ABSTRACT

The sedimentary fill of peripheral foreland basins has the potential to preserve a record of the processes of ocean closure and continental collision, as well as the long-term (i.e., 10⁵–10⁶ yr) sediment-routing evolution associated with these processes; however, the detrital record of these deep-time tectonic processes and the sedimentary response have rarely been documented during the final stages of supercontinent assembly. The stratigraphy within the southern margin of the Delaware Basin and Marathon fold and thrust belt preserves a record of the Carboniferous–Permian Pangean continental assembly, culminating in the formation of the Delaware and Midland foreland basins of North America. Here, we use 1721 new detrital zircon (DZ) U-Pb ages from 13 stratigraphic samples within the Marathon fold and thrust belt and Glass Mountains of West Texas in order to evaluate the provenance and sediment-routing evolution of the southern, orogen-proximal region of this foreland basin system. Among these new DZ data, 85 core-rim age relationships record multi-stage crystallization related to magmatic or metamorphic events in sediment source areas, further constraining source terranes and sediment routing. Within samples, a lack of Neoproterozoic–Cambrian zircon grains in the pre-orogenic Mississippian Tensus Formation and subsequent appearance of this zircon age group in the syn-orogenic Pennsylvaniaan Haymond Formation point toward initial basin inversion and the uplift and exhumation of volcanic units related to Rodinian rifting. Moreover, an upsection decrease in Grenvillian (ca. 1300–920 Ma) and an increase in Paleozoic zircons denote a progressive provenance shift from dominantly orogenic highland sources to that of sediment sources deeper in the Gondwanan hinterland during tectonic stabilization. Detrital zircon core-rim age relationships of ca. 1770 Ma cores with ca. 600–300 Ma rims indicate Amazonian cores with peri-Gondwanan or Pan-African rims, Grenvillian cores with ca. 580 Ma rims are correlative with Pan-African volcanism or the ca. 780–560 Ma volcanics along the rifted Laurentian margin, and Paleozoic core-rim age relationships are likely indicative of volcanic arc activity within peri-Gondwana, Coahuila, or Oaxaquia. Our results suggest that detrital sediment delivery to the Marathon region from the nearby southern orogenic highland; less sediment was delivered from the axial portion of the Ouachita or Appalachian regions suggesting that this area of the basin was not affected by a transcontinental drainage. The provenance evolution of sediment provides insights into how continental collision directs the dispersal and deposition of sediment in the Permian Basin and analogous foreland basins.

INTRODUCTION

Major tectonic and geologic events, such as ocean closure and continental collision, and the evolution of associated sediment-routing systems, are recorded within the sedimentary fill of foreland basins (Jordan et al., 1988; DeCelles and Giles, 1996; Ingersoll, 2012). Detrital zircon (DZ) U-Pb geochronology is a powerful provenance analysis tool for elucidating hinterland tectonic and erosional processes and the associated depositional record (Dickinson, 1988; Fedo et al., 2003; Gehrels, 2012; Gehrels, 2014). This methodology provides invaluable insights into the geological processes linked to continental assembly and can help track the complex temporal and spatial evolution of these foreland basin systems (Haughton et al., 1991; Lawton et al., 2010).

The Permian Basin is the result of the diachronous collision between the Gondwanan and Laurentian continental plates during the Late Mississippian to early Permian, completing the formation of the supercontinent Pangea. This collision led to the inversion of the Laurentian continental margin, over-thrusting of Gondwana crust, and the formation of several flexural foreland basins and uplifts (King, 1930; King, 1937; Ross, 1986; Yang and Dorobek, 1995; Poole et al., 2005). The Delaware Basin is the western of two major sub-basins that make up the Permian foreland basin. It contains extensive hydrocarbon reservoirs in conventional deep-water sandstones as well as unconventional shale and carbonate strata. These important resources have motivated numerous studies of the depositional environments and reservoir quality across the basin (Hills, 1984; Harms et al., 1988; Dutton et al., 2003; Gardner et al., 2003; Pyles et al., 2010). The Pennsylvaniaan to middle Permian stratigraphy exposed along the southern margin of the Delaware Basin (Figs. 1 and 2) offers the unique opportunity to study geological processes related to late Paleozoic Laurentia-Gondwana continental collision and foreland basin deposition near the orogenic front.

Provenance studies have been employed to reconstruct the evolution of numerous orogenic systems, such as the Andes or the Himalayas, which still preserve much of the orogenic hinterland and the adjacent basins. In contrast, the Permian Basin represents a more significant challenge because a significant portion of the Gondwanan hinterland subsequently rifted away during Mesozoic opening of the Gulf of Mexico (Hatcher et al., 1989; Thomas, 2006, 2011b), and what likely remains in northern and northeastern Mexico is covered and poorly understood. Hence, the sedimentary strata along the southern margin of the Permian Basin offer the potential to help unravel the long-term geological and tectonic evolution of this collisional episode despite the missing or inaccessible hinterland. Several models for the sediment
sourcing and routing have been proposed (Thomson and McBride, 1964; Kocurek and Kirkland, 1998; Soreghan and Soreghan, 2013). The recent advent of isotopic provenance analysis through DZ U-Pb dating has provided critical process-oriented insights into the linkages between basin formation, hinterland tectonics and/or unroofing, sediment routing, drainage reorganization, and basin subsidence as read in the basin fill history (Lawton et al., 2010, 2015a, 2015b; Gehrels, 2012; Sharman et al., 2015; Thomson et al., 2017).

Recent provenance studies have employed DZ U-Pb geochronology in order to interpret sediment sources for the voluminous clastic reservoirs within the Permian Basin (Soreghan and Soreghan, 2013; Anthony, 2015; Xie et al., 2018). Specifically, these studies identified a previously unexpected signal of southern sediment provenance (i.e., peri-Gondwana). However, interpretations of the sediment-routing scenario continue to be developed. For example, Soreghan and Soreghan (2013) interpret southerly provenance for the Guadalupian section in the northwestern Delaware Basin, but not by a direct feeder system. Rather, sediment was contributed via transcontinental river systems stemming from the Ouachita and Appalachian regions and deflated into eolian erg systems ultimately transporting sediment to the Delaware Basin.

We used DZ U-Pb geochronology to define the signal of southern provenance and direct sediment supply from the Marathon fold and thrust belt and Gondwanan hinterland terranes. Moreover, the southern margin of the Delaware Basin comprises strata that document the collisional phases of Pangea; the long-term \((10^7-10^8 \text{ yr})\) tectonic processes associated with this supercontinent assembly likely significantly influenced the provenance and sediment-routing evolution of the Delaware Basin (Graham et al., 1976).

### GEOLOGIC SETTING AND STRATIGRAPHY

#### Iapetan Rifted Margin—Rodinian Breakup

Prior to the assembly of Pangea, Neoproterozoic-Cambrian rifting of the Rodinian continent formed the inherited promontories and embayments of southern Laurentia (Fig. 3) (Arbenz, 1989a; Cawood et al., 2001; Thomas, 2011b). The traces of these large-scale features consist of the northwest-trending transform faults (Alabama-Oklahoma and Texas transforms) and northeast-trending rift segments (Blue Ridge, Ouachita, and Marathon) (Arbenz, 1989a; Thomas, 2006; Thomas, 2011b). Rifting of the Rodinian supercontinent occurred between ca. 825 Ma and 740 Ma with notable volcanic pulses from 780 to 540 Ma (Li et al., 2008; Hanson et al., 2016). Stabilization of the new Laurentian continent resulted in passive margin deposition of \(975-1100 \text{ m}\) of thin-bedded limestone, shale, chert, and shaly sandstone during the Late Cambrian–Devonian (King, 1978; McBride, 1989; Hickman et al., 2009). The interior southern margin of Laurentia contained the Tobosa Basin, a remnant feature of the Rodinian breakup during Neoproterozoic–Cambrian time (Fig. 3) (Walper, 1982; Keller et al., 1983; Arbenz., 1989a; Li et al., 2008).
This region was characterized by weak crustal extension and a low subsidence rate during the early Paleozoic (Galley, 1958; Horak, 1985).

**Convergence and Collision of Laurentia and Gondwana**

The Pangean accretionary margin preserves in outcrop the entire complex tectonic history of diachronous continental collision (Cawood and Buchan, 2007), making it of unique structural interest and the focus of palinspastic reconstruction of numerous studies (Fig. 2) (Tauvers, 1988; Arbenz, 1989a, 1989b; Muehlberger and Tauvers, 1989; Viele and Thomas, 1989; Reed and Stricker, 1990; Cawood et al., 2001; Thomas, 2006, 2011a, 2011b, 2014). During the Mississippian–Permian collision of Laurentia and Gondwana, mountain ranges formed across the axial continental divide through growth of orogenic wedges and their thrusting onto the southern margin of the Laurentian continent (Fig. 4) (Ross, 1986; Poole et al., 2005; Keppie et al., 2008). The combined influences of tectonic stress related to the advancing Marathon fold and thrust belt and preexisting lithospheric weakness from the antecedent Tobosa Basin segmented and isolated the Permian Basin along renewed northwest- to north-trending fault zones such as the Puckett-Gray Ranch fault, an intrabasinal

![Figure 2](https://www.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02108.1/4913532/ges02108.pdf)
Figure 3. Late Precambrian to middle Cambrian rift-transform breakup of Rodinia, subsequent thrust belt formation during Mississippian–Permian collision of Laurentia and Gondwana. Abbreviations: A—Alabama promontory; AF—late Paleozoic Appalachian thrust front; BRR—Blue Ridge Rift; D—Delaware aulacogen; L—Llano (or Texas) promontory; M—Marathon embayment; MR—Marathon Rift; O—Oklahoma Basin (early Paleozoic); OA—Oklahoma aulacogen; OF—late Paleozoic Ouachita thrust front; OR—Ouachita Rift; OU—Ouachita embayment; R—Redfoot rift (with early Paleozoic Mississippi Valley Basin); T—Tobosa Basin (early Paleozoic). From Arbenz (1989b) and Thomas et al. (2002).

