



Application of fluvial scaling relationships to reconstruct drainage-basin evolution and sediment routing for the Cretaceous and Paleocene of the Gulf of Mexico

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ABSTRACT

Fluvial systems represent a key component in source-to-sink analysis of ancient sediment-dispersal systems. Modern river channels and channel-related deposits possess a range of scaling relationships that reflect drainage-basin controls on water and sediment flux. For example, channel-belt sand-body thicknesses scale to bankfull discharge, and represent a reliable first-order proxy for contributing drainage-basin area, a proxy that is more robust if climatic regimes can be independently constrained. A database of morphometrics from Quaternary channel belts provides key modern fluvial system scaling relationships, which are applied to Cretaceous- to Paleocene-age fluvial deposits. This study documents the scales of channel-belt sand bodies within fluvial successions from the northern Gulf of Mexico passive-margin basin fill from well logs, and uses scaling relationships developed from modern systems to reconstruct the scale of associated sediment-routing systems and changes in scale through time.

We measured thicknesses of 986 channel-belt sand bodies from 248 well logs so as to estimate the scales of the Cretaceous (Cenomanian) Tuscaloosa-Woodbine, Paleocene–early Eocene Wilcox, and Oligocene Vicksburg-Frio fluvial systems. These data indicate that Cenozoic fluvial systems were significantly larger than their Cenomanian counterparts, which is consistent with Cretaceous to Paleocene continental-scale drainage reorganization that routed water discharge and sediment from much of the continental United States to the Gulf of Mexico. At a more detailed level, Paleocene–early Eocene Wilcox fluvial systems were larger than their Oligocene counterparts, which could reflect decreases in drainage-basin size and/or climatic change within the continental interior toward drier climates with less runoff. Additionally, these data suggest that the paleo-Tennessee River, which now joins the Ohio River in the northernmost Mississippi embayment of the central United States, was an independent fluvial system, flowing southwest to the southern Mississippi embayment, or directly to the Gulf of Mexico, through the early Eocene.

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Changes in scaling relationships through time, and interpreted changes in the scales of contributing drainage basins, are generally consistent with previously published regional paleogeographic maps, as well as with newly published maps of paleodrainage from detrital-zircon provenance and geochronological studies. As part of a suite of metrics derived from modern systems, scaling relationships make it possible to more fully understand and constrain the scale of ancient source-to-sink systems and their changes through time, or cross-check interpretations made by other means.

INTRODUCTION

Source-to-sink (S2S) approaches to stratigraphic research focus on reconstructing and predicting sediment production, transport, and storage through fluvial systems, delivery rate to deltaic and deepwater sediment sinks, and how allogenic signals and autogenic self-organization are preserved in the ancient stratigraphic record (Romans et al., 2016). Scaling relationships represent an important part of an S2S approach, because sediment and water flux, and the dimensions of modern sediment-dispersal system segments, scale to contributing drainage area (e.g., Syvitski and Milliman, 2007; Sømme et al., 2009; Helland-Hansen, 2016). Scaling relationships in sediment-dispersal systems generally follow power laws, where absolute dimensions are proportional to drainage-basin size and the corresponding flux of water and sediment, and parameters like grain size and transport slope scale inversely (e.g., Sømme et al., 2009). From the above, the scales and properties of segments within a sediment-dispersal system correlate to water and sediment flux from the drainage basin, and more importantly, the scales and properties of one segment within a sediment-dispersal system are therefore inherently related to, and can be predicted from, the scales and properties of another.

This paper applies empirical scaling relationships from modern systems to reconstruct the scales of fluvial systems for Late Cretaceous, Paleocene–earliest Eocene, and Oligocene sediment-dispersal systems of the northern Gulf of Mexico sedimentary basin from subsurface data, in this case well logs. This paper is conceptually linked to those of Blum et al. (2017), who recon-

structured drainage areas for the same stratigraphic intervals from detrital zircon U-Pb provenance and geochronological data; Snedden et al. (2018), who quantified changes in the scale of Gulf of Mexico basin-floor fans through time from subsurface data; and Xu et al. (2017), who focused on reconstructing early Miocene fluvial systems from both detrital-zircon and well-log data. Collectively, these papers are designed to use the data-rich northern Gulf of Mexico margin to test the utility of a semiquantitative S2S approach to reconstructing paleodrainage and sediment routing at the continental scale, and prediction of the scales of basin-floor fans in the terminal sink.

■ GULF OF MEXICO STRUCTURAL AND STRATIGRAPHIC CONTEXT

The northern Gulf of Mexico is a well-known sedimentary basin, with many studies that document tectonic evolution of the basin, as well as the Mesozoic to Cenozoic stratigraphic framework (see the summary in Galloway, 2008, and references herein). Early to middle Mesozoic paleogeographic evolution of the early northern Gulf of Mexico can be tied to initial rifting and breakup of Pangea, distribution and nature of basement crust (Sawyer et al., 1991; Peel et al., 1995; Bird et al., 2005), margin type (Marton and Buffler, 1993), and Jurassic salt deposition (Martin, 1978; Sawyer et al., 1991). During the Jurassic to middle Cretaceous, the Gulf of Mexico margin was dominated by a carbonate ramp with little clastic sediment dispersal to deepwater environments (Rainwater, 1967; Anderson, 1980; Winker and Buffler, 1988; Yurewicz et al., 1993).

Studies pertinent to early Gulf of Mexico sediment source regions suggest there was a continuous upland that connected the Appalachian and Ouachita Mountains through the early Cretaceous (Thomas, 1985; Viele and Thomas, 1989; Hale-Erlich and Coleman, 1993), followed by the initial breaching of the Mississippi embayment during the late Cretaceous to early Paleocene, perhaps in response to hot-spot activity that resulted in thermally generated uplift, erosion, and subsidence as the hot-spot location moved to the east (Van Arsdale and TenBrink, 2000; Cox and Van Arsdale, 2002; Whitaker and Engelder, 2006; Matton and Jébrak, 2009). Igneous activity (Moody, 1949; Kidwell, 1951; Baksi, 1997) and regional uplift (Anderson, 1980; Ewing, 1991; Harry and Londono, 2004) are linked to the late Cretaceous initiation of the modern Mississippi embayment (Cushing et al., 1964; Ervin and McGinnis, 1975; Kane et al., 1981; Baksi, 1997). In addition to a broad deepening of basement from onshore to offshore, a number of basement arches or broad uplifts rim the northern Gulf of Mexico basin (Bornhauser, 1958; Martin, 1978; Dallmeyer, 1989; Ewing, 1991) (Fig. 1) and influence sediment routing and accumulation patterns by subtly affecting accommodation and deformation. Throughout the Mesozoic to Cenozoic, these local, long-lived uplifts and arches impacted deposition and funneled sediment fairways through the interior salt basins, Mississippi embayment, Houston embayment, and Rio Grande embayment (Jung Echols and Malkin, 1948; Granata, 1963; Seni and Jackson, 1984; Lawless and Hart, 1990; Nunn, 1990; Xue, 1997; Ambrose et al., 2009; Adams and Carr, 2010) (Fig. 2).

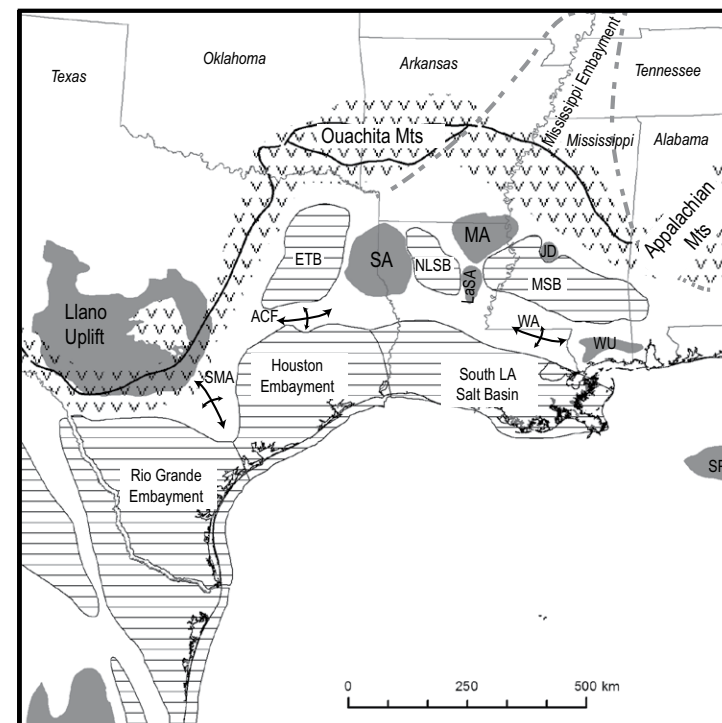


Figure 1. Northern Gulf of Mexico basin tectonic and structural elements. Modified from Ewing (1991) and Whitaker and Engelder (2006). SMA—San Marcos Arch; ETB—East Texas Basin; ACF—Angelina Caldwell flexure; SA—Sabine Arch; NLSB—North Louisiana (LA) Salt Basin; MA—Monroe Arch; LaSA—LaSalle Arch; JD—Jackson Dome; MSB—Mississippi Salt Basin; WA—Wiggins Arch; WU—Wiggins uplift; SP—Southern Platform. V pattern indicates high-relief uplifts; solid gray pattern and perpendicular arrows indicate low-relief uplifts and persistent arches; horizontal lines pattern indicates subsiding basins; gray dashed line outlines Mississippi Embayment.

Cenomanian Tuscaloosa-Woodbine fluvial-deltaic systems represent the first instance that clastic sediments prograded across the preexisting broad carbonate-dominated shelf and delivered a significant volume of sediment to the shelf margin and beyond (Barrell, 1997; Funkhouser et al., 1981; Dubiel et al., 2003). Commencing in the late Paleocene to early Eocene and persisting throughout the Oligocene, clastic influx significantly increased and was funneled through large fluvial systems centered in the Houston, Mississippi, and Rio Grande embayments (Stearns MacNeil, 1966; Galloway, 2005; Galloway et al., 2011) (Fig. 3).

