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Detrital-zircon records of Cenomanian, Paleocene, and Oligocene Gulf of Mexico drainage integration and sediment routing: Implications for scales of basin-floor fans

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ABSTRACT

This paper uses detrital zircon (DZ) provenance and geochronological data to reconstruct paleodrainage areas and lengths for sediment-routing systems that fed the Cenomanian Tuscaloosa-Woodbine, Paleocene Wilcox, and Oligocene Vicksburg-Frio clastic wedges of the northern Gulf of Mexico (GoM) margin. During the Cenomanian, an ancestral Tennessee-Alabama River system with a distinctive Appalachian DZ signature was the largest system contributing water and sediment to the GoM, with a series of smaller systems draining the Ouachita Mountains and discharging sediment to the western GoM. By early Paleocene Wilcox deposition, drainage of the southern half of North America had reorganized such that GoM contributing areas stretched from the Western Cordillera to the Appalachians, and sediment was delivered to a primary depocenter in the northwestern GoM, the Rockdale depocenter fed by a paleo–Brazos-Colorado River system, as well as to the paleo–Mississippi River in southern Louisiana. By the Oligocene, the western drainage divide for the GoM had migrated east to the Laramide Rockies, with much of the Rockies now draining through the paleo–Red River and paleo–Arkansas River systems to join the paleo–Mississippi River in the southern Mississippi embayment. The paleo–Tennessee River had diverted to the north toward its present-day junction with the Ohio River by this time, thus becoming a tributary to the paleo-Mississippi within the northern Mississippi embayment. Hence, the paleo-Mississippi was the largest Oligocene system of the northern GoM margin.

Drainage basin organization has had a profound impact on sediment delivery to the northern GoM margin. We use paleodrainage reconstructions to predict scales of associated basin-floor fans and test our predictions against measurements made from an extensive GoM database. We predict large fan systems for the Cenomanian paleo–Tennessee-Alabama, and especially for the two major depocenters of the early Paleocene paleo–Brazos-Colorado and late Paleocene–earliest Eocene paleo-Mississippi systems, and for the Oligocene paleo-Mississippi. With the notable exception of the Oligocene, measured fans reside within the range of our predictions, indicating that this approach can be exported to other basins that are less data rich.

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INTRODUCTION

The northern Gulf of Mexico (hereafter GoM) continental margin is dominated by the Mississippi River sediment-dispersal system. The Mississippi drainage stretches from the Rocky Mountains in the western U.S. to the Appalachian cordillera in the east, and feeds the alluvial-deltaic plain of south Louisiana as well as its linked basin-floor fan in the deepwater GoM (Fig. 1; Bentley et al., 2015). Regional-scale fluvial systems drain basin-margin terrain of the south-central U.S. to the west of the Mississippi, and the southern Appalachians to the east. More than 90% of the sediment load delivered to the northern GoM margin during the late Quaternary period comes from the Mississippi drainage (calculated from Syvitski and Milliman, 2007), a load reflected in the enormous scale of the Mississippi basin-floor fan. However, integration of a continental-scale Mississippi drainage is a Neogene phenomenon, and paleodrainage and sediment routing have changed over time (Galloway et al., 2011; Blum and Pecha, 2014).

This paper presents a detrital zircon (DZ) record of mid-Cretaceous to Paleogene GoM paleodrainage and sediment routing, focusing on Cenomanian, Paleocene, and Oligocene sediment-dispersal systems. Our research uses DZs to reconstruct basin-scale paleodrainage, then uses reconstructions to predict sediment routing to basin-floor fans. This is one of several ongoing parallel efforts that follow a GoM source-to-sink (S2S) theme, which quantify the scale of GoM basin-floor fans through time from subsurface data (Snedden et al., 2017) and reconstruct fluvial system scales through time from empirical scaling relationships between drainage-basin size and length, and point-bar thicknesses measured from well logs (Milliken et al., 2015). Finally, papers by Xu et al. (2016, 2017) focus specifically on reconstructing fluvial systems of the early Miocene. Collectively, these papers illustrate a relatively efficient, semiquantitative approach to reconstructing continental-scale paleo-

Figure 1. Modern drainage patterns in North America, illustrating the significance of the Mississippi River system to the Gulf of Mexico and the Mississippi deep-water fan system. A majority of the water flux for the Mississippi system comes from the Ohio River tributary and eastern North America (blue arrow), whereas the majority of sediment is derived from the Missouri River tributary and the Rocky Mountains and Great Plains regions (brown arrow). "WGoM" stands for western Gulf of Mexico drainage, including the Brazos and Colorado Rivers, whereas "EGoM" stands for eastern Gulf of Mexico drainage and includes the Apalachicola and Alabama Rivers (see Fig. 5).

drainage and sediment routing and predicting basin-floor fan systems in a well-known basin, an approach that can be exported to other basins that are less well known.

BACKGROUND

Source-to-Sink Concepts

The S2S approach emerged in association with the National Science Foundation (NSF) MARGINS program and is grounded on understanding sediment production rates, transport and storage through sediment-dispersal system segments, delivery rate to sediment sinks, and how the unsteadiness of sediment production and transfer through system segments is preserved in the ancient stratigraphic record (NSF MARGINS Program, 2004). Romans et al. (2016) illustrated how the tools required for S2S analyses vary with the time scale of investigation. Our goals require empirical data on modern sediment flux and scales of sediment-dispersal system segments, and tools that measure scales of terrestrial to marginal-marine components in ancient systems, so as to predict the scales and properties of linked deepwater components.

Our approach assumes that sediment-dispersal system segments develop self-similar geometries over 10^4–10^6 yr, regardless of absolute scale (equilibrium time of Paola and Mohrig, 1996). We assume that, at the first order, the scales and properties of each segment within a sediment-dispersal system correlate to water and sediment flux, and the scales and properties of one segment are inherently related to, and can be predicted from, the scales and properties of another in the same system. Syvitski and Milliman (2007) showed that, on a global scale, sediment flux scales to drainage area and relief at the first order, and at the second order, to hydrology and temperature. Somme et al. (2009) quantified scaling relationships between drainage area and the different segments of modern sediment-dispersal systems, a relationship further illustrated by Helland-Hansen et al. (2016), whereas Blum et al. (2013) focused more specifically on fluvial systems and published relationships between drainage basin size, bankfull discharge, and point-bar thickness (Fig. 2; Table 1). Scaling relationships such as these generally follow power laws, where absolute dimensions of dispersal-system segments scale to drainage area and sediment flux, and parameters like grain size and transport slope scale inversely.

In this paper, we rely on scaling relationships between maximum river-channel length and the lengths of basin-floor fans from Somme et al. (2009; see also Helland-Hansen et al., 2016), which show that the length of many modern fans is ~10%–50% of the length of the fluvial-channel system that feeds them. The modern Mississippi River system is a good example of this relationship, because the basin-floor fan is ~540 km in length, or ~10% of the maximum channel length of the Mississippi-Missouri system of 5475 km. We also rely on scaling relationships between drainage area and point-bar thickness, assumed to be a proxy for bankfull flow depth and one of the metrics that can be readily collected from subsurface data; these relationships are further discussed and refined in Milliken et al. (2015).

Gulf of Mexico Basin Fill

The GoM is a well-understood sedimentary basin: first-order paleogeography, patterns of sediment input, key elements of the stratigraphic record, and the overall basin-fill architecture and environments of deposition are known from generations of industry activity and academic research (summarized in Galloway, 2008; Galloway et al., 2011; Fig. 3).

The oldest unit of interest here is the Late Cretaceous (Cenomanian) Tuscaloosa-Woodbine trend, which represents the first major episode of clastic shelf-margin progradation into the GoM (Galloway, 2008; Snedden et al., 2016). The sand-rich lower Tuscaloosa Group crops out from Alabama through Mississippi, whereas the sand-rich lower Woodbine Group crops out through southern Oklahoma and north-central Texas. For the Cenozoic, major episodes of coarse-grained clastic influx and shelf-margin progradation include the Paleocene–Eocene Wilcox and the Oligocene Vicksburg-Frio depositional episodes, as well as the variously named episodes of the Neogene (Galloway, 2008; Galloway et al., 2011). Each contains fluvial, deltaic, and shore-zone facies, as well as slope to basin-floor equivalents in the deepwater GoM.

Cretaceous to Cenozoic sediment input to the GoM has been focused into a select few deep-seated structural embayments, even though hinterland drainage areas to the GoM have evolved in response to tectonics of the continental interior (Winker, 1982; Galloway, 2008; Galloway et al., 2011). From west to east, these include the Rio Grande embayment, the Houston embayment, and the Mississippi embayment (Fig. 4). For this reason, while hinterland source

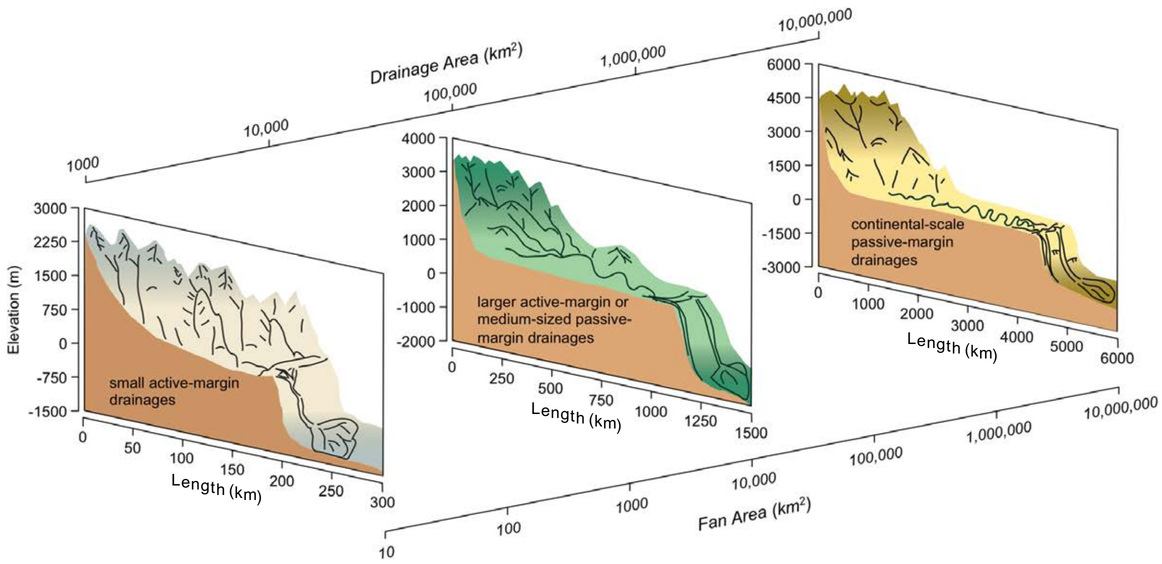


Figure 2. Summary of scaling relationships in sediment-dispersal systems, contrasting dimensions of system segments in small-, medium-, and large-scale drainage basins (after Somme et al., 2009).

TABLE 1. SUMMARY OF FLUVIAL TO DEEPWATER SOURCE-TO-SINK SCALING RELATIONSHIPS*

System size	Drainage basin area (km²)	Fluvial system length (km)	Fluvial sand body thickness (m)	Backwater length (km)	Fan length (km)	Fan width (km)	Fan area (km²)
Small	<10,000	75–100	<5	10–30 km	<25	25–50	<1000
Moderate	100,000	750–1000	10–15	50–100	100–200	100–200+	100,000
Large	>1,000,000	2000–4000	>25	300–500+	500–1000	500–1000+	10,000,000

*From Somme et al. (2009), Blum et al. (2013), and Milliken et al. (2015).

terrains have evolved, sediment input through time has largely corresponded with the general positions of extant river systems, including the Rio Grande, the Colorado and Brazos Rivers of central and east Texas, and the Red and Mississippi Rivers of south-central Louisiana (Fig. 5). In addition, the Tennessee River system, which drains much of the Appalachians, now flows north from northwestern Alabama and northeastern Mississippi to join the Ohio River, but likely maintained an independent course south-southwest to the GoM for much of the Cretaceous through Eocene.

Winker (1982) initially summarized linkages between tectonic organization of hinterlands, sediment routing to the GoM, and known Cenozoic fluvial-deltaic depocenters (Fig. 4). In this view, Paleocene–Eocene Wilcox deposition was concentrated in the Houston embayment and interpreted to reflect sediment input from Laramide uplifts in the western U.S., whereas Oligocene Vicksburg-Frio deposition was focused on the Rio Grande embayment and interpreted to reflect volcanic-rich debris derived from the Sierra Madre of northern Mexico and the southwestern U.S. The Mississippi embayment evolved into the primary fluvial axis during the Miocene and increased in importance during late Cenozoic glaciation, which diverted major tributaries like the Missouri and Ohio Rivers to the south from their former courses toward Hudson Bay (see Galloway et al., 2011). Early work focused on fluvial axes for major depocenters but has evolved as more data became available and contributions from smaller systems have become more fully resolved; the Cenozoic paleodrainage reconstructions of Galloway et al. (2011) represent a benchmark against which the DZ record is compared for this paper.

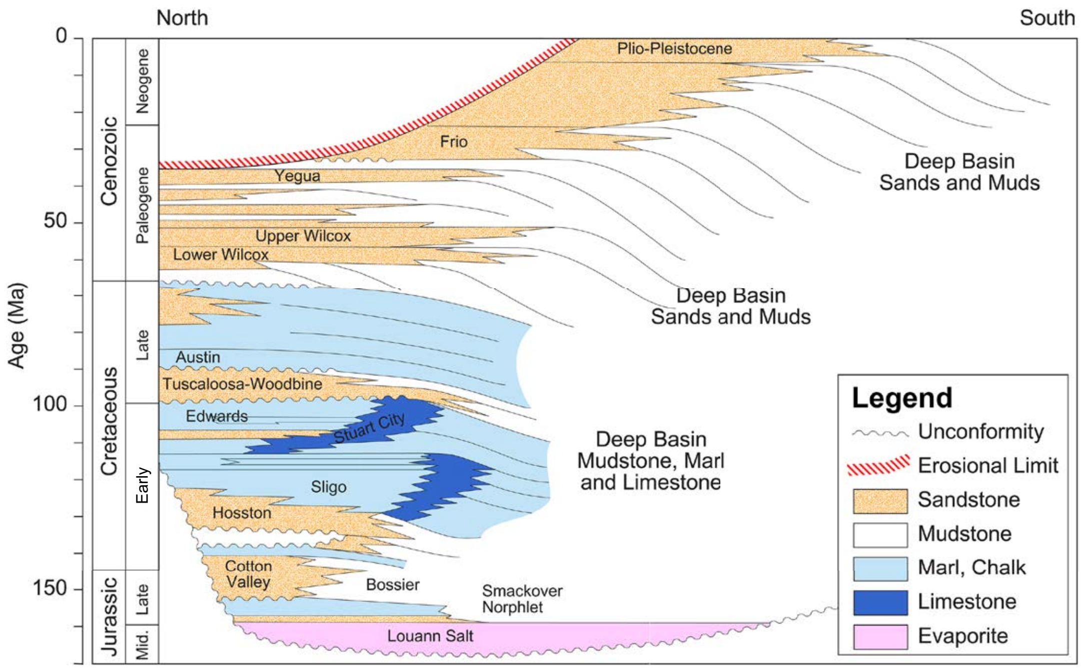


Figure 3. Summary of the stratigraphic framework for the Gulf of Mexico sedimentary basin (modified from Galloway, 2008), showing stratigraphic position and significance of the Cenomanian Tuscaloosa-Woodbine, early Paleocene–early Eocene Wilcox, and Oligocene Frio units within the basin fill as a whole.

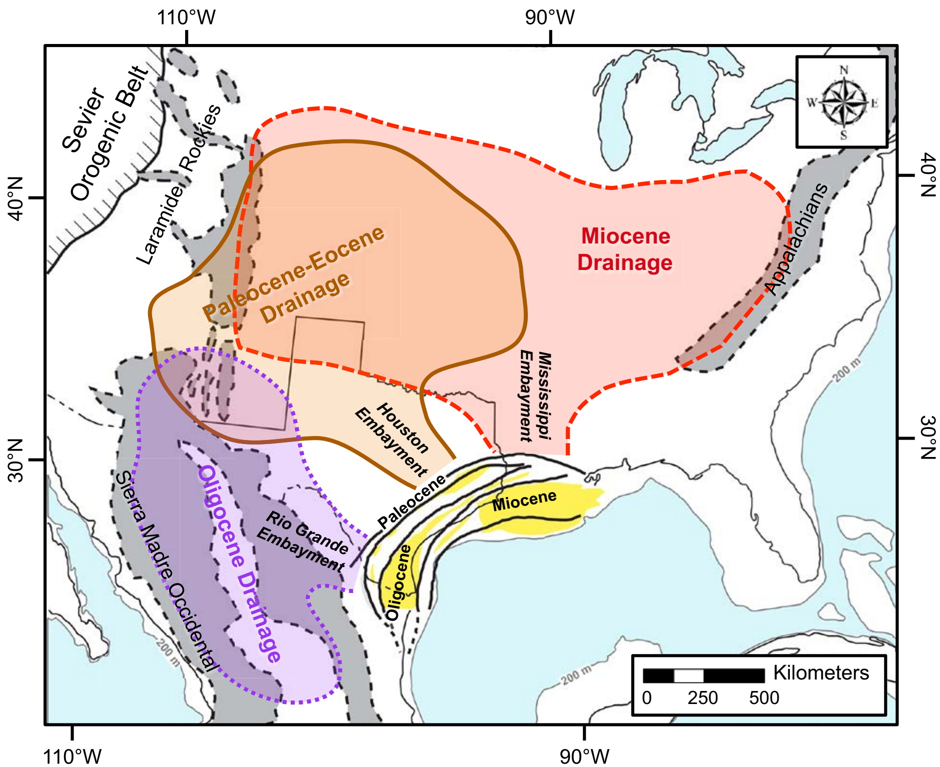


Figure 4. First-generation paleodrainage reconstruction after Winker (1982), interpreting drainage basins that contributed sediment to the major Paleocene–Eocene, Oligocene, and Miocene depocenters, Gulf of Mexico. Modified from Mackey et al. (2012).

METHODS

U-Pb dating of DZs in sandstones provides a fingerprint of source terrains (see Gehrels, 2014), such that DZs in fluvial sandstones can be used to constrain contributing drainage areas and sediment routing in a manner that complements and adds to traditional provenance studies. Protolith sources for zircon in North America are well known (Becker et al., 2005; Dickinson and Gehrels, 2009a; Park et al., 2010; Laskowski et al., 2013; Fig. 6) and reflect the major tectonic events that compiled the North American continent (e.g., Whitmeyer and Karlstrom, 2007). Table 2 summarizes DZ populations important to our data set.

Provenance interpretations using DZs can be complicated by a number of factors, including (1) differential fertility of zircons within source terrains (Malusà et al., 2016); (2) recycling through burial, exhumation, erosion, and deposition, (Dickinson and Gehrels, 2008; Thomas, 2011); (3) rims and cores that might yield different ages (inheritance); and (4) complications due to Pb loss. In our data set, the Mesoproterozoic Grenville (ca. 1250–950 Ma) DZ signal is an archetypal example of high fertility (Moecher and Samson, 2006) and recycling (Eriksson et al., 2004; Becker et al., 2005; Dickinson and Gehrels, 2008, 2009a; Park et al., 2010; May et al., 2013; Laskowski et al., 2013; Painter et al., 2014; Weislogel et al., 2015).

