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Drainage area estimates for synorogenic clastic wedges in the Central Appalachian Basin (sink) with implications for terrane accretion in the hinterland (source)

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Abstract

Source-to-sink studies typically utilize the sedimentary record preserved in basins to infer source area parameters such as estimates of drainage area and discharges of fluvial systems in the hinterland, the characterization of which remains elusive as few geomorphic elements of the hinterland are preserved. Clastic wedges within foreland basin settings often contain fluvial deposits, and the scale of fluvial architectural elements can be used to estimate drainage area and discharge within the accreted hinterland. This study uses thicknesses of fluvial architectural elements within the Late Ordovician Taconic, the Late Devonian-Early Mississippian Acadian, and the Late Mississippian to Early and Middle Pennsylvanian Alleghanian clastic wedges, together with climatic conditions interpreted from palaeosol data, to estimate the drainage areas and discharges of the river systems which drained the hinterlands of the accreted Taconic and Acadian terrains and the Alleghanian suture of Laurentia and Gondwana. Published detrital zircon age spectra provide insight into ages of source areas of sediments as well as the timing of terrane accretion. The increase in hinterland drainage areas calculated for Late Devonian Acadian Orogeny river systems compared to Late Ordovician Taconic Orogeny river systems can be attributed to the increase in size of accreted terranes to the east of the foreland basins during that period of time. The decrease in hinterland drainage area from the Late Devonian Acadian Orogeny to the Middle to Late Pennsylvanian Alleghanian Orogeny is attributed to the westward migration of the drainage divide as the Alleghanian orogeny proceeded. It is inferred that the drainage divide migrated towards the drier leeward side of the mountain range and caused drainage basins to shrink and split into smaller drainage basins.

KEYWORDS

drainage basin reconstruction, fluvial architecture, source-to sink-analysis, terrane accretion

1 | INTRODUCTION

A burgeoning research area in stratigraphy-sedimentology is source-to-sink analysis that utilizes the sedimentary record preserved in basins to infer source area parameters. The source is linked to the depositional sink via a transfer zone (Schumm, 1977), but the extent of the transfer zone and the nature of the source remain elusive as few geomorphic elements of the hinterland are preserved. During the past decade, source-to-sink studies have been used, for example, to: (1) reconstruct palaeogeography, compositions and ages of source regions; (2) estimate drainage basin areas (km^2) and bankfull discharge (m^3s^{-1}); (3) calculate sediment yields and denudation rate; and (4) document changing fluvial styles through time (e.g., Bhattacharya et al., 2016; Blum et al., 2013; Buller et al., 2018; Davidson & Hartley, 2010; Eriksson & McClung, 2021; Eriksson & Romans, 2017; Ielpi et al., 2017; Sømme et al., 2009; Walcott & Summerfield, 2009; Wang et al., 2020).

Understanding and linking scales of fluvial deposits to upstream controls such as drainage basin area characteristics and discharge are two of the goals of source-to-sink analysis. Studies from modern river systems have shown that river channels scale to discharge (e.g., Best & Ashworth, 1997; Best et al., 2003; Knighton, 1998; Leopold & Maddock, 1953) and that discharge, in turn, scales to drainage basin area (e.g., Syvitski & Milliman, 2007). Channel width and depth increase downstream with discharge because of cumulatively increasing drainage basin area (Leopold et al., 1964) and a wide variety of scaling relationships between fluvial systems and their drainage basin areas have been recognized (e.g., Blum et al., 2013; Mattheus et al., 2007; Milliman & Syvitski, 1992; Schumm & Winkley, 1994; Syvitski & Milliman, 2007). Foremost among these is the relationship between drainage basin area and the scale of fluvial architectural elements (e.g., Davidson & Hartley, 2014; Davidson & North, 2009). By integrating estimates of changing drainage basin areas through time with other data such as detrital zircon geochronology, insights can be gained on how fluvial depositional processes relate to upstream controls such as discharge which, in turn, is linked to paleoclimate. Furthermore, it may be possible to relate changes in drainage basin areas to hinterland tectonic processes such as terrain accretion.

This study focuses on fluvial facies preserved in three clastic wedges developed in the Central Appalachian Basin. The clastic wedges formed in foreland basins related to crustal loading associated with the accretion of various terranes in the hinterland to the east (Pollock et al., 2011). By utilizing architectural element analysis of Upper Ordovician-, Upper Devonian-, Lower and Upper Mississippian- and Lower to Middle Pennsylvanian-age fluvial deposits preserved in the three clastic wedges, from which drainage basin scale and discharge can be estimated, in combination with published detrital zircon spectra, new constraints will be provided on the timing of terrane accretion and changes in areal extent of the accreted terranes in the hinterland (Figure 1).

Highlights

- Fluvial architecture in the Appalachian foreland basins is used to reconstruct drainage evolution.
- Reconstruction provides insights into progressive terrane accretion in the hinterland.
- Late Ordovician drainage areas were small and consisted of uplifted Cambro-Ordovician passive-margin sediments.
- Late Devonian drainage areas expanded by an order of magnitude and sourced terranes accreted onto Laurentia.
- Early and Middle Pennsylvanian drainage areas contracted in response to westward migration of the continental divide.

2 | GEOLOGICAL EVOLUTION OF THE CENTRAL APPALACHIANS

The geological evolution of the central Appalachians commenced ca. 750 Ma ago with rifting of Rodinia. This rifting event did not proceed to continental separation. The second rifting event at 600–550 Ma (U–Pb zircon, Aleinikoff et al., 1995; Fetter & Goldberg, 1995), is recorded by sedimentary (Swift Run Formation) and volcanic (Catoctin Formation) rocks (Figure 2; Badger & Sinha, 1988; Wehr & Glover, 1985). This event proceeded to continental breakup and passive continental margin formation by the Early Cambrian (Simpson & Eriksson, 1989; Wehr & Glover, 1985). The ca. 3.5 km-thick, Cambro-Ordovician passive-margin succession consists of the upper Chilhowee Group, Shady Dolomite, Rome Shale, Elbrook Formation and Knox Group (Figure 2; Barnaby & Read, 1990; Read, 1989; Read & Eriksson, 2016; Simpson & Eriksson, 1990).

Ensuing assembly of Pangea involved three major orogenic events: the Ordovician Taconic, Devonian-Early Mississippian Acadian, and Late Palaeozoic Alleghanian orogenies (e.g., Drake et al., 1989; Hatcher, 1989).

2.1 | Taconic Orogeny

Passive-margin sedimentation was terminated by the Taconic Orogeny (Hatcher, 1989). Hinterland expressions

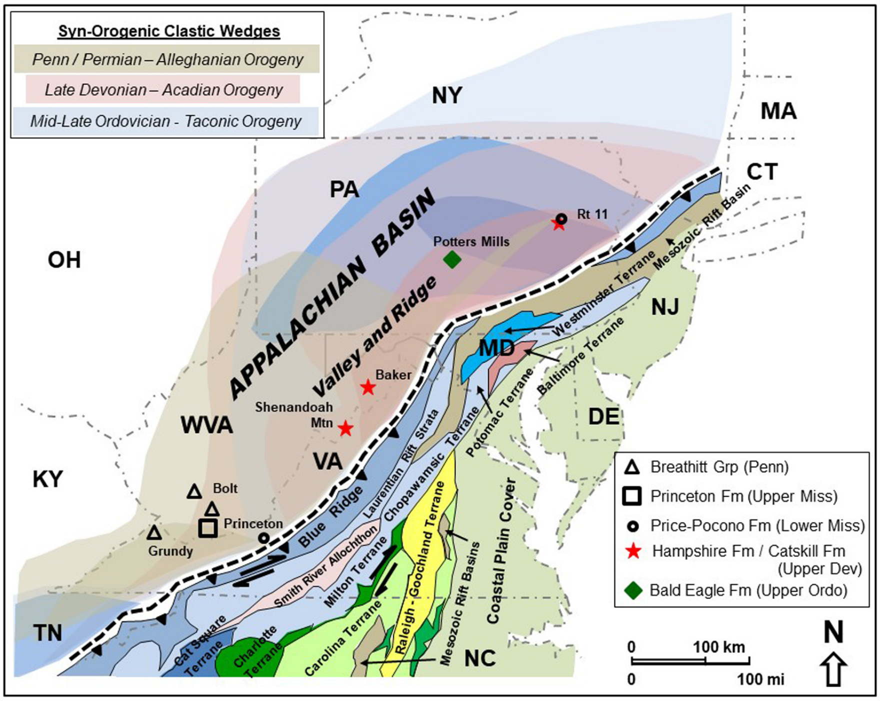

FIGURE 1 Map showing the major depocenters of the Late Ordovician Taconic, Late Devonian Acadian, and Carboniferous Alleghanian clastic wedges in the Valley-and-Ridge and Appalachian Plateau provinces west of the Blue Ridge, along with locations of studied sections. Also shown are associated accreted terranes within the crystalline Piedmont province east of the Blue Ridge as well as dextral transpression manifested as strike-slip faulting between the Blue Ridge and Goochland terranes which is interpreted to have occurred during the Acadian and possibly Alleghanian orogenies. Modified from Sinha et al. (2012) and Thomas and Hatcher (2021).

of this orogeny are the Chopawamsic and Milton and Potomac terranes (Figure 1) that are considered to represent remnants of an extensive 450–470 Ma volcanic and magmatic arc which collided with Laurentia starting in the Middle Ordovician (Coler et al., 2000; Thomas & Hatcher, 2021) closing the Iapetus Ocean (Figure 3). Granites associated with the Taconic arc range in age from 441 to 489 Ma (Sinha et al., 2012). Associated with the Chopawamsic–Milton–Potomac arc terranes are melanges and ophiolitic meta-mafic and -ultramafic slivers (Baltimore and Westminster terranes) (Figure 1) (Guice et al., 2021). The Smith River allochthon is of probable Laurentian affinity (Carter et al., 2006).

In the Valley and Ridge Province of the Appalachian Basin, the transition from passive-margin to foreland-basin sedimentation is demarcated by the Middle Ordovician Knox unconformity related to shelf flexure associated with the onset of thrust loading (Mussman & Read, 1986; Read & Eriksson, 2016). Shelf foundering was followed by deposition of the Middle to Late Ordovician, Taconic clastic wedge within a relatively narrow foreland basin occupying two depocenters, one in the Pennsylvania (PA) embayment and the other in the Tennessee (TN) embayment; the Virginia (VA) promontory separating the two embayments (Shammugam & Lash, 1982; Thomas & Hatcher, 2021). During the Late Ordovician, North America occupied mid-latitudes (Read & Eriksson, 2016).

The Taconic clastic wedge consists of a marine to continental, shoaling-upward succession that includes the Liberty Hall, Knobs, Bays, Martinsburg, Juniata and lower Tuscarora formations (Figures 1 and 2; Read & Eriksson, 2016). In PA, the clastic wedge is dominated by deep-water turbidites of the Martinsburg Formation that shoal upward into the shallow-marine to continental Juniata Formation (Figure 2; Read & Eriksson, 2016). Here, the fluvial Bald Eagle Formation either underlies the Juniata Formation or comprises its basal unit (Thompson, 1970; Willard & Cleaves, 1939; Yeakel, 1962). The Juniata Formation is predominantly marine in the southern parts of the depocenter in VA but in PA the Bald Eagle Formation contains braided-alluvial deposits that are analysed in this study for purposes of constraining the Taconic drainage area.

