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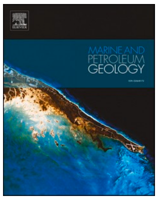

Sediment input, alongshore transport, and coastal mixing in the northeastern Gulf of Mexico based on detrital-zircon geochronology☆

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ABSTRACT

We present detrital-zircon U–Pb geochronology from the Mississippi, Mobile, and Apalachicola rivers, as well as five beach and barrier island deposits to determine sediment sources, alongshore transport, and sediment mixing in the northeastern Gulf of Mexico. The Mississippi River has a distinct age spectrum defined by prominent Cenozoic and Mesozoic populations coupled with minor Appalachian (490-270 Ma), Grenville (1200-900 Ma), Granite-Rhyolite (1500-1300 Ma), and Yavapai-Mazatzal (1800-1600 Ma) populations. The Mobile and Apalachicola rivers exhibit age spectra containing few to no Cenozoic grains, are proportionately dominated by Appalachian and Grenville populations, and have minor populations consisting of Iaptian Rifting/Gondwanan (850-550 Ma), Granite-Rhyolite, and Yavapai-Mazatzal ages. Comparison of U–Pb age spectra and inverse mixing models shows that beach and barrier island deposits are primarily derived of material from the Apalachicola River, with Mobile River contribution being dependent on geographic position west of Mobile Bay. Minor Mississippi River contribution in coastal deposits results from shelf bypass to deep marine sinks and when present is likely associated with recycling of Coastal Plain strata. Metamorphic zircon grain abundance (14–36%) in coastal deposits and chemical-age relationships to southern Appalachian eastern Blue Ridge and Inner Piedmont provinces corroborate Apalachicola and or Mobile river system provenance. Results from this study suggest that anthropogenic influences and hurricanes have little to no effect on the detrital-zircon age spectra at a regional scale, and that the northeastern Gulf of Mexico can be used as an analog for older Cenozoic and Mesozoic source to sink investigations in the eastern Gulf Coastal Plain.

1. Introduction

Paleo-reconstructions of Neogene and older clastic intervals focus on determining the stratigraphic age, depositional environment, and sediment provenance. These unknown variables are determined using sedimentological field observations, thin section petrography, biostratigraphic context, and various geochronology techniques. Detrital zircon U–Pb dating has become a leading approach for determining sediment provenance because it provides information on source rock terranes that can be used to reconstruct sediment transport pathways (Sircombe, 1999; Fedo et al., 2003; Dickinson and Gehrels, 2009; Gehrels, 2014; Gooley and Nieminski, 2021). However, provenance interpretations based on detrital-zircon geochronology often prove difficult when multiple source rocks exhibit similar age spectra, or when multiple generations of sediment recycling are involved (Thomas, 2011; Surpless et al., 2019). In the modern (Pleistocene and Holocene) sedimentary record, depositional environments, sediment provenance, and stratigraphic age relationships are known or well understood. Evaluation of these deposits provides an opportunity to assess the applicability of detrital-zircon geochronology and the appropriateness of ancient rock record interpretations (e.g., Mason et al., 2017; Ibañez-Mejia et al., 2018; Malkowski et al., 2019).

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The northeastern Gulf of Mexico between Apalachicola, Florida and New Orleans, Louisiana is an ideal natural laboratory to study alongshore transport and coastal sediment mixing using detrital-zircon geochronology. Three different river systems, the Mississippi, Mobile, and Apalachicola supply sediment to the coast and exhibit distinctive rock types and bedrock ages within drainage systems. While the Mississippi and Apalachicola rivers have previously been studied by detrital-zircon geochronology (Iizuka et al., 2005; Blum et al., 2017; Gregory et al., 2021), the Mobile River and coastal deposits remain unexamined. This region is also well suited to investigate possible anthropogenic (dredging, beach renourishment) and storm (hurricane) influences on detrital-zircon signatures because coastal processes have been well documented over the past 30 years (Stone and Stapor, 1996; Davis, 1997; Boudreau, 1998; Cipriani and Stone, 2001; Kossin, 2008; Parson and Swafford, 2012; Bergillos et al., 2016; Odezulu et al., 2020).

To determine sediment sources, alongshore transport, and sediment mixing of modern sediment in the northeastern Gulf of Mexico, we present detrital-zircon geochronology from the Mississippi, Mobile, and Apalachicola rivers, as well as five beach and barrier island deposits (Apalachicola Beach, Okaloosa Island, Dauphin Island, Ship Island, and Cat Island) along the northeastern Gulf of Mexico (Fig. 1). This study is centered on the hypothesis that drainage networks with different rock types and bedrock ages will produce unique zircon chemical-age data. We seek to address whether that chemical-age data can then differentiate between various river systems, be tracked in subsequent coastal deposits, and produce realistic results through Monte Carlo inverse mixing models. Documenting the detrital-zircon record of modern river and coastal deposits can also provide an analog for ancient (Neogene and older) sediment provenance studies in the eastern Gulf Coastal Plain.

2. Background

2.1. Northeastern Gulf of Mexico

The Gulf of Mexico is an ocean basin flanked by the continental United States to the north, Mexico to the west and south, and Cuba to the southeast. Tectonic initiation of the Gulf of Mexico began in the Late Triassic-Early Jurassic as continental rifting associated with the breakup of Pangea (Dickinson et al., 2010; Huerta and Harry, 2012; Weislogel et al., 2015; Frederick et al., 2020; Filina et al., 2022). Rifting and associated syntectonic sedimentation continued for ~20 to 30 Ma, while crustal extension persisted into the Cretaceous (Stern and Dickinson, 2010). By the mid Cretaceous thermal subsidence along the northern Gulf of Mexico led to basin filling by North American continent sediment, presumably from the southern Appalachians (Snedden et al., 2022). Jurassic through Holocene deposition established an overall prograding passive margin sequence that has resulted in the accumulation of >15 km of strata in certain regions (Galloway and Buster, 2011; Ewing and Galloway, 2019).

The northeastern Gulf of Mexico coast is characterized as a microtidal, storm-dominated environment, with low wave energy in the absence of tropical cyclone activity (Davis, 1997). Shelf water circulation is primarily controlled by the Gulf Loop Current which draws warm water from the Caribbean clockwise through the central Gulf of Mexico and exits through the Straights of Florida. Wave interaction with the coastline and wind-generated currents mix and rework coastal sediment with continental shelf sediment (Davidson Arnott et al., 2012). Prevailing southeasterly winds result in a generally east to west longshore current, promoting the development of alongshore beaches, barrier islands, elongated longshore bars, and coastal spits.