Our research reported here follows studies of Paleocene–Eocene Wilcox strata in southwestern Texas (Mackey et al., 2012), Paleocene through Oligocene strata of the Sabine uplift region of eastern Texas and western Louisiana (Craddock and Kylander-Clark, 2013), mid-Cretaceous through Paleocene continental-scale drainage reorganization (Blum and Pecha, 2014), and Paleocene–Eocene DZ signatures from east-central Texas (Wahl et al., 2016). We collected DZ samples from outcrops across the northern GoM coastal plain (Fig. 7), which represent fluvial sandstones of old alluvial-deltaic plains, analogous to the Pleistocene alluvial-deltaic plains that compose the modern GoM coastal plain (Blum and Price, 1998; Blum and Aslan, 2006); these updip remnants have been flexurally uplifted as the margin progrades, whereas downdip facies have subsided as the basin loads. Samples were collected systematically every 50–100 km along the outcrop belts of the Cenomanian Tuscaloosa-Woodbine, the Paleocene–earliest Eocene Wilcox to the north and east of the Mackey et al. (2012) study area, and the Oligocene Vicksburg-Frio stratigraphic units. Most samples were collected from fluvial sandstones that cut across and truncate

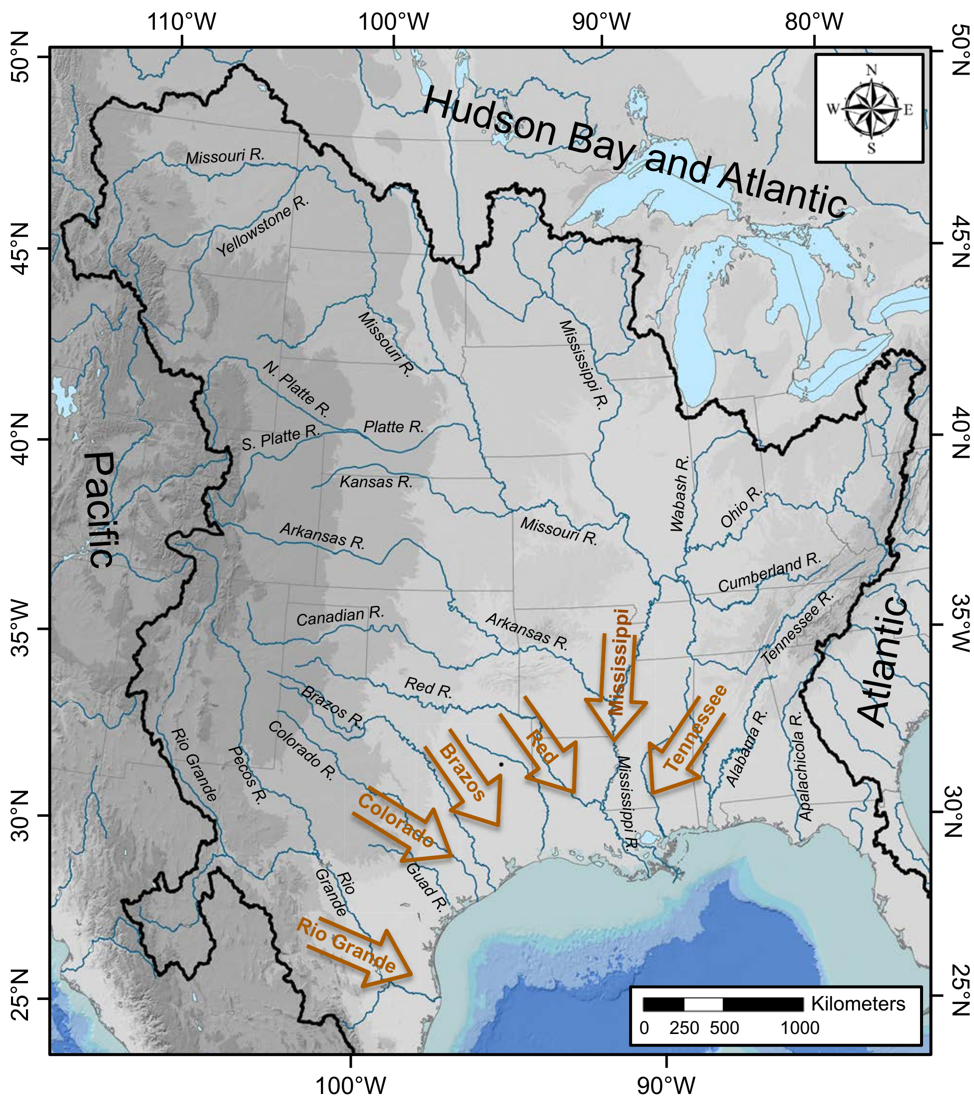
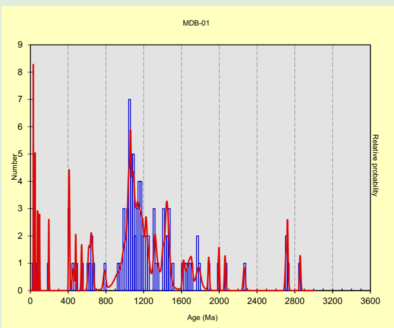


Figure 5. Contributing drainage area for the northern Gulf of Mexico (area within thick black line), with major extant rivers discussed in text as labeled. Superimposed are the long-term persistent drainage fairways into the northern Gulf of Mexico, which are referred to in the text and named after extant river systems in the same area. Large bold letters indicate areas that drain to the Hudson Bay, the Atlantic Ocean, and the Pacific Ocean. Guad—Guadalupe.

regionally mappable marine shales and therefore represent basinward extension of fluvial systems after basin-wide marine flooding. We also collected samples from modern sand bars in major rivers that contribute sediment to the northern GoM; these samples establish the fidelity of this approach by allowing reconstruction of contributing drainage areas that are independently known. For this paper, we summarize results from upstream to downstream positions along the modern Mississippi River, with downstream samples serving as analogs for samples from ancient strata in the GoM sedimentary basin. A total of 87 samples from the GoM margin and contributing fluvial systems were collected, with all sample analyses available in the Supplemental File[1]; data for individual samples can be downloaded from the searchable community database http://geochron.org.



[1]Supplemental File. Plots for modern river samples, as well as analytical data. Please visit http://doi.org/10.1130/GES01410.S1 or the full-text article on www.gsapubs.org to view the Supplemental File.

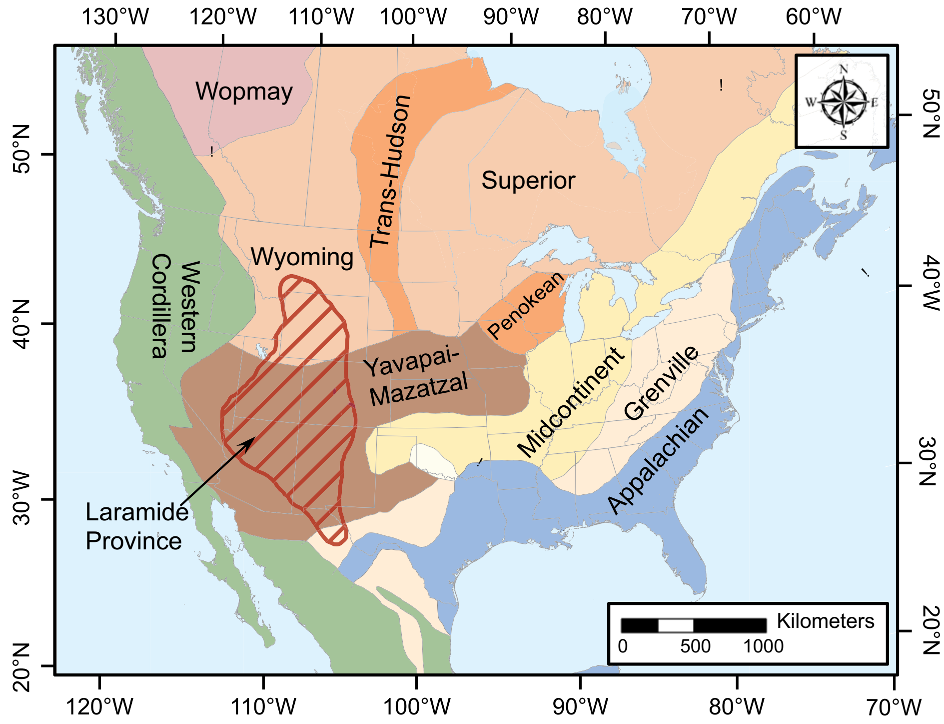


Figure 6. Protolith source terrains for detrital zircons in North America (modified from Dickinson and Gehrels, 2009a; Blum and Pecha, 2014; Fildani et al., 2016). For more explanation, including age ranges for each source terrain, see Table 2.

Detrital-zircon samples were processed and analyzed using laser ablation–inductively coupled plasma–mass spectrometery techniques at the Arizona LaserChron Center (see Gehrels, 2012). Analyses were based on a target population of $n = 100$ grains per sample (e.g., Vermeesch, 2004), with all samples producing between 90 and 110 concordant analyses; the entire GoM data set therefore includes >7800 concordant ^{238}U-^{206}Pb or ^{207}Pb-^{206}Pb ages. Our samples were collected and analyzed during 2011–2013, prior to the increasingly widespread use of larger numbers of grains per sample (Andersen, 2005; Pullen et al., 2014; Saylor and Sundell, 2016), which reduces the probability of non-representation of small populations. For this reason, we note the presence of small populations, but they generally play no significant role in interpretations.

Initial sample comparisons were conducted using the Kolmogorov-Smirnov (K-S) test, which tests whether two samples are not from parent populations with the same distribution (see Gehrels, 2012; Saylor and Sundell, 2016). We also use multi-dimensional scaling (MDS), as outlined by Vermeesch (2013) and Vermeesch et al. (2016), to further differentiate samples that are likely similar or dissimilar in terms of their source terrain; MDS plots for each stratigraphic unit are included in the Supplemental File (see footnote 1). We use normalized kernel-density estimates (KDEs) to visualize DZ populations. Because of the large number of samples, we lump KDE curves for samples from each stratigraphic unit that are interpreted to represent the same paleodrainage axes, based on (1) close geographic proximity, (2) similar K-S statistics and/or clustering in MDS space, and (3) similar maximum depositional ages (see below); we assume that this approach emphasizes major trends but may sacrifice local variability. K-S statistics were calculated using Microsoft Excel macros from the Arizona Laserchron Center's collection of online analytical, which can be found through https://sites.google.com/a/laserchron.org/laserchron/, whereas normalized KDE and MDS plots were developed using scripts described by Vermeesch (2012, 2016) and available from http://www.ucl.ac.uk/~ucfbpve/provenance/.

Detrital-zircon data can provide geochronological control on deposition, due to the "law of detrital zircons" (Gehrels, 2014) where the youngest U-Pb age(s) in a sample population define a stratigraphic unit's maximum depositional age (MDA). MDAs may approximate true depositional age if there is contemporaneous volcanism and significant ash deposition within the contributing drainage basin, although zircons begin to crystallize in magma chambers

TABLE 2. SOURCES FOR SPECIFIC DETRITAL-ZIRCON POPULATIONS PRESENT IN GULF OF MEXICO COASTAL PLAIN CENOMANIAN, PALEOCENE, OLIGOCENE, AND MODERN FLUVIAL DEPOSITS

Population name	Age range	Primary protolith source (see map in Fig. 6)	Common geographic and stratigraphic sources for reworked population
Laramide and post-Laramide volcanics	80–0 Ma	U.S. Rocky Mountains, Great Basin, Mexican Sierra Madre Occidental	Possible reworking from ashfall blankets associated with volcanic centers
Mesozoic Western Cordillera	275–80 Ma	Mesozoic magmatic arc, Baja California and Sonora of Mexico, Sierra Nevada of California, Idaho	Mesozoic foreland-basin strata of the U.S. Western Interior
Paleozoic Appalachian (Taconic, Acadian, and Alleghanian orogens)	500–290 Ma	Appalachian-Ouachita cordillera	Paleozoic Appalachian-Ouachita foreland-basin strata, Paleozoic passive margin strata of the western U.S.
Neoproterozoic Peri-Gondwanan terranes, Iapetus Rift, Wichita Mountains	800–500 Ma	Gondwanan margin of the Appalachian-Ouachita cordillera, Wichita Mountains of Oklahoma	Appalachian-Ouachita foreland-basin strata, Paleozoic passive margin strata of the western U.S.
Mesoproterozoic Grenville	1250–950 Ma	Appalachian cordillera, extending into central and western Texas and northwestern Mexico	Paleozoic sandstones of the U.S. Midcontinent, Appalachian-Ouachita foreland-basin strata, Paleozoic passive margin strata of the western U.S.
Mesoproterozoic Midcontinent granite-rhyolite province	1550–1300 Ma	Northeast-southwest trend across the eastern U.S. Midcontinent, plus numerous intrusions into Yavapai-Mazatzal basement in the Rocky Mountains	Paleozoic sandstones of the U.S. Midcontinent, Appalachian-Ouachita foreland-basin strata, Paleozoic passive margin strata of the western U.S.
Paleoproterozoic Yavapai-Mazatzal orogens	1800–1600 Ma	Northeast-southwest trend across the central U.S. Midcontinent to the southwestern U.S., including the central and southern Laramide Rockies and the Mogollon Rim of central Arizona	Paleozoic passive margin strata of the western U.S.
Paleoproterozoic Penokean orogen	2000–1800 Ma	South-central Canada (Manitoba and Saskatchewan) and Great Lakes region of the U.S. (especially Wisconsin)	Common in low concentrations throughout the area, and in all stratigraphic units
Archean Superior and Wyoming provinces, others	>2500 Ma	Northern U.S. Midcontinent to present-day northern Rocky Mountains province	Common in low concentrations throughout the area, and in all stratigraphic units

Note: Summarized from Becker et al. (2005), Whitmeyer and Karlstrom (2007), Dickinson and Gehrels (2009a), Park et al. (2010), and Laskowski et al. (2013). Not all populations illustrated in Figure 6 are present in Gulf of Mexico samples, and are not included above.

10^4–10^6 yr before the actual eruption (e.g., Simon et al., 2008). On the other hand, MDAs may depart significantly from true depositional age if there is no contemporaneous volcanism within the drainage basin, because there is an inherent lag time between zircon crystallization in intrusive rocks, exhumation and erosion of those rocks, and entrainment of sediments in fluvial systems. Thomas et al. (2004) showed that Pennsylvanian–early Permian clastics within the Appalachian foreland contain Mississippian–Devonian and older DZs, which suggests that non-volcanogenic Pennsylvanian–early Permian protoliths had not yet been exhumed. More broadly, Cawood et al. (2012) argued that sediments derived from convergent margins with arc volcanism contain MDAs that are close to depositional age, whereas sediments in other tectonic settings may not.

For our study, Cenomanian strata of the GoM contain no grains younger than ca. 275 Ma. However, we report MDAs for Paleocene–early Eocene and Oligocene strata and use MDAs to constrain paleodrainage reconstruction by comparison with the distribution of syndepositional felsic and intermediate-composition volcanic rocks. MDAs are calculated from the weighted mean of the youngest suite of grains whose error terms overlap and are <10% of the calculated age (e.g., Dickinson and Gehrels, 2009b). We extract the distribution of radiometrically dated syndepositional volcanic rocks from the NAVDAT community database (http://navdat.org).

RESULTS

Modern Mississippi River Detrital-Zircon Signal

A full discussion of DZ signatures for modern GoM rivers is beyond the scope of this paper; we include KDE plots for all GoM modern river samples, as well as analytical data, in the associated Supplemental File (see footnote 1). Given the significance of the Mississippi River system, however, we summarize results from upstream to downstream along the modern river. These data illustrate downstream changes in DZ signatures due to major tributary inputs, as well as the composite signal of the Mississippi River as it enters the GoM sedimentary basin (Fig. 8).

The lower Mississippi River has a complex water and sediment delivery system because it derives a large portion of its water supply from the Ohio River, which drains the eastern U.S., whereas most sediment comes from the Missouri River, which drains the central and northern U.S. Rockies and Great Plains (Knox, 2007; Figs. 1 and 5). The upper Mississippi River upstream from the Missouri confluence is the least significant part of the system, when measured in terms of either water or sediment discharge.

The upper Mississippi River derives sediment from a low-relief north-central U.S. landscape underlain by Archean shield (including the Wyoming

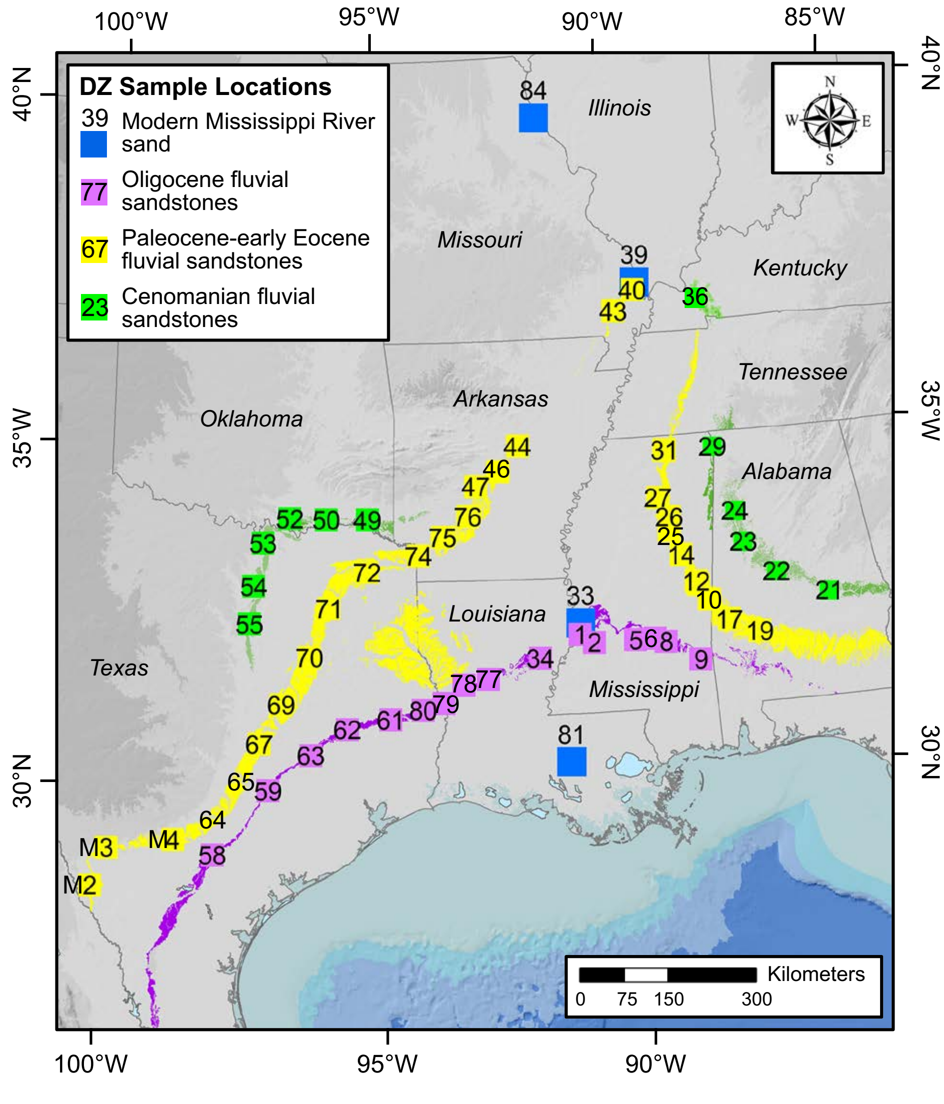


Figure 7. Locations of detrital-zircon (DZ) samples for the Cenomanian, Paleocene–early Eocene, and Oligocene fluvial sandstones of the northern Gulf of Mexico, superimposed on generalized maps of outcrop belts. DZ samples from the modern Mississippi River are shown as well. Paleocene–early Eocene samples, GoM-11 and GoM-13 are not shown because they are located too close to GoM-10 and GoM-12 to appear independently on this map, whereas samples designated with an M are from Mackey et al. (2012). Similarly, Oligocene samples GoM-3, GoM-4, and GoM-7 are not shown because they are located too close to GoM-5 and GoM-8 to appear independently on this map.

and Superior provinces), Proterozoic basement (including the Penokean orogen), Paleozoic sedimentary rocks, and Neogene glacial deposits. The DZ signal of the upper Mississippi River is dominated by Grenville (~35%) and shield (~25% each) ages; midcontinent, Western Cordillera, and Penokean–Trans Hudson ages represent ~8% each, and minor constituents include zircons of Appalachian and Yavapai-Mazatzal affinity. The shield signature is readily accounted for by Archean Superior province rocks exposed in the Mississippi River headwaters, whereas the Grenville signature is likely recycled from midcontinent Lower Paleozoic quartz arenites (Konstantinou et al., 2014).

The middle Mississippi River is defined here as below the Missouri confluence but above the Ohio River; the Missouri is the longest single river in North America and the largest Mississippi tributary by contributing area (see Fig. 5). Sediment for the Missouri River is derived from the central and northern Rockies and the northern and central Great Plains, which includes Proterozoic

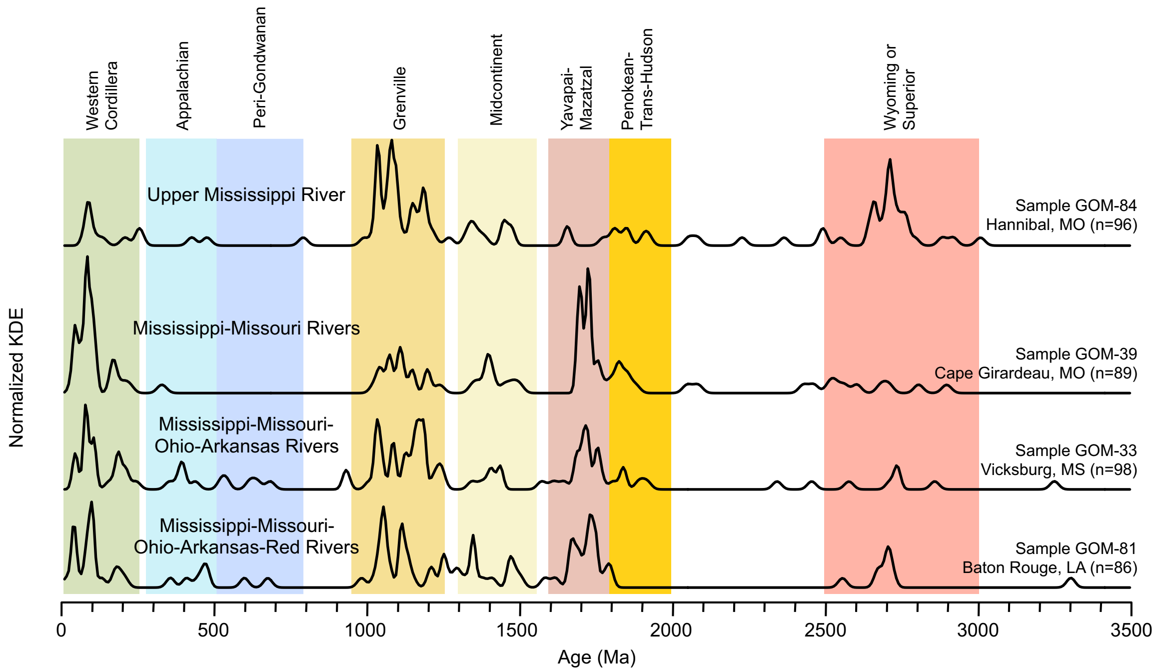


Figure 8. Normalized kernel-density estimate (KDE) plots of detrital-zircon (DZ) populations for the modern Mississippi River, illustrating upstream to downstream changes in DZ signals. The lower plot represents the lower Mississippi River below all major tributaries, and illustrates the composite nature of a DZ population derived from a continental-scale drainage basin (see also Iizuka et al., 2005). DZ source terrains are shown in Figure 6; sample locations are shown in Figure 7. Data plotted using software in Vermeesch (2016). MO—Missouri; MS—Mississippi; LA—Louisiana.

basement, Mesozoic foreland basin clastics, and Neogene glacial deposits. Here, the Grenville signal is muted by an influx of zircons that were ultimately derived from the Cordilleran magmatic arc and Yavapai-Mazatzal basement exposed in Laramide uplifts. The modern Missouri River does not drain Cordilleran arc terrain, hence this signal is likely recycled from Cretaceous foreland-basin strata, which contain significant proportions of arc-derived grains (e.g., May et al., 2013; Painter et al., 2014).