2.2 | Acadian Orogeny

Renewed convergence and dextral transpression dominated the Devonian-Mississippian Acadian Orogeny and is attributed to a zippered, north-to-south closing of the Rheic Ocean (Figure 3). Obduction occurred of the Carolina superterrane (peri-Gondwanan-age arc) onto the Cat Square and Laurentian assemblages, the latter consisting of Laurentia and accreted Taconic terranes (Bream & Hatcher, 2002; Hatcher, 1989; Thomas & Hatcher, 2021; Wortman et al., 2000). The Carolina superterrane consists of mafic to felsic volcanic and volcaniclastic rocks. Neo-Acadian plutons, related to the collision of the Carolina Superterrane with Laurentia range in age from 362 to 381 Ma (Sinha et al., 2012). The Goochland terrane in VA (Figure 1) is mainly Grenvillian age and represents either a continental fragment of Laurentian affinity

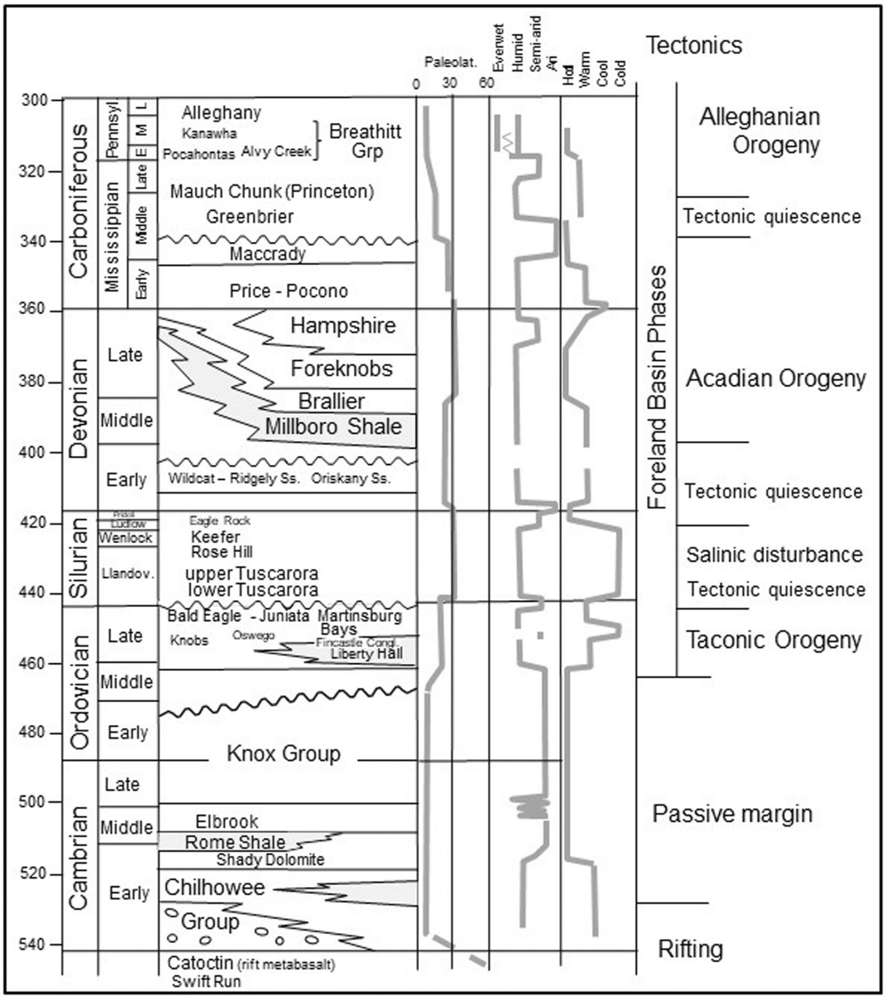

FIGURE 2 Stratigraphic column for Palaeozoic rocks in the Valley-and-Ridge and Appalachian Plateau provinces. Also shown are timing of orogenic events as well as interpreted paleolatitude and paleoclimatic conditions (modified from Read & Eriksson, 2016). Note that this figure includes only stratigraphic units referred to in the text.

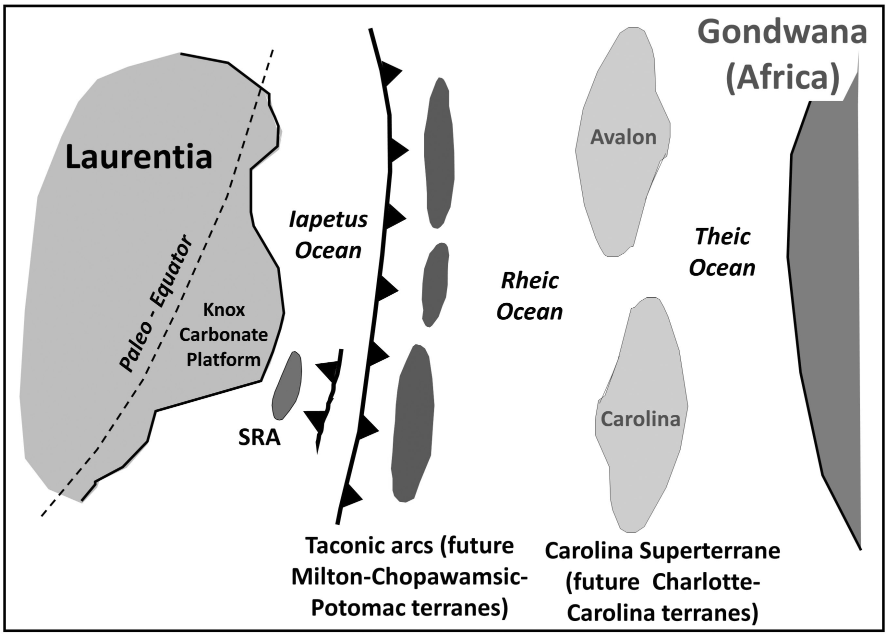

FIGURE 3 Tectonic model for terrane accretion (modified from Hatcher, 2010). Taconic arcs collided with Laurentia in the Late Ordovician, Avalon and Carolina microcontinents collided with Laurentia in the Late Devonian and Gondwana collided with Laurentia in the Late Carboniferous to Early Permian.

(Farrar, 1984) or an exotic terrane moved southward by dextral strike-slip and accreted to Laurentia during the Taconic or Acadian orogenies (Rankin et al., 1989; Spears et al., 2004). The Cat Square terrane (Figure 1), with a maximum age of 430 Ma and with Laurentian and peri-Gondwanan affinities, consists of a mélange of mafic and ultramafic meta-igneous rocks, and meta-sedimentary rocks, the protoliths of which are considered to have formed in the remnant Rheic ocean basin (Merschat & Hatcher, 2007) (Figure 3).

The Acadian Orogeny was most prominent in New England but the sedimentary response is expressed in the Valley and Ridge Province by southwestward progradation of a clastic wedge that extended as far south as VA. Important synorogenic components of this marine to continental, shoaling-upward, clastic wedge include the Upper Devonian Millboro Shale, Brallier, Foreknobs and Hampshire formations and the Lower Mississippian Price, Maccrady and Pocono formations (Figures 1 and 2; McClung et al., 2013; Osberg et al., 1989; Read & Eriksson, 2016).

The Acadian (Catskill) clastic wedge developed in a relatively wide foreland basin with one major depocenter in PA (Figure 1; Thomas & Hatcher, 2021). During the Late Devonian, North America was at mid-latitudes (Read & Eriksson, 2016). Continental red beds of the Upper Devonian, Hampshire Formation in VA, MD and WV and the equivalent Clarks Ferry and Duncannon Members of the Catskill Formation in central PA (Oest, 2015) as well as continental facies in the Lower Mississippian Pocono Formation of PA and Price Formation of VA are analysed in this study for purposes of constraining Acadian drainage areas.

2.3 | Alleghanian Orogeny

The Alleghanian Orogeny in the Late Mississippian-Pennsylvanian of VA resulted from the closing of the Theic ocean (Figure 3) with collision of Gondwana with Laurentia (Ettensohn, 1994; Hatcher, 1989, 2002; Thomas & Hatcher, 2021). Initial onset of thrust loading is reflected in the abrupt thickening of the Mississippian Greenbrier carbonates in the foredeep in southwestern VA (Figure 2). Synorogenic, mostly siliciclastic sedimentary rocks representing the Alleghanian clastic wedge, are preserved in the Valley and Ridge and Cumberland Plateau provinces, and include the predominantly continental, Upper Mississippian Mauch Chunk Group (Figure 2; Miller & Eriksson, 2000), and the Pennsylvanian Breathitt Group (Figures 1 and 2; Englund & Thomas, 1990; Greb & Chesnut, 1996; Greb & Martino, 2005; Grimm et al., 2013; Read & Eriksson, 2016). The Alleghanian orogeny extended from 330 to 260 Ma and culminated in overthrusting of Grenville basement producing the Blue Ridge Province (Figure 1; Cook et al., 1979; Hatcher, 1972, 2002). Ages of the Alleghanian-age plutons in the Inner Piedmont and Carolina superterrane range from 263 to 330 Ma.

The Alleghanian clastic wedge developed in a wide and relatively shallow foreland basin with a major depocenter located in VA and WV and extending north and south into PA and TN, respectively (Figure 1; Thomas & Hatcher, 2021). During the Mississippian and Pennsylvanian, North America occupied low latitudes (Read & Eriksson, 2016). This study focuses on one fluvial sandstone body from the Late Mississippian (Princeton Formation) and three fluvial sandstone bodies from the Lower and Middle Pennsylvanian Breathitt Group (Pocahontas, Alvy Creek and Kanawha formations) (Figure 2) that developed in incised valleys oriented transverse to the axis of the foreland basin. These transverse fluvial systems merged into a large, bedload-dominated longitudinal (axial) braided-river system draining an Amazon-scale cratonic watershed (Buller et al., 2018; Greb & Chesnut, 1996; Korus et al., 2008; Rice & Schwietering, 1988). During subsequent sea level rise, these broadly incised fluvial systems were transgressed forming estuaries (Greb & Chesnut, 1996; Greb & Martino, 2005; Grimm et al., 2013; Korus et al., 2008). Following drowning, small-scale, tropical, fluvial-dominated bayhead deltas prograded into the basin, infilling available accommodation (Grimm et al., 2013; Korus et al., 2008). This study focusses on these four Upper Mississippian and Lower and Middle Pennsylvanian fluvial sandstone bodies for purposes of constraining Alleghanian drainage areas.