2.2. Coastal deposits

The present development of beaches and barrier islands along the northeastern Gulf of Mexico coast are a result of longshore sediment transport in response to wave and tidal forcing (Hayes, 1979; Stone and Stapor, 1996; McBride et al., 2004; Rodriguez and Meyer, 2006; Byrnes et al., 2013; Otvos, 2012). East of Mobile Bay, the coastline is characterized by beach ridge plains and a barrier split, the Morgan Peninsula, in which sediment is derived from erosion of beaches to the east, and possibly offshore (Rodriguez and Meyer, 2006; Byrnes et al., 2013). To the west of Mobile Bay, barrier islands flank the Alabama, Mississippi, and Louisiana coasts and record east to west alongshore transport in island morphologies, in which islands taper in width from east to west (Byrnes et al., 1991, 2012, 2013; McBride and Byrnes, 1995; McBride et al., 1995). Coastal deposits initiated between 3000–5000 years ago in response to the slowing of Holocene sea level rise (Davis and Kuhn, 1985; Rodriguez and Meyer, 2006; Blum and Roberts, 2012). Modern terrestrial sediment supply rates are too low to contribute to beach and barrier island deposits (Davis, 1997); however, sediment accumulation on the continental shelf during the pre-Holocene provide the sediment source for beach and barrier island development and are sourced from drainage systems along the northeastern Gulf of Mexico.

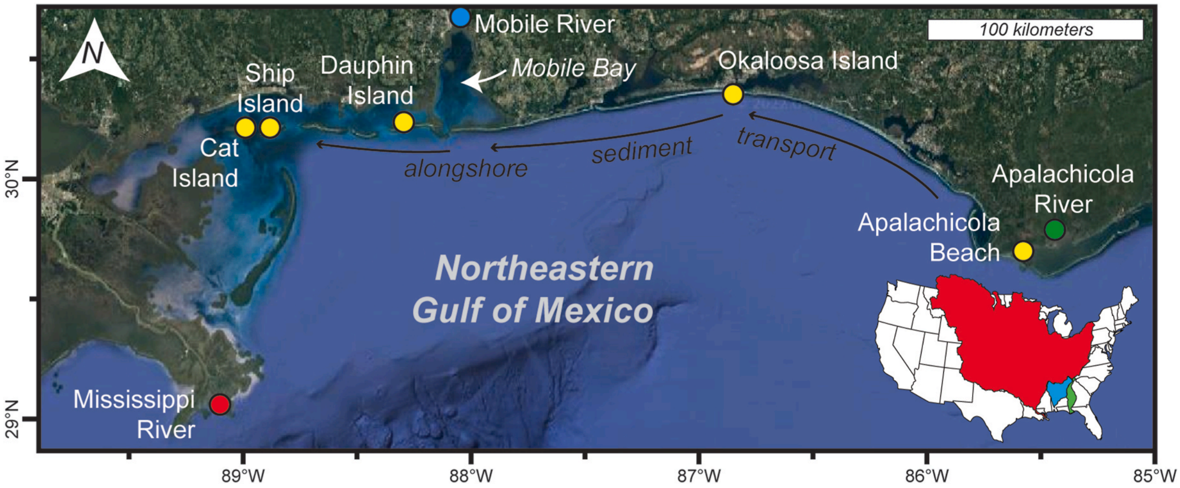

Fig. 1. Sample location and modern alongshore transport in the northeastern Gulf of Mexico. The insert map (bottom right) indicates extent of the Mississippi (red), Mobile (blue), and Apalachicola (green) drainages. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2.3. River systems

The Mississippi River drainage system expands 3.2 million km^2, covering 41% of the contiguous United States and part of southern Canada. The drainage contains surficial rock exposures and a detrital zircon signature spanning from the Precambrian to the Quaternary, characterized by populations associated with the western Cordillera province (<270 Ma), the Appalachian-Ouachita-Marathon orogenic system (490-270 Ma), Iaptian rifting/Gondwana (850-550 Ma), and basement rocks from the Grenville (1200-900 Ma), Granite-Rhyolite (1500-1300 Ma), Yavapai-Mazatzal (1800-1600 Ma), Penokean (2000–1800 Ma), and Wyoming/Superior (>2400 Ma) domains (Iizuka et al., 2005; Blum et al., 2017; Gregory et al., 2021). The Mobile River drainage network is ~115,000 km^2 and covers portions of Alabama, Mississippi, Georgia, and Tennessee. The Mobile drainage contains Paleozoic foreland (Black Warrior Basin) strata from the southern Appalachian and Ouachita thrust belts, Precambrian and Paleozoic metamorphic and igneous rocks from the southern Appalachian Piedmont (Blue Ridge and Inner Piedmont provinces), and Mesozoic through Cenozoic strata in the eastern Gulf Coastal Plain. The Apalachicola River drainage incorporates the Chattahoochee and Flint rivers and spans ~50,500 km^2. The Apalachicola River drainage incorporates metamorphic and igneous rock from the southern Appalachian Piedmont Province, a portion of Paleozoic southern Appalachian Valley and Ridge strata, and Mesozoic through Cenozoic strata in the Gulf Coastal Plain.

3. Methods

Eight sediment samples were collected for detrital-zircon U–Pb geochronology from rivers, beaches, and barrier islands along the northeastern Gulf of Mexico (Fig. 1; Table 1). Approximately 10–20 kg of unconsolidated sediment was collected for each sample at depths of 0.3–1.0 m. The Mississippi River sample was collected at Fort Jackson, Louisiana from a point bar located on the main channel of the Mississippi River delta. The Mobile River sample was collected from the northern end of Gravine Island, a channel bar along the Tensaw River ~15 km north of Mobile Bay. While Gravine Island is not a natural landform, it consists of dredge spoils from the canal between the Mobile and Tensaw river channels, which provides a characteristic sampling of the drainage system. The Apalachicola River sample was collected from a point bar ~8 km upstream from the mouth of the river. The locations for the subsequent beach and barrier island deposits were selected to establish a balance between analytical costs and spatial resolution between each river system. After collection, samples were dried in an oven at 50–60 °C for up to 8 h dependent on the moisture content.

3.1. Sand grain parameters

To compare river, beach, and barrier island deposits the grain size, shape, sorting, and mineralogy was determined for each sample. To characterize grain size parameters, 100 g of sediment was sieved for 15 min using a vibratory sieve shaker Analysette 3 Pro with Phi tray sizes of −2, −1,0,1,2,3, and 4, as well as a catch tray (Gee and Bauder, 1986). Sand minerology was determined by quartz-feldspar-lithic (QFL) estimates and X-Ray diffractometry (XRD) for both whole rock and heavy mineral aliquots. Approximately 10 g of unconsolidated sand grains were crushed with a mortar and pestle into a flour like consistency and placed on a puck for XRD evaluation. Samples were analyzed using a Bruker D8 Advanced X-Ray Diffractometer, scanning from 5 to 65° 2θ for bulk and 5–70° 2θ for heavy mineral analysis. Eva software was used to determine minerology based on d-spacing of prominent diffraction maxima.

