Detrital zircons from Cretaceous midcontinent strata reveal an Appalachian Mountains–Cordilleran foreland basin connection

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ABSTRACT

U-Pb ages ($n = 403$) of detrital zircons from the Dakota Formation in western Iowa and eastern Nebraska provide evidence for westward-flowing fluvial systems that stretched from the Appalachian highlands to the western U.S. Cordilleran foreland basin during Albian–Cenomanian time. Approximately 78% of detrital zircon grains match the ages of Grenvillian (1.3–1.0 Ga), Pan-African (750–500 Ma), and Paleozoic (500–310 Ma) bedrock sources located within the present-day Appalachian Mountains. The presence of minor detrital zircon grains of Paleo-proterozoic (2.5–1.5 Ga) or Archean age (>2.5 Ga) indicates that northern source regions in Minnesota, Wisconsin, and Canada did not contribute a significant volume of sediment, as had been previously interpreted. Based on similarities between detrital zircon signatures in the mid-continent strata and time-equivalent Cordilleran foreland basin strata, Appalachian sources may have contributed a previously unrecognized volume of sediment to the Albian–Cenomanian foreland basin system. Sediment flux from the Appalachian region to the Cordilleran foreland basin during middle Cretaceous time may have been related to increased uplift and exhumation due to passage over a mantle plume track.

INTRODUCTION

During middle Cretaceous time, North American tectonics were dominated by the growth of the North American Cordillera and development of a regional north-south–trending foreland basin system. The basin was flooded by the Western Interior Seaway during Cretaceous time and separated a convergent margin fold-and-thrust belt to the west (Sevier orogeny) from low-lying craton to the east (Fig. 1; McGokey, 1972; Williams and Stelck, 1975; Kauffman and Caldwell, 1993; Robinson Roberts and Kirschbaum, 1995; DeCelles, 2004). The traditional provenance model for foreland basins suggests that most of the sediment originated from the adjacent fold-and-thrust belt, with a relatively minor contribution from the craton (Dickinson and Suczek, 1979; Schwab, 1986; DeCelles and Giles, 1996). Recent studies of the northern Andean foreland basin, however, demonstrate that craton-derived sediment may be important in the early stages of foreland basin development (Horton et al., 2010a, 2010b; Nie et al., 2012).

New detrital zircon U-Pb geochronologic data are presented here from the Albian–Cenomanian Dakota Formation, which is exposed in a relatively continuous belt from southwestern Minnesota to central Kansas (Fig. 2). It is the oldest sedimentary unit preserved along the eastern margin of the Western Interior Seaway and therefore provides the earliest record of depositional systems on the eastern side of the Cordilleran foreland basin during Mesozoic time. Compared to well-studied contemporaneous depositional systems on the western margin of the basin, middle Cretaceous strata on

Figure 1. Locations of major igneous sediment source terranes in middle Cretaceous time. Arrows show dominant sediment transport directions based on detrital zircon age distributions from Albian–Cenomanian midcontinent strata. Dashed and solid arrows illustrate transport of sediment into the Cordilleran foreland basin foredeep and back bulge during Albian and Cenomanian time, respectively. BB—Bighorn Basin. Figure is adapted from DeCelles (2004) and Dickinson and Gehrels (2010).
the eastern margin have only recently become a focus of investigation (Witzke and Ludvigson, 1994; Brenner et al., 2000, 2003; Joeckel et al., 2005; Ludvigson et al., 2010), and new geochronologic provenance tools have not previously been applied to these strata. As a result, the middle Cretaceous paleogeography of the midcontinent, as well as the sediment supply from the craton to the Cordilleran foreland basin, has remained poorly constrained.

DAKOTA FORMATION

Sedimentologic and stratigraphic models for the Dakota Formation have been established from type section localities in eastern Nebraska and western Iowa (Fig. 2; Witzke and Ludvigson, 1994, 1996; Ludvigson, 1999; Brenner et al., 2000, 2003; Joeckel et al., 2005). The Albian Nishnabotna Member is characterized by conglomerate and sandstone interpreted to represent braided stream and tidally influenced incised-paleovalley deposits (Fig. 3). The paleovalleys are incised into Paleozoic bedrock, have up to 115 m of relief, and are interpreted to have developed sometime between 160 and 105 Ma (Late Jurassic–middle Cretaceous; Anderson and McKay, 1999; Ludvigson, 1999; Joeckel et al., 2005). The Cenomanian Woodbury Member is dominated by mudstone and shale with relatively minor sandstone and is interpreted to represent meandering stream and marginal marine deposits.