Figure 4. Paleogeographic reconstructions showing Laurentian, Gondwanan, and African continental pieces during Carboniferous reconstruction on the active Pacific margin with subduction beneath the Mixteca (Acatlán) and Oaxaquia terranes and Permian age construction of Pangea during continental collision of Laurentia and Gondwana (adapted from Kappel et al., 2008).
uplift known as the Central Basin Platform, and basin-bounding highs as seen in the Northwest Shelf, Eastern Shelf, and Devils River Uplift (Fig. 5) (Ross, 1986; Yang and Dorobek, 1995; Ewing, 2016). By defining the morphology of the Permian Basin, these basin-bounding fault zones and basement uplifts altered its structural evolution and subsidence history while simultaneously changing the patterns of foreland deposition (Muehlberger and Tavera, 1989; Yang and Dorobek, 1995). Yang and Dorobek (1995) characterize the Permian Basin as a composite foreland basin because of the complex system of tectonic and load-induced flexures that form the separate sub-basins and uplifts, which are not prevalent in all foreland basin systems (Hagen et al., 1985; Flemings et al., 1986; Beck et al., 1988; Yang and Dorobek, 1995).

Stratigraphic Record of the Glass Mountains and Marathon Fold and Thrust Belt

Situated in the southernmost Delaware Basin, the Glass Mountains and Marathon fold and thrust belt contain outcrops of the entire syn- to early post-collisional stratigraphic section (Figs. 2 and 6) (King, 1930, 1937, 1978; McBride, 1989). The deposits within this region record two stages of sedimentation, which include (1) pre-collisional passive margin strata of the southern Laurentian continent, generally characterized by thin-bedded limestone, shale, chert, and shaly sandstone (975–1100 m >170 m.y.) and (2) syn-orogenic strata, which accumulated rapidly to a thickness of 4200–5600 m during ~60 m.y. (Figs. 2 and 6) (King, 1937, 1978; Flawn et al., 1961; Thomson and McBride, 1964; McBride, 1988; Hickman et al., 2009). The Upper Mississippian–Lower Pennsylvanian Tesnus Formation is a shaly sandstone representing flysch deposits forming submarine fan and channel complexes sourced from the approaching Gondwana continental terranes (McBride, 1989; Hickman et al., 2009). Overlying the Tesnus are the Pennsylvanian Dimple Limestone and Haymond Formation. The Lower Pennsylvanian Dimple Limestone indicates a short period of waning tectonism in which its northern shelf equivalent fed carbonate turbidites southward (Hairabian and Janson, 2016). Deposited during ongoing tectonic activity, the sediment source history of the Haymond Formation remains controversial (King, 1958; Thomson and McBride, 1964; Denison et al., 1969; McBride, 1989; Gleason et al., 2007). The uppermost Pennsylvanian unit in the system is the Gaptank Formation. Regionally, coarse clastic fluvial and deltaic sediments mark the lower Gaptank. In contrast, the Gaptank in the Glass Mountains is composed of carbonate shelf deposits and phylloid algal mounds, indicative of tectonic quiescence in the region (King, 1937; Hairabian and Janson, 2016). A few miles north of these exposures are the Permian deposits of the Glass Mountains. The Glass Mountains expose a series of north-northwest–prograding mixed carbonate-siliciclastic deposits (Figs. 1 and 2). The 1500–2000 m of Wolfcampian–Guadalupian (early to middle Permian) stratigraphy of the Glass Mountains range in depositional setting from Wolfcampian proximal syn-orogenic conglomerates to Guadalupian carbonate reef-rimmed platform and slope (King, 1930, 1937; Ross, 1963; Hairabian and Janson, 2016).

Previous Provenance Studies

Long-standing interpretations (Fig. 7) have concluded that the majority of siliciclastic input to the Delaware Basin during middle Permian (Guadalupian) time was sourced from the Ancestral Rocky Mountains (ARM) of central Laurentia. Hull (1957) suggested that observed arkosic mineralogy of the sandy and silty units of the Artesia and Delaware Mountain groups of the Northwest Shelf were evidence of north-to-south transport of sediment from a plutonic-metamorphic source such as the ARM and midcontinent region of Laurentia. Fischer and Sarnthein (1988) emphasized similarities between the Delaware Basin (arid, low latitude, south of the northern trade-wind belt) to the Holocene–Pleistocene of northwest Africa, as well as generally north-south-trending paleocurrent data from dunes in the Grand Canyon region during late Paleozoic time to be evidence of an ARM source for the Delaware Mountain group of the
Guadalupe Mountains. Alternatively, Kocurek and Kirkland (1998) suggested that paleogeography and paleowinds would support eolian sediment transport from the Whitehorse Group of the Anadarko Basin, Oklahoma. More recently, through a combination of DZ U-Pb geochronology, compiled paleocurrent data, and paleoclimate data, Soreghan and Soreghan’s (2013) study of samples from the Guadalupe Mountains of West Texas (Fig. 3) refuted an ARM source for the Delaware Mountain Group. They documented dominant Paleozoic, Neoproterozoic, and Mesoproterozoic DZ age modes and minor late Paleoproterozoic ages, only the latter of which would be indicative of an ARM source (Yavapai-Mazatzal \( \approx \) 1825–1600 Ma). Instead, they suggest that measured U-Pb age modes combined with Laurentian paleocurrent data point to a combination of recycled Appalachian- and/or Ouachita-derived sources and Gondwanan and Pan-African terranes south of the Ouachita-Marathon suture. Using DZ samples from the central and southern Delaware Basin, Anthony (2015) and Xie et al. (2018) suggested sediment was sourced from the Appalachian orogenic belt, Ouachita orogenic belt, and peri-Gondwanan terranes while also noting a shift in provenance during the middle Permian, suggesting a continental-scale fluvial system spanning from the Appalachian orogenic belt westward across Pangea (Fig. 7). While the Guadalupe Mountains and Delaware Basin have been at the epicenter of stratigraphic and provenance studies, detailed work in the Glass Mountains has historically lacked similar treatment. Gleason et al. (2007) analyzed detrital zircons from the Pennsylvanian Haymond Formation of the Marathon fold and thrust belt, suggesting that sources range from the Laurentian craton, uplifted strata of the remnant-ocean basin, Gondwanan crustal sources, and Ouachita sources to the east. Gleason et al. (2007) went from the Guadalupe Mountains of West Texas (Fig. 3) refuted an ARM source for the Delaware Mountain Group. They documented dominant Paleozoic, Neoproterozoic, and Mesoproterozoic DZ age modes and minor late Paleoproterozoic ages, only the latter of which would be indicative of an ARM source (Yavapai-Mazatzal \( \approx \) 1825–1600 Ma). Instead, they suggest that measured U-Pb age modes combined with Laurentian paleocurrent data point to a combination of recycled Appalachian- and/or Ouachita-derived sources and Gondwanan and Pan-African terranes south of the Ouachita-Marathon suture. Using DZ samples from the central and southern Delaware Basin, Anthony (2015) and Xie et al. (2018) suggested sediment was sourced from the Appalachian orogenic belt, Ouachita orogenic belt, and peri-Gondwanan terranes while also noting a shift in provenance during the middle Permian, suggesting a continental-scale fluvial system spanning from the Appalachian orogenic belt westward across Pangea (Fig. 7). While the Guadalupe Mountains and Delaware Basin have been at the epicenter of stratigraphic and provenance studies, detailed work in the Glass Mountains has historically lacked similar treatment. Gleason et al. (2007) analyzed detrital zircons from the Pennsylvanian Haymond Formation of the Marathon fold and thrust belt, suggesting that sources range from the Laurentian craton, uplifted strata of the remnant-ocean basin, Gondwanan crustal sources, and Ouachita sources to the east. Gleason et al. (2007) went

Figure 6. Stratigraphic column of the Guadalupe Mountains, Delaware Basin, and Glass Mountains and Marathon fold and thrust belt (this study). Detrital zircon sample locations are denoted by white symbols within stratal intervals. Adapted from Barnaby et al. (2004), Olszewski and Erwin (2009), and Nestell et al. (2019).

Figure 7. Paleogeographic map of the Laurentian and Gondwanan continents during the middle Permian. Arrows indicate sediment routing interpretations by previous studies within the Delaware Basin. Modified from Blakey Deep Time Maps (https://deeptimemaps.com/). ARM—Ancestral Rocky Mountains.
further to interpret transport of this sediment as braid deltas and foredelta submarine-ramp environments emanating from the closing Pangean suture zone. The stratigraphic framework and biostratigraphy of the Glass Mountains are documented by a few studies (King, 1930, 1937; Rathjen, 1993; Haneef et al., 2000; Harris et al., 2000; Lambert et al., 2000; Wardlaw, 2000; Yang and Yancey, 2000; Lambert et al., 2002; Hairabian and Janson, 2016), but detailed provenance history of the clastic record has not been previously attempted.

