Detrital zircon age spectra of middle and upper Eocene outcrop belts, U.S. Gulf Coast region

William H. Craddock | James L. Coleman | Andrew R. C. Kylander-Clark

1Geology, Energy, and Minerals Science Center, U.S. Geological Survey, Reston, VA, USA
2U.S. Geological Survey, Fayetteville, GA, USA
3Department of Earth Science, University of California, Santa Barbara, CA, USA

Correspondence
William H. Craddock, Geology, Energy, and Minerals Science Center, U.S. Geological Survey, Reston, VA, 20192, USA.
Email: wc Bradley@usgs.gov

Funding information
U.S. Geological Survey Energy Resources Program

Abstract
Recently reported detrital zircon (DZ) data help to associate the Paleogene strata of the Gulf of Mexico region to various provenance areas. By far, recent work has emphasised upper Paleocene-lower Eocene and upper Oligocene strata that were deposited during the two episodes of the highest sediment supply in the Paleogene. The data reveal a dynamic drainage history, including (1) initial routing of western Cordilleran drainages towards the Gulf of Mexico in the Paleocene, (2) an eastward shift of the western continental divide, from the Jura-Cretaceous cordilleran arc to the eastern edge of the Laramide province after the Paleocene and (3) a southward shift, along the eastern Laramide province, of the headwaters of river systems draining to the Mississippi and Houston embayments at some time between the early Eocene and Oligocene. However, DZ characterisation of most (~20 Myr) of the middle Eocene-lower Oligocene section remains limited. We present 60 DZ age spectra, most of which are from the middle or upper Eocene outcrop belts, with 50–200-km spacing. We define six to eight distinct groups of DZ age spectra for middle and upper Eocene strata. Data from this and other studies resolve at least six substantial temporal changes in age spectra at various positions along the continental margin. The evolving age spectra constrain the middle and upper Eocene drainage patterns of large parts of interior North America. The most well-resolved aspects of these drainage patterns include (1) persistent rivers that flowed from erosional landscapes across the Paleozoic Appalachian orogen either into the low-lying Mississippi embayment or directly into the eastern Gulf; (2) at least during marine regressions, a trunk channel that likely flowed southward along the axial part of Mississippi Embayment and integrated tributaries from the east and west; and (3) rivers that flowed to the Houston embayment in the middle Eocene that likely originated in the Laramide province in central Colorado and southern Wyoming, as Precambrian basement highs in those source areas were being unroofed.

KEYWORDS
detrital zircon geochronology, Eocene, Gulf of Mexico, Paleogene, provenance, stratigraphy, U.S. Gulf Coast

The peer review history for this article is available at https://publons.com/publon/10.1111/bre.12464.

This article has been contributed to by US Government employees and their work is in the public domain in the USA.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2020 The Authors. Basin Research published by International Association of Sedimentologists and European Association of Geoscientists and Engineers and John Wiley & Sons Ltd.
1 | INTRODUCTION

In the U.S. Gulf Coast region, the Paleogene was characterised by two long-lived episodes of high sediment supply, first in the late Paleocene and again in the late Oligocene, with generally lower sediment supply in the Eocene (Galloway, Whiteaker, & Ganey-Curry, 2011). Gulf Coast geologists for decades have proposed paleo-catchment reconstructions for the North American interior to account for these changes in sediment supply rates (e.g., Winker, 1982). However, a rapidly expanding detrital zircon database (e.g., Blum et al., 2017; Blum & Pecha, 2014; Craddock & Kylander-Clark, 2013; Fan, Brown, & Li, 2019; Mackey, Horton, & Milliken, 2012; Wahl, Yancey, Pope, Miller, & Ayers, 2016) has provided new insights (e.g., Blum et al., 2017). Sampling efforts to date have emphasised upper Paleogene-lower Eocene and upper Oligocene strata, deposited during the episodes of the highest sediment supply in the western Gulf of Mexico Basin (e.g., Blum et al., 2017). These studies show that the earlier, ~Paleocene episode involved initial routing of large drainages from the western Cordillera towards the Gulf Coast, with recent reconstructions showing a drainage divide that extended as far west as the Jurassic-Cretaceous cordilleran arc (e.g., Blum et al., 2017; Sharman, Covault, Stockli, Wrobblewski, & Bush, 2017). The latter, Oligocene episode occurred when the western continental divide was offset significantly to the east, relative to the Paleocene, and also corresponded to a time when the headwaters of rivers bound for the Mississippi and Houston embayments had shifted southward along the eastern Laramide province (Blum et al., 2017). The ~20 Myr period between these two times, however, is less well known.

Initial detrital zircon data from Eocene strata indicate that Claiborne Group (middle Eocene) age spectra in northern Louisiana and in the north-central part of the Texas coastal plain (Craddock & Kylander-Clark, 2013; Wahl et al., 2016) are characterised by a relatively high proportion of 1,250–950 Ma zircons relative to underlying strata. The change appears to be correlated to an anomalous heavy mineral assemblage in northeastern Texas that is unique to the middle Eocene (e.g., McCarley, 1981; Todd & Folk, 1957 and references therein; Craddock & Kylander-Clark, 2013). However, the degree to which this change in detrital zircon age spectra and petrofacies is recorded along strike is not clear, and the detrital zircon stratigraphic resolution remains fairly sparse.

We present data from 60 detrital zircon samples, including 8,640 single grain ages that are interpreted to be robust based on discordance filtering. Samples are primarily from the middle Eocene Claiborne Group and the upper Eocene Jackson Group, collected along the strike of the basin between western Alabama and the southern border of Texas (Figure 1). Some additional samples from the older Wilcox Group and the younger Vicksburg and Frio Groups are presented as well.

Using geologic reasoning and multidimensional scaling analysis (Vermeech, Resentini, & Garzanti, 2016), we define six to eight distinct groups of detrital zircon age spectra along the strike of the Gulf Coast for the Claiborne and Jackson Groups. Stratigraphic changes in the character of the detrital zircon age spectra at given points in the basin define six changes through time. The objective of this study is to use aspects of the detrital zircon data to constrain ongoing efforts to interpret source-sink connections between the Gulf Coast region and upstream geologic elements (e.g., Blum et al., 2017; Galloway et al., 2011), particularly during the middle and late Eocene.

2 | BACKGROUND

The Paleogene outcrop stratigraphy of the Gulf Coast is known from over a century of field-based investigations complemented by enormous amounts of subsurface information from wells and seismic reflection data (Figures 1 and 2). Uppermost Cretaceous and lowermost Paleocene fine-grained strata are overlain regionally by the coarse-grained Wilcox Group (Figures 1 and 2). Owing to high sediment supply to the Gulf Coast during the late Paleocene—early Eocene, deposition of the Wilcox Group accompanied progradation of shelf margins by 10s of km in the northwestern portion of the basin (Texas and Louisiana) and the formation of deltas on updip portions of older continental shelf bathymetry in the northeastern part of the basin (generally east of Louisiana, Galloway, 2008; Galloway, Ganey-Curry, Li, & Buffler, 2000; Galloway et al., 2011). The overlying middle Eocene Claiborne Group (Figure 2) comprises several progradational deltaic successions divided by intervals of transgressive shale. It was deposited during a pronounced

Highlights

- 60 detrital zircon age spectra from the middle and upper Eocene outcrop belts of the U.S. Gulf Coast
- Complement recently published Paleocene-lower Eocene and upper Eocene outcrop belt data
- Define 6–8 groups along strike of outcrop belts; define or constrain 6 Paleogene temporal changes in groups located at a given point in the basin
- Data resolve persistent sediment routing from southern Appalachians to eastern Gulf Coast region in Paleogene, low lying Mississippi embayment that integrated western and eastern drainages in Paleogene, and middle Eocene Colorado/Wyoming Laramide-Houston Embayment source-sink connection as Laramide ranges were unroofed
minimum in sediment supply rates to the northern Gulf Coast (Galloway, 2008; Galloway et al., 2011). As such, deposition of these units accompanied minor amounts of shelf progradation across Texas (relative to the Wilcox episode), and no progradation in areas along strike to the east (Galloway, 2008). Of the progradational successions within...
the Claiborne Group, the Yegua Formation (also referred to as the uppermost Claiborne Group throughout the text—see Figure 2), was exceptional in that it recorded the highest rates of sediment supply to the western basin margin in the middle and late Eocene (Galloway et al., 2011). Throughout the text, we differentiate between the lower Claiborne Group in the western Gulf Coast (all Claiborne Group formations older than the Yegua Formation, see Figure 2) and the Yegua Formation (the youngest formation in the Claiborne Group).