The lower Mississippi River starts at the Ohio River confluence; the Ohio system, including the Tennessee and Cumberland Rivers, contributes sediment from the Appalachian cordillera and foreland basin to the east. The Arkansas and Red Rivers join farther downstream and contribute sediment from the central and southern Rockies and Great Plains to the west, as well as the Ouachita Mountains in Arkansas and Oklahoma. The Ohio system adds the coupled Appalachian-Grenville DZ signature to the Mississippi sediment load, whereas the Arkansas and Red Rivers complement the western signal already introduced by the Missouri River, and add additional Appalachian-Grenville signals from erosion of Mississippian–Pennsylvanian strata in the Ouachita Mountains (e.g., Shaulis et al., 2012). Samples from the lower Mississippi River therefore represent the composite Mississippi system (see also Iizuka et al., 2005; Wang et al., 2009).

From these data, the lower Mississippi River DZ population faithfully records source terrains within a continental-scale drainage basin. Downstream trends illustrate the significance of large tributary inputs, and all major zircon age populations within the southern half of North America are present where the Mississippi River enters the GoM depositional basin in southern Louisiana. The dominance of the Missouri River as a sediment source is faithfully recorded by the dominant DZ signatures from the western U.S., including the midcontinent granite-rhyolite and Yavapai-Mazatzal signatures from Laramide uplifts of the Rockies, the Mesozoic Cordilleran arc, and Cenozoic volcanic terrains. By contrast, the Ohio River tributary contributes the Appalachian-Grenville signature, characteristic of the eastern U.S. since the late Paleozoic (e.g., Eriksson et al., 2004; Becker et al., 2005; Park et al., 2010; Weislogel et al., 2015). As shown by Fildani et al. (2016), the late Pleistocene Mississippi fan in the deep GoM has a DZ signature that faithfully represents the Mississippi drainage as a whole and illustrates a close coupling between source and sink.

Gulf of Mexico Detrital-Zircon Record

Cenomanian Tuscaloosa-Woodbine Trend

Cenomanian fluvial deposits of the GoM coastal plain represent the routing system for the first significant delivery of sediments to the deepwater GoM (Galloway, 2008), the updip component of the Eagle Ford–Tuscaloosa supersequence of Snedden et al. (2016). Cenomanian deposition took place within a paleogeographic context that included the Paleozoic Appalachian-Ouachita cordillera in the eastern and southeastern U.S. (Thomas, 1991), a Mesozoic magmatic arc along the western North American continental margin, and the associated Sevier fold-and-thrust belt with a retroarc foreland basin in the U.S. western interior (DeCelles, 2004; Fig. 9). Moreover, the Western Interior Seaway connected the GoM to the Boreal Sea at times of maximum flooding and split North America into distinct eastern and western landmasses that have been referred to as Appalachia and Laramidia (e.g., Gates et al., 2010).

Cenomanian fluvial deposits in Alabama and Mississippi are referred to as the Tuscaloosa Group, and basal fluvial sandstones are referred to as the Coker Formation (Mancini, 1988), which rests unconformably on Paleozoic strata. In Arkansas, Oklahoma, and Texas, the same trend is referred to as the Woodbine Group: basal fluvial sandstones rest on older Cretaceous rocks and are referred to as the Dexter Formation. Mancini and Puckett (2002, 2005), Mancini et al. (2008), and Woolf (2012) discussed the subsurface Tuscaloosa in Mississippi and Louisiana, whereas Oliver (1971), Ambrose et al. (2009), and Adams and Carr (2010), among others, discussed the Woodbine in east Texas. Olson

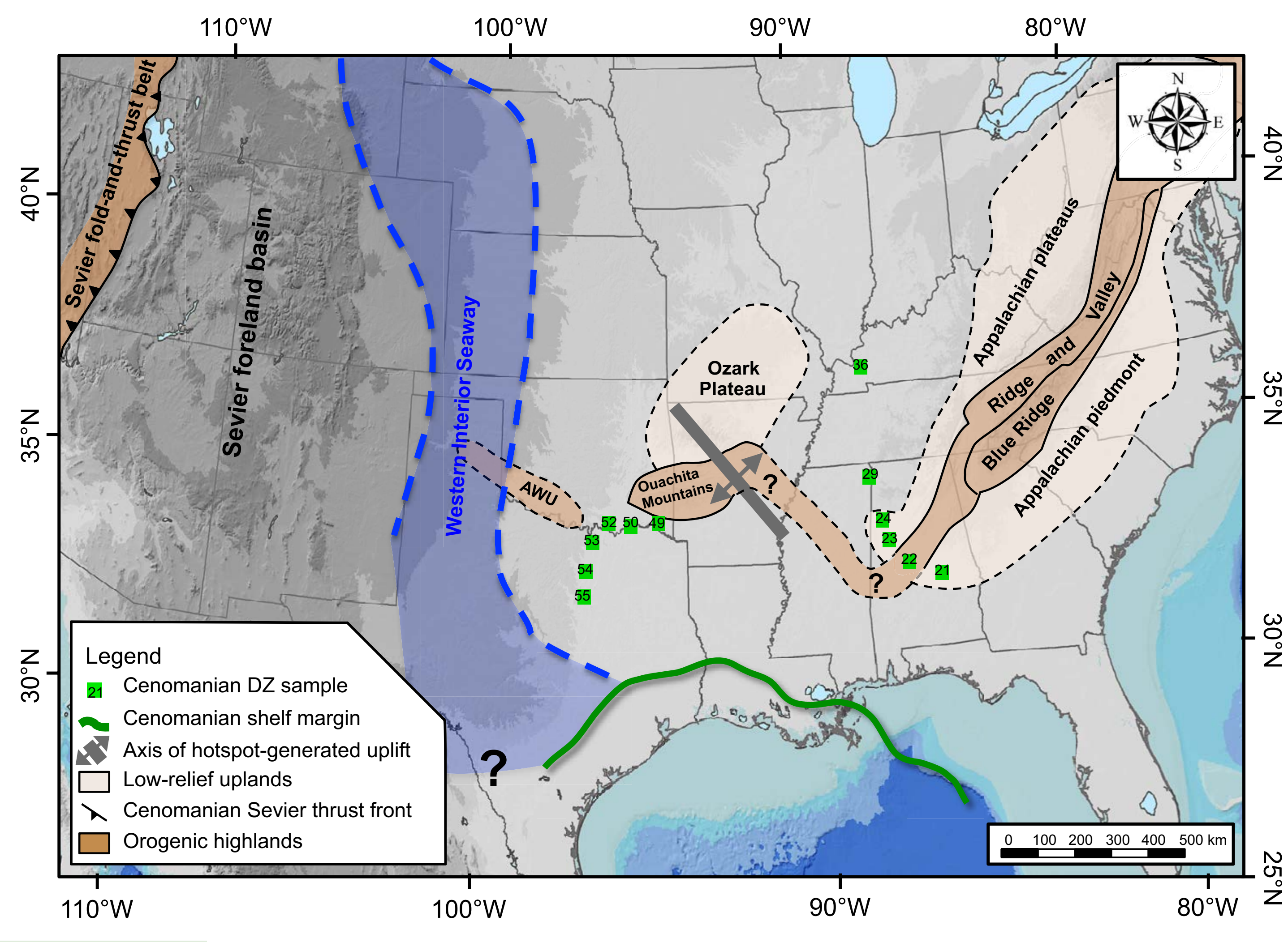


Figure 9. Cenomanian tectonic and physiographic features of significance to this paper. The Cenomanian position of the Sevier fold-and-thrust belt and foreland basin is based on DeCelles (2004); the location of Appalachian cordillera and possible inferred links with the Ouachita Mountains (dashed lines) are based on Thomas (1991), whereas the axis of presumed hot-spot driven uplift is based on Cox and Van Arsdale (2002). The Cenomanian Gulf of Mexico shelf margin is based on Galloway (2008). AWU—Amarillo-Wichita uplift; DZ—detrital zircon.

et al. (2015) placed the base of the Eagle Ford–Tuscaloosa supersequence at ca. 96 Ma. Twelve DZ samples were collected to characterize the Tuscaloosa-Woodbine outcrop belt from Alabama to Texas (Fig. 7).

Tuscaloosa samples from Alabama (GOM-21 through GOM-24) were collected from medium- to fine-grained fluvial sandstones, whereas samples GOM-29, collected in northeastern Mississippi, and GOM-36, collected in northwestern Kentucky, were conglomeratic. Like pre-Cretaceous fluvial deposits derived from the Appalachians (e.g., Eriksson et al., 2003, 2004; Moecher and Samson, 2006; Becker et al., 2005; Park et al., 2010; Blum and Pecha, 2014; Weislogel et al., 2015), Tuscaloosa samples are dominated by Grenville ages, which compose 50%–80% of the total, whereas Appalachian and peri-Gondwanan ages compose ~30% of zircons in the southernmost sample GOM-21 and <12% in samples farther north in Alabama and northeastern Mississippi; sample GOM-36 has no Appalachian grains and one peri-Gondwanan grain only. We also observe minor populations (<5% each) ultimately derived from the midcontinent granite-rhyolite province. K-S statistics and MDS plots indicate that samples GOM-22 through GOM-24 and GOM-29 are statistically indistinguishable and similar, respectively, but distinct from GOM-21 to the south, due to the higher percentage of Appalachian ages, and clearly distinct from GOM-36.

Woodbine outcrops occur through southwestern Arkansas, southeastern Oklahoma, and north-central Texas (Fig. 7), to the south and west of the Ouachita Mountains and the Wichita Mountains; outcrops in Arkansas are cherty conglomerates with a muddy matrix and are sand poor, hence sampling for DZs was restricted to sand-rich outcrops from Oklahoma and Texas. Like the Tuscaloosa samples, Woodbine DZ samples are dominated by Grenville ages (~50%), with Appalachian ages composing up to 15% of the population, but the peri-Gondwanan component is more prominent, composing up to 10%. Additional age clusters are consistent with ultimate derivation from the midcontinent (1500–1300 Ma), Yavapai-Mazatzal (1800–1600 Ma), Penokean (2000–1800 Ma), and Superior or Wyoming craton (>2500 Ma) sources. K-S statistics and MDS plots indicate that Woodbine samples in Oklahoma and Texas are mostly statistically indistinguishable and similar, respectively, and related to Tuscaloosa samples in Alabama. However, the increased representation of peri-Gondwanan ages, and ages that represent the broader midcontinent region, is likely derived from Mississippian and Pennsylvanian strata of the Ouachita fold-and-thrust belt (Shaulis et al., 2012). Woodbine strata are interpreted to reflect recycling of those deposits.

Figure 9 summarizes the paleogeographic setting for Tuscaloosa-Woodbine deposition, whereas Figures 10 and 11 summarize Tuscaloosa-Woodbine DZ signatures across the northern GoM. The first-order observation is the complete lack of grains younger than ca. 292 Ma. Hence, there was no connection between Cenomanian drainage in the GoM and the western U.S., where Mesozoic-age zircons from the Western Cordillera are common in Cretaceous sandstones as a whole (e.g., Laskowski et al., 2013), including the Albian–Cenomanian Dakota Group exposed in the central Laramide Rockies in Colorado (Blum et al., 2016). Similarly, Tuscaloosa-Woodbine fluvial systems did not extend headward into the continental interior, north and west of the Appalachian-Ouachita cordillera, because paleoflow indicators and DZ data from Albian–Cenomanian Dakota sandstones of the midcontinent indicate paleoflow to the west (Witzke and Ludvigson, 1996; Brenner et al., 2000; Joeckel et al., 2005; Finzel, 2014; Blum et al., 2016). In short, fluvial deposits exposed in the Rockies and the midcontinent represent Albian–Cenomanian sediment transport to the western and eastern

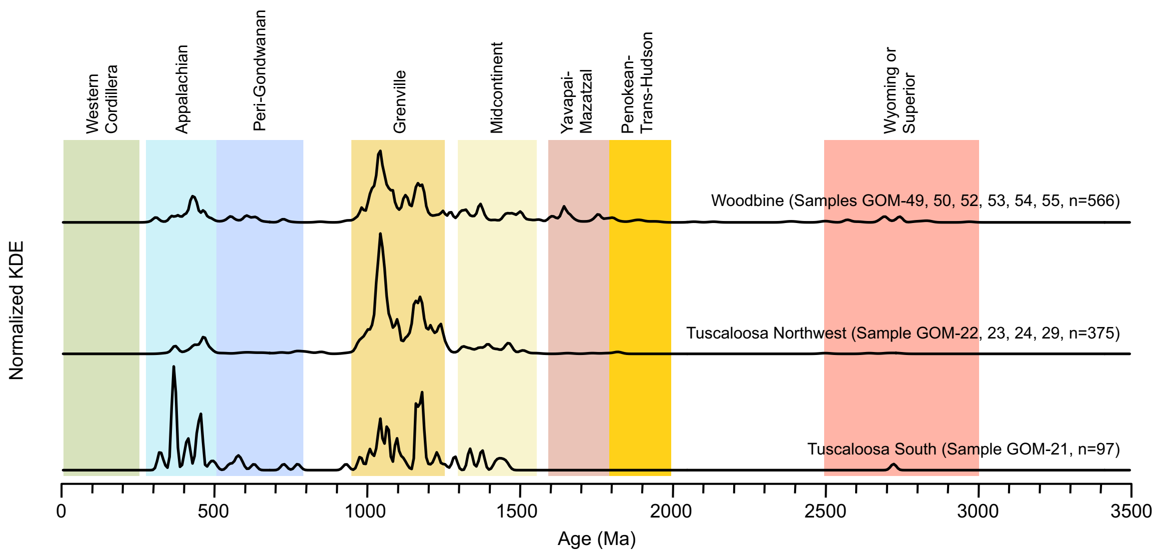


Figure 10. Normalized kernel-density estimate (KDE) plots of detrital-zircon populations for the Cenomanian Tuscaloosa-Woodbine trend. Sample locations shown in Figures 7 and 9. Note that the Tuscaloosa south plot represents a single sample, which was distinct from the others. Tuscaloosa northwest and Woodbine plots represent multiple individual samples lumped together on the basis of Kolmogorov-Smirnov statistics, multidimensional scaling plots, and geographic proximity. n = number of U-Pb ages.

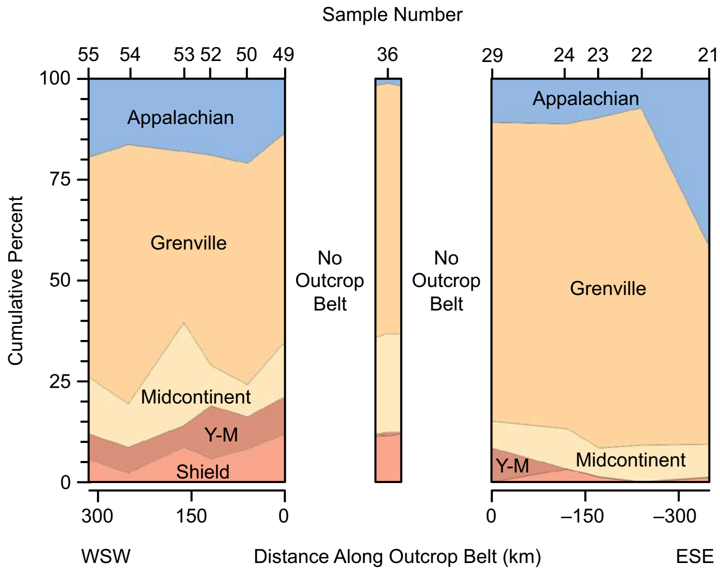


Figure 11. Trends in Cenomanian detrital-zircon populations across the northern Gulf of Mexico margin, illustrating spatial changes in percent contributions of different populations. Note that sample numbers are illustrated on the upper *x*-axis, but the diagram is scaled to distance along the outcrop belt on the lower *x*-axis. No distances are given for sample GOM-36, which is to the north of the Appalachian-Ouachita cordillera, because there are no outcrops between this sample and the others. Zero starts at the easternmost sample for the Woodbine samples on the left, and at the westernmost sample for Tuscaloosa samples on the right, where distances are shown as negative numbers. Appalachian includes peri-Gondwanan component with ages between 800–500 Ma. Y-M—Yavapai-Mazatzal.

margins of the Western Interior Seaway, respectively. With the exception of sample GOM-36, our samples show that Cenomanian Tuscaloosa-Woodbine fluvial systems flowed to the northern GoM margin, with source terrains restricted to the central and southern Appalachian-Ouachita cordillera.

Paleocene–Early Eocene Wilcox Trend

The Wilcox Group is known from outcrop and subsurface studies in Texas, Louisiana, Mississippi, and Alabama where fluvial, deltaic, and shallow-marine facies are significant oil and gas reservoirs (e.g., Fisher and McGowen, 1969; Galloway, 1968; Edwards, 1981). Biostratigraphic data indicate that the onshore Wilcox Group of Texas is Paleocene to early Eocene in age, deposited ca. 61–49.5 Ma (Crabaugh, 2001; Brown and Loucks, 2009). Starting in 2001, Wilcox basin-floor fans were recognized in the deepwater GoM, ~400 km from coeval deltaic strata in south Texas (Meyer et al., 2007; Zarra, 2007); Wilcox deepwater deposits are >1000 m thick, with sand-to-shale ratios of 40%–70% and a paucity of thick interbedded shales.

Wilcox deposition occurred within a broader context defined by the Paleozoic Appalachian-Ouachita cordillera in the eastern and southeastern U.S., a Mesozoic Western Cordillera where the Sevier fold-and-thrust belt was no longer active but arc magmatism had produced extensive sources for Mesozoic zircon populations, and where Laramide deformation (ca. 80–50 Ma) had segmented the Sevier foreland-basin system into discrete uplifts and basins (DeCelles, 2004; Heller and Liu, 2016). Magmatic activity associated with Laramide deformation produced areally extensive sources for zircon populations of that age as well, including felsic volcanic activity of Paleocene and earliest Eocene age (Fig. 12). Moreover, Wilcox deposition occurred under global "greenhouse" conditions, with minimal ice volumes and glacio-eustasy, and globally high sea level (e.g., Zachos et al., 2001).

There has been a multidecadal discussion of Wilcox source terrain, with some authors preferring Appalachian sources and others interpreting source terrains in the Laramide Rockies (see Mackey et al., 2012). Winker's (1982) early reconstruction of Wilcox drainage in Texas emphasized source terrains in the central and southern Laramide Rockies (Fig. 4), whereas Potochnik (2001) suggested that the western GoM would have received sediment from the Cordilleran fold-and-thrust belt and the Mogollon highlands of Utah and Arizona. Galloway et al. (2011) interpreted Appalachian and western-fed axes of sediment input, much like for the modern GoM, and noted that the Paleocene component of the Wilcox represents the highest rates of sediment influx to the GoM prior to the Plio-Pleistocene Mississippi system.

The Mackey et al. (2012) study focused on Wilcox strata of southern Texas, whereas Craddock and Kylander-Clark (2013) reported DZ results from the Sabine uplift of eastern Texas and western Louisiana, and a recent study by Wahl et al. (2016) presents Paleocene through Eocene DZ data from locations that overlap with those presented here. Our research collected samples from the outcrop belt across Texas to Arkansas, southern Missouri, Mississippi, and westernmost Alabama (Fig. 7), to the east and north of the Mackey et al. (2012) sampling area. To the west and north, fluvial sandstones that rest on Paleocene Midway Group mudstone are referred to as different members of the Wilcox (see Wahl et al. [2016] for a recent summary), whereas in Alabama and Mississippi, fluvial sandstones in the same stratigraphic position rest on the Midway-equivalent Porters Creek Formation mudstone and are referred to as the Naheola Formation. Twenty-six samples were collected, with a total of >2550 ^{238}U-^{206}Pb or ^{207}Pb-^{206}Pb ages. K-S statistics, MDS plots, geographic proximity, and MDAs permit discrimination of fluvial axes, around which the discussion below is organized. These data were initially discussed by Blum and Pecha (2014) in the context of Late Cretaceous through Paleocene continental-scale drainage reorganization, with the actual data released to http://geochron.org, but they are further elaborated on here.

