Loucks, R.G., Dutton, S.P., 2015. Sequence-stratigraphic and depositional controls on reservoir quality in lowstand incised-valley fill and highstand shallow-marine systems in the Upper Cretaceous (Cenomanian) Tuscaloosa Formation, Louisiana, U.S.A. *Gulf Coast Association of Geological Societies Journal* 4, 43–66.
- Bhattacharyya, A., Chanda, S.K., 1970. Petrography and Origin of Krol Sandstones Around Solon, Northwestern Himalaya, India. *AAPG Bulletin* 54 (5), 835–836. <https://doi.org/10.1306/5D25CA51-16C1-11D7-8645000102C1865D>.
- Blair, W., 1978. Gulf of California in Lake Mead Area of Arizona and Nevada during Late Miocene Time. *AAPG Bulletin* 62, 1159–1170. <https://doi.org/10.1306/C1EA4FCC-16C9-11D7-8645000102C1865D>.
- Blum, M.D., 1991. Climatic and eustatic controls on Gulf coastal plain fluvial sedimentation: an example from the Late Quaternary of the Colorado River, Texas. In: Armentrout, J.M., Perkins, B.F. (Eds.), *Sequence Stratigraphy as an Exploration Tool, Concepts and Practices in the Gulf Coast*. SEPM Gulf Coast Section, Eleventh Annual Research Conference, Program with Abstracts, pp. 71–83.
- Boswell, E.H., Lang, J.W., 1957. Ground-water conditions in the Aberdeen-Columbus area. U.S. Geological Survey Open-File Report, Mississippi, p. 57. <https://doi.org/10.3133/ofr5713>, 13.
- Braithwaite, C., 1967. Carbonate environments in the middle Devonian of South Devon, England. *Sedimentary Geology* 1, 283–320.
- Brandano, M., Ronca, S., 2014. Depositional processes of the mixed carbonate-siliciclastic rhodolith beds of the Miocene Saint-Florent Basin, northern Corsica. *Facies* 60, 73–90. <https://doi.org/10.1007/s10347-013-0367-z>.
- Burke, C., 1985. Paleogeologic interpretation of Ostracoda from the Skelley Member, Conemaugh Group (Pennsylvanian), southeastern Ohio. *Journal of Paleontology* 59, 839–848.
- Cant, D., 1992. Subsurface facies analysis. In: Walker, R.G., James, N.P. (Eds.), *Facies Models, Response to Sea Level Changes*. Geological Association of Canada, pp. 27–45.
- Cant, D., Walker, R., 1976. Development of a braided-fluvial facies model for the Devonian Battery Point Sandstone, Québec. *Canadian Journal of Earth Sciences* 13, 102–119.
- Carannante, G., Ruberti, D., Sirna, M., 2000. Upper Cretaceous ramp limestones from the Sorrento Peninsula (southern Apennines, Italy): micro- and macro-fossil associations and their significance in the depositional sequences. *Sedimentary Geology* 132, 89–123. [https://doi.org/10.1016/S0037-0738\(00\)00004-X](https://doi.org/10.1016/S0037-0738(00)00004-X).
- Catuneanu, O., 2006. *Principles of Sequence Stratigraphy*. Elsevier, Amsterdam, p. 375.
- Catuneanu, O., Galloway, W.E., Kendall, C.G.S.C., Miall, A.D., Posamentier, H.W., Strasser, A., Tucker, M.E., 2011. Sequence stratigraphy: methodology and nomenclature. *Newsletters on Stratigraphy* 44 (3), 173–245. <https://doi.org/10.1127/0078-0421/2011/00011>.
- Cecil, C.B., 1990. Paleoclimate controls on stratigraphic repetition of chemical and siliciclastic rocks. *Geology* 18, 533–536. [https://doi.org/10.1130/00917613\(1990\)018<0533:PCOSRO>2.3.CO;2](https://doi.org/10.1130/00917613(1990)018<0533:PCOSRO>2.3.CO;2).
- Chasteen, H., 1983. Re-evaluation of Lower Tuscaloosa and Dantzler Formations (Middle Cretaceous) with emphasis on depositional environments and time-stratigraphic relationships. *AAPG Bulletin* 67.
- Cox, R.T., Van Arsdale, R.B., 2002. The Mississippi Embayment, North America: a first order continental structure generated by the Cretaceous superplume mantle event. *Journal of Geodynamics* 34 (2), 163–176. [https://doi.org/10.1016/S0264-3707\(02\)00019-4](https://doi.org/10.1016/S0264-3707(02)00019-4).
