Lower–Middle Pennsylvanian strata in the North American midcontinent record the interplay between erosional unroofing of the Appalachians and eustatic sea-level rise

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ABSTRACT

Morrowan, Atokan, and Desmoinesian (Lower–Middle Pennsylvanian) clastic strata in the Forest City (Iowa, northwest Missouri, eastern Nebraska, and Kansas) and Illinois Basins on the North American midcontinent record the interaction between fluctuations in eustatic sea-level and major tectonic events. One of three major Paleozoic eustatic sea-level lows occurred near the Mississippian/Pennsylvanian boundary and was followed by an eustatic rise that continued into Late Pennsylvanian time. Alleghanian mountain building that is linked to the creation of the Pangean supercontinent also began during latest Mississippian time and continued until latest Pennsylvanian or earliest Permian time. Detrital-zircon geochronology and stratigraphic descriptions allow reconstruction of sediment dispersal patterns associated with these events. Our detrital-zircon signatures from Morrowan–lower Desmoinesian strata in the Illinois Basin are interpreted to reflect a change from regional drainages that reworked underlying Mississippian strata to extensive extrabasinal fluvial systems that supplied detritus shed from southeastern New England. By middle Desmoinesian time, detrital-zircon signatures in the Illinois Basin are more similar to those from coeval units in the central Appalachian Basin, indicating a southward shift in the provenance of the fluvial systems. In the Forest City Basin, Morrowan strata are absent and our detrital-zircon data indicate that Atokan–early Desmoinesian sedimentation was dominated by regional fluvial systems that recycled underlying strata. The introduction of extrabasinal fluvial systems with New England headwaters in the middle Desmoinesian coincided with the overtopping of the Mississippi River Arch and depositional linking of the Forest City and Illinois Basins. The Forest City and Illinois Basins collectively contain an Early–Middle Pennsylvanian sedimentary record in the backbulge depozone of the Alleghanian foreland basin system that reflects overtopping of the forebulge located along the Cincinnati Arch and the effects of eustatic sea-level rise. These results lend credence to the previously proposed transcontinental fluvial systems during late Paleozoic time and help to better constrain their courses.

INTRODUCTION

Paleogeographic reconstructions of the Carboniferous North American midcontinent have focused on Upper Pennsylvanian mixed carbonate-clastic strata that record sea-level highstands at the expense of the underlying Lower–Middle Pennsylvanian clastic-rich strata deposited during sea-level lowstand and transgression (e.g., Heckel, 1977, 1986, 2008, 2013; Boardman and Heckel, 1989; Klein and Willard, 1989; Hatch and Leventhal, 1992; Cruse and Lyons, 2004; Mazzullo et al., 2007; Tabor et al., 2008). The depositional context of Lower–Middle Pennsylvanian strata is significant, however, because these rocks record deposition of almost exclusively clastic sediment into intracratonic basins, including the Illinois and Forest City Basins (Fig. 1A), after a prolonged depositional period of carbonate-clastic cycles followed by a depositional hiatus during the Early Pennsylvanian. This rejuvenation of dominantly clastic deposition to the midcontinent was concurrent with both Alleghanian orogenesis (Hatcher, 1972, 2002) and eustatic sea-level rise (Haq and Schutter, 2008). Previous studies have speculated about the individual influence each of these events had on midcontinent Pennsylvanian depositional systems (e.g., Archer and Greb, 1995); however, the interplay between the two and a link to variations in sediment provenance have not been sufficiently explored.

For example, in the Illinois Basin, it was originally postulated that the Canadian Shield and highlands east of the Appalachian Basin were the primary sediment sources for Early Pennsylvanian quartz arenites (Potter and Siever, 1956a, 1956b; Siever and Potter, 1956). In the adjacent Forest City Basin, the Canadian Shield also was evoked as the dominant source for Early Pennsylvanian sediment (Lemish et al., 1981). Compositional variations, including the increasing preponderance of mica in Middle Pennsylvanian strata, however, have been cited as evidence for a more distal allochthonous unroofing sequence that strengthened support for the Appalachian orogen as playing a major role in midcontinent provenance (Fitzgerald, 1977; Quinlan and Beaumont, 1984; Scul, 1990; Archer and Greb, 1995; Patchett et al., 1999). More recently, detrital-zircon U-Pb data from Mississippian strata in the Grand Canyon were interpreted to reflect primary sediment input from plutonic assemblages on
Figure 1. (A) Regional index map of eastern North America including the modern extent of basement terranes (Whitmeyer and Karlstrom, 2007), sedimentary cover (shown in white; Reed et al., 2005), major sedimentary basins (Coleman and Cahan, 2012), and major igneous belts along the eastern margin (Reed et al., 2005). Stippled patterns show locations of sedimentary basins discussed in the text. Red arrows indicate generalized paleoflow directions for Pennsylvanian strata. (B) Generalized geologic map of the study area showing modern surface extent of Pennsylvanian strata (Reed et al., 2005) and sample locations. MCR—Midcontinental Rift; GC—Grand Canyon.
the Appalachian margin to the southwestern United States by early Carboniferous time, requiring the presence of a Pennsylvanian transcontinental fluvial system (Gehrels et al., 2011). The position of the Forest City and Illinois Basins between the Grand Canyon and former late Paleozoic Appalachian highlands means that the provenance record in those basins will test the transcontinental connection (e.g., Thomas, 2011).

In this paper, we present 3051 new U-Pb ages from detrital zircons collected from Early–Middle Pennsylvanian strata in the Forest City and Illinois Basins. Integration of these data with current paleogeographic models permits an improvement to our understanding of sediment transport across the North American midcontinent during Early–Middle Pennsylvanian time. Furthermore, our provenance interpretations are placed within the context of tectonic events along the Appalachian margin and eustatic sea-level variations affecting the midcontinent and demonstrate that provenance analysis may permit differentiation between the relative roles of each in a cratonic fluvial system.

## BACKGROUND

### Regional Geology

During the Carboniferous, the eastern and southern margins of Laurentia were dominated tectonically by the collision of Gondwana with Laurentia, which combined with other landmasses to form the supercontinent Pangea (e.g., Cocks and Torsvik, 2011). Collision of the two landmasses created the Ouachita orogeny along the southern margin of Laurentia and the Alleghanian orogeny on the eastern margin. Denudation of the exhumed orogens dispersed sediments into proximal foreland basins that were periodically overfilled, allowing orogen-sourced fluvial systems to distribute clastic sediment across the cratonic interior of Laurentia (Tankard, 1986; Dickinson and Gehrels, 2003; Thomas et al., 2004). Late Paleozoic cratonic sedimentation is largely encompassed by the Absaroka megasequence (Sloss, 1963), which began during the Late Mississippian. The basal unconformity of this package is a major disconformity present in all Laurentian cratonic basins and is most often characterized by a system of pre-Pennsylvanian incised valleys, such as those found in the Forest City and Illinois Basins, the fills of which preserve a record of sedimentation during Early Pennsylvanian and later base-level rise (Archer et al., 1994; Feldman et al., 1995).

The Forest City Basin (FCB) encompasses ~65,000 km² of Iowa, Missouri, Kansas, and Nebraska (Fig. 1A). The thickness of Cambrian to Late Pennsylvanian strata exceeds 1.5 km in the deepest parts of the basin (Derynck, 1980; Bunker et al., 1988). Pennsylvanian strata thicken toward the southern and western margins, attaining a maximum thickness of ~600 m in northwestern Missouri. The Illinois Basin (IB) lies to the east of the FCB, trends northwest-southeast encompassing Illinois and southwestern Indiana, and extends marginally into western Kentucky and eastern Iowa. It contains up to 4.5 km of Paleozoic strata, including up to 900 m of Pennsylvanian strata (Nelson et al., 2013).