3.2. Detrital zircon geochronology

Traditional heavy mineral separation techniques were used to isolate zircon grains from bulk sand samples (e.g., Gehrels et al., 2008). Approximately 5 kg of sediment was processed through a Wilfley water table. Heavy mineral aliquots were then dried in an oven and then processed through a hand magnet to separate magnetic from nonmagnetic minerals. Further magnetic separation, using a Frantz Magnetic Separator, was conducted over two iterations, the first at 0.5 amp and 1° and then at 1.5 amp and 1°. The nonmagnetic aliquot was then processed through heavy liquid separation using Lithium Sodium Tungstate (LST) in a separatory flask. After heavy liquid separation, zircons were picked in dry air with tweezers and mounted on clear acrylic disks with 3M double-coated tape using a Leica M125 stereomicroscope. To avoid hand picking biases of zircon grains, groups of heavy mineral grains were selected together not individual zircons.

Zircon U–Pb data were collected using an ESI NWR 193 nm Excimer laser ablation system coupled with a Thermo Scientific iCapQ quadrupole mass spectrometer, utilizing a 20 μm laser diameter at the University of Arkansas in the Trace Element and Radiogenic Isotope Lab (TRAIL). Zircon grains were selected using the ESI program by systematically moving in a grid pattern across the mounted sample and analyzing each zircon encountered to avoid selection bias. However, grains with obvious fracturing and inclusions were avoided due to the potential of lead loss.

Data were reduced using Iolite version 4 (Paton et al., 2011). The Plesovice standard (Sláma et al. 2008) was used as a primary standard along with R33 (Black et al., 2004) and 91,500 (Wiedenbeck et al., 1995) as secondary standards. The baseline was established with a 2 standard deviation (SD) outlier and all standards and samples were

Table 1
Sand grain analysis for river system inputs and beach and barrier island deposits in the northeastern Gulf of Mexico. Mean and median values reported in phi-scale.

Sample	Latitude and Longitude	Environment	Grain Size Parameters Mean	Median	Kurtosis	Skewness	STD	Sphericity	Roundness	Q-F-L
Apalachicola River	29.771, −85.041	River (point bar)	1.23	1.3	1.17	−0.07	0.65	0.1	Subangular	70-15–15
Mobile River	30.802, −87.924	River (channel bar)	1.68	1.6	1.34	0.28	0.56	0.14	Subrounded	75-20–5
Mississippi River	29.359, −89.453	River (point bar)	1.72	1.6	1.9	0.12	0.8	0.13	Subangular	60-10–30
Apalachicola Beach	29.716, −85.121	Beach (swash zone)	1.68	1.6	1.2	0.19	0.6	0.14	Subangular	75-10–15
Okaloosa Island	30.393, −86.593	Barrier Island (ocean side beach)	1.42	1.4	1.09	−0.09	0.43	0.19	Subrounded	90-5–5
Dauphin Island	30.253, −88.152	Barrier Island (lagoon side beach)	1.07	1.1	0.78	−0.09	0.62	0.17	Subrounded	85-5–10
Ship Island	30.211, −88.986	Barrier Island (ocean side beach)	1.68	1.6	1.11	0.24	0.58	0.16	Subangular	85-5–10
Cat Island	30.209, −89.087	Barrier Island (ocean side beach)	1.53	1.5	1.6	0.12	0.53	0.12	Subangular	90-5–5

analyzed with a 3 SD outlier. The baseline was cropped to show 1–30 s of the signal, whereas the standards and the samples were cropped to show 12–21 s of the signal. A transition of best age determinations at 1200 Ma from $^{206}Pb/^{238}U$ ages to $^{207}Pb/^{206}Pb$ ages was used based on uncertainties and the initiation of the Grenville orogeny. Some grains have been split into rims and cores based on multiple age domains that where visually identified using Iolite software. Analyses that had a percent discordance greater than 20% or less than −5% reverse discordance were discarded to provide a balance between analytical accuracy and a representative spectrum of detrital ages (e.g., Spencer et al., 2016). Age results for each sample are displayed as kernel density estimations (KDEs). To further interpret detrital-zircon age spectra, we utilize DZstats, DZmds, and DZmix software packages (Saylor and Sundell, 2017). Uranium and Th concentrations (ppm) reported during LA-ICPMS are used to report zircon Th/U values. Percent abundance of metamorphic zircons for each individual sample is calculated as the number of grains with values < 0.1 with respect to the overall number of analyses.

4. Results

4.1. Grain size, shape, sorting, and mineralogy

River, beach, and barrier island samples are medium-grained sands, with subangular to rounded textures (Fig. 2, Table 1). Sediment (>50%) in the 2.00 Φ size fraction has a mean grain size ranging from 1.07 to 1.72 Φ, median ranging from 1.1 to 1.6 Φ. All samples are well-sorted except for the Mississippi River sample that exhibits moderate sorting (Table 1). Samples range from finely skewed (Mississippi River, Mobile River, Apalachicola Beach, Ship Island, Cat Island) to nearly symmetrical (Apalachicola River, Okaloosa Island, Dauphin Island) and are platykurtic with kurtosis values ranging from 0.78 to 1.9. Quartz-Feldspar-Lithic (Q-F-L) estimates show that samples have a high (>75%) abundance of quartz with a low (<20%) amount of combined feldspar and lithic fragments except for the Mississippi River, which has a higher abundance of lithic fragments. X-Ray diffraction (XRD) for bulk analysis shows that all samples are dominantly quartz with the Mississippi River also having small amounts of feldspar, whereas analysis of heavy mineral aliquots shows abundant zircon from all sample locations (Supplemental Material).

4.2. Detrital zircon U–Pb ages and Th/U values

The Apalachicola River (n = 189) exhibits 38% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 37% percent associated with the Grenville (1200-900 Ma) orogeny (Fig. 3). Twenty-two percent of grains are Iaptian/Gondwana (850-500 Ma) but do not show a systematic, noticeable peak age. Three percent of grains are associated with a Granite-Rhyolite (1500-1200 Ma) age domain. The youngest single grain for the Apalachicola River sample is 297 Ma, and a weighted mean average of the youngest population (n = 3) results in a maximum depositional age of 318 Ma. The Apalachicola River sample contains 47 grains (25%) that exhibit Th/U values < 0.1 (>10 U/Th), and of those grains most exhibit Appalachian U–Pb ages.

The Mobile River (n = 400) exhibits 27% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 54% associated with the Grenville (1200-900 Ma) orogeny (Fig. 3). One percent of grains are Western Cordillera (<270 Ma), 8% of grains exhibit Iaptian/Gondwana (850-500 Ma), 9% of grains are Granite-Rhyolite (1500-1200 Ma), and <1% are Yavapai-Mazatzal (1800–1600). The youngest single grain for the Mobile River sample is 49 Ma, and a weighted mean average of the youngest population (n = 3) results in a maximum depositional age of 317 Ma. The Mobile River sample contains 72 grains (18%) that exhibit Th/U values < 0.1, and of those grains most exhibit Appalachian U–Pb ages.