Figures 13 and 14 summarize the Paleocene DZ record as a whole, whereas Figure 15 presents MDAs for different Wilcox axes. To begin, Wilcox samples from west-central Alabama to north-central Mississippi (samples GOM-10 through GOM-14, GOM-17, GOM-19, GOM-25, and GOM-26) are statistically indistinct from Cenomanian Tuscaloosa samples in Alabama, with an

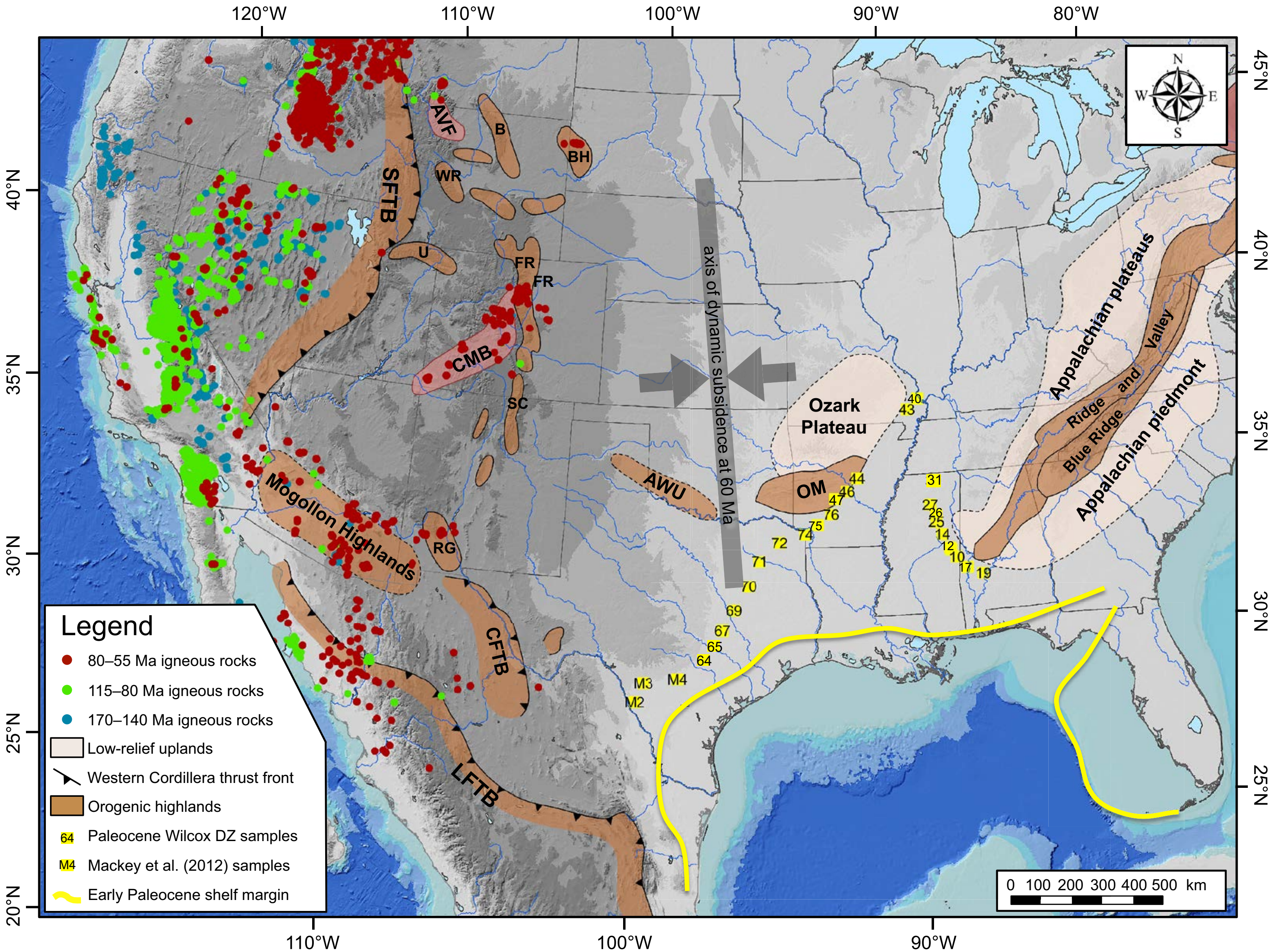


Figure 12. Paleocene tectonic and physiographic features of significance to this paper. Abbreviations: SFTB—Sevier fold-and-thrust belt; LFTB—Laramide fold-and-thrust belt; CFTB—Chihuahua-Coahuila fold-and-thrust belt; AVF—Absaroka volcanics; CMB—Colorado Mineral Belt; BH—Black Hills; B—Bighorn Mountains; WR—Wind River Mountains; U—Uinta Mountains; FR—Colorado Front Range; SC—Sangre de Cristo Mountains; RG—Rio Grande uplift; AWU—Amarillo-Wichita uplift; OM—Ouachita Mountains; DZ—detrital zircon. Based largely on Galloway et al. (2011). Also shown is the modeled axis of dynamic subsidence from Liu (2015). The distribution of igneous rocks of different age is based the NAVDAT database (http://navdat.org) and includes felsic and intermediate plutonic and volcanic rocks that have been radiometrically dated for discrete intervals through the Paleocene–earliest Eocene. These data represent the possible protolith sources for Mesozoic- and Cenozoic-age zircons in samples from the Paleocene–early Eocene Wilcox unit. For maps of volcanic zircons that represent sources for grains that produce maximum depositional ages, see Figure 15.

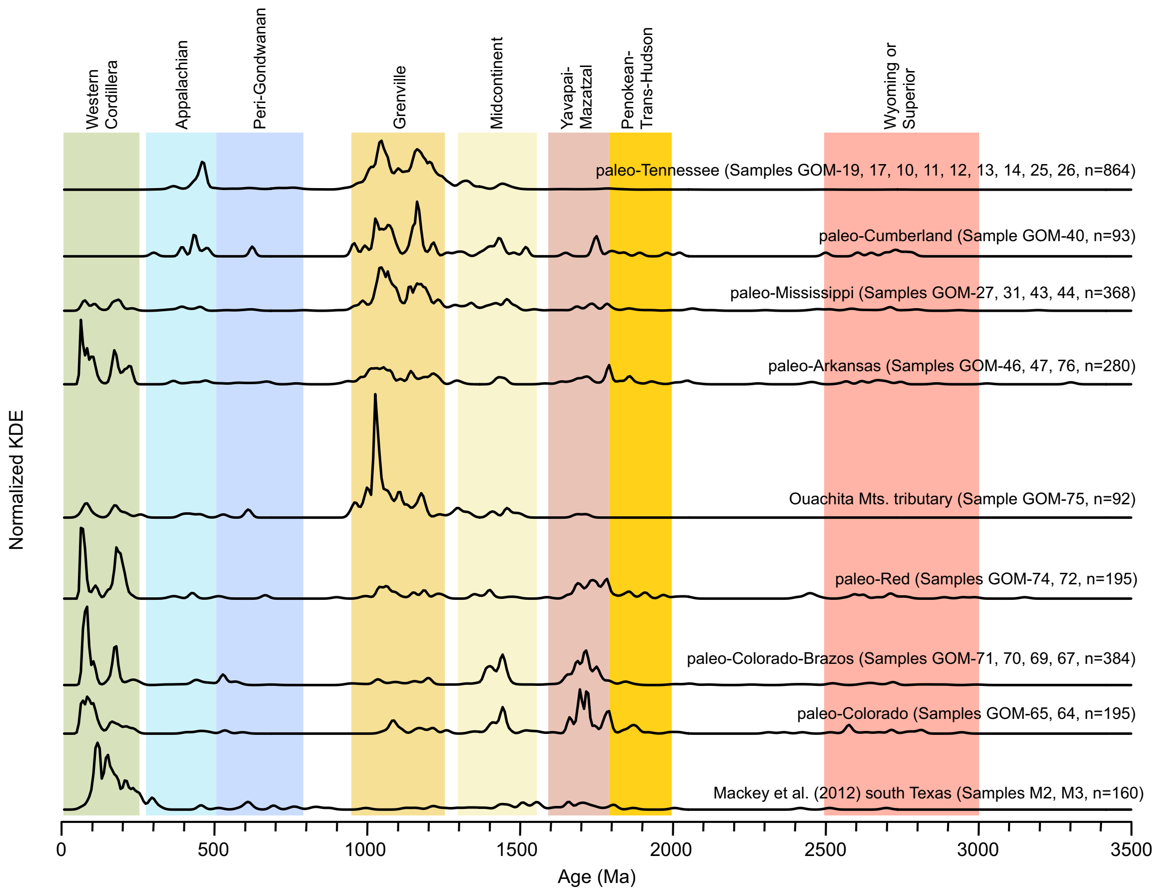


Figure 13. Normalized kernel-density estimate (KDE) plots of detrital-zircon populations for the Paleocene Wilcox trend. Sample locations are shown in Figures 7 and 12. Most plots represent multiple individual samples lumped together on the basis of Kolmogorov-Smirnov statistics, multi-dimensional scaling plots, geographic proximity, and maximum depositional ages (see Fig. 15). Samples labeled as paleo-Cumberland and Ouachita Mountains tributary represent single samples that were distinct from others in the vicinity. n = number of U-Pb pages.

unambiguous Appalachian cordillera signal, where Appalachian-Grenville ages compose up to 80% of the total population. Additional minor populations reflect derivation from peri-Gondwanan terranes associated with Appalachian assembly and from the midcontinent granite-rhyolite province. As was the case for Cenomanian Tuscaloosa samples in this area, Wilcox samples from west-central Alabama to north-central Mississippi are interpreted to represent the paleo-Tennessee drainage.

Beginning in the northern Mississippi embayment of north-central Mississippi (samples GOM-27 and GOM-31), southern Missouri (GOM-43), and central Arkansas (GOM-44), clear differences in Wilcox DZ signatures begin to emerge from east to west across the outcrop belt. Here, up to 12% of the population produced ages <275 Ma, derived from the Mesozoic Cordilleran arc and the latest Cretaceous through Paleocene volcanic terrains of the western U.S., and there are increased Yavapai-Mazatzal contributions. Even with this western signature, however, Grenville ages compose 40%–60% of the total, and the broader signal of the Appalachian cordillera (Appalachian, peri-Gondwanan, and Grenville ages) comprises 50%–75% of the total. The small number of grains from the Cordilleran arc can perhaps be explained by reworking of Jurassic and Cretaceous strata of the Sevier foreland basin (see May et al., 2013; Painter et al., 2014), but ~1% of all grains produced Paleocene ages, which indicate that the drainage must have extended westward far enough to include ashfall from eruptive centers in the Laramide Rockies. These samples are therefore interpreted to represent an ancestral Mississippi course with headwaters in the central U.S. and perhaps the central and northern Rockies. By contrast, sample GOM-40, from southern Missouri near the present Ohio-Mississippi confluence, is located in the middle of this Missis-

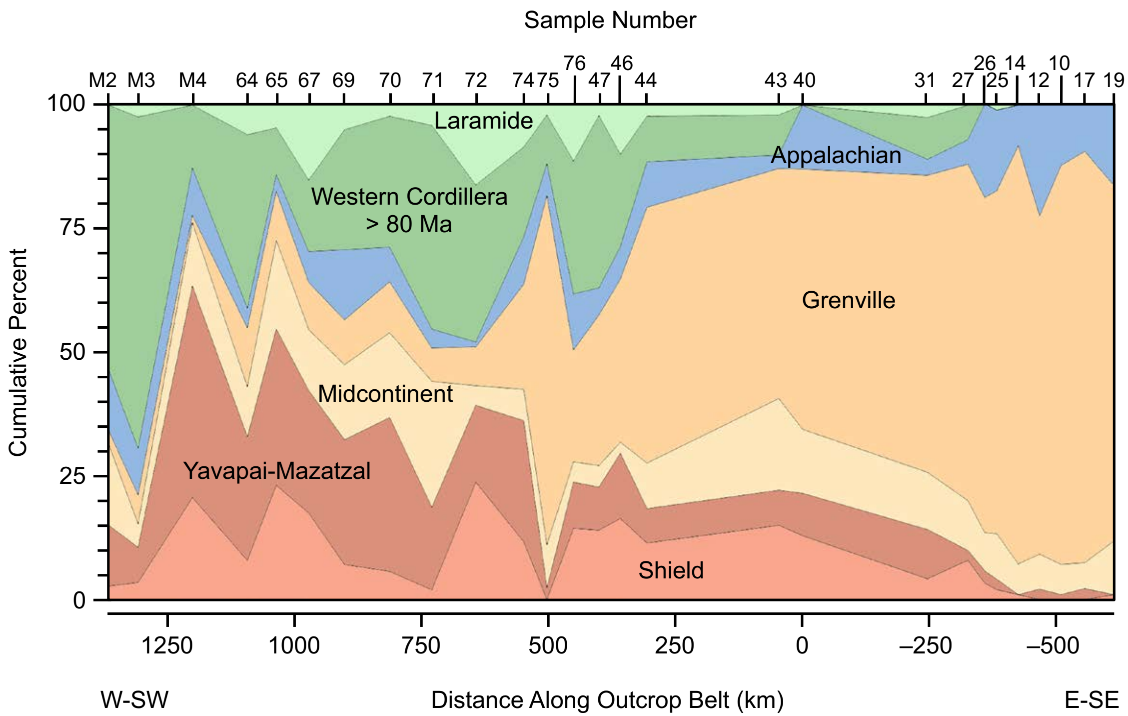


Figure 14. Trends in Paleocene detrital-zircon populations across the northern Gulf of Mexico margin, illustrating spatial changes in percent contributions of different populations. Note that sample numbers are illustrated on the upper *x*-axis, but the diagram is scaled to distance along the outcrop belt on the lower *x*-axis, with zero starting at sample GOM-40 and measured southeast (negative numbers) and southwest from there.

sippi embayment suite but displays a typical Appalachian-Grenville population with no western-source zircons. GOM-40 is interpreted to represent an eastern tributary, perhaps an ancestral Cumberland or Ohio River, which drained what is now part of the Ohio system.

Samples GOM-46, GOM-47, and GOM-76 were collected from south-central to west-central Arkansas, south of the present Arkansas River and southeast of the Ouachita Mountains (see Fig. 7). Here, the Wilcox outcrop belt appears to be a terrace that abuts an ancient bluff line cut into the Ouachitas, which defines the western margin of the Mississippi embayment. Some 25%–35% of the DZ population is derived from the Mesozoic arc and latest Cretaceous through Paleocene volcanics of the western U.S., including up to 10% zircons with Paleocene ages that were likely derived from the Colorado Mineral Belt in the central Laramide Rocky Mountains (e.g., Chapin, 2012). Each sample also contains a prominent suite from the Archean shield (>2500 Ma) and reduced proportions of grains from Appalachian-Grenville sources (<35%). We interpret these samples to represent an ancestral Arkansas River with headwaters that included the central Laramide Rockies, similar to the modern Arkansas and South Platte Rivers, and that entered the Mississippi embayment near the present-day Arkansas River course. This sample set is similar to results presented by Craddock and Kylander-Clark (2013) for samples farther south in Louisiana, and is bounded on the west by sample GOM-75, which is again dominated by the Appalachian-Grenville suite, with very small contributions from western sources; GOM-75 is interpreted to represent tributary contributions derived from the Ouachitas and older Mesozoic strata, and a drainage divide between fluvial systems represented by GOM-46, GOM-47, and GOM-76, discussed above, and by samples described below.

Samples GOM-74, GOM-72 through GOM-69, GOM-67, GOM-65, and GOM-64, collected from the outcrop belt in northeast to central Texas, display increased contributions from the Mesozoic arc and latest Cretaceous through Paleocene volcanics in the western U.S. (up to 45%), decreased Appalachian-Grenville signatures (<20%), and significant increases in midcontinent and Yavapai-Mazatzal ages (up to 50% of total). Moreover, these samples contain significant numbers of zircons with Paleocene ages, in some cases >15% of the total population, which again suggests derivation from the Colorado Mineral Belt of the south and central Rockies and/or, in this case, the Laramide magmatic arc in south-central Arizona and northwestern Mexico (e.g., McDowell et al., 2001; Ferrari et al., 2007; Ramos-Velázquez et al., 2008). The geographic source for Yavapai-Mazatzal ages is most likely the basement-cored Laramide uplifts of the central and southern Rockies, and the Mogollon Rim of south-central Arizona (Jacobson et al., 2011). We interpret these samples to represent

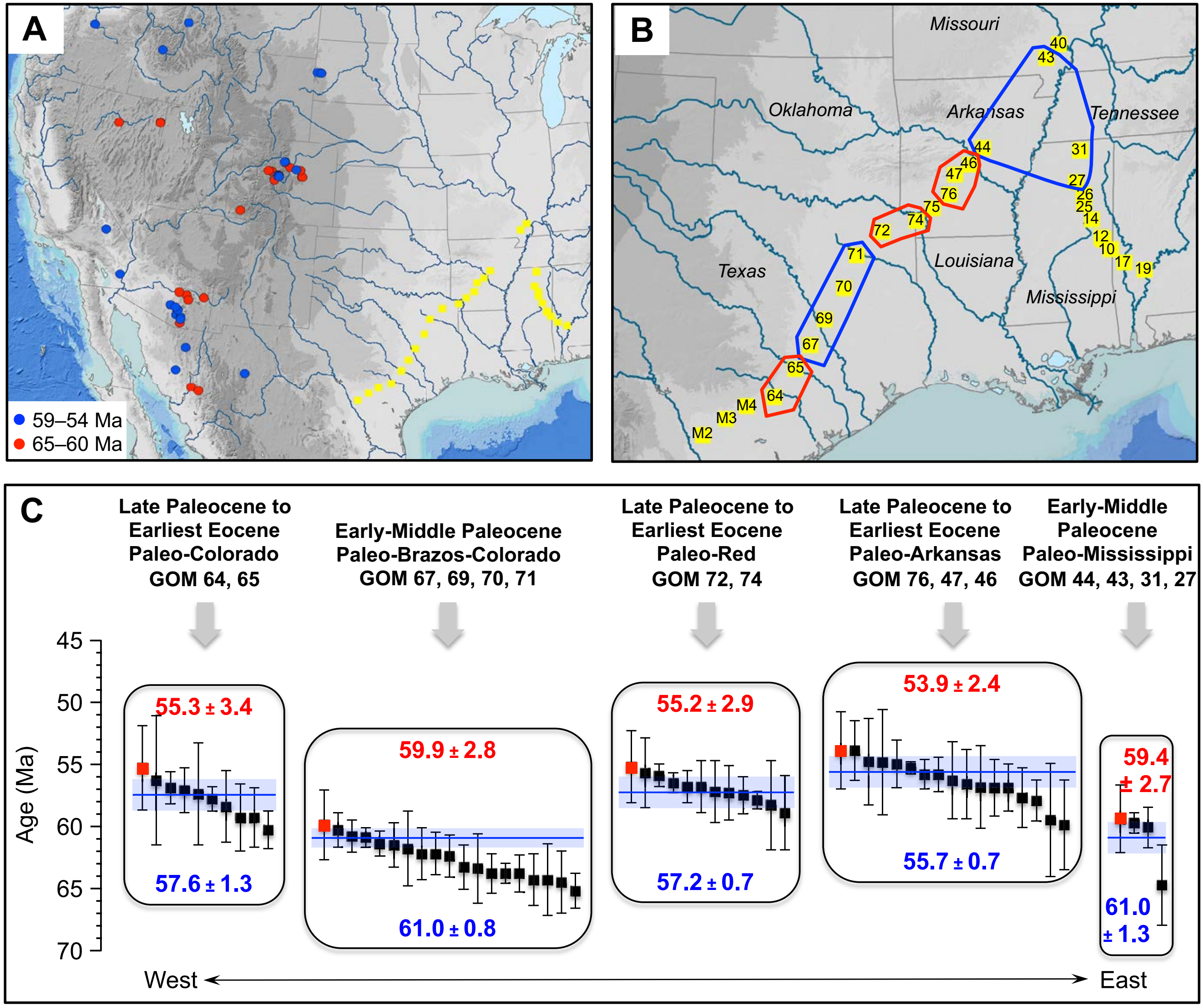


Figure 15. (A) Locations of radiometrically dated volcanic rocks of early–middle Paleocene age (red dots) and late Paleocene–earliest Eocene age (blue dots) from the NAVDAT community database (http://navdat.org), and locations of the Wilcox outcrop belt samples discussed herein (yellow). (B) Map view of sample clusters with statistically equivalent maximum depositional ages (MDAs). Blue polygons represent early–middle Paleocene, red polygons represent late Paleocene–earliest Eocene axes, whereas samples outside of these polygons had no MDAs. (C) MDAs for primary early–middle Paleocene and latest Paleocene–earliest Eocene fluvial axes, with sample numbers, as shown. Blue lettering represents calculated MDAs (in Ma), blue line represents MDAs, and blue box defines the weighted error. Red lettering and solid red box represent the youngest grain. Locations of sample clusters are shown in B.

fluvial systems that entered the GoM in positions similar to those of the modern Brazos and Colorado Rivers, and to represent the axial river systems for what has been referred to as the Rockdale delta system: headwaters extended from the Laramide Rockies of Colorado and New Mexico to the Mogollon Rim and volcanic terrain of central and south-central Arizona, and may have included the Sierra Nevada arc of southern California as well (see below).

Mesozoic arc-related ages. Jurassic and Cretaceous DZ populations in samples from the Wilcox outcrop belt in Arkansas and Texas deserve special consideration. Most notably, all samples from the Wilcox outcrop belt in west-central Arkansas to south-central Texas display concentrations of ages typical of the Late Jurassic to Early Cretaceous (ca. 170–140 Ma) and mid- to Late Cretaceous (ca. 115–80 Ma) periods of high magmatic flux in the Sierra Nevada (e.g., Ducea, 2001; Ducea and Barton, 2007; DeCelles et al., 2009; Laskowski et al., 2013; see Fig. 12). However, these samples lack U-Pb ages from the Early Cretaceous magmatic lull (ca. 140–115 Ma; Armstrong and Ward, 1993) in the U.S. part of the Cordilleran arc.

The simplest interpretation for the Mesozoic arc signature in Wilcox sediments of Arkansas and especially Texas would be that GoM Paleocene rivers drained the southern Californian and Mexican portions of the Cordilleran magmatic arc or, at the very least, ashfall blankets derived from the arc. However, this part of the Paleocene landscape has been claimed by a number of authors as a source terrain for river systems that flowed northeast to Utah (e.g., the California River of Davis et al. [2010]; see discussion below) or flowed west to the backarc basin in California (e.g., Sharman et al., 2015). An alternative end-member interpretation would be that the Wilcox arc signature is simply reworked from Cretaceous foreland-basin sediments, which contain an abundance of this population. However, this explanation is unsatisfactory because Late Cretaceous strata of the southwestern U.S. contain large populations of reworked Appalachian-Grenville grains, in addition to the arc signature (e.g., Dickinson and Gehrels, 2008; Szwarc et al., 2015; Laskowski et al., 2013), something that is not significant in Wilcox strata of Texas. For this reason, we favor a direct connection between Wilcox rivers and the magmatic arc in southeastern California, southwestern Arizona, and northwestern Mexico, or, at the very least, with the proximal fallout area for arc-derived volcanic ash.

Comparison of Gulf of Mexico Paleocene Wilcox data with previously published data. The Mackey et al. (2012) samples from southwestern Texas were collected from Paleocene lower Wilcox and early Eocene upper Wilcox strata, and from outcrops and core (see Fig. 7). They interpreted DZ populations to be derived from basement uplifts of the southern Rocky Mountains and northern Mexico, the Cordilleran magmatic arc, and inland magmatic centers of northern Mexico. Their samples from the lower Wilcox outcrop belt of southwestern Texas are stratigraphically equivalent to samples reported here, but their DZ populations are statistically distinct. Most significantly, >5% of U-Pb ages in the three lower Wilcox outcrop samples of Mackey et al. (2012) lie between ca. 140 and 115 Ma, which corresponds to the Early Cretaceous magmatic lull in the western U.S. (Armstrong and Ward, 1993). By contrast, this population occurs within the Sevier La Popa foreland-basin fill of northern Mexico and may be derived from the Peninsular Ranges batholith and Alisitos arc in northwest Mexico (see Lawton et al., 2009); for this reason, Blum and Pecha (2014) interpreted the presence of this Early Cretaceous population to indicate that the southern Texas part of the Wilcox outcrop belt reflects a source terrain that was restricted to northwestern Mexico, an interpretation continued here.

