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Detrital zircons and sediment dispersal in the eastern Midcontinent of North America

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ABSTRACT

Results of detrital-zircon analyses (U-Pb ages and initial Hf values, εHf_t) of Mississippian–Pennsylvanian sandstones in the Michigan, Illinois, and Forest City basins are remarkably similar to data for coeval sandstones in the Appalachian basin, indicating dispersal of sediment from the Appalachian orogen through the Appalachian basin to the eastern Midcontinent during the late Paleozoic. The similarities of results include matches of the two most prominent age groups (1300–950 Ma and 490–350 Ma), as well as matches of the less abundant age groups. Comparisons of the data are from observations of probability density plots and multidimensional scaling of U-Pb age data and of εHf_t values. Despite the dominance of an Appalachian signature in all samples, some samples contain grains with ages that suggest intermittent additional sources.

Four samples (three ranging in depositional age from Morrowan to Atokan–Desmoinesian in the Illinois basin, and one of Desmoinesian age in the Forest City basin), in addition to typical Appalachian age distributions, have prominent age modes between 768 and 525 Ma, corresponding in age to Pan-African/Brasiliano rocks in Gondwanan accreted terranes in the Appalachian orogen, suggesting intermittent dispersal from the Moretown terrane of the northern Appalachians.

Sandstones in the Appalachian basin and those in the Midcontinent basins have very few grains with ages that correspond to the Alleghanian orogeny in the Appalachian orogen. Nevertheless, three sandstones each in the Illinois basin and Forest City basin with depositional ages of 312–308 Ma have a few zircon grains in the age range of 321 ± 5 to 307 ± 4 Ma. The nearly identical crystallization and depositional ages suggest reworking at the depositional sites of air-fall volcanic ash from the Alleghanian orogen, rather than fluvial transport from the orogen.

The basal Pennsylvanian sandstones lap onto a regional unconformity around the northern rims of the Illinois and Forest City basins, suggesting sources for recycled grains. Along the northern edge of the Illinois basin, Ordovician sandstones beneath the unconformity may have contributed minor concentrations of Superior-age zircons in the basal Pennsylvanian sandstones. Basal Pennsylvanian sandstones in the Forest City basin lap onto Mississippian strata, suggesting possible recycling of zircons from eroded Mississippian sandstones.

INTRODUCTION

Various large-scale systems of drainage and sediment dispersal have been proposed for the late Paleozoic of Laurentia (North America), first, on the basis of regional stratigraphy and sedimentary petrology, and more recently, on the basis of detrital-zircon geochronology. A proposed Himalayan-Bengal model included westward sediment dispersal along the length of the diachronously closing Appalachian-Ouachita-Marathon foredeep during the late Paleozoic (Graham et al., 1976; Gleason et al., 2007). Amazon-scale rivers heading in the Canadian Shield were proposed to flow southward, one longitudinally along the Appalachian basin and another through the Michigan and Illinois basins to the Ouachita margin (Archer and Greb, 1995). A proposed continent-scale drainage system delivered sediment from the Appalachians to the western part of the continent at the present location of Grand Canyon (Gehrels et al., 2011). More localized studies have proposed drainage systems and sediment dispersal that ultimately mixed sediment from Appalachian sources and more local sources into the Permian basin (Soreghan and Soreghan, 2013; Xie et al., 2018a), the Fort Worth basin (Alsalem et al., 2018), and the Arkoma basin (Xie et al., 2016, 2018b). Appalachian-derived detritus has been recognized in the Illinois and Forest City basins (Kissock et al., 2018), and more distant dispersal has been proposed from the Appalachians to the Wyoming shelf (May et al., 2013; Garber et al., 2018). The interpretations based on detrital-zircon studies rely on matching the age distributions of detrital zircons with ages of potential sources. An equally important step, however, is to identify and trace the dispersal pathway from the inferred source to the depositional site by investigating the detrital-zircon age distributions in coeval deposits along the inferred pathway (Thomas, 2011). Sediment dispersal from an Appalachian provenance begins with drainage from the orogen into the proximal Appalachian basin (Appalachian foreland basin or foredeep), where Alleghanian synorogenic clastic wedges record the composition of sediment (including detrital-zircon ages) in the headwaters of regional-scale drainage systems and provide an "Appalachian signature" for regional tracing of detritus (Thomas et al., 2017).

Nearly all of the proposed large-scale dispersal pathways pass through the intracratonic Michigan, Illinois, and/or Forest City basins across the eastern craton of North America, west of the Appalachian basin and south of the Canadian Shield (Fig. 1). In the eastern craton (the eastern Midcontinent), large-scale basement arches and domes separate broad basins with wavelengths of hundreds of kilometers and amplitudes of no more than 4 km (e.g., Bunker et al., 1988; Collinson et al., 1988; Fisher et al., 1988). Post-Paleozoic erosion has dramatically reduced or completely removed the upper Paleozoic strata over the arches and domes, leaving upper Paleozoic strata isolated in the separate basins (Fig. 2). Late Paleozoic sediment dispersal pathways into, across, and beyond the separate basins have been interpreted from directions of paleocurrent indicators, orientations of depositional systems and directions of progradation, large-scale facies patterns in the context of transgression-regression cycles, and sandstone petrography (e.g., Potter and Siever, 1956a, 1956b; Siever and Potter, 1956; Potter, 1962a, 1962b; Swann, 1964; Wanless and Wright, 1978; Archer and Greb, 1995). Like the continent-scale dispersal interpretations, these interpretations focus on sediment dispersal from a composite provenance in the Appalachian orogen or, alternatively, from the Canadian Shield, or from both.

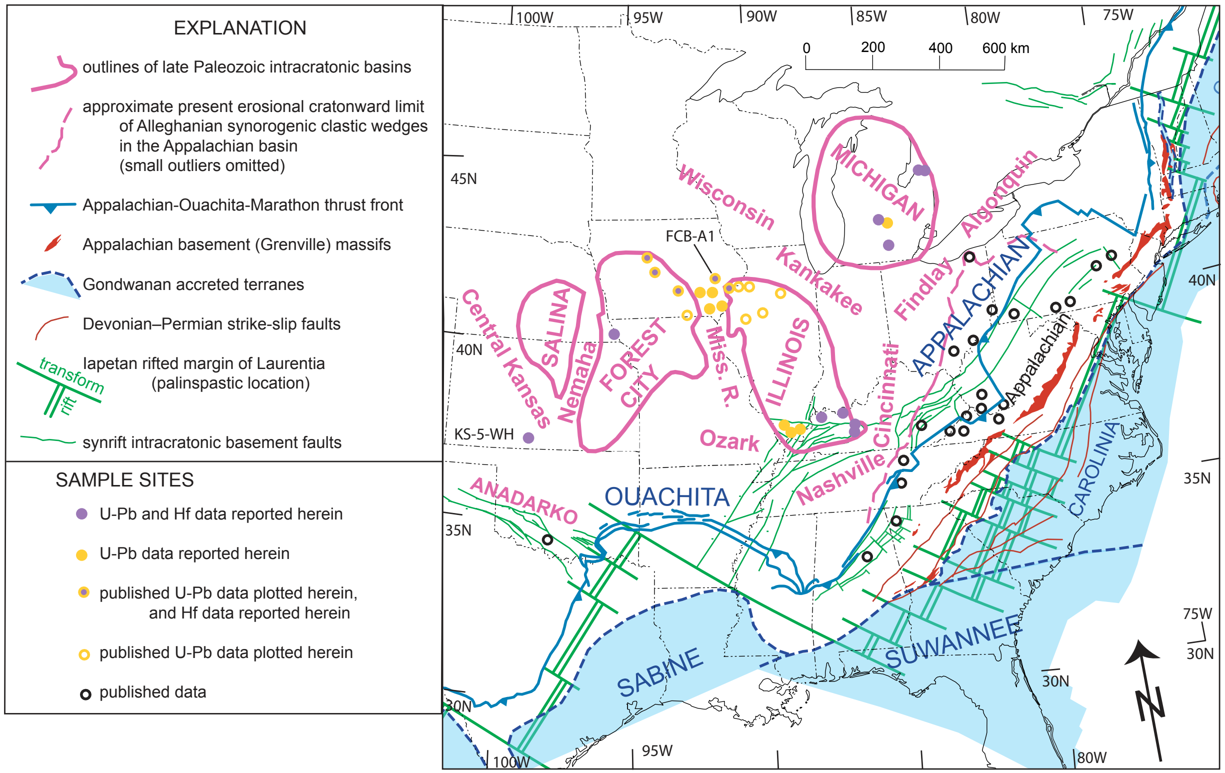


Figure 1. Regional map of the Michigan, Illinois, and Forest City intracratonic basins (names in all capital letters) and related large-scale arches (names in capital and lowercase letters; Miss. R.—Mississippi River arch); Iapetan rift margin and synrift intracratonic faults of Laurentia (multiple parallel rift symbols represent lower-plate extension), which outline the locations of synrift igneous and sedimentary rocks (from Thomas, 2014); locations of Gondwanan accreted terranes in the Appalachian-Ouachita orogen (from Hibbard et al., 2007; Hatcher, 2010; Thomas, 2014); Appalachian basement massifs of Grenville-age rocks (Hatcher, 2010); and trace of the Appalachian-Ouachita thrust front (compiled from Thomas et al., 1989; Hatcher, 2010). Locations of sample sites; some symbols represent multiple closely spaced samples.

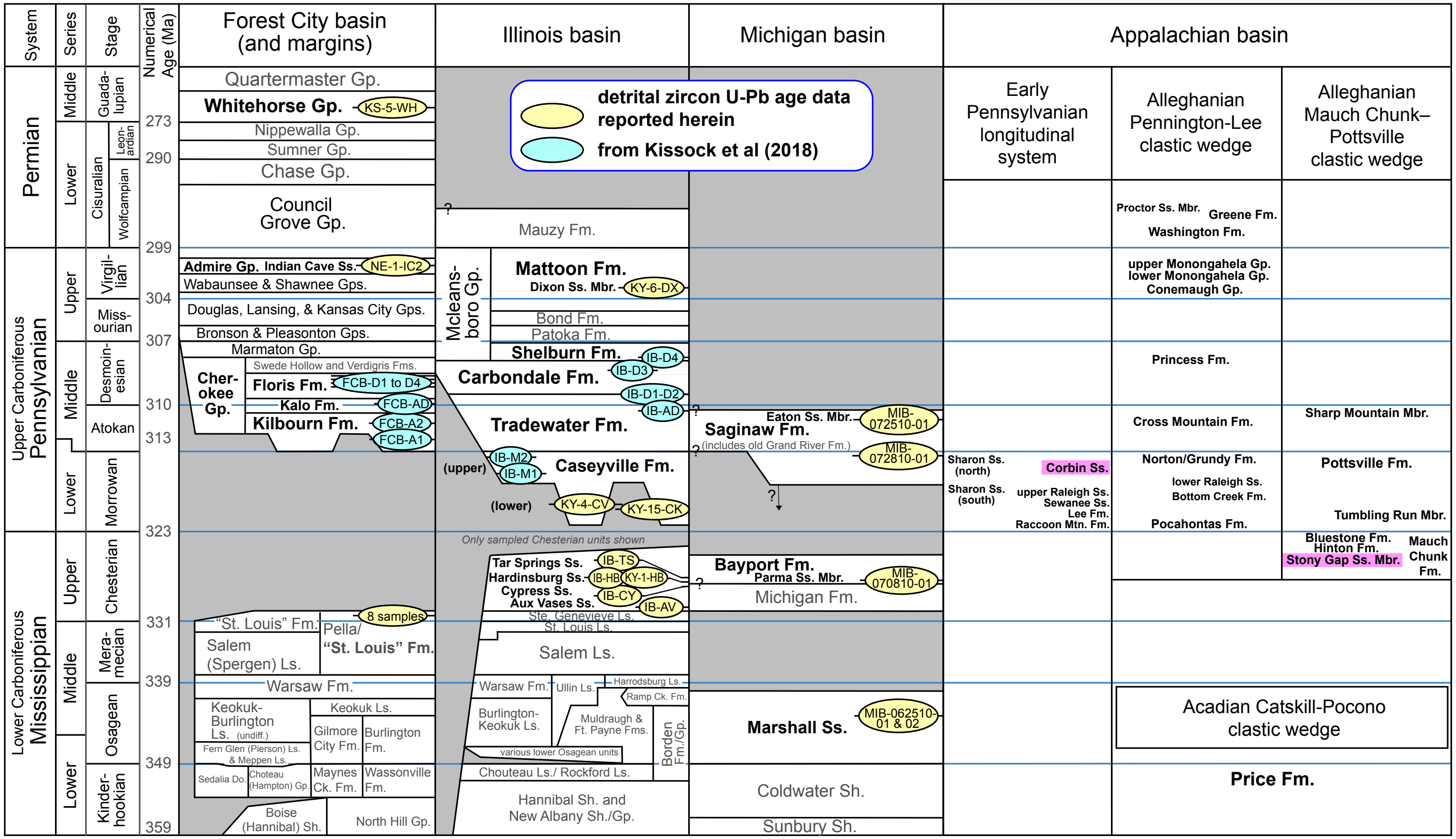


Figure 2. Stratigraphic columns for Michigan basin, Illinois basin, and Forest City basin, and correlation to sampled stratigraphic units in the Appalachian basin (from Thomas et al., 2017). Names of sampled stratigraphic units shown in bold type. Approximate numerical ages are extrapolated from correlation to the International Chronostratigraphic Chart (Cohen et al., 2013, updated) and are the basis for assignment of depositional ages of sampled stratigraphic units (Table 1). Ck.—Creek, Do.—Dolomite, Fm.—Formation, Fms.—Formations, Gp.—Group, Gps.—Groups, Ls.—Limestone, Mbr.—Member, Sh.—Shale, Ss.—Sandstone, undiff.—undifferentiated. Appalachian basin, Alleghanian synorogenic sandstones identified by name in the text (pink highlight).

This article reports detrital-zircon age distributions of the late Paleozoic detritus preserved in three large-scale intracratonic basins in the eastern craton (eastern Midcontinent) basins as a test of both the headwaters (provenance) and the pathways of sediment dispersal, both locally and on the continental scale. Ultimately, dispersal pathways through these basins are critical to the possibly more extensive late Paleozoic dispersal to the Ouachita foreland and to western Laurentia.

MICHIGAN BASIN

The Michigan basin forms a circular outline on the southern edge of the Canadian Shield (Figs. 1 and 3). South of the Michigan basin, the north-trending Cincinnati arch branches into the northeast-trending Findlay arch and northwest-trending Kankakee arch, which together frame the southern part of the Michigan basin. The Kankakee arch merges northward with the Wisconsin arch along the west side of the basin, and the Findlay arch merges northeastward with the Algonquin arch along the east side of the basin. The Findlay-Algonquin arch system separates the Michigan basin from the Appalachian basin (Fig. 1), which dips eastward beneath the Appalachian orogen.

The lower part of the Mississippian System in the Michigan basin includes siliciclastic rocks (including the Marshall Sandstone) of the most distal upper part of the Acadian clastic wedge in

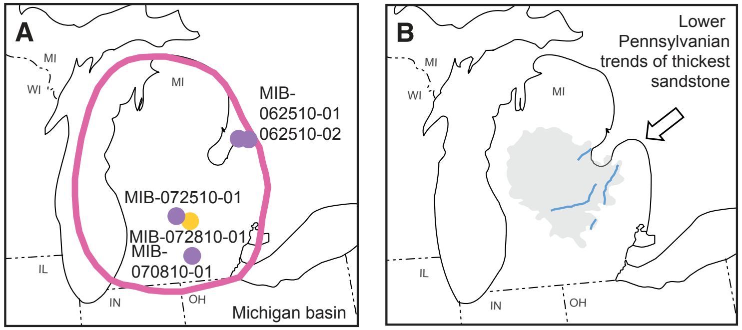


Figure 3. Sample sites and sediment dispersal in the Michigan basin. (A) Sample locations in the Michigan basin (outline of basin from Fig. 1; symbols for sample sites as in Fig. 1; sample location data in Supplemental Table S1 [text footnote 1]). (B) Linear patterns of thickest sandstone (blue lines) in Lower Pennsylvanian strata (adapted from facies maps in McKee and Crosby, coordinators, 1975) and interpreted sediment dispersal (white arrow) into the Michigan basin (Potter and Siever, 1956a; Shideler, 1969; Wanless and Shideler, 1975). IL—Illinois, IN—Indiana, MI—Michigan, OH—Ohio, WI—Wisconsin.

the Appalachian foreland (Fig. 2). Stratigraphically higher, Upper Mississippian strata comprise a cyclic succession of siliciclastic rocks, carbonates, and evaporites (Cohee, 1979). The Parma Sandstone, which previously was considered to be Early Pennsylvanian in age, has recently been reinterpreted to be Late Mississippian (Towne et al., 2018).