The FCB and IB are regarded as intracratonic basins that are separated from the Appalachian foreland region by a series of basement-cored arch complexes (Fig. 1A; Quinlan and Beaumont, 1984; Root and Onasch, 1999; Craddock et al., 2017). Deformation that defined the boundaries of the FCB was initiated in the Early Ordovician and continued sporadically into the Carboniferous (Anderson and Wells, 1968; Mason, 1980; Root and Onasch, 1999). To the west of the basin in eastern Kansas and Nebraska, uplift during the Late Mississippian exposed the Precambrian basement to over 120 m above the basin floor, forming the Nemaha Ridge (Bunker et al., 1988). This structural high separated the FCB from the Salina Basin during Early–Middle Pennsylvanian time but was overtopped by sediments during the Late Pennsylvanian. The Bourbon Arch and Ozark Uplift (Fig. 1A) separate the FCB from the Cherokee Platform to the south, whereas the Mississippi River Arch denotes the eastern margin of the basin. By middle–late Middle Pennsylvanian time, episodes of marine deposition had become continuous across the Mississippi River Arch, depositionally linking the FCB with the IB to the east (Nelson et al., 2013).

The modern IB is delineated structurally by a system of regional arches that emerged in the early Paleozoic and defined the margins of the basin by the end of the Ordovician (Potter, 1963; Root and Onasch, 1999). The basin is bound by the Cincinnati, Findlay, and Algonquin arches to the south and east, and the Kankakee Arch separates the IB from the Michigan Basin to the north. The Cincinnati and related arches are considered to have acted as a forebulge for the Appalachian foreland basin during the Pennsylvanian–Permian Alleghanian orogeny, and the Kankakee arch is interpreted as a secondary feature related to subsidence of the Illinois and Michigan Basins (Quinlan and Beaumont, 1984; Root and Onasch, 1999). Despite these potential topographic barriers, models by Quinlan and Beaumont (1988) suggest that both the Cincinnati and Kankakee arches were ultimately overtopped by sediments from the unroofing of the Appalachians by at least Late Pennsylvanian time, if not earlier, depositionally linking the intracratonic basins with the Appalachian foreland.

### Regional Stratigraphic Summary

The stratigraphic positions of the samples analyzed in this study were collected in the context of key marker beds within each basin. Therefore, we summarize below the existing sedimentology and stratigraphy for these strata with an emphasis on those key marker beds. Schematic stratigraphic columns with key marker beds and sample localities for the northeastern FCB and IB are shown in Figure 2. Detailed sample location information is provided in Table 1.

### Forest City Basin

The Kilbourn Formation extends from its unconformable basal contact with the pre-Pennsylvanian paleosurface to the bottom of the Blackoak Coal (Fig. 2; Ravn et al., 1984). Dominant lithologies include fine-grained sandstone,
Figure 2. Schematic stratigraphic columns for the Forest City (Anderson and Fields, 2007) and Illinois (Jacobson, 2002) Basins in the study area with stratigraphic positions of samples, key marker beds, and the long- and short-term eustatic sea-level curves (Haq and Schutter, 2008). Standard chronostratigraphy from Ogg et al. (2016) and North American (NA) stages from Heckel and Clayton (2006). SS—sandstone.
shall, 2010). The Floris Formation is characterized by channelized sandstone indicating increased marine influence relative to underlying formations (Mar- 

Shale, coal, and mudstone. Sandstones are generally texturally and compositionally mature quartz arenites (Fig. 3; Scal, 1990). The paleotopography of the pre-Pennsylvanian erosional surface is interpreted to have confined deposition of the generally thin and discontinuous beds of the Kilbourn Formation to a southwest-trending system of incised paleovalleys (Ravn et al., 1984).

The Kalo Formation extends from the Blackoak Coal to the base of the Laddsdale coal (Pope, 2012). Palynological assemblages in the coals from within this formation are consistent with the Kalo Formation straddling the Atokan–Desmoinesian stage boundary (Fig. 2). Lithologies are mud dominated, and marine layers are scarce (Gregory, 1982). Coals are more common relative to the underlying Kilbourn Formation, whereas channel-fill sandstone is less common. The sandstone is largely quartz arenite, but the proportions of mica and feldspar begin to increase above the Desmoinesian stage boundary (Fig. 3; Scal, 1990). Clastics in both the Kibbourn and Kalo Formations are interpreted to be derived from Mississippian and older strata (Ravn et al., 1984).

The Floris Formation extends from the Laddsdale Coal to the base of the Oakley Shale (Pope, 2012). While it typically overlies the Kalo Formation, channelized sandstone in the Floris Formation in some subsurface cores have deeply incised into the older Pennsylvanian strata and locally extend to the pre-Pennsylvanian erosional surface. Based on conodonts, palynology, and fern fossils, the Laddsdale and Whitebreast coals of the Floris Formation correlate with the Brush and Colchester coals of western Illinois, respectively (Peppers, 1970; Hopkins and Simon, 1975). Palynological assemblages in the coals of the Floris Formation are consistent with deposition during the Desmoinesian stage. Minor cyclothems occur in the upper part of this formation, indicating increased marine influence relative to underlying formations (Marshall, 2010). The Floris Formation is characterized by channelized sandstone interpreted to represent high-energy fluvial depositional systems with minor influence by marginal marine processes. In addition, sandstone in this unit contains more mica and feldspar than the underlying units, and the grains are more angular (Fig. 3; Isbell, 1985; Scal, 1990).

**Illinois Basin**

The Caseyville Formation extends from its unconformable basal contact with the pre-Pennsylvanian unconformity to the base of the Tradewater Formation (Fig. 2; Nelson et al., 2013). The Caseyville-Tradewater contact is defined as the uppermost limit of locally occurring quartz-pebble-bearing conglomerates (Potter, 1963; Fitzgerald, 1977; Nelson et al., 2013). This boundary is interpreted to coincide with the top of the Morrowan stage based on palynology (Peppers, 1996). In the western IB, the Caseyville Formation consists of thin-bedded sandstone, siltstone, shale, and thin coal. Caseyville Formation sandstone is texturally mature quartz arenite (Fig. 3) and is petrologically similar to the underlying Upper Mississippian sandstones (Potter and Glass, 1958). Similar to the Kilbourn Formation in the FCB, pre-Pennsylvanian paleotopography likely influenced Caseyville Formation fluvial systems, which are interpreted to have supplied reworked pre-Pennsylvania detritus to the basin (Potter and Glass, 1958; Fitzgerald, 1977). Paleocurrent trends are dominantly southwest directed, but in the northwest part of the basin are locally northwest and northeast directed likely due to deflection by the Mississippi River Arch (Isbell, 1985).

The Tradewater Formation extends from the Caseyville Formation to the Seelyville or Davis Coal Member of the Carbondale Formation (Nelson et al., 2013). Sandstone petrography of the informal lower member records a compositional

| Sample location | Latitude (°N) | Longitude (°W) | Location description (sampled interval) | Geologic unit | References |
|-----------------|--------------|---------------|----------------------------------------|---------------|------------|
| FCB-A1          | 41.67723     | 91.53146      | Outcrop south of Mayflower dormitory in Iowa City, Iowa | Pennsylvanian | Kissock, 2016 |
| FCB-A2          | 40.613315    | 92.627301     | Core sample from Iowa Geological Survey (IGS) #CP-09 (507–511') | Kilbourn Formation | Ravn et al., 1984; Ravn, 1986 |
| FCB-AD          | 40.613315    | 92.627301     | Core sample from IGS #CP-09 (389–390', 406–409', 412–415') | Kalo Formation | Ravn et al., 1984; Ravn, 1986 |
| FCB-D1          | 41.36988     | 92.98911      | Measured section near Red Rock Dam, Iowa (~6.5 m) | Floris Formation | Pope, 2012; Kissock, 2016 |
| FCB-D2          | 41.38928     | 93.03411      | Measured section in White Breast Recreation Area, Iowa (~8.2 m) | Floris Formation | Pope, 2012; Kissock, 2016 |
| FCB-D3          | 42.39288     | 94.0808       | Measured section in Dolliver State Park, Iowa (~4.0 m) | Floris Formation | Pope, 2012; Kissock, 2016 |
| FCB-D4          | 41.98279     | 93.8933       | Outcrop in Ledges State Park, Iowa | Floris Formation | Pope, 2012; Kissock, 2016 |
| IB-M1           | 41.43458     | 90.94035      | Measured section at Wyoming Hill road cut, Iowa (~0.8 m) | Caseyville Formation | Ravn et al., 1984; Kissock, 2016 |
| IB-M2           | 41.46379     | 90.57081      | Outcrop in Blackhawk State Park, Illinois | Caseyville Formation | Anderson et al., 1999; Nelson et al., 2013 |
| IB-AD           | 40.49139     | 90.36767      | Outcrop along tributary to Spoon River, Illinois | Tradewater Formation | Reinertsen et al., 1993 |
| IB-D1           | 41.43458     | 90.94201      | Outcrop at Wyoming Hill road cut, Iowa | Tradewater Formation | Fitzgerald, 1977 |
| IB-D2           | 41.46856     | 90.0808       | Outcrop in Wildcat Den State Park, Iowa | Tradewater Formation | Fitzgerald, 1977 |
| IB-D3           | 41.19389     | 88.90296      | Outcrop at Sandy Ford Nature Preserve, Illinois | Carbondale Formation | Nelson et al., 1996 |
| IB-D4           | 40.83748     | 89.65417      | Outcrop along Pfeiffer Road, Bartonville, Illinois | Shelburn Formation | Frankie et al., 1995 |