Craddock and Kylander-Clark (2013) reported on two Paleocene–Eocene Wilcox samples from western Louisiana, south of the outcrop belt sampled for our study, and interpreted the results to represent the ancestral Mississippi system. Their samples are statistically distinct from all of our samples within the northern Mississippi embayment (GOM-27, GOM-31, GOM-40, GOM-43, and GOM-44) north of the Arkansas River, but closely resemble GOM-46, GOM-47, and GOM-76 from west-central Arkansas. We interpret the Craddock and Kylander-Clark (2013) samples to represent fluvial systems that joined an ancestral Mississippi River within the southern Mississippi embayment and delivered sediment to the downdip ancestral Mississippi “Holly Springs” depocenter (e.g., Galloway, 1968; Fisher and McGowen, 1969; Tye et al., 1991; Galloway et al., 2011) but also to reflect tributary rivers that drained the central Rockies, similar to the modern Platte and/or Arkansas Rivers (see paleodrainage discussion below).

Wahl et al. (2016) presented DZ data from Paleocene Midway, Paleocene to early Eocene Wilcox, and middle Eocene Queen City Formation strata (see Fig. 3) of east-central Texas, in areas along the outcrop belt proximal to our samples GOM-65, GOM-67, and GOM-69 through GOM-71. Similar to Blum and Pecha (2014), they restricted the Mackey et al. (2012) southern Texas Wilcox samples to source terrains in northwest Mexico through southern Arizona because of the presence of the Early Cretaceous ages common to the Alisitos arc; key elements of their interpretation of Wilcox samples from east-central Texas include drainage of the central and southern Laramide Rockies and derivation of Paleocene-aged grains in the Wilcox from newly unroofed Paleocene plutons of the Colorado Mineral Belt. Wahl et al. (2016) therefore did not include a large drainage area that extends to the U.S. portion of the magmatic arc for Wilcox group strata of east-central Texas, in contrast to arguments presented by Blum and Pecha (2014) and elaborated on below. We also question whether it is possible to exhume the plutonic core of the Colorado Mineral Belt in such a short time period, and note below that there are volcanic sources that have been defined in those same areas.

Maximum depositional ages. Samples from east of the Mississippi embayment contain no Mesozoic or younger zircons, whereas samples from the Mississippi embayment and farther west contain significant numbers of Paleocene and earliest Eocene U-Pb ages. From the http://navdat.org database, the most likely source for grains of this age would be the volcanic centers and associated ashfall blankets of the Colorado Mineral Belt (e.g., Chapin, 2012) and/or the Sonoran part of the Cordilleran arc in south-central Arizona and northwestern Mexico (McDowell et al., 2001; Jacobson et al., 2011; Fig. 15A). Most importantly, MDAs cluster into a distinct early Paleocene group in central Texas (samples GOM-67 and GOM-69 through GOM-71), with means of ca. 62–61 Ma and youngest grains of ca. 60 Ma, and late Paleocene–earliest Eocene groups to the south and to the northeast, with means of 58–56 Ma and youngest grains of 54–53 Ma (Fig. 15C); this latter group includes one of the samples from Craddock and Kylander-Clark (2013). Individual samples from the northern Mississippi embayment do not have a minimum of three Paleocene-age grains, but the youngest grains from all samples are ca. 59 and 60 Ma.

Maximum depositional ages are consistent with Wilcox Group ages interpreted by other means (see Crabaugh and Elsik, 2000; Elsik and Crabaugh, 2001), and indicate transport from volcanic source terrains >1500–2000 km distant over million- and sub-million-year time scales. Moreover, the two distinct populations suggest that the lowermost Wilcox varies significantly in age along depositional strike, with early Paleocene axes located in central Texas and the northern Mississippi embayment. Late Paleocene to early Eocene axes were present in these two areas higher up in the section as well (see Wahl et al., 2016), and samples GOM-72 and GOM-74 in eastern Texas from the present study were collected from higher up in the Wilcox section, as basal outcrops in that area were not easily accessed, so MDAs for the lower Wilcox of that area are not known. However, samples from the west-central Arkansas part of the outcrop belt (GOM-46, GOM-47, and GOM-76) were collected close to the contact with underlying Midway Group mudstones and indicate that this part of the outcrop belt was not visited by Wilcox fluvial systems until the late Paleocene to early Eocene.

Oligocene Vicksburg-Frio Trend

Oligocene fluvial-deltaic strata of the northern GoM were deposited within a paleogeographic context (Fig. 16) where active Laramide deformation in the western U.S. had ceased but high-elevation mountain ranges and an orogenic plateau remained (Chase et al., 1998); Eocene and Oligocene volcanic activity in the western U.S. and northern Mexico was especially widespread (see Fig. 16; Chapin et al., 2004; Chapin, 2012). Moreover, the Oligocene was the first global "icehouse" of the Cenozoic, with high-amplitude fluctuations in global ice volume and corresponding glacio-eustasy (Zachos et al., 2001); regionally,

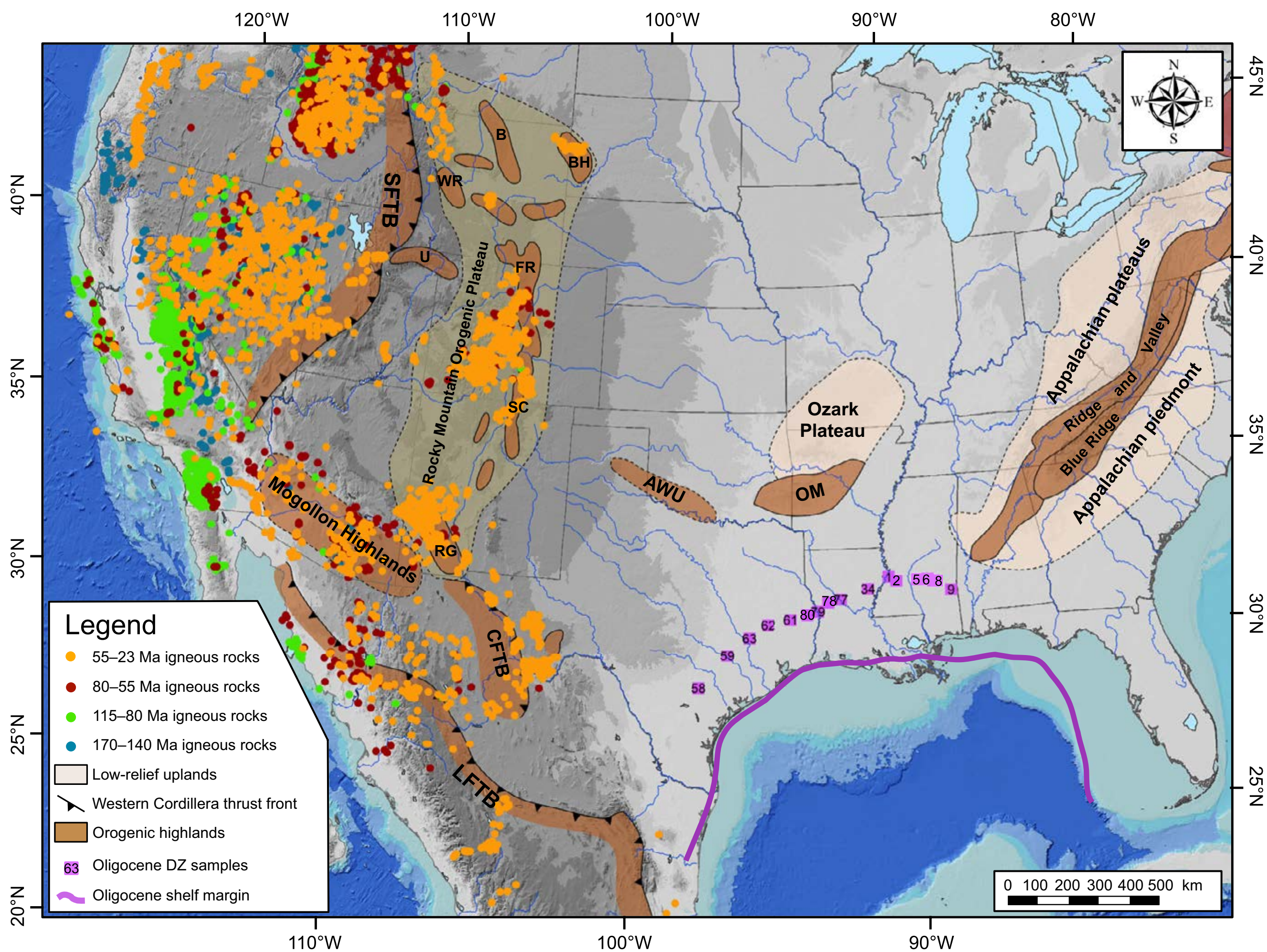


Figure 16. Oligocene tectonic and physiographic features of significance to this paper. Abbreviations are as in Figure 12. Based largely on Galloway et al. (2011). As in Figure 12, the distribution of igneous rocks of different age is based the NAVDAT database (http://navdat.org) and includes felsic and intermediate plutonic and volcanic rocks that have been radiometrically dated for discrete intervals through the Oligocene. These data represent the possible protolith sources for Mesozoic- and Cenozoic-age zircons in samples from the Oligocene fluvial sandstones across the Gulf of Mexico. For maps of volcanic zircons that represent sources for grains that produce maximum depositional ages, see Figure 19.

the western U.S. was characterized by an overall dry climate, with widespread eolian activity (e.g., Cather et al., 2008; Fan et al., 2015).

Fluvial sandstones within the Oligocene Vicksburg-Frio outcrop belt across the GoM coastal plain are referred to as the Catahoula Formation (see Galloway et al., 1982) through Texas and Louisiana, and the Waynesboro sandstone in Mississippi (Dockery and Thompson, 2016). Nineteen samples were collected from the Mississippi-Alabama border to south Texas (see Figs. 7 and 16), which produced 1730 ^{238}U-^{206}Pb or ^{207}Pb-^{206}Pb ages on zircon grains. Figures 17 through 19 summarize the Oligocene DZ record. In general, samples can be divided into four distinct clusters from K-S statistics, MDS plots, and the percentage of grains with latest Eocene to Oligocene ages: (1) a cluster that includes samples collected across most of the outcrop belt in Mississippi; (2) a cluster that defines the central part of the Mississippi embayment of eastern Louisiana and westernmost Mississippi, which includes one of the samples described by Craddock and Kylander-Clark (2013); (3) a small cluster that occurs in western Louisiana and also includes a sample from Craddock and Kylander-Clark (2013); and (4) a large cluster that extends from westernmost Louisiana through south-central Texas.

Most samples from Mississippi, samples GOM-1 and GOM-3 through GOM-9, are statistically indistinct from each other and, for the most part, indistinct from Cenomanian Tuscaloosa and Paleocene Naheola (Wilcox) samples from east of the Mississippi embayment; each displays the same strong Appalachian-Ouachita and Grenville signals (up to 75% of all grains). However, all samples include small populations of western-source zircons (ages <275 Ma); sample GOM-9, collected in far eastern Mississippi, includes only one western-source grain, with an age of ca. 44 Ma, whereas samples farther west contain 5%–15% western-source zircons, with ages as young as ca. 26 Ma. On the other hand, thicker point-bar sands characteristic of the Cenomanian and Paleocene were not observed in the Oligocene outcrop belt, suggesting that the paleo–Tennessee River had been diverted to the north by this time. Samples GOM-1 and GOM-3 through GOM-9 are therefore interpreted to represent fluvial systems that were not directly draining the Appalachians, but were instead draining the coastal plain and reworking older Paleocene–Eocene strata. The presence of Oligocene-age grains indicate that they must have been proximal to, and influenced by, an ancestral Mississippi River distributary within the Mississippi embayment.

The remaining DZ sample from Mississippi, GOM-2, is statistically distinct from samples farther east, but indistinct from GOM-34 as well as sample C5 from Craddock and Kylander-Clark (2013), which are located close to each other to the west of the modern Mississippi River and within the Mississippi embayment of south-central Louisiana. Relative to samples farther east, primary differences include reduced Appalachian-Grenville signals (<35%), increased significance of the midcontinent and Yavapai-Mazatzal province (combined 40%–50% of total), and increased significance of zircons ultimately derived

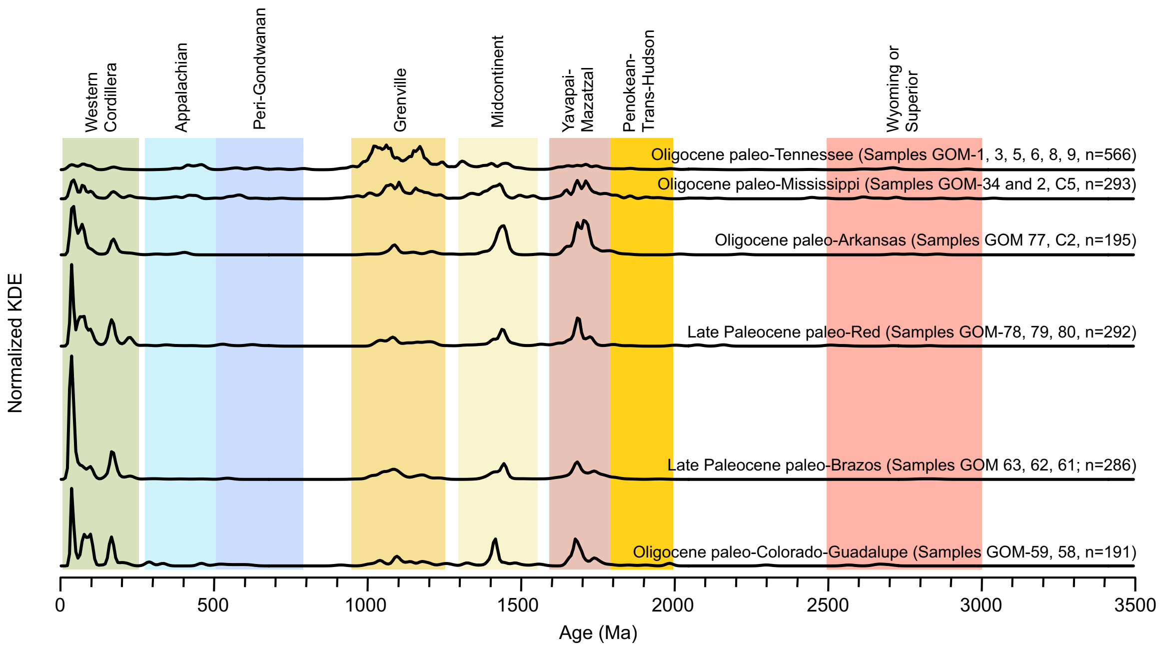


Figure 17. Normalized kernel-density estimate (KDE) plots of detrital-zircon populations for the Oligocene trend. Sample locations are shown in Figures 7 and 16. Each plot represents multiple individual samples lumped together on the basis of Kolmogorov-Smirnov statistics, multidimensional scaling plots, and geographic proximity. KDEs for the paleo-Mississippi and paleo-Arkansas include data published by Craddock and Kylander-Clark (2013).

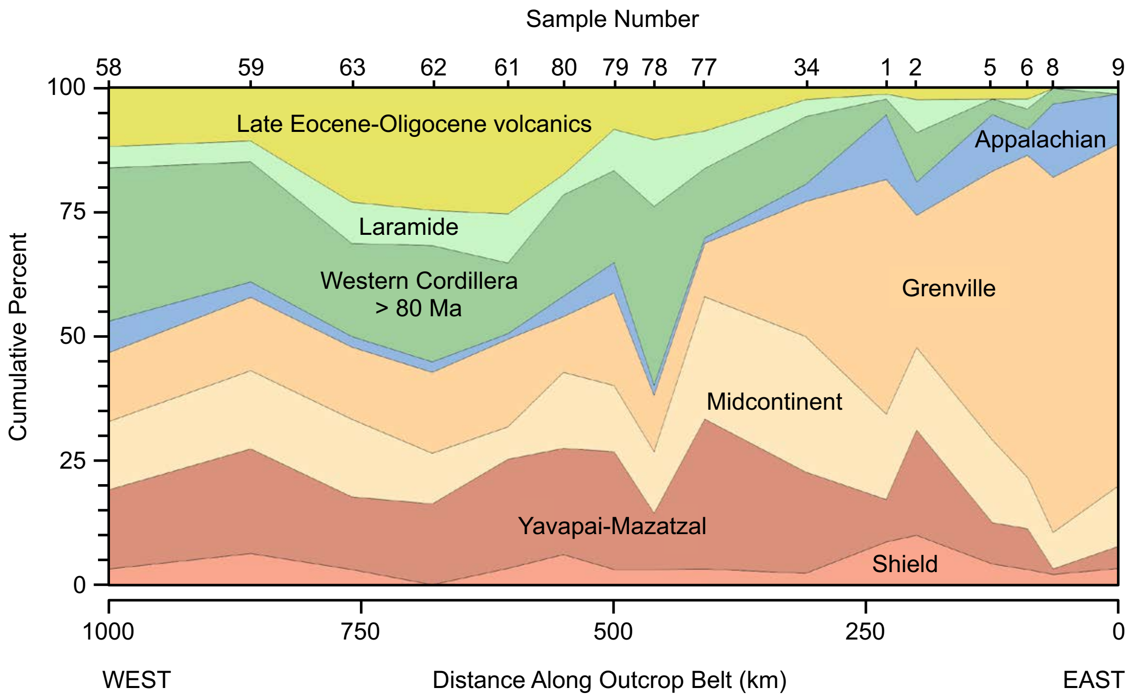


Figure 18. Trends in Oligocene detrital-zircon populations across the northern Gulf of Mexico margin, illustrating spatial changes in percent contributions of different populations. Note that sample numbers are illustrated on the upper *x*-axis, but the diagram is scaled to distance along the outcrop belt on the lower *x*-axis, with zero starting at the easternmost sample.

from the Mesozoic and Cenozoic Western Cordillera (15%–30% of total). However, each of these samples includes only 1%–2% grains of late Eocene to Oligocene age, indicating some linkage to ashfalls, but likely indicating reworking of older Cordilleran or Laramide basin fills of the central Great Plains or Paleocene to Eocene GoM coastal-plain strata; with such low concentrations, it is unlikely that the ancestral Mississippi drainage had headwaters in the Rockies or was linked in a significant way to fluvial systems that deposited the volcaniclastic late Eocene to early Oligocene White River Group of Wyoming, western Nebraska, and South Dakota (Larson and Evanoff, 1998; Rowley and Fan, 2016).

All samples from southwestern Louisiana through southern Texas contain 35%–55% western-source zircons, including >10% contribution from Eocene to Oligocene volcanic terrains. Moreover, Appalachian-Grenville ages compose <20% of all grains, but contributions from the midcontinent and Yavapai-Mazatzal sources remain at ~30%–35%. K-S statistics and MDS plots show that most samples from southwestern Louisiana through southern Texas are statistically distinct from samples within the Mississippi embayment and farther east, but related to each other, most likely due to the large populations of younger grains with relatively small error terms. However, we differentiate three distinct groups based primarily on geographic location and the percentage of grains of Oligocene age. First, samples GOM-77 through GOM-79 from southwestern Louisiana and easternmost Texas contain up to 35% grains ultimately derived from the Mesozoic Cordilleran arc and Late Cretaceous through Cenozoic volcanic terrains, but Oligocene-age grains compose <8% of the total. Second, samples GOM-80 and GOM-61 through GOM-63, from east-central Texas, contain up to ~25% Oligocene-age zircons. Third, samples GOM-58 and GOM-59, from central Texas along and south of the present-day Colorado River, again have <8% Oligocene-age grains. All samples from southwestern Louisiana through southern Texas are interpreted to indicate contributing drainage areas that extended to active volcanic centers in southern Colorado through northern Mexico.

Maximum depositional ages. Samples from central Louisiana to southern Texas contained at least three latest Eocene to Oligocene ages with overlapping error terms of <10%, and are therefore suitable for calculating MDAs. In contrast to the Wilcox, the larger number of grains and differences between samples in the Vicksburg-Frio trend make it useful to calculate MDAs for individual samples; unlike for the Wilcox, where multiple samples with similar MDAs cluster in one part of the outcrop belt or another, Oligocene MDAs differ from sample to sample across the outcrop belt (Fig. 19).