In the Michigan basin, Lower Pennsylvanian strata unconformably overlie Upper Mississippian strata. The Pennsylvanian succession (Fig. 2) includes dominantly siliciclastic strata, which range from marginal marine to fluvial, and also includes limestone beds (Wanless and Shideler, 1975). The successions are cyclic and have been interpreted in the context of cyclothems. Pennsylvanian facies include redbeds and evaporites in the northwestern part of the basin, whereas coal beds and gray shale characterize the southeastern part of the basin (Wanless and Shideler, 1975). Sandstone comprises a greater proportion of the succession on the east, and linear patterns of sandstone distribution suggest southwesterly trending fluvial systems from the east side of the basin (Fig. 3) (Shideler, 1969). Crossbed measurements indicate southwest-directed paleocurrents (Potter and Siever, 1956a). Dispersal of sediment from the east and northeast of the basin, generally recycled from older sandstones, is inferred from the sandstone distribution (Shideler, 1969; Wanless and Shideler, 1975; Cohee, 1979).

ILLINOIS BASIN

The Illinois basin is an oblong basin along the west limb of the Cincinnati arch and the southwest limb of the Kankakee arch (Fig. 1), which separates the Illinois basin from the Michigan basin. The Mississippi River arch forms the west side of the Illinois basin, separating it from the Forest City basin farther west. The Mississippi River arch merges southward with the structurally higher Ozark dome at the southwest corner of the Illinois basin. The Illinois basin plunges southward; the deeper, southern part of the basin is structurally complicated by the east-striking Rough Creek fault system along the north side of a secondary arch that connects the Ozark dome to the Nashville dome on the Cincinnati arch (Fig. 1). The Cincinnati arch separates the Illinois basin in the eastern craton from the Appalachian basin (Fig. 1).

The lower part of the Mississippian System in the Illinois basin includes siliciclastic rocks (Borden Formation) of the most distal upper part of the Acadian clastic wedge in the Appalachian basin (Fig. 2). Carbonate rocks dominate the Middle Mississippian strata. The Upper Mississippian (Chesterian) section contains 15–16 cyclic sequences of clastic and carbonate rocks (Smith and Read, 2001; Nelson et al., 2002), which commonly are used to interpret Late Mississippian sea-level changes (e.g., Swann, 1964; Ross and Ross, 1988; Smith and Read, 2000). Chesterian sandstones were deposited in fluvial, estuarine, and shallow-marine environments (Table 1), inferred to represent successive lowstand, transgressive, and highstand conditions (Smith and Read, 2001; Nelson et al., 2002). Fluvial sandstones generally are linear, elongate bodies with southwest-oriented paleocurrent indicators (e.g., Potter et al., 1958). Shallow-marine and estuarine sandstones are common and generally are broader sheet sandstones with bioturbation and more variable paleocurrent orientations (Swann, 1964; Wescott, 1982; Treworgy, 1988; Smith and Read, 2001; Nelson et al., 2002).

Lower Pennsylvanian strata unconformably overlie Upper Mississippian strata in the southern part of the Illinois basin. The unconformity cuts down through the succession to Ordovician strata around the northern rim of the basin, and Lower Pennsylvanian strata lap out northward on the unconformity (Willman et al., 1967; McKee and Crosby, 1975). Paleotopographic valleys, which are incised as much as 90 m, generally trend northeast-southwest (Fig. 4C), except along the Rough Creek graben in the southern part of the basin where two valleys trend east-west subparallel to structure (Potter and Desborough, 1965; Bristol and Howard, 1971; Davis et al., 1974; Droste and Keller, 1989; Greb, 1989a; Nelson et al., 2013). The easternmost preserved fill of one of the southern valleys, the Brownsville paleovalley, is only 100 km west of the most westerly preserved quartz-pebble conglomeratic sandstones in the Corbin Sandstone of the central Appalachian basin (Figs. 2 and 4C). Quartz-pebble–bearing quartzarenites (Caseyville Sandstone, Fig. 2) fill paleovalleys, and unconfined quartzose sandstones extend above the valleys (Davis et al., 1974; Greb et al., 1992, 2002; Nelson et al., 2013).

Paleocurrent data from Atokan sandstones suggest southwestward regional slope (e.g., Potter and

TABLE 1. LIST OF SAMPLES WITH DEPOSITIONAL AGES AND ENVIRONMENTS

Sample	Stratigraphic unit	Approximate depositional age[1]	Depositional environment	Reference
Michigan basin				
MIB-072510-01	Eaton	311 Ma	Fluvial	Venable et al., 2013
MIB-072810-01	Saginaw	314 Ma	Deltaic	Venable et al., 2013
MIB-070810-01	Parma	327 Ma	Deltaic	Shideler, 1969
MIB-062510-01	Marshall	342 Ma	Deltaic strand plain	Adducci and Barnes, 2018
MIB-062510-02	Marshall	342 Ma	Deltaic strand plain	Adducci and Barnes, 2018
Illinois basin/south				
KY-6-DX	Dixon	303 Ma	Fluvial	Greb et al., 1992
KY-4-CV	Caseyville	320 Ma	Fluvial	Greb, 1989a
KY-15-CK	Caseyville	320 Ma	Fluvial	Sedimentation Seminar, 1978
IB-TS	Tar Springs	326 Ma	Fluvial–estuarine	Treworgy, 1988
IB-HB	Hardinsburg	327 Ma	Shallow marine	Treworgy, 1988
KY-1-HB	Hardinsburg	327 Ma	Shallow marine	Nelson et al., 2002
IB-CY	Cypress	328 Ma	Shallow marine	Treworgy, 1988
IB-AV	Aux Vases	330 Ma	Fluvial–deltaic	Nelson et al., 2002
Illinois basin/north				
IB-D4	Shelburn	308 Ma	Fluvial	Nelson et al., 1996
IB-D3	Carbondale	308 Ma	Fluvial	Frankie et al., 1995
IB-D2	Tradewater	309 Ma	Fluvial	Potter and Glass, 1958
IB-D1	Tradewater	309 Ma	Fluvial	Potter and Glass, 1958
IB-AD	Tradewater	310 Ma	Fluvial	Reinertsen et al., 1993
IB-M2	Caseyville	315 Ma	Fluvial	Anderson et al., 1999
IB-M1	Caseyville	316 Ma	Fluvial	Isbell, 1985
Forest City basin				
KS-5-WH	Whitehorse	270 Ma	Eolian	Poland and Simms, 2012
NE-1-IC2	Indian Cave	301 Ma	Fluvial	Fischbein et al., 2009
FCB-D4	Floris	308 Ma	Fluvial	Marshall, 2010
FCB-D3	Floris	308 Ma	Fluvial	Marshall, 2010
FCB-D2	Floris	309 Ma	Fluvial	Marshall, 2010
FCB-D1	Floris	309 Ma	Fluvial	Marshall, 2010
FCB-AD	Kalo	310 Ma	Fluvial	Gregory, 1982
FCB-A2	Kilbourn	312 Ma	Fluvial	Ravn et al., 1984
FCB-A1	Kilbourn	313 Ma	Fluvial	Ravn et al., 1984
WBC-1	Waugh	331 Ma	Deltaic	Witzke et al., 1990
LK-1	Keosauqua	331 Ma	Fluvial–estuarine	Witzke, 2004
BSQ-1, BSQ-2, GSP-1, GQ-1, VSQ-1	Verdi	331 Ma	Shallow marine	Witzke et al., 1990
BC-1	Yenrougis	331 Ma	Shallow marine	Witzke et al., 1990

[1]Approximate depositional age extrapolated by correlation to International Chronostratigraphic Chart v 2019/05 (Cohen et al., 2013, updated).

Glass, 1958). Desmoinesian units contain the classic "cyclothems" (e.g., Wanless and Weller, 1932; Wanless and Shepard, 1936; Weibel, 1996), and many coals and marine shales can be correlated from the Midcontinent through the Illinois basin into the northern Appalachian basin (Wanless and Wright, 1978; Heckel, 1994, 1995), suggesting a lack of major drainage barriers between the eastern basins. Basin-scale paleochannels above the Springfield (Carbondale Formation) and Herrin (Shelburn Formation) coal beds indicate southwest flow through the southern part of the basin (Figs. 2 and 4D) (Hopkins, 1958; Potter and Simon, 1961; Beard and Williamson, 1979; Nelson, 1983; Eggert, 1984; Hatch and Affolter, 2002; Greb et al., 2003).

Upward changes in petrography in the Illinois basin have been interpreted to represent increasingly more immature source areas through the Pennsylvanian (Potter and Glass, 1958). Pebbles of polycrystalline and fractured monocrystalline quartz in the Caseyville Sandstone are interpreted to have primary sources in metamorphic terranes but recycled through older Paleozoic sandstones northeast of the basin (Potter and Siever, 1956b; Siever and Potter, 1956; Siever, 1957; Andresen, 1961). Quartz-pebble–bearing quartzarenites in the Caseyville Sandstone contrast with lithic arenites in the Tradewater Formation and successive formations. The Caseyville Sandstone contains tourmaline grains, which are lacking in younger Pennsylvanian sandstones. Apatite grains increase in abundance upward from the Middle to Upper Pennsylvanian, and garnet grains are more abundant in the Upper Pennsylvanian. In general, stratigraphically upward through the Middle Pennsylvanian succession, the sandstones are more lithic, argillaceous, and micaceous; and stratigraphic units are more widespread and laterally continuous (Atherton et al., 1960; Greb et al., 1992, 2002; Nelson et al., 2013).

FOREST CITY BASIN

The Forest City basin has a long, gentle eastern limb on the western flanks of the Ozark dome and Mississippi River arch, but the western limb is relatively steep and broken by basement-rooted normal

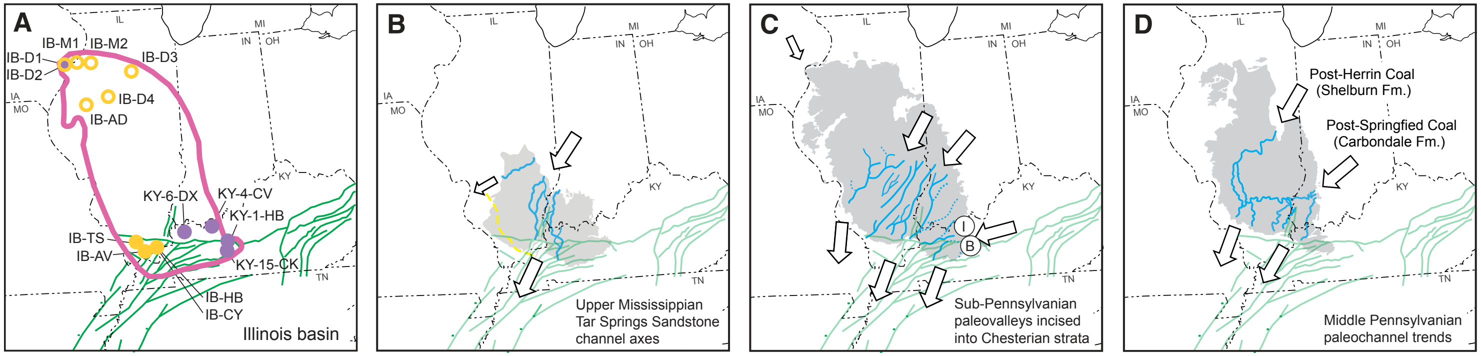


Figure 4. Sample sites and sediment dispersal in the Illinois basin. (A) Sample locations in the Illinois basin (outline of basin from Fig. 1; symbols for sample sites as in Fig. 1; sample location data in Supplemental Table S3 [text footnote 3]). Synrift basement faults of the Rough Creek graben across the southern part of the Illinois basin (green lines). (B) Trends of Upper Mississippian channel sandstones (blue lines) in the Tar Springs Sandstone (adapted from Wescott, 1982; Droste and Keller, 1989; unpublished data files at Kentucky Geological Survey); possible paleoshoreline (dashed yellow line). (C) Trends of paleovalleys (blue lines) eroded into Mississippian strata and filled with Lower Pennsylvanian sandstone (compiled from Bristol and Howard, 1971; Davis et al., 1974; Greb, 1989a; Droste and Furer, 1995) (B—Brownsville paleovalley, I—Indian Lake paleovalley). (D) Trends of paleochannels (blue lines) filled with upper Middle Pennsylvanian sandstones at two successive stratigraphic levels above major coal beds (modified from data in Hatch and Affolter, 2002; Greb, 2013). Maps B–D show interpreted sediment dispersal (white arrows) into the Illinois basin. IA—Iowa, IL—Illinois, IN—Indiana, KY—Kentucky, MI—Michigan, MO—Missouri, OH—Ohio, TN—Tennessee.

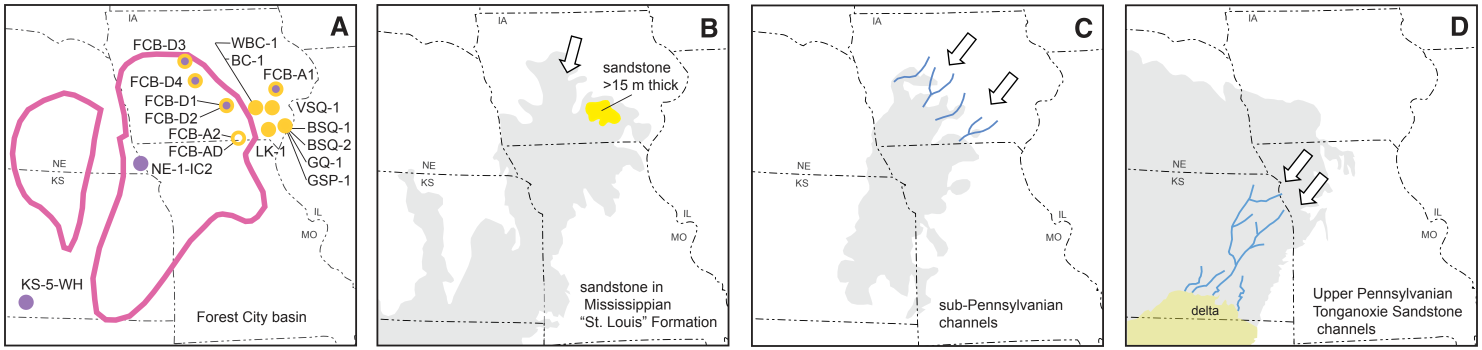


Figure 5. Sample sites and sediment dispersal in the Forest City basin. (A) Sample locations in the Forest City basin (outline of basin from Fig. 1; symbols for sample sites as in Fig. 1; sample location data in Supplemental Table S5 [text footnote 5]). (B) Distribution of sandstone interbeds in the Mississippian "St. Louis" Formation (compiled from online well database, Iowa Geological Survey, https://www.iihr.uiowa.edu/igs/geosam/home). (C) Trends of paleovalleys (blue lines) eroded into Mississippian strata and filled with Pennsylvanian sandstone (compiled from online well database, Iowa Geological Survey, https://www.iihr.uiowa.edu/igs/geosam/home). (D) Locations of channels (blue lines) filled with Upper Pennsylvanian Tonganoxie Sandstone continuing downstream to deltaic sandstone facies (adapted from Feldman et al., 1995). Maps B–D show interpreted sediment dispersal (white arrows) into the Forest City basin. IA—Iowa, IL—Illinois, KS—Kansas, MO—Missouri, NE—Nebraska.

faults along the Nemaha uplift (Figs. 1 and 5) (Bunker et al., 1988). The roughly north-south trending, oval-shaped basin fades out with gradual dips to the north and south. The Middle Pennsylvanian fault-bounded Nemaha uplift partitioned what had been a generally broader and shallower basin, separating the Forest City basin from the Salina basin on the west (Fig. 1) (Lee, 1943; Bunker et al., 1988). An unconformity below Upper Pennsylvanian strata records erosion of the uplift and truncation of the cover strata down to Precambrian basement rocks (Bunker et al., 1988). By Permian time, the Nemaha uplift had been mostly covered by sedimentary deposits that thicken broadly southwestward from the area of the Forest City basin.

Mississippian strata in the Forest City basin are dominated by limestone, but the "St. Louis" Formation (Fig. 2; quotes are used by the Iowa Geological Survey to express uncertainty of correlation to the type St. Louis [McKay, 1987]) includes laterally discontinuous sandstone interbeds within a limestone-dominated succession in the northeastern part of the basin near the crest of the Mississippi River arch (Fig. 5B). The upper part of the "St. Louis" probably is equivalent to the basal Upper Mississippian Ste. Genevieve Limestone in the Illinois basin (Witzke et al., 1990).