**Potential Sediment Sources**

**Archean and Paleoproterozoic (>1825 Ma)**

Detrital zircons older than 1825 Ma could potentially be sourced from the northern extents of the Laurentian craton or from the Amazonian paleohinterland of Gondwana. The continent of Amazonia has a multi-stage history of agglutination with both Laurentia, during the assembly of Rodinia (along the Grenvillian margin of Laurentia), and Gondwana during the opening of the Iapetus at ca. 600 Ma (Sánchez-Bettucci and Rapalini, 2002; Tohver et al., 2002; Cordani et al., 2009). Amazonian basement provinces contain a wide range of Archean and Paleoproterozoic ages. The Amazonian central craton (Fig. 8) contains the Carajás region southwest of the Amazon Basin. Basement rocks within Carajás are dated between 3200 and 2600 Ma (Cordani et al., 2009). The Maroni-Itacaiunas province occurs to the north and northeast of the Central-Amazonian province with rocks dated between 2250 and 1950 Ma (Fig. 8) (Cordani et al., 2009). Calc-alkaline, granite-gneiss complexes of the Ventuari-Tapajós and Rio Negro–Juruena provinces formed between 1980 and 1810 Ma (Fig. 8) (Santos, 2003; Cordani and Teixeira, 2007; Cordani et al., 2009). These Amazonian provinces were potential sources of Archean and Paleoproterozoic age zircons both during Rodinian time as well as during the formation of Pangea (connection with the Gondwanan hinterland). Potential sources within the Laurentian continent include the Wyoming and Superior Provinces (3000 and 2700–2500 Ma) of the northern Laurentian continent (Xie et al., 2018). Grains of 1900–1800 Ma and 1850–1780 Ma from the Penokean orogen and associated Wisconsin magmatic terrane and Trans-Hudson province of the northern Laurentian craton (Fig. 8) were also capable of shedding sediment south toward the Permian Basin (Sims et al., 1989; Beck and Murthy, 1991; Anderson and Morrison, 1992; Holm et al., 2007).

**Late Paleoproterozoic (ca. 1825–1578 Ma)**

Late Paleoproterozoic age zircons match closest with the Ancestral Rocky Mountains and Yavapai-Mazatzal (1800–1600 Ma) terranes of central Laurentia (Fig. 8). These first-cycle basement sources were exposed throughout the Pennsylvanian and earliest Permian (Anderson and Morrison, 1992; Anderson et al., 1993; Holm et al., 2007; Giles et al., 2013; Lawton et al. 2015a). These
ages have also been documented in detrital zircons from a multitude of basin studies of Paleozoic strata along the Ouachita-Marathon suture zone as well as north and northeast of the Permian Basin, giving the possibility of sediment recycling (Dickinson and Gehrels, 2003; Becker et al., 2005; Becker et al., 2006; Gehrels et al., 2011b; Giles et al., 2013; Link et al., 2014; Xie et al., 2016).

**Early Mesoproterozoic (ca. 1578–1300 Ma)**

Zircons within the early Mesoproterozoic age range are typically representative of anorogenic igneous activity of the granite-rhyolite province of the central North American plate, ranging in age between 1.49 and 1.34 Ga, and spanning from Labrador to California (Fig. 8) (Bickford et al., 1988; Hoffman et al., 1989; Anderson and Morrison, 1992). The Rodinian–San Ignacio province of Amazonia also contains accreted domains of intra-oceanic character, dated between 1550 and 1300 Ma (Geraldes et al., 2001; Santos, 2003; Cordani et al., 2009), granitoids dated between 1520 and 1470 Ma, and the Santa Helena plutonic arc (1450–1420 Ma) (Cordani et al., 2009). Additionally, zircons of this age range are found in other Pennsylvanian and Permian age basalts strata (Dickinson and Gehrels, 2003; Becker et al., 2005, 2006; Gehrels et al., 2011b).

**Mesoproterozoic (ca. 1300–920 Ma)**

Mesoproterozoic zircon grains are generally indicative of the Grenville orogen, present in southern and eastern North America, Mexico, and Gondwana (Fig. 8) (Rainbird et al., 1992; Rainbird et al., 1997; Gillis et al., 2005; Talavera-Mendoza et al., 2005; Soreghan and Soreghan, 2013; Xie et al., 2018). These grains typically make up a significant portion of the DZ population in North American sandstones from the Neoproterozoic to Mesozoic (Dickinson and Gehrels, 2003; Becker et al., 2005, 2006; Gehrels et al., 2011b).

**Neoproterozoic to early Cambrian (ca. 920–521 Ma)**

Because there are a number of potential sources, the Neoproterozoic to early Cambrian age suite remains contentious regarding provenance within the Permian strata of the Delaware Basin (Soreghan and Soreghan, 2013; Xie et al., 2018). The Appalachian orogenic belt traces the accretion of the (northern) Avalon terrane, (southern) Carolina terrane, and Suwannee (Florida) terrane, which were involved in the collision of Africa and North America during Alleghanian tectonism (Fig. 4) (Opydyke et al., 1987; Mueller et al., 1994; Heatherington et al., 1996; Wortman et al., 2000; Hibbard et al., 2002; Dickinson and Gehrels, 2008; Park et al., 2010). Specifically, magmatism of 650–550 Ma only occurred in the accreted Avalon, Carolina, and Suwannee terranes (Heatherington et al., 1996).

The Pennsylvanian to Permian strata of the Appalachian Basin generally are thought to capture the erosional history of the Alleghanian orogenic wedge (Becker et al., 2006). Zircon analyses within the Pennsylvanian and Permian strata of the Appalachian foreland basin, however, show that age modes of contemporary magmatism are typically underrepresented or absent from synorogenic strata (Thomas et al., 2004; Becker et al., 2005, 2006).

The exotic terranes associated with the collision of south and southwestern Laurentia (present-day Alabama-Texas) with Gondwana are also capable of supplying zircons of this age range. Peri-Gondwanan terranes along the Ouachita-Marathon suture as well as Pennsylvanian–Permian strata of the Yucatan/Maya, Coahuila, Oaxaquia, and Mixteca (Acatlan) terranes (Figs. 4 and 8) had been accreted and uplifted by Permian time (Sacks and Secor, 1990; Dickinson and Lawton, 2001, 2003; Poole et al., 2005; Soreghan and Soreghan, 2013; Xie et al., 2018). Though all of these now Mexican and Central American terranes are understood to have agglutinated to the Gondwanan continent during the formation of Pangea, accretion timing and positions of the terranes remain subject to debate (Dickinson and Lawton, 2001; Murphy et al., 2004; Keppie et al., 2008; Martens et al., 2010; Soreghan and Soreghan, 2013).

As stated previously, the Tesnus Formation is a shaly sandstone representing pre-collisional flysch deposits in the form of submarine fan and channel deposits sourced from the approaching Gondwanan continent (McBride, 1989; Hickman et al., 2009). The whole of the Mississippian Tesnus was sourced from the Gondwanan continent, yet it does not contain any Neoproterozoic to early Cambrian zircons as have been observed in the Yucatan/Maya, Coahuila, and Mixteca (Acatlan) terranes (Fig. 8).

Rodinian syn-rift volcanic rocks represent the most likely source of sediment that has been overlooked by previous studies. They are situated along the southwestern margin of the Laurentian rifted margin. Rifting of the Rodinian supercontinent occurred between ca. 825 Ma and 740 Ma with notable volcanic pulses from 780 to 540 Ma (Fig. 8) (Li et al., 2008; Dickinson and Gehrels, 2008; Hanson et al., 2016). These ancient syn-rift volcanic rocks are restricted to the distal southern Laurentian margin and were subsequently covered by strata deposited along the Laurentian passive margin (King, 1937; King, 1987; Flawn et al., 1981; McBride, 1989; Hickman et al., 2009). The basement of the Devils River Uplift to the east of the Delaware Basin preserves a portion of the distal Laurentian margin and were subsequently covered by strata deposited along the Laurentian passive margin (King, 1937; King, 1978; Flawn et al., 1981; McBride, 1989; Hickman et al., 2009). The basement of the Devils River Uplift to the east of the Delaware Basin preserves a portion of the distal Laurentian rifted margin (Figs. 1 and 5). This region contains a succession of Grenvillian-age basement (1246–1121 Ma Rb/Sr age) (Nicholas and Waddell, 1988; Rodriguez et al., 2017) and a metasedimentary-metavolcanic unit of Cryogenian–Early Cambrian age [Nicholas and Rozental, 1979; Denison et al., 1977; Nicholas and Waddell, 1989; Thomas, 2011b; Rodriguez et al., 2017].

**Paleozoic (ca. 521–263 Ma)**

The Appalachian orogenic ranges and related Ordovician–Devonian igneous rocks of the Taconic (490–440 Ma) and Acadian (390–350 Ma) tectonic regions function as potential east and northeast sources for Paleozoic-age zircons within the Permian Basin (Hatcher, Jr. et al., 1989; Park et al., 2010; Gehrels et al., 2011b). Portions of the Gondwanan Pan-African regions of Carolina
Supplemental Material. Zipped file containing Supplemental File S1: A PDF of detailed information regarding the process of data representation and processing involved in the study and three secondary standard concordia age plots, and a tabulated Excel table with secondary standard U-Pb measurements; Supplemental File S2: A PDF file of two sets of maximum depositional age (MDA) measurements of 13 individual samples (MDA plots gathered from detrital zircon [DZ] U-Pb data and processed and plotted in detritalPy [Sharman et al., 2018]); and Supplemental File S3: A tabulated Excel file with 10 tables: Table S1: TSS1 and TSS2 sample U-Pb analyses; Table S2: HF1 and HF2 sample U-Pb analyses; Table S3: WCS2SS sample U-Pb analyses; Table S4: WCSS1 and LS1 sample U-Pb analyses; Table S5: WSSS and VSS4 sample U-Pb analyses; Table S6: VSS3 and ALSS1 sample U-Pb analyses; Table S7: VSS1 and VSS2 sample U-Pb analyses; Table S8: Sample locations; Table S9: Sample sheet set up for detritalPy [Sharman et al., 2018]; and Table S10: Best age and 1σ error of sample analyses set up for detritalPy [Sharman et al., 2018]. Please visit https://doi.org/10.1130/GES02108.1 to view the Supplemental Material.