- Cox, R.T., Van Arsdale, R.B., 1997. Hotspot origin of the Mississippi Embayment and its possible impact on contemporary seismicity. *Engineering Geology* 46, 201–216. [https://doi.org/10.1016/S0013-7952\(97\)00003-3](https://doi.org/10.1016/S0013-7952(97)00003-3).
- Cushing, E.M., Boswell, E.H., Hosman, R.L., 1964. General geology of the Mississippi Embayment. United States Geological Survey Professional Paper 448-B, pp. 1–25.
- Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. *Journal of Sedimentary Petrology* 62, 1130–1146. <https://doi.org/10.1306/D4267A69-2B26-11D7-8648000102C186-5D>.
- Deconinck, J., Boué, D., Amédéo, F., Baudin, F., Bruneau, L., Huret, É., Landrein, P., Moreau, J., Santoni, A., 2021. First record of early Aptian Oceanic Anoxic Event 1a from the Paris Basin (France) – climate signals on a terrigenous shelf. *Cretaceous Research* 125. <https://doi.org/10.1016/j.cretres.2021.104846>.
- Dinkins, T., 1966. Subsurface stratigraphy of Claiborne County, 107. *Mississippi Geological Survey Bulletin*, p. 174.
- Dinkins, T., 1969. Subsurface stratigraphy of Copiah County, 110. *Mississippi Geological Survey Bulletin*, p. 172.
- Dockery, D.T., 1996. Toward a revision of the generalized stratigraphic column of Mississippi. *Mississippi Geology*, 17, pp. 1–9.
- Dockery, D.T., Thompson, D.E., 2016. *The geology of Mississippi* (p. 692). University Press of Mississippi.
- Ervin, C.P., McGinnis, L.D., 1975. Reelfoot Rift: reactivated precursor to the Mississippi Embayment. *Geological Society of America Bulletin* 86, 1287–1295. [https://doi.org/10.1130/0016-7606\(1975\)86<1287:RRRPTT>2.0.CO;2](https://doi.org/10.1130/0016-7606(1975)86<1287:RRRPTT>2.0.CO;2).
- Einsele, G., 2000. In: *Sedimentary Basins: Evolution, Facies, and Sediment Budget*, second ed. Springer-Verlag, Berlin, p. 792.
- Feldman, H.R., Franseen, E.K., Joeckel, R.M., Heckel, P.H., 2005. Impact of longer-term modest climate shifts on architecture of high-frequency sequences (cyclotheams), Pennsylvanian of Midcontinent U.S.A. *Journal of Sedimentary Research* 75, 350–368. <https://doi.org/10.2110/jsr.2005.028>.
- Frakes, L.A., 1979. *Climates Throughout Geologic Time*. Elsevier, Amsterdam, p. 310.
- Fujita, K., Shimoji, H., Nagai, K., 2006. Paleoenvironmental interpretations of Quaternary reef deposits based on comparisons of 10 selected modern and fossil larger foraminifera from the Ryukyu Islands, Japan. *Island Arc* 15, 420–436. <https://doi.org/10.1111/j.1440-1738.2006.00539.x>.
- Galloway, T.R.A.W.E., Hobday, D.K., 1983. Terrigenous Clastic Depositional Systems. Applications to Petroleum, Coal, and Uranium Exploration. *Geological Magazine* 121 (5), 527–528. <https://doi.org/10.1017/S0016756800030272>.
- Hackley, P.C., Enomoto, C.B., Valentine, B.J., Rouse, W.A., Lohr, C.D., Dulong, F.T., Hatcherian, J.J., Brennan, S.T., Craddock, W.H., Finn, T.M., Gaswirth, S.B., Le, P.A., Leathers-Miller, H.M., Marra, K.R., Mercier, T.J., Paxton, S.T., Whidden, K.J., Woodall, C.A., Schenk, C.J., 2018. Assessment of undiscovered continuous oil and gas resources in the Upper Cretaceous Tuscaloosa Marine Shale of the U.S. Gulf Coast. U.S. Geological Survey Fact Sheet 2018-2043, p. 2. <https://doi.org/10.3133/fs20183043>.