Nearly all of the Upper Mississippian succession is truncated below the regional unconformity at the base of the Middle Pennsylvanian. Paleotopography below the unconformity indicates northeast-southwest–oriented channels (Fig. 5C). Middle Pennsylvanian deposits are fluvial, but marine influence increases up section (Gregory, 1982; Ravn et al., 1984; Ravn, 1986) in a largely cyclic succession of classic cyclothems (Heckel, 1980). The "Kansas cyclothems" include both marine carbonates and non-marine shale with sandstone and coal; however, the cyclothems in the Forest City basin have proportionally more marine strata than do those in the Illinois basin. The lower part of the Pennsylvanian succession includes relatively thinner sandstone units with low-relief bases, in contrast to deep channels with thick sandstone fills in the upper part (Kissock et al., 2018). Linear patterns of sandstone distribution indicate northeast-southwest–trending channels, which are filled with fluvial to estuarine deposits (Fig. 5D) (Archer et al., 1994; Feldman et al., 1995). Crossbed orientations show paleocurrents dominantly to the southwest, and the channel sandstones pass southwestward into deltaic facies (Fig. 5D) (Feldman et al., 1995). Suggested possible sources of clastic sediment for the Pennsylvanian strata in the Forest City basin include the Canadian Shield to the north, the Appalachian orogen to the east, the Marathon-Ouachita orogen to the south, and the Ancestral Rocky Mountains to the west (Bunker et al., 1988). Some Pennsylvanian coarse, arkosic sandstones may have a source in the exhumed Precambrian basement rocks on the Nemaha uplift (Lee, 1943, 1956). Depositional settings along with detrital-zircon analyses of Middle Pennsylvanian sandstones suggest recycling from Mississippian strata around the northeastern rim of the Forest City basin, but sediment from extrabasinal sources was introduced later in the Pennsylvanian (Kissock et al., 2018).

The Lower Permian includes limestone-shale cyclothems but grades upward into shale-sandstone redbeds and evaporites in the Middle Permian. The Permian succession thins and pinches out eastward in the Forest City basin.

SAMPLE DISTRIBUTION AND DATA PRESENTATION

Michigan Basin

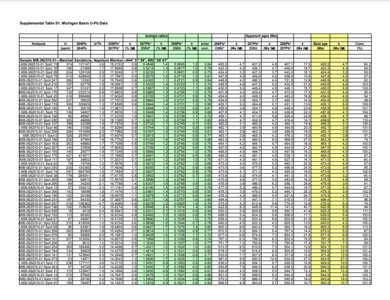
Five samples from four sandstones through the Mississippian–Pennsylvanian succession in the Michigan basin were analyzed for U-Pb ages of detrital zircons (Figs. 2 and 3A; Table 1; Supplemental Table S1[1]). Zircons from four of those samples were analyzed also for Hf isotopic compositions (Figs. 2 and 3A; Tables 1 and 2; Supplemental Table S2[2]).

Illinois Basin

New analyses of four samples for U-Pb ages (Supplemental Table S3[3]) and Hf isotopic

TABLE 2. SUMMARY OF εHf_t VALUES FOR SPECIFIC U-Pb AGE GROUPS

Basin/unit	Sample number	εHf_t for U-Pb zircon ages 335–287 Ma	εHf_t for U-Pb zircon ages 496–332 Ma	εHf_t for U-Pb zircon ages 801–500 Ma
Michigan/				
Eaton	MIB-072510-01		–8.5 to –12.6	
Parma	MIB-070810-01		+13.1 to –22.8	
Marshall	MIB-062510-01 and 02		+4.3 to –9.4	+10.8 to –26.4
Illinois/				
Dixon	KY-6-DX		+5.9 to –6.9	+6.1 to –13.9
Tradewater	IB-D1	+2.5 to –1.5	+7.2 to –2.1	+4.3 to –10.8
Caseyville	KY-4-CV		+5.4 to –20.9	+0.7
Caseyville	KY-15-CK		+9.1 to –18.7	-1.8 to –3.3
Hardinsburg	KY-1-HB		+7.3 to –9.9	+10.7 to –12.7
Forest City/				
Whitehorse	KS-5-WH	+4.8 to –5.8	+11.4 to –15.4	+7.1 to –10.6
Indian Cave	NE-1-IC2		+4.8 to –9.6	–1.0 to –7.8
Floris	FCB-D4	+6.5	+6.5 to –3.5	+7.7 to +0.8
Floris	FCB-D3		+7.4 to –8.3	+4.6 to –7.2
Floris	FCB-D2		+7.4 to –15.2	–3.1 to –12.4
Kilbourn	FCB-A1		+4.8 to –3.2	+5.0 to –0.4
Total range		+6.5 to –5.8	+13.1 to –22.8	+10.8 to –26.4



[1]Supplemental Table S1. Michigan basin U-Pb data. Please visit https://doi.org/10.1130/GES02152.S1 or access the full-text article on www.gsapubs.org to view this file.

[2]Supplemental Table S2. Michigan basin Hf data. Please visit https://doi.org/10.1130/GES02152.S2 or access the full-text article on www.gsapubs.org to view this file.

[3]Supplemental Table S3. Illinois basin south U-Pb data. Please visit https://doi.org/10.1130/GES02152.S3 or access the full-text article on www.gsapubs.org to view this file.

compositions (Supplemental Table S4[4]) represent the Mississippian–Pennsylvanian succession in the southernmost part of the Illinois basin (Figs. 2 and 4A; Tables 1 and 2). Four additional new U-Pb age analyses (Supplemental Table S3) are from Mississippian sandstones (Figs. 2 and 4A; Table 1) in the southern part of the basin. Seven previously published U-Pb age analyses (Kissock et al., 2018) range through the Pennsylvanian succession at the northern up-plunge end of the Illinois basin (Figs. 2 and 4A; Table 1). New Hf analyses are reported here from one of the seven Middle Pennsylvanian samples (Figs. 2 and 4A; Tables 1 and 2; Supplemental Table S4).

Forest City Basin

New analyses of two samples for U-Pb ages (Supplemental Table S5[5]) and Hf isotopic compositions (Supplemental Table S6[6]) from Upper Pennsylvanian and Middle Permian sandstones are from the youngest cover rocks in and near the Forest City basin (Figs. 2 and 5A; Tables 1 and 2). New analyses of eight samples document U-Pb ages (Supplemental Table S5) from lower Upper Mississippian sandstones within the "St. Louis" carbonate-dominated strata from the Mississippi River arch at the northeastern fringe of the Forest City basin (Figs. 2 and 5A; Table 1). Previously published U-Pb age data (Kissock et al., 2018) from seven sandstone samples represent the Middle Pennsylvanian coal-bearing cyclothems above the regional sub-Pennsylvanian unconformity in the Forest City basin (Figs. 2 and 5A; Table 1). New Hf analyses are reported here from four of the seven Middle Pennsylvanian samples (Figs. 2 and 5A; Tables 1 and 2; Supplemental Table S6).

ANALYTICAL METHODS

Sample Collection and Processing

An ~12 kg mass of medium- to coarse-grained sandstone was collected from a restricted stratigraphic interval for each detrital-zircon sample and then processed utilizing methods outlined by Gehrels (2000), Gehrels et al. (2008), Gehrels and Pecha (2014), and Thomas et al. (2017). Zircon grains were extracted using traditional methods of jaw crushing and pulverizing, followed by density separation using a Wilfley table. The resulting heavy-mineral fraction was further purified using a Frantz LB-1 magnetic barrier separator and methylene iodide heavy liquid. A representative split of the zircon yield was incorporated into a 2.54 mm epoxy mount along with multiple fragments of the U-Pb primary standards Sri Lanka SL-F, FC-1, and R33, and Hf standards R33, Mud Tank, FC-1, Plesovice, Temora, and 91500. The mounts were sanded down ~20 µm, polished to 1 µm, and imaged by back-scattered electrons (BSE) and cathodoluminescence (CL) using a Hitachi 3400N scanning electron microscope (SEM) and a Gatan Chroma CL2 detector system at the Arizona LaserChron SEM Facility or at the University of Iowa. Prior to isotopic analysis, mounts were cleaned in an ultrasonic bath of 1% HNO_3 and 1% HCl in order to remove surficial common Pb.

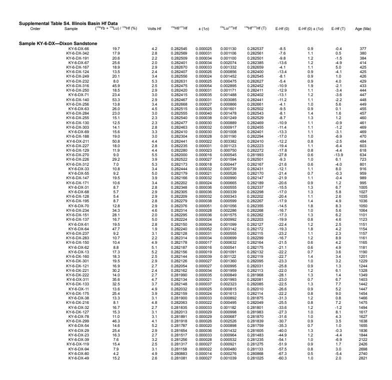
U-Pb Geochronologic Analysis

Uranium-lead geochronology of individual zircon crystals was conducted by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (www.laserchron.org). The isotopic analyses involved ablation of zircon using a Photon Machines Analyte G2 excimer laser coupled to either a Thermo Element2 single-collector ICPMS or a Nu Plasma HR multicollector ICPMS. Ultra-pure helium carried the ablated material from the HelEx cell into the plasma source of each ICPMS.

Analyses conducted with the Nu ICPMS utilized Faraday collectors for measurement of ^{238}U and ^{232}Th, either Faraday collectors or ion counters for ^{208}Pb, ^{207}Pb, and ^{206}Pb, and ion counters for ^{204}(Pb, Hg) and ^{202}Hg (see Supplemental Tables S1, S3, and S5 [footnotes 1, 3, and 5, respectively] for specific methods used for each sample), depending on grain size. For larger grains, a 30-µm-diameter spot was used, and masses 206, 207, 208, 232, and 238 were measured with Faraday detectors, whereas the smaller 202 and 204 ion beams were measured with ion counters. The acquisition routine included a 15 s integration on peaks with the laser off (for backgrounds), fifteen 1 s integrations with the laser firing, and a 30 s delay to ensure that the previous sample was completely purged from the system. Smaller grains were analyzed with all Pb isotopes in ion counters, using a 20 µm beam diameter, and consisted of a 12 s integration on peaks with the laser off (for backgrounds), twelve 1 s integrations with the laser firing, and a 30 s delay to purge the previous sample.

Analyses were conducted with the Element2 ICPMS that sequences rapidly through U, Th, and Pb isotopes. Ion intensities were measured utilizing a single Scanning Electron multiplier in pulse-counting mode for signals less than 50K cps, in both pulse-counting and analog mode for signals between 50K and 5M cps, and in analog mode above 5M cps. The calibration between pulse-counting and analog signals is determined line-by-line for signals between 50K and 5M cps, and is applied to >5M cps signals. Four intensities were determined and averaged for each isotope, with dwell times of 0.0052 s for 202, 0.0075 s for 204, 0.0202 s for 206, 0.0284 s for 207, 0.0026 s for 208, 0.0026 s for 232, and 0.0104 s for 238. With the laser set at an energy density of ~5 J/cm^2, a repetition rate of 8 Hz, and an ablation time of 10 s, ablation pits are ~12 microns in depth. Sensitivity with these settings is ~5,000 cps/ppm. Each analysis consists of 5 s on peaks with the laser off (for backgrounds), 10 s with the laser firing (for peak intensities), and a 20 s delay to purge the previous sample and save files.

Analyses were conducted with one U-Th-Pb measurement per grain (numbers of grains per sample vary and are reported in Supplemental Tables S1, S3, and S5). Grains were selected in random fashion; crystals were rejected only if they contained cracks or inclusions or were too small to be analyzed. The use of high-resolution BSE and CL images provided assistance in grain selection and spot placement.



[4]Supplemental Table S4. Illinois basin Hf data. Please visit https://doi.org/10.1130/GES02152.S4 or access the full-text article on www.gsapubs.org to view the supplemental table.

[5]Supplemental Table S5. Forest City basin U-Pb data. Please visit https://doi.org/10.1130/GES02152.S5 or access the full-text article on www.gsapubs.org to view this file.

[6]Supplemental Table S6. Forest City basin Hf data. Please visit https://doi.org/10.1130/GES02152.S6 or access the full-text article on www.gsapubs.org to view this file.

Data reduction was accomplished using AgeCalc (a Microsoft Excel macro), which is the standard Arizona LaserChron Center reduction protocol (Gehrels et al., 2008; Gehrels and Pecha, 2014). Data were filtered for discordance, $^{206}Pb/^{238}U$ precision, and $^{206}Pb/^{207}Pb$ precision as described in the notes in Supplemental Tables S1, S3, and S5. Data are presented on normalized probability density plots, which sum all relevant analyses and uncertainties, and divide each curve by the number of analyses, so that each curve contains the same area.

Hf Isotopic Analysis

Hafnium isotopic analyses were conducted utilizing the Nu multicollector LA-ICPMS system at the Arizona LaserChron Center following methods reported by Cecil et al. (2011) and Gehrels and Pecha (2014). An average of 56 Hf analyses was conducted for each sample. Grains were selected to represent each of the main age groups within the age distributions and to avoid crystals with discordant or imprecise ages. CL images were utilized to ensure that all Hf analyses are within the same growth domain as the U-Pb pit, although in most analyses the Hf laser pits (~40 microns in depth) were located directly on top of the U-Pb analysis pits. Complete Hf isotopic data and Hf evolution plots of individual samples are presented in Supplemental Tables S2, S4, and S6 (footnotes 2, 4, and 6, respectively).

Hafnium data are presented using Hf evolution diagrams, where initial $^{176}Hf/^{177}Hf$ ratios are expressed in εHf_t notation, which represents the Hf isotopic composition at the time of zircon crystallization relative to the chondritic uniform reservoir (CHUR) (Bouvier et al., 2008). Internal precision for $^{176}Hf/^{177}Hf$ and εHf_t is reported for each analysis in Supplemental Tables S2, S4, and S6. The average uncertainty for all analyses is 2.2 epsilon units (at 2σ). On the basis of the in-run analysis of zircon standards, the external precision is 2–2.5 epsilon units (2σ). Hf isotopic evolution of typical continental crust is shown with arrows on εHf_t evolution diagrams, which are based on a $^{176}Lu/^{177}Hf$ ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999).

RESULTS OF U-Pb GEOCHRONOLOGIC ANALYSES OF DETRITAL ZIRCONS FROM MICHIGAN BASIN

Marshall/Napolean Sandstone (Samples MIB-062510-01 and MIB-062510-02)

Two samples from the Lower–Middle Mississippian Napolean Sandstone Member of the Marshall Sandstone (Cohee, 1979) along the eastern rim of the Michigan basin (Figs. 1, 2, and 3A; Table 1) have dominant ages of 1226–904 Ma with dominant modes of 1015 and 1012 Ma and secondary modes of 1190 and 1179 Ma (Fig. 6). Another group with ages of 494–418 Ma has dominant modes of 466 and 449 Ma (Fig. 6). A minor group with ages of 677–500 Ma has minor modes of 637 and 613 Ma. A few grains have ages between 2135 and 1968 Ma. Ages are broadly distributed between 1893 and 1230 Ma, including several minor modes. Rare older grains have ages between 2789 and 2470 Ma.

Parma Sandstone (Sample MIB-070810-01)

A sample from the Upper Mississippian Parma Sandstone member of the upper part of the Bayport Formation (Towne et al., 2018) in the southern part of the Michigan basin (Figs. 1, 2, and 3A; Table 1) has dominant ages of 1224–931 Ma with a dominant mode of 1054 Ma and a secondary mode of 1142 Ma (Fig. 6). Another group with ages of 485–383 Ma has modes of 444 and 432 Ma (Fig. 6). Four ages are scattered between 782 and 596 Ma, and four others are scattered between 2100 and 1950 Ma. The Parma sample includes a distribution of ages between 1900 and 1242 Ma, which has a prominent mode of 1644 Ma and lesser modes of 1850, 1762, 1440, and 1356 Ma. A cluster of older ages of 2838–2403 Ma has a mode of 2716 Ma, and the sample includes a few older grains as old as 3562 Ma.

Saginaw Formation (Sample MIB-072810-01)

A sample from the Lower Pennsylvanian Saginaw Formation in the southern part of the Michigan basin (Figs. 1, 2, and 3A; Table 1) has dominant ages of 1228–1007 Ma with a dominant mode of 1053 Ma and a secondary mode of 1132 Ma (Fig. 6). Another group with ages of 478–419 Ma has modes of 469 and 420 Ma (Fig. 6). Two ages are 2131 and 2021 Ma. A broad distribution of ages between 1911 and 1227 Ma has prominent modes of 1649 and 1488 Ma and a lesser mode of 1803 Ma. Older ages are scattered between 2836 and 2508 Ma.

Eaton Sandstone/Grand River (Sample MIB-072510-01)

A sample from the Middle Pennsylvanian Eaton Sandstone (Grand River member of upper Saginaw Formation) in the central part of the Michigan basin (Figs. 1, 2, and 3A; Table 1) has dominant ages of 485–421 Ma with a mode of 462 Ma (Fig. 6), corresponding in age to modes in the stratigraphically lower samples from the Michigan basin. A group with ages of 1184–918 Ma has dominant modes of 1151 and 1036 Ma (Fig. 6), which is the dominant age group throughout the basin. Ages are scattered broadly between 1830 and 1217 Ma, but no grains are older than 1830 Ma.