Analytical Methodology

Analyses were run on a PhotonMachine Analyte G.2 excimer laser with a large-volume Helex sample cell and a Thermo Element2 ICP-MS. GJ1 was used as the primary reference standard (Jackson et al., 2004) and Pak1 (in-house thermal ionization mass spectrometry [TIMS] 206Pb/238U age of 43.03 ± 0.01), Plesovic zircon (337.13 ± 0.37; Sláma et al., 2008), and 91500 (1065 ± 0.4 Ma, Wiedenbeck et al., 1995) were used as secondary standards to ensure data quality and procedural integrity. Secondary standard data and weighted means from multiple LA-ICP-MS sessions are tabulated in Supplemental File S1.

Core-Rim Analysis

Depth profiling of each individual zircon grain yielded 85 concordant core-rim age relationships with three analyzed zircons having multiple concordant rims. That is to say, of the 1721 detrital zircon U-Pb ages, 85 U-Pb age pairs (Fig. 12) were extracted from both cores of zircons as well as igneous or metamorphic rims (Moecher and Samson, 2006; Marsh and Stockli, 2015).
Figure 9. Cumulative probability density plot and non-uniform kernel density estimation plots of each sample suite analyzed in this study. Highlighted color-coded groups designate broad-scale potential detrital zircon source terranes and dominant age range from each source (Fig. 8) (Lawton et al., 2015b). Dark blue—Mississippian Tesnus Formation (TSS1 and TSS2); light blue—Pennsylvanian Haymond Formation (HF1 and HF2); yellow—Wolfcampian Lenox Hills Formation (WCSS1 and WCSS2); orange—Leonardian Skinner Ranch Formation (LSS1); light red—Guadalupian Word Formation (WSS5); red—Guadalupian Vidrio Formation (VSS1, VSS2, VSS3, and VSS4); dark red—Guadalupian Altuda Formation (ALSS1). All colors coordinate with the given stratigraphic column (Fig. 6).
A more comprehensive history of zircon provenance and recycling can be gleaned by gathering multiple ages from single zircon grains. Specifically, these data help fingerprint a narrower range of potential sources by incorporating core-rim age relationships with previously published DZ data within potential sediment source terranes. All core-rim data are from the Permian strata of the Glass Mountains, while no such relationships were found from the zircon of the Marathon fold and thrust belt. When plotted, these analyses cluster into five relative core and rim clusters, each with 1–3 subgroups (Fig. 12) representing potential zircon growth and recycling history related to specific sediment source terranes.

### RESULTS

In total, 1721 detrital zircon U-Pb ages were measured in this study. All sample analytical data, sample locations, and detrital Py tables can be found in Supplemental File S3 [footnote 1]. Detrital zircon U-Pb data from the four Marathon fold and thrust belt samples and nine Glass Mountain samples were condensed into seven sample suites (grouped based on multiple samples in the same stratigraphic unit) and are shown as KDE plots, histograms, and cumulative probability density plots of Figure 9. Highlighted color-coded groups designate possible detrital zircon source terranes and dominant age range from each source (Fig. 8) (Lawton et al., 2015b). On the basis of these possible source ages, detrital zircon U-Pb ages can be separated into six groups: Archean and Paleoproterozoic (>1825 Ma), late Paleoproterozoic (ca. 1825–1578 Ma), early Mesoproterozoic (ca. 1578–1300 Ma), Mesoproterozoic (ca. 1300–920 Ma), Neoproterozoic to Early Cambrian (ca. 920–521 Ma), and Paleozoic (ca. 521–263 Ma).

#### Pre-Permian (Mississippian–Pennsylvanian)

The pre-Permian, syn-orogenic samples of the Marathon fold and thrust belt (blue-colored samples in Figs. 1 and 9) exhibit two distinct detrital zircon age spectra for the Mississippian Tesnus and the Pennsylvanian Haymond...
formations. Two samples from massive sandstone beds of the Mississippian Tesnus Formation (TSS1 and TSS2, n = 227) were taken along U.S. Highway 90, east of Marathon, Texas, within the Marathon fold and thrust belt (Fig. 1). The DZ U-Pb age spectrum (Fig. 9) exhibits a dominant Mesoproterozoic DZ U-Pb age component (51.1%), with a prominent age peak at ca. 1037 Ma. There exist minor fractions of detrital zircons of Archean and Paleoproterozoic (10.6%), Late Paleoproterozoic (14.5%), early Mesoproterozoic (12.3%), Paleozoic (11%) ages, and a single Neoproterozoic age zircon of 588 ± 5.7 Ma. Two turbiditic sandstone samples from the Pennsylvanian Haymond Formation (HF1 and HF2, n = 209) from along U.S. Highway 90, east of Marathon, Texas, exhibit a markedly different detrital zircon age spectrum with Neoproterozoic and Early Cambrian ages totaling 20.6%. The Mesoproterozoic age component continues to dominate and accounts for 36.4% of measured detrital zircons, while the Archean and Paleoproterozoic (14.8%), late Paleoproterozoic (7.2%), early Mesoproterozoic (7.7%), and Paleozoic (13.4%) age components are minor fractions.

Early Permian (Wolfcampian–Leonardian)

The younger, early Permian strata of the Glass Mountains (Fig. 1), north of Marathon, Texas, overlie the deformed strata of the Marathon fold and thrust belt. Two Wolfcampian samples (WCSS1 and WCSS2, n = 297) were taken from the conglomeratic Lenox Hills Formation of Leonard Mountain (Fig. 1), and the Leonardian sample (LSS1, n = 138) was taken from the massive sandstone turbidites of the Skinner Ranch Formation. These samples exhibit less dramatic changes in detrital zircon age distributions compared to changes observed between the Tesnus and Haymond samples. The DZ U-Pb age spectra of the Lenox Hills Formation exhibit minor age components of Archean and Paleoproterozoic (9.4%), late Paleoproterozoic (5.4%), and early Mesoproterozoic (5.4%). Paleozoic zircons make up 16.2% of total DZ U-Pb ages, while the Mesoproterozoic (32.3%) and Neoproterozoic to Early Cambrian (31.3%) age components represent the majority of detrital zircon ages with prominent age peaks at ca. 1090 Ma and ca. 524 Ma, respectively. The DZ age spectrum of the Skinner Ranch Formation (LSS1) is similar to that of the Lenox Hills (WCSS1 and WCSS2), with age components of Archean and Paleoproterozoic (9.4%), late Paleoproterozoic (2.2%), early Mesoproterozoic (5.1%), Mesoproterozoic (30.4%), Neoproterozoic and Early Cambrian (40.6%), and Paleozoic (12.3%).

Middle Permian (Guadalupian)

The middle Permian (Guadalupian) samples were taken from mixed carbonate-clastic turbidites of the Word (WSS5), Vidrio (VSS1, VSS2, VSS3, and VSS4), and Altuda formations (ALSS1) north of Marathon, Texas, and farthest north of the sampled Glass Mountains section (Fig. 1). The single sample of the Word Formation (WSS5, n = 138) was taken from the turbidite outcrops north of Leonard Mountain, and is lowest in the Guadalupian stratigraphic
section. The DZ U-Pb spectra of the Word Formation exhibit an increase in Paleozoic age component (27.7%) and a decrease in Neoproterozoic to Early Cambrian age component (28.5%) relative to the Wolfcampian and Leonardian samples. The Mesoproterozoic age component accounts for 24.1% of DZ U-Pb ages, and the early Mesoproterozoic (9.5%), late Paleoproterozoic (5.8%), and Paleoproterozoic and Archean (4.5%) age components maintain minor fractions of the age spectrum. The four Vidrio Formation samples (VSS1, VSS2, VSS3, and VSS4; n = 569) were taken in two separate locations. The first two samples (VSS1 and VSS2; n = 276) were taken above the Word sample, north of Leonard Mountain, while the second two samples (VSS3 and VSS4; n = 293) were taken from turbidites within Road Canyon, farther north of VSS1 and VSS2 (Fig. 1). The compiled age spectra (Fig. 9) exhibit similar components to that of the Word Formation, with high fractions of Paleozoic (27.1%), Neoproterozoic to Early Cambrian (21.6%), and late Mesoproterozoic (26.9%) age components, and low fractions of early Mesoproterozoic (9.5%), late Paleoproterozoic (7.7%), and Paleoproterozoic and Archean (7.2%) age components. The Altuda Formation (ALSS1, n = 144) marks the youngest stratigraphic unit sampled in this study. The sample was taken from a massive sandstone turbidite outcrop just northwest of Gilliland Canyon (King, 1930). The DZ U-Pb age spectrum remains similar to the previous Word and Vidrio samples, but with...
a noticeable enrichment in Paleozoic zircons (34.7%) and relative decrease in amount of late Mesoproterozoic zircons (14.6%).