The basal part of the overlying upper Eocene Jackson Group (Figure 2) also records relatively low sediment supply (Galloway et al., 2011). Fine-grained basal Jackson Group strata are overlain by sandstones associated with a minor deltaic system (Fisher, Galloway, Proctor, & Nagle, 1970; Galloway et al., 2011) in the Houston Embayment (Figure 1). Along strike to the east, the upper Moody’s Branch and the North Twistwood Creek Formation record slow sediment accumulation (Mancini & Tew, 1994). These eastern formations are thin, on the order of 10s of meters and relatively fine-grained. The youngest widely preserved strata in the Mississippi embayment are upper Eocene.

The Oligocene Vicksburg and Frio Groups (Figure 2) record the second major Paleogene phase of rapid, coarse-grained sediment influx into the northwestern Gulf Coast region, (e.g., Galloway et al., 2011). Deposition of these units drove progradation of the shelf margin by 50 km or more along most of the Louisiana and Texas coasts (Galloway, 2008). Along strike to the east, the correlative strata are fine-grained and/or carbonates, although the Forest Hill Formation is 10s of meters thick and consists of some delta plain sandstone deposits (Mancini & Tew, 1994). The upper Oligocene to lower Miocene Catahoula sandstone also records a major influx of sand (100 s of meters of stratigraphic thickness) into the eastern Gulf Coast.

Recent studies of the Paleogene of the Gulf Coast provide a framework for improved source-to-sink characterisation of these strata using detrital zircon age spectra analysis. In this paper, we rely on several recent studies as a framework for detrital zircon interpretation, specifically the zircon-age to protolith-source correlations of Blum et al. (2017, see their table 2, see also Whitmeyer & Karlstrom, 2007). We also use the Paleocene and Oligocene detrital zircon age spectra data of Blum et al. (2017); and the data of Mackey et al. (2012), and Fan et al. (2019) in southern Texas. These studies were selected for their emphasis on characterising large portions of the various outcrop belts along strike. Recent work by Wahl et al. (2016) has also provided constraints on the Paleocene-lower Eocene detrital zircon age spectra of east Texas with a high stratigraphic resolution.

### METHODS

We collected samples from five Paleogene stratigraphic groups in the Gulf Coast region, the upper Paleocene-lower Eocene Wilcox Group, the middle and upper Eocene Claiborne and Jackson Groups (respectively), and the lower and upper Oligocene Vicksburg Group and Catahoula Formation (respectively) (Figures 1 and 2). Owing to the pre-existing dense, along-strike sample coverage for the Paleocene and Oligocene outcrop belts (Blum et al., 2017; Blum & Pecha, 2014), sampling from these intervals was limited to a few select locations to ensure that results from this study are directly comparable to those of previous studies. We sampled along the portions of the Claiborne Group and Jackson outcrop belts that extend from west-central Alabama to the Mexican border in 2011–2015 (Figure 1, Supporting Information Table S1). Samples were collected...
**Table 1** Sample groupings

| DZ groups | Eastern Gulf Coast | Axial Miss. Emb. | West. Miss Emb. | Sabine uplift | East Texas | Central Texas | South Texas |
|-----------|--------------------|-----------------|-----------------|-------------|------------|--------------|------------|
| Abbreviation | EGC | AME | WME | SBU | ETX | CTX | STX |
| **Frio-Vicksburg Groups** | | | | | | | |
| Blum et al. (2017) fluvial axis | | | | | | | |
| Abbreviation | T | M | A | R | B | CG | X |
| Samples from this report | CG12-2; CG12-3 (Vicksburg Gp.) | CG11-5; CG12-13 (Vicksburg Gp.) | CG11-2 | – | – | – | – |
| Samples from previous reports | GOM-1°, GOM-3°, GOM-5°, GOM-6°, GOM-8°, GOM-9° | GOM-2°, GOM-34° | GOM-77° | GOM-78°, GOM-79°, GOM-80° | GOM-61°, GOM-62°, GOM-63° | GOM-58°, GOM-59° | 3°, 4° |
| **Jackson Group** | | | | | | | |
| Samples from this report | CG12-4, CG12-5 | CG14-9, CG14-10, CG14-11 | CG14-15 | CG14-34 | CG13-9, CG14-33 | – | CG13-5, CG15-5, CG15-6, CG15-10 |
| Samples from previous reports | – | – | – | – | – | – | 1°, 2° |
| **Yegua Formation** | | | | | | | |
| Samples in this report | – | – | – | – | – | CG13-22, CG14-27, CG14-31 | CG15-9 | CG15-20 |
| Samples in previous reports | – | – | – | – | – | – | – |
| **Claiborne Group (not including Yegua Formation)** | | | | | | | |
| Samples from this report | CG12-10, CG12-14, CG12-15, CG14-2, CG14-4, CG14-7 | CG14-13 | CG14-18 | CG14-23 (north), CG14-24 (north), CG14-25 (north), CG11-4 (south), CG11-6 (south), CG11-7 (south) | CG14-26, CG14-27, CG14-28, CG14-29, CG14-37 | CG13-20, CG13-29, CG15-1, CG15-2, CG15-4 | CG15-11, CG15-12, CG15-16, CG15-17, CG15-18, CG15-19 |

(Continues)
**TABLE 1**  (Continued)

| DZ groups | Eastern Gulf Coast | Axial Miss. Emb. | West. Miss Emb. | Sabine uplift | East Texas | Central Texas | South Texas |
|-----------|--------------------|------------------|-----------------|--------------|------------|---------------|-------------|
| Abbreviation | EGC | AME | WME | SBU | ETX | CTX | STX |
| Samples from previous reports | – | – | – | – | – | – | – |

**Wilcox Group**

| Blum et al. (2017) fluvial axis | Tennessee | Mississippi | Arkansas | Red | Brazos-Colorado | Colorado | south Texas |
|-------------------------------|-----------|-------------|----------|-----|-----------------|----------|-------------|
| Abbreviation | T | M | A | R | BC | C | X |
| Samples from this report | CG12-7, CG12-17, CG12-19, CG12-22 | – | CG11-10 | CG11-3 | – | – | – |
| Samples from previous reports | GOM-10*, GOM-11*, GOM-12*, GOM-13*, GOM-14*, GOM-17*, GOM-19*, GOM-25*, GOM-26* | GOM-27*, GOM-31*, GOM-43*, GOM-44* | GOM-46*, GOM-47*, GOM-76* | GOM-72*, GOM-74* | GOM-67*, GOM-69*, GOM-70*, GOM-71* | GOM-64*, GOM-65* | M2c, M3c |

*Blum et al. (2017).  
*Fan et al. (2019).  
*Mackey et al. (2012).
at a spacing of 50 to 200 km where outcrop belts are continuous and exposure permitted. Sedimentary facies of samples are heterogeneous and difficult to characterise in coastal plain outcrops, likely spanning a spectrum of delta plain and shallow marine facies associations common to continental margins. Our sampling strategy was intended to focus on outcrops with depositional age control and/or outcrops with features that help to establish the presence of Tertiary (as opposed to Quaternary) strata (e.g., degree of induration, lack of reworking indicated by preserved sedimentary structures). Compared to the Wilcox or Frio Groups, transgressive shale units and distinct glauconitic sandstone units of the middle Paleogene can be used to establish stratigraphy in the field. Consequently, we collected at some sites without previously documented depositional age control. Our strategy also involved sampling through the middle Paleogene stratigraphy at discrete positions along strike to evaluate stratigraphic changes in age spectra. Seven samples reported herein were originally reported by Craddock and Kylander-Clark (2013). We now consider one of those previously reported samples (sample CG11-4) to be from reworked strata based on the presence of granule to gravel size clasts, which are more common in late Neogene-Quaternary deposits. However, the age spectrum of the sample is similar, if not indistinguishable, from Tertiary in-situ samples nearby, suggesting local reworking. We collected ~10 kg of material from a variety of beds, typically ranging over 0.5–3 m of stratigraphic section when possible. This sampling strategy was used to obtain a relatively well-mixed sediment sample.