RESULTS OF U-Pb GEOCHRONOLOGIC ANALYSES OF DETRITAL ZIRCONS FROM ILLINOIS BASIN

Aux Vases Sandstone (Sample IB-AV)

A sample from the Aux Vases Sandstone, which is the stratigraphically lowest laterally extensive Mississippian sandstone in the Illinois basin (Figs. 1, 2, and 4A; Table 1), has dominant ages of 1214–910 Ma with a dominant mode of 1054 Ma (Fig. 7). A secondary group with ages of 491–370 Ma has a mode of 438 Ma (Fig. 7). The sample includes one grain each with ages of 2142 and 554 Ma. Ages are scattered from 1943 to 1257 Ma with minor modes of 1916, 1792, 1632, 1474, and 1318 Ma. Scattered older grains include a minor mode of 2712 Ma.

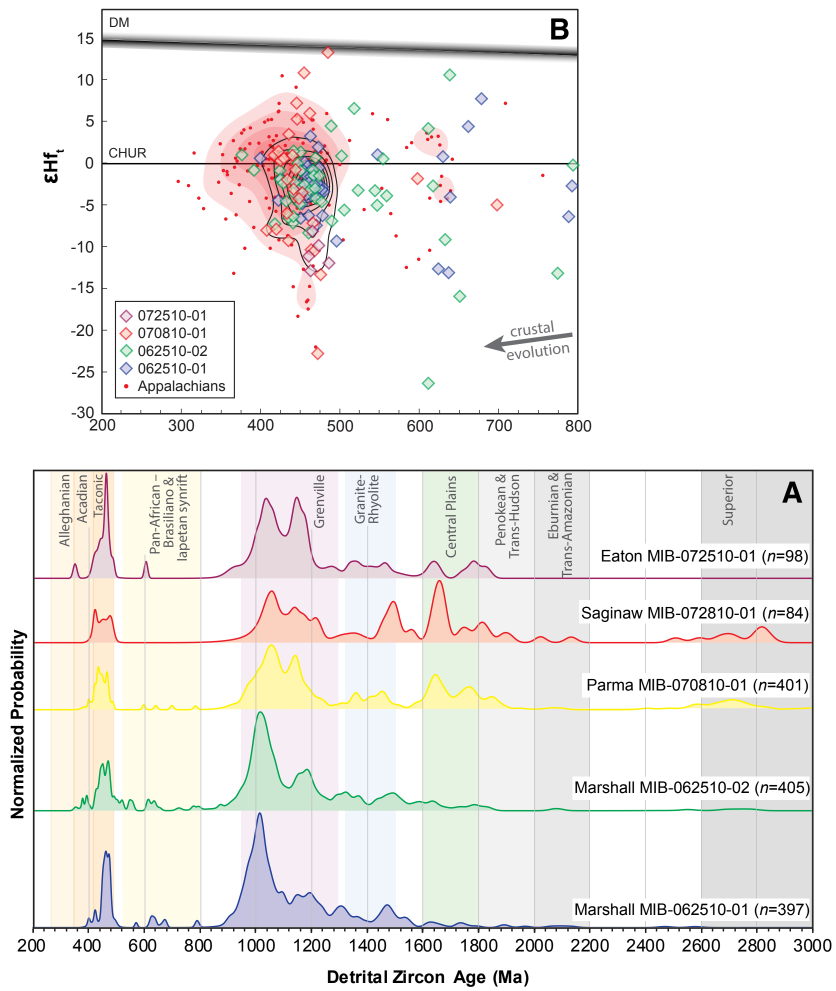


Figure 6. U-Pb probability density plots (A) and Hf-evolution diagram (B) showing results from analyses of Mississippian–Pennsylvanian sandstones in the Michigan basin with respect to potential provenance provinces in the Appalachians and North American craton (age ranges shown by vertical color bands). (A) U-Pb probability density plots for five analyzed samples (data in Supplemental Table S1 [text footnote 1]). (B) εHf_t data for four samples (data in Supplemental Table S2 [text footnote 2]). Data points are color coded as in panel A. The average uncertainty of Hf isotopic analyses is 2.6 epsilon units at 2 sigma. The Hf-evolution diagram shows the Hf isotopic composition at the time of zircon crystallization, in epsilon units, relative to the chondritic uniform reservoir (CHUR) (Bouvier et al., 2008) and to the depleted mantle (DM) (Vervoort et al., 1999). Shown for reference is the evolution of typical continental crust, which is based on a $^{176}Lu/^{177}Hf$ ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999). Black contour lines show relative concentration of data points. For comparison, εHf_t data from Appalachian samples (Thomas et al., 2017) are shown by red dots, and pink shading shows relative concentration of data points.

Cypress Sandstone (Sample IB-CY)

In a sample from the Cypress Sandstone (Figs. 1, 2, and 4A; Table 1), three dominant groups have ages of 475–363 Ma with a mode of 428 Ma, of 1211–909 Ma with modes of 1094 and 1048 Ma, and of 1691–1594 Ma with a mode of 1643 Ma (Fig. 7). The sample includes two grains with ages of 2055–1993 Ma and one of 767 Ma. Ages are scattered from 1827 to 1252 Ma with minor modes of 1780, 1491, 1371, and 1281 Ma, in addition to a more prominent mode of 1643 Ma. Scattered older grains range from 3011 to 2383 Ma and include minor modes of 2868, 2756, and 2529 Ma.

Hardinsburg Sandstone (Sample IB-HB)

In a sample from the Hardinsburg Sandstone north of the site of sample KY-1-HB in the Illinois basin (Figs. 1, 2, and 4A; Table 1), a dominant group has ages of 1181–920 Ma with a mode of 1026 Ma; a secondary group has ages of 478–375 Ma with a mode of 438 Ma (Fig. 7). Three grains have ages between 646 and 581 Ma, and two grains have ages of 2245 and 2130 Ma. A range of ages from 1992 to 1274 Ma includes secondary modes of 1646 and 1486 Ma and minor modes of 1826, 1782, and 1346 Ma. A few older grains have ages scattered between 3748 and 2489 Ma with a minor mode of 2860 Ma.

Hardinsburg Sandstone (Sample KY-1-HB)

A sample from the Hardinsburg Sandstone along the Rough Creek fault system at the southern edge of the Illinois basin is from a sandstone within a cyclic succession of sandstone, shale, and limestone (Figs. 1, 2, and 4A; Table 1). Dominant groups have ages of 1217–939 Ma with a mode of 1032 Ma and of 482–365 Ma with a mode of 435 Ma (Fig. 7). A minor group has ages between 706 and 518 Ma with a minor mode of 563 Ma. A single grain has an age of 2111 Ma. A range of ages from 1950 to 1350 Ma includes minor modes of 1905, 1739, 1659, 1523, 1400, and 1361 Ma. A few older grains have

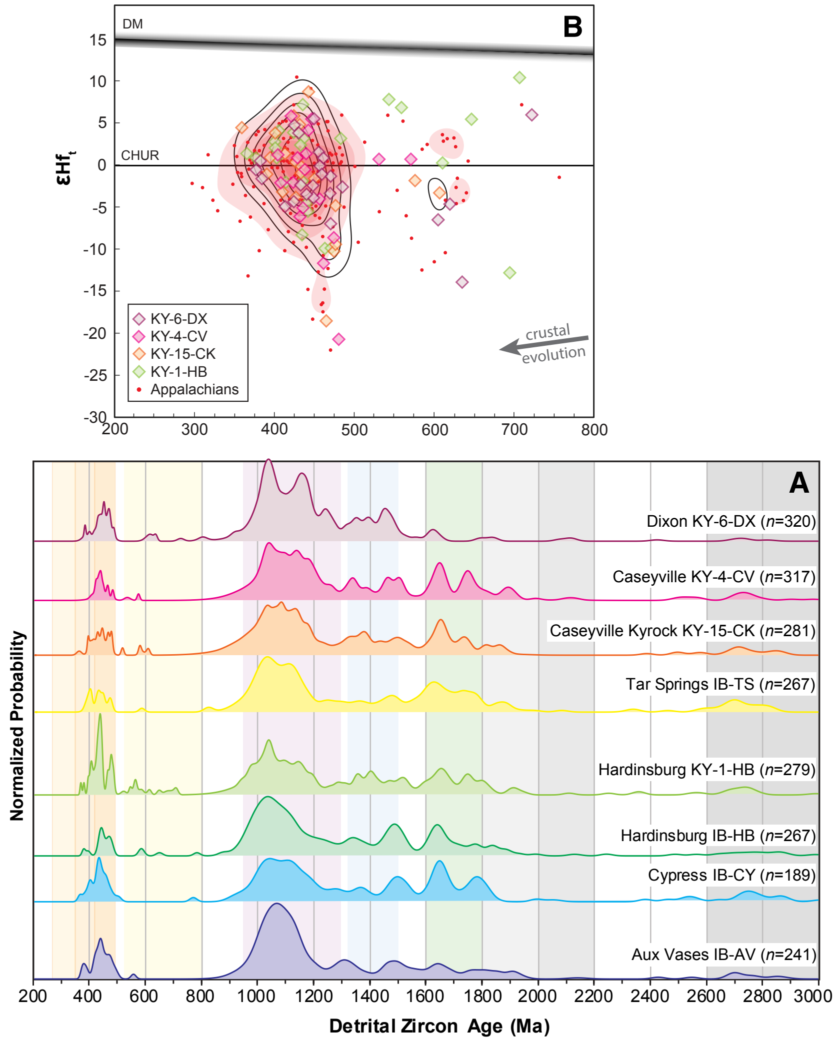


Figure 7. U-Pb probability density plots (A) and Hf-evolution diagram (B) showing results from analyses of Mississippian–Pennsylvanian sandstones in the southern part of the Illinois basin with respect to potential provenance provinces in the Appalachians and North American craton (age ranges shown by vertical color bands; province names are shown in Fig. 6). (A) U-Pb probability density plots for eight analyzed samples (data in Supplemental Table S3 [text footnote 3]). (B) εHf$_t$ data for four samples (data in Supplemental Table S4 [text footnote 4]). Data points are color coded as in panel A. Specifications for the Hf-evolution diagram are described in the caption for Figure 6.

ages scattered between 2994 and 2360 Ma with a minor mode of 2742 Ma.

Tar Springs Sandstone (Sample IB-TS)

A sample from the Upper Mississippian Tar Springs Sandstone (Figs. 1, 2, and 4A; Table 1) has dominant ages of 1185–901 Ma with a mode of 1040 Ma and a secondary mode of 1098 Ma (Fig. 7). A secondary group has ages of 471–383 Ma with modes of 428 and 396 Ma (Fig. 7). Rare ages include one grain with an age of 2085 Ma, two of 827–817 Ma, and one of 584 Ma. A range of ages from 1894 to 1215 Ma includes a secondary mode of 1622 Ma and minor modes of 1868, 1718, 1470, 1368, and 1242 Ma. Scattered older grains between 3622 and 2333 Ma include a secondary mode of 2698 Ma.

Caseyville (Kyrock) Sandstone (Sample KY-15-CK)

A sample of the Caseyville Sandstone from the thick sandstone that regionally characterizes the lowermost part of the Pennsylvanian System is from the east-west–oriented Brownsville paleovalley (Sedimentation Seminar, 1978) along the Rough Creek fault system in the southeastern corner of the Illinois basin (Figs. 1, 2, 4A, and 4C; Table 1). The dominant ages of 1219–902 Ma include multiple modes of 1128, 1081, and 1029 Ma (Fig. 7). A secondary group has ages of 475–359 Ma with modes of 463 and 425 Ma (Fig. 7). Two grains have ages of 828 and 823 Ma, and a minor group has ages of 606–514 Ma. Ages are scattered between 1927 and 1263 Ma with a strong mode of 1641 Ma and minor modes of 1862, 1823, 1739, 1478, and 1372 Ma. Older grains include ages between 3276 and 2388 Ma with a minor mode of 2716 Ma.

Caseyville Sandstone (Sample KY-4-CV)

Another sample from the Caseyville Sandstone is from the northeast-southwest–oriented Indian Lake paleovalley (Greb, 1989a) northwest of the

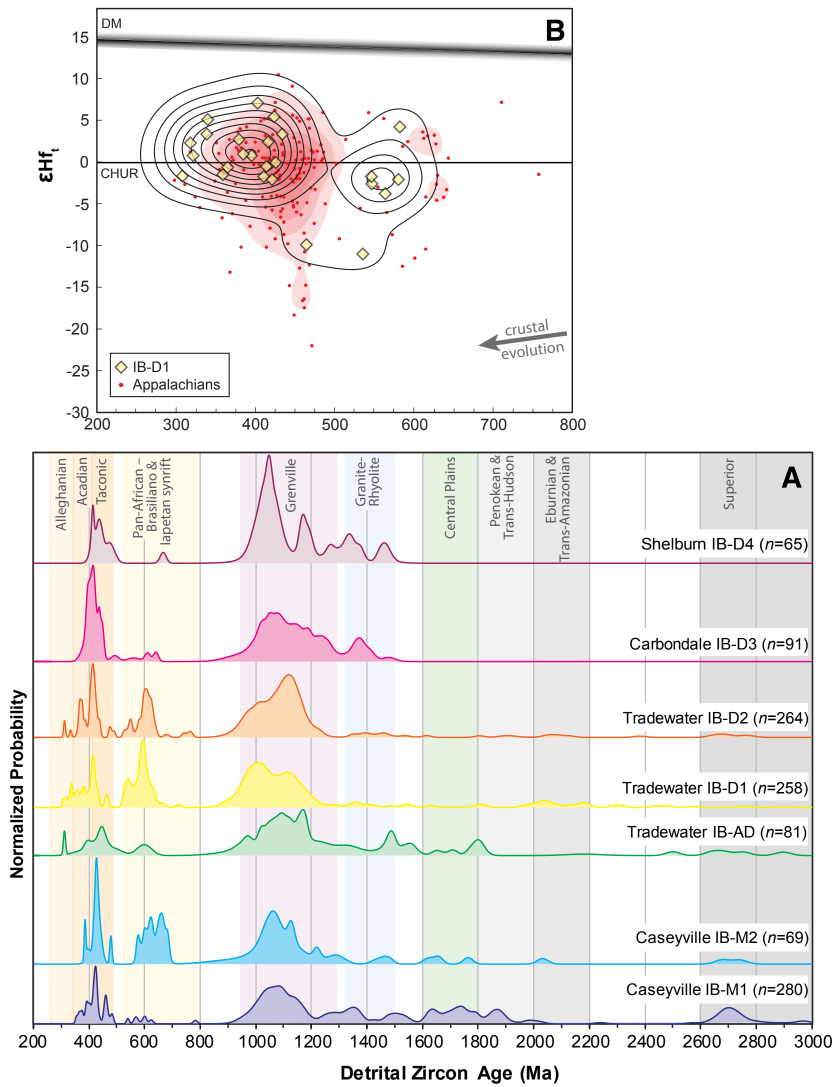


Figure 8. U-Pb probability density plots (A) and Hf-evolution diagram (B) showing results from analyses of Pennsylvanian sandstones in the northern part of the Illinois basin with respect to potential provenance provinces in the Appalachians and North American craton (age ranges shown by vertical color bands). (A) U-Pb probability density plots for seven analyzed samples (all data published in Kissock et al., 2018). (B) εHf_t data for one sample (data in Supplemental Table S4 [text footnote 4]). Data points are color coded as in panel A. Specifications for the Hf-evolution diagram are described in the caption for Figure 6.

location of sample KY-15-CK (Figs. 1, 2, 4A, and 4C; Table 1). The dominant ages of 1286–910 Ma have a mode of 1045 Ma and a secondary mode of 1132 Ma (Fig. 7). A younger secondary group has ages of 479–404 Ma and a mode of 437 Ma (Fig. 7). Minor age groups include three grains with ages between 2132 and 2082 Ma and two grains with ages of 571–532 Ma. A distribution from 1991 to 1306 Ma has a secondary mode of 1648 Ma and five lesser modes of 1876, 1755, 1506, 1467, and 1336 Ma. A scatter of grains with older ages between 2986 and 2501 Ma has a secondary mode of 2705 Ma.

Dixon Sandstone (Sample KY-6-DX)

A sample of the Dixon Sandstone Member of the Mattoon Formation is from one of the stratigraphically youngest Pennsylvanian sandstones preserved in outcrop in the Illinois basin (Figs. 1, 2, and 4A; Table 1). Dominant ages of 1212–914 Ma have a prominent mode of 1039 Ma and a secondary mode of 1158 Ma (Fig. 7). A secondary group with ages of 484–377 Ma has a mode of 448 Ma (Fig. 7). Minor age groups include three grains with ages of 801–722 Ma and four grains of 634–603 Ma. A spread of ages from 1844 to 1229 Ma includes a secondary mode of 1452 Ma and lesser modes of 1624, 1345, and 1245 Ma. Grains with older ages are scattered from 2821 to 2426 Ma.

