Journal of the Iowa Academy of Science: JIAS

Volume 119 | Number 1-4 Article 4

2012

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Jour. Iowa Acad. Sci. 119(1–4):8–15, 2012

Evidence from Detrital Zircon Ages for Middle Pennsylvanian Uplift and Drainage in the Source Area of the Chariton Conglomerate and Marmaton Group Sandstones, Southern Iowa and Northern Missouri

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The Chariton Conglomerate is a quartz/limestone conglomerate of Middle Pennsylvanian age sparsely exposed in southern Iowa and northern Missouri. In Iowa it is characterized by quartz granules and rounded crinoid columnals. The objective of this study was to use detrital zircon ages to determine the provenance of the Chariton Conglomerate and possibly associated Marmaton Group sandstone beds. Detrital zircon ages were obtained for five conglomerate and two sandstone beds of the Chariton Conglomerate in Iowa, three conglomerate beds of the Chariton Conglomerate in Missouri, and two sandstone beds of the Marmaton Group in Iowa. According to the Kolmogorov-Smirnoff Test, the 12 detrital zircon age spectra were statistically indistinguishable, consistent with a common provenance for all beds. The combined age spectrum (879 zircons) showed both a young cluster (1.1% of zircons) in the range 320–364 Ma (Late Devonian Period – Late Mississippian Subperiod) and a much older cluster (0.3% of zircons) in the range 3198–3269 Ma (Paleoarchean – Mesoarchean Eras). The Devonian Period – Mississippian Subperiod (318–416 Ma) and the Paleoarchean – Mesoarchean Eras (2800–3600 Ma) accounted for 2.8% and 3.6% of zircon ages, respectively. A model consistent with the above ages and the paleocurrent directions in the Chariton Conglomerate is an Early – Middle Pennsylvanian river originating in the Devonian – Mississippian crystalline rocks of New England and entering Minnesota – Wisconsin from the northeast to collect sediments from crystalline rocks of Paleoarchean – Mesoarchean age. However, a Middle Pennsylvanian uplift in the Minnesota – Wisconsin region is also required to produce the headwaters necessary for the production of quartz granules, which is consistent with the model of hotspot epeirogeny.

INDEX DESCRIPTORS: Chariton Conglomerate, detrital zircons, hotspot epeirogeny.

The Chariton Conglomerate is a quartz/limestone conglomerate of Middle Pennsylvanian age sparsely exposed in southern Iowa and northern Missouri (see Fig. 1). The matrix consists of ferruginous sandstone and smaller particles of limestone (Bain 1896, Lees 1909). The cement is calcareous and is occasionally coarsely crystalline (Wallace 1941). Fragments of coal and carbonaceous materials are conspicuous (Bain 1896, Lees 1909, Wallace 1941, Gentile 1967). Wallace (1941) noted that quartz grains, ranging in size from silt to coarse sand, are always present. Kraber et al. (2007) observed that subangular to rounded quartz granules make up about 10% of the clasts. The conglomerate beds are occasionally interbedded with cross-bedded sandstones (Lugn 1927, Wallace 1941). The vast majority of the fossils are crinoid columnals, but brachiopods, corals, bryozoans, fusulinids, fish fragments and plant fossils are also present (Bain 1896, Lugn 1927, Wallace 1941, Pope et al. 2002). The very rounded crinoid columnals give clear evidence of transportation by water (Kraber et al. 2007). Although the three exposures in Missouri were classified as Chariton Conglomerate by Hinds and Greene (1915) and by Gentile (1965, 1967), they lack the quartz granules that are characteristic of the Chariton Conglomerate in Iowa, and, while crinoid columnals are present, they are not rounded (Kraber et al. 2007).