Mineral separations and U and Pb isotope measurements were conducted at the University of California, Santa Barbara. Isotopic measurements were conducted with a laser ablation inductively coupled plasma mass spectrometer, following methods that are similar to the detrital zircon age analysis procedures described in Cottle, Horstwood, and Parrish (2009) and Cottle, Kylander-Clark, and Vrijmoed (2012) and described in detail specific to this study in the Supporting Information. Due to the fact that this study compares detrital zircon age spectra of middle and upper Eocene strata to underlying and overlying units (see Blum & Pecha, 2014; Fan et al., 2019; Mackey et al., 2012), we adopted the data filters applied by Blum and Pecha (2014), the largest single source of pre-existing data for Paleogene strata. These filters are also described in detail in the Supporting Information.

All single grain isotope ratio and age data are reported in an accompanying U.S. Geological Survey Data Release (Craddock, Kylander-Clark, & Coleman, 2020) and illustrated graphically in the Supporting Information figures. Maximum depositional ages (hereafter, MDAs) were calculated following the recommendations of Dickinson and Gehrels (2009) (see Supporting Information text, Supporting Information Table S2, Supporting Information figures).

We group samples based on consideration of several criteria, particularly including (1) spatial clustering of samples and (2) similarity in age spectra as defined by qualitative inspection of sample age spectra and non-metric multidimensional scaling (MDS) analysis (Vermeesch et al., 2016) (Table 1; Figure 3, see also Supporting Information text). The MDS approach was also recently employed by Xu, Snedden, Stockli, Fulthorpe, and Galloway (2017) for a study of the lower Miocene outcrop belt of the U.S. Gulf Coast region and by Blum et al. (2017). Our methods are similar except that we used the Sircombe-Hazelton measure of dissimilarity, following the recent discussion of dissimilarity measures in detrital zircon age spectra analysis by Wissink, Wilkinson, and Hoke (2018). Also similar to the Xu et al. (2017), geographic names were assigned to the various groups of detrital zircon age spectra.

4 | RESULTS

The detrital zircon age spectra tend to cluster into geographic groups on the MDS plots, and generally tend to extend from east-to-west along the first dimension of the plots (Figure 3). We define at least six distinct groups across the study area for each outcrop belt (Table 1; Figures 3–5). For the purpose of this report, we highlight key results from Claiborne and Jackson Group age spectra. Wilcox Group and Frio-Vicksburg Group strata are largely similar to results presented by previous authors. This similarity ensures that our results are comparable to those studies, and we do not review the Wilcox Group or Frio-Vicksburg Group data in additional detail here (e.g., Blum et al., 2017; Blum & Pecha, 2014; Wahl et al., 2016).

The lower Claiborne Group (Figure 2) exhibits eight distinct groups of detrital zircon age spectra along strike (Table 1, Figures 1 and 4). Along the southeast side of the Mississippi embayment, the eastern Gulf Coast group (EGC on Figures 3–5) exhibits primary and secondary age distributions that are 1,250–950 Ma and 500–250 Ma, respectively (Figures 4 and 5), and plot in a distinct portion of the MDS plot (Figure 3). In the southeastern part of this group, samples exhibit higher proportions of 500–250 Ma zircons, similar to the modern Alabama River (Blum & Pecha, 2014). The proportion of 500–250 Ma zircons generally diminishes in the northeastern parts of the Mississippi embayment, similar to the modern Tennessee or Cumberland rivers (Blum & Pecha, 2014). To the northwest, a single sample defines the axial Mississippi embayment group (AME on Figures 3–5). It exhibits age distributions similar to the eastern Gulf Coast group, with additional, albeit minor, 1,800–1,600 Ma and 190–40 Ma age distributions that are not found in the eastern Gulf Coast age spectra along strike (Figures 4 and 5). The axial Mississippi embayment sample is well differentiated
Non-metric multidimensional scaling analysis (MDS) plots generated in the Provenance library in R (Vermeesch et al., 2016) for Claiborne and Jackson Group detrital zircon samples in this report. Dissimilarity was determined using the Sircorbe-Hazelton distance. The CG prefix is dropped from sample names to make the plot more readable. The colored circles highlight the sample groupings used in this study. In general, the groupings were based on (1) spatial clustering of samples, and (2) similarity in age spectra as defined by qualitative inspection of sample age spectra and non-metric MDS analysis. For the lower (pre-Yegua Formation) Claiborne Group samples in Texas, four samples lie outside of the polygons for the groups to which they are assigned. These are samples CG13-29, which is assigned to the central Texas group; CG14-27, which is assigned to the east Texas group; and CG15-11 and CG15-16, which are both assigned to the south Texas group. On the same plot, the groupings for the Yegua Formation (STXy, CTXy, and ETXy) are defined by polygons with red, as opposed to black, outlines. The insets on both MDS plots are Shepard diagrams, which indicate the goodness of the fit of the non-metric configuration.
from the eastern Gulf Coast group along the first dimension of the multi-dimensional scaling plot (Figure 3).

To the west and southwest along strike, age distributions are more heterogenous. In the western Mississippi embayment (WME on Figures 3–5) and the Sabine uplift region (SBU on Figures 3–5) detrital zircon age spectra are dominated by 1,250–950 Ma zircons, but also include 190–40 Ma, 1,800–1,600 Ma, 1,250–950 Ma and 500–250 Ma zircons (Figures 4 and 5). Age spectra across this region are similar to each other and groups are differentiated partially based on the spatial separation of the samples (100 km or more) and by analogy to the underlying Wilcox Group (Blum et al., 2017). The western Mississippi embayment sample also exhibits a distinctly high abundance of 500–250 Ma zircons and low abundance of 190–40 Ma zircons (Figures 4 and 5), and is slightly differentiated from the Sabine uplift and axial Mississippi embayment sample groups on the multidimensional scaling plot (Figure 3).

Continuing along strike to the southwest, samples from along the Texas coastal plain cluster together on the MDS plot, although they are subtly differentiated into groups based on their spatial position (Figure 3, see also Figure 4). We define an east Texas group (ETX on Figures 3–5) down-dip from the Houston embayment, a central Texas group in the area of the San Marcos arch (Figure 1, group labelled as CTX on Figures 3–5), and a south Texas group (STX on
Figures 3–5) near the southern border of Texas. The subdivision of these age spectra into three groups reflects the fact that paleogeographic reconstructions show extrabasinal fluvial input axes to the Texas coastal plain in south Texas and east Texas during Claiborne Group deposition (Galloway et al., 2011), with an area of barrier bars and strandplains in between. The three sample groups exhibit age distributions similar to the western Mississippi embayment and Sabine uplift groups. However, the proportions of 190–40 Ma and 1,800–1,600 Ma zircons are generally relatively high and the proportion of 1,250–950 Ma zircons is generally relatively low. The south Texas group contains a particularly high proportion of 190–40 Ma zircons.

In the lower Claiborne Group detrital zircon age spectra of the western Mississippi embayment and Texas, the modal age within the 1,800–1,600 Ma age distribution varies systematically along strike (Table 2). The primary age modes in this age range for the western Mississippi embayment, Sabine uplift, east Texas and central Texas groups are >1,700 Ma, whereas the primary age mode in this range is ~1,690 Ma in south Texas. Within the 190–40 Ma range, each of the three Texas sample groups exhibits a particularly large number of 85–70 Ma zircons, as well as 105–85 Ma and 180–160 Ma zircons. The lower Claiborne Group samples generally do not exhibit well defined detrital zircon MDAs, however, four samples in Texas exhibit MDAs ranging from...
49–42 Ma that are consistent with paleontological age constraints (Figure 6).