PUBLISHED U-Pb GEOCHRONOLOGIC ANALYSES OF DETRITAL ZIRCONS FROM ILLINOIS BASIN

Analyses for U-Pb ages of zircons from seven samples (Figs. 1, 2, and 4A; Table 1) from Pennsylvanian sandstones around the northern rim of the Illinois basin have been thoroughly documented; the analytical data are reported in Kissock et al. (2018). The results of these analyses are plotted (Fig. 8) for comparison with samples from the southern part of the Illinois basin and to give a comprehensive coverage of detrital-zircon data from the basin. Only a general description is summarized here.

All of the samples have several zircon-age groups in common. The consistently most dominant group with ages of 1220–930 Ma has prominent modes between 1090 and 1000 Ma, and most samples have secondary modes between 1170 and 1100 Ma (Fig. 8). Another prominent group with ages of 500–333 Ma has modes between 430 and 410 Ma (Fig. 8).

Most of the samples have scattered grains in the age range of 1900–1250 Ma (Fig. 8). Three samples (IB-M1, IB-M2, and IB-AD) have minor modes around 1770 and 1480 Ma. Grains in this age range are most abundant in the stratigraphically lowest samples and are less abundant in samples IB-D1 and IB-D2; the stratigraphically highest samples (IB-D3 and IB-D4) have no grains older than 1481 Ma (Fig. 8).

Older grains in the range of 3342–2305 Ma are most abundant in the stratigraphically lowest sample (IB-M1), which has an intermediate mode of 2693 Ma (Fig. 8). The older grains are less abundant in the stratigraphically higher samples, and the upper two samples (IB-D3 and IB-D4) have no grains of this age.

Three samples (IB-M2, IB-D1, and IB-D2) have relatively abundant grains in the age range of 768–527 Ma with modes between 655 and 547 Ma (Fig. 8). The other samples have relatively few grains in that age range. All samples, except the two stratigraphically highest, have a more sparsely represented group of a few grains with ages of 2189–1976 Ma (Fig. 8).

Three samples (IB-AD, IB-D1, and IB-D2) have a distinctive younger group with ages of 321–307 Ma (Fig. 8); however, in each of the other four samples, the youngest grain is 355 Ma or older. Tradewater sample IB-AD has one grain with an age of 312 ± 4 Ma (Fig. 8), which is equal to the approximate depositional age (310 Ma) of the sandstone (Fig. 2; Table 1). Tradewater sample IB-D1 has three grains in the range of 321–307 Ma; the youngest grain (307 ± 4 Ma) is within error of the approximate depositional age (309 Ma) of the sandstone (Fig. 2; Table 1). Tradewater sample IB-D2 has two grains with ages of 313–312 Ma; the youngest grain (312 ± 4 Ma) is within error of the approximate depositional age (309 Ma) of the sandstone (Fig. 2; Table 1).

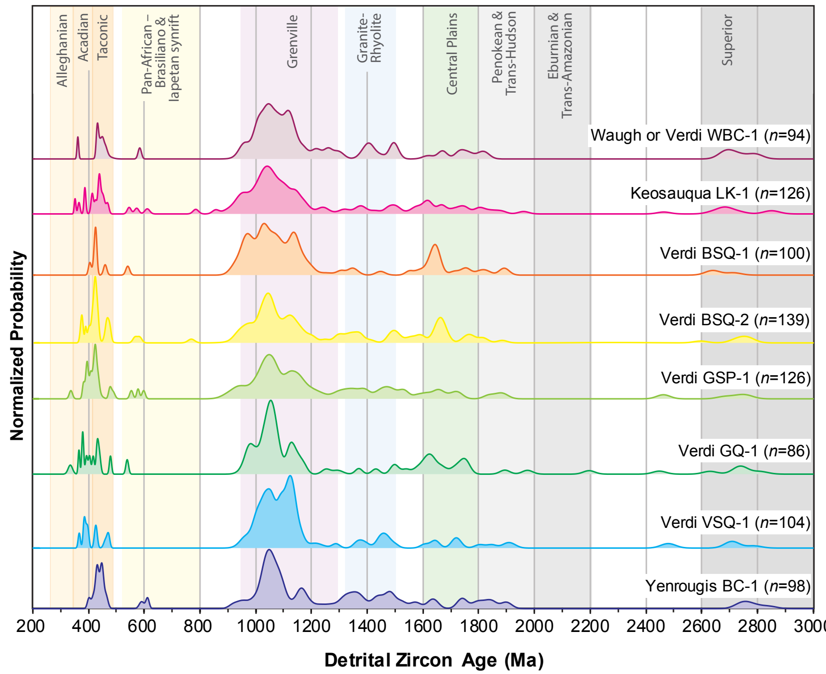


Figure 9. U-Pb probability density plots showing results (data in Supplemental Table S5 [text footnote 5]) from analyses of eight samples of Mississippian sandstones around the northern end of the Forest City basin with respect to potential provenance provinces in the Appalachians and North American craton (age ranges shown by vertical color bands).

RESULTS OF U-Pb GEOCHRONOLOGIC ANALYSES OF DETRITAL ZIRCONS FROM FOREST CITY BASIN

Mississippian Sandstones

Eight samples from Mississippian sandstone interbeds in the "St. Louis" Formation, structurally high on the eastern limb of the Forest City basin and Mississippi River arch, were analyzed for U-Pb ages of detrital zircons (Figs. 1, 2, and 5A; Table 1). The analytical data are in Supplemental Table S5 (footnote 5) and are shown in probability density plots separately for each sample in Figure 9. The samples are all from a relatively thin succession (~15 m thick) and are from a relatively small area. The detrital-zircon age distributions are generally similar throughout the sample set. For simplicity, the results from all eight samples are discussed here as a group.

The dominant age group in each of the samples is in the range of 1210–920 Ma with a mode between 1054 and 1031 Ma (Fig. 9). A consistent secondary group in all of the samples has ages of 489–375 Ma with modes between 440 and 424 Ma (Fig. 9). All of the samples have a spread of ages between 1976 and 1210 Ma, including several minor modes. Samples BSQ-1 and BSQ-2 have more prominent secondary modes of 1640 and 1662 Ma, respectively. Most of the samples have a few grains with ages of 615–540 Ma. All of the samples have older ages scattered between 3164 and 2448 Ma.

Indian Cave Sandstone (Sample NE-1-IC2)

A sample of the Upper Pennsylvanian Indian Cave Sandstone is from a channel-filling complex within a succession of gray mudstones (Figs. 1, 2, and 5A; Table 1) and is one of the stratigraphically highest sandstones in the Forest City basin (Fischbein et al., 2009). The dominant group has ages of 1235–954 Ma and a dominant mode of 1058 Ma and a secondary mode of 1165 Ma (Fig. 10). Another dominant group has ages of 463–363 Ma and a mode of 418 Ma (Fig. 10). Minor groups have ages of 1602–1251 Ma and of 629–565 Ma. A few ages are scattered widely between 2919 and 1750 Ma.

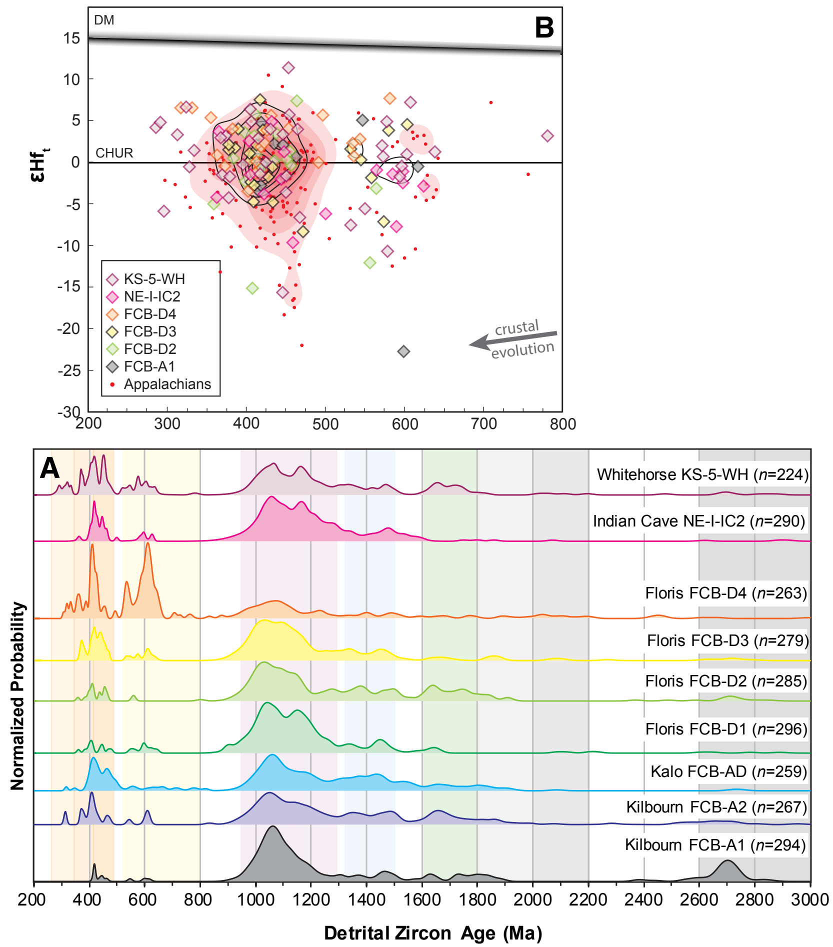


Figure 10. U-Pb probability density plots (A) and Hf-evolution diagram (B) showing results from analyses of Pennsylvanian–Permian sandstones in and around the Forest City basin with respect to potential provenance provinces in the Appalachians and North American craton (age ranges shown by vertical color bands; province names are shown in Fig. 9). (A) U-Pb probability density plots for two analyzed samples (data in Supplemental Table S5 [text footnote 5]) and previously published results for seven samples (all data published in Kissock et al., 2018). (B) εHf_t data for six samples (data in Supplemental Table S6 [text footnote 6]). Data points are color coded as in panel A. Specifications for the Hf-evolution diagram are described in the caption for Figure 6.

Whitehorse Sandstone (Sample KS-5-WH)

A sample of the Middle Permian (lower Guadalupian) Whitehorse Sandstone is from a sandstone within a succession of redbeds and evaporites, well above an upward transition from dominantly gray to dominantly red in the Lower Permian and within a regional northeast-thinning succession of Permian redbeds southwest of the Forest City basin (Figs. 1, 2, and 5A; Table 1). The analytical data have two prominent age groups: one of 1240–961 Ma with modes of 1162 and 1065 Ma; and the other of 478–370 Ma with a dominant mode of 417 Ma and secondary modes of 452 and 370 Ma (Fig. 10). A distinctively young secondary group has ages of 335–287 Ma with a mode of 319 Ma (Fig. 10). Three other secondary groups have ages of 1831–1602 Ma with a mode of 1657 Ma, of 1525–1261 Ma with a minor mode of 1468 Ma, and of 638–519 Ma with a minor mode of 576 Ma (Fig. 10). Four grains have ages of 2196–2021 Ma. A few older grains have ages scattered between 2877 and 2477 Ma. The youngest grain in the sample is 287 Ma, and the approximate depositional age of the sandstone is 270 Ma (Fig. 2; Table 1).

PUBLISHED U-Pb GEOCHRONOLOGIC ANALYSES OF DETRITAL ZIRCONS FROM THE FOREST CITY BASIN

Analyses for U-Pb ages of seven samples (Figs. 1, 2, and 5A; Table 1) from Middle Pennsylvanian sandstones in the Forest City basin are reported in Kissock et al. (2018). The results are plotted here (Fig. 10) for comparison with samples from Upper Pennsylvanian and Middle Permian sandstones to the south, and only a general description is summarized here.

All of the samples have several zircon-age groups in common. The consistently most dominant group has ages of 1278–930 Ma and modes between 1070 and 1032 Ma (Fig. 10). Another prominent group has ages of 499–332 Ma and generally a mode between 418 and 406 Ma (Fig. 10). Most of the samples have scattered grains in the age range of 1975–1300 Ma (Fig. 10).

Older grains in the age range of 3594–2285 Ma generally decrease stratigraphically upward in abundance (Fig. 10). The stratigraphically lowest sample (FCB-A1) has a minor mode of 2686 Ma (Fig. 10), contrasting with the other samples from Pennsylvanian sandstones in the Forest City basin.

One sample (FCB-D4) has a prominent zircon-age group in the range of 876–525 Ma, mostly between 654 and 525 Ma, with a dominant mode of 611 Ma (Fig. 10). The other samples from the Forest City basin have relatively few grains in that age range. The same sample (FCB-D4) has twelve grains with ages scattered between 2209 and 1977 Ma, an age range that is represented more sparsely in the other samples in the basin.

Samples FCB-A2, FCB-AD, and FCB-D4 have a distinctive younger group with ages of 321–307 Ma (Fig. 10). In each of the other samples from Pennsylvanian sandstones in the Forest City basin, the youngest grain is 359 Ma or older. Kilbourn sample FCB-A2 has three grains with ages of 317–310 Ma (Fig. 10); the youngest grain is 310 ± 5 Ma, which is equal to the approximate depositional age (312 Ma) of the sandstone (Fig. 2; Table 1). Kalo sample FCB-AD has a single young grain with an age of 318 ± 7 Ma, near the approximate depositional age (310 Ma) of the sandstone (Fig. 2; Table 1). Floris sample FCB-D4 has four grains with ages of 321–307 Ma; the youngest grain (307 ± 4 Ma) is within error of the approximate depositional age (308 Ma) of the sandstone (Fig. 2; Table 1).

RESULTS OF Hf ISOTOPIC ANALYSES

The results of Hf isotopic analyses are reported in Supplemental Tables S2, S4, and S6 (footnotes 2, 4, and 6, respectively); listed in Table 2; and plotted in Figures 6–8 and 10. The Hf isotopic data are interpreted within the standard framework of juvenile (positive) values indicating magma consisting mainly of material extracted from the mantle during or immediately prior to magmatism, versus more evolved (negative) values that record incorporation of significantly older crust. Vertical arrays that span both positive and negative values on εHf_t diagrams are interpreted to represent mixing of magmas that contain materials derived both from the mantle during (or immediately prior to) magmatism and from significantly older crust. The results from the Michigan, Illinois, and Forest City basins are consistent throughout the sample set. In three age groups (801–500, 496–332, and 335–287 Ma), the εHf_t values range from +13.1 to –26.4 (Table 2), indicating involvement of older crustal rocks in the juvenile magmas.

POTENTIAL PROVENANCE ELEMENTS FOR MIDCONTINENT LATE PALEOZOIC SANDSTONES

Canadian Shield

The Canadian Shield previously has been interpreted to be a primary source of sediment supplied to the Midcontinent basins, as well as to the distal side of the Appalachian basin (e.g., Potter and Siever, 1956a, 1956b; Siever and Potter, 1956; Wanless and Shideler, 1975; Cohee, 1979). Distinct Precambrian age provinces of crystalline rocks in the eastern North American craton reflect successive episodes of supercontinent accretion that ultimately formed the crust of Laurentia, including: Superior (3000–2600 Ma); Penokean and Trans-Hudson (2000–1800 Ma); Central Plains, Yavapai, and Mazatzal (1800–1600 Ma); Granite-Rhyolite (1500–1320 Ma); and Grenville (1300–950 Ma) (e.g., Hoffman, 1988; Van Schmus et al., 1993; Whitmeyer and Karlstrom, 2007; Bickford et al., 2015). Much of the Canadian Shield, however, was covered by sedimentary deposits by Mississippian time and, therefore, was not available as a primary source of sediment during the late Paleozoic (e.g., Sloss, 1988; Cecile and Norford, 1993).