Abbreviations: FCB—Forest City Basin; IB—Illinois Basin.
transition from quartz arenite of the Caseyville Formation to lithic arenite of the informal upper Tradewater Formation (Fig. 3; Potter, 1963). The upper part contains very fine to coarse-grained sandstone comprising ~5%–10% mica, feldspar, lithic grains (mainly chlorite schist), and argillaceous matrix (Potter and Glass, 1958). Multi-story sandstone channels that fine upward from basal conglomerates become increasingly common upsection. Paleoflow trends in the upper member demonstrate dominantly south-southwest flow directions (Potter and Glass, 1958). The transition away from variable flow directions in the underlying Caseyville Formation has been interpreted to reflect inundation of the Mississippi River Arch and leveling of the depositional plain (Isbell, 1985).

The Carbondale Formation extends from the top of the Tradewater Formation to the base of the Providence or Brereton Limestone Member of the Shelburn Formation. The top of the Shelburn Formation is marked by the Scottville Limestone or Trivoli Sandstone of the Patoka Formation (Nelson et al., 2013). Both formations contain abundant marine cyclothems that record sea-level highstands, in addition to thick channelized sandstone bodies that are interpreted to reflect lowstand conditions (Rusnak, 1957; Hopkins, 1958; Potter and Simon, 1961; Eggert and Adams, 1979; Utgaard, 1979; Eggert, 1981). Argillaceous sandstone in the Carbondale and Shelburn Formations generally occurs in thick, fining-upward channel sequences similar to the upper Tradewater Formation. The sandstone also has petrological characteristics that are similar to the upper Tradewater Formation. Paleoflow measurements in these formations have south-southwest trends. However, the vector means of cross-bedding exhibit a subtle change from S39°W in the Pennsylvania strata below the lowest portion of the Carbondale Formation to S47°W over the interval between the lowest Carbondale to just above the top of the Sheldon Formation (Potter and Glass, 1958). This westward transition continues upward in Missourian strata above the Shelburn Formation, where the vector mean is S52°W.

**Potential Sediment Sources**

Based on previous provenance work, several regions have been identified as potential sources of sediment for the Pennsylvania FCB and IB strata. Prospective crystalline sources include (Fig. 1A): (1) plutonic assemblages associated with the Alleghenian (270–330 Ma), Acadian (350–420 Ma), and Taconic (440–490 Ma) orogenies along the eastern margin of North America, collectively referred to in this study as an Appalachian source; (2) Pan-African terranes that are generally situated within and outboard of the Appalachian igneous belts along the eastern margin of North America, or Iapetan synrift rocks along the eastern Laurentian margin that produce Neoproterozoic ages (530–750 Ma); (3) the Grenville igneous belt in the Appalachian region (980–1300 Ma) and the Midcontinent Rift belt in the northern midcontinent (1080–1120 Ma); (4) the Granite-Rhyolite belt (1300–1550 Ma) and Yavapai and Mazatzal terranes (1653–1750 Ma) that extend from northeastern Canada (Mazatzal ages are associated with the Labradorian Province in the Quebec Region) to the southwestern United States and are collectively referred to in this study as midcontinent terranes; (5) the Trans-Hudson (1800–1900 Ma) and Penokean (1800–1900 Ma) provinces located in northern and central Canada, and Wisconsin and northern Michigan, respectively; and (6) the Superior Province (>2500 Ma) in central Canada. Some of the potential source terranes listed above, including large tracts of the Midcontinent Rift belt, Granite-Rhyolite belt, and Yavapai and
Mazatlan terranes, are beneath pre-Pennsylvanian strata today and so are not considered to be a primary source for the Pennsylvanian sandstones.

There is also the potential for the erosion and recycling of Neoproterozoic–early Paleozoic clastic units in the midcontinent region, which were exposed north of the Illinois and Forest City Basins during the Pennsylvanian. Malone et al. (2016) in their study of the Neoproterozoic Jacobsville Sandstone, which was deposited during tectonic inversion of the Midcontinent Rift, reported zircons of Grenville, Granite-Rhyolite, Penokean, and Archean ages. Konstantinou et al. (2014) provided an analysis of the detrital-zircon age distribution of Cambrian and Ordovician quartz arenites in Minnesota, Wisconsin, Illinois, and Missouri. They determined that these rocks were dominated by Archean and Grenville-age zircons.

Pennsylvaniaan strata across most of the FCB and IB overlie Mississippian–Devonian strata that are composed of both carbonate and clastic intervals. These strata are exposed today on the arches that bound the basins and thus could have been recycled into the basins in the past. To the east, recycling of pre-Pennsylvanian sandstone from the Appalachian fold-and-thrust belt is also possible; however, the foreland basin fill in that region is still largely intact and was likely not a significant contributor. Uplift in the Ozark region to the south was not renewed until the Late Pennsylvaniaan (Branson, 1962) and the abundance of southwest directed paleoflow indicators in Pennsylvanian strata of the FCB and IB generally preclude the potential for southern or westerly sources.

METHODS

Seven sandstone samples were collected for detrital-zircon analyses from Atokan and Desmoinesian strata in the FCB, as well as seven sandstone samples from Morrowan through Desmoinesian strata in the IB (Figs. 1B and 2).

Forest City Basin

Atokan Strata

FCB-A1 was collected from an ~2-m-thick, thin-bedded (3–10 cm) quartz arenite in eastern Iowa (Figs. 1B and 4A–4C). Strata in this outcrop are considered Pennsylvanian (PH. Heckel, 2015, personal commun.), but the precise stratigraphic position is uncertain. We consider these strata to be basal Pennsylvaniaan, probably Atokan, because they lie directly on the sub-Pennsylvanian unconformity. This interpretation is supported by the widespread occurrence of Atokan stage strata above the basal Pennsylvaniaan unconformity and a demonstrable lack of spatially continuous Morrowan strata in the FCB (Pope, 2012).

FCB-A2 was collected from an ~1-m-thick, fine-grained quartz arenite from the Iowa Geological Survey (IGS) core #CP-09 (Fig. 1B) at the 507–511’ interval. A detailed core description can be found on the IGS Web site (https://www.iihr.uiowa.edu/igs). The sample interval falls within the Kilbourn Formation as defined by palynological studies of coals in the core by the Iowa Coal Project (Ravn et al., 1984; Ravn, 1986).

Atokan to Desmoinesian Strata

FCB-AD is a composite sample that was collected from several ~1–2-m-thick, fine-grained quartz arenites in the IGS core #CP-09 from southeastern Iowa (Fig. 1B) at the 389–390’, 406–409’, and 412–415’ intervals. These intervals fall within the upper part of the Kalo Formation as defined by palynological studies of the Iowa Coal Project (Ravn et al., 1984; Ravn, 1986).