For the Yegua Formation (the uppermost formation in the Claiborne Group, Figure 2), three distinct groups of age spectra are defined across the Texas coastal plain (Table 1; Figures 1 and 4), similar to the groupings defined for the lower Claiborne Group. The three Yegua Formation sample groups are differentiated spatially, with an east Texas group between the Texas-Louisiana border and the northern side of the San Marcos Arch, a central Texas group on the south side of the San Marcos Arch and a south Texas group near the southern border. These three groups are also differentiated from each other along the second dimension of the MDS plot (Figure 3). The Yegua Formation samples are broadly similar to the spatially overlapping lower Claiborne samples in terms of important age distributions and their relative proportions (Figures 3–5). However, compared to the lower Claiborne Group, a relatively large proportion of the Yegua Formation

| Lower Claiborne Gp. (Ma) | Upper Claiborne Gp. (Yegua Fm.) (Ma) | Jackson Gp. (Ma) |
|--------------------------|--------------------------------------|------------------|
| Axial Mississippi embayment | 1,668<sup>a</sup> | Axial Mississippi embayment 1,720 |
| Western Mississippi embayment | 1,717 | Western Mississippi embayment 1,707 |
| Sabine uplift (south) | 1,723 | |
| Sabine uplift (north) | 1,727 | Sabine uplift 1,747 |
| East Texas | 1,712 | East Texas 1,715 East Texas 1,695 |
| Central Texas | 1,709 | Central Texas 1,697 |
| South Texas | 1,693 | South Texas 1,682 South Texas 1,694 |

<sup>a</sup>All modes determined graphically in Density plotter (Vermeesch, 2009), using kernel density approximations of age spectra with a bandwidth of 30 Myr.
samples exhibit zircons with crystallisation ages that are within a few Myr of the depositional age (Figure 5). As such, a relatively high proportion of Yegua Formation samples exhibit well-defined MDAs (Figure 6). These MDAs range from about 39–37 Ma and constrain the depositional age of the Yegua Formation regionally.

The Yegua Formation detrital zircon age spectra groups also exhibit a north-south gradient in the 1,800–1,600 Ma modal age, with the east Texas group exhibiting an age mode of >1,700 Ma and the central and south Texas groups exhibiting age modes of <1,700 Ma (Table 2). Sample CG15-20, which defines the Yegua south Texas detrital zircon age spectra group, lacks a robust Jurassic age mode, whereas underlying and overlying strata do not.

The Jackson Group (Figure 2) exhibits at least six distinct groups of detrital zircon age spectra (Table 1; Figures 1 and 4). The samples form distinct clusters on the MDS plots (Figure 3), and, generally, are ordered from east to west along the first dimension of the plot. Samples from the eastern Gulf Coast exhibit primary and secondary age distributions of 1,250–950 Ma and 500–250 Ma, respectively, with age distributions and proportions similar to spatially overlapping samples from the Claiborne Group. The axial Mississippi embayment samples are similar to the eastern Gulf Coast samples, albeit with the addition of minor 190–34 Ma, 1,800–1,600 Ma and 1,500–1,300 Ma age distributions into the axial Mississippi embayment age spectra that are not found in samples to the southeast.

Along the western Mississippi embayment and across Texas, the Jackson Group age spectra are relatively uniform along the northwestern basin margin in terms of significant age distributions and their relative proportions (Figures 4 and 5). Specifically, the western Mississippi embayment, east Texas and south Texas groups of age spectra are dominated by 190–34 Ma age distributions, with additional secondary or tertiary 1,800–1,600 Ma, 1,500–1,300 Ma and 1,250–950 Ma age distributions. This contrasts with the Claiborne Group where the 190–34 Ma and 1,800–1,600 Ma age modes are of secondary importance along the western Mississippi Embayment, but of primary importance to the southwest across Texas. Between the western Mississippi embayment and east Texas samples, a single sample is dominated by 1,250–950 Ma zircons and we consider the sample to represent a distinct Sabine uplift sample group. Due to the fact that the sample is dominated by 1,250–950 Ma zircons, it plots closer to the eastern Gulf Coast and axial Mississippi embayment samples than the western Mississippi embayment samples on the MDS plots. In contrast to the Claiborne Group samples, the Sabine uplift sample clearly separates the western Mississippi embayment sample to the northeast from the east Texas group to the southwest.

Within the 1,800–1,600 Ma age range, Jackson Group detrital zircon age spectra also exhibit a north-to-south gradient in the modal age along the northwestern basin margin. The western Mississippi embayment and Sabine uplift sample groups exhibit age modes >1,700 Ma, whereas the east Texas and south Texas groups exhibit age modes <1,700 Ma (Table 2). Within the 190–34 Ma age distribution, significant sub-distributions for the western Mississippi embayment, east Texas, and south Texas sample groups are 180–160 Ma, 105–85 Ma, 85–70 Ma and <40 Ma (nearly syndepositional) (Figure 5). Overall, these Mesozoic-Cenozoic age distributions are similar to the Claiborne Group, with the addition of a young, approximately syndepositional <40 Ma age mode. In the Sabine uplift sample, the only robust <190 age mode is <40 Ma. Syndepositional zircons are sufficiently common that most of the samples from the Texas coastal plain have well-defined MDAs, ranging from ~36–34 Ma (Figure 6).

5 | DISCUSSION

In the following, we interpret the ways in which the detrital zircon age spectra presented above constrain the provenance of sediments supplied to the Gulf Coast by paleo-rivers originating beyond the basin margins. The objective is not to present a comprehensive source-to-sink interpretation, but rather to show how well the detrital zircon data constrain aspects of the paleo-drainage patterns. We first discuss the Claiborne Group data, moving from east to west along the outcrop belt (section 5.1). We then discuss implied changes between the previously documented Wilcox Group (e.g., Blum et al., 2017) and the Claiborne Group (section 5.2). We then discuss the Jackson Group, from east to west and compare it to the underlying Claiborne Group (section 5.3). Finally, we discuss changes between the Jackson and the overlying Frio-Vicksburg Groups (section 5.4). Many of the groups of age spectra are associated with deltaic depocentres along the strike of the Gulf Coast region (e.g., Galloway et al., 2011), and those associations are noted throughout the discussion.

5.1 | Middle Eocene Claiborne Group sediment provenance

The easternmost group of Claiborne Group detrital zircon age spectra extend for hundreds of km along the strike of the outcrop belt. Although some regional compilations emphasise Eocene deltaic units in the eastern Gulf Coast, the Kosciusko and Lisbon Formations record 10 s to about 100 meters of deltaic sedimentation in the Mississippi-Alabama border region (Mancini & Tew, 1994), suggesting that this was a local depocentre. Samples from these two formations are included in the eastern Gulf Coast sample group (Supporting Information Table S1). The eastern Gulf Coast group exhibits a high degree of similarity to...
the age spectra of Appalachian foreland basin fill (Becker, Thomas, Samson, & Gehrels, 2005; Eriksson, Campbell, Palin, Allen, & Bock, 2004; Park, Barbeau, Rickenbacker, Bachmann-Krug, & Gehrels, 2010; Thomas et al., 2017) as well as the modern Tennessee and Alabama Rivers (Blum & Pecha, 2014). The modern Tennessee and Alabama rivers originate (mostly) in the Appalachian foreland basin and the Appalachian hinterland, respectively. Given that the relatively high proportion of 500–250 Ma versus 1,250–950 Ma zircons in the Claiborne Group eastern Gulf Coast age spectra makes them more similar to the modern Alabama River than the modern Tennessee River (see Blum & Pecha, 2014), we schematically depict a paleo-river that originated in the interior, hinterland portion of Appalachian orogen, where Paleozoic plutonic rocks are widely exposed (e.g., Hatcher, 1987), and flowed towards the Mississippi-Alabama region (Figure 7). Paleo-rivers that originated in, or flowed across, portions of the foreland may also have flowed towards the eastern Gulf Coast, but with relatively minor sediment supply. We also schematically depict this drainage connection. A relatively low elevation and low relief foreland basin region, with a low sediment yield, would account for the relatively small component of 1,250–950 Ma zircons (enriched in Appalachian foreland, see Eriksson et al. (2004), Becker et al. (2005), Park et al. (2010), Thomas et al. (2017)) found in the Gulf Coastal plain.

Along strike to the north and west, the axial Mississippi embayment sample is located updip from deltas in the northern Louisiana-Mississippi border region. This sample defines a paleo-Mississippi River system that flowed southward down the axis of the Mississippi embayment, at least during times when the embayment was not inundated by marine transgressions. The northern reaches of the river are depicted as three tributaries that merge in the northern Mississippi embayment from an eastern source, with relatively minor sediment supply. We also schematically depict this drainage connection. A relatively low elevation and low relief foreland basin region, with a low sediment yield, would account for the relatively small component of 1,250–950 Ma zircons (enriched in Appalachian foreland, see Eriksson et al. (2004), Becker et al. (2005), Park et al. (2010), Thomas et al. (2017)) found in the Gulf Coastal plain.