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The stratigraphic position of the Chariton Conglomerate has long been debated, largely due to the scarcity of exposures and lack of visible contact with other stratigraphic units. The stratigraphic debate is discussed in some detail here and we will argue for its importance in the Discussion section. Both Bain (1896) and Lees (1909) placed the Chariton Conglomerate above the Mystic Coal Member (see stratigraphic column in Table 1). Lees (1909) placed the Chariton Conglomerate below the Lonsdale Coal (later called the Mulberry Coal and now included within the Bandera Shale (Anderson 1998)). Later workers located the Chariton Conglomerate within what is now called the Bronson Group. Hinds and Greene (1915), Lugn (1927), Wood (1935) and Gentile (1965, 1967) all placed the Chariton Conglomerate within the Pleasanton Group (now the Bronson Group below the base of the Hertha Limestone). Wilmarth (1938) described the Chariton Conglomerate as a member of the Pleasanton Formation. Wallace (1941) found fragments of *Chaetetes* and dermal denticles of fish from the Pawnee Formation and Worland Limestone Member of the Altamont Limestone in the Chariton Conglomerate and noted the Chariton Conglomerate incised through the Pawnee Formation. According to Cline (1941), the Chariton Conglomerate is definitely younger than the Coal City Limestone Member of the Pawnee Formation and tentatively placed the Chariton Conglomerate between the Hertha Limestone and the Exline Limestone Member of the Pleasanton Formation. Wilcox (1941) found the Chariton

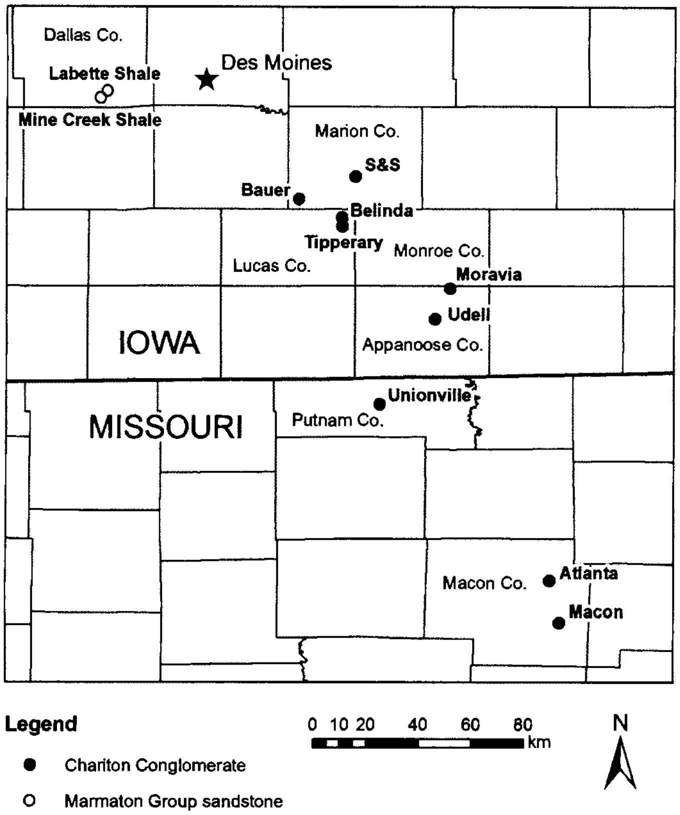

Fig. 1. Samples were collected from six exposures of the Chariton Conglomerate in Iowa and three in Missouri. Exposures are named after the nearest village, except for S & S, which is the name of the active quarry. The three exposures in Missouri lack the quartz granules and rounded crinoid columnals that are characteristic of the Chariton Conglomerate in Iowa. Two sandstone beds of the Marmaton Group (labeled after the stratigraphic unit) were studied for comparison with the Chariton Conglomerate.

Table 1. Simplified stratigraphic column for the Pennsylvanian Subsystem in Iowa, including all groups, all formations of the upper Marmaton Group, and any other stratigraphic units mentioned in the text (modified from Pope (2012)).

Waubansee Group
Shawnee Group
Douglas Group
Lansing Group
Kansas City Group
Bronson Group
Hertha Limestone
Pleasanton Formation
Shale Hill Member
Ovid Coal Bed
Exline Limestone Member
Marmaton Group
Lost Branch Formation
Memorial Shale
Lenapah Limestone
Nowata Shale
Altamont Limestone
Worland Limestone Member
Bandera Shale
Pawnee Formation
Coal City Limestone Member
Mine Creek Shale Member
Labette Shale
Mystic Coal Bed
Cherokee Group
Floris Formation

Conglomerate a few feet below the Hertha Limestone. Weller et al. (1942) located the Chariton Conglomerate below the Ovid Coal and above the Exline Limestone. Landis and Van Eck (1965) placed the Chariton Conglomerate at the base of the Pleasanton Formation below the Ovid Coal Bed, which they placed below the Exline Limestone Member. Brown et al. (1977) called the Chariton Conglomerate a member of the Memorial Shale, which they placed above the Exline Limestone. (Compared to the contemporary stratigraphic column, Landis and Van Eck (1965) reverse the relative positions of the Exline Limestone and Ovid Coal, while Brown et al. (1977) reverse the relative positions of the Exline Limestone and Memorial Shale.)