Desmoinesian Strata

FCB-D1 was collected from a <1-m-thick, thin-bedded sandstone that is interbedded with mudstone and coal in southcentral Iowa (Figs. 1B and 4D). The strata at the FCB-D1 sample site are inferred to belong to the Floris Formation due to their similar stratigraphic position as the strata at the nearby FCB-D2 site that is discussed below. FCB-D2 was collected from the base of an ~8-m-thick outcrop of thin-bedded sandstone that is interbedded with mudstone and coal in southcentral Iowa (Fig. 1B). These strata have been identified as the Floris Formation (Pope, 2012).

FCB-D3 was collected from an ~10-m-thick outcrop of medium- to thick-bedded (10–100 cm) sandstone with scarce mudstone interbeds in northcentral Iowa (Figs. 1B and 4E). Pope (2012) identified the strata at this locality as the Floris Formation. Because the strata are essentially flat lying along depositional strike (northwest to southeast), we infer the stratigraphic position of the FCB-D3 sandstone to be above FCB-D1 and FCB-D2 based on the differences in elevation between the outcrops.

FCB-D4 was collected from an ~10-m-thick outcrop of thick- to very thick-bedded (~1 m or greater), fine- to coarse-grained micaceous litharenite in central Iowa (Figs. 1B and 5A). Osolin (1983) considered this outcrop to be part of the Swede Hollow Formation (middle–upper Desmoinesian stage) based on its position above the Whitebreast Coal and Ardmore Limestone that had been tentatively identified in nearby cores. More recently, however, this outcrop was identified as the Floris Formation (Pope, 2012). We infer it to be near the same stratigraphic position as FCB-D3 based on the elevation of the sample site.

Illinois Basin

Morrowan Strata

IB-M1 was collected from an ~2-m-thick, thin-bedded, fine-grained quartz arenite in the upper part of the Caseyville Formation in eastern Iowa (Figs. 1B and 4G). Ravn et al. (1984) constrained the stratigraphic position of this
Figure 4. Outcrop photographs of Type 1 sandstone localities. Forest City Basin: (A) Thin-bedded sandstone overlying mudstone at FCB-A1 (note hammer for scale); (B) tidal rhythmites at FCB-A1; (C) bioturbated tidal rhythmites at FCB-A1; (D) thin-bedded sandstone overlying coal and siltstone at FCB-D1; (E) planar tangential cross-bedding at FCB-D3 (note hammer for scale). Illinois Basin: (F) tidal rhythmites at IB-M1; (G) two fine-grained sandstone bodies separated by a coal horizon at IB-M1; and (H) thin-bedded sandstone at IB-AD.
Figure 5. Outcrop photographs of Type 2 (A–E) and Type 3 (F–G) sandstone localities. Forest City Basin: (A) Thick, cross-bedded sandstone exposure at FCB-D4. Illinois Basin: (B) thick-bedded sandstone exposure at IB-M2; (C) thick-bedded sandstone exposure at IB-D1; (D) planar tangential cross-bedding at IB-D1; (E) thick-bedded sandstone exposure at IB-D2; (F) thick-bedded sandstone exposure at IB-D3; and (G) thin-bedded sandstone exposure at IB-D4.
### Supplemental Table S1. Detrital-zircon data

Please visit [here](http://doi.org/10.1130/GES01512.S1) for the full text on Table S1.

**FCB-A1**

| Spot | Age (Ma) | Error (Ma) | U/Pb Ratio | Lead Correction | Discordance |
|------|----------|------------|-------------|-----------------|-------------|
| 2051 | 60       | 3889       | 1.2         | 13.629          | 37%         |
| 3144 | 84       | 0966       | 1.11        | 3.5793          | 27%         |
| 2702 | 70       | 167193     | 1.3         | 13.5407         | 30%         |
| 1281 | 47       | 192725     | 1.5         | 13.4652         | 30%         |
| 1201 | 81       | 270873     | 1.5         | 13.4695         | 30%         |
| 1681 | 34       | 114695     | 1.0         | 13.4771         | 31%         |
| 2031 | 79       | 362051     | 1.9         | 13.4597         | 30%         |
| 1451 | 20       | 274800     | 0.8         | 13.4917         | 31%         |
| 1831 | 25       | 346845     | 1.5         | 13.5131         | 31%         |
| 1702 | 75       | 270591     | 1.5         | 13.9358         | 31%         |
| 1222 | 96       | 1002102    | 0.4         | 13.4523         | 30%         |
| 2012 | 78       | 569832     | 0.6         | 13.8803         | 31%         |
| 1766 | 10       | 1293700    | 0.6         | 17.9076         | 31%         |
| 1362 | 55       | 397763     | 0.4         | 13.8123         | 30%         |
| 2345 | 48       | 1286621    | 0.4         | 13.8195         | 30%         |
| 2942 | 55       | 1196931    | 0.6         | 13.8116         | 30%         |
| 2261 | 06       | 330202     | 0.5         | 16.3420         | 31%         |
| 1012 | 54       | 299281     | 0.8         | 15.8314         | 31%         |
| 1342 | 11       | 833838     | 0.8         | 14.2089         | 31%         |
| 79   | 1073     | 3108       | 3.61        | 3.6719          | 37%         |
| 40   | 45       | 226003     | 0.6         | 13.6936         | 30%         |
| 60   | 1456     | 4735       | 3.81        | 3.6943          | 37%         |
| 15   | 1203     | 9279       | 1.21        | 8.0254          | 35%         |
| 99   | 45       | 582472     | 0.1         | 13.4480         | 30%         |
| 21   | 81       | 458041     | 0.9         | 13.7719         | 30%         |

### RESULTS

#### Detrital-Zircon U-Pb Type Signatures

Grenville-age zircons (980–1300 Ma) make up the dominant population of 13 of the 14 samples in both basins. However, Grenville igneous rocks are notoriously zircon-fertile (Moecher and Samson, 2006) and were deposited in older strata across the North American continent, limiting their utility in provenance interpretation (e.g., Gehrels et al., 2011; Rainbird et al., 2012). Therefore, we define three type signatures based on the presence (>10% of total distribution) and relative abundance of the other age populations present. Type 1 signatures are characterized by the dominance of a Midcontinent population (1300–1750 Ma) with a minimal Neoproterozoic (530–750 Ma) population. Superior (>2500 Ma) and Appalachian (270–490 Ma) populations may or may not be present as well. Type 2 signatures are dominated by Appalachian and Neoproterozoic populations that are present in relatively even proportions, with lesser amounts of all other populations. Type 3 signatures have a large Appalachian population, a minimal Neoproterozoic population, and no grains with ages older than the Granite-Rhyolite province (>1550 Ma). On a cumulative probability density plot (Fig. 6), the major difference between Type 2 and the others, however, is in the Neoproterozoic age range (530–750 Ma). There, the Type 1 and Type 3 curves remain relatively flat, reflecting an absence of this population in their distributions. The Type 2 signatures, in contrast, have a steeper slope that records the presence of a Neoproterozoic population in those samples.

**Forest City Basin**

All but one of the samples from the Forest City Basin have Type 1 signatures. FCB-A1 (n = 294) has prominent age groups representing the Midcontinent terranes (21%) and Superior grains (16%) (Fig. 7). FCB-A2 (n = 267) is characterized by Appalachian (10%) and Midcontinent (32%) populations. FCB-AD (n = 259) contains 12% Appalachian grains and 30% Midcontinent grains. FCB-D1 (n = 296) has a signature with 15% Midcontinent ages and negligible proportions of the other non-Grenville populations. FCB-D2 (n = 265) has –34% of grains that are Midcontinent age. FCB-D3 (n = 279) contains 14% Appalachian and 17% Midcontinent grains. Only FCB-D4 (n = 263) has a Type 2 signature that contains significant Appalachian (23%) and Neoproterozoic (33%) populations.