Continuing along strike to the southwest, the western Mississippi embayment and Sabine uplift sample groups have age spectra that indicate sediment sourcing from the western United States, but with a large proportion of sediment derived from a source area dominated by 1,250–950 Ma and 500–250 Ma zircons. The Ouachita highlands, which are characterised by Paleozoic strata containing zircons with these ages (Gleason, Finney, & Gehrels, 2002), must have contributed some sediment to this part of the U.S. Gulf Coast. Therefore, we depict relatively short rivers that originated in the Ouachitas and that may have been joined by rivers that originated farther west. However, we do not consider the Ouachitas to be the sole source of 1,250–950 Ma and 500–250 Ma zircons, and we revisit this issue in a more regional context in section 5.2. Notably, there were no distinct deltaic depocentres located downdip of the areas where the western Mississippi embayment and Sabine uplift detrital zircon age spectra groups were defined, so any paleo-rivers entering the basin in the southwest Mississippi embayment and Sabine uplift region likely would have merged with larger sediment dispersal systems to the east or west. We depict one of the Ouachita-derived rivers joining with the downstream part of the paleo-Mississippi. The overall paleo-Mississippi river is similar to other recent interpretations (Galloway et al., 2011) with the addition of the Appalachian-derived tributary system (Sharman et al., 2017).

The east Texas group of samples, which is located updip from a relatively large delta (e.g., Galloway et al., 2000; Galloway et al., 2011), has detrital zircons that require sediment sourcing from the cordillera of the western United States. Furthermore, the Cretaceous-Paleogene magmatic province in central Colorado appears to be the most plausible source of the abundant 190–37 Ma zircons in the samples from this region. Additional source areas farther north cannot necessarily be discounted, but Cretaceous-Paleogene magmatic rocks are generally less widespread across the eastern Laramide province in northern Wyoming. Alternative source areas located to the south of central Colorado do not seem viable when put into a regional context. For one, this would imply a drainage connection between the central Colorado magmatic rocks and the Mississippi embayment. This is not consistent with the lack of large 190–37 Ma sample distributions in contemporaneous strata from the western Mississippi embayment. Moreover, MDAs for the Yegua Formation bracket the depositional age of the formation in Texas to about 39–37 Ma (Figure 6). Geologic markers pin the Duchesnian unconformity to the same age ~39–37 Ma (Cather, Chapin, & Kelley, 2012). The unconformity is located in the Colorado and Wyoming portion of the Laramide province, adjacent to the magmatic provinces of central Colorado that also
appear to be sediment sources to east Texas (Figure 7a). The sediment generated by beveling this unconformity could have sourced the relatively large Yegua Formation delta in east Texas, and does not seem to have been routed towards smaller deltas to the east in Louisiana (Galloway et al., 2000, 2011). Overall, this paleo-river is similar to several middle Eocene reconstructions (Cather et al., 2012; Galloway et al., 2011; Lawton, 2008; Sharman et al., 2017), although
our reconstruction involves a connection to interior portions of the Laramide province of Wyoming, certainly during the late part of the middle Eocene when the Duchesnian unconformity was beveled and the Yegua Formation was deposited.

Another salient aspect of the lower Claiborne Group in east Texas and the Sabine uplift area in northern Louisiana is the anomalous, Appalachian/Ouachita-like heavy mineral assemblage (McCarley, 1981; Todd & Folk, 1957), which is correlated to the 1,250–950 Ma age distribution in the lower Claiborne and the Yegua east Texas sample groups (Craddock & Kylander-Clark, 2013; Wahl et al., 2016). Several authors have recently integrated this observation into detrital zircon-based provenance analysis, and we contend that (a) at least some direct sourcing from high-standing Ouachita foreland basin strata accounts for the anomalous heavy minerals (e.g., Wahl et al., 2016). Moreover, (b) although any rivers that originated in the Appalachian foreland and flowed west would have been integrated into a coeval Mississippi river system (therefore, precluding a direct source-sink connection between the southern Appalachian orogen and eastern Texas), it seems plausible that some of this material could have been reworked westward along the continental margin during a time of low sediment supply (e.g., Smith et al., 2019).

To the south, groups of detrital zircon age spectra from central and southern Texas are similar to each other and require sourcing from the cordillera of the western United States. The south Texas group is located updip from another distinct deltaic depocentre, but the central Texas group is not. There are at least three plausible source areas for the abundant 190–37 Ma zircons observed from central to southern Texas, which are (1) the magmatic province in northwestern Mexico, (2) the magmatic province in the southern Arizona-New Mexico border region, and (3) the southwest flank of the central Colorado magmatic provinces (see labels 1, 2 and 3 in the western cordillera in Figure 7). Drainage reconstructions of the middle Eocene itself, or else immediately preceding or superseding episodes, have invoked each of these source areas (e.g., Blum et al., 2017; Galloway et al., 2011; Lawton, 2008; Lawton, Bradford, Vega, Gehrels, & Amato, 2009; Sharman et al., 2017; Wahl et al., 2016). Because of the similarity in detrital zircon age spectra along the Texas outcrop belt (Figures 3–5) the data do not seem to provide strong constraints, except that the southerly depocentre was connected to a relatively southerly source region (Table 2), compared to the east Texas system discussed above.

In terms of the northernmost possible sediment source to southern Texas (number 3 on Figure 7), analysis of the interior Laramide region in northwestern New Mexico has suggested that rivers draining the southwestern parts of the Colorado magmatic provinces flowed to the east across a break in the Laramide structural front in central New Mexico (Gorham & Ingersoll, 1979; Lawton, 2008; Smith, Lucas, & Elston, 1985; Smith et al., 2019). Rivers also likely originated on the eastern flank of the Laramide province at this latitude and flowed eastward towards the Gulf Coast (Bush, Horton, Murphy, & Stockli, 2016). We tentatively route these rivers to the central portion of the Texas coastal plain, simply because the along strike changes in 1,800–1,600 Ma age modes imply a source area that was geographically between those for deltas to the north and south (Table 2). This is also consistent with a recent detrital zircon-based analysis, focused on Laramide basins in north-central New Mexico (Smith et al., 2019).

Source area 2 (Figure 7) in southwestern New Mexico could have supplied Cretaceous-Paleogene zircons (and various other key zircon age distributions) to southern Texas without requiring that Gulf Coast drainages integrated vast portions of the interior Laramide province at a time of modest sediment supply to south Texas. We suggest that, at a minimum, any paleo-river bound for the Rio Grande embayment in south Texas integrated as far west as southwestern New Mexico, however a longer drainage network extending into the Mexican cordillera is also permissible.

5.2 | Contrasting Paleocene-early Eocene and middle Eocene age spectra

In contrast to the middle Eocene paleo-rivers entering the northwestern basin margin depicted herein, recent Paleocene-earliest Eocene reconstructions of the interior western United States involve a drainage connection between the cordilleran