Zircon Core-Rim and Analysis of Maximum Depositional Age

Here, we present a group-by-group breakout and interpretation of the five separate core-rim age clusters. Each grouping is first separated by color on the basis of core age (x axis). Within these core age groupings, unique subgroups have been further broken out according to rim ages (y axis). The combination of a unique core and rim age sheds light on potential source and recycling history (Fig. 12).

Paleoproterozoic and Archean Cores

Zircon core crystallization ages of Paleoproterozoic and Archean age could have been sourced from a broad range of terranes within and attached to the Laurentian and Gondwanan continents, but specifically the Amazonian terranes of the Gondwanan hinterland (Cordani et al., 2009) and Yavapai-Mazatzal, Wyoming, Superior, and Penokean provinces of northern Laurentia (Anderson and Morrison, 1992). The E1 group, with core ages ranging ca. 1770–1560 Ma and rim ages ranging ca. 600–300 Ma, captures potential core ages from Amazonia or Yavapai-Mazatzal but has much younger rim ages. These rim ages are most likely representative of peri-Gondwanan or Pan-African origin, suggesting a combined core-rim provenance history of southern or eastern origin. The single zircon grain within E2 (Fig. 12) contains a 1641 ± 33 Ma core with a 921 ± 71 Ma rim. A core of this age would typically be grouped with the Yavapai-Mazatzal province of Laurentia; however, the Grenvillian-age rim correlates with the younger Grenville-age basement of Oaxaquia as presented by Gillis et al. (2005).

Early–Middle Mesoproterozoic Cores

Zircon core-group D falls between the early–middle Mesoproterozoic age ranges, a range that could be represented by either the granite-rhyolite provinces of the North American interior craton (Bickford et al., 1986; Hoffman et al., 1989; Anderson and Morrison, 1992) or Amazonian basement and recycled terranes (Geraldès et al., 2001; Santos, 2003; Cordani et al., 2009). Subgroups D2 and D1 of the plotted core-rim ages (Fig. 12) show concordant rims of Ectasian–Tonian and Tonian–Carboniferous age ranges, respectively. Group D2 contains Grenvillian age rims, which could potentially be related to either Laurentian or Gondwanan magmatic or metamorphic activity. Zircons within the subgroup D1 have a broad range of rim ages with the youngest at 343 ± 17 Ma, an age that potentially adheres to volcanic activity or tectonism within the peri-Gondwanan terranes.

Grenvillian Cores

Grenvillian zircons are ubiquitous in the Neoproterozoic–Mesozoic sandstones of North America (Dickinson and Gehrels, 2003; Moecher and Samson, 2006), impeding provenance interpretations for these detrital age components. However, depth profiling of zircons from this study (C core groups, Fig. 12) presents some revealing data. The oldest rims of the Grenvillian-core suite are of contemporaneous Grenvillian age, shown in the C3 subgroup (Fig. 12). Provenance of this group is difficult to decipher due to the potential for core and rim generation within a Grenvillian province. However, subgroup C2 displays Grenvillian cores with rims of Neoproterozoic–middle Paleozoic age. Magmatic overprinting of 650–550 Ma volcanism within rocks of the Avalon, Carolina, and Suwannee terranes (Heatherington et al., 1996; Samson et al., 2005; Moecher and Samson, 2006) could be potential sources for these zircons, but this is less likely for the Suwannee terrane because its DZ age spectra are not well represented by Grenvillian-age zircons (Mueller et al., 1994). A more likely source for these multi-age zircons would be the terranes of Coahuila and Oaxaquia. Lopez et al. (2001) dated Grenvillian and Pan-African rocks within basement terranes of Coahuila and Oaxaquia. Zircon U-Pb analyses of the Grenville rocks presented grains of 1201 ± 60 Ma to 1232 ± 7 Ma with concordia intercepts at ca. 580 Ma, and Pan-African rocks presented grains of 580 ± 4 Ma. These were interpreted as being interrelated through melting of the Grenvillian basement during Pan-African–age volcanism, supporting our observation of similar core-rim relationships within single zircons (subgroup C2, Fig. 12). Additionally, these ages line up well with volcanism from the rifted Laurentian margin (780–660 Ma), supporting the interpretation that during orogenesis, the continental margin would have been included into the accreted wedge. Subgroup C2, which plots within subgroup C3, has rim ages of 422 ± 17 Ma and 432 ± 24 Ma. These rim ages are characteristic for the peri-Gondwanan terranes of Mixteca (Acatlán) (480–440 Ma; metamorphic ages of 416–388 Ma) and Yucatan–Maya (418 Ma).

Neoproterozoic–Early Paleozoic Cores

Group B contains zircon cores of Neoproterozoic–early Paleozoic ages and rims of Neoproterozoic–late Paleozoic ages. The core ages are likely to be of Rodinian volcanic origin (Li et al., 2008) or potentially from Pan-African terranes (Heatherington et al., 1996; Lopez et al., 2001; Samson et al., 2005; Moecher and Samson, 2006). Notably, the top right-hand cluster of core-rim ages within group B trend close to the 1:1 line, indicating secondary anatectic growth and crystallization, relatively soon after initial crystallization. This kind of growth behavior could be indicative of the first intermittent volcanic pulses following the breakup of Rodinia. On the other hand, the cluster at the bottom left-hand corner of group B contains younger cores, which appear to have Pan-African sourcing and a secondary growth related to the younger, peri-Gondwanan terranes.
**Paleozoic Cores**

Core-rim relationships with purely Paleozoic cores are shown in group A (Fig. 12). These are the youngest core-rim relationships and are almost certainly indicative of the peri-Gondwana terrane and/or volcanic arc activity within the peri-Gondwanan, Coahuila, or Oaxaquian terranes (Fig. 8). We suggest rim growth to be indicative of zircon recycling and inclusion in the volcanic arc activity within the Gondwanan hinterland and subsequent transport during the collision of Gondwana and Laurentia.

**Maximum Depositional Ages**

The youngest zircon grain age or youngest age mode is a powerful method for determining maximum depositional ages (MDAs), particularly in the absence of biostratigraphic age constraints (Dickinson and Gehrels, 2009). This approach is predominantly limited by the generation of new, first-cycle volcanic zircons and their airborne or near-instantaneous fluvial input into the basinal strata. These MDA estimates not only provide chronostratigraphic control, but also important insights into the presence or absence of local and/or regional volcanic or plutonic sources as well as erosional lag-time constraints (i.e., the difference between MDA and depositional age) for independently dated strata (Rahl et al., 2007). MDA interpretations by means of the youngest grain ages in a stratigraphic unit have been used to determine the lag time between zircon crystallization and delivery into a sedimentary basin. This observation assists with the differentiation of volcanic, plutonic, or recycled and multi-cycle zircons and their sources (e.g., Dickinson and Gehrels, 2009; Xu et al., 2017). While volcanic and plutonic zircons are commonly characterized by lag times of <1 and <20–40 m.y., respectively, multi-cycle zircons often exhibit lag times >>50 m.y.

Integrating MDA values with coeval biostratigraphic and sequence stratigraphic information from previous regional studies in the Glass Mountains and Marathon fold and thrust belt provides insight into regional volcanic influence. Specifically, this comparison exhibits the presence of active volcanic arc magmatism, the unroofing of magmatic belts in the hinterland drainage system, as well as the long-term recycling of pre-contractional sedimentary sequences in the source terrane. Figure 10 displays the MDAs of all 13 samples plotted against their independent best stratigraphic ages, using both the YSG and YC1a (2+) approaches (Dickinson and Gehrels, 2009; Xu et al., 2017). Here, the independent best stratigraphic ages are based on regional biostratigraphic and sequence stratigraphic data (Olszewski and Erwin, 2009; Glasspool et al., 2013; Richards, 2013; Nestell et al., 2019). The results of this analysis show that volcanic zircons with negligible lag times did not arrive in the basinal system until the middle Permian (Guadalupian), marking the input and onset of Cordilleran or East Mexico Arc volcanism at ca. 280–270 Ma (Dickinson et al., 2000; Dickinson and Lawton, 2001). Prior to middle Permian time, however, no zero-lag-time volcanic zircons were recorded in any of the Pennsylvanian–Permian strata, while minimum lag times deduced from the youngest zircon components are nearly constant at ~30–40 m.y. Due to correlation between plutonic arc exhumation and calculated lag time, we interpret the zircons with lag times of 30–40 m.y. to have been derived from arc magmatic rocks emplaced along the Gondwanan convergent margin during closure of the Rheic Ocean in Carboniferous time (Torres et al., 1999; Keppie et al., 2008). In summary, based on the differences between true depositional age and zircon-based MDA, there are three dominant sources of zircons in the southern Permian Basin: (1) multi-cycle zircons eroded and recycled from Proterozoic to early Paleozoic or younger Gondwanan or Laurentian strata; (2) plutonic sources eroding and unroofing within the hinterland arc related to Rheic closure; and (3) first-cycle volcanic zircons derived from active volcanic arc magmatism in the middle Permian. In particular, the presence of Carboniferous arc magmatic zircons with relatively constant lag times is noteworthy because they unequivocally point to derivation from the Gondwanan convergent margin and to protracted unroofing of this magmatic arc. Furthermore, the presence of these ages suggests essentially continuous Devonian–Carboniferous arc magmatism related to Rheic closure. This is noteworthy given the sparse record of this magmatism along the Gondwanan margin from Florida to NE Mexico, including the Las Delicias Arc (Steiner and Walker 1996; McKee et al., 1999; Lopez et al., 2001; Keppie, 2004; Keppie et al., 2008; Soreghan and Soreghan, 2013).