**Illinois Basin**

All three type signatures are represented in the Illinois Basin. Type 1 signatures are found in the Morawan and Atokan strata. For example, IB-M1 (n = 280) contains approximately equal proportions of Appalachian (15%)

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**Supplemental Table S1. Detrital-zircon data.** Please visit [here](http://doi.org/10.1130/GES01512.S1) for the full text on Table S1.

**Atokan to Early Desmoinesian Strata**

IB-AD was collected from a ~2-m-thick, thin-bedded, fine-grained, quartz arenite from the Bernadoite member of the lower Tradewater Formation (Reinertsen et al., 1993) in western Illinois (Figs. 1B and 4H).

**Middle to Late Desmoinesian Strata**

IB-D1 was collected from an ~15-m-thick, thick- to very thick-bedded, fine- to coarse-grained micaceous litharenite in the upper Tradewater Formation (Fitzgerald, 1977) in eastern Iowa (Figs. 1B, 5C, and 5D). IB-D2 was collected from an ~10-m-thick, thick- to very thick-bedded, fine- to coarse-grained micaceous litharenite in the upper Tradewater Formation (Fitzgerald, 1977) in eastern Iowa (Figs. 1B and 5E). IB-D3 was collected from an ~3-m-thick outcrop of thin- to medium-bedded, fine- to medium-grained micaceous litharenite in the Vermilionville member of the Carbondale Formation (Nelson et al., 1996) in northcentral Illinois (Figs. 1B and 5F). The Vermilionville Sandstone can be up to 24 m thick (Wanless, 1956). IB-D4 was collected from an ~2-m-thick outcrop of thin- to medium-bedded, fine- to medium-grained micaceous litharenite in the Copperas Creek member of the Shelburn Formation (Frankie et al., 1995) in central Illinois (Figs. 1B and 5G). The Copperas Creek Sandstone can be up to 9 m thick (Wanless, 1957).

**U-Pb Geochronology**

Zircons were separated via crushing, milling, water table, sieving, and magnetic and heavy liquid separations. Analysis of individual grains was performed at the Arizona LaserChron Center. U-Pb analyses were conducted by laser ablation–multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) following the methods described by Gehrels and Pecha (2014). Final age data have been filtered using a cut-off of >20% for discordance and >5% for reverse discordance. For grains younger than 900 Ma, discordance was calculated by comparing the 206Pb/238U age to the 206Pb/207Pb age, and the 206Pb/238U ages are reported. For grains older than 900 Ma, discordance was calculated by comparing the 206Pb/235U age to the 206Pb/207Pb age, and the 206Pb/207Pb ages are reported. A common lead correction is applied to all grains following the method of Gehrels (2014). The analytical data are reported in Supplemental Table S1.1.
and Superior (11%) populations, with a dominant Midcontinent cluster (31%). IB-M2 (n = 69) has approximately equal proportions of Appalachian (14%), Neoproterozoic (19%), and Midcontinent (12%) populations. IB-AD (n = 81) is dominated by a Midcontinent population (24%) and a subsidiary Appalachian population (10%).

Desmoinesian strata in the Illinois Basin have both Type 2 and Type 3 signatures. IB-D1 (n = 258) has a Type 2 signature that is dominated by Appalachian (16%) and Neoproterozoic (23%) populations. IB-D2 (n = 264) also has a Type 2 signature with approximately equal proportions of Appalachian (16%) and Neoproterozoic (~15%) populations. IB-D3 (n = 91) has a Type 3 signature with 26% Appalachian grains, 10% Midcontinent grains, and is devoid of grains older than 1481 ± 23 Ma. IB-D4 (n = 65) has approximately equal proportions of Appalachian (15%) and Midcontinent (17%) populations and no grains older than 1484 ± 48 Ma.

## PROVENANCE INTERPRETATIONS

### Type 1 Signature

A composite Type 1 detrital-zircon signature is characterized by the dominance of a Midcontinent population (1300–1750 Ma; 15%–35%), a minimal Neoproterozoic (530–750 Ma; <4%) population, and minor to moderate amounts of Superior (>2500 Ma; 6%–17%) and Appalachian (270–490 Ma; 5%–16%) populations (Fig. 8). Cambrian and older strata from the upper midcontinent and Midcontinent Rift, which contain substantial Paleoproterozoic and Archean detrital-zircon populations (e.g., Craddock et al., 2013; Lovell and Bowen, 2013), are likely not primary contributors to sandstones with Type 1 signatures. Underlying Mississippian strata from the midcontinent region, however, contain nearly identical zircon populations as the Type 1 signature (Fig. 8). Therefore, we infer that remobilization of Mississippian sandstone in the IB and FCB by fluvial incision resulted in the detrital-zircon signature exemplified by Type 1 sandstones. This interpretation is supported by the lithological observations by Potter (1963), Potter and Pryor (1961), and Isbell (1985) in the IB and by Gregory (1982) and Scal (1990) in the FCB that sandstones identified as Type 1 are often more compositionally similar to Mississippian sandstone than their overlying Pennsylvanian counterparts. Furthermore, Mississippian strata were likely exposed on topographic highs (i.e., the Mississippi River and Transcontinental Arches) adjacent to the IB and FCB (Potter and Siever, 1956a, 1956b; Siever and Potter, 1956; Potter and Pryor, 1961) and could have been a significant source of sediment during Early and Middle Pennsylvanian time.

### Type 2 Signature

A composite Type 2 detrital-zircon signature is characterized by the dominance of Appalachian (15%–24%) and late Neoproterozoic (15%–36%)
Figure 7. Normalized relative age probability diagrams of detrital-zircon data. Colored rectangles illustrate age ranges of potential source terranes, and colors coordinate with basement terranes and magmatic belts shown on Figure 1A. $n$ = number of grains.
populations, with minor to moderate Midcontinent grains (5%–13%; Fig. 8). Detrital-zircon signatures from older strata in the midcontinent (Lowell and Bowen, 2013; Konstantinou et al., 2014), as well as Laurentian midcontinent basement rocks, are virtually devoid of Neoproterozoic ages. Potential known sources of Neoproterozoic-age zircons include the Iapetan synrift ca. 520–620 Ma dikes and rhyolites that range from Newfoundland to the southern Oklahoma fault system (e.g., Thompson et al., 1996; Hogan and Gilbert, 1998; Cawood and Nemchin, 2001), the ca. 750 Ma Mt. Rogers volcanics in western North Carolina (e.g., Su et al., 1994), and Pan-African metasedimentary terranes that underlie present-day New England and Newfoundland, as well as Maritime Canada and the southeastern United States (Fig. 1A; Zartman et al., 1988; Heatherington et al., 1999; Wortman et al., 2000; Hibbard et al., 2002; Pollock et al., 2007; Fyffe et al., 2009).

Several lines of evidence suggest that the Pan-African terranes underlying southeastern New England may be the most likely source for these populations in Type 2 sandstones. Neoproterozoic ages are largely absent in Paleozoic strata adjacent to the central and southern portions of the Appalachian Basin (Fig. 8; Thomas et al., 2004; Becker et al., 2005), precluding those regions as a potential source area. However, they are relatively common in Cambrian–Ordovician sediments in Newfoundland (Pollock et al., 2007), New Brunswick (Fyfee et al., 2009), and New York (McLennan et al., 2001), where they sit on peri-Gondwanan basement.

The Gander and Avalonia peri-Gondwanan terranes that originated on the margin of Amazonia (Gondwana) docked on the Laurentian margin either during Silurian and Devonian time (Fyffe et al., 2009) or during Carboniferous time (Wintsch et al., 2014). The Gander terrane comprises Archean through Neoproterozoic basement covered by Cambrian and Ordovician strata, while the Avalonia terrane is composed of Neoproterozoic (ca. 760 Ma) volcanic and plutonic rocks and Neoproterozoic to Cambrian (545–630 Ma) volcanic, sedimentary, and plutonic assemblages. Today, these terranes are exposed from southeastern New England to Newfoundland (Fig. 1A).