In the Jurassic to Cenozoic strata, workers have long recognized large-scale packages of sediment that are bounded above and below by regional flooding surfaces. They have described these packages as transgressive-regressive

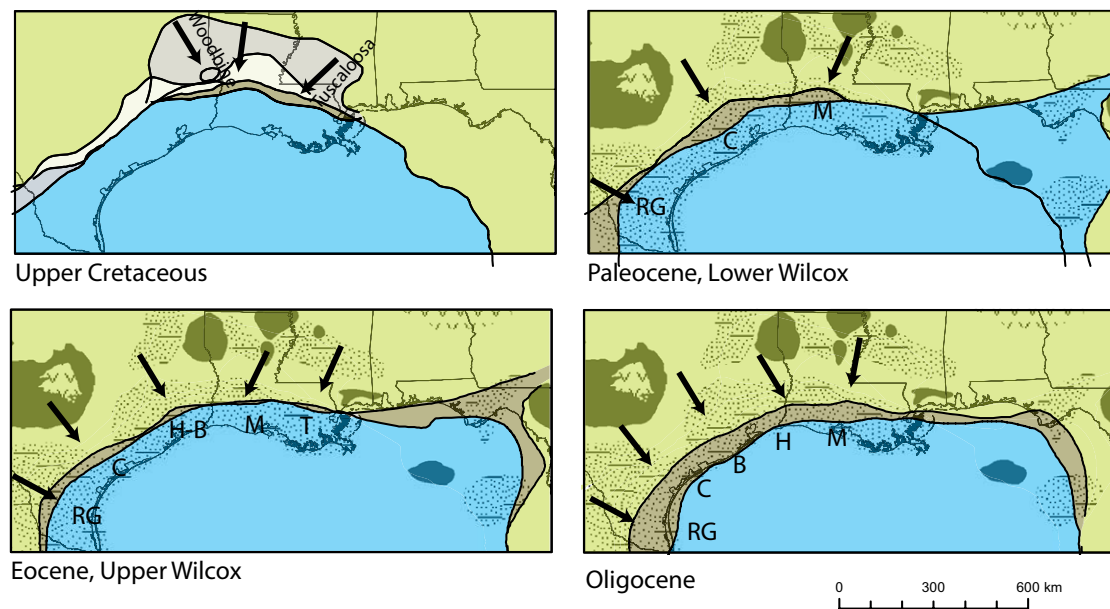


Figure 2. Fluvial axes (arrows) for the northern Gulf of Mexico from the Upper Cretaceous to Oligocene. Dark-green inland areas mark persistent uplifts and arches; gray area indicates subsiding region during late Cretaceous; beige area indicates Jurassic to lower Cretaceous shelf progradation; brown area indicates shelf progradation; stipple pattern indicates basins; blue area indicates offshore. Modified from compilations of Galloway (2001), Galloway (2005), Galloway (2008), and Galloway et al. (2011). RG—Rio Grande paleo-fluvial axis; C—Colorado paleo-fluvial axis; M—Mississippi paleo-fluvial axis; H-B—Houston-Brazos paleo-fluvial axis; H—Houston paleo-fluvial axis; B—Brazos paleo-fluvial axis; T—Tennessee paleo-fluvial axis.

(TR) cycles of terrigenous offlapping wedges (Claudet, 1950; Stearns, 1957; Martin, 1978; Mitchum and Van Wagoner, 1991; Mancini and Puckett, 2005) (Fig. 4) and have placed them into a sequence stratigraphic framework. The progradational parts of the packages are prone to preserve the target fluvial facies (e.g., Baum and Vail, 1988; Galloway et al., 2000; Mancini et al., 2008). This study utilizes this preexisting stratigraphic framework to recognize and extract metrics from the fluvial channel belts preserved within the terrigenous offlapping wedges (TR cycles). Furthermore, the results of this study provide an independent test of preexisting maps delineating North American Cenozoic drainage-basin evolution (Galloway, 2005; Galloway et al., 2011).

In addition to empirical scaling relationships to derive drainage-basin size, recent studies have utilized geochronological tools including detrital zircon to test the provenance and drainage-basin configuration for the northern Gulf of Mexico basin during the Late Cretaceous to Eocene (Mackey et al., 2012; Blum and Pecha, 2014; Blum et al., 2017; Wahl et al., 2016). Their findings provide alternatives and/or modifications to the paleodrainage configurations as outlined by Galloway et al. (2011). Geochronological tools such as detrital zircon provide a direct means to locate the source of sediment (provenance) and up-dip extent for a drainage basin.

This study builds on an established regional stratigraphic framework for the northern Gulf of Mexico derived from well logs and seismic data that, in conjunction with biostratigraphic zonation, provide chronostratigraphic controls (Galloway, 2008; Mancini et al., 2008).

METHODS

This study is grounded on recognition and measurement of channel-related sand bodies of fluvial origin in subsurface data. For the purposes of this paper, we use the term “point bar” to represent a morphological feature in rivers that develops on concave banks, and accumulates sand primarily by lateral accretion. Following Blum et al. (2013, and references therein), we use the term “channel belt” to define the area over which a channel has migrated during a specific interval of time, and the term “channel-belt sand body” represents the deposit that forms from that lateral migration. Most channel belts are active over a few thousands of years (not tens or hundreds of thousands): Additionally, low-gradient coastal-plain rivers typical of passive-margin settings like the Gulf of Mexico consist of channel-belts that are constructed by a continuum of highly migratory to non-migratory channels. Highly migratory channels construct multiple point bars that are laterally amalgamated with channel-belt widths being 7–30 times the active channel width; whereas non-migratory channels construct a single narrow point bar that has migrated only 2–5 times the channel width (Fig. 5). Blum et al. (2013) and Fernandes et al. (2016) showed that these end members characterize positions that are above and below the backwater limits respectively, where lateral migration rates decrease, aggradation and avulsion become common, and the river channel system becomes distributive in the backwater zone. The net result is that channel-belt width-to-thickness (W:T) ratios decrease

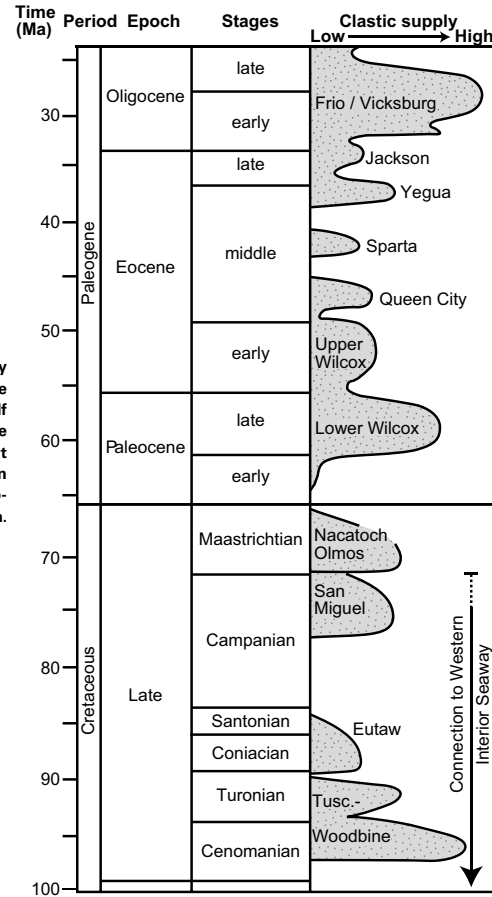
Well-log identification of channel belts

As described in classic works by Allen (1978), Bernard et al. (1970), Jackson (1976, 1977) and summarized by Bridge (2003), fluvial channel belts and abandoned channels have typical blocky to fining upward lithologic patterns (Collinson, 1978). The shape of the lithological variation translates roughly to shape of well logs such as, gamma ray, resistivity, and SP (Fig 1). The shape of the well log can be used as an indicator of depositional environment and sandstone body type. Wireline log shapes are often described as funnel- 'upward coarsening', bell- 'upward fining', cylinder- 'blocky' and further described as smooth or serrated (Cant 1984; Snedden 1984, Scheibling and Atkinson 1992; Bridge and Tye, 2000). However, log shape in gamma ray or SP (spontaneous potential) in siliclastic rocks is related more to argillaceous content than to grain size. The coarser-grained material at the base typically exhibits low gamma ray, and an excursion in the SP and resistivity (direction varies depending upon salinity and fluid content of pore waters) grading into or overlain by finer-grained material (commonly containing increase argillaceous content) exhibiting slightly higher gamma ray or less excursion in the SP/Resistivity curves and producing the 'blocky' or 'bell' shaped curve as illustrated in the SP wireline log curves of Figure 1.

For example, in the modern Brazos river, several boreholes were drilled through a meander bend and logged with SP tool (Bernard et al 1970). These curves illustrate the 'fining upward' as well as serrated blocky wireline shapes observed in fluvial channel belt deposits. Additionally, the channel belt wireline log signature can be compared to a typical abandoned channel wireline log signature. The abandoned channel wireline log signature typically contains a blocky to serrated pattern at the base that is sharply overlain by serrated low SP or Gamma Ray. The blocky to serrated pattern at the base indicates coarser-grained flood scour deposits overlain by finer-grained abandoned channel fill which is typically muddy (Fig. 2). The channel-belt sandbodies (commonly described as point bars in the literature) are the fundamental building block of coarse-grained fluvial deposits in modern systems as well as the stratigraphic record (e.g. Karges 1962; Berg and Cook 1968; Fisher and McGowen 1969).

¹Supplemental Files. Text, 11 figures, Quaternary database, and Gulf of Mexico channel-belt measurement database. Please visit <http://doi.org/10.1130/GES01374.S1> or the full-text article on www.gsapubs.org to view the Supplemental Files.

Figure 3. Stratigraphy and chronology of Upper Cretaceous to Oligocene clastic deposits in the northern Gulf of Mexico basin. Clastic supply is the relative amount of clastic sediment delivered to the margin. Formation names of the clastic sediment supply also indicated. Tusc.—Tuscaloosa. Modified from Galloway (2008).



substantially downstream through the backwater transition, from 70:1–300:1 or more to 20:1–50:1.

Most channel-related fluvial sand bodies are deposited as a series of bars by lateral accretion, and produce a general fining-upwards pattern of grain size and thinning of bed sets. Early studies of modern Gulf of Mexico point bars and valley fills by Bernard et al. (1970) and Coleman and Prior (1982) established recognition criteria for fluvial channel-belt sand bodies from well logs. Bridge (1993; see also Bridge, 2003; Bridge and Lunt, 2006) showed that, within this general template, multiple log patterns can result, depending on upstream versus downstream position within the bar itself (Fig. 6). Heterolithic bar-top facies form at elevations up to bankfull stage, but likewise vary in terms of grain size, and, when muddy, can be difficult to differentiate from near-channel overbank facies. Regardless, vertical variation in grain size

translates to vertical patterns that are identifiable in gamma ray, resistivity, and Spontaneous Potential well logs (Fig. 6), which are commonly used to interpret and correlate sedimentary deposits in the subsurface. Hence, well-log shape can be used to identify channel-belt sand bodies in subsurface data: as noted by Bridge and Tye (2000), no single well log can be representative, but sand-body thicknesses measured from multiple well logs are a proxy for bankfull depth.