- Hackley, P., Dennen, K., Garza, D., Lohr, C., Valentine, B., Hatcherian, J., Enomoto, C., Dulong, F., 2020. Oil-source rock correlation studies in the unconventional Upper Cretaceous Tuscaloosa marine shale (TMS) petroleum system, Mississippi and Louisiana, USA. *Journal of Petroleum Science and Engineering* 190. <https://doi.org/10.1016/j.petrol.2020.107015>.
- Haq, B.U., 2014. Cretaceous eustasy revisited. *Global and Planetary Change* 113, 44–58. <https://doi.org/10.1016/j.gloplacha.2013.12.007>.
- Haq, B.U., Hardenbol, J., Vail, P.R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science* 235, 1156–1167. <https://doi.org/10.1126/science.235.4793.1156>.
- Hatcher, R.D., Jr., 1989. Tectonic synthesis of the U.S. Appalachians. In: *The Geology of North America* (Vol. F-2). Geological Society of America. <https://doi.org/10.1130/DNAG-GNA-F2.511>.
- Heap, A.D., Nichol, S.L., 1997. The influence of limited accommodation space on the stratigraphy of an incised-valley succession: Wei River estuary, New Zealand. *Marine Geology* 144, 229–252. [https://doi.org/10.1016/S0025-3227\(97\)00107-2](https://doi.org/10.1016/S0025-3227(97)00107-2).
- Hein, F.J., Walker, R.G., 1977. Bar evolution and development of stratification in the gravelly, braided, Kicking Horse River, British Columbia. *Canadian Journal of Earth Sciences* 14, 562–570.
- Helland-Hansen, W., Gjølberg, J., 1994. Conceptual basis and variability in sequence stratigraphy: a different perspective. *Sedimentary Geology* 92, 31–52. [https://doi.org/10.1016/0037-0738\(94\)90053-1](https://doi.org/10.1016/0037-0738(94)90053-1).
- Helland-Hansen, W., Martinsen, O.J., 1996. Shoreline trajectories and sequences: description of variable depositional-dip scenarios. *Journal of Sedimentary Research* 66, 670–688.

- Hildenbrand, T.G., Kane, M.F., Hendricks, J.D., 1982. Magnetic Basement in the Upper Mississippi Embayment Region—a Preliminary Report, 1236. US Geological Survey Professional Paper, pp. 39–53.
- Johansson, M., Stow, D.A.V., 1995. A classification scheme for shale clasts in deep water sandstones. *Geological Society, London, Special Publications* 94 (1), 221–241. <https://doi.org/10.1144/GSL.SP.1995.094.01.15>.
- John, C.J., Jones, B.L., Moncrief, J.E., Bourgeois, R., Harder, B.J., 1997. An unproven unconventional seven billion barrel oil resource—the Tuscaloosa Marine Shale. *BRI Bulletin* 7, 20.
- John, C.J., Jones, B.L., Harder, B.J., Bourgeois, R.J., 2005. Exploratory progress towards proving the billion barrel potential of the Tuscaloosa Marine Shale. *Gulf Coast Association of Geological Studies* 55, 367–372.
- Johnson, P.R., Zietz, I., Thomas, W.A., 1994. Possible neoproterozoic-early Paleozoic grabens in Mississippi, Alabama, and Tennessee. *Geology* 22 (1), 11–14. [https://doi.org/10.1130/0091-7613\(1994\)022<0011:PNEPGI>2.3.CO;2](https://doi.org/10.1130/0091-7613(1994)022<0011:PNEPGI>2.3.CO;2).
- Kehew, A.E., 2006. In: *Geology for Engineers and Environmental Scientists*, third ed. Pearson Education.
- Lowery, C.M., Cunningham, R., Barrie, C.D., Bralower, T., Snedden, J.W., 2017. The northern Gulf of Mexico during OAE2 and the relationship between water depth and black shale development. *Paleoceanography* 32 (12), 1316–1335. <https://doi.org/10.1002/2017PA003180>.
- Makurath, J., 1977. Marine faunal assemblages in the Silurian-Devonian Keyser Limestone of the central Appalachians. *Lethaia* 10, 235–256. <https://doi.org/10.1111/j.1502-3931.1977.tb00618.x>.
- Mancini, E.A., Puckett, T.M., 2002. Transgressive-regressive cycles in Lower Cretaceous strata, Mississippi Interior Salt Basin area of the northeastern Gulf of Mexico, USA. *Cretaceous Research* 23 (3), 409–438. <https://doi.org/10.1006/cres.2002.1012>.