3 | METHODS

3.1 | Outcrop selection

Outcrops of the following fluvial sandstones in the Valley-and-Ridge and Cumberland Plateau provinces in the Appalachians were examined to understand the internal architecture of sediment bodies: (1) the Upper Ordovician Bald Eagle Formation in PA (Taconic Clastic Wedge); (2) the Upper Devonian-Lower Mississippian Hampshire and Price formations in VA and WV and the Upper Devonian-Lower Mississippian Catskill and Pocono formations in PA (Acadian Clastic Wedge); and (3) the Upper Mississippian Princeton Formation in WV, and the Lower Pennsylvanian Pocahontas and Alvy Creek formations and Middle Pennsylvanian Kanawha Formation of the Breathitt Group in VA and WV (Alleghanian Clastic Wedge) (Figure 2). Selection of these outcrops was based on the following criteria: (1) fluvial strata of Taconic-age are present only in PA; (2) the Acadian orogeny was primarily a New England orogenic event with minimum expression in the Central Appalachians. By investigating Acadian-age strata in PA as well as in VA and WV, it is possible to compare the scale of channel elements close to the orogeny (PA) and with those in more distal settings (VA and WV) to evaluate whether a single or two or more paleodrainage basins existed; (3) the Alleghanian orogeny was primarily a Central Appalachian phenomenon and, as a consequence, this study focusses on Upper Mississippian and Lower and Middle Pennsylvanian age strata from VA and WV. Localities were chosen based on quality of road cut exposures, lateral continuity of individual sandstone bodies (up to 5 km) and vertical stacking of multiple sandstone bodies (of up to 500 m) within formations.

3.2 | Data collection and paleodepth estimates

Architectural elements (macroforms) were documented in the field and on photomosaics (mostly from road cuts) using the architectural element and bounding surface framework developed by Miall (1985, 1988). Architectural elements are characterized by distinctive assemblages of facies, internal geometry, external form and, in some instances, vertical profile (Figure 4; Miall, 1985, 1988). In this study, emphasis was placed on determining the thicknesses of erosionally based, channel architectural elements; thicknesses of architectural elements are listed in Supplemental Table A. Bankfull channel depths, representing depths at peak discharge, were estimated from thicknesses of architectural elements. Statistical analysis has shown that thicknesses of preserved channel elements in the stratigraphic record represent 40%–75% (59% mean) of the original channel flow depth (Paola & Bergman, 1991). Based on the mean scaling ratio, mean bankfull depth = 1.695 channel element thickness. In a more recent study, Alexander et al. (2020) proposed a scaling ratio of 20%–60% (mean 39%) for bar-scale inclined strata (clinoforms). In this analysis, maximum element thicknesses are used for two reasons: (1) upper parts of elements were removed by erosion because bar-tops rollovers are not preserved in the studied intervals; and (2) thicker elements are more likely to record trunk rather than tributary fluvial systems. Examination of 3-D exposures in this study reveals that channel elements are a product of scour-and-fill by migrating dunes and do not involve downstream accretion of bars (Figure 4). For this reason, the scaling factor of Paola and Bergman (1991) rather than that of Alexander et al. (2020) was used to generate first approximations of paleoflow depth (Table 1).

3.3 | Estimates of drainage area, discharge and areas of distributive fluvial systems

Drainage basin areas and discharge were estimated using the approach of Davidson and North (2009). Regional hydraulic curves developed by Davidson and North (2009) from modern river catchment surveys have the allometric form:

$$y = a(x)^b,$$

where y = bankfull depth or discharge, x = drainage basin area, and (a) and (b) are region-specific variables dependent on climate, geographic location and lithology (Table 1). Ideally, the selected regional curve should mimic the characteristics of the example from the rock-record, notably similar paleolatitude and climate. Calculations were performed in imperial units and then converted to metric because the coefficient and exponents for the regional curves of Davidson and North (2009) were derived from data in imperial measurement.

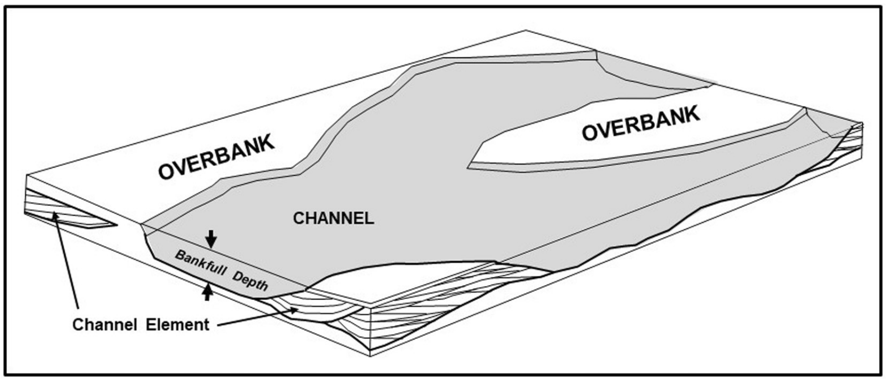

FIGURE 4 Architectural element diagram illustrating geometries of channel (CH) elements. Channel elements within the Upper Ordovician Bald Eagle Formation, Upper Devonian Catskill and Hampshire formations, Lower Mississippian Price and Pocono formations, and Upper Mississippian Princeton Formation and Pennsylvanian Lower to Middle Breathitt Group are mainly concave-upward channel fills perpendicular to flow and tangential foresets parallel to flow. Channel elements are interpreted to be a product of scour-and-fill by downstream-migrating dunes.

TABLE 1 Architectural element data, modern regional curve explanation and bankfull depth/discharge parameters used, and resultant drainage areas, discharges, and DFS areas.

Formation	Max channel element thickness	Max bankfull-channel depth[a]		Modern regional curve location	Climate classification and description[b]	Regional curve parameters[c] Bankfull depth	Regional curve parameters[c] Discharge	Estimated drainage area (km^2)	Estimated average discharge (m^3/s)	DFS area (km^2)[d]
Kanawha	3.7 m	6.2 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	16,926	928	437
"	3.7 m	6.2 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to humid continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	106,151	4534	1157
"	3.7 m	6.2 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	1,939,785	12,331	5397
"	3.7 m	6.2 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	60,801	995	861
Alvy Creek	3.7 m	6.2 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	16,926	928	437
"	3.7 m	6.2 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to humid continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	106,151	4534	1157
"	3.7 m	6.2 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	1,939,785	12,331	5397
"	3.7 m	6.2 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	60,801	995	861
Pocahontas	2.4 m	4.1 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	6061	466	254
"	2.4 m	4.1 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to humid continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	31,534	1596	608
"	2.4 m	4.1 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	365,538	3411	2229

TABLE 1 (Continued)

Formation	Max channel element thickness	Max bankfull-channel depth[a]		Modern regional curve location	Climate classification and description[b]	Regional curve parameters[c] Bankfull depth	Discharge	Estimated drainage area (km^2)	Estimated average discharge (m^3/s)	DFS area (km^2)[d]
"	2.4 m	4.1 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	12,248	319	368
Princeton	3.6 m	6.1 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	16,292	905	429
"	3.6 m	6.1 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to humid continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	101,468	4361	1130
"	3.6 m	6.1 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	1,823,106	11,755	5223
"	3.6 m	6.1 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	57,285	953	835
Pocono	7.2 m	12.2 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	96,350	2976	1099
"	7.2 m	12.2 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to humid continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	828,977	26,552	3440
"	7.2 m	12.2 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	32,741,873	108,653	24,137
"	7.2 m	12.2 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	916,567	6827	3628
Price	2.1 m	3.6 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	4303	371	212
"	2.1 m	3.6 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to humid continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	21,040	1127	491

TABLE 1 (Continued)

Formation	Max channel element thickness	Max bankfull-channel depth[a]		Modern regional curve location	Climate classification and description[b]	Regional curve parameters[c]: Bankfull depth	Regional curve parameters[c]: Discharge	Estimated drainage area (km^2)	Estimated average discharge (m^3/s)	DFS area (km^2)[d]
"	2.1 m	3.6 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	209,556	2222	1659
"	2.1 m	3.6 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	7180	218	278
Catskill	4.9 m	8.3 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	35,505	1524	648
"	4.9 m	8.3 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to Humid Continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	254,769	9626	1840
"	4.9 m	8.3 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	6,464,857	31,156	10,216
"	4.9 m	8.3 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	193,109	2259	1589
Hampshire	3.7 m	6.2 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	16,926	928	437
"	3.7 m	6.2 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (Ds*a*, Ds*b*, Ds*c*) to humid continental with no dry season (Df*b*, Df*c*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	106,151	4534	1157
"	3.7 m	6.2 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	1,939,785	12,331	5397
"	3.7 m	6.2 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (Cf*a*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	60,801	995	861
Bald Eagle	2.2 m	3.7 m	A	Pacific maritime Mts of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of cool Mediterranean (Cs*b*) seasonal climates and maritime temperate (Cf*b*) with no seasonal variation in precipitation	$a = 0.66$ $b = 0.39$	$a = 91.05$ $b = 0.67$	4587	387	219

TABLE 1 (Continued)

Formation	Max channel element thickness	Max bankfull-channel depth[a]		Modern regional curve location	Climate classification and description[b]	Regional curve parameters[c] Bankfull depth	Discharge	Estimated drainage area (km^2)	Estimated average discharge (m^3/s)	DFS area (km^2)[d]
"	2.2 m	3.7 m	B	Western Cordillera of US Pacific Northwest coast (Castro & Jackson, 2001)	Combination of dry summer continental climates with seasonal precipitation (*Dsa*, *Dsb*, *Dsc*) to humid continental with no dry season (*Dfb*, *Dfc*)	$a = 0.61$ $b = 0.33$	$a = 17.28$ $b = 0.86$	22,689	1203	511
"	2.2 m	3.7 m	C	Western Interior Basin and range of US Pacific Northwest coast (Castro & Jackson, 2001)	Semi-Arid, Steppe (BSk) climate with seasonal precipitation	$a = 0.79$ $b = 0.24$	$a = 13.05$ $b = 0.77$	232,462	2407	1753
"	2.2 m	3.7 m	D	Alabama and North West Florida coastal plains (Metcalf, 2004)	Humid subtropical climate with significant precipitation in all seasons (*Cfa*)	$a = 1.64$ $b = 0.25$	$a = 27.7$ $b = 0.71$	7932	234	293

[a]1.695 correction factor of Paola and Bergman (1991) applied to maximum measured element thicknesses.

[b]Koppen climate symbols are as follows: Af, tropical rainforest; Am, tropical monsoon; Aw, tropical savannah; BW, arid desert; BS, arid steppe—subscripts *h* and *k* refer to hot and cold, respectively; Cs, temperate dry summer; Cw, temperate dry winter; Cf, temperate without dry season—subscripts *a*, *b*, and *c* refer to hot summer, warm summer, and cold summer, respectively; Ds, cold dry summer; Dw, cold dry winter; Df, cold without dry season—subscripts *a*, *b*, *c*, and *d* refer to hot summer, warm summer, cold summer, and very cold winter, respectively; ET, polar tundra; EF, polar frost.

[c]The coefficient (a) and exponent (b) are quoted in the original source and were computed for imperial units of measure; results have been converted to metric units.