The oldest populations occur in south-central Texas (GOM-58 and GOM-59) and central Louisiana (GOM-78, GOM-77 and GOM-34, as well as C2 and C5 from Craddock and Kylander-Clark, 2013, which are located close to GOM-77

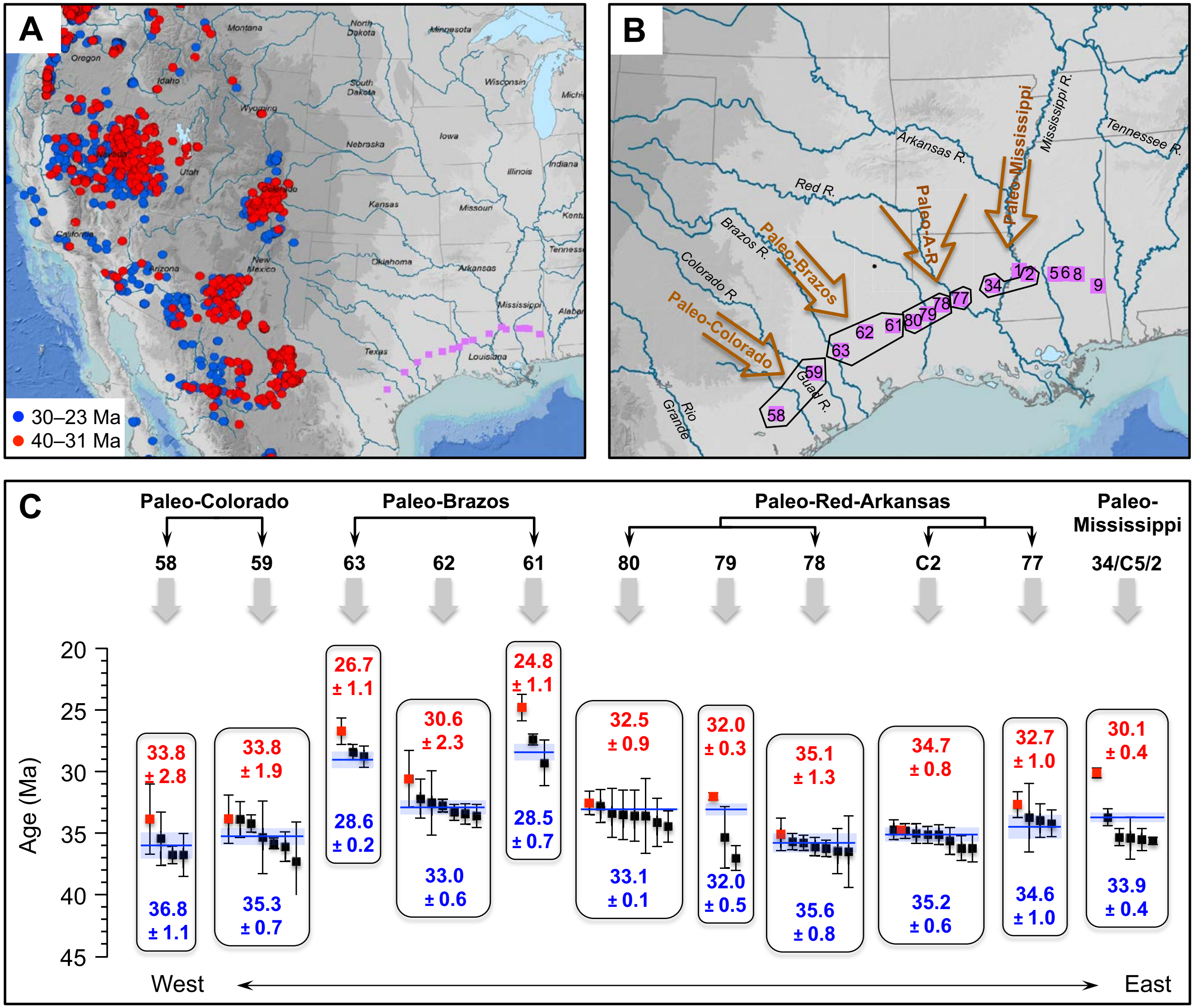


Figure 19. (A) Locations of radiometrically dated felsic and intermediate volcanic rocks of latest Eocene and Oligocene age from the NAVDAT community database (http://navdat.org). Oligocene detrital-zircon sample locations are shown in purple dots. (B) Enlarged view of A, with sample numbers and polygons enclosing samples from specific paleoriver systems (A-R—Arkansas-Red; Guad—Guadalupe). Sample C2 from Craddock and Kylander-Clark (2013) is just to the west of sample 77, whereas sample C5 is in the same location as sample 34. (C) Maximum depositional ages (MDAs) for individual Oligocene samples, with interpreted fluvial axes as shown. Blue lettering (in Ma) and blue lines represent MDAs, and blue box defines the weighted error. Red lettering and solid red box represent the youngest grain. Sample numbers are shown above the thick gray arrows, representing the Gulf of Mexico samples presented in this paper, except those prefixed by C are from Craddock and Kylander-Clark (2013).

and GOM-34 respectively), with MDAs of ca. 33.9–36.8 Ma that straddle the Eocene-Oligocene boundary. Samples GOM-62 in east-central Texas, and GOM-80 and GOM-79 in east Texas to western Louisiana yield early Oligocene MDAs of ca. 32–33 Ma. Finally, a third set in east Texas (GOM-63 and GOM-61) yields MDAs of ca. 28.5 Ma, the early to late Oligocene boundary. The youngest individual grains define the same sample sets, but can be up to 3 m.y. younger than calculated MDAs; inclusion of grains with error terms >10% does not change the overall group of three sample sets, but modestly changes calculated MDAs. In aggregate, these results indicate that lowermost Oligocene fluvial deposits vary significantly in age across the outcrop belt.

DISCUSSION

Paleodrainage Reconstruction and Sediment Routing

Detrital-zircon data, in conjunction with previous work, indicate that continental- and regional-scale GoM drainage areas have reorganized significantly over the last ~100 m.y. Below we interpret paleodrainage for the Cenomanian, Paleocene, and Oligocene; Cenomanian reconstructions have not been attempted in any detail in the past, but Paleocene and Oligocene DZ-based records can be compared with reconstructions by Galloway et al. (2011). In each case, we incorporate insights from independent measures of drainage-basin scale from Milliken et al. (2015), based on point-bar thicknesses from well logs.

As noted above, Somme et al. (2009) demonstrated a scaling relationship between length of the longest fluvial channel and the length of basin-floor fans; this relationship is illustrated schematically, and with the GoM as an example, in Figure 20. Here, we substitute drainage-basin length for channel length, which is not easily measured in ancient systems; from Google Earth measurements of rivers in the Somme et al. (2009) data set and other rivers in North America and elsewhere, the ratio of channel length to drainage-basin length has a mean of 1.54 (R^2 = 0.984) (Fig. 21A). Most fans in the Somme et al. (2009a) database still reside within a domain where fan lengths are 10%–50% of drainage-basin length (Fig. 21B). We use our DZ-based paleodrainage reconstructions and estimates of paleodrainage length to estimate lengths of basin-floor fans in the deepwater GoM, and compare these estimates with empirical measurements (Snedden et al., 2017).

Cenomanian Paleodrainage Reconstruction

Previous work shows that Aptian to early Albian drainage of North America, from the Appalachians to the Western Cordillera, flowed north to the Western Canada sedimentary basin and Boreal Sea (Blum and Pecha, 2014). The middle to late Albian and Cenomanian were, by contrast, times when the Western Interior Seaway was more extensive, and the Gulf of Mexico and Boreal Sea were at times connected. From previous work (e.g., Witzke and Ludvigson, 2996; Brenner et al., 2000; Joeckel et al., 2005; Finzel, 2014; Blum et al., 2016), Albian–Cenomanian Dakota fluvial systems whose deposits crop out in the U.S. midcontinent drained the Appalachian-Ouachita cordillera, flowed generally west, and discharged to the eastern margin of the Western Interior Seaway, whereas Dakota fluvial systems whose deposits crop out in the Colorado Front Range drained the Western Cordillera, flowed generally east, and discharged to the western seaway margins.

Cenomanian Tuscaloosa-Woodbine fluvial deposits of the GoM coastal plain were deposited within this paleogeographic context. The Appalachian-Ouachita cordillera and associated plateaus served as the continental divide for eastern North America (Appalachia), a situation inherited from Early- and pre-Cretaceous times (Blum and Pecha, 2014), and western North America (Laramidia) had no sediment input to the northern GoM per se. Moreover, as Cox and Van Arsdale (2002) argued, what is now the northern Mississippi embayment may have been uplifted 1–2 km in association with superplume activity from the passing Bermuda hotspot, and did not exist as a topographic low until later in the Cretaceous. Woolf (2012) documented an extensive Tuscaloosa depocenter in the southern Mississippi embayment of southeast Louisiana.

Tuscaloosa fluvial deposits crop out in Alabama and Mississippi to the west (downstream) of the modern Tennessee River's right-angle north-northwest turn across structural grain to join the Ohio River, and to the west of the modern Alabama River's right-angle southerly turn to the GoM (see Fig. 5). The geological history of the Tennessee and Alabama systems have been discussed for more than a century, with arguments for and against stream capture to explain these right-angle turns. The older geological literature is split on this issue (see Johnson, 1905; Adams, 1928), whereas more recent biogeographical research has identified genetically related fish communities in headwaters of the present-day Tennessee plus other Appalachian tributaries that now drain to the Atlantic and/or GoM, which implies that these drainages were connected as a single "Appalachian River" in the past. For example, Mayden (1988) concluded that the upper Alabama and upper Tennessee were connected during the Tertiary, whereas Jones et al. (2006) estimated that certain fish populations of the upper Tennessee and headwaters of modern-day eastern GoM and Atlantic rivers diverged prior to ca. 10 Ma.

Figure 22 summarizes our proposed Cenomanian paleodrainage reconstruction. We interpret DZ populations from most of the Tuscaloosa outcrop belt to record a paleo–Tennessee River that flowed axially through, and routed sediments from, the Appalachian fold-and-thrust belt in the southeastern U.S., then continued southwest to enter the GoM in the Mississippi embayment. By contrast, the southern part of the outcrop belt has a DZ signature consistent with the modern Alabama or Apalachicola Rivers, which drain the southern margins of the Appalachians; these data suggest that the paleo-Alabama continued southwest parallel to structural grain as well, and contributed to the Tuscaloosa depocenter of Woolf (2012). We interpret the paleo-Tennessee to have been the largest Cenomanian system discharging to the northern GoM, with a drainage area similar to that of the modern Tennessee plus Alabama-Tombigbee Rivers, upstream from the Cenomanian outcrop belt; total drainage area is estimated to have been 300,000–400,000 km^2, with an estimated drainage-basin length of 1200–1600 km. Point-bar thicknesses (Milliken et al., 2015) and the scale of the Tuscaloosa depocenter (Woolf, 2012) require a regionally significant fluvial system, consistent with the DZ record.

Cenomanian DZ samples were not collected through the outcrop belt in Arkansas. Hence, paleodrainage for this part of the region is not clear; we note that Woolf (2012) mapped a Cenomanian fluvial axis in the southern Mississippi embayment, which enters the western margins of the Tuscaloosa depocenter in south Louisiana. By contrast, it is clear that Woodbine fluvial deposits in Oklahoma and Texas farther to the west and south had headwaters in the Ouachita Mountains and represent a series of smaller river systems that flowed south to enter the GoM in the Houston embayment and East Texas basin (see Ambrose et al., 2009). Smaller Woodbine systems of the Houston embayment are interpreted to have had maximum lengths of 200–300 km.

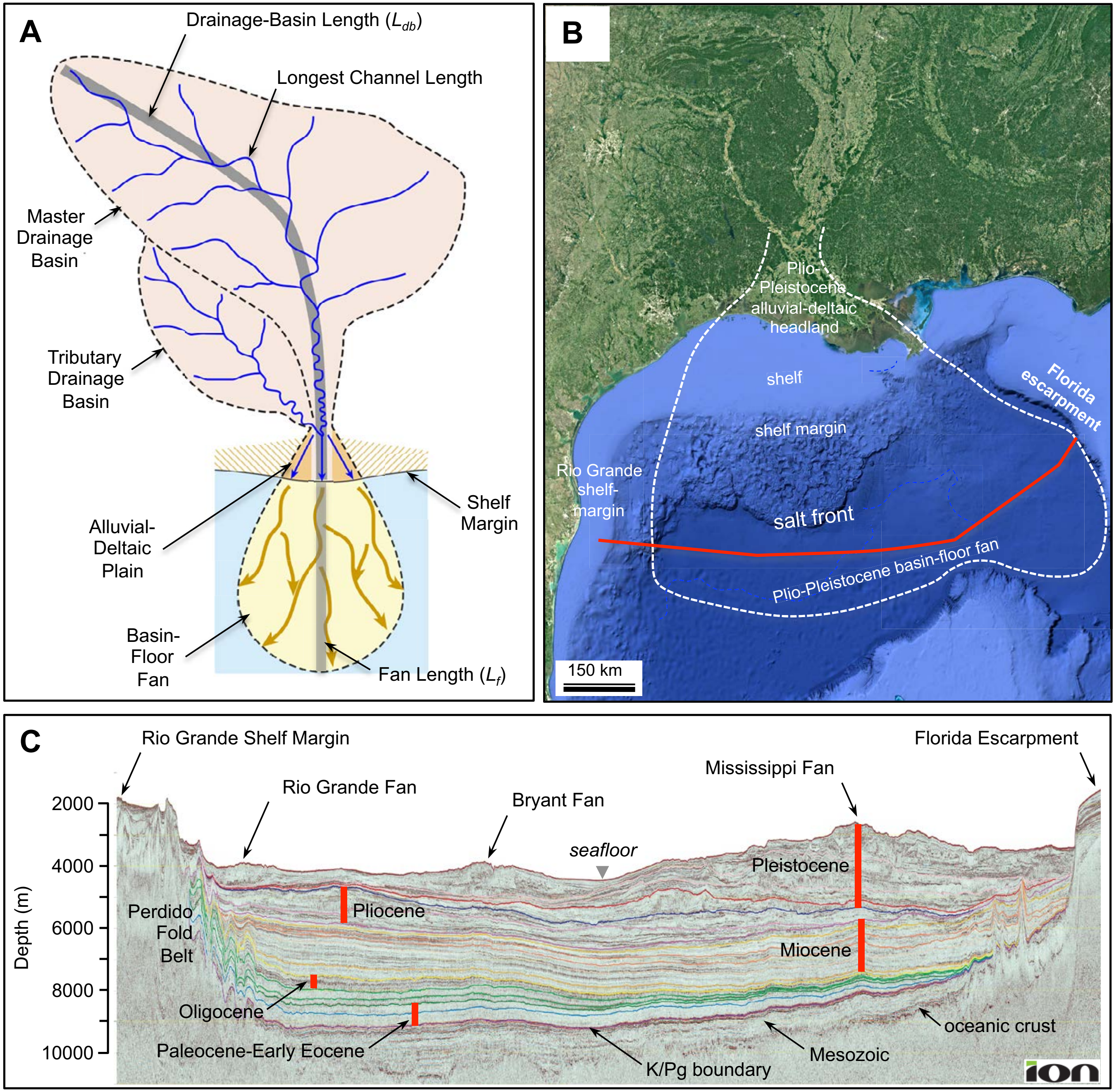


Figure 20. (A) Definition sketch for scaling relationships between drainage basins and basin-floor fans. Drainage basin, longest channel length, and drainage-basin length are as noted. L_{db}—length of contributing drainage basin; L_f—length of slope and basin-floor fan, which are undifferentiated here and in Figs. 22–25 for simplicity. Based on Somme et al. (2009) and Blum et al. (2013). (B) Satellite image of the Mississippi valley and Gulf of Mexico, illustrating the scale of the Plio-Pleistocene shelf to basin-floor depocenter, and key bathymetric features of the Gulf of Mexico (image from Google Earth). The red line shows the location of C. (C) Regional depth-migrated seismic line across the Gulf of Mexico, illustrating the scale and thickness of basin-floor fan sediments (undecompacted) for key intervals of the Cenozoic (maximum thickness for each interval indicated by a red bar). Image courtesy of ION Geophysical, with generalized location illustrated by the red line in B. The Mississippi fan and Bryant fan (see Damuth and Olson, 2015; Bentley et al., 2015) are both part of the greater Mississippi fan system. K-Pg—Cretaceous-Paleogene.

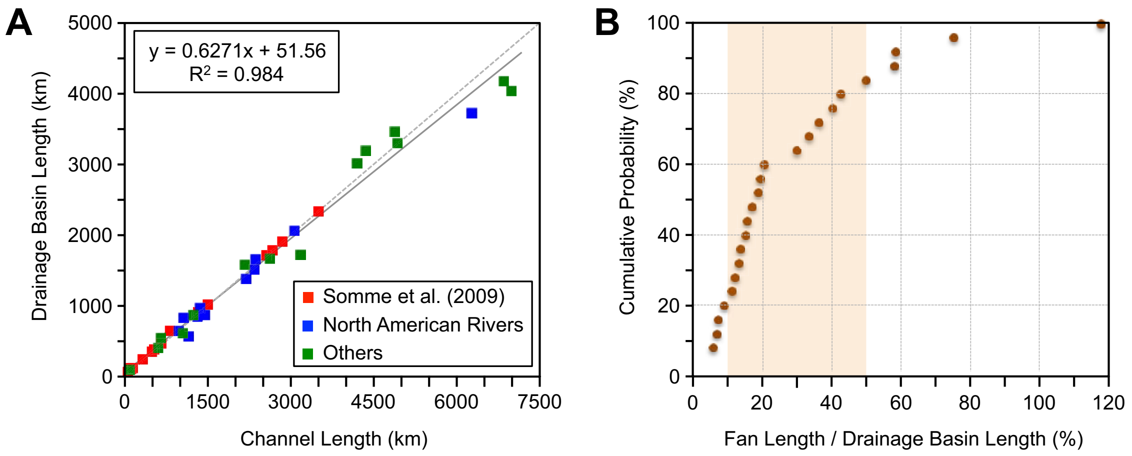


Figure 21. (A) Relationship between measured channel lengths from Somme et al. (2009) and Syvitski and Milliman (2007), and drainage-basin lengths measured from Google Earth. In cases where there were different values given by the above references, we used the Syvitski and Milliman (2007) data. Dashed gray line represents a channel length / drainage-basin length ratio of 1.5, whereas the solid gray line represents the value of 1.54, generated by the regression equation shown in the inset box. (B) Cumulative probability of the scaling relationship between length of basin-floor fans and drainage-basin length. Shaded box defines fan length / drainage-basin length = 10%–50%, which defines 20%–80% of the fans within the Somme et al. (2009) data set.

Paleocene Paleodrainage Reconstruction

As shown in Figure 12, Paleocene paleogeography in the western U.S. had evolved significantly from the Cenomanian. The Western Interior Seaway had withdrawn, although a smaller Cannonball Sea remained in the northern U.S. Great Plains and southern Canada (see Wroblewski, 2006). The Sevier hinterland remained as a topographically high orogenic plateau, referred to as the Nevadaplano (e.g., DeCelles, 2004; Ernst, 2010; Chamberlain et al., 2012), but Laramide deformation had partitioned the Sevier foreland into a series of smaller basement-cored ranges with associated subsiding basins (see Heller and Liu [2016] for a recent summary of Laramide timing); fluvial deposits accumulated in these basins, but river systems were through-going until the early Eocene, after ca. 53–52 Ma, when closed lacustrine systems prevailed (e.g., Carroll et al., 2006). Moreover, flat-slab subduction (Saleeby, 2003; Liu et al., 2010; Heller and Liu, 2016) was ongoing along the western margin of North America; numerical modeling by Liu et al. (2014) and Liu (2015) suggested that, by the Paleocene, as the slab continued to migrate east, there would have been a broad north-south–oriented moat of dynamic subsidence that extended from the Great Plains to Texas. Last, Cox and Van Arsdale (2002) argued that the Mississippi embayment was a topographic low by the early Paleocene, following Late Cretaceous uplift, erosion, and subsidence associated with the west-to-east passage of the Bermuda hotspot.

Galloway et al. (2011) presented a comprehensive model for Cenozoic GoM drainage evolution. Our DZ-based reconstruction for the early Paleocene is shown in Figure 23, with the late Paleocene–earliest Eocene in Figure 24; these reconstructions are broadly consistent with Galloway et al. (2011), but suggest differences as well, which can be the topic of future research. To begin, DZ data from Paleocene Wilcox strata indicate that Appalachian-Grenville populations dominate all samples in Alabama and Mississippi, as they did during the Cenomanian; only the westernmost samples in northern Mississippi include a small population of grains with a Western Cordillera affinity. These data are interpreted to reflect persistence of an Appalachian-sourced paleo-Tennessee and paleo-Alabama system that flowed southwest from the outcrop belt across Mississippi, to enter the Mississippi embayment in central Louisiana. We cannot resolve whether this paleo-Tennessee system merged with the paleo-Mississippi in the southern Mississippi embayment to become part of the Holly Springs depocenter (e.g., Galloway, 1968), or discharged separately to the GoM. This interpretation differs from that of Galloway et al. (2011), who showed diversion of a Paleocene Tennessee River to the south toward the present-day Florida panhandle, but is consistent with point-bar measurements of Milliken et al. (2015), where a large paleo-Tennessee system was present in southwest Mississippi and southeast Louisiana through the early Eocene. In this model, the paleo-Tennessee had a drainage area similar to that of the Cenomanian, estimated at 300,000–400,000 km^2, with an estimated drainage-basin length of 1200–1600 km.