The Mississippi River (n = 203) exhibits 10% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 9% associated with the Grenville (1200-900 Ma) orogeny (Fig. 3). Fifty-six percent of grains are Western Cordillera (>270 Ma), 1% of grains exhibit Iaptian/Gondwana (850-500 Ma), 7% of grains are Granite-Rhyolite (1500-1200 Ma), and 17% are Yavapai-Mazatzal (1800–1600). The youngest single grain for this sample is 14 Ma, and a weighted mean average of the youngest population (n = 3) results in a maximum depositional age of 17 Ma. The Mississippi River sample contains 13 grains (6%) that exhibit Th/U values < 0.1, and of those grains most exhibit Appalachian U–Pb ages.

Apalachicola Beach (n = 174) exhibits 45% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 38% associated with the Grenville (1200-900 Ma) orogeny (Fig. 3). Three percent of grains exhibit Western Cordillera (>270 Ma), 12% of grains exhibit Iaptian/Gondwana (850-500 Ma), and 3% of grains are Granite-Rhyolite (1500-1200 Ma). The youngest single grain for this sample is 194 Ma, and a weighted mean average of the youngest population (n = 3) results in a maximum depositional age of 320 Ma. The Apalachicola Beach sample contains 25 grains (14%) that exhibit Th/U values < 0.1, and of those grains most exhibit Appalachian U–Pb ages.

Okaloosa Island (n = 150) exhibits 48% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 28% associated with the Grenville (1200-900 Ma) orogeny (Fig. 3). Five percent of grains exhibit Western Cordillera (>270 Ma), 19% of grains exhibit Iaptian/Gondwana (850-500 Ma), and 1% of grains are Granite-Rhyolite (1500-1200 Ma). The youngest single grain for this sample is 65 Ma, and a weighted mean average of the youngest population (n = 5) results in a maximum depositional age of 322 Ma. The Okaloosa Island sample contains 45 grains (30%) that exhibit Th/U values < 0.1, and of those grains most exhibit Appalachian U–Pb ages.

Dauphin Island (n = 199) exhibits 27% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 46% associated with the Grenville (1200-900 Ma) orogeny (Fig. 3). Two percent of grains exhibit Western Cordillera (>270 Ma), 21% of grains exhibit Iaptian/Gondwana (850-500 Ma), and 6% of grains are Granite-Rhyolite (1500-1200 Ma). The youngest single grain for this sample is 36 Ma, and a weighted mean average of the youngest population (n = 4) results in a maximum depositional age of 322 Ma. The Dauphin Island sample contains 58 grains (29% of all grains) that exhibit Th/U values < 0.1, and of those grains most exhibit Appalachian U–Pb ages.

Ship Island (n = 146) exhibits 32% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 41% percent associated with the Grenville (1200-900 Ma) orogeny (Fig. 3). Twenty-four percent of grains exhibit Iaptian/Gondwana (850-500 Ma), and 3% of grains are Granite-Rhyolite (1500-1200 Ma). The youngest single grain for this sample is 306 Ma, and a weighted mean average of the youngest population (n = 5) results in a maximum depositional age of 356 Ma. The Ship Island sample contains 44 grains (30%) that exhibit Th/U values < 0.1, and of those grains most exhibit Appalachian U–Pb ages.

Cat Island (n = 162) exhibits 36% zircon grain abundance associated with Appalachian tectonism (490-270 Ma) and 40% abundance with the Grenville (1200-900 Ma) orogeny (Fig. 3). One percent of grains exhibit Western Cordillera (>270 Ma), 18% of grains exhibit Iaptian/Gondwana (850-500 Ma), 4% of grains are Mid-Continent (1500-1200 Ma), and 1% are Yavapai-Mazatzal (1800–1600). The youngest single grain for this sample is 56 Ma, and a weighted mean average of the youngest population (n = 4) results in a maximum depositional age of 335 Ma. The Cat Island sample contains 58 grains (36%) that exhibit Th/U values < 0.1, and of those most grains exhibit Appalachian U–Pb ages.

5. Interpretations

5.1. Detrital zircon geochronology

All three river samples provide detrital-zircon age spectra that can be differentiated from one another. The Mississippi River contains major