[d]From equation 1 in Davidson and Hartley (2014): DFS Area = $2.51(DA)^{0.53}$ $R^2 = 0.95$ (braided bifurcating DFSs).

In this study, four different climatic scenarios (regional curves) from Davidson and North (2009) are evaluated for fluvial units in each of the Taconic, Acadian and Alleghanian clastic wedges (Table 1). Estimates of areas of distributive fluvial systems (DFS) are based on the study by Davidson and Hartley (2014) who demonstrated a strong correlation between DFS and drainage area using the equation:

$$\text{DFS area} = 2.51\ \text{DA}^{0.53},$$

where DA = drainage area. This equation is used when the fluvial system is of the braided bifurcating type.

4 | RESULTS

4.1 | Taconic clastic wedge

4.1.1 | Facies and architectural element analysis

Architectural element data are from fluvial facies of the Bald Eagle Formation at Potters Mills along Route 322 in central PA (Figure 1). The Bald Eagle Formation at Potters Mills is dominated by coarse- to medium-grained, grey-white sandstone with rare (<0.3 m) conglomerate units (Figure 5). Rounded pebbles of vein quartz-chlorite, feldspar, granite and siderite up to 3.5 cm in diameter and angular mudstone clasts <1 cm long define bases of cross set boundaries and are distributed along foresets. Tabular to erosionally-based sandstone bodies range in thickness from 0.3 m (1.0 ft) to 2.2 m (7.2 ft) (Figure 5; Supplemental Table A). Basal erosional surfaces are up to 0.2 m (0.8 ft) in relief. Internally, the lower two thirds of depositional units are coarse-grained with large-scale tangential cross strata (Figure 6). Horizontal stratification is rare. These depositional units fine upwards to medium-grained sandstone dominated by cosets of small-scale, tangential cross strata. Pebbles and mudstone clasts are more common in the lower coarse-grained portions of depositional units. Mudstone interbeds and trace fossils are absent. The association of criteria listed above are interpreted as channel elements, consistent with a braided-fluvial setting of higher-energy floods followed by waning energy.

4.1.2 | Bankfull depth estimates and results of drainage area and discharge estimates

Based on the maximum thicknesses for channel elements of 2.2 m (ca. 7.2 ft) in the Bald Eagle Formation at Potters Mills in PA, maximum bankfull depths for the

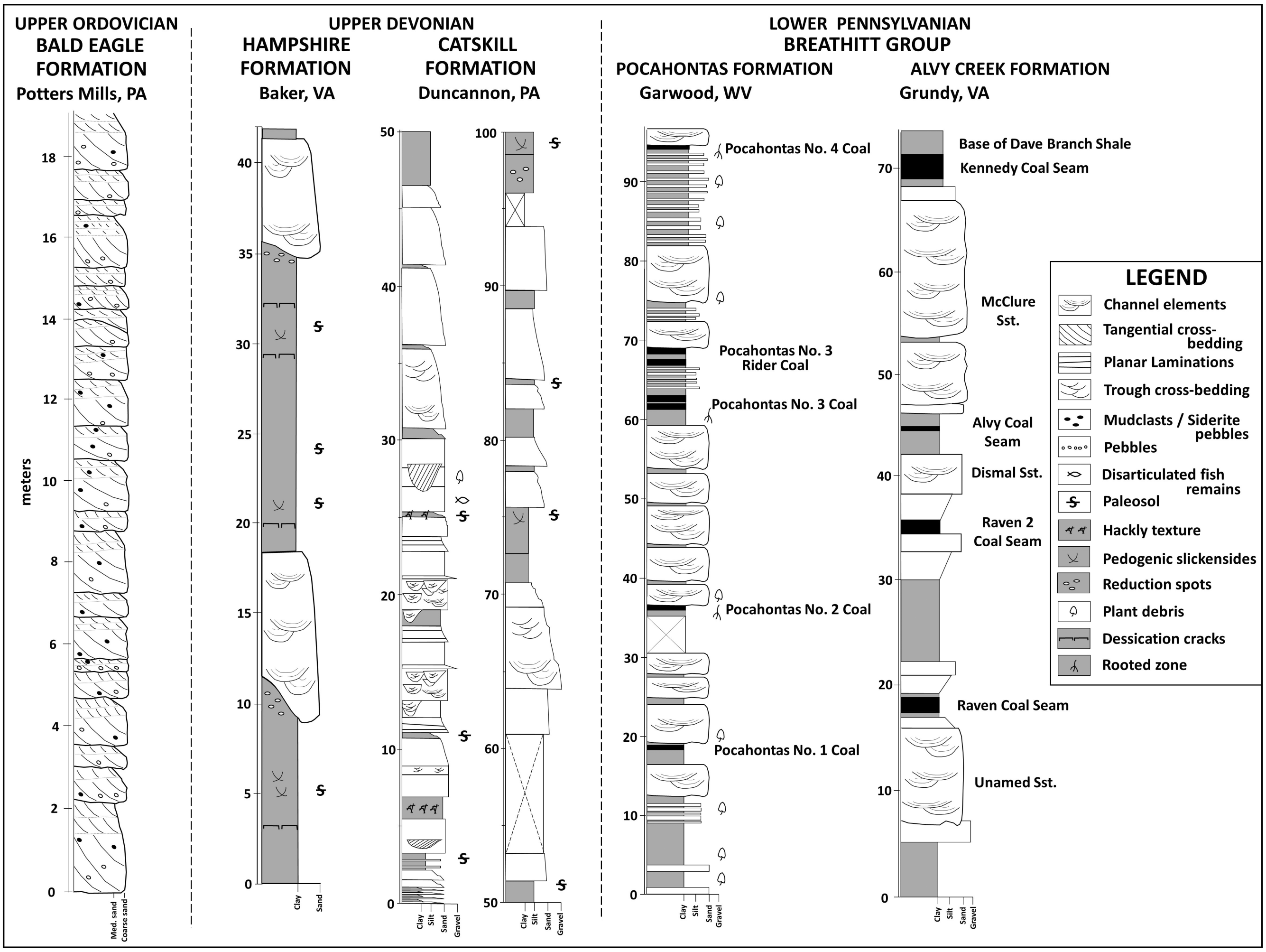

FIGURE 5 Examples of measured sections of stratigraphic intervals from which channel thickness measurements were measured.

elements at Potters Mills can be estimated as 3.7 m (ca. 12.2 ft) (Table 1). Calculated drainage areas for the Bald Eagle Formation range from 4587 km^2 for scenario "A" to 232,462 km^2 for scenario "C" (Table 1). Estimated discharge values correspondingly, range from 387 to 2407 m^{3}s^{-1} (Table 1). Calculated DFS areas for the Bald Eagle Formation range from 219 to 1753 km^2 (Table 1).

4.2 | Acadian clastic wedge

4.2.1 | Facies and architectural element analysis

Architectural element data are from the Clarks Ferry and Duncannon Members of the Catskill Formation along Route 11 and the Pocono Formation along I 81 in central PA, and the equivalent Hampshire Formation along Routes 33 and 55 in VA and WV and Price Formation along the Huckleberry Trail in Montgomery Co, VA (Figure 1). The Catskill-Pocono and Hampshire-Price formations at all five locations are dominated by braided and subordinate meandering channel facies interbedded with overbank red mudstones and paleosols (Figure 5). In cross sections perpendicular to flow, sandstone intervals with rare pebble lags are dominated by multilateral-multistory channel elements that range in thickness from 0.4 m (1.3 ft) to 7.2 m (23.6 ft) in PA and 0.8 m (2.5 ft) to 3.7 m (12 ft) in VA and WV (Supplemental Table A). In cross sections parallel to flow, large-scale tangential cross beds are the dominant sedimentary structure (Figure 7a–c) and indicate paleoflow to the west.

Overbank fines are dominated by mudstone, most of which were subjected to pedogenesis. Paleosols identified in the Catskill Formation of PA include argillic gleysols, argillic calcisols and argillic vertisols indicative of occasionally waterlogged to semi-arid conditions (Oest, 2015; Retallack et al., 2009, soil classification after Mack et al., 1993). Paleosols intercalated within predominantly shallow-marine facies in the upper portion of the Foreknobs Formation below the Hampshire Formation (Figure 2) include entisols and vertisols (McClung

FIGURE 6 Erosionally-based, shallow channel element from the Upper Ordovician, Bald Eagle Formation at Potters Mills, PA (scale in centimetres and inches).

et al., 2013). Sand-filled desiccation cracks up to 25cm deep (Figure 7d) and local pedogenic slickensides and reduction haloes are developed in overbank deposits in the Hampshire Formation.

4.2.2 | Bankfull depth estimates and results of drainage area and discharge estimates

Based on the maximum thickness of 4.9m (ca. 16ft.) for channel elements in the Catskill Formation of PA, maximum bankfull depth can be estimated as 8.3m (ca. 27.1ft) (Table 1). Calculated drainage areas range from 35,505 km^2 for scenario “A” to 6,464,857 km^2 for scenario “C” (Table 1). Estimated discharge values, correspondingly, range from 1524 to 31,156 m^{3}s^{-1} (Table 1). Calculated DFS areas for the Catskill Formation range from 648 to 10,216 km^2 (Table 1). Based on the maximum thickness of 3.7m (ca. 12ft.) for channel elements in the equivalent Hampshire Formation of central and northern VA, maximum bankfull depth can be estimated as 6.2m (ca. 20.3ft.) (Table 1). Calculated drainage areas range from 16,926 km^2 for scenario “A” to 1,939,785 km^2 for “C” (Table 1). Estimated discharge values, correspondingly, range from 928 to 12,331 m^{3}s^{-1} (Table 1). Calculated DFS areas for the Hampshire Formation range from 437 to 5397 km^2 (Table 1).

Based on the maximum thickness of 7.2m (ca. 23.6ft) for channel elements in the Pocono Formation of central PA, maximum bankfull depth can be estimated as 12.2m (ca. 40.0ft.) (Table 1). Calculated drainage areas range from 96,350 km^2 for scenario “A” to 32,741,873 km^2 for “C” (Table 1). Estimated discharge values, correspondingly, range from 2976 to 108,653 m^{3}s^{-1} (Table 1). Calculated DFS areas for the Pocono Formation range from 1099 to 24,137 km^2 (Table 1). Based on the maximum thickness of 2.1m (ca. 7ft.) for channel elements in the equivalent Price Formation of central VA, maximum bankfull depth can be estimated as 3.6m (11.9ft.) (Table 1). Calculated drainage areas range from 4303 km^2 for scenario “A” to 209,556 km^2 for C (Table 1). Estimated discharge values, correspondingly, range from 371 to 2222 m^{3}s^{-1} (Table 1). Calculated DFS areas for the Price Formation range from 212 to 1659 km^2 (Table 1).

4.3 | Alleghanian clastic wedge

4.3.1 | Facies and architectural element analysis

Architectural element data are from the Upper Mississippian Princeton Formation along I 77 north of Princeton, WV, from a Lower Pennsylvanian sandstone above the Pocahontas #2 coal seam of the Pocahontas Formation along I77 north of Princeton, WV, from the “unnamed sandstone” of the Alvy Creek Formation below the Raven coal seam along Routes 460 and 83 in Grundy, VA, and from the Middle Pennsylvanian Kanawha Formation along Route 99 northeast of Bolt, WV (Figures 1 and 5).