Blum et al. (2013) presented a series of scaling relationships for modern river systems that represents an earlier generation of the data used here, and which is included in the Supplemental Data¹. The morphometrics of 279 modern channel belts were collected from studies of more than 60 rivers that span drainage basin sizes from 120 km² to 3,000,000+ km², in climatic conditions ranging from tropical to periglacial (Blum et al., 2013; Supplemental Data [footnote 1]). The planform measurements of a meander involved digitization of a georeferenced point-bar deposit and associated channel using Google Earth (open-platform software, <https://www.google.com/earth/desktop/>). The channel represents the abandoned channel, and is likely filled with finer-grained sediment, whereas the point bar or meander refers to the compound bar or storey composed of coarser-grained sediment. The digitized polygons were transferred to ESRI ArcGIS software (<http://www.esri.com/arcgis/about-arcgis>) with an equal area projection. ArcMap was used to calculate the area (in m²). The perimeter of the channel (or abandoned channel) was divided by two to get an approximate length (in m) of the channel, which provided a consistent, reproducible method if not exactly accurate. The average width of the channel or abandoned channel was computed by dividing the calculated area (in m²) by the length (in m). A minimum rectangular bounding container was used to extract the long and short axes of the point bar. Visual inspection was used to differentiate whether the long or short axis was the expansion length. The amplitude length was used as a proxy for a minimum meander-belt or channel-belt width. The half-wavelength measurement was extracted along the downstream direction of the meander. Measured parameters are illustrated in a schematic diagram in Figure 7. Holocene channel-belt deposits are readily linked via stream gauge measurements to channel-forming discharge. Only rivers that have been sufficiently studied to supply reliable bankfull depth and complete point-bar measurements from either lithological descriptions or stream cross sections were included.

Most important here would be power-law relationships between drainage area and bankfull discharge (see also Davidson and North, 2009), and between bankfull discharge and sand-body thickness: these two relationships can be combined to give a relationship between drainage area and sand-body thickness (Fig. 8A; Supplemental Data [footnote 1]). We treat these as first-order relationships, and a number of uncertainties must be kept in mind. First, there is inherent variation within a single river system due to variation in flow depth: at the local scale, variation in depth occurs within single meander bends, whereas regionally, downstream increases in flow depth occur from tributary inputs and/or flow dynamics within the backwater reach (Fig. 8B). Based on the modern and Holocene Mississippi River, variations in channel depth of

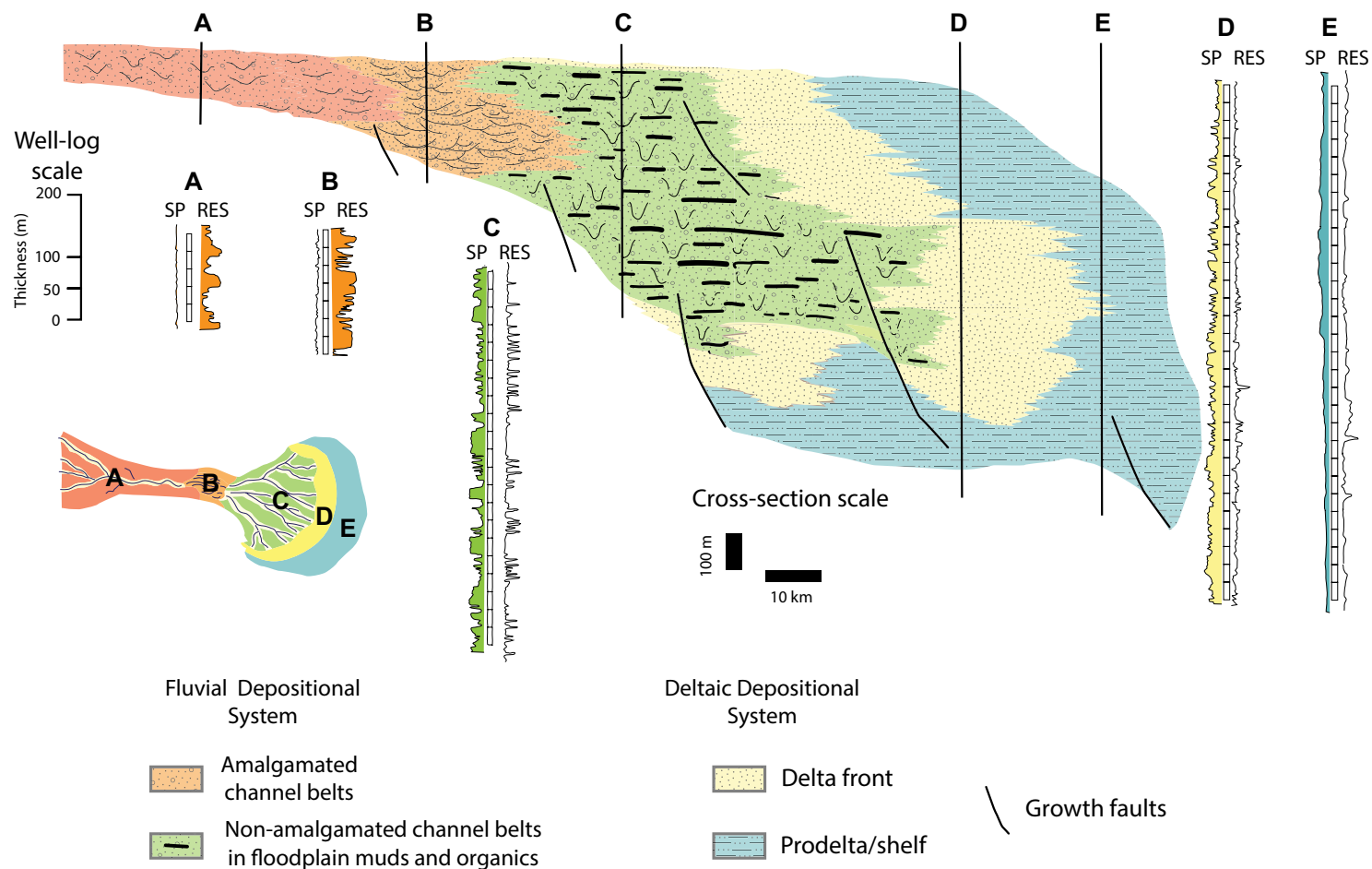


Figure 4. Example transgressive-regressive cycle facies and well-log signature, showing updip to downdip facies variation from amalgamated fluvial at A and B to non-amalgamated fluvial at C to deltaic and shallow-marine strata at D and E. Modified from Fisher and McGowen (1969). SP—spontaneous potential, RES—resistivity well logs.

this kind are less than a factor of two (see also Bridge and Tye, 2000). Second, variations in bankfull discharge and depth occur between river systems due to differences in climate regimes: holding drainage area constant, river systems in humid or highly seasonal monsoonal climates will have larger bankfull discharge values than river systems in cold and/or dry climates (see Plink-Björklund, 2015). However, data from modern systems show that variations of this kind result in bankfull depths from individual river systems that are within a factor of two of the regressed values for drainage basin areas within the population as a whole (Fig. 9).

We have examined 1879 well logs from the Gulf Basin Depositional Synthesis (GBDS) Program database at the Institute of Geophysics of The University of Texas at Austin. We focus on fluvial and coastal-plain stratigraphic intervals in the Cenomanian Tuscaloosa-Woodbine, Paleocene to early Eocene Wilcox, Eocene Queen City and Yegua, and Oligocene Vicksburg-Frio depositional episodes (Galloway, 2008; Galloway et al., 2011). From these well logs, we have compiled 986 measurements of channel-belt thickness from 248 well logs for these stratigraphic units across the Gulf of Mexico coastal plain, in an area stretching from south Texas to southern Mississippi. We focus on intervals that

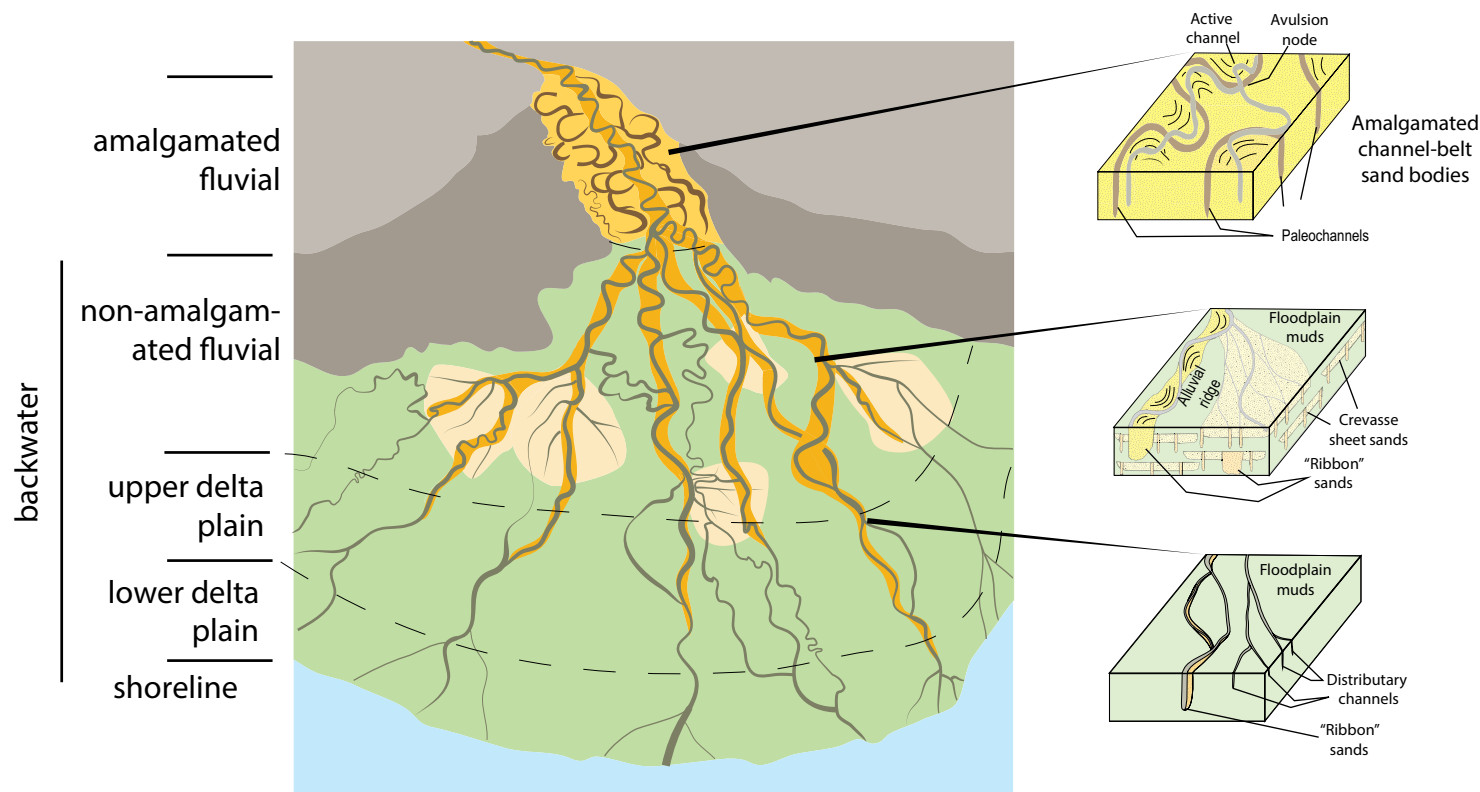


Figure 5. Generalized schematic to illustrate the typical channel-belt styles within the backwater zone. The backwater zone consists of non-amalgamated ribbon-like sand bodies or channel belts and associated crevasse splay deposits that transition downdip to low-gradient anastomosing channel belts and distributary channels. The backwater zone of fluvial sedimentation is composed of channel belts encased in floodplain muds and is typically associated with high subsidence and greater preservation potential. Modified from Blum and Törnqvist (2000).