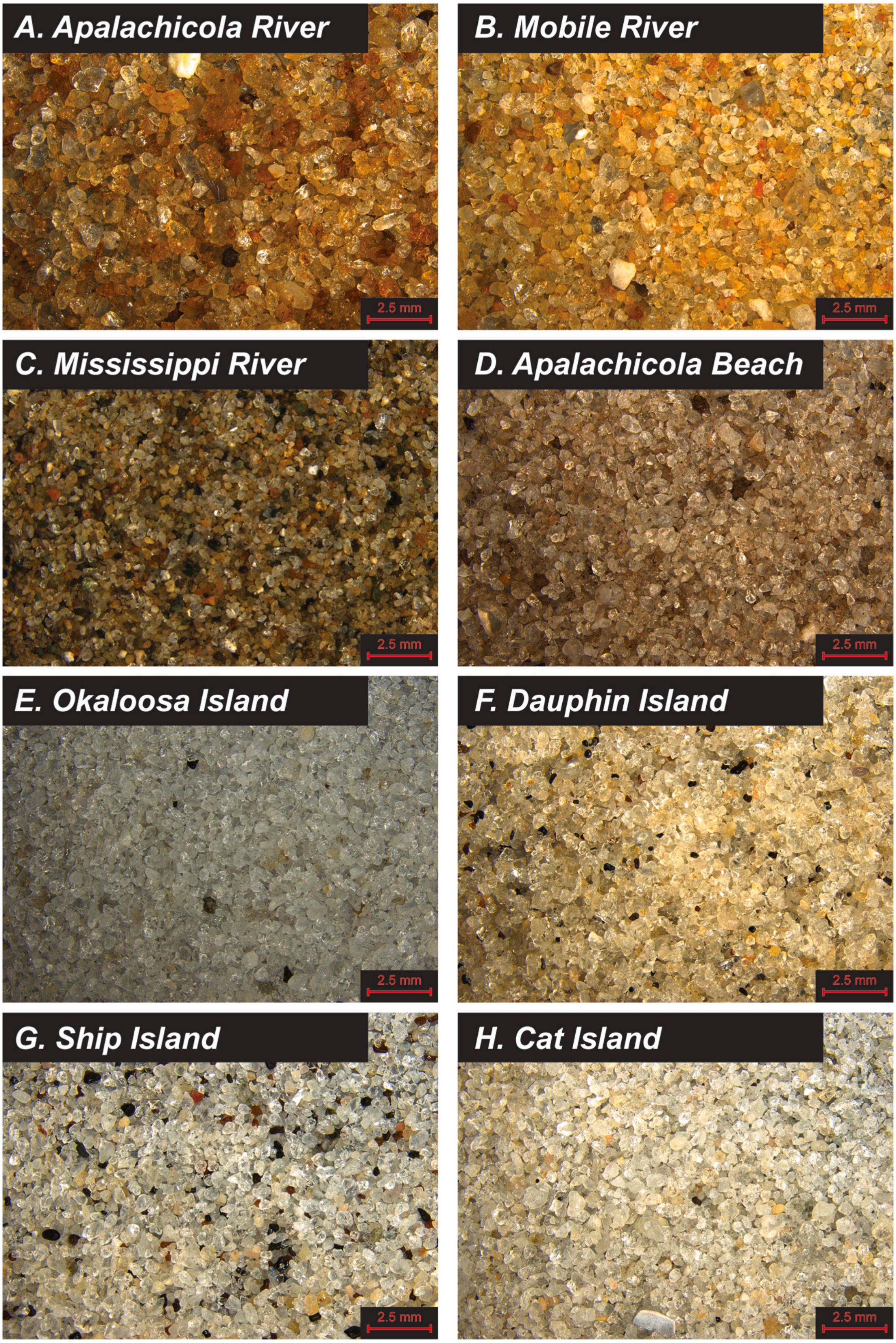

Fig. 2. Stereomicroscope images for rivers, beach, and barrier island samples. The red scale bar in the bottom right of each image is 2.5 mm. Visual heterogeneity in Quartz-Feldspar-Lithics content can be qualitatively assessed for each sample. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

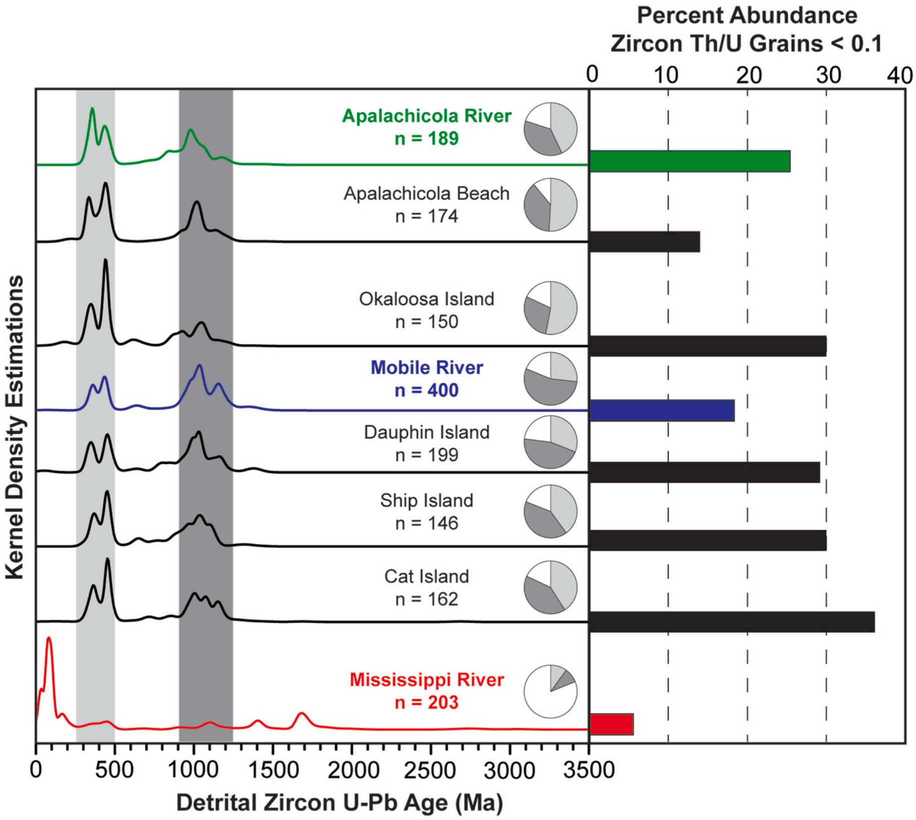

Fig. 3. Kernel density estimations (KDEs) for detrital-zircon geochronology. Samples are stacked spatially from east (top) to west (bottom). KDEs were normalized using 'Provenance' (Vermeesch, 2016) using with a bandwidth of 20. Percent abundance of zircon grains with Th/U values < 0.1.

Cenozoic and Mesozoic populations associated with western US Cordillera sediment sources. The presence of these grain ages is negligible or absent in other river samples, as well as beach and barrier island samples. The Mississippi River spectrum also differs from other samples based on an increased proportion of Granite-Rhyolite and Yavapai-Mazatzal ages. The Mobile and Apalachicola rivers are defined by two prominent populations associated with Appalachian (490-270 Ma) and Grenville (1200-900 Ma) ages. Each river system can be distinguished based on proportions of Appalachian versus Grenville grains, in which the Mobile River exhibits a greater proportion of Grenville grains, and the Apalachicola River exhibits a greater proportion of Appalachian grains.

Each beach and barrier island sample exhibits an age spectrum dominated by Appalachian and Grenville populations. Dauphin Island has a higher abundance of Grenville grains, which can be associated with a spatial relationship to the mouth of the Mobile River and Mobile Bay (Fig. 1). Apalachicola Beach and Okaloosa Island have a higher abundance of Appalachian grains compared to Grenville. Ship Island and Cat Island have a higher abundance of Appalachian grains than Grenville, the amount of grains is smaller than the islands east of Dauphin Island. Based on these age spectra, we interpret coastal deposits east of Mobile Bay to be primarily sourced from the Apalachicola River. Barrier island deposits at and west of Mobile Bay are interpreted to be a mixture between Mobile and Apalachicola river systems. These data also suggest that material from the Mississippi River is mostly bypassing the continental shelf and being deposited in deep marine environments. When the Mississippi River signature is present it is likely a product of recycling from older Coastal Plain strata.