Farther west, Wilcox fluvial deposits show clear affinity with the U.S. midcontinent and western U.S., such that significant post-Cenomanian continental-scale drainage reorganization had taken place by this time (Blum and Pecha, 2014). DZ data are interpreted to indicate that the U.S. continental interior, from the Appalachians to the western Great Plains, drained to the early Paleocene GoM through a paleo-Mississippi system that flowed through the northern Mississippi embayment, and contributed to the Holly Springs depocenter of south-central Louisiana (e.g., Galloway, 1968; Tye et al., 1991; Galloway et al., 2011). The small number of Paleocene U-Pb ages in samples from the northern Mississippi embayment indicate some connection with ashfall blankets that were most likely derived from the Colorado Mineral Belt. However, the remaining western DZ signal can be accounted for by reworking of Mesozoic foreland-basin strata of the Great Plains and does not require the early

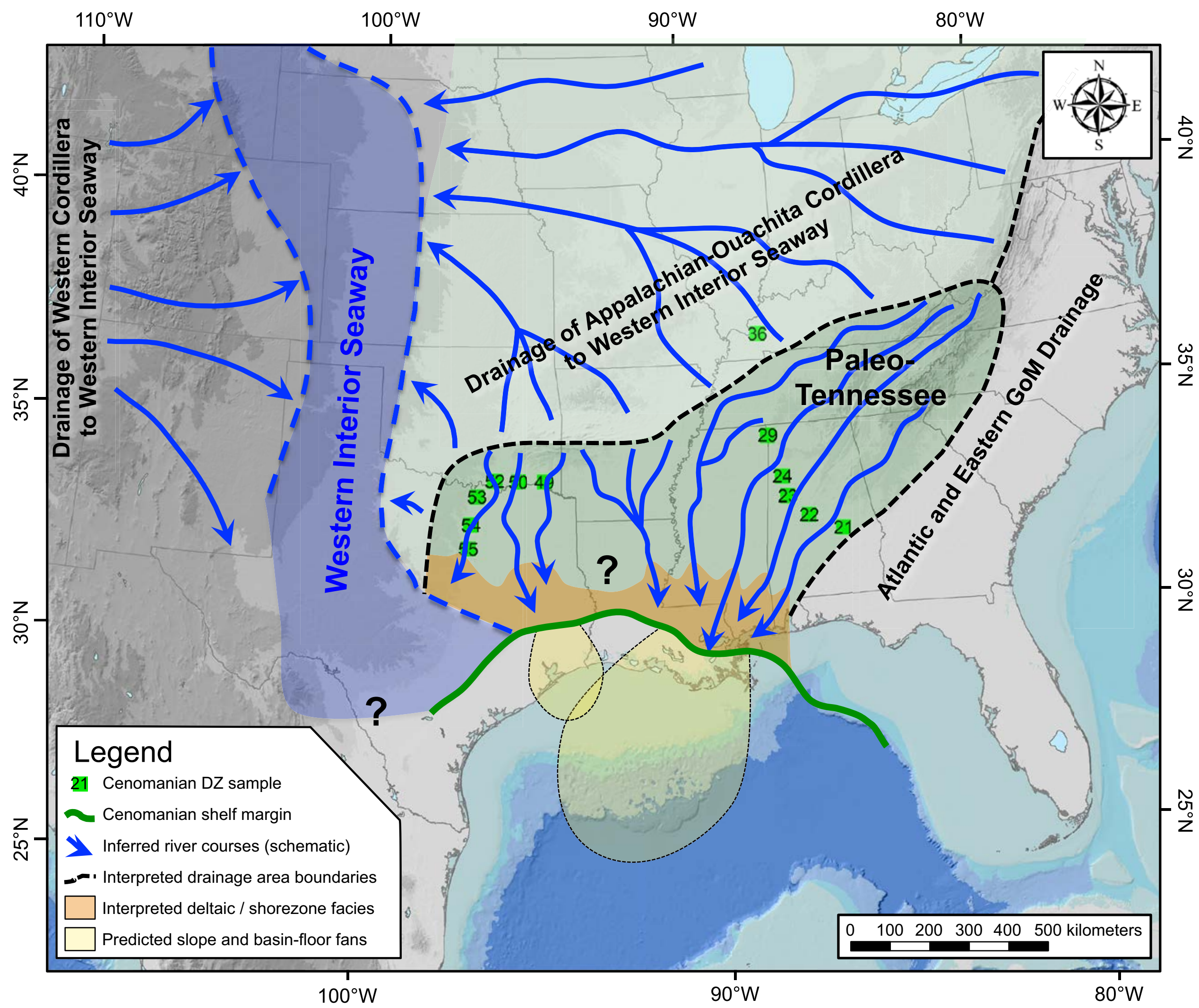


Figure 22. Paleodrainage reconstruction for the Gulf of Mexico (GoM) Cenomanian Tuscaloosa-Woodbine trend, and inferred Albian-Cenomanian drainage to the north (after Blum et al., 2016). Tuscaloosa deltaic and shore-zone depocenter is from Woolf (2012). The map extent of the Western Interior Seaway is based on a variety of sources, including https://deeptimemaps.com and Brenner et al. (2000), but also DZ data reported in Blum et al. (2016). Also shown are predicted length scales for basin-floor fans, using the scaling relationship of $L_f = 0.5\ L_{db}$ (L_f—length of slope and basin-floor fan; L_{db}—length of contributing drainage basin). DZ—detrital zircon.

Paleocene paleo-Mississippi headwaters to have extended headward into the northern and central Rockies. As a result, the paleo-Mississippi drainage area that contributed sediment to the early Paleocene Holly Springs depocenter is estimated to have been ~1.2×10^6 km^2, with a maximum length of ~2000 km.

Detrital-zircon data from south-central Arkansas through central Texas include larger populations of latest Cretaceous through Paleocene ages, which show that GoM river systems drained active volcanic terrain of the central and southern Rocky Mountains as well as the Sonoran arc of southern Arizona and northern Mexico. Moreover, the midcontinent granite-rhyolite and Yavapai-Mazatzal signals become increasingly important to the west. The Wilcox “Rockdale” depocenter of Fisher and McGowen (1969), within the Houston embayment of central Texas, has long been interpreted to have been the primary Paleocene–early Eocene fluvial axis for the northern GoM (e.g., Winker, 1982; Galloway et al., 2011); DZ data support this view for the early Paleocene,

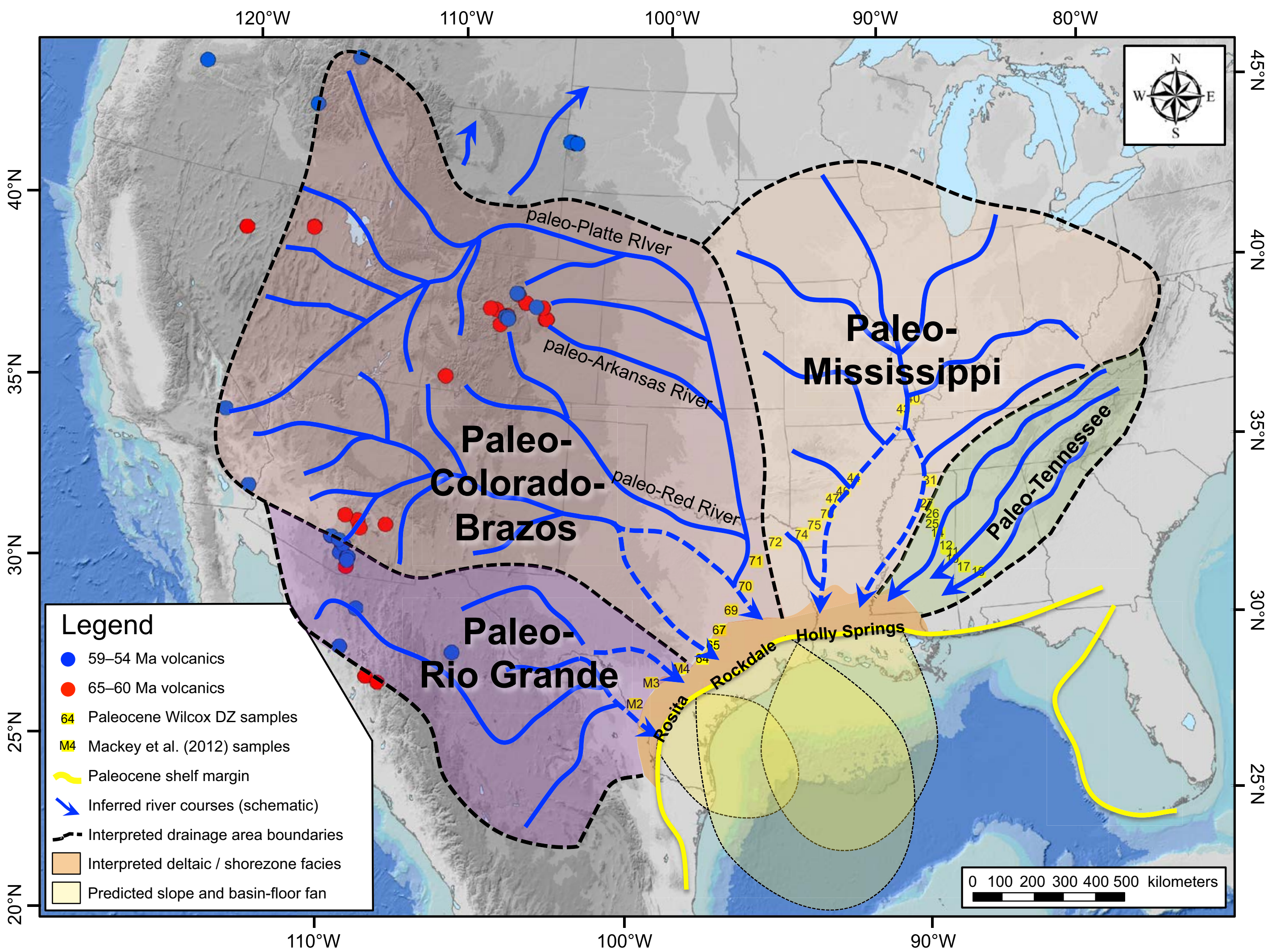


Figure 23. Paleodrainage reconstruction for the northern Gulf of Mexico early Paleocene Wilcox trend. Rockdale, Holly Springs, and Rosita depocenters are as shown, based on Fisher and McGowen (1969), Galloway (1968), Edwards (1981), and Galloway et al. (2011). Dashed blue lines in the paleo–Colorado-Brazos and paleo-Mississippi systems represent the area over which the trunk streams would have migrated. Locations of radiometrically dated Paleocene and earliest Eocene felsic and intermediate volcanic rocks are from Figure 15 and http://navdat.org. Also shown are predicted length scales for basin-floor fans, using the scaling relationship of $L_f = 0.5\ L_{db}$ (L_f—length of slope and basin-floor fan; L_{db}—length of contributing drainage basin). DZ—detrital zircon.

and indicate that the Rockdale depocenter was fed by a paleo–Colorado-Brazos system with headwaters that extended west to the Sonoran arc and Mogollon Rim of southern Arizona, respectively, and northwest to the southern and central Rockies. The bimodal Jurassic and Late Cretaceous arc signature from the Rockdale depocenter is similar to that of the broader Sierra Nevada region, including Paleocene fluvial deposits that drained the eastern arc flank (e.g., Lechler and Niemi, 2011). Moreover, Paleocene Wilcox systems predate interpreted eastward migration of drainage divides to the Mogollon Rim of central Arizona and the expansion of west-flowing drainage (see Ingersoll et al., 2013; Sharman et al., 2015). We interpret an early Paleocene Rockdale drainage area that drained the area with significant Sierra Nevada ashfall, but cannot rule out headwaters within the southern Sierra Nevada batholiths per se.

Unraveling contributions to the early Paleocene Rockdale system from the central to northern Rockies is a complicated issue. Galloway et al. (2011) inter-

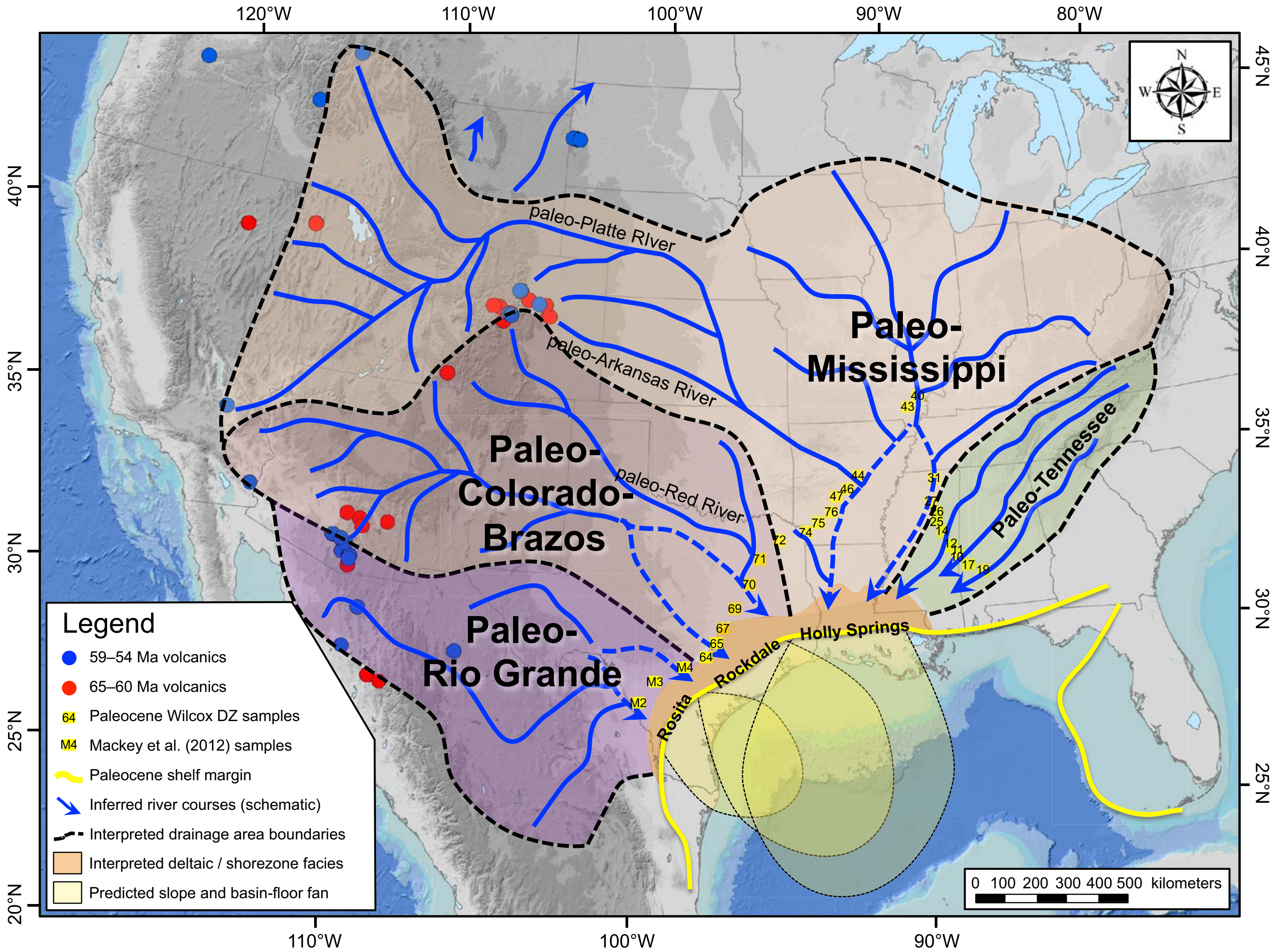


Figure 24. Paleodrainage reconstruction for the late Paleocene to earliest Eocene Wilcox trend, after the headwater regions of the paleo-Arkansas and paleo-Platte were captured and routed through the present-day Arkansas course in the Ouachita Mountains of Arkansas to join the paleo-Mississippi system. Rockdale, Holly Springs, and Rosita depocenters are as shown, based on Fisher and McGowen (1969), Galloway (1968), Edwards (1981), and Galloway et al. (2011). Dashed blue lines in the paleo–Colorado-Brazos and paleo-Mississippi systems represent the area over which the trunk streams would have migrated. Locations of radiometrically dated Paleocene and earliest Eocene felsic and intermediate volcanic rocks are from Figure 15 and http://navdat.org. Also shown are predicted length scales for basin-floor fans, using the scaling relationship of $L_f = 0.5\ L_{db}$ (L_f—length of slope and basin-floor fan; L_{db}—length of contributing drainage basin). DZ—detrital zircon.

preted a tributary network within the central and northern Rockies, similar to the present-day Platte system, to be part of the paleo-Mississippi system that entered the northern Mississippi embayment. Wahl et al. (2016), by contrast, inferred an ancestral Platte headwaters region in the Colorado Front Range that discharged to the Rockdale depocenter. We likewise suggest that the ancestral Platte was steered to the south and through a north-south–oriented moat of dynamic subsidence in the Great Plains modeled by Liu (2015); while flowing south, this ancestral Platte would have been joined by the ancestral Arkansas and Red River systems, then joined the paleo–Colorado-Brazos system to deliver sediment to the Rockdale depocenter. This interpretation is consistent with the small number of latest Cretaceous and Paleocene U-Pb ages within the northern Mississippi embayment, and with the absence of early Paleocene Wilcox strata in the Arkansas part of the Wilcox outcrop belt, south of the present-day Arkansas River. These observations combine to suggest that early Paleocene Rocky Mountain–sourced rivers flowed to the west of the Ouachita Mountains, through this moat of dynamic subsidence, to join the Rockdale system. At a minimum, then, source terrains for the early Paleocene Rockdale depocenter included the southern to central Laramide Rockies.

At a maximum, drawing on reconstructions from Flores (2003), we suggest that this ancestral Platte drainage extended westward to, and beyond, the Sevier fold-and-thrust belt in Utah to an east-west drainage divide in present-day Nevada (see Jacobson et al., 2011), and included arc terrain from southern California to Idaho (Fig. 12). In this model, the ancestral Platte represents the downstream extension of Late Cretaceous to Paleogene fluvial systems of the Sevier foreland: the southernmost headwaters fed an axial Late Cretaceous fluvial system in southwest Utah (Szwarc et al., 2015), which became the Paleogene California River of Davis et al. (2010) and Dickinson et al. (2012), whereas the northernmost headwaters fed the Paleogene Idaho River of Chetel et al. (2011) and Dumitru et al. (2013). This ancestral Platte network extended eastward with withdrawal of the Western Interior Seaway, then flowed through Laramide alluvial basins to emerge onto the Great Plains. Carroll et al. (2006) argued that the volume of eroded foreland-basin strata during the Paleocene exceeds the volume of preserved Paleocene-age Laramide basin fill by a factor of two. In our interpretation, the remainder of this eroded sediment would have been exported to the east through the ancestral Platte system, then south to the early Paleocene Rockdale depocenter and GoM. In this scenario, the Rockdale paleodrainage area is estimated to have been ~2.4×10^6 km^2, with a maximum length of ~2500 km measured from modern physiography. However, headwaters reside within the area of the southwestern U.S. that was subject to significant Neogene Basin and Range extension (e.g., Wernicke, 1992; McQuarrie and Wernicke, 2005); subtracting extended terrain decreases in drainage area and length by ~10%.

Maximum depositional ages from samples in south-central Arkansas (see Fig. 15C), south of the present-day Arkansas River where it emerges from the Ouachita Mountains, indicate that drainage of the central to northern Rockies must have been diverted to the east by the late Paleocene; this diversion could have occurred via the ancestral Platte system and through the northern Mississippi embayment, or through the deep bedrock-confined course occupied by the Arkansas River today (Fig. 24). This ancestral Platte-Arkansas system would have joined the ancestral Mississippi and flowed south through the western Mississippi embayment to south Louisiana, and would have significantly increased drainage area for the late Paleocene paleo-Mississippi Holly Springs depocenter, with corresponding decreases for the late Paleocene paleo–Colorado-Brazos Rockdale system. The late Paleocene Holly Springs depocenter is therefore estimated to have a contributing drainage area of ~2.1×10^6 km^2, with a maximum length of ~2800 km. Such an interpretation is consistent with significant increases in point-bar thickness for upper Wilcox strata of the Holly Springs depocenter as well (Milliken et al., 2015). However, we note that as erosion of foreland-basin strata on Laramide uplifts proceeded, and resistant basement cores were increasingly exposed (e.g., Carroll et al., 2006), total sediment flux from the Laramide Rockies likely decreased. As a result, increases in sediment load to the Holly Springs depocenter following capture of the ancestral Platte-Arkansas system may have been less significant.

From the above, much of the continental U.S. drained to the Rockdale and Holly Springs depocenters during the Paleocene and early Eocene. However, the Mackey et al. (2012) DZ data indicate that a river system of significant size entered the GoM in southern Texas. As noted above, DZ signatures from lower Wilcox outcrops sampled by Mackey et al. (2012) are statistically distinct from those of most Wilcox samples farther north and east because the Mackey et al (2012) samples lack significant populations of latest Cretaceous and Paleocene grains and have early Cretaceous ages that are uncommon for the U.S. part of the Mesozoic arc. We therefore restrict drainage area for lower Wilcox fluvial systems sampled by Mackey et al. (2012) to the Mexican Cordillera, and suggest that these samples are linked to fluvial systems whose headwaters contributed to Paleocene strata of the La Popa basin in northern Mexico (e.g., Lawton et al., 2009) and flowed through the Rio Grande embayment to what has been described as the Rosita depocenter (e.g., Edwards, 1981). We estimate the contributing area for this paleo–Rio Grande and the Rosita depocenter to have been ~400,000–500,000 km^2, with a maximum length of ~1500 km. Point-bar thicknesses measured from subsurface data by Milliken et al. (2015) are comparable to those of the Holly Springs depocenter and support a large system as well.

Oligocene Paleodrainage Reconstruction

Winker (1982) initially interpreted the Rio Grande embayment to be the primary focus for Oligocene sediment input to the GoM, with the Sierra Madre Occidental as the primary source terrain (see Fig. 4). Galloway et al. (2011) confirmed that the Rio Grande embayment was important in terms of sediment flux, but the Houston and Mississippi embayments and their associated depocenters were important as well. Our Oligocene paleodrainage reconstruction from DZ data is summarized in Figure 25, and again generally supports Galloway et al. (2011), although subtle details are interpreted differently so as to be consistent with DZ data.