contain channel-belt sand bodies but are otherwise dominated by floodplain mudrocks and organic-rich facies (Fig. 5; Supplemental Data [footnote 1]), which we interpret to represent distributive channel belts that formed within the backwater reach. Figure 10 illustrates this approach with well logs from the Cenomanian Woodbine Group in east Texas (Ambrose et al., 2009) and the Paleocene Wilcox Group in central Louisiana (Tye et al., 1991). Uncertainties in measurements are likely due to difficulties in recognition of channel-belt sand-body boundaries within an individual well log. In some cases, this may reflect muddy upper-bar facies that make identification of the upper limits difficult, resulting in underestimation of bankfull depth. In other cases, individual channel-belt sand bodies may stack on top of each other and be impossible to differentiate, resulting in overestimation of bankfull depth.

We bin well-log measurements by stratigraphic unit and geographic area, and follow conventions in Galloway et al. (2011) and Blum et al. (2017), where

ancient fluvial axes are named for extant river systems in the area today. For each paleo-fluvial axis and stratigraphic interval, measured channel-belt sand bodies are compiled into probability density functions (PDFs) and cumulative-frequency curves to show thickness distributions; the number of measurements per stratigraphic unit per fluvial axis ranges from $n = 10$ to $n = 143$ (Figs. 11 and 12). Even with uncertainties from natural variability and measurement issues, sand-body thickness populations vary significantly and systematically. For example, statistical analysis involving t -tests of two samples assuming unequal variances on Cenomanian versus lower Wilcox channel-belt deposits for the paleo-Tennessee River and paleo-Mississippi River fluvial axes shows statistically significant differences in sand-body thickness populations.

Using a best-fit equation between modern sand-body thickness and contributing drainage-basin area, we estimate a range of contributing drainage

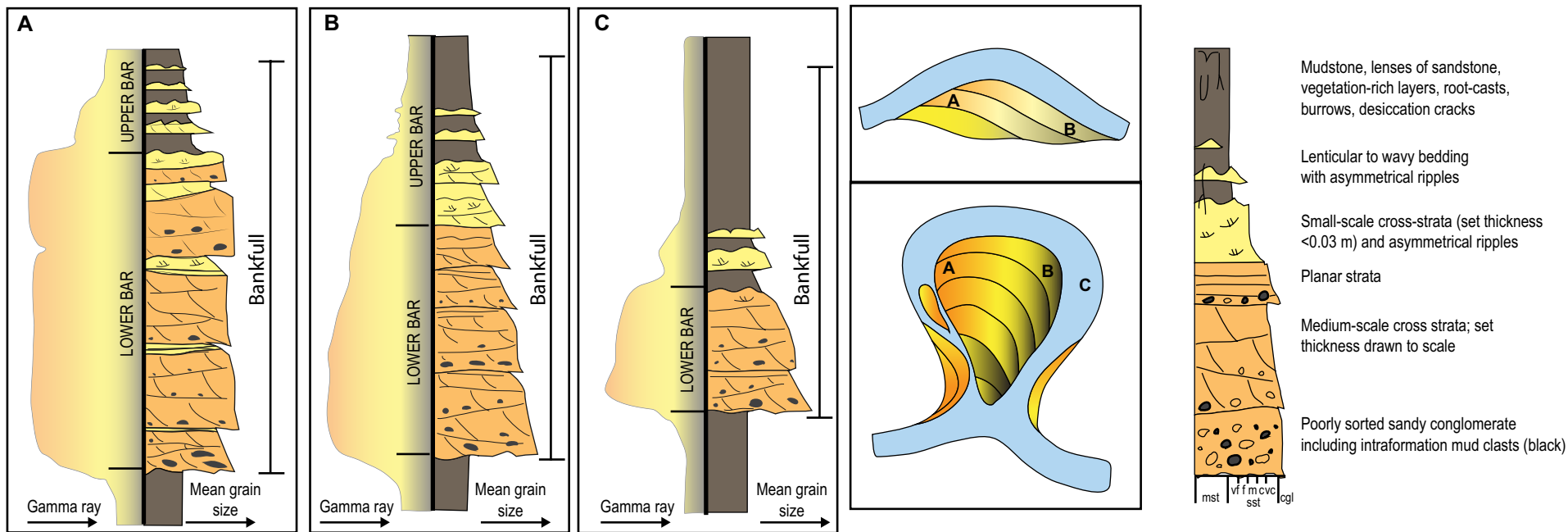


Figure 6. Channel belt map-view diagrams illustrating (1) relatively coarse- versus fine-grain deposition as well as ideal vertical log pattern deposition and (2) general map-view location of ideal vertical log pattern. Grain-size abbreviations: mst—mudstone, sst—sandstone, vf—very fine, f—fine, m—medium, c—coarse, vc—very coarse, cgl—conglomerate.

areas for ancient systems from PDF peaks and the P90 value in cumulative frequency curves. The P90 value is the 90% statistical confidence that the channel-belt measurements have captured the thickness of the representative channel and drainage basin. Although we measured sand bodies in the Eocene Queen City and Yegua intervals, we focus here on the Cenomanian Tuscaloosa-Woodbine, the Paleocene–early Eocene Wilcox, and the Oligocene Vicksburg-Frio episodes. All data are included in the Supplemental Files (footnote 1).

APPLICATION TO CENOMANIAN AND PALEOCENE GULF OF MEXICO SYSTEMS

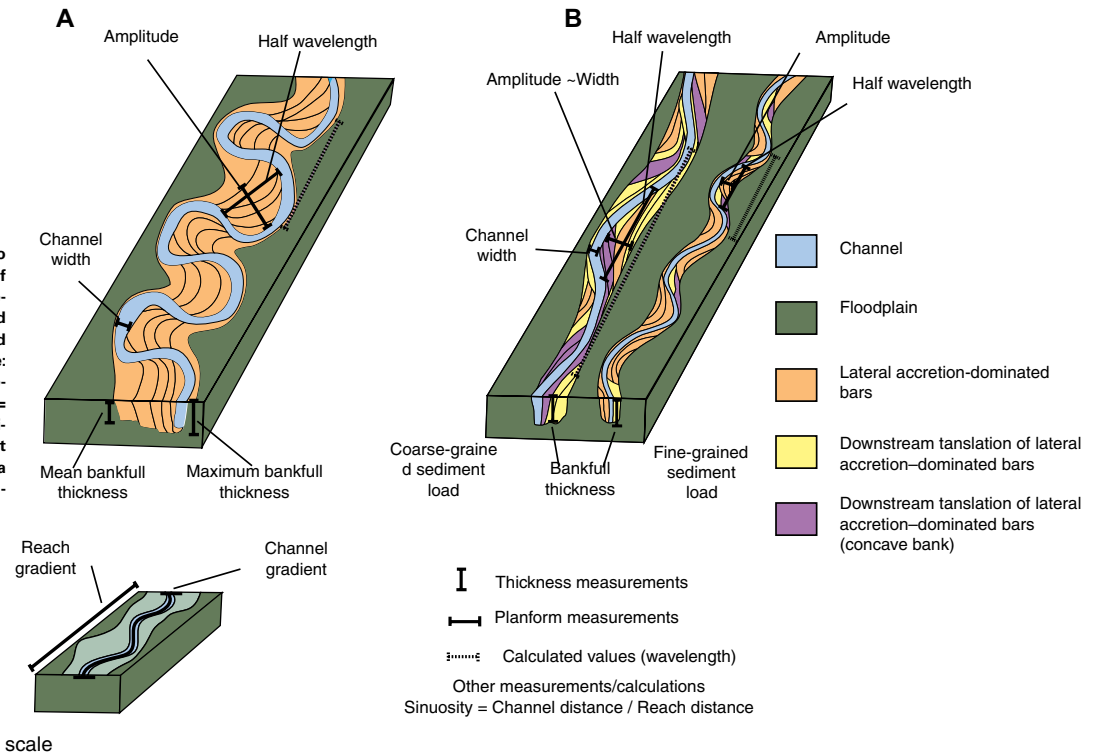
For each paleo-fluvial axis and interval, the measured channel belts are visualized as PDFs in order to understand the thickness populations that compose that particular fluvial system ($n = 10$ to $n = 143$; Fig. 12). Analysis of fluvial channel-belt thickness through time and space shows significant thickness variations. Natural thickness variations in a population of channel belts representing one fluvial axis can be explained as (1) variability in the basal erosion surface, which can account for up to twice mean bankfull thickness

(Leopold et al., 1962; Willis, 1989; Salter, 1993; Willis and Tang, 2010; Supplemental Files [footnote 1]), and (2) variable-size fluvial systems residing within a fluvial axis during a stratigraphic interval (Supplemental Data [footnote 1]). Therefore, many channel-belt thickness measurements are required to characterize the fluvial system(s). Significant fluvial system preservation correlates with mapped shelf progradation. For example, during the lower Wilcox deposide, measurable fluvial channel belts correlate with significant shelf-margin progradation in the fluvial axes (Fig. 11). Fluvial channel belts and/or alluvial deposition are not readily recognized in other areas of the northern Gulf of Mexico basin during this time and are not recognized as fluvial axes (Galloway et al., 2000; Galloway, 2008). Similar correlations are illustrated for the upper Wilcox and the Oligocene (Fig. 11).