5.2. Zircon Th/U values

Zircon Th/U values are a product of the enrichment of U in environments with abundant metamorphic fluids, the preferential purging of Th relative to U during zircon recrystallization, and/or the depletion of Th during growth of metamorphic monazite (Hoskin and Schaltegger, 2003; Harley et al., 2007). Metamorphic zircon Th and U values can vary over several orders of magnitude yet tend to exhibit Th/U values < 0.1 (or U/Th > 10), potentially providing a first-order approach to distinguish between metamorphic and igneous growth processes (Williams and Claesson, 1987; Vavra et al., 1999; Williams, 2001; Rubatto et al., 2001; Rubatto, 2002, 2017; Hoskin and Schaltegger, 2003; Kelly and Harley, 2005; Harley et al., 2007; Gehrels et al., 2009). Yakymchuk et al. (2018) explore the variability of Th/U in metamorphic and igneous zircons from western Australia and show that metamorphic zircons exhibit a median Th/U value of 0.44, while igneous zircons exhibit a median value of 0.68. Their evaluation also shows that the 25th percentile of Th/U values is 0.08 for metamorphic zircons and 0.49 for igneous zircons. These results can be interpreted to suggest that while variability of zircon Th/U values does exist in metamorphic and igneous rocks, values < 0.1 are likely associated with metamorphism. McKay et al. (2018) show that the amount and type of variability in zircon Th/U values can be used to distinguish between zircons formed in subduction-related melts or extensional-related melts. Therefore, the variability in zircon Th/U values can be utilized for establishing chemical-age relationships for detrital-zircons, providing an enhanced fingerprint to potential sediment source terranes during provenance evaluations.

The Apalachicola River, Mobile River, and all coastal deposit exhibit sample abundance of 14–36% for zircons with Th/U values < 0.1 (Fig. 3). In contrast, the Mississippi River sample contains 6% grain abundance of zircon Th/U values < 0.1. The Apalachicola River drainage network is primarily comprised of the southern Appalachian eastern Blue Ridge and Inner Piedmont provinces providing the largest surficial availability for metamorphic source rocks. Portions of the southern Appalachian Piedmont are also located within the Mobile River drainage through the Tallapoosa tributary. A visual chemical-age comparison of zircon U–Pb ages versus zircon Th/U show qualitative matches between coastal deposits and the Apalachicola and Mobile river samples (Supplemental Material). We interpret these relationships to collaborate a sediment provenance for coastal deposits derived from the Apalachicola and Mobile river systems.

5.3. *DZstats and DZmds*

Cross Correlation Coefficient (CCC), Likeness, Similarity, Kolmogorov-Smirnov (K–S) D value, and Kuiper V value statistical tests indicate dissimilarity relationships between the three river samples to alongshore beach and barrier island deposits (Fig. 4; Supplemental Material). The Mississippi River sample is dissimilar to all coastal deposits, independent of test version. From Apalachicola Beach to Dauphin Island a spatial relationship in dissimilarity is identified in each test and shows that coastal deposits are more similar to the closest river system (Apalachicola or Mobile) and or the most proximal coastal deposit. To the west of Dauphin Island, Ship and Cat Island samples are most similar to one another. The Dauphin Island sample is most similar to the Mobile River sample, while all other coastal deposits are more similar to the Apalachicola River sample.

Mixing models corroborate statistical evaluations of detrital zircon age spectra (Fig. 5; Supplemental Material). Models based on cross correlation coefficient, Kolmogorov-Smirnov (K–S) D value, and Kuiper V value tests consistently show minor Mississippi River contribution to coastal deposits. All three models indicate a dominant contribution from the Apalachicola River system in coastal deposits except Dauphin Island, which indicates a majority contribution from the Mobile River system. Saylor and Sundell (2016) show that CCC modeling using KDEs does not produce reliable results from synthetic data sets. While K–S and Kuiper produce somewhat similar modeling results of coastal deposits, we rely on Kuiper V evaluations because models yielded more precise standard deviation values and produce results that more realistically mimic the east to west alongshore sediment transport processes.

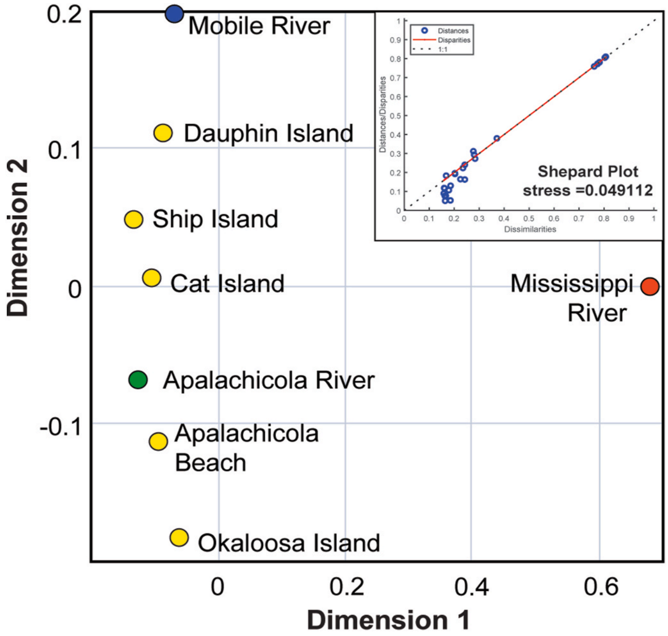

Fig. 4. Multi-dimensional plot using DZmds (Saylor and Sundell, 2017) Kuiper V statistics. Plot compares the dissimilarity between river, beach, and barrier islands U–Pb age spectra. Each coastal deposit (yellow) and river system (red = Mississippi; blue = Mobile; Green = Apalachicola) are label next to their corresponding sample. Cross correlation coefficient, Likeness, and K–S D value statistical results available in supplemental material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

The Kuiper V mixing model suggests that coastal deposits receive the majority of sediment from both the Apalachicola and Mobile rivers. In this model, sediment is delivered to the coast and then mixed, via alongshore transport, dependent on the geographic position relative to river systems. East of Mobile Bay, coastal deposits are primarily comprised of Apalachicola River sediment, with lesser amount of the Mississippi River system and the Mobile River system. Just to the west-southwest of Mobile Bay, the Dauphin Island deposit is comprised of 51% Mobile River sediment and 48% Apalachicola River sediment. To the west of Mobile Bay, coastal deposits are comprised primarily of Apalachicola River sediment, with lesser amounts of Mobile and Mississippi river sediment. The proportion of Mobile River sediment decreases to the west, presumably in response to further mixing during east to west alongshore transport.

The increased presence of a Mississippi River sediment signature at Okaloosa Island in this model requires evaluation. Either shelf mixing preferentially concentrated the limited amount of Mississippi River material to the Okaloosa Island region, or a Mississippi River signature was introduced to the coast from older onshore deposits. Based partially on detrital-zircon geochronology, Xu et al. (2017) demonstrate a west to east alongshore current in the northeastern Gulf of Mexico during the Miocene. We suggest that local drainages between the Apalachicola and Mobile drainages supplied sediment containing the Mississippi River signature that proportionately mixed with the Apalachicola derived alongshore sediment at Okaloosa Island. The Apalachicola and Mobile rivers systems lack the ability to supply enough sediment to the coast for beach and barrier island development because of damns upstream in the drainage systems. This requires that shelf material be introduced and mixed to the alongshore coastal setting during the late Holocene transgression (Galloway and Buster, 2011). This supports an interpretation that pre-existing Pleistocene (and possibly older) strata contributed to local influxes of sediment with an enhanced Mississippi River signature.