## PROVENANCE EVOLUTION

The detrital zircons from the Marathon fold and thrust belt and Glass Mountains represent a wide range of crystallization ages and a complex history of sediment recycling (Fig. 9). By comparing the DZ U-Pb signatures with respect to deposition during pre-, syn-, or post-collisional time windows, we are able to interpret and reconstruct proximal basin sedimentary evolution during progressive collision. Further, incorporation of other provenance studies regionally helps to establish a broader understanding of how sediment dispersal from the southern orogenic highlands and distal hinterland influenced sediment dispersal during foreland basin formation and fill.

A few key provenance trends can be inferred from the DZ U-Pb analyses in this study: (1) appearance of Neoproterozoic–Cambrian zircon grains in the Pennsylvanian Haymond Formation points toward basin inversion and the uplift and exhumation of volcanic units related to Rodinian rifting; (2) upsection decrease in Grenvillean (ca. 1300–920 Ma) and increase in Paleozoic zircons denote a steady provenance shift from a dominantly orogenic highland source to one of sediment sources deeper in the Gondwanan hinterland; and (3) lack of drastic changes in provenance during the early to middle Permian supports the argument for waning tectonism within the collisional domain during this time period as does overlap of strata of those ages onto deformed rocks of the orogenic front in the Glass Mountains (Fig. 2).
Mississippian–Pennsylvanian Provenance Evolution

Previous DZ provenance studies of the Permian Basin focused their efforts on resolving the age spectra of the Delaware Mountain Group, which includes the Brushy, Cherry, and Bell Canyon formations of the Guadalupe Mountains and Delaware Basin (Soreghan and Soreghan, 2013; Anthony, 2015; Xie et al., 2018). While these studies made significant contributions to the understanding of provenance during basin fill of the Delaware Basin, they only capture provenance during post-tectonic sedimentation. Results from this study evaluate the evolutionary component of southern provenance during basin formation and fill. By defining the evolution of DZ age spectra over an extensive period of tectonism and sediment transport, results from this study help to resolve long-term trends in provenance observed both locally and regionally.

Tesnus Formation

A wide range of age modes is present in the Tesnus DZ spectra (Fig. 9) with a notably high Grenvillian (ca. 1300–920 Ma) age mode and absence of a middle Neoproterozoic–Cambrian (ca. 920–521 Ma) age mode. Because of its presence in the rest of the samples throughout this study, the lack of Neoproterozoic–Cambrian zircon grains is conspicuous. We interpret the Tesnus Formation to be completely sourced from the southern Gondwanan continental assemblage. Using the Tesnus as a baseline for provenance evolution helps in understanding provenance shifts within the younger strata of the Marathon fold and thrust belt and Glass Mountains.

Grenville Signature. The Grenville orogen, present in southern and eastern North America, Mexico, and the Gondwanan continents (Rainbird et al., 1992; Rainbird et al., 1997; Soreghan and Soreghan, 2013), typically makes up a significant portion of the DZ population in North American sandstones from Neoproterozoic to Mesozoic (Dickinson and Gehrels, 2003; Moecher and Samson, 2006), adding difficulty to resolution of true source for these age modes. Grenvillian zircon within the Tesnus are no different, constituting >50% of the DZ population. However, as stated in a previous section, depth profiling of Grenvillian zircons can make constraining their original source region possible. Gillis et al. (2005) presented a compilation of DZ U-Pb ages from the Oaxaquian crystalline basement terrane and Paleozoic strata of southern Mexico, which showed strong age peaks of 981 Ma and 993 Ma, respectively. When compared to Grenville ages of southwestern and northeastern North America, the Oaxaquian DZ U-Pb ages are consistently younger (<1100 Ma) (Gross et al., 2000; Stewart et al., 2001; Eriksson et al., 2003; Gillis et al., 2005). For this reason, we attribute the most prominent Grenvillian DZ peak within the Tesnus age spectra (1037 Ma) to the Oaxaquian source terrane during pre-collisional sediment transport.

Paleozoic Signature. Zircons of Paleozoic age are the youngest among Tesnus age spectra with a prominent peak at ca. 422 Ma. Peri-Gondwanan terranes (Fig. 8) are the most likely sediment sources because of the pre-collisional nature of the Tesnus Formation. Specifically, the peri-Gondwanan terranes of Mixteca (Acatlán) (480–440 Ma; metamorphic ages of 416–388 Ma) and Yucatan-Maya (418 Ma) function as the closest match to the DZ U-Pb age modes of the Tesnus age spectra (Steiner and Walker, 1996; Keppie, 2004; Gillis et al., 2005; Steiner and Anderson, 2005; Talavera-Mendoza et al., 2005; Keppie et al., 2006, 2008; Weber et al., 2006, 2008; Martens et al., 2010). By applying these age domains and collisional timing based on paleogeographic and tectonic reconstructions of the peri-Gondwanan terranes (Keppie, 2004; Centeno-García et al., 2005; Weber et al., 2008) previous provenance studies argue for initial denudation of the peri-Gondwanan terranes to be during the middle Pennsylvanian (Soreghan and Soreghan, 2013; Anthony, 2015; Xie et al., 2018). Alternatively, based on the measured Paleozoic DZ ages from the Tesnus Formation, denudation and incorporation of sediment from these terranes were likely to have initiated in the Carboniferous, during migration of the Gondwanan continent.

Haymond Formation

Deposited during ongoing tectonism, the sediment source history of the Haymond Formation has been controversial (Denison et al., 1969; King, 1958; McBride, 1989; Gleason et al., 2007). As stated previously, we can effectively use the Tesnus Formation DZ U-Pb age spectra as a baseline for the younger strata sampled, and, based on shifts in provenance, we are able to make inferences regarding evolution of the collisional and foreland system. In this case, the Haymond DZ U-Pb age spectra exhibit a marked change in age population with the appearance of the previously absent Neoproterozoic–Cambrian age mode. It is important to note that this is the only significant provenance difference between the Tesnus and Haymond DZ spectra. This change in provenance denotes the inversion and exhumation of the distal Laurentian margin during Pennsylvanian collision with Gondwana. Further, this defines the Haymond age spectra as a transitional unit between pre- and syn-orogenic units.

Rifting of the Rodinian supercontinent occurred between ca. 825 Ma and 740 Ma with notable volcanic pulses from 780 to 540 Ma (Li et al., 2008; Dickinson and Gehrels, 2009; Hanson et al., 2016). Strata deposited along the southern passive margin of Laurentia covered these ancient syn-rift volcanic rocks (King, 1937, 1978; Flawn et al., 1961; McBride, 1989; Hickman et al., 2009). Therefore, the most viable method to explain inclusion of these volcanic units into younger strata of the Marathon fold and thrust belt (and eventually the southern Delaware Basin) would be through uplift of the deep-seated continental margin. We propose the formation of a duplex zone between the Gondwanan continent and Laurentian margin (e.g., Devils River Uplift) (Fig. 13), to exhum syn-rift volcanic rocks. Therefore, the Haymond Formation is most likely composed of a combination of southern remnant-ocean basin sediment similar to that of the Tesnus Formation and uplifted strata of the ancient Laurentian passive margin during the onset of continental collision.
Figure 13. Tectonostratigraphic reconstruction of the evolving Laurentian-Gondwanan margin throughout the Mississippian–middle Permian based on detrital zircon U-Pb data accompanied with coeval plan view paleogeographic maps. Dark-brown shading is indicative of high relief, eroding landscapes, while light-brown shading is indicative of low-relief, depositional landscapes. Light blue to dark blue represents varying water depth with light blue being shallow and dark blue being deep. Strata colors in the cross-sectional view are age equivalent with stratigraphic units of Figure 6. Paleogeographic figures adapted from Blakey Deep Time Maps. (A) Pre-collisional deposition of Tesnus Formation on the leading edge of approaching Gondwanan continent, deposition of thin-bedded limestone, shale, and chert. (B) Continental collision during the Pennsylvanian. (C) Collision of Laurentia and Gondwana, incorporation of rifted Laurentian crust through crustal duplexing. (D) Post-collisional figure representing tectonic quiescence, sediment supply from deeper within the Gondwanan hinterland, supporting progradation of stable clinoforms along the southern margin of the Delaware Basin. See text for further explanation.
Early–Middle Permian Deposits: Unroofing and Tectonic Quiescence

The latest syn-orogenic deposits of Wolfcampian age and potentially first post-orogenic deposits of Leonardian age display DZ U-Pb age spectra similar to that of the Pennsylvanian Haymond Formation. We interpret this similarity to be indicative of ongoing unroofing of the orogenic highlands. The deposition of 4200–5600 m of siliciclastic strata during Wolfcampian time correlates well with the rapid erosion of the massive accreted wedge adjacent to the basin (King, 1937; Flawn et al., 1961; Thomson and McBride, 1964; King, 1978). The age spectra observed within the Wolfcampian samples are consistent with the interpretation of Thomas et al. (2019) on potential sourcing of zircons from the Coahuila block of Mexico. Additionally, the Leonardian Skinner Ranch Formation is a sandy turbidite facies, much more distal than the Wolfcampian conglomerates of the Lenox Hills Formation; yet the sediment source appears to remain the same.

Transfer from the unroofing sequence seen during the Wolfcampian–Leonardian depositional period to that of post-tectonic sediment transport is captured within the middle Permian deposits, but it is far more subtle than the previously observed provenance shifts. Tracking the Grenvillian and Paleozoic DZ U-Pb age components upsection shows this subtle, progressive shift in provenance evolution, consisting of tectonic quiescence within the collisional domain and catchment stabilization resulting in sediment sourcing from deeper in the hinterland (Fig. 13D). By this point in time, the large orogenic wedge had been denuded to the point that sediment sourced deeper within the hinterland was possible and could feed the N-NW progradation of the Guadalupian (middle Permian) deposits.