Cenomanian Tuscaloosa-Woodbine

The Upper Cretaceous Cenomanian interval includes the Woodbine Group of the East Texas Basin and North Louisiana Salt Basin, and the Tuscaloosa Formation of the Mississippi Salt Basin. Cenomanian channel-belt thicknesses in the East Texas Basin paleo-Colorado River fluvial system ($n = 23$) range

Figure 7. Schematic block diagrams to illustrate measurement methodology of various channel-belt styles. (A) Measurements in amalgamated channel belts and (B) measurements in non-amalgamated channel belts. Key measurements include: Channel-belt (point-bar) width, half wavelength ($\times 2 =$ wavelength), amplitude ($\times 2 =$ channel-belt width), and mean and maximum bankfull thickness. Channel-belt morphometric, discharge, and climate data are provided in the supplemental information [footnote 1].



from 9 to 24 with a peak at 15 m (Fig. 12). Channel-belt thicknesses in the North Louisiana Salt Basin paleo-Mississippi fluvial system ($n = 19$) show a distinctive peak at 6 m. The Cenomanian strata (Tuscaloosa) in the Mississippi Salt Basin paleo-Tennessee fluvial system ($n = 53$) exhibit channel-belt thicknesses that range from 6 to 24 m with a major peak at 14 m and a minor peak at 18 m.

Early–Middle Paleocene Lower Wilcox

The Paleocene lower Wilcox interval contains significant fluvial axes in the paleo–Rio Grande, paleo–Colorado, paleo–Mississippi, and paleo–Tennessee systems ($n = 42$, $n = 108$, $n = 143$, $n = 47$, respectively; Fig. 12). The majority of the paleo–Rio Grande channel-belt thicknesses range from 9 to 33 m with PDF peaks at 15, 24, and 33 m (Fig. 12). Out of 42 interpreted channel belts, four were between 33 and 36 m thickness and represent another population peak. The paleo–Colorado channel-belt thicknesses range from 9 to 48 m with three prominent PDF peaks at 24, 29, and 36 m. The 29 m peak contains a coarse tail which tapers off at 42 m. The paleo–Mississippi fluvial axis contains a channel-

belt thickness population ($n = 143$) with a P90 of 26 m and PDF peaks at 15, 23, and 33 m. The 15 m PDF peak was generated from channel belts situated between the Monroe uplift and the LaSalle Arch.

Late Paleocene–Early Eocene Upper Wilcox

The Eocene upper Wilcox fluvial axes occur in the paleo–Rio Grande, paleo–Colorado, paleo–Houston–Brazos, paleo–Mississippi, and paleo–Tennessee systems (Fig. 12). The South Texas paleo–Rio Grande channel-belt thickness population ($n = 31$) averages 21 m with dominant peaks at 18 m and 24 m and a lesser peak at 33 m (Fig. 12). The upper Wilcox paleo–Colorado channel-belt thickness population ($n = 15$) averages 24 m with prominent peaks at 12 m, 24 m, and 30 m and a coarse tail at 38 m. The upper Wilcox paleo–Houston–Brazos channel-belt thickness population ($n = 10$) shows three peaks at 12 m, 18 m, and 33 m. The upper Wilcox paleo–Mississippi channel-belt thickness population ($n = 41$) averages 23 m with peaks at 15 m, 21 m, 36 m, and 51 m. The upper Wilcox paleo–Tennessee channel-belt thickness population ($n = 11$) shows a peak at 16 m.

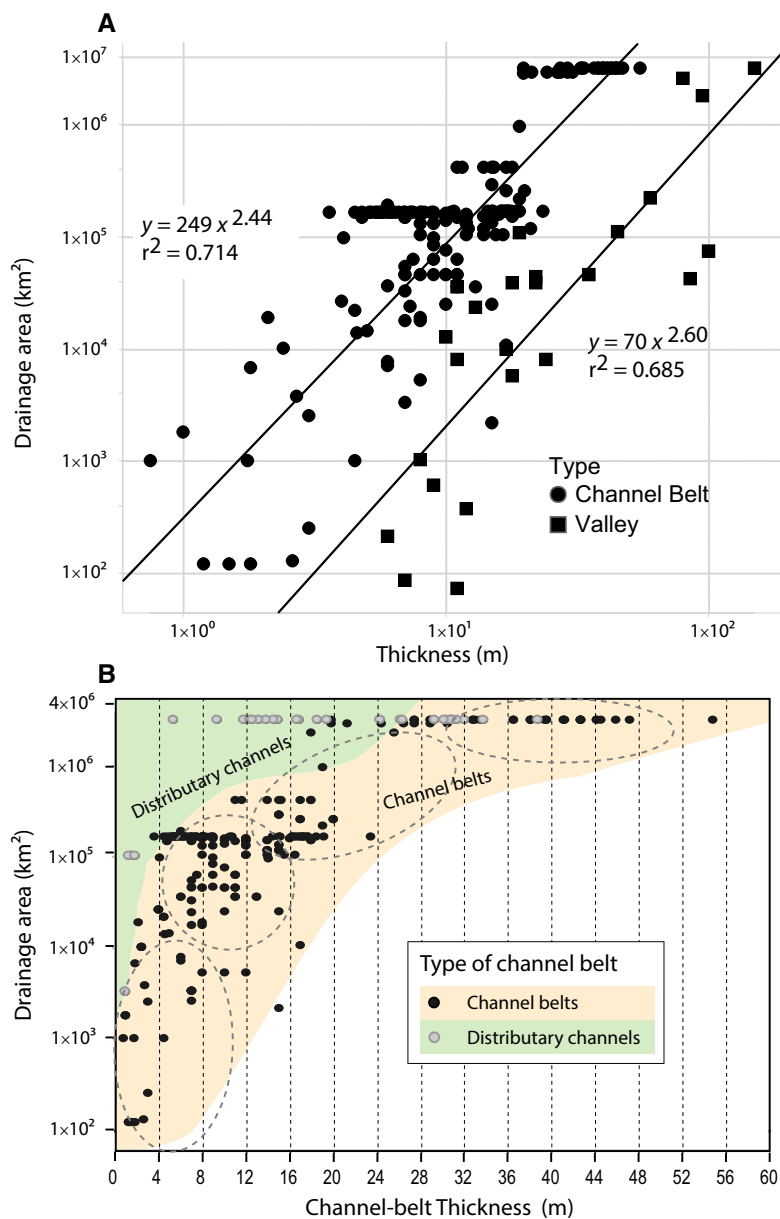


Figure 8. Quaternary channel-belt and valley thickness versus drainage basin area. (A) Log-log plot of thickness versus drainage area of channel belts and valleys. (B) Linear-log plot of channel-belt thickness versus drainage area that distinguishes distributary channels from channel belts. Modified from Blum et al. (2013).

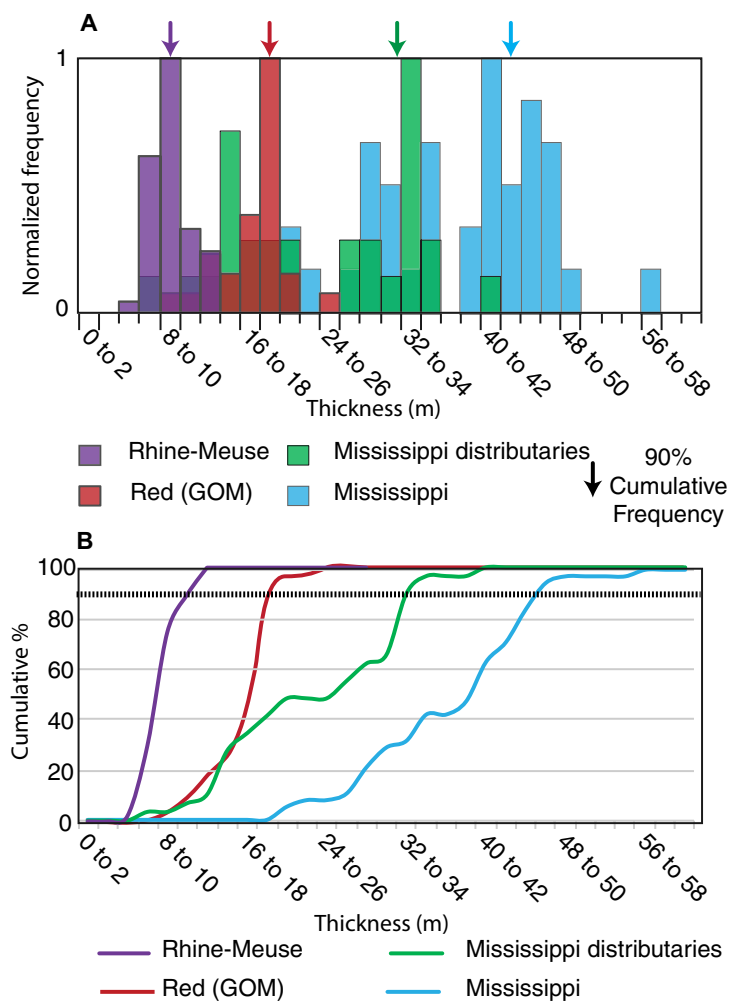


Figure 9. Probability density function and cumulative frequency plot of channel-belt thickness data for Rhine-Meuse (Netherlands), Red (Gulf of Mexico [GOM]), and Mississippi (GOM) fluvial systems. The Mississippi data were divided into two subsets, distributary channels and trunk-system channel belts.

Oligocene Vicksburg-Frio

The Oligocene Frio Formation fluvial axes can be documented in the paleo-Rio Grande, paleo-Colorado, paleo-Houston-Brazos, and paleo-Mississippi systems (Fig. 12). The paleo-Rio Grande channel-belt thickness population ($n = 54$) has a P80 of 24 m and prominent peaks at 15 m, 24 m, and 30 m (Fig. 12).

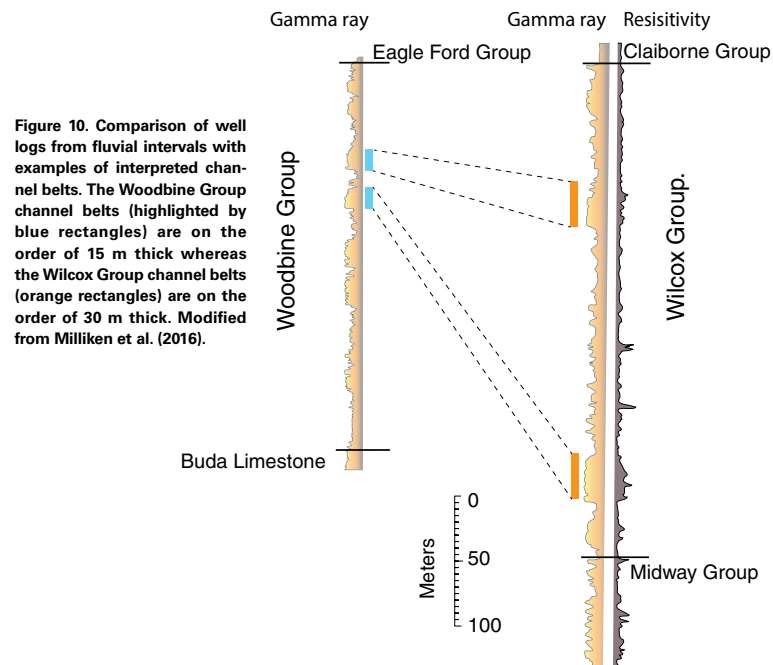


Figure 10. Comparison of well logs from fluvial intervals with examples of interpreted channel belts. The Woodbine Group channel belts (highlighted by blue rectangles) are on the order of 15 m thick whereas the Wilcox Group channel belts (orange rectangles) are on the order of 30 m thick. Modified from Milliken et al. (2016).