6. Discussion

6.1. *Sample comparisons*

A comparison of our results for the Mississippi River and the Apalachicola River to previously reported detrital-zircon geochronology provides an opportunity to evaluate data reproducibility in modern settings (Supplmental Material). We compare the Mississippi River sample to results from Iizuka et al. (2005), Blum et al. (2017), and Gregory et al. (2021). All Mississippi River samples contain similar age distributions but exhibit different proportional distributions. This variance in proportion may be a result of the differences in the number of analyses per sample (n value ranges from 82 to 415) or sedimentological processes controlling sediment mixing signatures in the lower reaches of the Mississippi River. Discussions on the number of analyses per sample for detrital-zircon geochronology focus on the confidence level that every population in the age spectrum is capture (Vermeesch, 2004; Pullen et al., 2014). The four Mississippi River samples contain similar age spectra, so while the number of analyses per sample differs, each sample captures similar age presence in the system. This seems to suggest that increasing individual sample analysis numbers to similar values would promote more homogenous results.

The Mississippi River samples express a spatial relationship to statistical dissimilarity. Our Mississippi River sample is the furthest downstream sample along the system and each comparable sample becomes more dissimilar the farther upstream. It is hard to envision specific sedimentological processes, downstream of any major tributary confluences, which would be capable of producing this relationship. We interpret these results to be a reflection of the heterogeneity character of terrestrial systems in general, where packages of sediment may stay within the system for longer time periods than the average transient

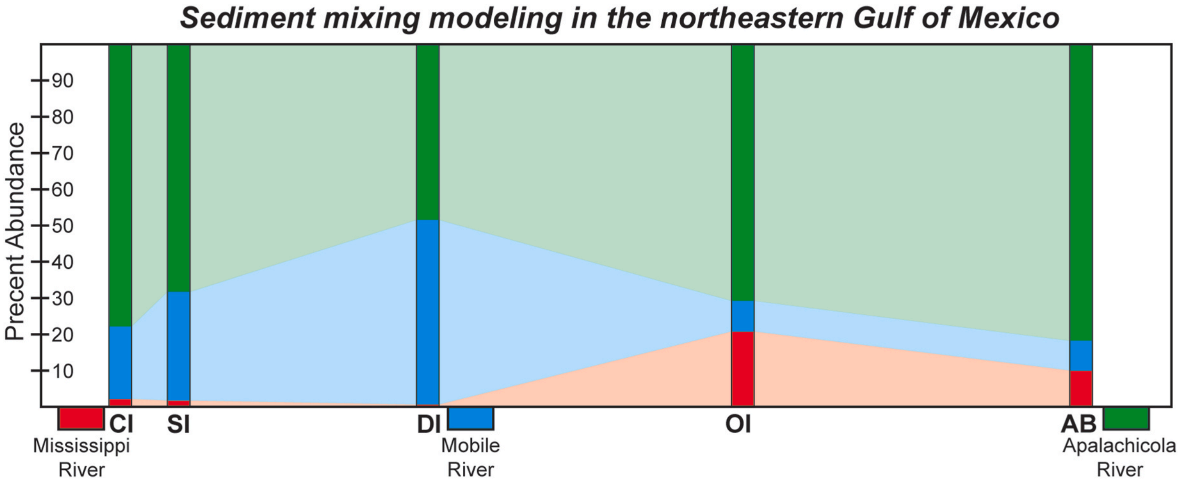

Fig. 5. Monte Carlo inverse mixing model results using Keiper V statistics for coastal deposits along the northeastern Gulf of Mexico (DZmix; Saylor and Sundell, 2017). For each coastal deposit the Mississippi River (red), Mobile River (blue), and Apalachicola River (green) where used as input samples. CI = Cat Island, SI = Ship Island, DI = Dauphin Island, OI = Okaloosa Island, AB = Apalachicola Beach. The spatial relationships between river input samples and coastal samples is depicted along the bottom x-axis. Cross correlation coefficient and K–S D statistical results available in supplemental material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

time length required to transport material from the headwaters to the mouth of the system (e.g., Romans et al., 2016). We also compared our Mississippi River sample to results from Late Pleistocene-Holocene deep-sea fan deposits in the Gulf of Mexico (Fildani et al., 2016). Dobbs et al. (2022) demonstrate that detrital-zircon results from a deltaic system that feeds fan deposits should produce similar detrital-zircon geochronology results. The ability for our Mississippi River sample to correlate to these deep marine deposits suggests data is reproducible and that a more detailed investigation of terrestrial sediment mixing in the lower reaches of the Mississippi River system is needed. We also report dissimilarity values between our Apalachicola River sample and that from Blum et al. (2017), which further support the ability to replicate detrital-zircon geochronology results in the northeastern Gulf of Mexico.

6.2. *Anthropogenic influences*

Dredging and beach renourishment are interpreted as beneficial anthropogenic efforts in the northeastern Gulf of Mexico because they open waterways for commercial shipping and can be used for beach and barrier island restoration projects, which supports the tourism industry (Parson and Swafford, 2012). However, these efforts also influence sedimentological and biological processes, and the effects remain understudied. Ship Island is currently undergoing a restoration project connecting the east and west islands to restore damage from Hurricane Camille and Katrina and annual dredging efforts result in >76, 000, 000 m^3 of sediment being dredged in the Gulf of Mexico (Parson and Swafford, 2012). The Mississippi River, Apalachicola River, Ship Island, and the channel between Dauphin Island and Fort Morgan, Alabama are all active dredged sites.

Our data suggests that dredging and beach renourishment efforts have little to no influence on detrital-zircon results in the northeastern Gulf of Mexico. The ability for each coastal deposit to be correlated to certain river samples and to produce statistical similarities that mimic natural sediment transport seems to suggest that shelf deposits preserve river input signatures over time and that upon mixing follow natural sediment mixing processes. The enhanced percent abundance in metamorphic zircons for coastal deposits is likely a product of natural filtering during alongshore transport and possibly more rapid subsidence rates towards the Louisiana coast. However, to further substantiate the potential influence of dredging and beach renourishment projects on detrital-zircon geochronology, we suggest a more localized study in which Mobile Bay and the Mississippi Sound are strategically sampled on either side of Mobile Bay and on the landward and ocean sides of the barrier islands.

Hurricanes can cause horizontal mixing and sediment transport along the continental shelf (Boudreau, 1998). The Dauphin Island sample was taken 10 days after Hurricane Zeta (category 3) and the Mississippi River sample was taken 9 days after Hurricane Laura (category 4). This presents another possible explanation for the deviation of Apalachicola and Mobile River systems at Dauphin Island; however, modern shelf deposits are unlikely to have a large amount of Mobile River system sediment and the mixing depth is presumably to shallow to incorporate older deposits that may have larger amounts of Mobile River system sediment. We interpret hurricane activity to have little to no effect on detrital-zircon results in the northeastern Gulf of Mexico. However, to substantiate this interpretation a detailed temporal (coring) study of barrier island splay deposits is needed.