Previous studies that utilized sandstone petrography, conglomerate clast compositions, clay mineralogy, paleocurrent analyses, and orientations of the incised paleovalleys suggested that the sediment source terranes for the Dakota Formation were Paleozoic carbonate bedrock and Precambrian crystalline rocks located in eastern Iowa, Minnesota, Wisconsin, and Illinois (Witzke and Ludvigson, 1994, 1996). The authors did note, however, that several lines of evidence would allow for sediment contribution from Appalachian sources. Specifically, the lack of a topographic barrier between the Western Interior Seaway and the Appalachian Mountains, the presence of isolated middle Cretaceous coarse-grained strata widespread across eastern North America, and a lack of middle Cretaceous sediments in the Mississippi Embayment strata south of the Ouachita uplands all suggest that a transcontinental fluvial system could have flowed from east to west across the continent during middle Cretaceous time.

METHODS

Four samples were collected from Dakota Formation outcrops located in western Iowa and eastern Nebraska. Two samples each were collected from the Nishnabotna Member (Highway 25 and Gravel Pit) and Woodbury Member (Homer and Stone Park; Figs. 2 and 3). Zircons were separated using standard methods (crushing, sieving, magnetic separation, and heavy liquid separation) and mounting protocols at the University of Iowa. U-Pb analyses of detrital zircons were conducted by laser ablation–multicollector–inductively coupled plasma–mass spectrometry (LA-MC-ICP-MS) at the Arizona LaserChron Center (i.e., Gehrels, 2000, 2012; Gehrels et al., 2006). The analytical data are reported in Table DR1.1 Interpreted ages are corrected for common Pb and are based on 206Pb/238U for younger than 900 Ma grains and on 206Pb/207Pb for older than 900 Ma grains. This division at 900 Ma results from the increasing uncertainty of 206Pb/238U ages and the decreasing uncertainty of 206Pb/207Pb ages as a function of age. Analyses that are >20% discordant (by comparison of 206Pb/238U and 206Pb/207Pb ages) or >5% reverse discordant are not included in the results and interpretation. Variations in U-Pb ages among the four samples are insignificant; therefore, individual age probability and concordia diagrams for each sample are reported in the supplementary material (see footnote 1), and a composite plot of all four samples is presented in Figure 4A.

DETRITAL ZIRCON AGE DISTRIBUTIONS AND PROVENANCE

The new detrital zircon data from the Dakota Formation reveal primary contributions from all key plutonic assemblages of the Appalachian orogeny (Fig. 4A). Approximately 78% of detrital zircon grains are Grenvillian (1.3–1.0 Ga; Mesoproterozoic on Fig. 1), Pan-African (725–555 Ma; Neoproterozoic on Fig. 1), or Paleozoic (515–285 Ma) in age, which closely match the ages of bedrock sources located within the Appalachian Mountains (Fig. 1). The lack of significant Paleoproterozoic (~1.85–1.6 Ga) or Archean-aged (~2.5 Ga) zircons indicates that northern source regions in Minnesota, Wisconsin, and Canada did not contribute the bulk of sediment, as was previously interpreted.

Grenvillian, Pan-African, and Paleozoic grains may also have been recycled from Appalachian or Ouachita foreland basin strata (Figs. 4B and 4C); however, a sediment source in the Appalachian or Ouachita foreland basins would still require continental-scale, westward-flowing fluvial systems. Recycling of grains from Paleozoic strata located in the midcontinent

1GSA Data Repository Item 2014330, Table DR1—detrital zircon U-Pb data and Figure DR1—individual Concordia and age probability plots, is available at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
DISCUSSION AND CONCLUSIONS

Appalachians-Cordilleran Connection

The data set presented here represents the first analysis of detrital zircon age distributions from the Dakota Formation in the midcontinent, and is interpreted to document the presence of a westward-flowing transcontinental fluvial system that stretched from the Appalachian region to at least the midcontinent during middle Cretaceous time. In western North America, the archetypal Sevier thrust belt and foreland basin began to take shape during late Albian and Cenomanian time (Fig. 1). Foreland basin models define four depozones in foreland basin systems, including, from proximal to distal, the wedge top, foredeep, forebulge, and back bulge (DeCelles and Giles, 1996). These models suggest that only a minor amount of sediment in foreland basins is typically derived from the craton and is primarily confined to the back-bulge region (Dickinson and Suczek, 1979; Schwab, 1986; DeCelles and Giles, 1996).