Oligocene strata to the east of the Mississippi embayment continue to show an overwhelmingly dominant Appalachian-Grenville signature. However, as noted above, channel-belt sand bodies that crop out are notably thinner than Cenomanian or Paleocene equivalents from the same area, and significant point-bar sand bodies were not observed downdip to the southwest in the subsurface (Milliken et al., 2015). These observations suggest that by the Oligocene, the ancestral Tennessee River had been diverted northwest toward its present confluence with the Ohio and Mississippi Rivers, the ancestral Alabama had been diverted to the south and the GoM coast, and a direct connection between the Appalachian cordillera and the southern Mississippi embayment was no longer present. From DZ and point-bar data, diversions of the Tennessee and Alabama Rivers are inferred to have occurred during the Eocene, which is consistent with zoogeographical estimates (Mayden, 1988; Jones et al., 2006). We therefore interpret the Oligocene DZ record for

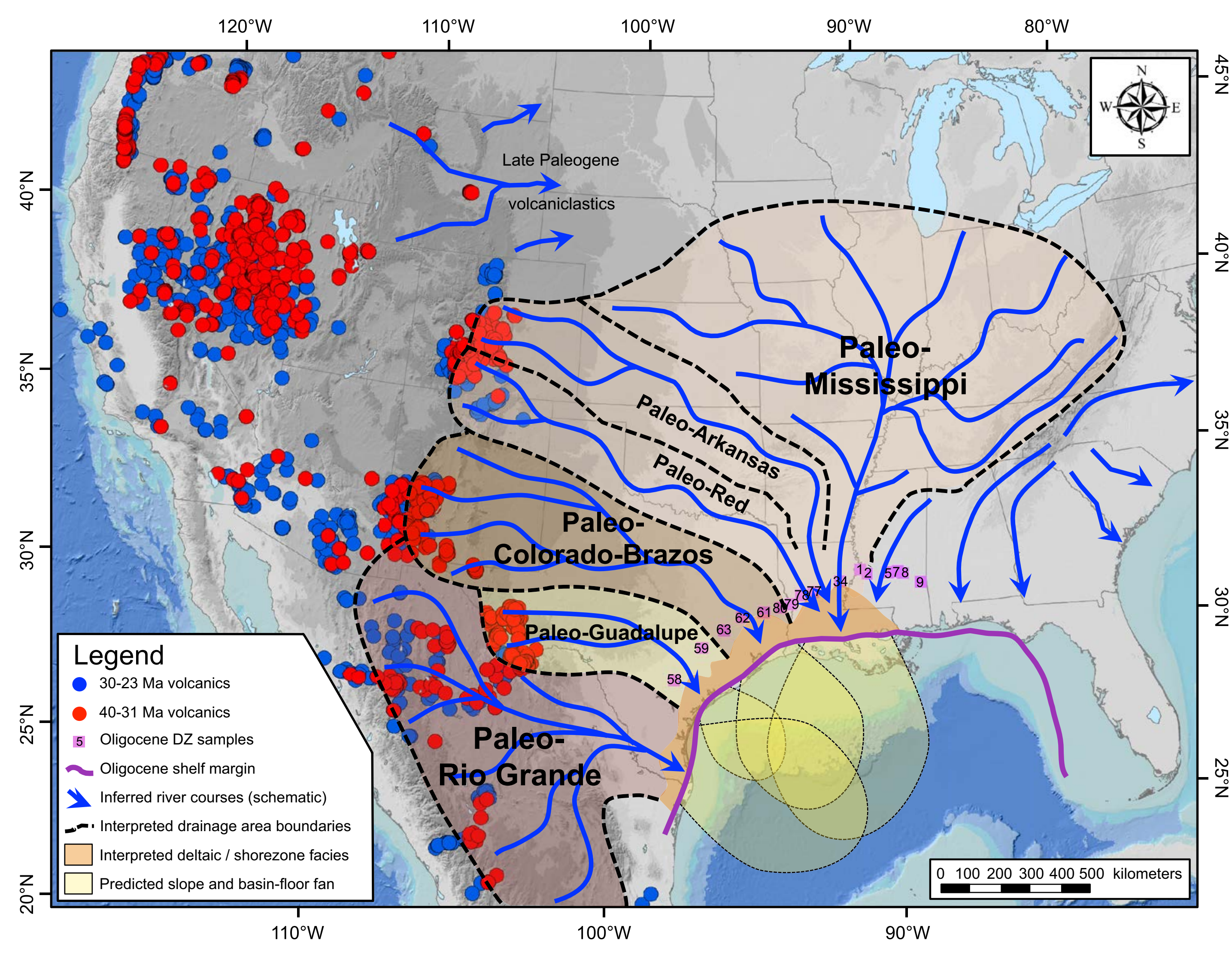


Figure 25. Paleodrainage reconstruction for the northern Gulf of Mexico (GoM) Oligocene trend. Major depocenters are as shown, based on Galloway et al. (1982 and 2011). Also shown are predicted length scales for basin-floor fans, using scaling relationship of $L_f = 0.5\ L_{db}$ (L_f—length of slope and basin-floor fan; L_{db}—length of contributing drainage basin). Locations of radiometrically dated latest Eocene to Oligocene felsic and intermediate volcanic rocks are from Figure 19 and http://navdat.org. Schematic river courses to the north of the inferred GoM drainage area are from Fan et al. (2015), whereas distribution of the Eocene to Oligocene volcaniclastic apron is from Galloway et al. (2011). Reconstructed paleo–Rio Grande is from Winker (1982). DZ—detrital zircon.

the area east of the Mississippi embayment to represent a series of small fluvial systems with headwaters in Cenomanian through Eocene, mostly Appalachian-derived coastal-plain strata.

Farther west, Oligocene fluvial deposits contain abundant zircons with Eocene and Oligocene U-Pb ages, which were ultimately derived from volcanic centers or ash blankets in the Rocky Mountains and/or western Great Plains. Samples from the Mississippi embayment in western Mississippi through central Louisiana (samples GOM-34, GOM-1, and GOM-2; and sample C5 of Craddock and Kylander-Clark, 2013) contain the lowest concentration of young grains, which suggests no direct connection to the central Rockies or the ash-rich Oligocene fluvial deposits in Wyoming and western Nebraska (Swinehart et al., 1985; Larson and Evanoff, 1998; Fan et al., 2015); these volcaniclastics instead represent river systems that flowed to the east and north from headwaters in the Sevier fold-and-thrust belt of western Wyoming (Fan et al., 2015). This interpretation restricts the northwestern extent of the paleo-Mississippi drainage to the central Great Plains through the upper Midwest, however the eastern limits are increased due to accretion of the paleo-Tennessee system.

Samples from western Louisiana show an increased percentage of zircons with late Eocene and Oligocene U-Pb ages, which is interpreted to reflect a direct connection to the central Rockies in Colorado and ash blankets of the western Great Plains via the paleo–Red and Arkansas Rivers (samples GOM-77 through GOM-80). These samples are located within the western Mississippi embayment and likely represent drainages that joined the paleo–Mississippi River to the south of the outcrop belt and contributed to the southern Louisiana depocenter, much as they do today. We therefore estimate the greater paleo-Mississippi drainage area to have been 1.4–1.5 × 10^6 km^2, with a maximum length of 1200–1500 km. These estimates are consistent with estimates from point-bar measurements in the subsurface (Milliken et al., 2015).

The largest percentage of zircons with Eocene to Oligocene U-Pb ages (up to 30% of the total population) occurs within the Houston embayment in eastern Texas (samples GOM-61 through GOM-63) and represents drainages that fed the Houston delta system of Galloway et al. (1982); this population is interpreted to represent the paleo–Colorado-Brazos system, referred to as the Chita-Corrigan fluvial systems by Galloway et al. (1982), with headwaters proximal to eruptive centers in the southern Rockies of southern Colorado and New Mexico (see Chapin et al., 2004). Drainage area for the paleo–Colorado-Brazos system was reduced from its maximum extent in the Paleocene due to tectonic disruption of drainage and development of widespread eolian sand seas in western New Mexico and eastern Arizona (Cather et al., 2008). Point-bar thicknesses measured by Milliken et al. (2015) are consistent with this view and suggest a river system that was significantly smaller than that which fed the Paleocene Rockdale depocenter. We estimate the drainage area to have been 600,000–700,000 km^2, with a length of ~1500 km.

In addition to the above, samples GOM-58 and GOM-59 from south-central Texas, south of the Houston embayment, have a similar overall western signature within the DZ population but a smaller proportion of Eocene and Oligocene grains than samples within the Houston embayment. We interpret these samples to represent a relatively small paleo–Guadalupe River system, referred to by Galloway et al. (1982) as the Choke Canyon–Flatonia system, with headwaters in western Texas and northern Mexico. We estimate the drainage area to have been 100,000–150,000 km^2, with a maximum length of 500 km. Last, the Rio Grande embayment has been recognized as a major Oligocene depocenter for almost four decades, and is referred to as the Norias delta (Galloway et al., 1982). DZ data are not available from this area, however point-bar thicknesses from Milliken et al. (2015) suggest a large system, consistent with the original view in Winker (1982; see Fig. 5) of a paleodrainage with headwaters in the Mexican Cordillera; the drainage area inferred by Winker (1982) yields a drainage area of 600,000–700,000 km^2 and a maximum drainage length of 1200–1500 km.

Predicting Basin-Floor Fan Scales in the Deep Gulf of Mexico

From the above, detrital zircons provide a view of contributing drainage areas for the pre-Cenozoic GoM sedimentary basin and subsequent changes through the Paleogene (see also Xu et al. [2016] for early Miocene paleodrainage reconstruction). Our reconstructions for the Paleocene and Oligocene are broadly consistent with the previous model of Galloway et al. (2011), which synthesized data collected over many decades, although we present revisions that are consistent with the presence of specific DZ signatures or the lack thereof. The most significant differences pertain to: (1) the significant contributions of a paleo-Tennessee system during the Paleocene and diversion of the paleo-Tennessee to the north by the Oligocene; (2) the details of Paleocene Western Cordilleran and Rocky Mountain paleodrainage, especially the headward extent and downstream path of the Paleocene paleo–Platte-Arkansas system; and (3) the northern and western extent of Paleocene and Oligocene paleo-Mississippi headwaters routed through the northern Mississippi embayment.

As noted above, Somme et al. (2009) demonstrated a relationship between length of the longest fluvial channel and the length of basin-floor fans (see Fig. 20), which we have adjusted to use interpreted drainage-basin length instead (Fig. 21). We use this relationship and our DZ-based paleodrainage reconstructions to estimate the first-order lengths of basin-floor fans in the deepwater GoM. We compare estimates of fan length from our DZ-based paleodrainage reconstructions with empirical measurements (Snedden et al., 2017), with the important caveat that measurements are minimum values because they are based on the limits of mappable sandy facies and do not include what could be a considerable downdip muddy fringe.

Our paleodrainage reconstructions in Figures 22–25 include schematic illustrations of fans that are ~50% as long as our reconstructed drainage, whereas Table 3 summarizes predictions for fan lengths compared with empirical measurements. Most measured fans fall within the range of predictions derived from paleodrainage reconstructions, where fan lengths equal 10%–50% of estimated drainage-basin length. These include predictions for the Cenomanian paleo-Tennessee, the early Paleocene paleo–Colorado-Brazos, the early Paleocene and late Paleocene–early Eocene paleo-Mississippi, and the Oligocene paleo–Rio Grande systems. In particular, our inferred routing of much of the western U.S. drainage to the Rockdale depocenter during the early Paleocene, and capture of the paleo–Platte-Arkansas system by the paleo-Mississippi by late Paleocene time, are consistent with the locations of major Wilcox basin-floor fans shown by Zarra (2007). These examples suggest that our approach produces a general first-order pattern for sediment routing and a first-order estimate for the scale of basin-floor fans, which are consistent with measured dimensions in a well-known, mature sedimentary basin. This approach can therefore be applied to reconstruct large sediment-routing systems and predict the scale of basin-floor fans in basins that are less data rich.

Interestingly, however, a notable misfit occurs for the Oligocene paleo-Mississippi and paleo–Colorado-Brazos systems, where DZ-based paleodrainage areas and length scales are not substantially different from previous work

TABLE 3. SUMMARY OF PALEODRAINAGE RECONSTRUCTIONS, PREDICTED BASIN-FLOOR FAN SCALES, AND MEASURED FAN SCALES, GULF OF MEXICO

Paleodrainage system	Reconstructed drainage area from DZ studies	Reconstructed drainage area from point-bar scales	Reconstructed drainage length from DZ studies	Predicted basin-floor fan lengths (L_f = 0.1–0.5 L_{db})	Measured basin-floor fan lengths
Cenomanian paleo-Tennessee	400,000 km²	300,000 km²	1600 km	160–800 km	670 km
Cenomanian paleo–Colorado-Brazos	<150,000 km²	180,000 km²	300 km	30–150 km	<100 km
Early Paleocene Paleo-Mississippi	1,200,000 km²	1,300,000 km²	2000 km	200–1000 km	383 km
Early Paleocene paleo–Colorado-Brazos	2,200,000 km²	1,600,000 km²	2750 km	275–1375 km	398 km
Early Paleocene paleo–Rio Grande	500,000 km²	1,300,000 km²	1500 km	150–750 km	†
Late Paleocene to earliest Eocene paleo-Mississippi	2,200,000 km²	1,600,000 km²	2500 km	250–1250 km	392 km
Late Paleocene to earliest Eocene paleo-Colorado	1,200,000 km²	1,900,000 km²	1800 km	180–900 km	482 km
Oligocene paleo-Mississippi	1,500,000 km²	1,500,000 km²	1200 km	120–600 km	7 km
Oligocene paleo–Colorado-Brazos	600,000 km²	700,000 km²	1200 km	120–600 km	13 km
Oligocene paleo–Rio Grande	700,000 km²*	1,000,000 km²	1200 km*	120–600 km	133–347 km

Note: Reconstructed drainage areas from point-bar thickness measurements are from Milliken et al. (2015), whereas measured basin-floor fan lengths are from Snedden et al. (2017). Predictions and measurements in blue are consistent with each other, whereas those in red are not. DZ—detrital zircon; L_f—length of slope and basin-floor fan; L_{db}—length of contributing drainage basin.

*Denotes drainage area and length estimates from Winker (1982).

†No measurements were made for this interval and area.

(e.g., Galloway et al., 2011), but measured fans are more than an order of magnitude smaller than predicted. Mismatches such as these provide an opportunity to interrogate other factors that might be important. For example, in the GoM case: (1) Oligocene fans may be insufficiently mapped; (2) Oligocene fans may be insufficiently sandy to be represented by the mapped extent of sandy facies; (3) sediment discharge during the Oligocene may have been abnormally low due to an overall dry continental interior climate; (4) sediment may have been preferentially stored on the shelf during Oligocene icehouse climate conditions (e.g., Sweet and Blum, 2016); or (5) sediment may have been trapped in shelf-margin growth-faulted structures and not transferred to the slope and basin floor (e.g., Brown et al., 2004).

Our reconstructed paleodrainage areas for Cenomanian, Paleocene–early Eocene, and Oligocene fluvial systems are large by modern global standards: they would rank within the top 40 of the >6300 rivers systems that discharge to the global coastal oceans today, and the larger Paleocene and Oligocene systems would rank in the top 10 (Syvitski and Milliman, 2007). Most fan systems predicted from our paleodrainage reconstructions, and measured in the GoM, also reside within the upper part of the scale domain in the Somme et al. (2009) database. Large fluvial systems such as these, with large fine-grained sediment loads and low-gradient slopes by virtue of their large drainage areas, produce large low-gradient fans that extend hundreds of kilometers into the deeper parts of continental-margin sedimentary basins. Most analogs for basin-floor fans have been derived from relatively short systems that formed in active-margin settings; however, large low-gradient rivers drain most of the terrestrial landscape that contributes water and sediment to the coastal oceans in the modern world (see Milliman and Syvitski, 1992), a situation that seems likely for most of Earth history as well. We think it likely that large fan systems are more common in the ancient record of continental margins than heretofore thought.

CONCLUSIONS

This paper presents a large data set of U-Pb and Pb-Pb ages on detrital zircons (DZs) from Cenomanian, Paleocene–early Eocene, and Oligocene fluvial sandstones of the northern Gulf of Mexico (GoM) continental margin. We used DZ-based provenance and geochronological data to reconstruct paleodrainage areas and lengths for sediment-routing systems that have been important to the GoM sedimentary basin during deposition of Cenomanian Tuscaloosa-Woodbine, early Paleocene and late Paleocene–early Eocene Wilcox, and Oligocene Vicksburg-Frio clastic wedges. This research was conducted in parallel with Milliken et al. (2015), who independently measured point-bar thicknesses from well logs for these and other stratigraphic intervals as a proxy for paleodrainage area and length. We then used source-to-sink scaling relationships to estimate the length scales of basin-floor fans from reconstructed paleodrainage areas and lengths, and compared those estimates to measurements from a large GoM database (Snedden et al., 2017).

Our interpretations regarding paleodrainage reconstruction and sediment routing can be summarized as follows:

- The template of present-day GoM contributing drainage area can be traced to latest Cretaceous continental-scale drainage reorganization

(Blum and Pecha, 2014). During the mid-Cretaceous and earlier, the Appalachian-Ouachita cordillera formed a continental divide that separated drainage and sediment routing to the west and north from drainage to the GoM. During the Cenomanian, an ancestral Tennessee-Alabama River was the largest system contributing water and sediment to the GoM through the Mississippi embayment and to the Tuscaloosa depocenter in south Louisiana, with a series of smaller fluvial systems draining the Ouachitas and discharging sediment to the western GoM or the eastern margins of the Western Interior Seaway.

- By the early Paleocene, drainage of the southern half of North America had reorganized such that river systems with headwaters that stretched from the Western Cordillera to the Appalachians discharged to the GoM. The "Rockdale" deltaic depocenter in the Houston embayment of east-central Texas has long been recognized as the primary Paleocene Wilcox depocenter; the early Paleocene Rockdale delta was fed by the paleo–Brazos-Colorado River, which had headwaters that stretched from northwest Mexico to southern California to southern Utah and Colorado, then flowed east-southeast to the Houston embayment.
- We interpret Paleocene paleodrainage of, and sediment routing from, the Mojave and Sierra Nevada parts of the magmatic arc farther north to be descendant from Late Cretaceous fluvial systems in south-central Utah (e.g., Szwarc et al., 2015), and consistent with the Eocene California River of Davis et al. (2010) and Dickinson et al. (2012), which flowed from the Mojave part of the arc to east-central Utah. Similarly, the magmatic arc farther north in Idaho was drained by an ancestor of the Eocene Idaho River of Chetel et al. (2011), which flowed from central Idaho to the greater Green River basin in Wyoming. These systems represent river systems that were extant during the Late Cretaceous and extended eastward following withdrawal of the Western Interior Seaway to form the headwaters of an ancestral Platte River. This paleo-Platte emerged from the Laramide Rockies and was routed south through the Great Plains, through a moat caused by eastward-propagating dynamic subsidence, to join the paleo–Brazos-Colorado River and discharge to the Rockdale depocenter. Along the way, this paleo-Platte system was joined by the ancestral Arkansas and Red Rivers as well, such that most of the Western Cordillera, including the Laramide Rockies, contributed sediment to the Rockdale depocenter. Paleodrainage areas and lengths for this early Paleocene Wilcox system exceeded 2,000,000 km^2 and 2000 km, respectively, and the paleo–Brazos-Colorado River represented the continental-scale system of that time.
- A paleo–Mississippi River had emerged within the northern Mississippi embayment by the early Paleocene as well, with a drainage that extended into the U.S. midcontinent, but was not yet integrated with the Rocky Mountains. During this time, a paleo-Tennessee system continued to flow to the southwest from the Appalachians, but it remains unknown whether this paleo-Tennessee system joined the paleo-Mississippi within the southern Mississippi embayment to deliver water and sediment to the Wilcox "Holly Springs" deltaic depocenter, or discharged independently to the GoM farther to the east.
- By the latest Paleocene, the ancestral Platte and Arkansas Rivers, with their extensive Western Cordilleran headwater regions, are interpreted to have been captured and routed through the present bedrock valley of the Arkansas River to the Mississippi embayment, where they joined the ancestral Mississippi to deliver water and sediment to the Wilcox Holly Springs deltaic depocenter. Sediment supply to the Rockdale system would have diminished accordingly, with accretion of new supply to the Holly Springs system, and the paleo-Mississippi was, for the first time, linked with the Laramide Rockies and beyond. However, the connection between the paleo-Mississippi and the Western Cordillera hinterlands, via the California and Idaho Rivers, was severed shortly thereafter in the early Eocene when Laramide basins became endorheic and trapped water and sediment.
- By the Oligocene, the western headwaters and drainage divide for the paleo–Colorado-Brazos system had migrated significantly to the east to present-day southern Colorado, western New Mexico, and eastern Arizona, with corresponding decreases in water and sediment contributions to the northwestern GoM margin and Houston embayment. Moreover, the ancestral Platte system likely drained to the east and north, rather than east and south into the Mississippi embayment, hence western drainage contributions to the GoM as a whole had decreased significantly. However, the paleo–Arkansas-Red systems joined the paleo-Mississippi in the southern Mississippi embayment, and the paleo-Tennessee was diverted to the north toward its present-day junction with the Ohio River by this time, thus becoming a tributary to the paleo-Mississippi within the northern Mississippi embayment. Hence, the paleo-Mississippi was the largest Oligocene system of the northern GoM margin, with drainage area and length estimated at 1,500,000 km^2 and 1200 km, respectively.
- Although not part of this study, previous work by Winker (1982) and Galloway et al. (2011) shows that the major Oligocene depocenter for the GoM as a whole was located in the Rio Grande embayment, and likely represents a paleo–Rio Grande–Rio Bravo system that drained the Mexican Cordillera.

We used drainage areas and lengths from our paleodrainage reconstructions to predict the length scales of basin-floor fans in the deepwater GoM using scaling relationships in Somme et al. (2009) and Blum et al. (2013). For the Cenomanian, we predict a paleo–Tennessee-Alabama basin-floor fan system with lengths of 160–800 km in the east-central GoM, with a very minor system in the western GoM. By contrast, the large drainage areas and lengths of both early and late Paleocene rivers lead to predictions of essentially basin-filling fans associated with the Rockdale and Holly Springs depocenters, with lengths of 200–1000 km or more. We predict the Rockdale basin-floor fan system to have been the largest and most volumetrically significant during the early Paleocene, with the paleo-Mississippi Holly Springs fan system to have been the most significant during the late Paleocene, following capture of the paleo–Platte-Arkansas systems. The predicted scales of basin-floor fans for each depocenter are of the same scale as or larger than the modern Mississippi fan and reside within the upper part of the scale domain for all modern fans that have been measured (Somme et al., 2009). Our Cenomanian and Paleocene predictions bracket measurements of fan scales (Snedden et al., 2017) and our early Paleocene and late Paleocene–early Eocene fan scales and locations are consistent with mapping by Zarra (2007). By contrast, for the Oligocene, our drainage reconstructions predict smaller fan systems for the northwestern GoM and the paleo-Mississippi system in the central GoM, relative to their Paleocene–early Eocene precursors. However, measurements by Snedden et al. (2017) show very small fan systems for these areas, with the largest Oligocene fans related to a paleo–Rio Grande system that drained the Mexican Cordillera. With the notable exception of the Oligocene, measured fans reside within the range of our predictions.

Considered broadly, this research was designed as a first-order test of source-to-sink concepts (see Somme et al., 2009; Helland-Hansen et al., 2016) in a well-known sedimentary basin. Our DZ record is based on systematic sampling for discrete time slices within the GoM basin fill as a whole, and demonstrates that distinct paleodrainage areas and sediment-routing systems can be differentiated in a manner that is, in aggregate, consistent with but refines previous work (e.g., Galloway et al., 2011) and can be accomplished in a relatively short period of time. Coupled with independent metrics of point-bar thicknesses for these same units in the outcrop or subsurface, this approach can be exported to other basins that are less data rich to predict the basinward extent of basin-floor fans and/or can be used in an iterative way to examine inconsistencies in paleogeographic interpretations and/or genetic understanding.

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