The tendency from the 1980s on was to place the Chariton Conglomerate lower in the stratigraphic column within the Marmaton Group. Howe (1982) correlated the Chariton Conglomerate with the "Red Rock" sandstone, but Ravn et al. (1984) argued that the "Red Rock" sandstone is part of the much younger Floris Formation of the Cherokee Group. According to Ravn et al. (1984), the Chariton Conglomerate should not be regarded as a formal member because of the uncertainty in its stratigraphic position. Pope et al. (2002) identified in the Chariton Conglomerate the fusulinid foraminifer *Beedeina megista* (Thompson 1934), also found in the Worland Limestone, and concluded that the Chariton Conglomerate is younger than the Altamont Limestone and may be as young as the lower Missourian Stage (Bronson Group). Pope et al. (2002) provisionally placed the Chariton Conglomerate in the upper Marmaton Group. Gentile and Thompson (2004) recognized two horizons of Chariton Conglomerate and concluded that the conglomerate may occur at more than one stratigraphic horizon. The most recent Iowa stratigraphic columns (Iowa Geological & Water Survey 2012, Pope 2012) do not list the Chariton Conglomerate as a formally recognized stratigraphic unit, again because of the uncertainty in its stratigraphic position.

All of the components of the Chariton Conglomerate except for the quartz clasts could have been derived from the underlying Pennsylvanian beds. The mystery of the Chariton Conglomerate is the provenance of the quartz clasts, since there is no crystalline bedrock in Iowa aside from a small outcrop of Sioux Quartzite in the farthest northwest corner of Iowa. The closest crystalline bedrock to the exposures of the Chariton Conglomerate in Iowa is 330 km away in southern Minnesota (see Fig. 2). Kraber et al. (2007) measured 16 paleocurrent directions in interbedded sandstones in the Chariton Conglomerate and found a mean direction of 178° (SD = 35°), which was consistent with the mean paleocurrent direction of 167° found by Hansen (1978) for 343 measurements in the Cherokee Group (see Table 1) in Marion County (see Fig. 1), both indicating transport from the north during the Middle Pennsylvanian. Kraber et al. (2007) extracted 75 crinoid columnals from exposures of the Chariton Conglomerate in Iowa and measured their roundness. By carrying out laboratory experiments with rotary tumblers on quartz

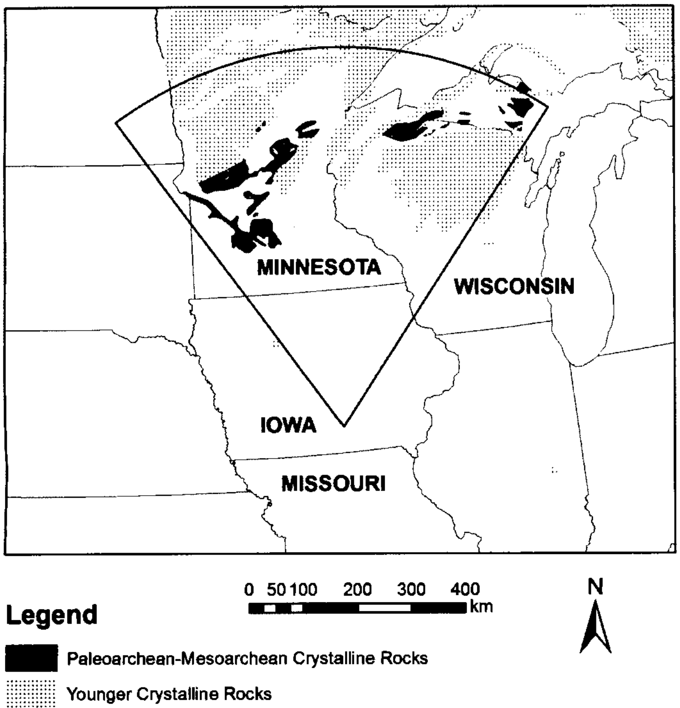

Fig. 2. Paleocurrent directions and comparison of rounded crinoid columnals with laboratory experiments predicted that the quartz clasts and crinoid columnals of the Chariton Conglomerate originated in a wedge of radius 700 km with apex at the average position of exposures of the Chariton Conglomerate in southern Iowa and sides with orientations 323° and 33° (Kraber et al. 2007). There are many sources of crystalline rocks within the wedge in Minnesota, Wisconsin and the Upper Peninsula of Michigan, including rocks of Paleoarchean – Mesoarchean age (USGS 2012).