![Multidimensional scaling (MDS) map from all Delaware Basin samples. Data compiled from this study, Soreghan and Soreghan (2013), and Anthony (2015). Abbreviations: GlM—Glass Mountains sample; GdM—Guadalupe Mountains sample; SEDB—southeastern Delaware Basin. Color key: dark blue—Mississippian Tensas Formation (TSS1 and TSS2); light blue—Pennsylvanian Haymond Formation (HF1 and HF2); yellow—Wolfcampian Lenox Hills Formation (WCSS1 and WCSS2); orange—Leonardian Skinner Ranch Formation (LSS1); light red—Guadalupian Vidrio Formation (VSS1, VSS2, VSS3, and VSS4) and samples of coeval age from other studies; red—Guadalupian Altuda Formation (ALSS1) and samples of coeval age from other studies. All colors coordinate with the given stratigraphic column (Fig. 6).](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/doi/10.1130/GES02108.1/4913532/ges02108.pdf)
foreland deposition: (1) pre-collisional deposition of the Tesnus Formation; (2) transition into syn-collisional deposition of the Haymond Formation with Laurentian margin uplift; and (3) tectonic quiescence and hinterland catchment maturity.

The Tesnus Formation samples plot as a distinct grouping that is most dissimilar from the youngest (Guadalupian) post-collisional samples. As previously stated, we interpret the Tesnus to be of pre-collisional, southern origin, and the degree of dissimilarity seen in the MDS analysis bolsters the argument that the Tesnus is unique in being a baseline for how a purely southern-sourced DZ profile would look. The samples of the Haymond Formation and Wolfcampion–Leonardian samples mark a sharp provenance difference related to the orogenic activity and inversion of the Laurentian passive margin and, hence, the mixing of Gondwanan and Laurentian margin sources. The shift from the Tesnus Formation to the Haymond Formation appears to be marked by the sudden input of Laurentian passive margin elements, including a higher concentration of older Grenvillian zircons (>1100 Ma) and Neoproterozoic zircons. Though it should be noted that while the Rodinian rift volcanics display a distinct DZ age signature (780–560 Ma) that can be tied to the ancient Laurentian margin (Li et al., 2008; Hanson et al., 2016), there exists no complete data set documenting the DZ signature of the Cambrian–Devonian Laurentian passive margin strata. These data will help in understanding the DZ mixing component between the two colliding plates. Subsequently, from the Haymond Formation to the Early Permian Lenox Hills Formation (Wolfcampion), the MDS shows a relatively smooth trajectory from initial inclusion of the Laurentian passive margin into the orogenic wedge and initial sediment dispersal from the orogenic highlands (Figs. 13C and 13D).

In MDS space, the DZ signature of strata deposited during post-collisional tectonic quiescence and their provenance evolution appear to differ strongly from the syn-orogenic trajectory (Fig. 11). The Word (WSS5), Vidrio (VSS1, VSS2, VSS3, and VSS4), and Altuda (ALSS1) formations appear to plot as a steady provenance shift from oldest to youngest, with the exception of VSS1 plotting closer to the Wolfcampion–Leonardian (WCSS1 and WCSS2, and LSS1, respectively) samples than the stratigraphically older Word (WSS5) sample. These trends and trajectories observed in MDS space are clear and intuitively reflect the overall tectonic evolution of the system from convergence, to continental collision, to post-collisional deposition (Fig. 11B).

# DISCUSSION

## Integration of Regional Delaware Basin Provenance

The results from the collisional domain and proximal foreland may be informed by comparison with samples collected regionally across the Delaware Basin. Soreghan and Soreghan (2013), Anthony (2015), and Xie et al. (2018) each performed provenance analyses with the use of DZ U-Pb geochronology in different parts of the Delaware Basin. These studies focus on testing previous hypotheses for sediment sourcing during the deposition of the Guadalupian-age Delaware Mountain Group (Figs. 14). Here, we compare our collected data from the southern Delaware Basin with the data of those authors from the northern and southeastern Delaware Basin (Figs. 14 and 15).

Soreghan and Soreghan (2013) interpreted DZ data from the Brushy and Bell Canyon members of the Guadalupe Mountain region to indicate sediment sources from the proximal Ouachita foreland as well as sources south of the accreted Ouachita margin. Anthony (2015) used DZ data from core in the southeastern Delaware Basin, specifically from the Cherry and Bell Canyon members, and his interpretation aligns with Soreghan and Soreghan (2013). Our documentation of provenance from coeval deposits from the most southernly portion of the Delaware Basin provides an opportunity to evaluate these interpretations. While potential distal transport of Ouachita regional sources is likely for both of these cases, the importance lies more with volumes contributed. During margin inversion, large volumes of sediment were shed into the southern Permian Basin (4200–5600 m in some places) (King, 1937, 1978; Flawn et al., 1961; Thomson and McBride, 1964; McBride, 1989; Hickman et al., 2009). This begs the question of where south-north transport of sediment ends and sediment transport from other regions surrounding the basin begins. Comparison of samples from Soreghan and Soreghan (2013), Anthony (2015), and this study provides insight into this issue (Table 1; Figs. 14 and 15) (DZ age data can be found in Supplemental File S3 [footnote 1]). Figure 14 shows that the sediment in the Glass Mountains is more similar to the southeastern portion of the Delaware Basin than that of the northern Delaware Basin. The disparities in distance and DZ age spectra are highlighted in Figure 15, in which the number of Neoproterozoic–age zircons within each sample suite decreases from south to north. It is important to remember that samples within our study effectively define the southern provenance signal for the entire formation period of the Permian Basin as well as post-collisional deposition of Guadalupian age strata in the southern Delaware Basin. Thus, higher similarity between samples of this study and those of Anthony (2015) and dissimilarity with those of Soreghan and Soreghan (2013) indicate a more diverse range of sources in the northern portion of the basin and more pronounced southern signal in some of the central and south-central portions of the Delaware Basin (Anthony, 2015). More work is needed, likely from core within the northern portion of the basin and denser upstream sampling of regional sediment feeders from the NW and NE. However, we argue that the Guadalupian section within the southern portion of the basin was being fed almost entirely by proximal Marathon sources as opposed to Ouachita region transport.

## Mississippian–Permian Tectonics

Pre-tectonic strata of the Laurentian passive margin consisted of variable mechanically weak, thin-beded intervals and strong chert layers, ultimately leading to the formation of the complex structural features observed in the Marathon fold and thrust belt (Hickman et al., 2009). Studies have documented...
the unique mechanical stratigraphy and structural style of the fold and thrust belt (DeMig, 1983; Tauvers, 1988; Muehlberger and Tauvers, 1989; Hickman et al., 2009). Our results clearly indicate temporal evolution of the Marathon fold and thrust belt through tracking of sediment provenance evolution of the pre-, syn-, and post-collisional deposits of Mississippian–Permian age. Notably, these tectonostratigraphic units can be separated into three distinct phases of tectonic evolution and subsequent sediment transport and deposition: (1) pre-tectonic deposition of the Mississippian Tesnus Formation; (2) uplift and exhumation of the passive Laurentian margin and ensuing unroofing of the orogenic wedge; and (3) post-tectonic margin stabilization coupled with catchment maturity and hinterland sediment transport (Fig. 13).

During early to middle Paleozoic time, a relatively thin marine sequence was deposited along the Laurentian passive margin (Fig. 13A), with indication of a north or northwest source of clastic sediment supply (King, 1978; McBride, 1989). Mississippian deposition of the Tesnus Formation in the form of flysch deposits is the first record of the approaching Gondwanan continental margin as displayed by its unique DZ U-Pb age spectra (Fig. 9). These age spectra lack the entire section of Neoproterozoic-age zircons (Cryogenian–earliest Cambrian) with the exception of a single grain dated at 588 ± 5.7 Ma. This is a clear indication of the pre-collisional nature of the Tesnus Formation and demonstrates that, while subduction of the Laurentian oceanic crust was possible, incorporation of even distal portions of the Laurentian marginal sediment was unlikely.

Incorporation of Neoproterozoic zircons during the deposition of the Haymond Formation suggests incorporation of the Laurentian rifted margin into the uplifting orogenic wedge during the Pennsylvanian (Fig. 13C). Hickman et al. (2009) noted that the multiple décollement horizons within the pre-tectonic section of Marathon strata led to formation of a large-scale duplex zone, a likely mechanism that formed the Devils River uplift (e.g., Nicholas and Rozendal, 1975; Nicholas and Waddell, 1989). This idea is bolstered by the appearance of what we interpret to be zircons from the volcanic rocks extruded during Rodinian rifting phases of the Laurentian margin (780–540 Ma). This potential source is unaccounted for by previous regional provenance studies (Soreghan and Soreghan, 2013; Anthony, 2015; Xie et al., 2018). The similarity in DZ U-Pb age spectra of the Wolfcampian–Leonardian strata is indicative of constant unroofing of the accreted orogenic wedge. Knowledge of the sheer volume of sediment deposited over this time interval (King, 1937; Flawn et al., 1961; Thomson and McBride, 1964; King, 1978; McBride, 1989; Hickman et al., 2009)
combined with our knowledge of a consistent orogenic sediment source leads us to believe that the large volumes of syn-orogenic sediment deposited into the proximal foreland basin are dominated by a source in the orogenic wedge, potentially over long periods of time (~60 m.y.).