---

**FIGURE 7** Synthesis of detrital zircon constraints on (a) middle and (b) late Eocene drainage to the Gulf Coast region. Samples on map are from this study and are colour coded according to the groupings in Figure 3 and Table 1 (also see explanation on figure). Dashed line perpendicular to Eocene outcrop belt represents the boundary between age spectra with a 1,800–1,600 Ma age mode >1,700 Ma to the north and <1,700 Ma to the south. Cenozoic stratigraphic map units are from Reed et al. (2005) and Garrity and Soller (2009). Middle and upper Eocene deltas along the Gulf Coast are from Galloway et al. (2011) and references therein. Distribution of Phanerozoic magmatic rocks from navdat.org for the cordillera of the western United States. The NAVDAT database was filtered to include all rocks with greater than 52 weight percent silica and the polygons on the figures represent a summary of those data. Other geologic elements are after several sources, especially including Galloway et al. (2011), Wahl et al. (2016) and Blum et al. (2017). Duchesnian unconformity after Cather et al. (2012). AWU = Amarillo-Wichita uplift, LU = Llano uplift. Selected U.S. States: CA = California, NV = Nevada, UT = Utah, WY = Wyoming, CO = Colorado, NM = New Mexico, AZ = Arizona. Selected Mexican states: BC = Baja California, BS = Baja California Sur, SO = Sonora, CH = Chihuahua, CO = Coahuila.
arc terrane of Nevada and California and a major river that flowed into the Houston embayment (e.g., Blum et al., 2017; Blum & Pecha, 2014; Sharman et al., 2017). However, by the middle Eocene (or even the late part of the early Eocene), the evidence seems reasonably clear that the cordilleran arc drainage had been disrupted (e.g., Sharman et al., 2017). The stratigraphic evidence for disruption includes the presence of closed basins in the interior Laramide region in the early middle Eocene (e.g., Davis, Mulch, Carroll, Horton, & Chamelain, 2009; Lawton, 2008; Smith, Carroll, & Singer, 2008), detrital evidence for unroofing in those Laramide basins and local sediment storage (Bush et al., 2016; Carroll, Chetel, & Smith, 2006; Smith et al., 2019), and a decrease in sediment supply to the Gulf Coast in the early middle Eocene (e.g., Galloway et al., 2011). In addition to this evidence, we note that Wilcox Group detrital zircon age spectra from south Texas to the Sabine uplift lack the 1,250–950 Ma age distributions that are found in younger, spatially overlapping Claiborne Group strata, as described above (e.g., Blum et al., 2017; Blum & Pecha, 2014; Craddock & Kylander-Clark, 2013; Wahl et al., 2016). Whereas anomalous Claiborne Group heavy mineral assemblages and abundant 1,250–950 Ma zircons from eastern Texas likely were at least partially sourced from areas adjacent to the basin margins (e.g., the Ouachitas, see McCarley, 1981; Wahl et al., 2016), the existence of the additional 1,250–950 Ma zircons in southern Texas would seem to require a record of unroofing of Mesoproterozoic magmatic rocks in Laramide structural highs, similar to what has been documented in basins across the Laramide province in the Early to Middle Eocene (e.g., Carroll et al., 2006). Any drainages that originated in the Ouachitas, flowed to the south, and carried recycled Paleozoic sediment likely would have been integrated into the sediment dispersal system that supplied the contemporaneous delta in east Texas (Galloway et al., 2011), before reaching south Texas. As such, the 1,250–950 Ma zircons in Middle Eocene strata from east Texas to the Sabine uplift area of Louisiana may represent a mix of material recycled from Paleozoic strata near the basin margins (and/or recycled from Appalachian derived strata in the eastern Gulf Coast) and an unroofing sequence for detritus derived from Laramide ranges farther west.

5.3 Late Eocene Jackson Group sediment provenance

There are no obvious contrasts between the middle and upper Eocene detrital zircon data in the eastern Gulf Coast region or the axial part of the Mississippi Embayment, and, therefore, we envision sediment provenance was similar for these two time periods. Sediment supply was apparently low to the eastern Gulf Coast region and any rivers flowing to the region were not connected downdip to contemporaneous deltas. However, a small Mississippi delta system persisted in the Mississippi-Louisiana border region.

Farther to the west and relative to the middle Eocene, the most obvious changes in the upper Eocene detrital zircon age spectra generally are (a) the increased prevalence in syndepositional zircon ages in the western part of the U.S. Gulf Coast (a change which is also recorded in the latest middle Eocene Yegua Formation, see temporal changes 2a and 2b in Figures 4 and 5), and (b) an abrupt increase in the proportion of 190–34 Ma and 1,800–1,600 Ma zircons, relative to 1,250–950 Ma zircons (temporal change 3, Figures 4 and 5), along the western Mississippi embayment. The following discussion will emphasise these two changes.

Temporal change 2 does not require any change in drainage patterns relative to the middle Eocene. Rather, the change could be explained by the development of magmatic centres within pre-existing catchments, and/or the blanketing of catchments with volcanic ash. Change 3, however, does imply a change in paleo-drainage configuration. Whereas the western Mississippi embayment detrital zircon age spectra were interpreted to be supplied by a river that originated near the basin margin in the middle Eocene, the most plausible source for the 190–34 Ma zircons in upper Eocene strata of the region appears to be the magmatic province of central Colorado. This implies that by the late Eocene, some of the rivers that originated in the magmatic province in central Colorado were rerouted from the Houston embayment to the southwestern Mississippi embayment. Any sediment supplied by this paleo-river system must have been minor, though, to account for the lack of a large delta system downdip from the Mississippi embayment at this time. To the south, the Sabine uplift sample seems to record an area between larger sediment dispersal systems that received sediment shed off of the Ouachita highlands. Farther south along the Texas coastal plain, we consider that a spectrum of drainage patterns to the Rio Grande embayment is permissible for the late Eocene. This spectrum of possibilities is similar to the middle Eocene, and we therefore depict a similar configuration of paleo-drainage to Texas for these two time periods.

5.4 Contrasting the upper Eocene and Oligocene age spectra

The detrital zircon age spectra from upper Eocene Jackson Group exhibit some significant differences from the overlying Frio-Vicksburg Groups (Blum et al., 2017; Blum & Pecha, 2014). In the eastern Gulf Coast, detrital zircon age spectra of the Frio-Vicksburg Groups show higher
proportions of 1,250–950 Ma versus 500–250 Ma zircons in comparison to older strata (temporal change 6, Figures 4 and 5). This change may correspond to the beginning of enhanced erosion of the southern Appalachian foreland region, which reached a climax in the middle Miocene (e.g., Combellas-Bigott & Galloway, 2006; Galloway et al., 2011).

In the axial Mississippi embayment region, there was a marked increase in 190–34 Ma and 1,800–1,600 Ma zircons at the expense of 1,250–950 Ma zircons (temporal change 4, Figure 2) between the late Eocene and Oligocene. The change appears to have occurred gradually from deposition of the Jackson Group to deposition of the Vicksburg and then, Frisco Groups. There was also sufficient sediment supply to the paleo-Mississippi to prograde the shelf margin by 50 km or more in the Oligocene (Galloway, 2008), however, drainage reconstructions for the Oligocene do not imply a major capture event in the northwestern Mississippi headwaters at this time (Blum et al., 2017). Rather, this change in detrital zircon age spectra may correspond to renewed erosion of northeastern Laramide region basins in the middle of the Cenozoic and/or reworking of large volumes of volcanic ash deposited on the upper reaches of the paleo-catchment. The youngest preserved strata in many of the northern Laramide basins are Oligocene (Dickinson et al., 1988; Lawton, 2008), consistent with a phase of erosion beginning in the Oligocene. The reworking of large volumes of volcanic ash is consistent with the large volume of relatively muddy sediment delivered to the paleo-Mississippi delta (Galloway et al., 2011) and well-defined MDAs (Blum et al., 2017). Overall, for Paleogene strata, the axial part of the Mississippi Embayment seems to separate age spectra with zircons derived from sources in the western cordillera to the west, from age spectra with no western cordilleran zircons to the east. The Mississippi embayment appears to have been a persistently low-lying region in the Paleogene, integrating drainages that flowed towards the southern part of the mid-continent region.

There are no obvious, significant changes in detrital zircons in east Texas between the late Eocene and Oligocene. However, compared to the Eocene, the Oligocene detrital zircon age distributions in south Texas are relatively homogenous, dominated by a large age distribution that is close to the depositional age (temporal change 5). This may simply reflect an increased proportion of magmatic material. If so, then the age spectra do not necessarily require a major drainage reorganisation in the headwaters of the south Texas paleo-river system between the late Eocene to the Oligocene.

In any case, between the Paleocene and the Oligocene, the most recent drainage reconstructions (Blum et al., 2017) involve a southward expansion of the portion of Laramide province integrated into Mississippi-embayment-bound drainages and a southward shift of the headwaters of drainages bound for the Texas coastal plain. Although we are uncertain about the exact position of the drainage divides in the Eocene, the appearance of large 190–34 Ma and 1,800–1,600 Ma age modes in the western Mississippi embayment, which first occurred in the Late Eocene, and continued into the Oligocene (Figures 4 and 5), seems to indicate that rivers that originated in central Colorado were rerouted from the Houston Embayment to the Mississippi embayment in the Late Eocene. The northward shift of the <1,700 Ma age mode within the 1,800–1,600 Ma age range on the Texas coastal plain, between the Claiborne and Jackson Groups, is also consistent with southward shift in the paleo-river headwaters (Table 2, annotated on Figure 7). The large sediment volume supplied to south Texas in the Oligocene implies that the upstream drainage area was vast, and/or characterised by higher relief than in the Eocene (Blum et al., 2017).