granules and unabraded crinoid columnals, Kraber et al. (2007) found that 0–700 km of transport was required to achieve the roundness of the crinoid columnals. Based on the above, Kraber et al. (2007) located the provenance of the quartz clasts of the Chariton Conglomerate within a wedge of radius 700 km with apex at the average position of exposures of the Chariton Conglomerate in southern Iowa and sides with orientations 323° and 33° (see Fig. 2). There are many sources of crystalline rocks within the wedge in Minnesota, Wisconsin and the Upper Peninsula of Michigan, including rocks of Paleoarchean – Mesoarchean age (USGS 2012).

The objective of this study was to obtain detrital zircon U-Pb ages for the Chariton Conglomerate and sandstone beds of the Marmaton Group. This was the first detrital zircon dating study carried out in rocks found in either Iowa or Missouri. It was hoped that dating detrital zircons and, therefore, better establishing the provenance of the components (not only the quartz clasts) of the Chariton Conglomerate would help to address the following questions:

1) What were the drainage and uplift patterns during the Middle Pennsylvanian in the source area of the Chariton Conglomerate and Marmaton Group sandstones?
2) Do the Chariton Conglomerate exposures in Iowa and Missouri belong to the same stratigraphic unit?
3) Does the Chariton Conglomerate belong in the Marmaton Group?

We would have liked to have also compared the provenances of the Chariton Conglomerate with sandstones of the Bronson Group, but we were unable to locate any sandstones of the Bronson Group in Iowa.

METHODS

About 0.5 kg of rock were collected from a sandstone bed and a conglomerate bed of the six known exposures of the Chariton Conglomerate in Iowa and the three known exposures in Missouri (see Fig. 1) (Kraber et al. 2007). After completing this study, we became aware of a reference to a seventh Iowa exposure (Beyer and Young 1903) just north of the Moravia exposure in Monroe County (see Fig. 1). Rock samples were also collected from exposures of sandstone beds of the Labette Shale and Mine Creek Shale of the Marmaton Group (see Table 1) at locations in Iowa described as Stops One, Two and Three by Wolf et al. (1990). Although sandstone beds are uncommon in the Marmaton Group, no attempt was made to locate all exposures as was done for the Chariton Conglomerate.

The detrital zircon separation procedure is briefly described here. A document describing the complete procedure is available from the authors. The primary objective was to randomize the extraction process so as not to favor any particular size, shape or age of zircon. Rock samples were crushed and sieved and the <150 μm fraction was retained for detrital zircon separation. The fine fraction was washed to remove as much clay as possible. Grains denser than s-Tetrabromoethane (TBE) were separated in a separatory funnel, after which a Frantz magnetic separator set to 0.5 G was used to separate the low-magnetic fraction. Low-magnetic grains denser than methylene iodide were separated in a separatory funnel, after which the Frantz magnetic separator was used four times at strengths 0.75–1.5 G to again separate the low-magnetic fraction. A dental tool was finally used to remove non-zircons from the low-magnetic fraction that was denser than methylene iodide. Detrital zircons from five conglomerate beds and two sandstone beds of the Chariton Conglomerate in Iowa, three conglomerate beds of the Chariton Conglomerate in Missouri, and two sandstone beds of the Marmaton Group in Iowa were mounted for U-Pb dating.