The thickness of post-tectonic (Guadalupian) stratigraphy of the proximal foreland basin is far more modest than that of the syn-orogenic deposits (Fig. 13D). The DZ U-Pb age spectra of these samples suggest regional tectonic quiescence, aligning with a change in depositional environment during transgression of the southern margin of the Delaware Basin (King, 1930; Hairton et al., 2010; Gehrels et al., 2011a; Bande et al., 2012; Colleps et al., 2018). This study resolves sparse Grenvillian-age zircons, a few core-rim relationships exist (Fig. 12). Grenvillian cores with Pan-African rims ranging from 583 to 422 Ma suggest that Gondwana terranes, especially those of Oaxaquia and Coahuila were likely candidates for sediment supplied to the foreland basin during this time. Finally, the youngest DZ U-Pb age modes within the Guadalupian age spectra are >300 Ma, indicating sediment sourcing from volcanic arc terranes, specifically the Las Delicias Arc located within the Coahuila terrane (Figs. 13B and 13C) (Lopez et al., 2001; Thomas et al., 2019).

Provenance studies within the collisional domain and foreland basin have been performed in a variety of basins globally, especially in the Andean (retroarc) and Himalayan regions (DeCelles et al., 1998; Horton et al., 2010; Gehrels et al., 2011a; Bande et al., 2012; Colleps et al., 2018). This study resolves a provenance evolution of both spatial and temporal significance prior to collision, within collisional domain during continental collision, and during post-collisional sediment dispersal to the resultant foreland basin setting. It is intuitive that the most high-relief, proximal region of the fold-thrust belt

### TABLE 1. STRATIGRAPHIC STAGE, FORMATION, LITHOLOGY, LATITUDE AND LONGITUDE, LOCATION, AND DATA SOURCE OF EACH SAMPLE FROM THE PERMIAN BASIN, WEST TEXAS, USA

| Sample ID | Stage      | Formation                  | Lithology                                      | Latitude (°) | Longitude (°) | Location                        | Data source                  |
|-----------|------------|----------------------------|-----------------------------------------------|--------------|--------------|--------------------------------|------------------------------|
| ALSS1     | Guadalupian| Altuda                    | Siltstone and/or very fine-grained sandstone | 30.383844    | −103.304593  | Southern Delaware Basin         | This study                   |
| JCT-4946  | Guadalupian| Bell Canyon               | Siltstone and/or very fine-grained sandstone | 31.304495    | −103.145150  | South Eastern Delaware Basin    | Anthony (2015)               |
| Bell Canyon (Yates) | Guadalupian | Bell Canyon | Siltstone                                        | 32.282550    | −104.363613  | Northern Delaware Basin         | Soreghan and Soreghan (2013) |
| Bell Canyon (Rader) | Guadalupian | Bell Canyon | Sandstone                                         | 31.931592    | −104.731086  | Northern Shelf                    | Soreghan and Soreghan (2013) |
| VSS4      | Guadalupian| Vidrio                    | Siltstone and/or very fine-grained sandstone | 30.396849    | −103.243585  | Southern Delaware Basin         | This study                   |
| VSS3      | Guadalupian| Vidrio                    | Siltstone and/or very fine-grained sandstone | 30.396649    | −103.243585  | Southern Delaware Basin         | This study                   |
| VSS2      | Guadalupian| Vidrio                    | Siltstone and/or very fine-grained sandstone | 30.381872    | −103.231476  | Southern Delaware Basin         | This study                   |
| VSS1      | Guadalupian| Vidrio                    | Siltstone and/or very fine-grained sandstone | 30.381794    | −103.231211  | Southern Delaware Basin         | This study                   |
| JCT-5872  | Guadalupian| Cherry Canyon             | Siltstone and/or very fine-grained sandstone | 31.304495    | −103.145150  | South-eastern Delaware Basin    | Anthony (2015)               |
| JCT-6068  | Guadalupian| Cherry Canyon             | Siltstone and/or very fine-grained sandstone | 31.304495    | −103.145150  | South-eastern Delaware Basin    | Anthony (2015)               |
| JCT-6446  | Guadalupian| Cherry Canyon             | Siltstone and/or very fine-grained sandstone | 31.304495    | −103.145150  | South-eastern Delaware Basin    | Anthony (2015)               |
| WSS5      | Guadalupian| Word                     | Fine-grained sandstone                        | 30.382164    | −103.231126  | Southern Delaware Basin         | This study                   |
| BCSand    | Guadalupian| Brushy Canyon             | Siltstone                                      | 32.848033    | −104.839661  | Northern Delaware Basin         | Soreghan and Soreghan (2013) |
| BCS1      | Guadalupian| Brushy Canyon             | Sandstone                                      | 31.848303    | −104.839661  | Northern Delaware Basin         | Soreghan and Soreghan (2013) |
| LSS1      | Leonardian  | Skinner Ranch             | Sandstone                                     | 30.326233    | −103.235566  | Southern Delaware Basin         | This study                   |
| WCSS2     | Wolfcampian | Lenox Hills               | Sandstone and/or conglomerate                 | 30.323535    | −103.234836  | Southern Delaware Basin         | This study                   |
| WCSS1     | Wolfcampian | Lenox Hills               | Sandstone and/or conglomerate                 | 30.323490    | −103.234193  | Southern Delaware Basin         | This study                   |
| HF2       | Pennsylvanian | Haymond                | Sandstone                                     | 30.212437    | −102.988188  | Marathon fold and thrust belt    | This study                   |
| HF1       | Pennsylvanian | Haymond                | Sandstone                                     | 30.208736    | −102.984907  | Marathon fold and thrust belt    | This study                   |
| TSS2      | Mississippian | Tesnus               | Sandstone                                     | 30.204687    | −102.973623  | Marathon fold and thrust belt    | This study                   |
| TSS1      | Mississippian | Tesnus               | Sandstone                                     | 30.204225    | −102.967016  | Marathon fold and thrust belt    | This study                   |
would supply the majority of sediment to the adjacent foreland basin system, and we have demonstrated that is the case in the Glass Mountains of the southern Delaware Basin. Moreover, and curiously enough, there are similarities in the dominant age modes of detrital zircons throughout the basin (e.g., Soreghan and Soreghan, 2013). However, decades of sedimentological and stratigraphic analysis of the depositional fairways suggest a dominant northwest to south paleoflow direction, at least for the Guadalupian strata (Rosen and Sarg, 1987; Gardner et al., 2003; Pyles et al., 2010). Thus, the ubiquitous provenance signal in the Permian Basin does not necessarily reflect direct sediment input from Laurentian source terranes. Indeed, Soreghan and Soreghan (2013) and Kocurek and Kirkland (1998), among others, interpret convoluted Gondwanan hinterland; and (3) lack of drastic changes in provenance during the permian to dominantly orogenic highland source to sediment sources deeper in the Delaware Basin. Future work in the Delaware Basin and beyond should focus on retracing the sediment-routing pathways from predominantly peri-Gondwanan source terranes to the northern basin margins. Our analyses of the earliest pre collisional strata in the southern Delaware Basin helped us to trace sediment dispersal and provenance evolution. Difficulties may stem from gaps in the geologic record, but, where possible, this method can elucidate a record of sediment sourcing from areas that have undergone extensive and complex tectonic deformation.

CONCLUSIONS

By dating the crystallization age of individual detrital zircon grains, we are able to correlate detrital zircon ages with regional paleogeography of potential sediment source terranes to interpret provenance. By sampling strata from the pre-, syn-, and post-orogenic region of the late Paleozoic Delaware Basin, we were able to define a type section of provenance from a southern source across a dynamic tectonic system. Here, we present 1721 new detrital zircon (DZ) U-Pb ages and 85 separate age core-rim relationships from 13 samples within the Marathon fold and thrust belt and Glass Mountains of West Texas. To analyze provenance, we supplement our new data with published DZ geochronologic data sets of regional provenance studies from older and contemporaneous basin-filling episodes along the Appalachian-Ouachita suture zone as well as within the Laurentian cratonic interior. Key findings include: (1) appearance of Neoproterozoic–Cambrian zircon grains in the Pennsylvanian Haymond Formation indicates basin inversion and the uplift and exhumation of volcanic units related to Rodinian rifting; (2) an upsection decrease in Grenvillian (ca. 1300–920 Ma) and increase in Paleozoic zircons denotes a steady provenance shift from a dominantly orogenic highland source to sediment sources deeper in the Gondwanan hinterland; and (3) lack of drastic changes in provenance during the early to middle Permian supports the argument for tectonic quiescence within the collisional domain during this time period. Additionally, depth profiling and core-rim relationships aided in tracing sources for Grenvillian-age zircons, which, due to universal abundance in both Gondwanan and Laurentian source terranes, have been particularly difficult to interpret in past regional DZ studies. Elucidating an extensive history of zircon transport and recycling during multiple stages of tectonism coupled with the ability to tie these data to their original sources improves our understanding of potential source to sink relationships within the basin. By tracking provenance trends across long-term (10^7–10^8 yr) sedimentation and tectonic deformation, we observed a regional change in provenance through the final stages of continental collision. Specifically, the three main provenance stages observed were: (1) pre-tectonic deposition; (2) uplift and exhumation of a passive margin and ensuing unroofing of the orogenic wedge; and (3) post-tectonic margin stabilization coupled with catchment maturity and hinterland sediment transport. Similar collisional events are ubiquitous across the geologic record. This work could help to guide others studying sediment sourcing and evolution of the orogenic system of foreland basins.

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