6 | CONCLUSIONS

Detrital zircon age spectra from middle and upper Eocene strata of the U.S. Gulf Coast define at least six to eight groups that correspond to distinct sediment provenance areas. In aggregate, detrital zircon data from this and other studies define at least six temporal changes in detrital zircons at given points along the Gulf Coast during the Paleogene. The spatial and temporal changes in detrital zircon age spectra help to place additional constraints on the permissible paleo-drainage patterns of the interior United States during the Cenozoic. Several summary statements can be applied to the middle and late Eocene reconstructions. First, the Paleozoic Appalachian orogen was likely characterised by an erosional landscape in the Eocene, and generally throughout the Paleogene. At least some of the rivers draining this landscape were routed southwestward, either towards the low-lying Mississippi Embayment or directly to the Gulf Coast region. A relatively high proportion of sediment in these rivers was derived from the hinterland during the Paleocene and Eocene, and from the foreland after the Eocene. This temporal contrast indicates enhanced erosion of the southern Appalachian foreland after the Eocene. Second, during times when the Mississippi embayment was not inundated by marine transgressions, a Mississippi-like trunk channel likely flowed southward across the low-lying central Mississippi embayment. This trunk channel integrated tributaries that originated in the east and in the west, although not always as far west as the Laramide structural front. Third, in the middle Eocene, several lines of evidence indicate that rivers that originated in the magmatic province in central Colorado and adjacent basins Wyoming, flowed to the Houston embayment, as Precambrian basement highs in the Laramide region were being unroofed. The unroofing appears to be recorded along the Texas and northwestern Louisiana coastal plains by the appearance of large 1,250–950 Ma zircon age distributions,
relative to older strata. A Paleocene drainage connection to the western cordilleran arc had been disrupted by the middle Eocene. By the late Eocene, the northwestern reaches of this drainage network were probably integrated into a river bound for the southwestern Mississippi embayment. This configuration appears to have persisted into the Oligocene, although erosion of Laramide basins and/or volcanic ash deposits upstream may have changed the character of the detrital zircon age spectra along the western Mississippi embayment in the Oligocene. In the broadest terms, these constraints on paleodrainage reconstructions from detrital zircon age spectra are important because they help to correlate stratigraphic packages in the Gulf Coast region to geologic elements upstream, and further elucidate the erosion of these upstream elements.

ACKNOWLEDGEMENTS
This work was funded by the U.S. Geological Survey Energy Resources Programme. Any use of trade, firm or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This manuscript benefitted from thoughtful reviews by USGS reviewer Dave Houseknecht and journal reviewers William Galloway and Joel Saylor.

CONFLICT OF INTEREST
The authors declare no competing financial interests.

DATA AVAILABILITY STATEMENT
This paper is accompanied by a USGS Data Release, which contains a permanent online record of all of site metadata as well as all of the U and Pb isotope ratio and age measurements. The data are archived on sciencebase.gov which contains a permanent online record of all of site metadata with DOIs. It can be accessed at this address: https://doi.org/10.5066/P9122ZD7.

ORCID
William H. Craddock https://orcid.org/0000-0002-4181-4735

REFERENCES
Becker, T. P., Thomas, W. A., Samson, S. D., & Gehrels, G. E. (2005). Detrital zircon evidence of Laurentian crustal dominance in the lower Pennsylvania deposits of the Alleghanian clastic wedge in eastern North America. Sedimentary Geology, 182, 59–86. https://doi.org/10.1016/j.sedgeo.2005.07.014
Blum, M. D., Milliken, K. T., Pecha, M. A., Sneed, J. W., Frederic, B. C., & Galloway, W. E. (2017). Detrital-zircon records of Cenomanian, Paleocene, and Oligocene sediment routing: Implications for scales of basin-floor fans. Geosphere, 13, 2169–2205. https://doi.org/10.1130/GE01410.1
Blum, M. D., & Pecha, M. A. (2014). Mid-Cretaceous to Paleocene North American drainage reorganization from detrital zircons. Geology, 42, 607–610. https://doi.org/10.1130/G35513.1
Bush, M. A., Horton, B. K., Murphy, M. A., & Stockli, D. F. (2016). Detrital record of initial basement exhumation along the Laramide deformation front, southern Rocky Mountains. Tectonics, 35, 2117–2130. https://doi.org/10.1002/2016TC004194
Carroll, A. R., Chetel, L. M., & Smith, M. E. (2006). Feast to famine: Sediment supply control on Laramide basin fill. Geology, 34, 197–200. https://doi.org/10.1130/G22148.1
Cather, S. M., Chapin, C. E., & Kelley, S. A. (2012). Diachronous episodes of Cenozoic erosion in southwestern North America and their relationship to surface uplift, paleoclimate, paleodrainage, and paleoaltimetry. Geosphere, 8, 1177–1206. https://doi.org/10.1130/GE008011.1
Combellas-Bigott, R. I., & Galloway, W. E. (2006). Depositional and structural evolution of the middle Miocene depositional episode, east-central Gulf of Mexico. American Association of Petroleum Geologists Bulletin, 90(3), 335–362. https://doi.org/10.1306/10040404054132
Cottle, J. M., Horstwood, M. S. A., & Parrish, R. R. (2009). A new approach to single shot laser ablation analysis and its application to in situ Pb/U geochronology. Journal of Analytic Atomic Spectrometry, 24, 1355–1363. https://doi.org/10.1039/b821899d
Cottle, J. M., Kylander-Clark, A. R. C., & Vrijmoed, J. C. (2012). U-Th/Pb geochronology of detrital zircon and monazite by single shot laser ablation inductively coupled plasma mass spectrometry (SS-LA-ICPMS). Chemical Geology, 332–333, 136–147. https://doi.org/10.1016/j.chemgeo.2012.09.035
Craddock, W. H., & Kylander-Clark, A. R. C. (2013). U-Pb ages of detrital zircons from the Tertiary Mississippi River delta in central Louisiana: Insights into sediment provenance. Geosphere, 9, 1832–1851. https://doi.org/10.1130/GE00917.1
Craddock, W. H., Kylander-Clark, A. R. C., & Coleman, J. L. (2020). U-Pb of detrital zircons in Paleogene strata of the Gulf Coast. U.S. Geological Survey Data Release. https://doi.org/10.5066/P9122ZD7
Davis, S. J., Mulch, A., Carroll, A. R., Horton, T. W., & Chamerlain, C. P. (2009). Paleogene landscape evolution of the central North American Cordillera: Developing topography and hydrology in the Laramide foreland. Geological Society of America Bulletin, 121(1/2), 100–116. https://doi.org/10.1130/B26308.1
Dickinson, W. R., & Gehrels, G. E. (2009). Use of U-Pb ages of detrital zircons to infer maximum depositional ages of strata: A test against a Colorado Plateau Mesozoic database. Earth and Planetary Science Letters, 228, 115–125. https://doi.org/10.1016/j.epsl.2009.09.013
Dickinson, W. R., Klute, M. A., Hayes, M. J., Janecke, S. U., Lundin, E. R., McKittrick, M. A., & Olivares, M. D. (1988). Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region. Geological Society of America Bulletin, 100, 1023–1039. https://doi.org/10.1130/0016-7606(1988)100<1023:-PAPSOL>2.3.CO;2
Eriksson, K. A., Campbell, I. H., Palin, J. M., Allen, C. M., & Bock, B. (2004). Evidence for multiple recycling in Neoproterozoic through Pennsylvaniaian sedimentary rocks of the central Appalachian basin. Journal of Geology, 112, 261–276. https://doi.org/10.1086/382758
Fan, M., Brown, E., & Li, L. (2019). Cenozoic drainage evolution of the Rio Grande paleoriver recorded in detrital zircons in South Texas. International Geology Review, 61, 622–636. https://doi.org/10.1080/00206814.2018.1446368
Fisher, W. L., Galloway, W. E., Proctor, C. V. Jr., & Nagle, J. S. (1970). Depositional Systems in the Jackson Group of Texas and their...
relationship to oil gas, and uranium. Gulf Coast Association of Geological Societies, 20, 234–261.