During the mid-Cretaceous, Iowa and Nebraska were located on the craton east of the Cordilleran foreland basin system, whereas the modern-day Bighorn Basin in Wyoming was located in the foredeep (Fig. 1). Paleocurrent indicators and provenance studies from Albian and Cenomanian strata in the Bighorn Basin demonstrate that the development of the fold-and-thrust belt created new sediment sources and increased sediment flux from the western margin of the evolving Cordilleran foreland basin (DeCelles, 2004). Existing detrital zircon data from the Bighorn Basin provide evidence that most of the sediment in the foredeep was derived from the adjacent fold-and-thrust belt (May et al., 2013).

The exception to this is the early-middle Albian Greybull Sandstone of the Cloverly Formation in the eastern Bighorn Basin (GB on Fig. 3), which exhibits west- and southwest-directed paleoflow indicators (Winslow and Heller, 1987; Kvale and Vondra, 1993; Zaleha, 2006). Similar to the Dakota Formation, the Greybull Sandstone also overlies a major regional unconformity with up to 23 m of local relief (Kvale and Vondra, 1993; Weimer, 1984). Detrital zircon age distributions from the Greybull Sandstone (Fig. 5D) contain very similar age peaks and abundances compared to Albian Dakota Formation distributions (Fig. 5C); however, a link between the Greybull Sandstone and the Appalachian region has not previously been proposed.

When taken together, the Greybull Sandstone and Dakota Formation data suggest that sediment derived from the Appalachian region during Albian time was transported >2000 km across the continent before being deposited in the distal foredeep of the Cordilleran foreland basin. Cenomanian strata in the Bighorn Basin (Fig. 5B), in contrast, have a very different detrital signature compared to the coeval Dakota Formation in the midcontinent (Fig. 5A), indicating that Appalachian-derived sediment was no longer being deposited in the foredeep of the foreland basin. The continued existence of the transcontinental fluvial systems through at least Cenomanian time, however, suggests that sediment was likely still being delivered to the back-bulge region after Albian time. These results indicate that standard foreland basin models may underestimate the amount of sediment input from the craton side of the basin, especially in the back-bulge region.

Implications for North American Paleogeography

Transcontinental sediment transport from the Appalachian region to the North American Cordillera has previously been inferred based on detrital zircon age spectra from Upper Jurassic–Albian foreland basin deposits in Alberta,
Canada (Benyon et al., 2014; Blum and Pecha, 2014; Raines et al., 2013). These authors, however, were not able to differentiate between first-cycle sediment delivered directly from the Appalachians versus sediment recycled from older strata in the southwestern United States or the fold-and-thrust belt to the west. The detrital zircon signatures from the Dakota Formation, however, also contain the same Appalachian age groups inferred to have been derived either directly from Appalachian igneous belts or recaptured from Paleozoic strata of the Appalachian foreland. This new result provides the first direct evidence that a fluvial system did extend from the Appalachian region to the North America Cordilleran foreland basin during middle Cretaceous time.

Appalachian-derived sediment delivered to the western United States has also been inferred based on detrital zircon age spectra from Mississippian–Permain strata in the Grand Canyon (Gehrels et al., 2011) and Early–Middle Jurassic erg deposits on the Colorado Plateau (Dickinson and Gehrels, 2009, 2010). These depositional systems, however, existed prior to the Late Jurassic initiation of the Cordilleran foreland basin (DeCelles, 2004; Miall et al., 2008). These previously published detrital zircon age distributions in combination with the new data from the Dakota Formation reflect an evolution in source regions within the Appalachian region. In Mississippian strata of the Grand Canyon, Paleozoic ages are relatively more abundant than Pan-African ages, but the two populations become more balanced by Permian time (Gehrels et al., 2011). This pattern is interpreted to reflect the outboard location of the Pan-African terranes relative to the Paleozoic igneous units (Fig. 1), and it suggests that the late Paleozoic west-flowing transcontinental river systems eroded headward (eastward) across the Paleozoic igneous belt to tap into the more easterly Pan-African terranes.