Exposures of the Gander and Avalonia terranes in eastern Canada can be ruled out as potential sources for the Neoproterozoic grains because abundant paleocurrent information from the Maritimes Basin in eastern Canada support the presence of a complex of internally drained sedimentary basins with dominant sediment transport toward the north-northeast (Fig. 1A; Gibling et al., 1992; van de Poll et al., 1995; Gibling et al., 2008). Therefore, we favor a headwater position in southeastern New England for rivers that deposited Type 2 sandstones in the FCB and IB. If accretion of the Gander and Avalonia terranes did occur during Carboniferous time (Wintsch et al., 2014), deformation associated with accretion could have exhumed parts of these peri-Gondwanan terranes and provided a new sediment source to the intracratonic basins. However, even if accretion took place much earlier (e.g., Silurian–Devonian), deformation associated with the Alleghenian orogeny could have exhumed these potential source rocks.

**Type 3 Signature**

A composite Type 3 detrital-zircon signature has prominent Appalachian (15%–26%) and Midcontinent (10%–17%) populations but lacks pre-Granite Rhyolite grains (>1550 Ma; Fig. 8), which suggests that recycling of the underlying Type 1 or Type 2 sandstones or older strata was minimal. The diminished amount of Neoproterozoic ages also suggests abandonment of the northeastern provenance that was characteristic of Type 2 signatures. Type 3 signatures most closely resemble the signatures of coeval strata in the central Appalachian foreland basin (Fig. 8; Eriksson et al., 2004; Becker et al., 2005; Becker et al., 2006); these strata also contain very few Neoproterozoic grains and are dominated by Appalachian and Midcontinent ages. Therefore, we infer that the Type 3 sandstones represent sediment derivation from the distal central Appalachian orogen. This interpretation is supported by numerical models that suggest that the Cincinnati Arch was covered by sediments from the unroofing of the Appalachians by at least Late Pennsylvanian time, if not earlier, depositionally linking the IB with the Appalachian foreland (Quinlan and Beaumont, 1984).
DISCUSSION

Early–Middle Pennsylvanian Paleogeography

Morrowan Time

Although mudstone-dominated Morrowan strata occur as small, isolated paleokarst fills in eastern Iowa and western Illinois, between the FCB and IB, intact stratigraphic sections of Morrowan strata have not been identified within the FCB (Pope, 2012). In the IB, two samples from the Caseyville Formation suggest variable provenance during Morrowan time. IB-M1 from eastern Iowa has a Type 1 signature that suggests a regional-scale fluvial system that was reworking locally derived and underlying strata, whereas IB-M2 from northern Illinois has a Type 2 signature indicative of a more distal provenance in the New England region.

Grimm et al. (2013) documented Lower Pennsylvanian transverse and longitudinal fluvial systems in the Pocahantas subbasin of the Appalachian foreland basin in southern West Virginia, Virginia, and eastern Kentucky. There, the deposits of transverse systems are characterized by channelized, interbedded sandstone and mudstone bodies 5–25 m thick with mostly trough cross-bedded cosets from 0.1 to 2 m thick. Longitudinal systems, however, have 10–50-m-thick multi-story sandstone bodies, with individual cross-bed sets that are 0.5–1.5 m thick. Combined, these strata are interpreted to represent a S- to SW-flowing, continental-scale axial fluvial system in the Appalachian Basin during Lower Pennsylvania time (Fig. 9A).

In the eastern IB, lithological variations in the Morrowan Caseyville Formation have also been attributed to the interplay between trunk (i.e., longitudinal) and tributary (i.e., transverse) rivers as well (Kvale and Archer, 2007). Trunk systems are dominated by purely fluvial deposits consisting of medium- to coarse-grained sandstone and conglomerate. In contrast, tributary systems have mudstone with thin, interbedded sandstone, as well as tidal rhythms, traces fossils, and macro- and microfauna that provide evidence for marine influence far inboard from the paleoshoreline. Evoking the modern Amazon Basin as an example, where marine influences are observed ~800 km inland from the shoreline, those authors postulated that sandy trunk rivers, similar to our Type 2 deposits, had the capability to efficiently dampen marine processes from the distant shoreline as well as supply extrabasinal detritus. In contrast, muddy tributary rivers, similar to our Type 1 deposits, were more strongly influenced by long tidal ranges and consisted of more locally derived sediments.

Type 1 sandstones in this study share several key characteristics with the transverse and tributary deposits described above, including (1) being very fine to fine-grained, thin- to medium-bedded, quartz-rich sandstone (Fig. 3) in single- or multi-story bodies generally <5 m thick; (2) dm-scale cross-bedding and low-relief erosional or sharp bases; (3) abundant and thick fine-grained interbeds; (4) evidence for marine influence (Figs. 4C, 4D, and 4F). Furthermore, Type 1 sandstones are stratigraphically positioned in the lower parts of both basins, often near the basal Pennsylvanian unconformity (Table 2; Wanless, 1956, 1957; Kosanke et al., 1960; Fitzgerald, 1977; Lemish et al., 1981; Gregory, 1982; Ravn et al., 1984). In general, in both basins, Lower–Middle Pennsylvanian strata that have a Type 1 signature have been interpreted as fluvial deposits in regional-scale depositional systems with relatively small watersheds and spatially limited provenance located on adjacent structural highs or the Canadian Shield (Fitzgerald, 1977; Lemish et al., 1981; Gregory, 1982).

Type 2 sandstones, in contrast, share different key characteristics with the longitudinal and trunk systems described above, including (1) being multi-story, >10-m-thick sandstone bodies; (2) 1–1.5-m-thick cross-bedding and moderate-to-high-relief erosional bases (Fig. 5); (3) litharenite sandstone compositions with an increase in the relative proportion of mica (Fig. 3); and (4) a general paucity of fine-grained interbeds (Table 2; Fitzgerald, 1977; Osolin, 1983; Anderson et al., 1999). Strata at Type 2 localities have generally been interpreted as channel deposits from larger fluvial systems, indicating that the watershed regions were larger compared to those for Type 1 sandstones (Fitzgerald, 1977; Osolin, 1983; Isbell, 1985). Furthermore, analyses by Siever and Potter (1956), Fitzgerald (1977), Osolin (1983), and Scal (1990) classify Type 2 sandstones as less compositionally mature than typical Type 1 sandstones, and thus more likely to have been derived at least in part from a crystalline source.

Our model for Morrowan axial rivers in the western IB is similar to the previously proposed Early Pennsylvanian sediment dispersal models in the eastern IB (Bristol and Howard, 1971; Rice and Schwieder, 1988; Droste and Keller, 1989; Archer and Greb, 1995). In the model by Archer and Greb (1995), rivers with headwaters as far north as southeastern Canada drained into the eastern IB on the western side of the southwest-trending Cincinnati Arch (Fig. 9A). Our data suggest that another far-traveled fluvial system with headwaters in the New England area brought sediment to the western IB during Morrowan time (Fig. 9B).

Combined uplift and erosion of source areas to the north and east of the IB and FCB that was initiated by Alleghenian crustal loading, along with a lower base level and marine basin in the Ouachita region during Mississippian time (Beaumont et al., 1988), resulted in a continental-scale, southwest-inclined palaeo-slope that facilitated transcontinental sediment dispersal prior to and during Morrowan time (Potter and Pryor, 1961). Paleoflow indicators and petrological observations in the northern part of the IB indicate Morrowan rivers reworked pre-Pennsylvanian sedimentary strata exposed to the west and northeast of the basin (Fitzgerald, 1977). The Mississippi River Arch, situated between the FCB and the IB, served as a topographic high and possible sediment source during this time (Isbell, 1985).