Detrital zircon U-Pb ages were measured in April 2009 at the Arizona LaserChron Center by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) (Gehrels et al. 2006, 2008). The procedure is described briefly

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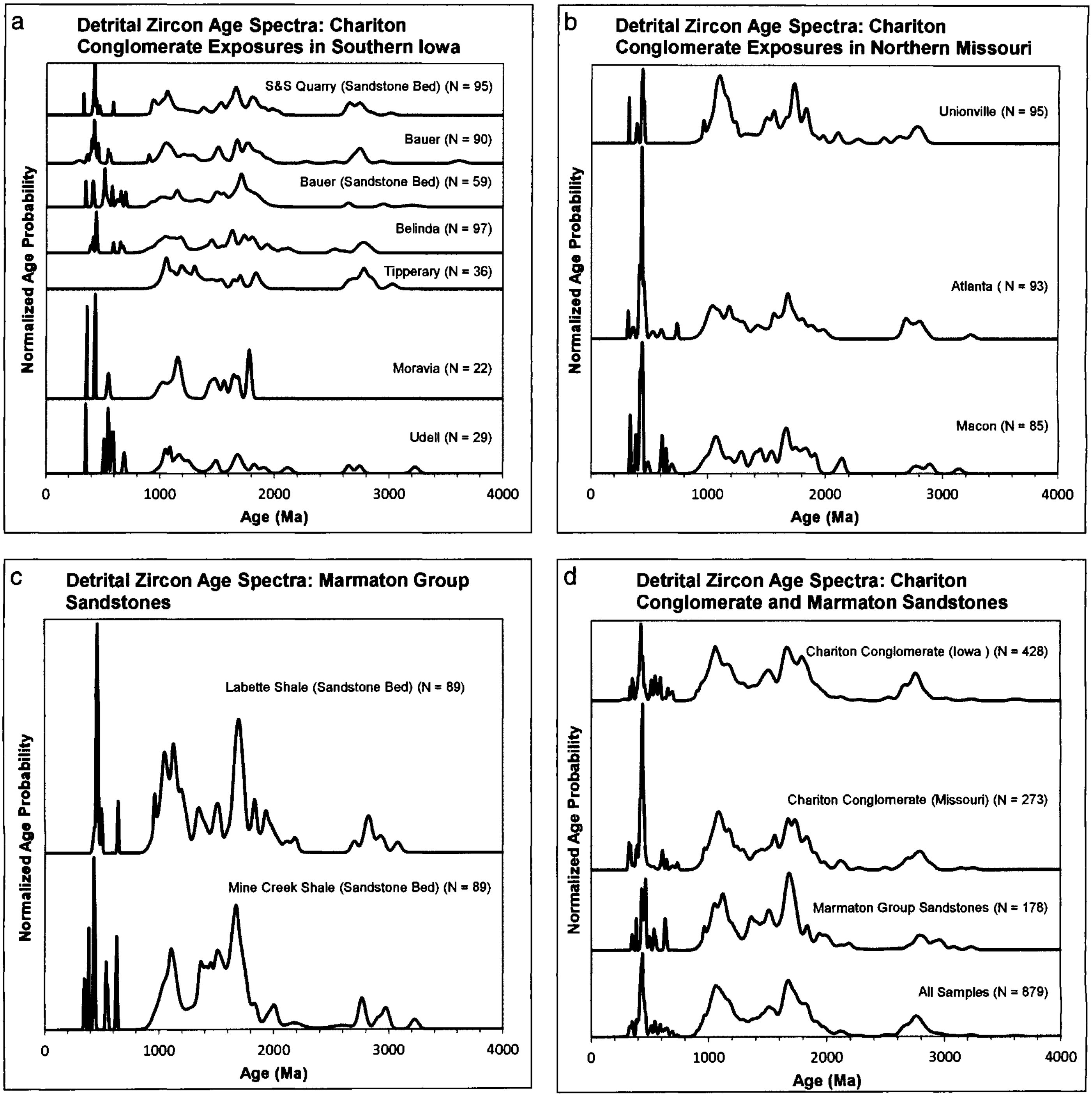
Fig. 3a. Differences among detrital zircon age spectra for exposures of the Chariton Conglomerate in southern Iowa were not statistically significant at the 95% confidence level according to the Kolmogorov-Smirnoff Test. Exposures are ranked from north (top) to south (bottom). All exposures are conglomerate beds unless otherwise indicated. Number of zircons dated at each exposure is shown in parentheses. Fig. 3b. Differences among detrital