Galloway, W. E. (2008). Depositional evolution of the Gulf of Mexico sedimentary basin. In A. D. Miall (Ed.), Sedimentary Basins of the World: Volume 5, The Sedimentary Basins of the United States and Canada (pp. 505–549). Amsterdam, The Netherlands: Elsevier. https://doi.org/10.1016/S1874-5997(08)00015-4

Galloway, W. E., Ganey-Curry, P. E., Li, X., & Buffler, R. T. (2000). Cenozoic depositional history of the Gulf of Mexico basin. American Association of Petroleum Geologists Bulletin, 84, 1743–1774.

Galloway, W. E., Whiteaker, T. L., & Ganey-Curry, P. (2011). History of Cenozoic North American drainage basin evolution, sediment yield, and accumulation in the Gulf of Mexico basin. Geosphere, 7, 938–973. https://doi.org/10.1130/GES00647.1

Garry, C. P., & Soller, D. R. (2009). Database of the Geologic Map of North America; adapted from the map by J.C. Reed, Jr. et al. (2005). U.S. Geological Survey Data Series 424. Retrieved from https://pubs.usgs.gov/ds/0424/

Gleason, J. D., Finney, S. C., & Gehrels, G. E. (2002). Paleotectonic implications of a Mid- to Late-Ordovician provenance shift, as recorded in sedimentary strata of the Ouachita and southern Appalachian Mountains. Journal of Geology, 110, 291–304. https://doi.org/10.1086/339533

Gorham, T. W., & Ingersoll, R. V. (1979). Evolution of the Eocene Galisteo basin, north-central New Mexico. In R. V. Ingersoll, L. A. Woodward, & H. L. James (Eds.), Fall field conference guidebook 30: Santa fe country (pp. 219–224). Socorro, NM: New Mexico Geological Society.

Hatcher, R. D. Jr. (1987). Tectonics of the southern and central Appalachian interdines. Annual Reviews of Earth and Planetary Science, 15, 337–362.

Lawton, T. F. (2008). Laramide sedimentary basins. In A. D. Miall (Ed.), Sedimentary Basins of the World: Volume 5. The Sedimentary Basins of the United States and Canada (pp. 429–450). Amsterdam, The Netherlands: Elsevier. https://doi.org/10.1016/S1874-5997(08)00012-9

Lawton, T. F., Bradford, I. A., Vega, F. J., Gehrels, G. E., & Amato, J. M. (2009). Provenance of Upper Cretaceous-Paleogene sandstones in the foreland basin system of the Sierra Madre Oriental, northeastern Mexico, and its bearing on fluvial dispersal systems of the Mexican Sedimentary Basin. In A. Salvador (Ed.), Rock salt field and core guidebook, Gulf of Mexico. Geological Society of America Bulletin, 121, 820–836. https://doi.org/10.1130/B26450.1

Ludwig, K. R. (2012). User’s manual for Isoplot 3.75: A Geochemical Toolkit for Microsoft Excel. Berkeley Geochemistry Center Special Publication, 5, 75 p.

Mackey, G. N., Horton, B. K., & Milliken, K. L. (2012). Provenance of the Paleocene-Eocene Wilcox Group, western Gulf of Mexico basin: Evidence for integrated drainage of the southern Laramide Rocky Mountains and Cordilleran arc. Geological Society of America Bulletin, 124, 1007–1024. https://doi.org/10.1130/B30458.1

Mancini, E. A., & Tew, B. H. (1994). Claiborne-Jackson Group Contact (Eocene) in Alabama and Mississippi. Gulf Coast Association of Geological Societies Transactions, 44, 431–439.

McCarley, A. B. (1981). Metamorphic terrane favored over Rocky Mountains as source of Claiborne Group, Eocene, Texas coastal plain. Journal of Sedimentary Petrology, 51, 1267–1276.

Park, H., Barbeau, D. L. Jr., Rickenbacker, A., Bachmann-Krug, D., & Gehrels, G. E. (2010). Application of foreland basin detrital-zircon geochronology to the reconstruction of the southern and central Appalachian Orogen. Journal of Geology, 118, 23–44. https://doi.org/10.1086/648400

Reed, J. C. Jr., Wheeler, J. O., & Tucholke, J. E., compilers. (2005). Geologic map of North America. Boulder, CO: Geological Society of America, Decade of North American Geology Continental Scale Map 001, scale 1:5,000,000.

Salvador, A., & Muieton, J. M. Q., compilers. (1989). Stratigraphic correlation chart, Gulf of Mexico Basin. In A. Salvador (Ed.), The Gulf of Mexico basin, The Geology of North America (Vol. J, plate 5). Boulder, CO: Geological Society of America.

Sharman, G. R., Covault, J. A., Stockli, D. F., Wrobleski, A.- F.-J., & Bush, M. A. (2017). Early Cenozoic drainage reorganization of the United States Western Interior-Gulf of Mexico sediment routing system. Geology, 45, 187–190. https://doi.org/10.1130/G38765.1

Smith, L. N., Lucas, S. G., & Elston, W. E. (1985). Paleogene stratigraphy, sedimentation, and volcanism of New Mexico. In R. M. Flores & S. S. Kaplan (Eds.), Rocky Mountain Paleogeography Symposium 3: Cenozoic Paleogeography of the West-Central United States (pp. 293–316). Denver, CO: Rocky Mountain Section of the Society of Economic Paleontologists and Mineralogists.

Smith, M. E., Carroll, A. R., & Singer, B. S. (2008). Synoptic reconstruction of a major ancient lake system: Eocene Green River Formation, western United States. Geological Society of America Bulletin, 120(1/2), 54–84. https://doi.org/10.1130/B26073.1

Smith, T. M., Sundell, K. E., Johnston, S. N., Guilherme Andrade, C. N., Andrea, R. A., Dickinson, J. N., … Saylor, J. E. (2019). Drainage reorganization and Laramide tectonics in north-central New Mexico and downstream effects in the Gulf of Mexico, Basin Research, 32(3), 419–452. https://doi.org/10.1111/bre.12373

Thomas, W. A., Gehrels, G. E., Greb, S. F., Nadon, G. C., Satkoski, A. M., & Romero, M. C. (2017). Detrital zircons and sediment dispersal in the Appalachian foreland. Geosphere, 13(6), 2206–2230. https://doi.org/10.1130/GES1525.1

Todd, T. W., & Folk, R. L. (1957). Basal Claiborne of Texas, record of Appalachian tectonism during Eocene. American Association of Petroleum Geologists Bulletin, 41, 2545–2566.

Van Arsdale, R. B., & TenBrink, R. K. (2000). Late Cretaceous and Cenozoic Geology of the New Madrid Seismic Zone. Geological Society of America Bulletin, 90, 345–356. https://doi.org/10.1785/019990088

Vermeesch, P. (2009). RadialPlotter: A Java application for fission track, luminescence and other radial plots. Radiation Measurements, 44(4), 409–410.

Vermeesch, P., Resentini, A., & Garzanti, E. (2016). An R package for statistical provenance analysis. Sedimentary Geology, 336, 14–25. https://doi.org/10.1016/j.sedgeo.2016.01.009

Wahl, P. J., Yancey, T. E., Pope, M. C., Miller, B. V., & Ayers, W. B. (2016). U-Pb detrital zircon geochronology of the Upper Paleocene to Lower Eocene Wilcox Group, east-central Texas. Geosphere, 12, 1517–1531. https://doi.org/10.1130/GES01313.1

Whitmeyer, S. J., & Karlstrom, K. E. (2007). Tectonic model for the Proterozoic growth of North America. Geosphere, 3, 220–259. https://doi.org/10.1130/GES00055.1

Winker, C. D. (1982). Cenozoic shelf margins, northwestern Gulf of Mexico. Gulf Coast Association of Geological Societies Transactions, 32, 427–448.

Wissink, G. K., Wilkinson, B. H., & Hoke, G. D. (2018). Pairwise comparisons and multidimensional scaling of detrital zircon ages with examples from the North American platform, basin, and passive margin settings. Limestone, 10(3), 478–491. https://doi.org/10.1130/L700.1
Xu, J., Snedden, J. W., Stockli, D. F., Fulthorpe, C. S., & Galloway, W. E. (2017). Early Miocene continental-scale sediment supply to the Gulf of Mexico Basin based on detrital zircon analysis. *Geological Society of America Bulletin*, 129(1–2), 3–22. https://doi.org/10.1130/B31465.1

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.