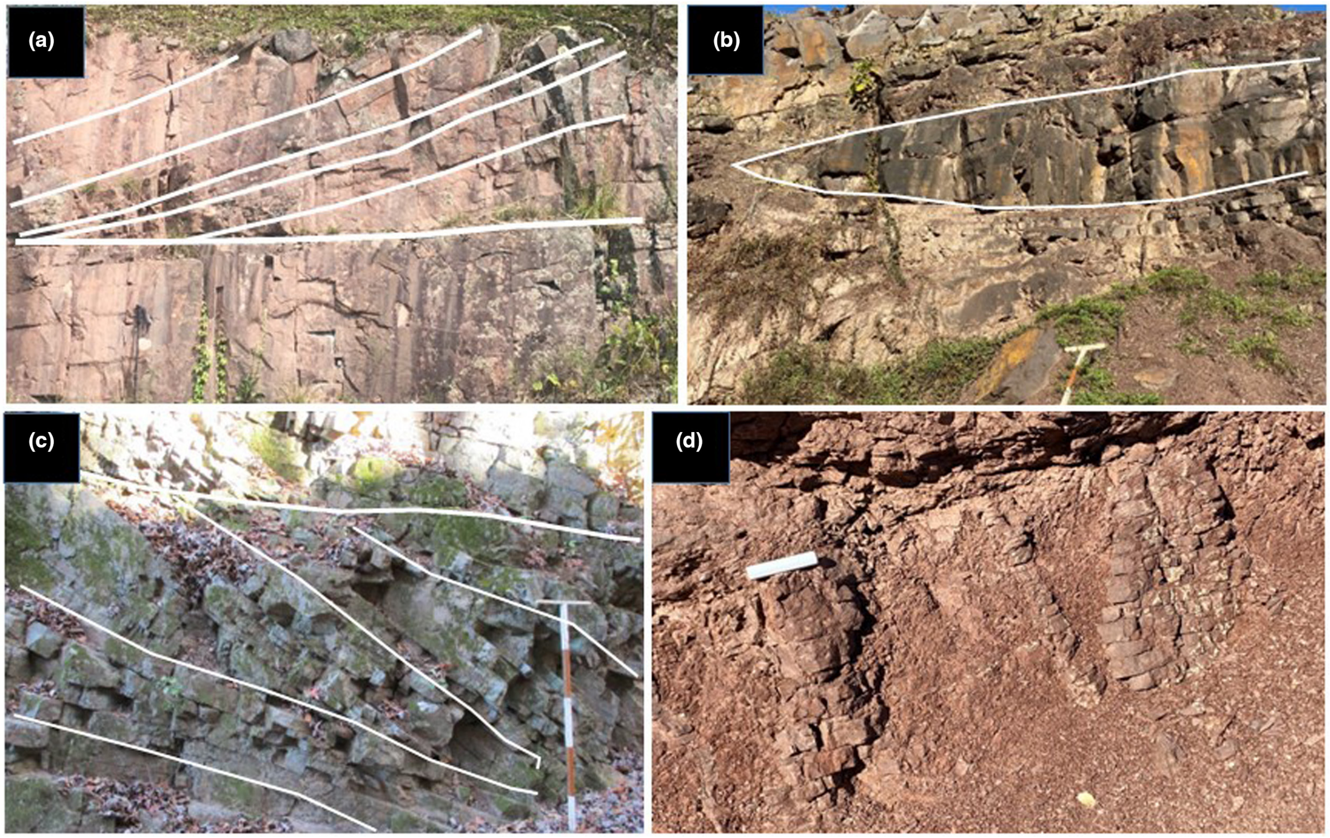

FIGURE 7 Field photos of Upper Devonian, Acadian fluvial facies: (a) Large-scale tangential cross beds infilling shallow channels, Hampshire Formation along Route 33, Shenandoah Mountain, VA. Scale is 1.5 m in length; (b) Cross section of a shallow channel element, Hampshire Formation along Route 55, near Baker, WV. Scale is 1.6 m in length; (c) Large-scale, tangential cross strata infilling a shallow channel, Price Formation along Huckleberry Trail, Montgomery Co, VA; (d) Sand-filled desiccation cracks within overbank fines of the Hampshire Formation along Route 55, near Baker, WV. Scale is 6 cm in length.

Incised valley fills of the Princeton Formation and Breathitt Group transverse fluvial systems are 1–10 km wide and up to 30 m thick (Korus et al., 2008; Miller & Eriksson, 2000). Infilling erosive-based sandstone bodies are 5 to 20 m thick and consist of multistory-multichannel elements which fine-upward from coarse- to fine-grained sand (Figure 8a,b). Erosive bases exhibit 2 to 10 m of localized relief. In outcrop and in core, sandstones are medium grey along fresh surfaces, with common conglomerate lags containing siderite, shale fragments and plant debris. Rare quartz pebbles exhibit a bluish tint suggestive of a Grenvillian provenance (Herz & Force, 1984). Paleocurrent modes are to the northwest to southwest. Subordinate planar cross-beds, horizontal laminations, ball-and-pillow structures, and climbing ripples are locally present at the top of sandstone bodies passing upward into a rooted top surface below a tabular coal horizon (Grimm et al., 2013). Coal seams in the Lower and Middle Pennsylvanian, in general, are associated with estuarine facies above the incised valley fills, and with overlying deltaic facies. Dark grey to black mudstone underlying coalbeds universally grades upward into seat earths characterized by gleyed, rooted mudstones with drab, blocky textures and common *Stigmaria* root structures and other plant fragments (histosols). Overlying coalbeds range from 0.1 to 2 m in thickness in the study interval. Cecil et al. (1985, 1993) and Cecil (1990) proposed that these coals developed in domed ombrogenous peat swamps that are peat-forming vegetation communities lying above ground water level and thus dependent on rainwater for mineral nutrients.

In cross sections perpendicular to flow, individual channel elements of sandstone bodies are between 0.3 (1 ft) and 3 m (10 ft) thick. In cross sections parallel to flow, architectural elements range in thickness from 0.6 to 3.7 m (2 to 12 ft) and consist of large-scale, tangential cross beds defined by reactivation surfaces (Figure 8c and Supplemental Table A).

4.3.2 | Bankfull depth estimates and results of drainage area and discharge estimates

Based on maximum channel element thicknesses of 3.6 m (ca. 11.8 ft) for the Princeton Formation, maximum

FIGURE 8 Field photos of Alleghanian fluvial facies: (a) Erosionally based, multistory-multichannel elements in the Upper Mississippian Princeton Formation along I77 north of Princeton, WV at the Route 7 exit off I77. Scale bar is 2 m in length; (b) Erosionally based, multistory-multichannel elements in the Lower Pennsylvanian Pocahontas Formation along I77 north of Princeton, WV. Scale is 1.5 m in length; (c) Large-scale, tangential cross beds defined by reactivation surfaces within a channel element in the Lower Pennsylvanian Alvy Creek Formation at the intersection of Routes 460 and 83, Grundy, VA. Scale is 15 cm in long dimension.

bankfull depth can be estimated as 6.1 m (ca. 20.0 ft). Calculated drainage areas range from 16,292 km^2 for scenario "A" to 1,823,106 km^2 for scenario "C" (Table 1). Estimated discharge values, correspondingly, range from 905 to 11,755 m^3s^{-1} (Table 1). Calculated DFS areas for the Princeton Formation range from 429 to 5223 km^2 (Table 1).

Based on maximum channel element thicknesses of 2.4 m (ca. 8 ft) for the Pocahontas Formation, maximum bankfull depth can be estimated as 4.1 m (ca. 13.6 ft) (Table 1). Calculated drainage areas range from 6061 km^2 for scenario "A" to 365,538 km^2 for scenario "C" (Table 1). Estimated discharge values correspondingly range from 466 to 3411 m^3s^{-1} (Table 1). Calculated DFS areas for the Pocahontas Formation range from 254 to 2229 km^2 (Table 1).

Based on the maximum thickness of 3.7 m (ca. 12 ft) for channel elements in the Alvy Creek Formation of southwestern Virginia and the Kanawha Formation of West Virginia, maximum bankfull depth can be estimated as 6.2 m (ca. 20.3 ft) (Table 1). Similar maximum paleodepth estimates of ca. 5.5 m based on bar thicknesses were proposed for the overlying Middle to Upper Pennsylvanian Allegheny Formation in West Virginia (Abatan & Weislogel, 2020; Figure 2). Calculated drainage areas range from 16,926 km^2 for "A" and 1,939,785 km^2 for "C" (Table 1). Estimated discharge values, correspondingly, range from 928 to 12,331 m^3s^{-1} (Table 1). Calculated DFS areas for the Alvy Creek and Kanawha formations range from 437 to 5397 km^2 (Table 1).

5 | DISCUSSION

5.1 | Selection of regional curves

Regional hydraulic curves that ideally match conditions during the Late Ordovician, Late Devonian, Early and Late Mississippian, and Early and Middle Pennsylvanian in the Central Appalachian Basin are not available. However, paleoclimatic conditions for these time intervals can be inferred using a combination of criteria that permit one or more of the regional hydraulic curves A–D (Table 1) to be used to estimate drainage areas and discharges from fluvial facies for the different time intervals.

5.1.1 | Taconic

Paleoclimate interpretations for the Late Ordovician are based on paleosols. Well-developed vertisols with large-scale pedogenic slickensides are described from estuarine and tidal flat facies in the southern Appalachians and are interpreted to indicate a subtropical to warm-temperate, seasonal paleoclimate with 4–8 dry months per year (Driese & Forman, 1992); this interpretation is consistent with that of Retallack (2011) for paleosols of similar age in the northern Appalachians.

Palaeosol evidence, coupled with the presence of coarse-grained, high-energy pebbly sandstones in the Bald Eagle Formation, are consistent with scenario "B" or "C" in Table 1. Scenario "A", characterized by no seasonal variation in precipitation, and scenario "D" characterized by a humid, subtropical climate with significant precipitation in all seasons, are incompatible with the palaeosol evidence for alternating wet and dry monsoonal conditions. Scenario "B", characterized by a combination of dry summer continental climates with seasonal precipitation to humid continental with no dry season, is favoured over scenarios "A" and "D". The larger drainage area estimated for scenario "C" (232, 462 km^2), with similar seasonal but more arid climatic conditions than scenario "B", is inconsistent with Late Ordovician paleogeographic reconstructions of Blakey (2022) involving accretion of a linear island arc system. Based on the scenario "B" curve, the estimated drainage area for the Bald Eagle Formation was on the order of 22,689 km^2.