The paleo-Colorado channel-belt thickness population ($n = 45$) averages 24 m with dominant PDF peaks at 15 m, 21 m, and 36 m, and a less-prominent peak at 52 m. The paleo-Houston-Brazos channel-belt thickness population ($n = 26$) averages 17 m with dominant peaks at 12 m and 18 m and less-prominent peaks at 27 m, 39 m, and 45 m. The paleo-Mississippi channel-belt thickness population ($n = 135$) averages 24 m with dominant peaks at 15 m and 21 m and a less-prominent peak at 35 m.

Changes in Fluvial Systems through Time and Space

Comparison amongst fluvial systems illustrates differences in fluvial channel-belt thickness. Application of analog modern fluvial-system thickness–drainage basin size correlations suggests that thickness of channel belts in ancient systems should also scale to paleo–drainage basin size. Cenomanian fluvial systems have significantly thinner channel belts as compared to Paleocene paleo-Colorado and paleo-Mississippi lower Wilcox fluvial systems (Fig. 13A).

The P90 channel thickness of the fluvial systems of the lower Wilcox (Paleocene) to upper Wilcox (early Eocene) increase in the paleo-Mississippi fluvial axis, but appear stable in the paleo–Rio Grande and the paleo-Colorado axes. The paleo-Houston-Brazos fluvial system, while prominent during

the Paleocene, is not a significant fluvial axis during the early Eocene (upper Wilcox) (Fig. 13B).

The Oligocene paleo-Colorado fluvial system contains slightly thicker channel belts as compared to the lower Wilcox paleo-Colorado. The paleo–Rio Grande fluvial system contains comparable fluvial channel belts in the Oligocene as compared to the Paleocene. The Oligocene paleo-Mississippi fluvial system exhibits thicker P90 channel belts than the lower Wilcox (Paleocene) paleo-Mississippi (Fig. 13C).

A particular paleo-fluvial system can also be temporally analyzed using this methodology. For example, the paleo–Rio Grande fluvial system is relatively small during the Paleocene, but systematically grows in discharge and fluvial channel-belt thickness through the Eocene and is relatively small again in the Oligocene (Fig. 13D).

DISCUSSION

Probability Density Function Interpretation

As outlined in the methodology, care was taken to identify intervals and regions of the progradational clastic wedge packages where fluvial channel belts encased in floodplain muds were likely to have been deposited and preserved, in order to minimize thickness overestimation due to vertical channel-belt amalgamation or underestimation due to partial preservation. Many channel-belt measurements were also made to produce a population of channel-belt thickness for a given interval and region in order to encompass the potential range of thickness inherent in a fluvial system. Channel-belt measurements typically cluster into modes that translate into peaks in a population PDF. The thickness difference within a mode typically varies by a factor of two and may illustrate a channel-belt population's inherent thickness variation due to lateral migration. (For discussion on inherent thickness variation within a channel belt, see the supplemental information [footnote 1].)

For each paleo-fluvial axis, the population of thickness measurements exhibited one to five PDF peaks (Fig. 12). Multiple PDF peaks could be due to multiple, various-size fluvial systems feeding sediment into an area and/or interval. Multiple PDF peaks for a paleo-fluvial axis may also indicate measurement of a population of channel belts and distributary channels. Because channel-belt thickness is largely controlled by bankfull discharge within the fluvial channel, factors that affect the water discharge of a drainage basin will affect the channel-belt thickness. For example, in small (<100,000 km²) drainage basins, the channel belts deposited by fluvial systems draining humid climatic regimes are thicker (by a factor of about two) than channel belts deposited by fluvial systems draining arid climates (supplemental information [footnote 1]). Once a drainage basin increases in size to very large to continental scale, the climate influence on channel-belt thickness may not be as important due to (1) the likelihood of very large drainage basins traversing multiple climatic zones and (2) significant discharge.

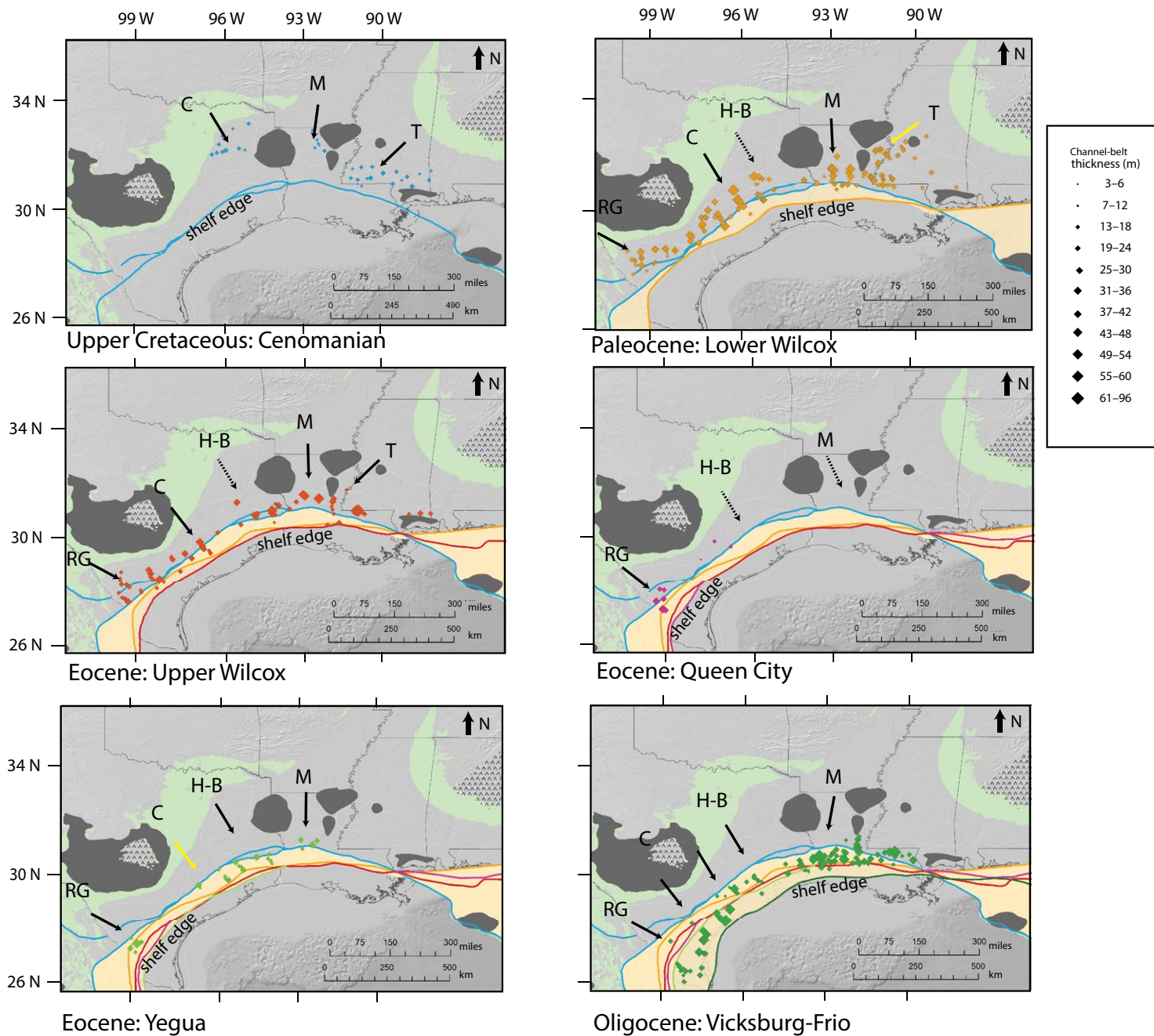


Figure 11. Channel-belt thickness measurements extracted from well logs associated with fluvial axes through time as defined by Galloway (2005). T—paleo-Tennessee; M—paleo-Mississippi; H-B—paleo-Houston-Brazos; C—paleo-Colorado; RG—paleo-Rio Grande. Solid black arrows denote the fluvial axes of Galloway (2005) that are also recognized in our data set. Dashed black arrows denote fluvial axes described by Galloway (2005), but not observed in our data. Yellow arrows denote fluvial axes not recognized by Galloway (2005) but documented in this data set. Size of colored data points indicates the channel-belt thickness interpreted from well logs at that location. Colored lines indicate shelf-edge position for each interval. Beige polygon indicates area of shelf progradation for each interval. Upside-down v-pattern and dark-gray polygons indicate highlands or uplifts as denoted in Figure 1. Light green polygons denote onshore Cretaceous-age outcrop. Data from the Eocene Queen City and the Eocene Yegua intervals are included in the measurements (Supplemental Data [footnote 1]), but are not discussed in detail in the text of this paper.