6.3. *Eastern Gulf Coastal Plain*

Establishing source to sink relationships in the southeastern United States is difficult because of homogenous zircon age spectra for Paleozoic strata in the southern Appalachian and Ouachita forelands (Moecher and Samson, 2006; Thomas, 2011). This homogeneity is expressed by a proportionally small population of Appalachian grains, a dominating Grenville population, and various amounts of Iaptian/-Gondwanan, Granite-Rhyolite, Yavapai-Mazatal, and Wyoming-Superior populations (Gray and Zeitler, 1997; Bream et al., 2004; Thomas et al., 2004; Becker et al., 2005; Park et al., 2010). To overcome this difficulty, studies tend to focus on chemical-age relationships (i.e., U–Pb ages coupled with eHf values; Mueller et al., 2008; Thomas, 2011), age determinations from other detrital minerals such as monazite and rutile (Hietpas et al., 2011; O'Sullivan et al., 2016; Zotto et al., 2020), thermochronology (Stowell et al., 2019; McKay et al., 2021), or proportional abundance of Appalachian versus Grenville grains and percent abundance of metamorphic detrital zircons (Jackson et al., 2021).

Modern drainage systems in the southeastern United States may not provide an exact analog to ancient deposits, but they do contain detrital-zircon age spectra that can be used to understand signatures in older eastern Gulf Coastal Plain strata (Blum et al., 2017; Snedden and Galloway, 2019; Snedden et al., 2022). The Mississippi River exhibits a unique age spectrum compared to other drainages in the eastern United

States based on the presence of Cenozoic and Mesozoic grains (Fig. 3). The grains are derived from the western United States and allow for easy identification of paleo-Mississippi drainage systems in coastal plain deposits because the grains have not undergone multiple trans-continental transport paths, unlike older (≥1 Ga) grains (i.e., Dickinson and Gehrels, 2009; Thomas, 2011).

Tennessee River deposits are proportionally dominated by Grenville grains alongside minor populations associated with Appalachian, Granite-Rhyolite, Yavapai-Mazatzal, and Wyoming-Superior ages (Blum et al., 2017). This age spectrum mimics Paleozoic southern Appalachian foreland deposits and is a common signature in eastern Gulf Coastal Plain strata (Blum and Pecha, 2014; Xu et al., 2017; Craddock et al., 2021; Snedden et al., 2022). Based on Paleozoic sediment provenance studies (Thomas, 2011; references within), it is likely that this signature results from material being sourced from Appalachian thrust sheets containing Cambrian passive margin sequences, Ordovician through Devonian clastic deposits associated with the Taconic and Acadian orogenic cycles, and Paleozoic low-grade metamorphic rock in the western Blue Ridge province.

The Apalachicola River contains a higher abundance of Appalachian grains than Grenville grains (Fig. 3). This proportional distribution provides a unique age spectrum in Gulf Coastal Plain strata. The enhanced abundance of Appalachian grains seems to be indicative of drainages sourcing material from the eastern Blue Ridge and Inner Piedmont regions of the southern Appalachians and is temporally identified as far back as the Cretaceous (Blum and Pecha, 2014; Jackson et al., 2021; Snedden et al., 2022). This relationship between Appalachian and Grenville populations also suggests that the paleo-Tennessee and paleo-Apalachicola drainages can be recognized spatially throughout the eastern Gulf Coastal Plain over time.

The Mobile River contains a mixed signature between the Tennessee and Apalachicola rivers based on approximately equal proportions of Appalachian and Grenville populations (Fig. 3). A mixed signature for can be expected if sediment source regions control proportionality of Appalachian and Grenville populations because the modern Mobile drainage incorporates Paleozoic foreland, western and eastern Blue Ridge, and Inner Piedmont bedrock. Therefore, detrital-zircon geochronology seems to provide information capable of reconstructing the divides between major drainages in the southeastern United States over time. When coupled with other stratigraphic context (i.e., Snedden et al., 2022) these data can provide an enhanced understanding for the development of the eastern Gulf Coastal Plain.

7. Conclusions

The U–Pb age spectrum for the Apalachicola River is defined by prominent peaks associated with Appalachian (490-270 Ma) and Grenville (1200-900 Ma) ages, of which the proportion of Appalachian grains exceeds Grenville, as well as minor peaks associated with Iaptian/Gondwanan (850-550 Ma) and Granite-Rhyolite (1500-1300 Ma) ages. The Mobile River exhibits prominent Appalachian and Grenville age peaks as well, but with Grenville grains exhibiting a higher proportion. The Mobile River age spectrum also exhibits minor peaks associated with Iaptian/Gondwanan, Granite-Rhyolite, and Yavapai-Mazatzal (1800-1600 Ma) ages. The Mississippi River contains prominent peaks associated with western Cordillera ages (<270 Ma) and minor peaks associated with Appalachian, Grenville, Midcontinent, and Yavapai-Mazatzal ages.

Coastal deposits along the northeastern Gulf of Mexico exhibit detrital-zircon U–Pb age spectra similar to the Apalachicola and Mobile rivers. Contribution of each river system can best be determined based on the proportions of Appalachian versus Grenville ages and percent abundance of metamorphic zircon grains. Apalachicola Beach, Okaloosa Island, Ship Island, and Cat Island contain more Appalachian grains than Grenville grains. Dauphin Island contains more Grenville grains than Appalachian grains. The Apalachicola and Mobile rivers and coastal deposits contain enhanced abundance of metamorphic grains (14–36%) compared to the Mississippi River, which exhibits 6% abundance.

Statistical dissimilarity evaluations show that coastal deposits are similar to the Apalachicola and Mobile rivers, primarily based on spatial proximity to river mouths. The Mississippi River is dissimilar to all coastal deposits. Inverse mixing models suggest that coastal deposits east of Mobile Bay are primarily composed of material derived from the Apalachicola River, whereas coastal deposits west of Mobile are either primarily composed of Mobile River material (Dauphin Island) or a mixture of Apalachicola and Mobile rivers, with a diminishing Mobile River contribution towards the west. The agreement of detrital-zircon age spectra, percent abundance of metamorphic zircon grains, and inverse mixing models indicates detrital-zircon geochronology for modern beach and barrier island deposits records these processes. At a regional-scale, our results also suggest that anthropogenic influences and hurricanes have little to no influence on the detrital-zircon age signature and that the northeastern Gulf of Mexico can be used as an analog for older Cenozoic and Mesozoic source to sink investigations in the eastern Gulf Coastal Plain.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Data availability

The data used for this publication is available through the supplemental file

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.marpetgeo.2022.105997.

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