zircon age spectra for exposures of the Chariton Conglomerate in northern Missouri were not statistically significant at the 95% confidence level according to the Kolmogorov-Smirnoff Test. Exposures are ranked from north (top) to south (bottom). All exposures are conglomerate beds. Number of zircons dated at each exposure is shown in parentheses. Fig. 3c. Differences between detrital zircon age spectra for Marmaton Group sandstones were not statistically significant at the 95% confidence level according to the Kolmogorov-Smirnoff Test. Number of zircons dated for each exposure is shown in parentheses. Fig. 3d. Differences among detrital zircon age spectra for combined samples of the Chariton Conglomerate in Iowa, combined samples of the Chariton Conglomerate in Missouri, and combined samples of the Marmaton Group sandstones were not statistically significant at the 95% confidence level according to the Kolmogorov-Smirnoff Test. On that basis, provenance analysis was carried out on the combined age spectrum of all samples. Number of zircons in each grouping is shown in parentheses.

Table 2. Detrital zircon age clusters: Combined Chariton Conglomerate and Marmaton Group sandstones.

Range (Ma)[a]	Zircons[b]	Geologic Time Units[c]
320–364	10 (1.1%)	Late Devonian Period – Late Mississippian Subperiod
377–707	107 (12.2%)	Neoproterozoic Era – Late Devonian Period
822–2351	661 (75.2%)	Paleoproterozoic – Neoproterozoic Eras
2434–3025	89 (10.1%)	Mesoarchean – Paleoproterozoic Eras
3198–3269	3 (0.3%)	Paleoarchean – Mesoarchean Eras

[a]Age clusters obtained from AGE PICK program (Arizona LaserChron Center 2012b). Clusters with fewer than three zircons omitted. Range contains ages within two standard deviations of the mean
[b]Number of zircon ages within cluster with percentage of total (N = 879) in parentheses. Percentages add to 98.9% because nine zircons did not fall into any clusters
[c]International Commission on Stratigraphy (2012)

here as the complete procedure is available online (Arizona LaserChron Center 2012a). The analyses involved ablation of zircon with a New Wave UP193HE Excimer laser (replaced with a Photon Machines Analyte G2 Excimer laser in May 2011) using a spot diameter of 30 µm, resulting in an ablation pit ~15 µm in depth. The ablated material was carried in helium into the plasma source of a Nu HR ICPMS, which was equipped with a flight tube of sufficient width that U, Th, and Pb isotopes were measured simultaneously.

For each analysis, the errors in determining $^{206}Pb/^{238}U$ and $^{206}Pb/^{204}Pb$ resulted in a measurement error of ~1–2% (at two standard deviations) in the $^{206}Pb/^{238}U$ age. The errors in measurement of $^{206}Pb/^{207}Pb$ and $^{206}Pb/^{204}Pb$ also resulted in ~1–2% (at two standard deviations) uncertainty in age for grains that were >1000 Ma, but were substantially larger for younger grains due to low intensity of the ^{207}Pb signal. The best age was determined from the $^{206}Pb/^{238}U$ age for analyses with $^{206}Pb/^{238}U$ age <1000 Ma and from the $^{206}Pb/^{207}Pb$ age for analyses with $^{206}Pb/^{238}U$ age > 1000 Ma. Analyses were discarded if they showed >10% uncertainty (one standard deviation) or were >20% discordant or >5% reverse discordant. After 66 analyses were rejected, 879 successful analyses remained. Although the intention had been to analyze 100 zircons per sample, some samples had insufficient zircons (see Figs. 3a–c).

Detrital zircon ages were analyzed using Excel macros available on the web site of the Arizona LaserChron Center (2012b). Statistical comparison of detrital zircon age spectra was carried out using the Kolmogorov-Smirnoff Test (Press et al. 1986, Berry et al. 2001, DeGraaff-Surpless et al. 2003). Age probability plots were created by producing a normal distribution curve for each detrital zircon age using the age as the mean and uncertainty as the standard deviation, and then summing the normal distribution curves for all detrital zircon ages in a sample to yield a single curve (see Figs. 3a–d). The age probability plots were normalized according to the number of constituent detrital zircon ages so that each curve contained the same area (see Figs. 3a–d).