5.1.2 | Acadian

Paleoclimate interpretations for the Hampshire and Catskill formations are based on types of paleosols and the presence of desiccation cracks and plant fossils. Argillic calcisols and vertisols with well-developed shrink-swell textures support seasonal, semi-arid conditions; an interpretation consistent with the presence of deep, sand-filled, desiccation cracks in overbank deposits (Figure 7d) as indicative of long-term subaerial exposure. Argillic gleysols are suggestive of occasionally waterlogged conditions during which early land plants developed in overbank settings. These observations are consistent with most of the Hampshire Formation having been deposited under dry, sub-humid conditions (Cecil, 1990; McClung et al., 2013). The increase in abundance of plant fossils upwards in the Hampshire Formation may imply a gradual change to more humid conditions with time (Cecil, 1990).

The abundance of evidence from the Catskill and Hampshire formations supports a climate similar to the Western Cordillera of the US Pacific Northwest coast (Castro & Jackson, 2001) that compares favourably with scenario "B" in Table 1. The climate for this regional curve is characterized by a combination of dry summer continental climates, with seasonal precipitation, and humid continental climates with no dry season. Based on this curve, the estimated maximum drainage basin area for the Hampshire-Catskill deposits equates to ca. 106,000 to 255,000 km^2 (Table 1). Scenario "A" from the Pacific Maritime Mountains of the Pacific Northwest Coast, characterized by a combination of cool Mediterranean seasonal climate and Maritime temperate with no seasonal variation in precipitation, is worthy of consideration but this scenario is not compatible with a seasonal paleoclimate inferred from the paleosols. Scenario "C" is unrealistic because the estimated drainage areas for the Catskill Formation is comparable to the Amazon River (6,300,000 km^2) whereas scenario "D" with a humid, subtropical climate with significant precipitation in all seasons is incompatible with the paleoclimatic evidence for the Late Devonian.

An increase in abundance of plant debris upwards in the Hampshire Formation (Brezinski et al., 2009) coupled with the presence of thin coal seams in the Price and Pocono formations is suggestive of more humid conditions in the Early Mississippian than in the Late Devonian (Figure 2; Read & Eriksson, 2016). The increase in rainfall however was accompanied by a decrease in temperatures related to the onset of the Late Devonian glaciation (Brezinski et al., 2010). The evidence for everwet but relatively cool conditions in the Early Mississippian may favour scenario "A" for the Price and Pocono formations with drainage areas between 4303 and 96,350 km^2 (Table 1).

5.1.3 | Alleghanian

Paleoclimate interpretations for the Princeton, Pocahontas, Alvy Creek and Kanawha formations are based on types of paleosols, plant fossils, coals, character of the peat swamps and seat earths. Extensive red beds, vertisols and calcisols in the Hinton Formation beneath the Princeton Formation have been cited as evidence for semi-arid conditions in the Late Mississippian (Cecil, 1990; Miller & Eriksson, 1999, 2000). The presence of seat earths characterized by gleyed, rooted mudstones with drab, blocky textures and common *Stigmaria* root structures and other plant fragments coupled with the overlying coals, supports an everwet, tropical climate during the Early Pennsylvanian and persisting through the mid-Middle Pennsylvanian (Cecil, 1990). Frequent tropical rainy periods were necessary to sustain the domed ombrogenous peat swamps (Cecil, 1990; Cecil et al., 2003).

The abundance of evidence from the Late Mississippian supports a paleoclimate most comparable to that on which scenario "B" is based, namely a combination of dry summer climate with no seasonal precipitation to humid continental with no dry season producing a drainage area estimate of ca. 100,000 km^2 (Table 1). A similar drainage basin area has previously been proposed for the Princeton Formation (Buller et al., 2018; Eriksson & Romans, 2017). A change occurred in the Early and Middle Pennsylvanian to a paleoclimate on which scenario "D" is based, namely a humid, everwet, subtropical climate with significant precipitation in all seasons. Based on this curve, the estimated maximum drainage basin area for the Pocahontas, Alvy Creek and Kanawha formations equates from ca. 12,000 to 61,000 km^2 (Table 1). Alternative scenarios "A", "B" and "C" are incompatible with the paleoclimatic interpretation.

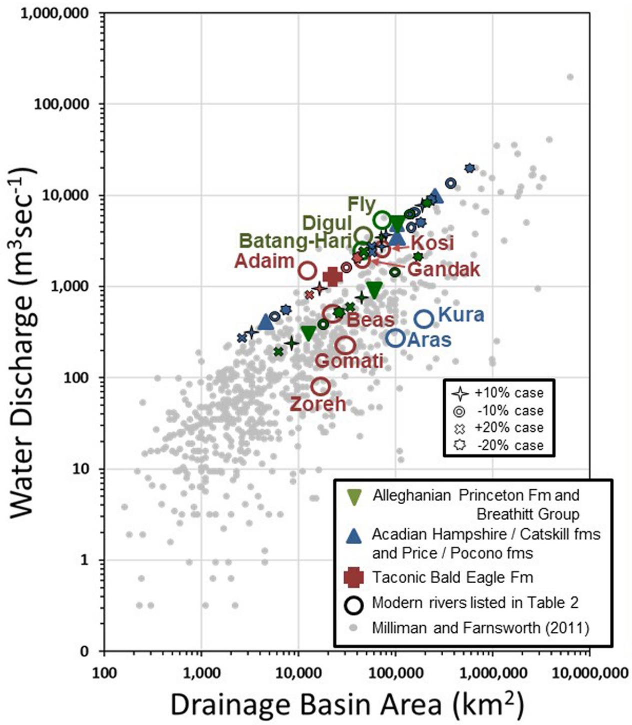

FIGURE 9 Relationship between discharge and drainage area for 736 modern global rivers (Milliman & Farnsworth, 2011) with drainage basin and discharge estimates for fluvial units in the Taconic, Acadian and Alleghanian clastic wedges. For each of the estimated river systems in this study, drainage areas and discharges were calculated using the mean as well as the ±10% and ±20% errors in estimates of paleoflow depths. Note that estimates based on these errors fall within the envelope for modern rivers of Milliman and Farnsworth (2011). Also shown are Holocene analogs for the selected river systems.

5.2 | Modern analog rivers

Drainage basin area and discharge estimates for scenario "B" for the Bald Eagle Formation (Taconic), scenario "B" for the Hampshire and Catskill formations (Acadian), scenario "A" for the Price and Pocono formations, scenario "B" for the Princeton Formation and scenario "D" for the Pocahontas, Alvy Creek and Kanawha formations (Alleghanian) fall within the drainage area versus discharge envelope for modern rivers (Figure 9; data from Milliman & Farnsworth, 2011, supplemented by data from Wikipedia, 2022).

Modern analogs for the Taconic river systems (Table 2) are tributaries to the Ganges River in northern India and Nepal such as the Beas, Gomati, Gandak and Kosi rivers with drainage areas from 20,203 to 74,500 km^2 and mean discharge values from 234 to 2500 m^3s^{-1} (Table 2). Other possible analogs for the Taconic rivers are the Adaim River in Iraq and Iran which is a tributary to the Tigris River with a drainage area of 12,482 km^2 and a mean discharge of 1476 m^3s^{-1} (Hussein & Hameed, 2019) and the Zoreh River in western Iran which flows through the Zagros Mountains directly into the Persian Gulf foreland basin and has a drainage area of 17,150 km^2 and a mean discharge of 79 m^3s^{-1} (Table 2). All of the above rivers are appropriate analogs for the Taconic fluvial deposits because of the prevailing semi-arid to monsoonal climatic conditions and their association with active orogenic belts. Most of these analogs display multi-channel braiding consistent with sedimentary structures in the Upper Ordovician Bald Eagle Formation.

Analogs for the Acadian river systems (Table 2) are the Aras and Kura rivers in the Caucasus that originate is eastern Turkey before flowing through northern Iran, Armenia, Georgia and Azerbaijan and into the Caspian Sea. The Aras and Kura rivers have drainage areas of 102,000 and 198,000 km^2 and mean discharge values of 285 and 442 m^3s^{-1}, respectively (Figure 8, Table 2). Climatic conditions in the drainage areas of both rivers are semi-arid steppe with grassland vegetation similar to the paleoclimate inferred for the Catskill and Hampshire

River system		Drainage basin area (km^2)	Discharge (m^3/s)
Middle Penn. Kanawha (WVA)	**Breathitt Group**	**60,801**	**995**
Lower Penn. Alvy Creek (VA)		**60,801**	**995**
Lower Penn. Pocahontas (WVA)		**12,248**	**319**
Upper Miss. Princeton (WVA)		**101,468**	**4361**
Fly River: Papua, New Guinea		76,000	5704
Digul River: Papua, New Guinea		45,900	4000
Batang-Hari River: Sumatra, Indonesia		44,890	2560
Lower Miss. Pocono (PA)		**96,350**	**2976**
Lower Miss. Price (VA)		**4303**	**371**
Upper Devonian Catskill Fm. (PA)		**254,769**	**9626**
Upper Devonian Hampshire Fm. (WVA, VA)		**106,151**	**4534**
Aras River: Iran/Turkey		102,000	285
Kura River: Iran/Turkey		198,000	442
Upper Ordovician Bald Eagle Fm. (PA)		**22,689**	**1203**
Beas River: India		20,203	499
Gomati River: India		29,865	234
Gandak River: Nepal/India		46,300	2025
Kosi River: Nepal/India		74,500	2500
Adaim River: Iraq/Iran		12,482	1476
Zoreh River: Iran		17,150	79

Bold letters and values refer to fluvial deposits investigated in this study. Non-bold letters and values refer to modern analog rivers.

TABLE 2 Drainage area and discharge estimates for Upper Ordovician Bald Eagle Formation, Upper Devonian Hampshire/Catskill and Lower Miss. Price/Pocono formations, and Upper Miss. Princeton Formation and Lower to Middle Penn. Breathitt Group river systems with modern river analogs from Milliman and Farnsworth (2011) and Wikipedia (2022) for comparison.

formations. In addition, both rivers are characterized by multi-channel, braiding (many abandoned/filled channels) and more meandering reaches (Khorsandi et al., 2004). These are also suitable analogs for the Upper Mississippian Princeton Formation (Table 2).

Analogs for the Alleghanian, Pennsylvanian-age river systems (Table 2) are from tropical, equatorial settings of Papua New Guinea and Indonesia including the Fly and Digul rivers of New Guinea with drainage areas of 76,000 and 45,900 km^2 and mean discharge values of 5704 and 4000 m^3s^{-1}, respectively (Figure 9; Table 2). Both rivers flow into the Gulf of Carpentaria of the Arafura Sea, a shallow, epicontinental foreland basin which has been compared to the Alleghanian depository in terms of tectonic setting, climate and latitude (Edgar et al., 2003). Another possible analog is the Batang-Hari River from Sumatra in Indonesia with a drainage basin of 44,890 km^2 and a mean discharge of 2560 m^3s^{-1}. The two New Guinea rivers, in particular, display lateral accretion and numerous mid-channel bars (now islands) which would most likely display internal down-current accretion surfaces similar to the sedimentary structures in the Pennsylvania Breathitt Group fluvial deposits.

5.3 | Paleogeographic constraints on drainage parameters and implications for terrane accretion

Estimates of drainage areas of river systems that supplied sediment to the Taconic, Acadian and Alleghanian foreland basins suggest an increase in size from the Late Ordovician to the Late Devonian followed by a decrease in the Early and Middle Pennsylvanian (Tables 1 and 2).