In contrast, the Jurassic erg and Dakota Formation detrital zircon age distributions contain more abundant populations of Paleozoic grains relative to Pan-African peaks (Fig. 3). This reversal may be due to the opening of the Atlantic Ocean and the rejuvenation of east-flowing rivers that eroded headward (westward) across the uppercatchment areas, which previously lay within the late Paleozoic west-flowing transcontinental river systems. Consequently, by Jurassic time, the outboard Pan-African terranes were again recaptured by the east-flowing systems and were mostly isolated from the west-flowing transcontinental rivers.

Based on the stratigraphic record in middle Atlantic offshore sedimentary basins, there have been several temporally isolated epeirogenic increases in sediment flux from the Appalachian region since Triassic–Early Jurassic rifting of Pangea (Poag and Sevon, 1989; Poag, 1992). An increase in flux during Middle Jurassic time (ca. 170 Ma) is attributed to the existence of prostrit topography (Pazzaglia and Brandon, 1996) and may be responsible for the presence of the previously inferred Middle–Late Jurassic transcontinental fluvial systems.

Widespread deposition of the Dakota Formation in the midcontinent is interpreted in this study as the sedimentary record of a second post-tectonic erosional event that is preserved to the west of the Appalachian belt. Sediment flux to the Atlantic margin basins east of the Appalachian belt were 3–7 times higher than background rates during middle Cretaceous time (Poag and Sevon, 1989; Poag, 1992; Pazzaglia and Brandon, 1996). Sediment eroded toward the west during middle Cretaceous time could not have been transported to the Gulf of Mexico because it predates opening of the Mississippian Embayment, and the Ouachita Mountains would still have been a topographic barrier to the south (Cox and Van Arsdale, 2002). Furthermore, sedimentation in the Gulf of Mexico was dominated by carbonates during Barremian–Albian time, which precludes a significant influx of silicilastic material into that region (Galloway, 2008).

Numerical modeling indicates that a middle Cretaceous increase in sediment flux from the Appalachian region is consistent with a change in asthenospheric flow related to passage over a mantle plume (Pazzaglia and Brandon, 1996). Recent low-temperature thermochronologic data from the southern Appalachians demonstrate that beginning ca. 120 Ma and continuing for ∼60 m.y., the modern river valleys draining the southern Blue Ridge Mountains experienced erosion at nearly twice the background rate (35 m/m.y. vs. 20 m/m.y.) and that present-day valley floors were exhuming at almost twice the rate of the modern ridge tops (McKeon et al., 2014). Although these erosion rates are low, inverse modeling requires nearly 1 km of relief generated during this phase of the Cretaceous (McKeon et al., 2014). Therefore, even though the Appalachian region had not experienced any major tectonic events since Triassic–Early Jurassic rifting, perturbation of the dormant orogenic system due to mantle dynamics significantly increased exhumation, erosion, and sediment flux. This mantle-driven process was significant enough to reorganize major fluvial drainages and initiate a second Mesozoic continental sediment transport system that dispersed Appalachian-derived sediment across the North American continent and into the western U.S. Cordilleran foreland basin.

ACKNOWLEDGMENTS

I thank George Gehrels for generous use of the Arizona LaserChron Laboratory to acquire the data presented here. Support for the Dakota Formation was provided by the National Science Foundation Instrumentation and Facilities Program. Brian J. Witzke and Carl E. Jacobson provided fruitful discussions related to this project. Kenneth D. Ridgway, Ingrid Utskar Pedra, Dale Ledes, Bill Craddock, and an anonymous reviewer reviewed early versions of this manuscript. External reviewers, Andrew Leier and an anonymous reviewer handled later versions of this manuscript. Samples were processed and mounted by University of Iowa undergraduate researchers Brittany Hendrix and Jordan Gillard.

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MANUSCRIPT RECEIVED 19 JUNE 2014
REVISED MANUSCRIPT RECEIVED 3 JULY 2014
MANUSCRIPT ACCEPTED 21 JULY 2014
Printed in the USA