RESULTS

Differences among detrital zircon age spectra were not statistically significant at the 95% confidence level for the Chariton Conglomerate exposures in southern Iowa (see Fig. 3a), the Chariton Conglomerate exposures in northern Missouri (see Fig. 3b), and the Marmaton Group sandstones (see Fig. 3c). Differences among detrital zircon age spectra were also not statistically significant for the combined Chariton Conglomerate in Iowa, the combined Chariton Conglomerate in Missouri, and the combined Marmaton Group sandstones (see Fig. 3d). The common detrital zircon age spectra for all exposures is consistent with a common provenance for all exposures, which is consistent with a common stratigraphic unit for the Chariton Conglomerate in Iowa and Missouri, and with the placement of the Chariton Conglomerate within the Marmaton Group. All further analysis was carried on the combined age spectrum of all samples (879 zircons).

The youngest zircon age was (287.9 ± 24.5) Ma, which had a barely acceptable uncertainty (8.5%). Although the youngest best age lies in the Early Permian Period, the uncertainty of one standard deviation could place the age in the Early Pennsylvanian Subperiod. The second youngest zircon age was (318.9 ± 5.6) Ma with the best age in the Late Mississippian Subperiod. Therefore, the youngest zircon ages do not constrain the date of deposition of the Chariton Conglomerate any better than what was already known. The oldest zircon was (3639.1 ± 11.2) Ma from the Eoarchean Era. The vast majority of zircon ages (75.2%) clustered in the range 822–2351 Ma (Paleoproterozoic – Neoproterozoic Eras) (see Table 2). The cluster containing the next largest number of zircon ages (12.2%) was the range 377–707 Ma (Neoproterozoic Era – Late Devonian Period) (see Table 2). There are many possible sources of zircons over such large time ranges. However, the key to identifying provenance from zircon ages is to locate age clusters of restricted time range that, hopefully, also have restricted geographic extent. The key clusters are probably the youngest cluster (1.1% of zircons) in the range 320–364 Ma (Late Devonian Period – Late Mississippian Subperiod) and the oldest cluster (0.3% of zircons) in the range 3198–3269 Ma (Paleoarchean – Mesoarchean Eras) (see Table 2). Since geologic maps are often based upon the standard geologic time units, it is noted that the Devonian Period – Mississippian Subperiod (318–416 Ma) and the Paleoarchean – Mesoarchean Eras (2800–3600 Ma) accounted for 2.8% and 3.6% of zircon best ages, respectively. (Taking age uncertainties into account would increase the numbers of zircons falling into the above time units.)

The results necessary for determining the provenance of the Chariton Conglomerate are summarized as follows:

1) The components of the Chariton Conglomerate were transported into Iowa roughly from the north.
2) The quartz clasts and rounded crinoid columnals originated within a wedge of radius 700 km (see Fig. 2).
3) The source area includes crystalline rocks of Devonian – Mississippian age.

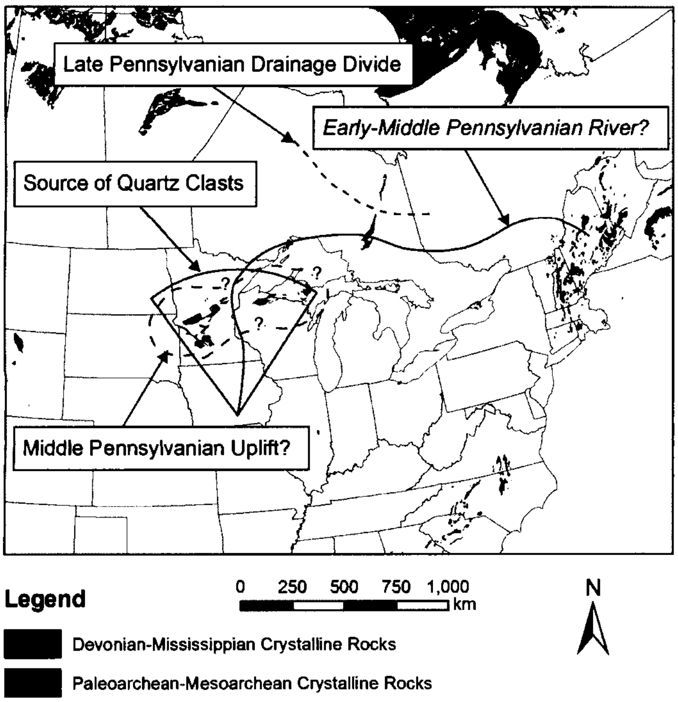


Fig. 4. An Early – Middle Pennsylvanian river originating in present-day New England and entering present-day Minnesota – Wisconsin from the northeast is consistent with paleocurrent directions, the combination of Devonian – Mississippian and Paleoarchean – Mesoarchean detrital zircon ages, and a Late Pennsylvanian drainage divide (Colorado Plateau Geosystems 2012). Middle Pennsylvanian uplift within the Minnesota – Wisconsin region is consistent with a source of quartz clasts within the wedge-shaped zone (Kraber et al. 2007). Geologic units are based on USGS (2012).