Appalachian Orogen

Two large-scale Alleghanian synorogenic clastic wedges constitute the late Paleozoic fill of the Appalachian foreland basin (foredeep) east of the Midcontinent craton (Figs. 1 and 2) and document down-to-southeast load-driven flexural subsidence of the foreland, as well as northwestward (toward the craton) thinning and progradation of the synorogenic clastic facies (e.g., Quinlan and Beaumont, 1984; Tankard, 1986). The clastic wedges are semi-circular in outline and prograde semi-radially from separate centers in the Pennsylvania and Tennessee embayments of the Iapetan rifted margin of Laurentia (Thomas, 1977). The Mauch Chunk–Pottsville clastic wedge in the Pennsylvania embayment is thickest and most extensive toward the southwest in the Mississippian components, whereas the Pennington-Lee clastic wedge in the Tennessee embayment is progressively more extensive toward the north in the Pennsylvanian and Permian strata. Superimposed on the transverse cratonward drainages in the clastic wedges, southward longitudinal drainage along the western distal parts of the clastic wedges prevailed during the Early Pennsylvanian (Archer and Greb, 1995). Detrital-zircon age distributions show that the massive sandstones deposited within the longitudinal system are ultimately from sources in the Appalachian orogen (Thomas et al., 2017), reflecting diversion from the transverse drainages in the clastic wedges into the longitudinal system with the potential for multiple points of sediment input from the clastic wedges. Before and after Early Pennsylvanian, transverse drainage from the Appalachians extended to the western limit of the preserved deposits. The interplay between transverse and longitudinal drainage in the Appalachian basin has important implications for the dispersal of sediment from the Appalachians onto the eastern craton, including the Michigan, Illinois, and Forest City basins.

A composite plot (N = 29, n = 3564) of detrital-zircon U-Pb ages from Mississippian–Permian sandstones in the proximal clastic wedges in the Appalachian basin documents an "Appalachian signature" (Fig. 11) for Alleghanian synorogenic sediment (Thomas et al., 2017). Ages of the Grenville province (1300–950 Ma) dominate the Appalachian detrital-zircon age distributions, and the second most dominant age range (490–350 Ma)

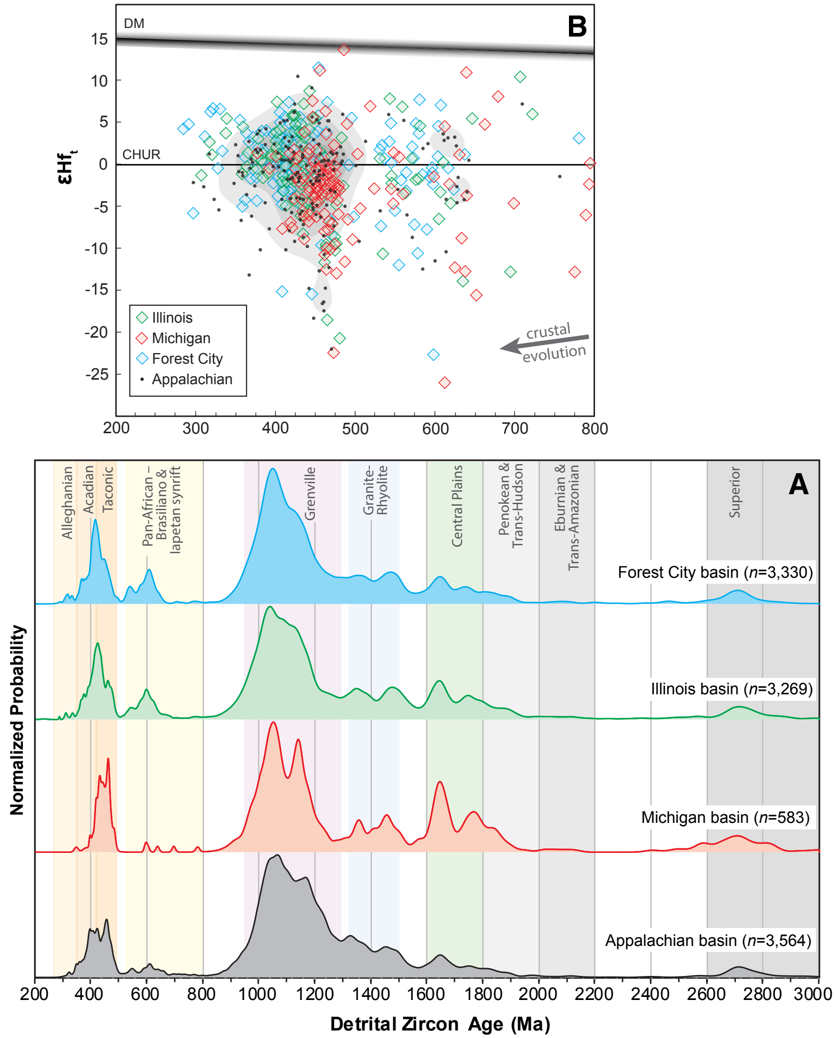


Figure 11. U-Pb probability density plots (A) and Hf-evolution diagram (B) comparing results of analyses of detrital zircons from Mississippian–Permian sandstones in the Appalachian basin (the "Appalachian signature") with those from sandstones in the Michigan, Illinois, and Forest City basins in the context of potential provenance provinces in the Appalachians and North American craton (age ranges shown by vertical color bands). (A) U-Pb probability density plots of composites of results from the Michigan, Illinois, and Forest City basins (from data shown in Figs. 6–10) and from the Appalachian basin (from Thomas et al., 2017). (B) εHf$_t$ data from the Michigan, Illinois, and Forest City basins (from Figs. 6–8 and 10) and from the Appalachian basin (from Thomas et al., 2017). Data points are color coded as in panel A. Specifications for the Hf-evolution diagram are described in the caption for Figure 6.

represents the Taconic and Acadian orogenies in the Appalachians. The Appalachian age distributions include a wide range of less abundant components.

Grenville basement rocks, which are exposed along the external and internal basement massifs in the Appalachian orogen (Fig. 1), provide a primary source for detrital zircons. The Grenville basement rocks include enclaves of older rocks, which range in age from 1800 to 1350 Ma and provide primary sources for zircons of those ages (Ownby et al., 2004; Rivers et al., 2012). In addition to the primary sources, abundant Grenville-age detrital zircons in post-Grenville sedimentary rocks along the Appalachians provide a source for recycled detrital zircons (Thomas et al., 2017). Grenville basement rocks are exposed now in the eastern Canadian Shield; however, they were covered and not available as a sediment source during the late Paleozoic (Sloss, 1988; Cecile and Norford, 1993), indicating that the Appalachian orogen is the source of the abundant Grenville-age detrital zircons in the Alleghanian clastic wedges.

The detrital zircons with ages of 490–350 Ma in the Alleghanian clastic wedges reflect primary sources in synorogenic crystalline rocks from Taconic and Acadian plutons in the Appalachian orogen (Drake et al., 1989; Osberg et al., 1989), and are, thus, a distinctive indicator of an Appalachian provenance (Thomas et al., 2017). In contrast, zircons with ages of 330–270 Ma, corresponding to the ages of plutons associated with the Alleghanian orogeny, are essentially lacking in sandstones of the Alleghanian clastic wedges (7 grains from a total of 3564, Fig. 11) (Thomas et al., 2017). Despite the general lack of synorogenic Alleghanian detrital zircons in the synorogenic clastic wedges, tonsteins (volcanic ash beds) within Pennsylvanian coal beds document synorogenic volcanism with ages of 316 ± 1 Ma (U-Pb zircon) and 311.2 ± 0.7 Ma ($^{40}Ar/^{39}Ar$) (Lyons et al., 1992, 1997; Kunk and Rice, 1994).

During Iapetan rifting of Laurentia and initial passive-margin transgression (late Neoproterozoic to Early Cambrian), the exposed craton provided a primary source of zircons with ages from Superior to Grenville, which were dispersed irregularly to parts (but not all) of the rifted margin (e.g., Cawood and Nemchin, 2001; Thomas et al., 2004; Allen et al., 2010) and were reworked by passive-margin transgression (e.g., Konstantinou et al., 2014). Synrift sedimentary rocks, incorporated tectonically into the Appalachian orogen, form a source for recycling of the older grains (Thomas et al., 2017). A few sandstones in the Alleghanian clastic wedges have a minor group of detrital-zircon ages that correspond to the Superior province, suggesting local temporary drainages that tapped deformed synrift or passive-margin sandstones in the Appalachian orogen.

Detrital zircons in the age ranges of 2200–2000 Ma and 800–530 Ma correspond to the Eburnian/Trans-Amazonian and Pan-African/Brasiliano components, respectively, of Gondwanan accreted terranes in the Appalachian orogen (Thomas et al., 2017). These ages are generally not abundant in the analyzed sandstones from the Alleghanian clastic wedges, suggesting only limited dispersal from the accreted terranes along the internal parts of the Appalachians during the late Paleozoic. Synrift igneous rocks along the Iapetan rifted margin constitute an alternative primary source for detrital zircons in the age range of 765–530 Ma (Thomas et al., 2017). Although synrift zircons cannot be distinguished from Pan-African/Brasiliano zircons on the basis of age alone, synrift zircons with positive εHf_t values (juvenile magmas) contrast with intermediate to more negative values (crustal contamination) in Pan-African/Brasiliano zircons (Thomas et al., 2016).

Sources for Recycling from Basin Margins

In addition to potential sources in the Appalachians, unconformities around the margins of Midcontinent basins suggest sources for recycling from Paleozoic sandstones. These potential sources for recycled grains had diverse original sources.

Around the northern rim of the Illinois basin, Lower and Middle Pennsylvanian strata onlap onto an unconformity that truncates strata as old as Ordovician (plate 2 in McKee and Crosby, 1975). Among the exposed strata, the Ordovician St. Peter Sandstone is dominated by Superior-age grains (2700 Ma), originally derived from the Canadian Shield and reworked in shelf environments (Lovell, 2017). Recycling detrital zircons from the St. Peter Sandstone is a potential source for some of the Pennsylvanian detritus in the Illinois and Forest City basins.

In the northeastern part of the Forest City basin (the western flank of the Mississippi River arch), Middle Pennsylvanian strata onlap onto an erosion surface on lowermost Upper Mississippian carbonate rocks and interbedded sandstones (Fig. 2). The truncated Upper Mississippian succession is a potential source for recycled detrital zircons (Kissock et al., 2018). The probable composition of truncated sandstones may be inferred from the preserved lowermost Upper Mississippian sandstones below the unconformity in the Forest City basin or from the more-completely preserved Upper Mississippian sandstones in the Illinois basin. Detrital-zircon age distributions in the preserved sandstones are similar to the Appalachian signature (compare Figs. 7 and 9 with Fig. 11), suggesting an ultimate source in the Appalachians and complicating a distinction from direct Appalachian supply.

PROVENANCE OF SANDSTONES AND SEDIMENT DISPERSAL IN MIDCONTINENT BASINS

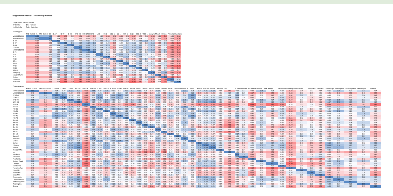
Early–Middle Mississippian (Acadian Clastic Wedge)

Samples from the Lower–Middle Mississippian Marshall/Napoleon Sandstone in the Michigan basin are coeval with the distal parts of the Acadian clastic wedge in the Appalachian foreland (Fig. 2). The samples from the Michigan basin have dominant age groups of 1218–904 Ma (modes between 1015 and 1012 Ma, secondary modes of 1190 Ma) and of 494–418 Ma (modes between 466 and 449 Ma) (Fig. 6). These age groups correspond to Grenville and Taconic–Acadian detrital-zircon age groups in the Lower–Middle Mississippian Price Formation (Park et al., 2010) in the Acadian clastic wedge in the Appalachian basin; however, Acadian ages generally are rare in synorogenic sandstones (e.g., Thomas et al., 2017). Distributions of older ages are similar to those in the Price Formation. The similarities to the Price Formation indicate that sediment in the distal foreland of the Acadian orogen reached the Michigan basin in the Early–Middle Mississippian. Multidimensional scaling plots show that detrital-zircon ages of the Lower–Middle Mississippian Marshall/Napoleon samples are distinct from those of Upper Mississippian sandstones in the Appalachian basin, as well as from those of the Upper Mississippian sandstones in the three eastern Midcontinent basins (Fig. 12A; Supplemental Table S7[7]).

Late Mississippian

Numerous sandstone units in cyclic sequences characterize the Upper Mississippian in the Illinois basin, and similar cyclic sequences are recognized in the Michigan basin (Towne et al., 2018). The regional sub-Pennsylvanian unconformity truncates most of the Upper Mississippian succession throughout the Forest City basin (Fig. 2); beneath the unconformity, sandstone interbeds in the upper part of the limestone-dominated "St. Louis" Formation in the northeastern corner of the Forest City basin may be depositionally coeval with the oldest Upper Mississippian sandstones in the Illinois basin (Fig. 2) (Witzke et al., 1990). Sandstones in the erosionally truncated Mississippian succession in the Forest City basin have detrital-zircon age distributions similar to those in the Mississippian sandstones in the Illinois basin (Fig. 12A), suggesting that these sands are within the same regional dispersal system; however, the preserved sandstones in the Forest City basin are much more limited in southward extent than the preserved sandstones in the Illinois basin (compare Figs. 4B and 5B).

The Upper Mississippian sandstones analyzed from the Michigan basin, the southern part of the Illinois basin, and the northeastern corner of the Forest City basin have dominant groups of detrital-zircon ages with modes between 1055 and 1025 Ma (Figs. 6, 7, and 9), corresponding in age to the dominant group in Upper Mississippian sandstones in the Appalachian basin (Fig. 11) (Thomas



[7]Supplemental Table S7. Dissimilarity matrices. Please visit https://doi.org/10.1130/GES02152.S7 or access the full-text article on www.gsapubs.org to view this file.

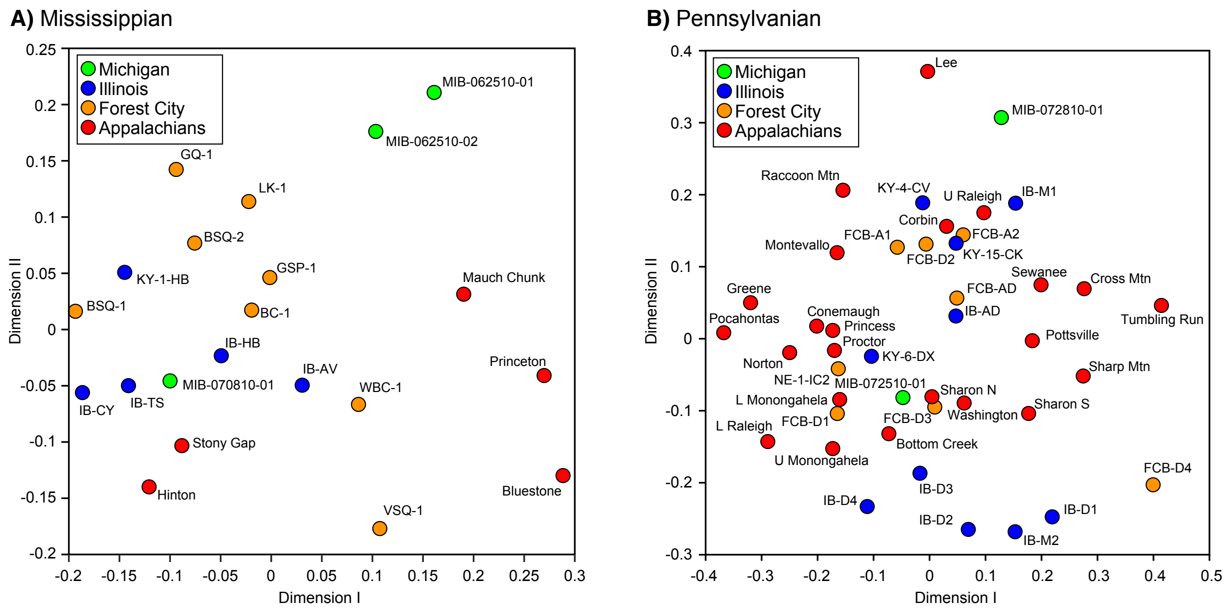


Figure 12. Two-dimensional multidimensional scaling (MDS) plots for detrital-zircon U-Pb age distributions for (A) Mississippian and (B) Pennsylvanian sandstones in the Michigan, Illinois, and Forest City basins for comparison with distributions in the Appalachian basin (Appalachian data include Lower Permian samples). Points that plot closer together have greater correspondence (are more similar) for detrital-zircon ages. The MDS plots (Vermeesch, 2013) were constructed using the program DZmds (github.com/kurtsundell/DZmds) (Saylor et al., 2018) with the Kuiper Test V statistic (Kuiper, 1960; Press et al., 2007) to calculate dissimilarity (dissimilarity matrices in Supplemental Table S7 [text footnote 7]). Transformation to Cartesian distance was calculated using metric stress, resulting in stress values for parts A and B of 0.178 and 0.171, respectively, indicating a reasonable transformation (Vermeesch, 2013). Axis scales are calculated dissimilarities between samples. L—lower, U—upper, N—north, S—south; Mtn—Mountain.

et al., 2017). Another group of detrital-zircon ages between 490 and 360 Ma with modes between 444 and 424 Ma (Figs. 6, 7, and 9) is similar in age to groups in Upper Mississippian sandstones in the Appalachian basin (Fig. 11) (Thomas et al., 2017). Detrital-zircon ages older than 1300 Ma in the eastern Midcontinent basins cover the same age ranges as in coeval sandstones in the Appalachian basin. Many (but not all) of the samples from the eastern Midcontinent basins have a few grains in the age range of 782–510 Ma, corresponding to Pan-African/Brasiliano components of accreted Gondwanan terranes; grains in this age range are similarly sparse in sandstones in the Appalachian basin.