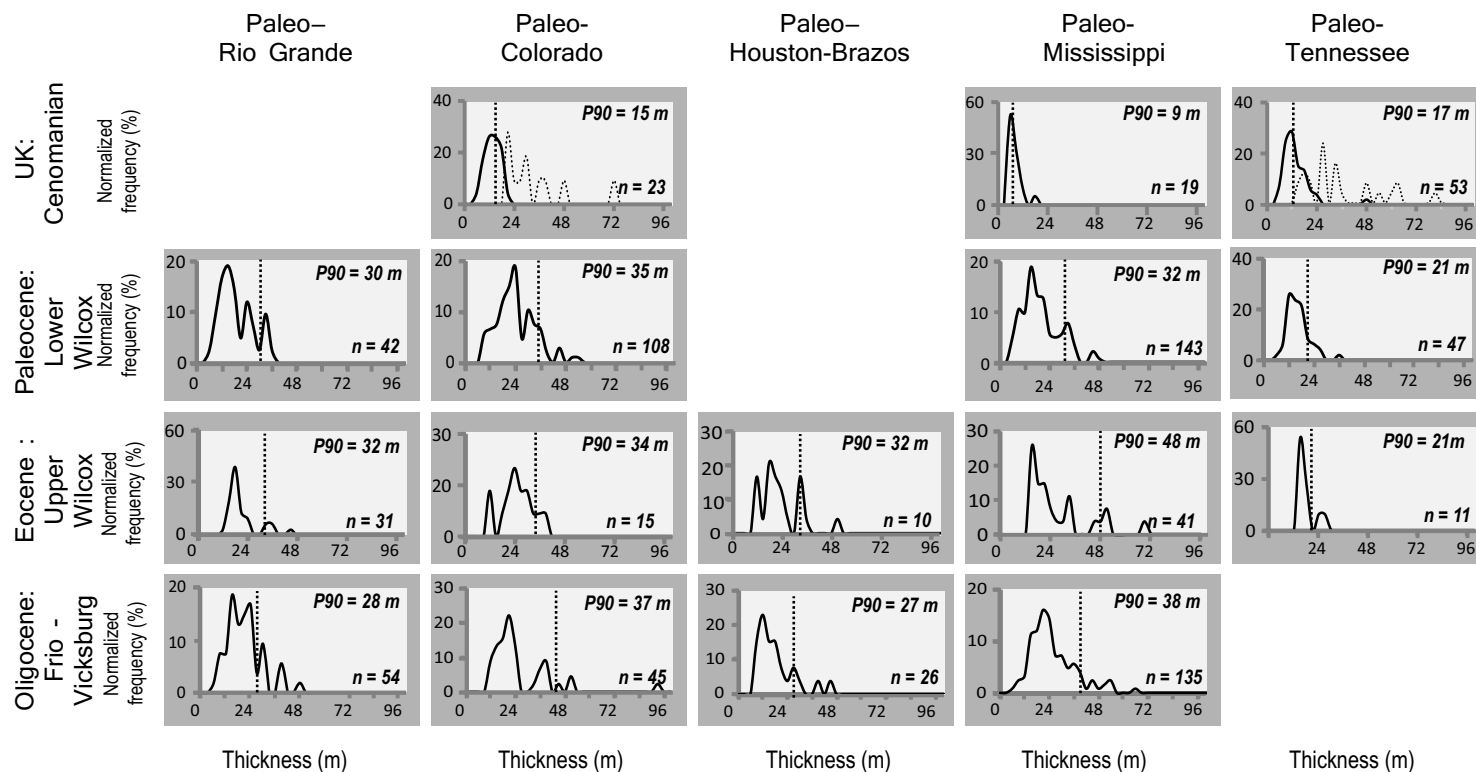


Figure 12. Channel-belt thickness probability density functions (PDFs) that describe the thickness variation as well as various fluvial system populations in a region during a specific stratigraphic interval. Solid PDF lines indicate single-cycle channel belts, as compared to dashed PDF lines that indicate interpreted multi-cycle channel belts or possibly valleys. Dashed vertical lines highlight P90 value which is the 90% statistical confidence or thickness which represents 90% of the channel-belt measurements within a given channel-belt population. UK—Upper Cretaceous.

The 90th percentile (P90) thickness was transformed into a representative drainage basin size using the Quaternary channel-belt database and best-fit line $y = 249 * x^{2.44}$ (Fig. 8A), as shown in Table 1. The P90 thickness value was chosen to reconstruct the paleo-drainage basin because this thickness most likely represents bankfull discharge of the trunk channel. As noted above, there are multiple possible explanations for the thinner populations of channel belts in a fluvial axis: the population might contain (1) measurements of distributary or anastomosing channels in addition to the trunk channel belts, and/or (2) tributary fluvial system channel belts (for additional description, see the supplemental information [footnote 1]). The most representative drainage basin area when describing the ability of the fluvial system to supply sediment to the margin is also generally the largest. Generally, the larger the drainage basin area, the greater the ability of the associated fluvial system to supply water and sediment to the margin. Fluvial systems' distributive channels that transport more water and sediment are also thicker and result in thicker channel-belt

deposits. Comparison of drainage basin size derived from channel-belt thickness shows a statistically significant correlation to drainage basin size derived from detrital zircon studies (Fig. 14; Blum et al., 2017).

Cenomanian Tuscaloosa-Woodbine

Cenomanian paleo-drainage basins for the paleo-Tennessee and paleo-Colorado had their uplands in the Ouachita and Appalachian Mountains and were on the order of 200,000 km² (Table 1; Blum et al., 2017; Fig. 14). The paleo-Tennessee channel-belt thickness is not significantly greater than that of other Cenomanian fluvial systems, but considering an arid climate in the Mississippi Salt Basin area as compared to the East Texas Basin (Chasteen, 1983), the paleo-Tennessee drainage basin might have been significantly larger. Channel-belt thicknesses in the East Texas Basin and North Louisiana Salt Basin are

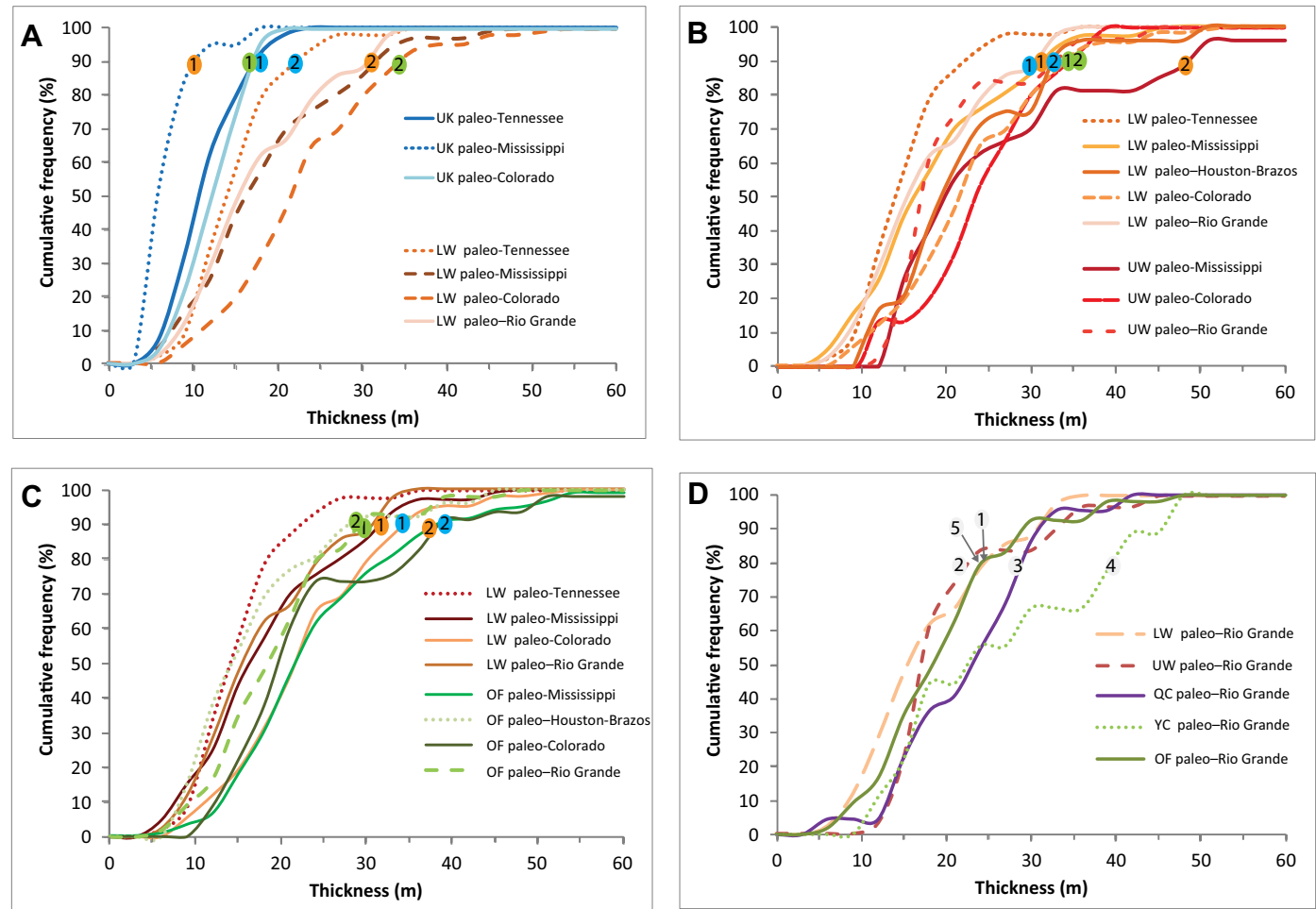


Figure 13. Cumulative frequency plots. The symbols numbered 1–5 designate relative age channel-belt thickness populations. (A) Comparison of channel-belt thickness between Cenomanian (Upper Cretaceous, UK) channel belts and Paleocene lower Wilcox (LW) channel belts. (B) Comparison between Paleocene lower Wilcox and Eocene upper Wilcox (UW) channel-belt thickness. (C) Comparison between Paleocene lower Wilcox and Vicksburg-Frio (OF) channel-belt thickness. (D) Comparison of paleo-Rio Grande fluvial system channel-belt thicknesses through time from Paleocene to Oligocene (QC—Queen City; YC—Yegua).

consistent with published well logs and conventional wisdom that links the East Texas and North Louisiana Salt Basin fluvial systems to a provenance in the Ouachita uplands (Adams and Carr, 2010; Ambrose et al., 2009; Barton, 1982; Berg and Leethem, 1985; Bonnaffé et al., 2008; Bunge, 2007; DeDominic, 1988; Dolloff et al., 1967; Halbouty and Halbouty, 1982; Harrison, 1980; McGowen and Lopez, 1983; Oliver, 1971; Scott, 1926; Stehli et al., 1972; Turner and Conger, 1984).

The channel-belt thicknesses measured in the Mississippi Salt Basin are also consistent with published well logs and literature that links the fluvial systems near the Mississippi-Louisiana state line to the Appalachian Highlands (Adams and Carr, 2010; Berg and Cook, 1968; Blum et al., 2017; Corcoran et al., 1993; Cronquist and Aime, 1968; Eisenstatt, 1960; Garrison and Chancellor, 1991; Gruebel, 1985; Hamlin and Cameron, 1987; Hogg, 1988; Karges, 1962; Klicman et al., 1988; Moore, 1962; Raymond, 2005; Stancliffe and Adams, 1986;

TABLE 1. SUMMARY OF PALEODRAINAGE RECONSTRUCTIONS, GULF OF MEXICO BASIN

Paleodrainage system	P90 point-bar thickness (m)	Reconstructed drainage area from point-bar scales (km ²)	Reconstructed drainage area from DZ studies (km ²)
Cenomanian paleo-Tennessee	17	250,000	400,000
Cenomanian paleo-Colorado*-Brazos	16	220,000	<150,000
Early Paleocene paleo-Mississippi	32	1,170,000	1,200,000
Early Paleocene paleo-Colorado	35	1,460,000	2,200,000
Early Paleocene paleo-Rio Grande	30	1,000,000	500,000
Late Paleocene to earliest Eocene paleo-Mississippi	48	3,150,000	2,200,000
Late Paleocene to earliest Eocene paleo-Colorado	34	1,360,000	1,200,000
Oligocene paleo-Mississippi	38	1,780,000	1,500,000
Oligocene paleo-Colorado**-Brazos	37	1,670,000	600,000
Oligocene paleo-Rio Grande	28	850,000	700,000

Note: P90 point-bar thickness is the statistical cumulative value that captures 90% of the channel-belt thickness measurements within a given channel-belt population. Drainage area values are plotted in Figure 14. Reconstructed drainage areas from detrital zircon (DZ) studies are from Blum et al. (2017).