- Mancini, E.A., Mink, R.M., Payton, J.W., Bearden, B.L., 1987. Environments of deposition and petroleum geology of Tuscaloosa Group (Upper Cretaceous), South Carlton and Pollard Fields, southwestern Alabama. *AAPG Bulletin* 71, 1128–1142.
- Mancini, E.A., Puckett, T.M., 2005. Jurassic and Cretaceous transgressive-regressive (T-R) cycles, Northern Gulf of Mexico, USA. *Stratigraphy* 2 (1), 31–48. <https://doi.org/10.29041/strat.02.1.02>.
- Martinuš, M., Fio, K., Pikelj, K., Aščić, Š., 2012. Middle Miocene warm-temperate carbonates of Central Paratethys (Mt. Zrinska Gora, Croatia): paleoenvironmental reconstruction based on bryozoans, coralline red algae, foraminifera, and calcareous nannoplankton. *Facies* 59, 481–504. <https://doi.org/10.1007/s10347-012-0327-z>.
- Masuda, H., 2017. Sedimentary environment of reef limestones in Kuzu area, Sano city, Tochigi Pref. Japan Geoscience Union.
- McBride, E., 1974. Significance of color in red, green, purple, olive, brown, and gray beds of Difunta Group, northeastern Mexico. *Journal of Sedimentary Research* 44, 760–773. <https://doi.org/10.1306/212F6B9A-2B24-11D7-8648000102C1865D>.
- Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth Science Reviews* 22, 261–308. [https://doi.org/10.1016/0012-8252\(85\)90001-7](https://doi.org/10.1016/0012-8252(85)90001-7).
- Miall, A.D., 1996. *The Geology of Fluvial Deposits: Sedimentary Facies. Basin Analysis, and Petroleum Geology*. Springer-Verlag, Berlin, p. 598.
- Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. *Science* 312, 1293–1298. <https://doi.org/10.1126/science.1116412>.
- Milne, I., Earley, J., 1958. Effect of source and environment on clay minerals. *AAPG Bulletin* 42, 328–338.
- Mitchum, R.M., Vail, P.R., Thompson, S., 1977. Seismic stratigraphy and global changes of sea level, Part 2: the depositional sequence as a basin unit for stratigraphic analysis. In: Payton, C.V. (Ed.), *Seismic Stratigraphy – Application to Hydrocarbon Exploration*, vol. 26. AAPG Memoir, pp. 53–62.
- Mooney, W.D., Andrews, M.C., Ginzburg, A., Peters, D.A., Hamilton, R.M., 1983. Crustal structure of the northern Mississippi Embayment and a comparison with other continental rift zones. *U.S. Geological Survey* 945, 327–348. [https://doi.org/10.1016/0040-1951\(83\)90023-9](https://doi.org/10.1016/0040-1951(83)90023-9).
- Oertel, G., 1985. The barrier island system. *Marine Geology* 63, 1–18.
- Parker, J.R., 1977. Deep sea sands: development in petroleum geology. In: Hobson, G.D. (Ed.), *Applied Science*. Barking, pp. 225–242.
- Penland, J., Suter, J.R., 1983. Transgressive coastal facies preserved in barrier island arc retreat paths in the Mississippi River delta plain. *Gulf Coast Association of Geological Societies Transactions* 33, 367–382.
- Penland, R., Boyd, D., Nummedal, D., Roberts, H., 1981. Deltaic barrier development on the Louisiana coast. *Gulf Coast Association of Geological Societies Transactions* 31, 471–476.
- Radwan, A., Sen, S., 2020. Stress path analysis for characterization of in situ stress state and effect of reservoir depletion on present-day stress magnitudes: reservoir geomechanical modeling in the Gulf of Suez Rift Basin, Egypt. *Natural Resources Research* 30, 463–478. <https://doi.org/10.1007/s11053-020-09731-2>.
- Rider, M., 1996. In: *The Geological Interpretation of Well Logs*, second ed. Whittles Publishing, Scotland, p. 280.
- Ruberti, D., 1997. Facies analysis of an Upper Cretaceous high-energy rudist-dominated carbonate ramp (Matese Mountains, central-southern Italy): sub-tidal and peritidal cycles. *Sedimentary Geology* 113, 81–110. [https://doi.org/10.1016/S0037-0738\(97\)00047-X](https://doi.org/10.1016/S0037-0738(97)00047-X).