Multidimensional scaling shows that all Upper Mississippian sandstones in the Michigan, Illinois, and Forest City basins plot near the distribution for Upper Mississippian sandstones in the Appalachian basin (Fig. 12A). The distribution of εHf_t values for Upper Mississippian sandstones in the Michigan and Illinois basins is similar to that of an Upper Mississippian sandstone in the Appalachian basin (Fig. 13A). These similarities strongly indicate an Appalachian provenance for all of the Upper Mississippian sandstones in the eastern Midcontinent.

Pennsylvanian

In a multidimensional scaling plot (Fig. 12B), data from most Pennsylvanian sandstones in the Michigan, Illinois, and Forest City basins are tightly clustered within a somewhat broader spread of data from the Appalachian basin. The distribution of εHf_t values for most of the Pennsylvanian sandstones in the three basins is nearly identical to that of Pennsylvanian sandstones in the Appalachian basin, especially in the most dominant groups of zircon ages (Fig. 13B). The broad similarities indicate a provenance for the Pennsylvanian sandstones in the eastern Midcontinent basins like that for the Appalachian basin.

All of the Pennsylvanian sandstones in the three eastern Midcontinent basins have detrital-zircon age distributions with dominant modes between 1086 and 1000 Ma, and most have secondary modes between 1165 and 1106 Ma (Figs. 6–8 and 10). The Pennsylvanian sandstones also have prominent modes between 470 and 339 Ma (Figs. 6–8 and 10). These dominant age groups are similar to the dominant age groups in the Appalachian basin, and the

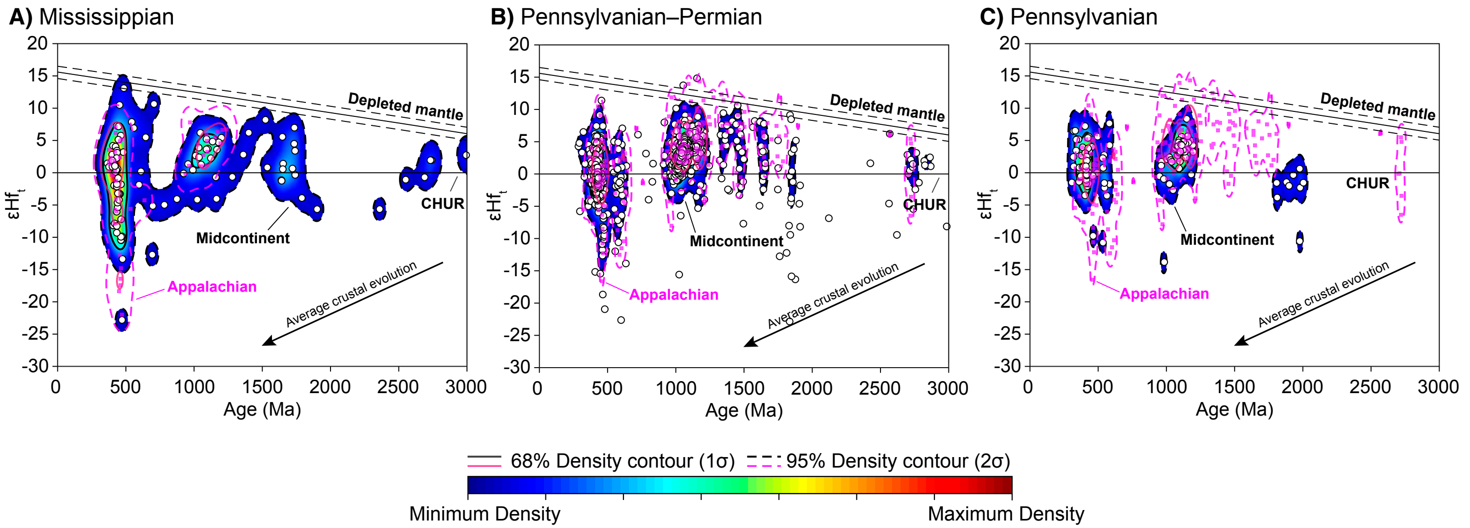


Figure 13. Comparisons of εHf_t data for the Michigan, Illinois, and Forest City basins with respect to the Appalachian basin (A—Mississippian samples; B—Pennsylvanian–Permian samples, except those in panel C; C—Pennsylvanian samples with strong Pan-African/Brasiliano age concentrations). Age-εHf_t data are plotted as bivariate kernel density estimates (KDEs) using HafniumPlotter version 1.5 (github.com/kurtsundell/HafniumPlotter; Sundell et al., 2019). Construction of bivariate KDEs follows a similar formulation as standard one-dimensional KDEs (Silverman, 1986), and incorporate set kernel bandwidths of 25 m.y. along the *x* axis (U-Pb age) and 2 ε units along the *y* axis (εHf_t value). The bivariate KDEs are constructed on a two-dimensional *x-y* grid of 512 × 512 cells, in which each cell has a corresponding density value on the *z* axis. When viewed parallel to the *z* axis, bivariate KDEs produce a density map that is contoured to specified intervals. Contours are plotted at 68% (solid lines) and 95% (dashed lines) (1σ and 2σ, respectively) of peak density; density is the height of the *z* axis and is shown by a color gradient, in which hotter colors represent larger (higher) *z*-axis values. In B, note the similarity between the 1σ contour for the Midcontinent Pennsylvanian–Permian values and that of Appalachian data points in the age groups of 1750–950 Ma and 650–350 Ma. CHUR—chondritic uniform reservoir.

spread of detrital-zircon ages >1300 Ma in the eastern Midcontinent basins generally matches the age groups represented in Pennsylvanian sandstones in the Appalachian basin (Fig. 11). Some detrital-zircon age groups in the Midcontinent basins, however, suggest some variation in sediment supplies.

Samples IB-M1 (Caseyville) and FCB-A1 (Kilbourn) from the sandstones just above the sub-Pennsylvanian unconformity around the northern rims of the Illinois basin and Forest City basin, respectively, have slightly greater abundances of Superior-age grains than do the other Pennsylvanian sandstones (Figs. 8 and 10). The Superior-age detrital zircons may have been recycled from truncated Ordovician sandstones around the northern rim of the Illinois basin into the onlapping sandstones (Figs. 8 and 10). Alternatively, Superior-age grains were available for dispersal through the Appalachian basin (Fig. 11). A few sandstones in the Appalachian basin have somewhat greater abundances of Superior-age grains (for example, the Upper Mississippian Stony Gap Sandstone and Lower Pennsylvanian Corbin Sandstone in eastern Kentucky, Fig. 2; Thomas et al., 2017) than do most of the sandstones in the Alleghanian synorogenic clastic wedges. In a multidimensional scaling plot (Fig. 12B), the Caseyville and Kilbourn (as well as the Corbin) samples fit within the tight cluster of Midcontinent samples from Pennsylvanian sandstones, suggesting that these groups of Superior-age grains may reflect only a minor addition to the same sediment supply as that of the other samples.

Many of the Pennsylvanian sandstones have minor groups of detrital zircons with ages between 685 and 525 Ma (Neoproterozoic), corresponding in age to Pan-African/Brasiliano components of Gondwanan accreted terranes along the Appalachian orogen (Figs. 6–8 and 10). Similarly, although generally less abundant to very rare, detrital zircons with ages of 2200–2000 Ma correspond in age to Eburnian/Trans-Amazonian components of the Gondwanan terranes. Although these ages generally are only minor components of the sandstones in the eastern Midcontinent basins, four samples (termed "type 2" by Kissock et al., 2018) have more abundant zircons with ages of 685–525 Ma and modes between 655 and 547 Ma. These samples are spread between two basins and through a range of depositional ages: one from the Early Pennsylvanian (Morrowan) Caseyville Sandstone (IB-M2) and two from the Middle Pennsylvanian (Atokan–Desmoinesian) Tradewater Formation (IB-D1, IB-D2) in the northern part of the Illinois basin, and one from the Middle Pennsylvanian (Desmoinesian)

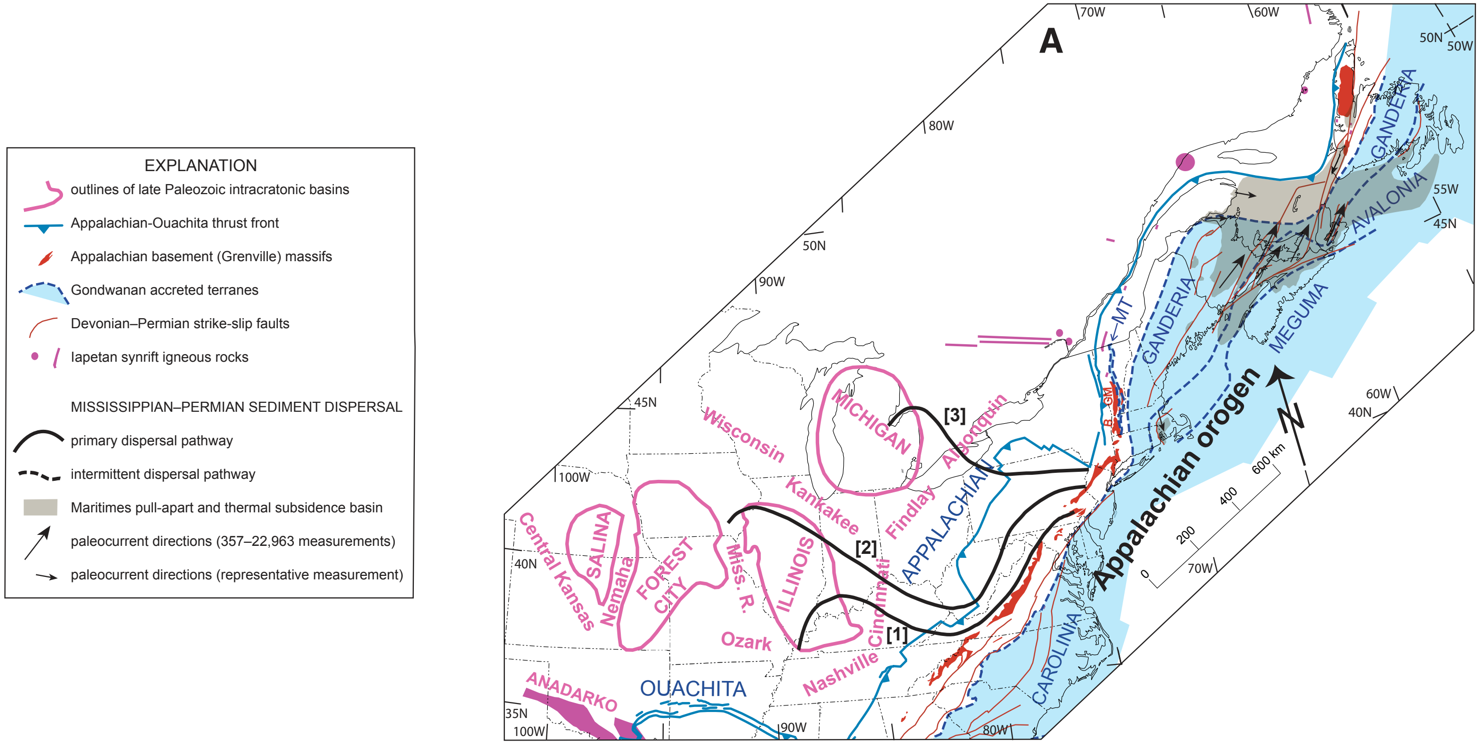


Figure 14. Regional maps showing interpreted sediment dispersal to and across the eastern Midcontinent. Abbreviations: B—Berkshire massif; GM—Green Mountains massif; MT—Moretown terrane. In addition to those mapped separately in the Appalachian foreland, synrift igneous rocks are distributed along some mapped basement (Grenville) massifs. (A) Late Mississippian: dispersal from the Appalachian orogen to [1] fluvial and deltaic sands in the southern part of the Illinois basin, [2] shallow-marine sands in the northeastern-most part of the Forest City basin and associated Mississippi River (Miss. R.) arch, and [3] channel sands in the Michigan basin. (*Continued on following page.*)

Floris Formation (FCB-D4) in the northern part of the Forest City basin (Figs. 2, 4A, 5A, 8, and 10), but none from the Michigan basin. Although not abundant, grains with ages of 2200–2000 Ma are slightly more numerous in these four samples than in other sandstones in the basins. These four samples are distinguished by the prominent Neoproterozoic modes in probability density plots but otherwise have distributions of detrital-zircon ages like those of the other Pennsylvanian sandstones in the Midcontinent basins (Figs. 8 and 10). The four samples with the prominent groups of Neoproterozoic grains are slightly separated from the other Pennsylvanian sandstones in the multidimensional scaling plot (Fig. 12B); however, separate plots of εHf_t values from two of the four samples show no clear distinction from the other Pennsylvanian sandstones (compare Fig. 13B and Fig. 13C). The prevalence of the "Appalachian signature" in all of the samples suggests that the abundant Neoproterozoic grains reflect an addition to the dispersal system that supplied the Appalachian basin.

Pan-African/Brasiliano rocks in accreted Gondwanan terranes are scattered along the internal parts of the Appalachian orogen (Fig. 1) (e.g., summary in Thomas et al., 2017); however, sandstones in the Appalachian basin in all recognized dispersal systems have relatively few grains with Pan-African/Brasiliano (Neoproterozoic) ages (Fig. 11). No systematic pattern of drainage from Gondwanan terranes through the Appalachian basin has been recognized; thus, the prominent Neoproterozoic age groups in four sandstones in the Illinois and Forest City basins require some drainage system that has not yet been sampled in the Appalachian basin and that did not pass through the Michigan basin. The span of approximate depositional ages (315–308 Ma; Fig. 2; Table 1) and the geographic distribution of the samples with prominent Pan-African/Brasiliano age groups in the Illinois and Forest City basins indicate variable temporary supplies during the Early to Middle Pennsylvanian (Figs. 14B and 14C).

Two alternatives can be suggested for the provenance of the Neoproterozoic grains, which apparently has no alternative other than within the Appalachian orogen. One alternative includes temporary headwater streams that tapped Gondwanan accreted terranes in the Appalachian internides; however, the lack of any clear indication of such a stream in the available samples (*N* = 29; Thomas et al., 2017) seems to preclude dispersal directly through the Appalachian basin. A longer trunk river north of the presently preserved sandstones in the Appalachian basin might have tapped Gondwanan accreted terranes in the northern Appalachians and supplied sediment to the northern parts of the Illinois and Forest City basins (Kissock et al., 2018). The well-documented Gondwanan accreted terranes northeast of the Appalachian basin are within the Maritimes basins, a system of Devonian–Permian strike-slip basins and uplifts that generally had internal drainage (Figs. 1 and 14) (Thomas and Schenk, 1988; van de Poll et al., 1995; Williams, 1995). Whether sediment spilled out of the pull-apart basins onto the eastern craton cannot be determined conclusively, because no Paleozoic sedimentary cover is preserved west of the basins on the Canadian Shield. In contrast, the Moretown terrane (Macdonald et al., 2014), a narrow tectonic slice east of the Green Mountains and Berkshire external basement massifs in the New England Appalachians (Fig. 14), is west of the Maritimes basins and outside the restricted internal drainage. Detrital-zircon ages of 800–514 Ma with modes between 770 and 560 Ma clearly document the Gondwanan affinity of the Moretown terrane (Macdonald et al., 2014; Karabinos et al., 2017). The Moretown terrane is a viable source for the unusual concentrations of Pan-African/Brasiliano grains in the four sandstones in the Illinois and Forest City basins, and the probable dispersal pathway across the strike of the Appalachian basement massifs and the proximal Taconic–Acadian foreland (Figs. 14B and 14C) provides a source for the "Appalachian signature" in those sandstones, as well. An alternative possible source along the northern Appalachians for the grains with ages of 685–525 Ma is in Iapetan synrift rocks (Figs. 14B and 14C), which are exposed in several places along the leading structures and foreland of the Canadian Appalachians, west of potential blocking faults of the Maritimes basins, and may have been available for erosion during the late Paleozoic (Figs. 1 and 14). Although synrift rocks and Pan-African/Brasiliano rocks are indistinguishable on the basis of age, Hf isotopic data suggest a discriminant. εHf_t values from two samples in the Midcontinent basins range from positive to negative (+7.7 to –10.8, mostly between +2.7 and –3.5; Fig. 13C; Table 2); these values are similar to those of Appalachian sandstones (Fig. 13C) but differ from the more positive values (+10.1 to +4.7) that indicate juvenile magmatic synrift rocks along the Southern Oklahoma fault system (Thomas et al., 2016). Among all the options, the Moretown Gondwanan terrane emerges as the most likely provenance for the Pan-African/Brasiliano grains in the Illinois and Forest City basins (Figs. 14B and 14C).