The role of the northern portion of the Cincinnati Arch in Ohio and southern Canada in preventing east-to-west sediment transport during the Carboniferous, however, is still poorly understood due to the absence of Mississippian and Pennsylvanian sediments on the arch (Root and Onasch, 1999). Nonetheless, in Kentucky, stratigraphic relationships indicate that the arch was a prominent topographic feature until Middle Pennsylvanian time (Tankard, 1986; Rice and Schwieder, 1988). In contrast, our results suggest that the Kankakee and Wisconsin arches between the Michigan and Illinois Basins were structural
Figure 9. Schematic paleogeographic reconstructions showing previously interpreted as well as our inferred paleogeographic evolution of eastern North America during Early-Middle Pennsylvanian time. These diagrams illustrate the general sediment dispersal patterns for each time period shown. Details of each illustration are discussed in the text. Positions of structural basement arch complexes that are inferred to have a topographic expression are shown in red, and those inferred to not influence sediment dispersal patterns for each time period are shown in gray.
separate the IB from the Appalachian Basin and sediment sources located fluvial system. Furthermore, the Cincinnati and related arches continued to be a region of nondeposition or sediment bypass for this extrabasinal migrating to the west in the IB. The Kankakee Arch appears to have continued from Morrowan time into Atokan and early Desmoinesian time. The persistence of variable provenance into Atokan and early Desmoinesian time.

We infer that the topographic configuration of the basin-bounding arches but not topographic highs that presented a southward-directed sediment dispersal pattern across the two basins. Furthermore, numerical models by Beaumont et al. (1988) infer that the Kankakee Arch was a region of non-deposition, but not erosion, during Early Pennsylvanian time.

**Atokan to Early Desmoinesian Time**

In the FCB, Atokan and early Desmoinesian strata exhibit Type 1 detrital-zircon signatures and sedimentological characteristics consistent with regional-scale fluvial systems and local sediment reworking. These strata represent the oldest widespread evidence for establishment of post-Mississippian depositional systems in the FCB. Our results suggest that regional-scale fluvial systems dominated during this time and that Mississippian strata were eroded from adjacent topographic highs and deposited into the basin (Fig. 9C).

In the IB, three samples from the Tradewater Formation suggest the persistence of variable provenance into Atokan and early Desmoinesian time. IB-AD from west-central Illinois has a Type 1 detrital-zircon signature and sedimentological characteristics that are consistent with smaller-scale fluvial systems and regional provenance. IB-D1 and IB-D2 from eastern Iowa, however, have Type 2 detrital-zircon signature and sedimentological characteristics that we infer to represent a larger network of fluvial systems that supplied detritus from southeastern New England to the basin. This pattern demonstrates a slight westward shift of the extrabasinal fluvial systems from northern Illinois in Morrowan time to eastern Iowa by early Desmoinesian time.

We infer that the topographic configuration of the basin-bounding arches persisted from Morrowan time into Atokan and early Desmoinesian time (Fig. 9C). The Mississippi River Arch likely served as a barrier to the large-scale fluvial system head-watered in southeastern New England that was migrating to the west in the IB. The Kankakee Arch appears to have continued to be a region of nondeposition or sediment bypass for this extrabasinal fluvial system. Furthermore, the Cincinnati and related arches continued to separate the IB from the Appalachian Basin and sediment sources located in the central and southern Alleghenian orogeny (Tankard, 1986; Rice and Schwietering, 1988).

**Middle Desmoinesian Time**

In the FCB, our stratigraphically highest sample (IB-D4) has a Type 2 detrital-zircon signature and sedimentological characteristics consistent with the continued westward migration of a large-scale fluvial system with headwaters in southeastern New England into central Iowa (Fig. 9D). This inference, as well as stratigraphic data and correlations between the IB and FCB (Isbell, 1985; Nelson et al., 2013), indicate that the Mississippi River Arch was overtopped by sediment during middle Desmoinesian time, and that the basins became depositionally linked.

In the IB, however, middle Desmoinesian strata have Type 3 detrital-zircon signatures. Type 3 sandstones in this study share several key characteristics, including (1) being multi-story, multimeter-thick sandstone with moderate-to-high-relief erosional bases (Figs. 5F and 5G); (2) having litharenite sandstone compositions with high proportions of mica; and (3) being the stratigraphically highest samples in the IB (Table 2). Strata at our Type 3 localities have previously been interpreted as deposits of continent-scale fluvial systems (Wanless et al., 1963).

Earlier workers had inferred that by the end of the Middle Pennsylvanian, filling of the Appalachian Basin and overtopping of the Cincinnati Arch likely leveled the depositional plain between the Alleghenian orogen and the Laurentian midcontinent (Nelson et al., 2013). Type 3 signatures in the IB indicate that transverse, orogen-perpendicular drainage systems extended into the basin during Middle Pennsylvanian time, replacing axial systems and shifting provenance to central or southern Appalachian sources (Fig. 9D). The overtopping of the Cincinnati and related arches would have removed the barrier to transverse flow and enabled the westward propagation of these fluvial systems. A subtle transition from southwest (~220°) to west-southwest (~252°) paleoflow directions in Missourian strata just above our Type 3 sandstones (Potter and

### TABLE 2. SEDIMENTOLOGIC CHARACTERISTICS OF TYPE SANDSTONES

| Type signature | Sedimentologic characteristics | Sandstone composition | Stratigraphic position |
|---------------|-------------------------------|-----------------------|-----------------------|
| Type 1        | Very fine to fine-grained, thin-bedded (<1 m), <~5 dm-thick cross beds when present, evidence for tidal influence, low-relief erosional or sharp bases, abundant and thick fine-grained interbeds | Quartz-arenite with minor mica and carbonate lithics | Lower parts of both basins, often near the basal Pennsylvanian unconformity |
| Type 2        | Fine- to coarse-grained, multi-story, multi-meter-thick sandstone, <~1.5-m-thick cross beds, moderate- to high-relief erosional bases, general lack of fine-grained interbeds | Dominantly subarkose or sublithic to lithic arkose or feldspathic litharenite, ~5%–10% mica, feldspar, lithic grains | Throughout the Illinois Basin and in the upper part of the Forest City Basin |
| Type 3        | Fine- to coarse-grained, multi-story, multi-meter-thick sandstone with moderate- to high-relief erosional bases, general lack of fine-grained interbeds | Dominantly subarkose or sublithic to lithic arkose or feldspathic litharenite, ~6%–10% mica, feldspar, lithic grains | Stratigraphically highest samples in the Illinois Basin; not found in Forest City Basin |

Note: Each type has a distinct detrital-zircon signature as well as unique sedimentologic characteristics.
Pryor, 1961) may reflect this inferred shift in drainage style, from rivers with catchment areas in the New England area to more westward-flowing systems with headwaters in the central Appalachians.

**Interplay between Sedimentation, Sea-Level Rise, and Tectonics**

During late Paleozoic time, variations in eustatic sea level and significant changes in the global tectonic configuration of landmasses affected the North American continent. One of three major Paleozoic eustatic sea-level lows occurred near the Mississippian/Pennsylvanian boundary and was followed by a eustatic rise that continued into Late Pennsylvanian time (Haq and Schutter, 2008). Alleghenian mountain building that is linked to the creation of the Pangaea supercontinent also began in latest Mississippian time and continued until latest Pennsylvanian or Permian time (Hatcher, 1989). Lower to Middle Pennsylvanian strata deposited in the IB and FCB record the interplay between these two pivotal events.

During Morrowan time, eustatic sea level was falling and reached its ultimate low position at the Morrowan/Atokan boundary (Fig. 2). There are no intact Morrowan strata preserved in the FCB, but the Caseyville Formation was deposited and preserved in the IB. Although accommodation for sediment accumulation was likely limited by eustatic fall, the IB is located in a more proximal position to the advancing thrust loads located in the Ouachita and Appalachian regions than the FCB. Therefore, it may have experienced more profound flexural depression that permitted accumulation of sediments in the basin.

Beaumont et al. (1988) predicted ~240 m of tectonic subsidence at the center of the IB during Early Pennsylvanian time. In the classic model of tectonic subsidence of foreland basins (e.g., DeCelles and Giles, 1996), the degree of subsidence induced by thrust loading decreases dramatically inboard from the forebulge. The IB sits adjacent to the Alleghenian forebulge (Cincinnati Arch) and therefore was affected by tectonically driven subsidence; whereas the FCB is situated ~400 km farther inboard and thus was not affected by Alleghenian thrust loading (e.g., Beaumont et al., 1988).