- Rust, B.R., 1972. Structure and process in a braided river. *Sedimentology* 18, 221–246.
- Salvador, A., 1991. Origin and development of the Gulf of Mexico basin. In: *The Geology of North America*. Geological Society of America J, pp. 389–444. <https://doi.org/10.1130/DNAG-GNA-J-389>.
- Sanders, D., Pons, J., 1999. Rudist formations in mixed siliciclastic-carbonate depositional environments, Upper Cretaceous, Austria: stratigraphy, sedimentology, and models of development. *Palaeogeography, Palaeoclimatology, Palaeoecology* 148, 249–284. [https://doi.org/10.1016/S0031-0182\(98\)00186-2](https://doi.org/10.1016/S0031-0182(98)00186-2).
- Schlager, W., 1993. Accommodation and supply — a dual control on stratigraphic sequences. *Sedimentary Geology* 86, 111–136. [https://doi.org/10.1016/0037-0738\(93\)90136-5](https://doi.org/10.1016/0037-0738(93)90136-5).
- Scrutton, C., 2000. Discussion of 'Palaeocurrent direction and velocity in the Great/Main Limestone on the Alston and Askrigg blocks of northern England'. *Proceedings* 52 (4), 353–359. <https://doi.org/10.1144/pygs.52.4.353>.
- Seli, A., Finthan, B., 2022. The primary depositional structures of the Upper Bima Member from Fufure and environs, Yola Arm of the Upper Benue Trough, Northeastern Nigeria: implications for paleoenvironment. *Dutse Journal of Pure and Applied Sciences* 8. <https://doi.org/10.4314/dujopas.v8i3b.14>.
- Serra, O., 1985. *Sedimentary Environments from Wireline Logs*. Schlumberger Limited, Paris.
- Smith, E.A., Johnson, L.C., 1887. Tertiary and Cretaceous strata of the Tuscaloosa, Tombigbee, and Alabama Rivers. *U.S. Geol. Survey Bull* 43, 189.
- Stefano, P., Ruberti, D., 2000. Cenomanian rudist-dominated shelf-margin limestones from the panormide carbonate platform (Sicily, Italy): facies analysis and sequence stratigraphy. *Facies* 42, 133–160. <https://doi.org/10.1007/BF02562570>.
- Swift, D.J.P., 1975. Barrier-island genesis: evidence from the central Atlantic shelf, eastern U.S.A. *Sedimentary Geology* 14, 1–43. [https://doi.org/10.1016/0037-0738\(75\)90015-9](https://doi.org/10.1016/0037-0738(75)90015-9).
- Vail, P.R., 1987. Seismic stratigraphy interpretation using sequence stratigraphy: Part 1: seismic stratigraphy interpretation procedure. In: *Atlas of Seismic Stratigraphy*. AAPG Studies in Geology 27, 1–10.
- Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990. Siliciclastic sequence stratigraphy in well logs, cores and outcrops. *AAPG Methods in Exploration* 7, 55.
- Woolf, K.S., 2012. Regional character of the Lower Tuscaloosa Formation depositional systems. University of Texas at Austin, Austin, USA. Ph.D. Dissertation.
- Woolf, K., Wood, L., 2010. The regional character of the Lower Tuscaloosa Sandstone depositional systems (Late Cretaceous) and implications for the influence of basement structure on the depositional trends. *Gulf Coast Association of Geological Societies Transactions* 60, 847.
- Yang, W., Harmsen, F., Kominz, M.A., 1995. Quantitative analysis of a cyclic peritidal carbonate sequence, the Middle and Upper Devonian Lost Burro Formation, Death Valley, California - a possible record of Milankovitch climatic cycles. *Journal of Sedimentary Research* 65B, 306–322.
- Zecchin, M., 2007. The architectural variability of small-scale cycles in shelf and ramp clastic systems: the controlling factors. *Earth-Science Reviews* 84 (1–2). <https://doi.org/10.1016/j.earscirev.2007.05.003>.
- Zubi, H., Platt, B.F., Abdalla, M., 2025. Diagenetic characterization of the Tuscaloosa Group in the south-central Mississippi Embayment, USA: implications for reservoir quality evaluation. *Journal of Sedimentary Environments*. <https://doi.org/10.1007/s43217-025-00242-9>.