In contrast to the relative abundance of Taconic–Acadian detrital-zircon ages in the eastern Midcontinent basins, grains with ages corresponding to the Alleghanian orogeny of the Appalachians are rare (Figs. 6–8 and 10). Similarly,

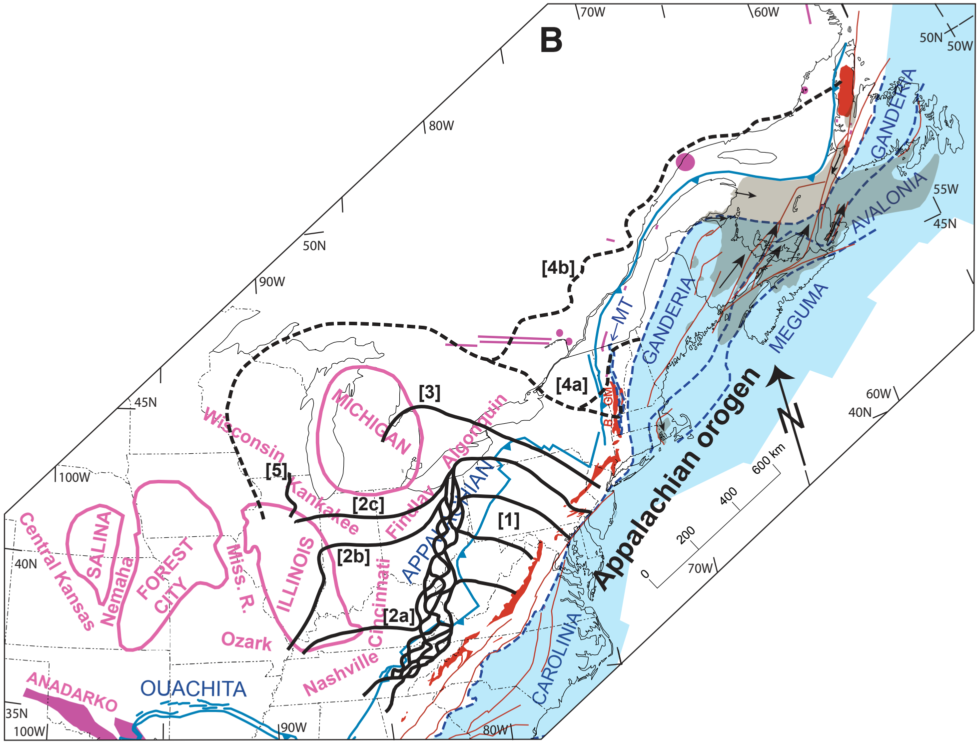


Figure 14 (*continued*). (B) Early Pennsylvanian: dispersal from the Appalachian orogen to [1] a longitudinal braid plain with south-southwest currents (shown schematically, adapted from Archer and Greb, 1995) in the distal Appalachian basin and diversion to channel sands in the [2a] southern, [2b] eastern, and [2c] northern parts of the Illinois basin; dispersal from the Appalachian orogen [3] to the Michigan basin; intermittent dispersal from [4a] the Moretown Gondwanan accreted terrane in the northern Appalachians or, less likely, from [4b] Iapetan synrift igneous rocks in the northern Appalachian foreland to the northern part of the Illinois basin; and [5] recycling from the eroded Kankakee arch into the northern part of the Illinois basin. (*Continued on following page.*)

Alleghanian-age detrital zircons are rare (7 grains in a total of 3564) in Mississippian–Permian sandstones in the Appalachian basin (Fig. 11) (Thomas et al., 2017). With the exception of three samples, the youngest grain in sandstones of the Illinois basin is 355 Ma (Acadian age; Fig. 8); however, samples IB-AD, IB-D1, and IB-D2 from the Atokan–Desmoinesian Tradewater Formation in the northwestern part of the Illinois basin have a few exceptionally young zircon grains (six grains in three samples) in the age range of 321 ± 5 to 307 ± 4 Ma (Fig. 8). The detrital-zircon ages are within error of, or slightly older than, the approximate depositional age of the Tradewater Formation, which is 310–309 Ma (Fig. 2; Table 1). In addition, the Atokan Kilbourn (FCB-A2) and Kalo (FCB-AD) Formations and Desmoinesian Floris Formation (FCB-D4) in the Forest City basin have a few zircon grains (eight grains in three samples) in the age range of 321 ± 5 to 307 ± 4 Ma (Fig. 10). The approximate depositional age of the Kilbourn–Floris succession is 312–308 Ma (Fig. 2; Table 1). The exceptionally young grains are within the age range of the Alleghanian orogeny.

Tonsteins within Pennsylvanian-age coal beds in the Appalachian basin have ages of 316 ± 1 Ma (U-Pb zircon) and 311.2 ± 0.7 Ma ($^{40}Ar/^{39}Ar$) (Lyons et al., 1992, 1997; Kunk and Rice, 1994), representing Alleghanian synorogenic volcanism. The close match of the detrital-zircon ages from the Illinois and Forest City basins with documented Alleghanian volcanism, as well as with depositional age of the containing sediment, suggests that the contemporaneous zircon crystals were dropped within an air-fall ash onto the depositional surface in the distal basins and reworked locally into the fluvial sand deposits. The contemporaneity of the zircon crystallization and sandstone deposition, as well as the paucity of grains of this age in the Appalachian basin, suggests that these are not detrital grains transported fluvially with other sediment from primary sources. Sparse zircon grains from air-fall ash may have been overwhelmed in the more voluminous proximal detritus in the Appalachian basin and not detected there; whereas, in the context of lower depositional rates in the more distal deposits, the grains from air-fall ash are detected in small numbers in the northwestern part of the Illinois basin and northern part of the Forest City basin.

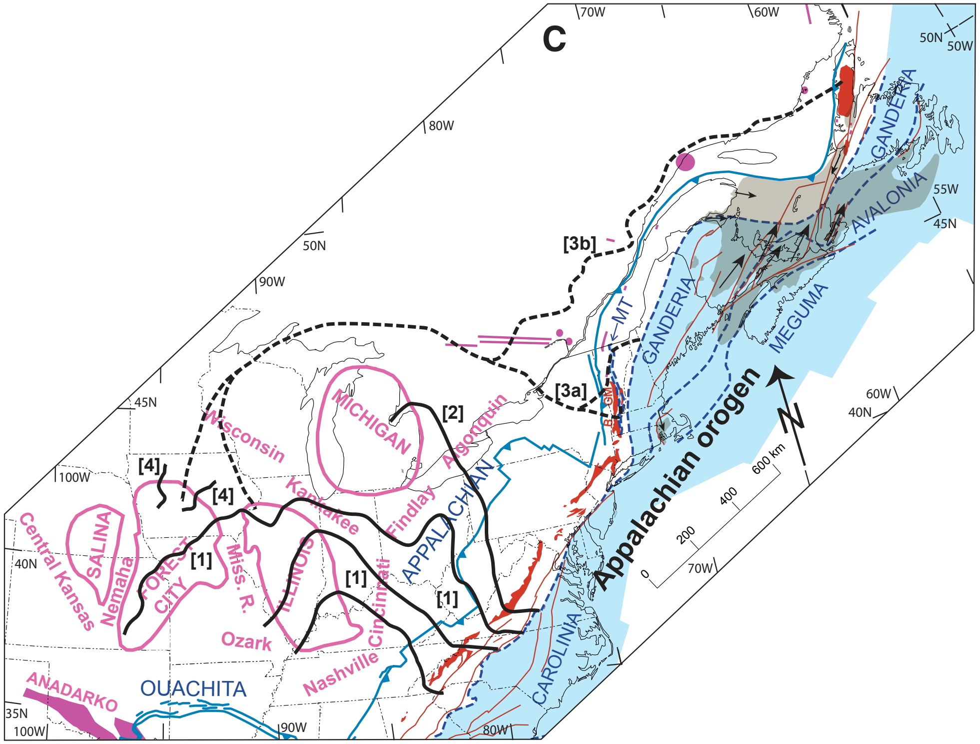


Figure 14 (*continued*). **(C) Middle and Late Pennsylvanian: dispersal from the Appalachian orogen to [1] the Illinois and Forest City basins; dispersal from the Appalachian orogen [2] to the Michigan basin; intermittent dispersal from [3a] the Moretown Gondwanan accreted terrane in the northern Appalachians or, less likely, from [3b] Iapetan synrift igneous rocks in the northern Appalachian foreland to the northern parts of the Illinois and Forest City basins; and [4] recycling from eroded Mississippian strata across the Forest City basin into the northern part of the Forest City basin.**

Permian

The stratigraphically highest sample (Middle Permian Whitehorse Sandstone, sample KS-5-WH) is from a succession of Permian redbeds and evaporites southwest of the Forest City basin (Figs. 1 and 5A). The redbeds and evaporites contrast with the underlying succession of gray-colored cyclothems. The Permian succession thins and pinches out northeastward across the southern flank of the Forest City basin, and evidently represents a sediment-dispersal system different from the Appalachian-derived system that extended throughout the three eastern Midcontinent basins during the Late Mississippian and Pennsylvanian. The Whitehorse sample includes dominant detrital-zircon groups with Grenville and Taconic–Acadian ages, as well as secondary groups of older grains like those in other samples from Appalachian sources. In contrast to all of the other samples, the Whitehorse sample has a secondary group in the age range of 335–287 Ma (Fig. 10). Although these younger grains correspond in age to the Alleghanian orogeny in the Appalachians, the paucity of detrital grains of Alleghanian ages in the Appalachian basin suggests almost no dispersal of synorogenic detritus from Alleghanian sources in the Appalachians (Thomas et al., 2017). In addition, a secondary group with ages of 638–519 Ma (Pan-African/Brasiliano) in the Whitehorse sample exceeds the number of sparse grains of that age range in other samples (except for the four samples with prominent groups of that age range, which are restricted to the most northerly parts of the Forest City and Illinois basins). The ages of detrital zircons, as well as the red color, suggest that the Whitehorse sandstones may record a dispersal system that extended onto the southern Midcontinent from accreted terranes along the Marathon margin (Thomas et al., 2019), thereby marking a limit to westward dispersal from the Appalachians.

SUMMARY AND CONCLUSIONS: PROVENANCE AND SEDIMENT DISPERSAL

The detrital-zircon age distributions of Mississippian–Pennsylvanian sandstones in the Michigan, Illinois, and Forest City basins correspond closely to the signature of late Paleozoic sandstones in the Appalachian basin (Figs. 11–13), indicating a provenance in the Alleghanian orogen and cratonward dispersal of sediment through the Appalachian basin to the eastern Midcontinent basins (Fig. 14). Although the bulk of the age distributions in all samples displays the "Appalachian signature," some secondary additional components of some samples are distinct in age and/or proportion, suggesting other contributions to the sediment supply.

The greatest abundances of detrital-zircon ages in Mississippian–Pennsylvanian sandstones in the Michigan, Illinois, and Forest City basins are in the age ranges of 1300–950 Ma (Grenville) and 490–350 Ma (Taconic–Acadian) (Figs. 6–11). Those age ranges are also the most abundant in Mississippian–Permian sandstones in the Appalachian basin (Fig. 11) (Thomas et al., 2017). Composite probability density plots show that other ages with lesser abundances in the eastern Midcontinent basins also generally are comparable to lesser abundances in sandstones of the Appalachian basin (Fig. 11). Multidimensional scaling shows that detrital-zircon age distributions in Midcontinent Mississippian–Pennsylvanian sandstones are similar to those in the Appalachian basin (Fig. 12). The greatest densities of εHf_t values from Midcontinent Mississippian–Pennsylvanian sandstones are nearly identical to those for the Appalachian basin (Fig. 13).

Sedimentary facies, channel orientations, and paleocurrent directions indicate generally southwest-directed fluvial systems in the Michigan, Illinois, and Forest City basins (Figs. 3–5), although west-directed currents followed structural strike along the Rough Creek fault system on the southern flank of the Illinois basin (Fig. 4). Fluvial-estuarine and reworked deltaic deposits in the Michigan basin (Towne et al., 2013, 2018) suggest limited dispersal beyond the basin. Some Mississippian channel sandstones in the Illinois basin end southwestward in coastal-deltaic facies, although some lowstand channels may have extended south of the basin (Fig. 4B). In contrast, the sparse Mississippian sandstones in the Forest City basin give way southwestward to carbonate facies (Fig. 5B). The distribution and orientation of Pennsylvanian channel sandstones in the Illinois basin suggest that sediment spilled out southwestward from the basin (Fig. 4). Southwest-directed fluvial channels in the Illinois basin (Figs. 4 and 14) probably did not contribute sediment to the Forest City basin; however, the detrital-zircon age distributions in Pennsylvanian sandstones in the Forest City basin indicate an ultimate Appalachian provenance. Channel sandstones in the Forest City basin pass southwestward into deltaic facies, indicating the terminus of the dispersal system (Fig. 5).

Erosion of Mississippian sandstones around the northern rim of the Forest City basin may have contributed recycled zircon grains to a mix of sediment in Pennsylvanian sandstones (Kissock et al., 2018), but these detrital grains would be indistinguishable on the basis of age from other Appalachian detritus. Recycling from Ordovician sandstones around the northern rim of the Illinois basin may have contributed the relatively large component of Superior-age grains in the stratigraphically lowest Pennsylvanian sandstones on the northern flanks of both the Illinois and Forest City basins (Fig. 14B); however, some sandstones in the Appalachian basin have similar, somewhat isolated, groups of Superior-age zircons (Thomas et al., 2017).

Four samples from the northern parts of the Illinois and Forest City basins have a significantly larger proportion of detrital-zircon grains with ages of 700–525 Ma (Pan-African/Brasiliano) than do any sandstones in the Appalachian basin (Figs. 8, 10, and 11), suggesting a different source and dispersal system than for most of the sandstones. The Gondwanan Moretown accreted terrane in the Appalachians northeast of the Appalachian basin (Figs. 14B and 14C) is the most likely provenance for these grains, and sediment dispersal might have crossed the eastern craton north of the Michigan basin (which has only rare Pan-African/Brasiliano grains) and entered the northern edges of the Illinois and Forest City basins (Figs. 14B and 14C). The range of depositional ages of these sandstones from Morrowan to Desmoinesian shows that they do not represent a single persistent dispersal system, and temporary drainages must have supplied the basins separately (Figs. 14B and 14C).

Three samples each from the northwestern Illinois basin and northeastern Forest City basin have a few zircon grains with ages that correspond to the Alleghanian orogeny in the Appalachian orogen; crystallization ages of the zircons are nearly the same as the age of deposition of the sandstones. Grains of this age are nearly lacking in sandstones in the Appalachian basin; however, the Alleghanian-age grains in the Midcontinent basins are the same age as tonsteins in some coal beds in the Appalachian basin. The age relationships suggest that the Alleghanian-age zircons are from air-fall ash, which spread to the eastern craton from Alleghanian volcanism.

A sample from a Middle Permian sandstone southwest of the Forest City basin has a detrital-zircon age distribution similar to an Appalachian signature but with a distinctive small group of Alleghanian-age grains greater than the Alleghanian-age components in the Appalachian basin or in the Forest City or Illinois basins. The age distribution is similar to that of a Permian sandstone in the Anadarko basin, which has a source in the Marathon-Ouachita orogen (Thomas et al., 2016, 2019), suggesting that this Permian sandstone may represent the distal part of a dispersal system from the south, thus, limiting possible Permian dispersal from the Appalachians (Fig. 1).

Sediment dispersal patterns and provenance indicators combine to suggest regional drainage systems onto the eastern craton from the Appalachian orogen during the Alleghanian orogeny (Fig. 14). Drainage from the Appalachian orogen may not have extended beyond the Michigan basin to any of the other intracratonic basins. Drainage into the Illinois basin from the northeast and east may have extended through the basin and out to the southwest. Drainages from the northeast into the Forest City basin end in deltaic facies within the basin. A more distant source in the northern Appalachians may have supplied sediment intermittently, but separately, to the northern fringes of both the Illinois and Forest City basins, but that system did not enter the Michigan basin (Fig. 14). Air-fall ash from Alleghanian volcanism spread to the Illinois and Forest City basins. Possibly, distal sediment from the Marathon-Ouachita orogen lapped onto the southern rim of the Forest City basin in the Permian. In summary, late Paleozoic sediment dispersal to the eastern Midcontinent basins was dominated by Appalachian sources and only mildly modified by other sources.

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