During the Late Ordovician, relatively small drainage areas supplied sediment to the Taconic basin (Figure 10a). Distributive fluvial systems were similarly small and on the order of 500 km^2 (Table 1; Figure 11a). Collision of the Taconic arc with Laurentia involved eastward subduction during the early convergent history of the Appalachian orogeny (Mussman & Read, 1986). Older passive-margin successions, containing mostly Grenville-age (current Appalachian region) and Granite-Rhyolite-age (current

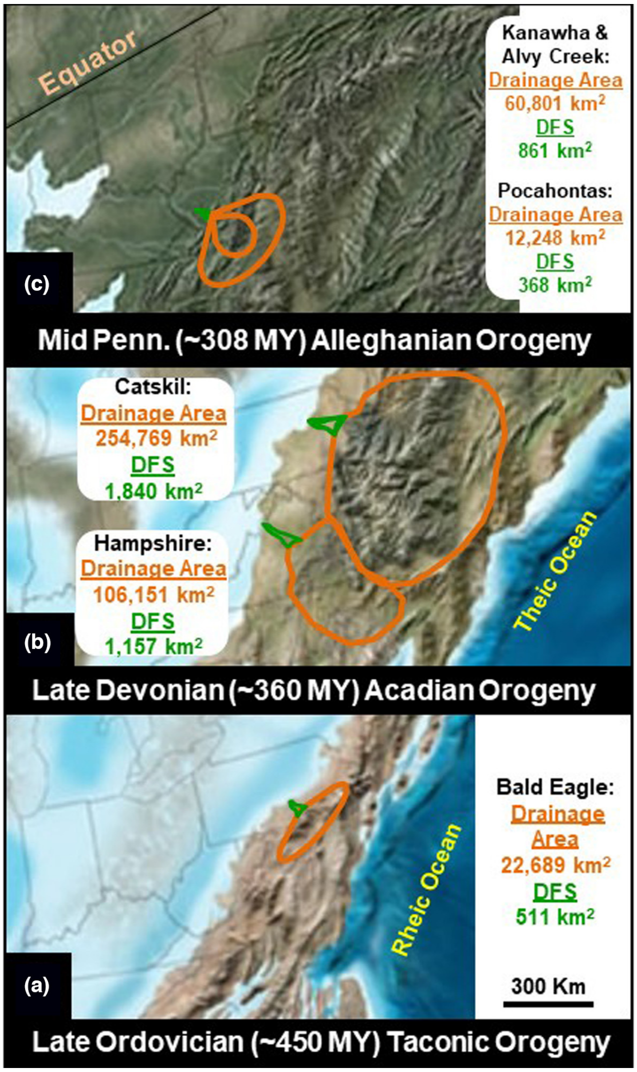

FIGURE 10 Published post-terrane-accretion paleogeographic maps for the Late Ordovician Taconic Orogeny (a), Late Devonian Acadian Orogeny (b), and Mid Pennsylvanian Alleghanian Orogeny (c) for the Central Appalachian region (Blakey, 2022). Calculated drainage areas (km^2) are plotted as leaf-shaped dendritic patterns and the mouth of the river system is placed near an outcrop from which the data were taken. Drainage areas match up reasonably well to the interpreted sizes of accreted terranes. Also shown are distributive fluvial system (DFS) areas for each time interval calculated according to the methodology of Davidson and Hartley (2014). The paleogeographic maps are not constructed on a palinspastic base which would increase the length and decrease the width of each DFS. Each map is a snapshot in time with drainage basins changing in shape as a result of erosion in the hinterlands and DFS areas migrating back-and-forth across the floodplain to produce laterally persistent, braided-river sandstone bodies interbedded with overbank fines.

mid-west region) zircons, were uplifted in an accretionary prism and recycled into the foreland basin to the west (Figure 11a; Eriksson et al., 2004). The presence of only rare Taconic-age zircons (Figure 12a) suggests that the arc was largely isolated from the basin by this emerging accretionary prism, which impeded sediment transport from the active arc to the contemporaneous foreland basin (Eriksson et al., 2004; McLennan et al., 2001). The range of Nd isotopic compositions in Middle to Late Ordovician Taconic foreland-basin sediments is also consistent with a provenance dominated by a Laurentian, mainly Grenville provenance (Bock et al., 1996, 1998; Eriksson et al., 2004). Detrital zircons in quartzites that nonconformably overlie the igneous rocks of the Chopawamsic arc, namely the Arvonia and correlative Quantico formations, show a paucity of Grenville and older ages and a strong peak at 440–470 Ma implying that the quartzite protoliths were deposited prior to accretion onto Laurentia; accretion may have been as recent as 390 Ma, the age of the youngest detrital zircons, at which time the Iapetus Ocean closed (Figure 3; Bailey et al., 2008).

Expansion of drainage areas in the Late Devonian (Figure 10b) was coincident with the progressive accretion of arcs onto Laurentia beginning with the Chopawamsic-Milton-Potomac terranes (arcs) in the Late Ordovician (or possibly as late as 390 Ma) followed by the Avalonia (Carolina) arcs in the Late Devonian (Figure 11b; Park et al., 2010). The large drainage system of the Lower Mississippian Pocono Formation may reflect the culmination of these multiple accretionary events. Multiple melanges along the strike of the orogenic belt (Figures 1 and 3) resulted from closure of the Iapetus and Rheic oceans. The absence of Pan-African (peri-Gondwanan) age zircons (525–800 Ma) in post-Taconic, Silurian-age sandstones, including in the Shawangunk conglomerate in Pennsylvania (Gray & Zeitler, 1997), argues against accretion of Avalonia in the Silurian as proposed by Stampfli (2000). Detrital zircon age spectra for the Acadian clastic wedge indicate that Taconic-age terranes including 441 to 489 Ma granites were exhumed in the provenance and supplied a significant number of Early Palaeozoic-age zircons to the basin (Figure 12b). Grenville ages still predominate and likely were recycled from older sedimentary strata uplifted in the zone of terrane accretion. Pan-African- and Acadian-age zircons are present but in small numbers in the Acadian clastic wedge (Figure 12b) and likely were derived, respectively, from Avalonian and Devonian granites (362–381 Ma) in the hinterland. Distributive fluvial systems were significantly larger than during the Taconic orogeny approaching 1900 km^2 possibly implying that the Catskill and Hampshire basins were linked to separate drainage areas (Table 1; Figure 11b).

Drainage areas in the Late Mississippian and Early to Middle Pennsylvanian were small relative to those that existed in the Late Devonian (Figure 10c) and coincided with the onset of collision of Gondwana with Laurentia (but prior to overthrusting) and closing of the Theic Ocean

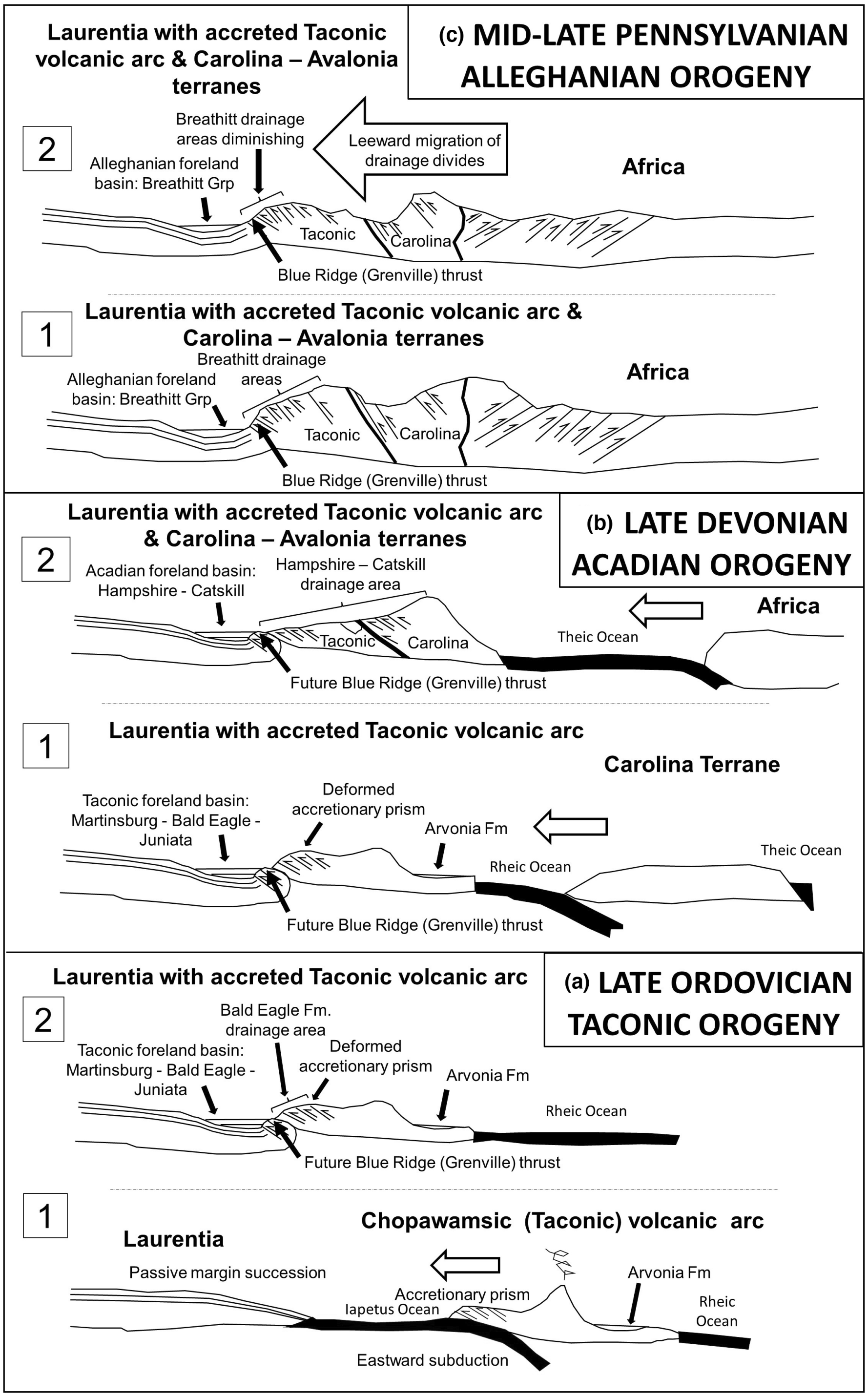

FIGURE 11 Tectonic cross-sections for the Taconic, Acadian, and Alleghanian orogenies (based, in part, on Thomas & Hatcher, 2021). (a) Time 1; Early to Middle Ordovician, shows the Taconic volcanic arc moving towards Laurentia. Time 2; Late Ordovician, shows the Taconic volcanic arc accreted to Laurentia and a relatively small Bald Eagle drainage basin delivering sediments to the Taconic foreland basin to the west. (b) Time 1; Early Silurian with Carolina-Avalonia terranes moving towards Laurentia with accreted Taconic terrane. Time 2; Late Devonian with Carolina-Avalonia terranes docked onto the previously accreted Taconic terrane forming a relatively large Catskill-Hampshire drainage basin providing copious sediment to the Acadian clastic wedge to the west. (c) Time 1, Early-Middle Pennsylvanian after collision of Gondwana with Laurentia and accreted Taconic and Acadian terranes. Time 2; Late Pennsylvanian as erosion steps up on windward side of Alleghanian orogen causing leeward migration of drainage divides and splitting up of Breathitt drainage basins. Note that these tectonic cross-sections are schematic and may not totally or accurately reflect the details of subduction and the exact configuration of accreted terrains.