A significant provenance region for some of the Morrowan Caseyville Formation strata in the IB is inferred to be southeast New England. That region experienced intense deformation with the Acadian orogeny during Middle Devonian to Early Mississippian time (Hatcher, 1989). Relict highlands in that region, combined with flexural loading along the southwest margin of the continent during Late Mississippian to Early Pennsylvanian time (Beaumont et al., 1988) produced an overall southward slope to the continental surface (Siever and Potter, 1956) that likely contributed to the New England provenance signature.

Beginning in Atokan time, eustatic sea level began to rise (Fig. 2). Although the controls on fluvial aggradation are complicated and can include climate, sediment supply, and stream power, it is generally agreed that during eustatic sea-level rise there is a downstream decrease in sediment transport rate and increase in the rate of channel-bed aggradation (Schumm, 1993; Blum and Tornqvist, 2000; van Heijst and Potsma, 2001). In the FCB, we infer that fluvial systems responded to eustatic rise by aggrading and accumulating sediments that comprise the Kalo and Kilbourn Formations.

Schumm (1993) proposed that sea-level rise would result in “backfilling” of incised valleys, the deposits of which should thicken downstream and fine upward. Although the overall thickness of the Kalo and Kilbourn Formations increases in a general down-dip direction in the FCB, the thickness of these units in individual paleovalleys has not been explored. However, there is an overall increase in grain size in the Kalo and Kilbourn Formations as opposed to the eustatic sea-level rise as a potential mechanism for these units. Furthermore, because our data preclude a significant extrabasinal sediment source during this time, we infer that the Kilbourn and Kalo river systems recycled older, underlying sedimentary strata in order to aggrade their beds.

In the IB, sedimentation continued during Atokan to early Desmoinesian time with deposition of the Tradewater Formation. The Tradewater Formation is interpreted to represent dominantly nonmarine environments; however, cyclothems are better developed and more prominent in the upper parts of the Tradewater Formation during latest Atokan and earliest Desmoinesian time (Nelson et al., 2013). This increase in marine influence earlier in the IB relative to the FCB may be related to both the south-directed depositional slope and greater amount of subsidence produced by Alleghenian crustal loading and, as a result, seaways that impinged in the IB before the FCB.

Eustatic sea level continued to rise during Desmoinesian time (Fig. 2). As a result in the FCB, the first appearance of poorly developed cyclothems occurs in the upper part of the Floris Formation, with the first well-developed cyclothems in the overlying Verdigris Formation (Pope, 2012). Lowstand conditions, however, continued to afford episodic fluvial deposition in both the IB and FCB.

Alleghenian deformation continued along the eastern margin of the continent including the southern and central Appalachians (Hatcher, 1989). Exhumation of those regions likely increased the sediment flux to the Appalachian foreland basin, which became overfilled during Middle Pennsylvanian time and allowed sediments derived from the southern and central Appalachians to reach the IB. The low-amplitude, long-wavelength foreland subsidence in the Appalachian Basin also promoted rapid overfilling of the basin (Thomas et al., 2004). This westward migration of depositional systems is mimicked in the FCB by the arrival of the large fluvial system with a New England provenance.

Farther west, late Paleozoic strata in the Grand Canyon have detrital-zircon age populations that are interpreted to reflect sediment flux from the southern and central Appalachians (Gehrels et al., 2011). Mississippian and Pennsylvanian strata there have signatures that are similar to our Type 1 in that they contain abundant Appalachian (270–490 Ma) and Grenville (980–1300 Ma) ages, with smaller proportions of Superior ages (>2500 Ma) but essentially lack any Neoproterozoic ages (530–750 Ma). By Early Permian time, however, strata in the Grand Canyon record the influx of Neoproterozoic age populations, more similar to our Type 2 signature. We infer this trend to represent the continued westward migration of the transcontinental fluvial system with headwaters in
southeastern New England across the North American continent from the Illinois Basin during Early Pennsylvanian time, to the Forest City Basin during late Middle Pennsylvanian time, to the southwestern United States by Early Permian time.

**Implications for Foreland Basin Systems**

The Cincinnati Arch is considered to have acted as a forebulge during the Alleghanian orogeny, placing the IB in a backbulge position in the Appalachian foreland basin system during Pennsylvanian time (Quinlan and Beaumont, 1984; Root and Onasch, 1999). Sediment preservation in the backbulge region of collisional foreland basin systems is relatively uncommon (DeCelles, 2012). Nevertheless, several factors, including gradual weakening of the lithosphere, availability and efficiency of sediment transport, and prevalence of accommodation, all play a role in determining whether backbulge deposits are preserved in the stratigraphic record (Jordan, 1995).

Deposition in the Appalachian backbulge region during Early to Middle Pennsylvanian time was likely enabled by a number of factors. The midcontinent was situated within tropical to equatorial latitudes on or near the equator during the Early Pennsylvanian (Witzke, 1990). The climate transitioned from semi-arid during Late Mississippian time to tropical and monsoonal equatorial during Early Pennsylvanian time (Cecil et al., 1985). These subtropical climatic conditions are conducive to high rates of erosion. This circumstance, in combination with the axial fluvial systems with larger watersheds, may have resulted in higher rates of sediment flux than are normally found in the backbulge depocenter. In addition, accommodation on the craton continued to increase during Pennsylvanian time as a result of eustatic sea-level rise (Haq and Schutter, 2008), as well as potentially from reactivation of basement structures beneath the basins (Anderson and Wells, 1988; Mason, 1980; Root and Onasch, 1999).

While continental-scale drainages in cratonic settings may exist independently of orogenic-related exhumation, the progradation of transverse rivers across the continent, even during a time of overall sea-level rise, was likely the result of a massive erosional response to the formation of Pangea. The flooding of cratons with orogen-derived sediments is a documented byproduct of supercontinent cycles (Veevers, 2004; Cawood et al., 2007). For example, the Grenville orogen was a major late Mesoproterozoic mountain-building event that included the amalgamation of continents to form the Rodinian supercontinent (Rainbird et al., 2012; Konstantinou et al., 2014; Spencer et al., 2014; Malone et al., 2016). The exhumation and denudation of the Grenville orogen is recorded in sedimentary basins on all margins of Laurentia, as far away as the Amundsen Basin in northwest Canada, several thousands of kilometers from the sediment source (Rainbird et al., 2012). Transcontinental sediment dispersal related to mountain building during amalgamation of a supercontinent is a typical response for coeval depositional systems preserved in the stratigraphic record. Under such conditions, intracratonic basins, such as the FCB, may be more likely to experience a transition from axial to transverse provenance that is typically associated with the distal portions of a foreland basin system.

**CONCLUSIONS**

New detrital-zircon geochronologic data from Early to Middle Pennsylvanian strata in the Illinois and Forest City Basins provide additional constraints on the paleogeography and sediment dispersal patterns on the North American midcontinent. Morrowan–middle Desmoinesian strata in the Illinois and Forest City Basins have detrital-zircon signatures and sedimentologic characteristics that are interpreted to reflect the presence of both regional-scale fluvial systems that recycled underlying sedimentary strata and large-scale fluvial systems that supplied detritus shed from southeastern New England. By Early Permian time, the fluvial systems with headwaters in New England may have been delivering sediment to the Grand Canyon area in the southwestern United States. In the midcontinent, these depositional systems were ultimately replaced by transverse fluvial systems that supplied sediment from the southern and central Appalachians to the intracratonic basins. Increased subsidence in the intracratonic Illinois Basin, due to its backbulge position, in combination with high sediment flux from the Alleghanian orogeny, climatic conditions conducive to high rates of erosion, and accommodation created by rising eustatic sea level may have resulted in the greater thickness of Pennsylvanian strata in that basin. In a broader sense, our results suggest that aggradation of sediments in cratonic depositional systems that are responding to eustatic sea-level rise should result in a provenance signature that reflects recycling of readily available, underlying strata. When tectonics plays a dominant role in compelling sedimentation, however, the provenance signature would be characterized by extrabasinal sediment sources.

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