*This study's Cenomanian paleo-Colorado is equivalent to the Cenomanian paleo-Colorado-Brazos of Blum et al., 2017.

**This study's Oligocene paleo-Colorado and paleo-Houston-Brazos (Figs. 2 and 12) is equivalent to the Oligocene paleo-Colorado-Brazos of Blum et al. (2017).

Stephenson and Monroe, 1938; Stevenson, 1981; Wiygul and Young, 1987; Womack, 1950). Several studies documented the paucity of fluvial strata and significant shallow-marine and deltaic strata in southern Alabama, Florida, and western Georgia (Munyan, 1943; Mancini and Payton, 1981; Mancini et al., 1987; Mancini and Tew, 1995; Petty, 1997; Warner, 1993; Galloway, 2008), which is consistent with a fluvial fairway from the Appalachians to southwestern Mississippi.

The abundance of lignite interspersed in coastal plain environments can be utilized as an indicator of groundwater inundation and climate. The Cenomanian strata of the Mississippi Salt Basin (paleo-Tennessee) do not contain significant lignite and are interpreted to represent a semi-arid climate, whereas the Cenomanian strata of the East Texas Basin (paleo-Colorado) contain abundant lignite and are interpreted to represent a humid climate (Chasteen, 1983).

Early-Middle Paleocene Lower Wilcox

The lower Wilcox paleo-drainages expanded significantly, a finding similar to those of previous studies (Galloway, 2005; Galloway et al., 2011; Mackey et al., 2012; Blum and Pecha, 2014). This study suggests that the catchment area or drainage basin of the lower Wilcox paleo-Colorado was continental scale (Blum et al., 2017; Table 1; Fig. 14). In contrast to the 20–30+-m-thick preserved channel belts in the paleo-Colorado fluvial axis, the paleo-Tennessee fluvial axis may be represented by the 16–17 m PDF peak generated from channel belts situated between the Monroe uplift and the LaSalle Arch. The differences in preserved channel-belt thickness between fluvial axes (e.g., paleo-Colorado versus paleo-Tennessee) lend credence to the fidelity of the stratigraphic record and faithful preservation of fluvial scales in ancient strata.

Previously published lower Wilcox stratigraphic studies that document blocky to fining-upward patterns in well logs, indicative of storeys or channel belts, are consistent with the channel-belt thickness populations collected in the present study. Wilcox-equivalent strata in northern Mississippi contain blocky to fining-upward patterns in well logs in lignite-rich fluvial strata on the

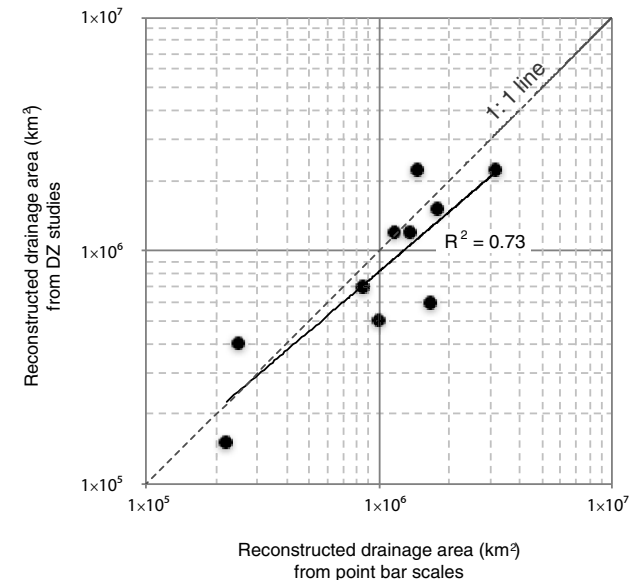


Figure 14. Plots of reconstructed drainage area from point-bar scales and detrital zircon (DZ) provenance studies (Blum et al., 2017). Data is shown in Table 1.

order of 15 m thick in NE-SW-oriented mapped sand bodies (Cleaves, 1980; Dueitt et al., 1985; Glawe et al., 1999; Hackley et al., 2007). Paleocene to Eocene strata in southwestern Mississippi are described as shallow marine, with little evidence for significant fluvial strata recorded (Dockery, 2001). Galloway (1968) documented lignite-rich fluvial strata within the Mississippi embayment from fluvial systems that fed deltas that were similar in scale to Rockdale delta lobes in Texas. Tye et al. (1991) published long regional well-log cross sections in the Wilcox strata of the Mississippi embayment that illustrate 20–30+ m-thick blocky to fining-upward log patterns in the fluvial intervals (Fig. 9). In central Texas, the lower Wilcox also contains 20–30+ m-thick blocky to fining-upward fluvial channel belts (Devine and Wheeler, 1989; Xue and Galloway, 1993). In South Texas, paleo-Rio Grande abundant lignite deposits attributed to peat swamps indicate a relatively humid climate (Breyer, 1997).

The significant variation of channel-belt thickness between 11 and 13 m in Cenomanian fluvial systems and 20–30+ m in Paleocene fluvial deposits coincides with documented plate-scale tectonic reorganization involving the Laramide orogeny (Galloway et al., 2000) and significant clastic flux to the northern Gulf of Mexico basin (Galloway, 2008).

Late Paleocene–Early Eocene Upper Wilcox

As described in the lower Wilcox section above, previous studies have documented 20–30+ m thick blocky to fining-upward well-log patterns in the upper Wilcox-age fluvial strata of the Mississippi embayment (paleo-Mississippi) and Houston embayment (paleo-Colorado; Xue and Galloway, 1995; Tye et al., 1991). Additionally, Cleaves (1980) and Hackley et al. (2007) did not differentiate the Wilcox into upper or lower in central to northern Mississippi, but illustrate 8–15-m-thick blocky to fining-upward storeys or channelbelts in lignite-rich mudstones, which is consistent with the thicknesses documented for the paleo-Tennessee. Dingus and Galloway (1990) showed a 37-m-thick fining-upward log pattern in upper Wilcox strata overlying Yoakum canyon, an interpreted buried submarine channel situated on the slope. This 37-m-thick fining-upward sequence could be interpreted as a channel belt. In South Texas, the upper Wilcox is composed of a prograding fluvial-deltaic system with 20–30-m-thick blocky to fining-upward channel belts (Edwards, 1981; Hamlin, 1983).

Previous studies that describe the depositional facies for the Eocene-age Queen City Formation (cite Fig. 3) included shallow-marine deposits in central Texas (Guevara and Garcia, 1972) and east Texas (Ramos and Galloway, 1990). A lack of fluvial channel belts in fluvial axes could be due to post-depositional passive-margin uplift and erosion of the particular facies or non-preservation because of reworking by shallow-marine processes into shallow-marine strata.

During the period correlative to the Yegua Formation, a modest rejuvenation of sediment influx related to middle Cenozoic volcanism in the Rocky Mountains resulted in fluvial progradation (Galloway, 2008) and an increase in mass wasting at the shelf margin (Edwards 1990, 1991).

Oligocene Vicksburg-Frio

Previous studies that illustrate Oligocene fluvial systems and thickness of channel belts show 10–15-m-thick fining-upward to blocky well-log patterns in an updip (potentially tributary systems) location in the paleo-Rio Grande fluvial axis (Kerr and Jirik, 1990), 13–30-m-thick channel belts (fining-upward to blocky log signature) in the paleo-Houston-Brazos fluvial axis (Reedy, 1949), and 25–30-m-thick blocky to fining-upward log packages in the central Texas paleo-Colorado fluvial axis (Combes, 1993). The Oligocene Frio Formation consists of numerous fluvial feeders across the area rather than specific input points along the Houston, Mississippi, or Rio Grande embayments (Combes, 1993; Galloway et al., 1982).

Our Oligocene drainage-basin reconstructions differ from those published by Galloway (2005) and Galloway et al. (2011), which place the headwaters of the Oligocene fluvial systems within the Rocky Mountains and ~500,000 km² drainage basins. Oligocene channel belts in the thickness range of 30–40+ m translate to drainage basins of 1,000,000 to 2,000,000 km² (Table 1).

CONCLUSIONS

A modern-river empirical relationship between fluvial channel-belt thickness and contributing drainage-basin area provides a mechanism to derive the size of ancient river catchments. The large number of drilled wells and plethora of previously published studies in the northern Gulf of Mexico basin facilitates a rigorous test of the thickness–drainage-basin area scaling relationship in ancient fluvial successions. This large clastic basin derived sediment from multiple source terrains and across different climatic regimes. The intervals studied ranged from Paleocene to Oligocene age and spanned from South Texas to eastern Alabama. For example, channel-belt thickness as interpreted and measured from well logs is substantially different in the Cenomanian-age fluvial strata as compared to the Paleocene-age fluvial strata of the northern Gulf Coast. Using Quaternary fluvial scaling to predict the drainage-basin areal extent and length suggests that the Paleocene fluvial systems were an order of magnitude larger than the Cenomanian fluvial systems. Moreover, the populations with the thickest channel belts occur in the regions underlain by tectonic embayments as compared to the areas underlain by tectonic arches. For moderate-size drainage basins, channel belts deposited in a humid climate regime are approximately two times thicker than channel belts deposited in an arid climate regime.

In general, the findings of this study corroborate the vast number of regional syntheses conducted on the northern Gulf of Mexico basin over the past several decades. General comparison of fluvial channel-belt thickness shows a positive correlation to gross sediment volume, grain-volume rate of supply, and shore-zone or delta volume metrics (Galloway, 2001; Galloway et al., 2011), and paleogeographic compilations (Galloway et al., 2000; Galloway, 2008). Furthermore, the fluvial system channel-belt thickness measurements (both

thickness and number of measurements in a given area) match shelf-margin progradation maps (Galloway, 1989, 2008) and scale predictably to drainage-basin size (Blum et al., 2017).

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