(Figures 3 and 11c). The decrease in size of drainage area can be explained as resulting from the westward migration of the drainage divide as the Alleghanian orogeny proceeded. Modelling studies by Bonnet (2009) demonstrated that the drainage divide migrates in response to horizontal tectonic motion or orographic precipitation. In the model, the drainage divide migrates towards the drier leeward side of the mountain range because of more intense weathering on the windward side, and causes drainage basins to shrink and split into smaller basins. During the Alleghanian orogeny, the leeward side of the mountain range is surmised to have been to the west (Hoffman & Grotzinger, 1993) and it is proposed that Pennsylvanian-age sediments were supplied from multiple small drainage basins in the evolving orogenic belt. Detrital zircon age spectra indicate ongoing recycling of Grenville-age zircons from older sedimentary units and the supply of Taconic- and Acadian-age zircons from accreted provenance terranes or, less likely, via recycling of Acadian-age sedimentary units (Figure 12c). Archean-age

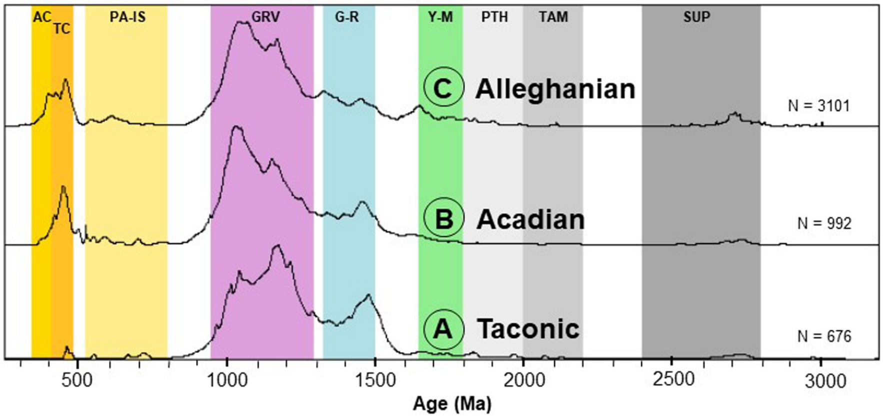

FIGURE 12 Relative age-probability plots of published detrital zircon ages for the Taconic (a), Acadian (b) and Alleghanian (c) clastic wedges in the Valley-and-Ridge and Appalachian Plateau provinces in the central Appalachians. Also shown are provenance ages: AC: Acadian (345–410 Ma); TC: Taconic (410–480 Ma); PA-IS: Pan-African-Brasilliano and Iapetan Synrift (525–800 Ma); GRV: Grenville (950–1290 Ma); G-R: Granite-Rhyolite (1325–1500 Ma); Y-M: Yavapai-Mazatzal (1650–1800 Ma); PTH: Penokean and Trans-Hudson (1800–2000 Ma); TAM: Trans Amazonian (2000–2200 Ma); SUP: Superior (2400–2800 Ma). Taconic-age samples are from the Bays, Martinsburg (Fincastle Member), Oswego, Tuscarora, Rose Hill, Keefer, Shawangunk and Austin Glen formations. Acadian-age samples are from the Oriskany, Foreknobs, Chemung, Price, Grainger, Hampshire, Catskill and Frog Mountain formations and Cloyd conglomerate. Alleghanian-age samples are from the Upper Mississippian Stony Gap Sandstone and the Hinton, Mauch Chunk, Princeton and Bluestone formations, the Lower Pennsylvanian Pocahontas Formation and Lower Raleigh, Upper Raleigh, Lee, Corbin and Sewanee sandstones and the Sharon Conglomerate Member, and the Middle Pennsylvanian Grundy and Norton formations, Cross Mountain sandstone and a sandstone associated with the Princess #7 coal. Data are from Gray and Zeitler (1997), McLennan et al. (2001), Eriksson et al. (2004), Becker et al. (2005, 2006), Park et al. (2010), Thomas et al. (2017).

zircons in Late Mississippian and Pennsylvanian sandstones (Figure 12c) were derived either from the Superior provenance to the north (Buller et al., 2018; Eriksson et al., 2004; Gray & Zeitler, 1997) or through recycling from older stratigraphic units (Thomas et al., 2017). Distributive fluvial systems were small and on the order of 400 to 1130 km^2 (Table 1; Figure 11c).

5.4 | Uncertainties

Challenges in this study, as in any investigation of this type, are related to interpreting paleoclimates and paleolatitudes from the rock record and accurately estimating paleoflow depths. Interpretations of paleoclimate are based largely on types of paleosols (vertisols, calcisols and histosols) whereas paleolatitude interpretations are based on an extensive paleomagnetic dataset for the Appalachian Orogen. Paleoclimate and paleolatitude interpretations for the Central Appalachians are summarized on Figure 2 (Read & Eriksson, 2016). An additional challenge to applying the methods of Davidson and North (2009) and Davidson and Hartley (2014) is the lack of an appropriate modern regional hydraulic curve for pre-Devonian strata on an Earth devoid of vascular plants (Cardona-Correa et al., 2016).

Thicknesses of channel elements were measured on outcrop at multiple locations and from strata of different ages (Supplemental Table A). Because of the channelized nature of the elements, thicknesses are not necessarily true thicknesses which is the reason that only maximum thicknesses of elements were used in calculations. Estimates of paleoflow depths were based on the study by Paola and Bergman (1991) on modern river channels. These authors proposed that mean bankfull depth = 1.695 preserved maximum channel element thickness. To evaluate the effect of underestimating or overestimating paleodepths, drainage areas and discharges were calculated for ±10% and ±20% errors in estimates of paleoflow depths for each of the selected river systems (Figure 9 and Table 3). This analysis demonstrates that although errors in paleodepth estimates do affect drainage basin and discharge estimates, the revised estimates fall within the envelope for modern rivers (Milliman & Farnsworth, 2011; Figure 9) and do not detract from the main conclusions that drainage areas increased in size from the Taconic to the Acadian and contracted in size during the Alleghanian.

6 | CONCLUSIONS

Source-to-sink analysis utilizes the sedimentary record in basins to infer source area parameters. Typically, the nature of the source area is unknown as few geomorphic

TABLE 3 Channel element thicknesses, bankfull depths, drainage areas, and discharges (−10%, +10%, −20%, +20% cases).

Orogeny	Formation	Max. channel element thickness (m)	Bankfull depth[a] (m)				Chosen regional curve	Drainage area (km^2)				Discharge (cu m/s)			
			10% case	10% case	20% case	20% case		−10%	+10%	−20%	+20%	−10%	+10%	−20%	+20%
Alleghanian	Kanawha (WV)	3.7	5.7	7.0	5.2	7.9	D	43,782	100,193	30,613	161,110	788	1418	611	1987
	Alvy Creek (VA)	3.7	5.7	7.0	5.2	7.9	D	43,782	100,193	30,613	161,110	788	1418	611	1987
	Pocahontas (VA)	2.4	3.7	4.5	3.4	5.1	D	7675	17,178	5435	27,848	229	405	179	571
	Princeton (WV)	3.6	5.5	6.8	5.1	7.7	B	73,735	141,120	58,751	206,869	3314	5792	2726	8047
Acadian	Pocono (PA)	7.2	11.1	13.6	10.1	15.3	A	75,654	127,371	59,293	172,499	2531	3588	2149	4396
	Price (VA)	2.1	3.2	4.0	3.0	4.5	A	3122	5506	2616	7528	299	437	266	539
	Catskill (PA)	4.9	7.5	9.2	6.9	10.4	B	190,007	353,741	146,952	511,123	7480	12,765	5997	17,518
	Hampshire (WV, VA)	3.7	5.7	7.0	5.2	7.9	B	82,772	154,976	63,120	222,097	3660	6277	2899	8554
Taconic	Bald Eagle (PA)	2.2	3.4	4.2	3.1	4.7	B	17,509	32,961	13,188	45,958	962	1658	754	2207

[a]Bankfull depth = max. channel element thickness × 1.538 for −10% case; 1.887 for +10% case; 1.408 for −20% case; 2.128 for +20% case.

elements of the hinterland are preserved. Previous studies have shown that modern river channels scale to discharge and that discharge scales to drainage area. It has also been shown that sedimentary structures scale to channel size such that, if the paleoclimate is known, it is possible to calculate the drainage area and discharge of a river knowing the size and scale of the channel elements or sedimentary structures of the ancient river system. Data from detrital zircon age spectra within clastic wedges can be used to constrain the age of the source region as well as the timing of terrane accretion and changes in areal extent of the accreted terranes in the hinterland.

This study has demonstrated that the drainage basin area of the Upper Ordovician Bald Eagle (Taconic Orogeny) river systems was less than ca. 22,000 km^2. The presence of only rare Taconic-age zircons (410–480 Ma) within Taconic-age sedimentary rocks of the foreland basin suggests that during and after accretion of the arc, the arc was largely isolated from the foreland basin by an uplifted accretionary prism comprised of older passive-margin successions containing Grenville- and Granite-Rhyolite-age zircons. Upper Devonian Catskill and Hampshire (Acadian Orogeny) river systems were an order of magnitude larger (ca. 200,000 km^2) than during the Taconic because, by the time of the Acadian Orogeny, river systems were draining the eroding and uplifted accreted terranes of both the Taconic and Acadian orogenies. This conclusion is supported by the presence of abundant Taconic-age and less abundant Acadian- and Pan-African-age detrital zircons. Drainage basin areas of the Middle to Upper Pennsylvanian Breathitt Group (Alleghanian Orogeny) river systems were relatively smaller (ca. 60,000 km^2) than those of the Upper Devonian Catskill Formation (Acadian Orogeny) possibly because of migration of the drainage divide towards the leeward side of the orogen. Erosion is faster on the windward side of orogenic belts and causes drainage basins on the leeward side to shrink and split and form smaller drainage basins.

In this paper, the utilization of architectural element analysis of fluvial deposits within Taconic, Acadian, and Alleghanian clastic wedges in the context of source-to sink studies has proven valuable in reconstructing aspects of palaeogeography, the compositions and ages of source regions, and the timing of terrane accretion and changes in the areal extent of accreted terrains in the hinterland.

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CONFLICT OF INTEREST STATEMENT

No, there is no conflict of interest.

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DATA AVAILABILITY STATEMENT

Data are provided in Supplemental Table A.

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Additional supporting information can be found online in the Supporting Information section at the end of this article.

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