4) The source area includes crystalline rocks of Paleoarchean – Mesoarchean age.

DISCUSSION

The simplest model that accounts for the above results is an Early – Middle Pennsylvanian river that originated in the Devonian – Mississippian crystalline rocks of New England, meandered through Quebec and Ontario, and entered Minnesota – Wisconsin from the northeast to collect sediments from Paleoarchean – Mesoarchean crystalline rocks before depositing its collection of sediments in Iowa and Missouri (see Fig. 4). The above model is also constrained by a Late Pennsylvanian drainage divide constructed by Dr. Ron Blakey (Colorado Plateau Geosystems 2012) (see Fig. 4). The coincidence between the belt of Paleoarchean – Mesoarchean crystalline rocks and the wedge predicted by paleocurrent directions and crinoid columnal rounding in the Chariton Conglomerate is remarkable (see Figs. 2, 4). Any other model would be considerably more complex and would require transport of Devonian – Mississippian zircons from the Alabama – Virginia region or the existence of Devonian – Mississippian crystalline bedrock in Minnesota, Wisconsin or Ontario that has been removed by erosion since the Pennsylvanian Subperiod. Becker et al. (2005, 2006) used detrital zircons to document the input of sediment from igneous rocks of the Alleghanian Orogeny into the Appalachian Basin. The present study extends that result to the mid-continent region.

The result that the Minnesota – Wisconsin region is the apparent source of quartz clasts still requires explanation. Fluvial gravel would not normally occur 3000 km from the headwaters of a major river. Therefore, the quartz clasts require Middle Pennsylvanian uplift in the Minnesota – Wisconsin region so that this region became a new source of headwaters. One possibility is that the Early – Middle Pennsylvanian river (see Fig. 4) acted as an antecedent river cutting a deep gorge through uplifted cliffs of Paleoarchean – Mesoarchean crystalline rock so that there may have been a continuous contribution of Devonian – Mississippian zircons even during the uplift. A second possibility is that the uplifted region of Minnesota –Wisconsin acted as headwaters for a tributary to a major river that bypassed the uplift. The proper stratigraphic position of the Chariton Conglomerate can now be seen as having possible critical importance for understanding the mid-continental Paleozoic geology as it dates the hypothesized Minnesota – Wisconsin uplift.

The minimum elevation difference required to transport granule-sized clasts from a source area in the middle of the Paleoarchean – Mesoarchean exposures in Minnesota to a depositional area in southern Iowa (see Fig. 2) can be estimated using two well-established empirical relations. In the range $D \leq 4$ mm, the Hjulström curve (Knighton 1998) for the threshold velocity required for transportation of particles of a given diameter can be approximated by the power-law relation

$$v = 0.765 D^{0.985}, \quad (1)$$

where v is velocity (m/s) and D is particle diameter (mm). According to the Manning Equation (Dingman 2009), stream velocity in wide channels can be estimated by

$$v = \frac{d^{2/3} S^{1/2}}{n}, \quad (2)$$

where v is stream velocity (m/s), d is stream depth (m), S is the slope of the stream bed, and n is the Manning roughness coefficient. Combining Eqs. (1) and (2) with the assumption of constant slope

$$S = \frac{\Delta z}{L}, \quad (3)$$

where L is stream length and Δz is elevation difference, leads to

$$\Delta z = \frac{0.586 D^{1.97} n^2 L}{d^{4/3}}. \quad (4)$$

Eq. (4) gives the minimum required elevation difference for three related reasons:

1) The calculated slope is the slope required for transportation of clasts of a given size at the edge of the depositional area. However, slope nearly always decreases in the downstream direction so that streams have a concave upward longitudinal profile (Knighton 1998).
2) Although the particle diameter D is measured at the depositional area, particle sizes decrease in the downstream direction (Knighton 1998).
3) The stream could have been flowing faster than necessary for transportation of particles of the size present in the stream.

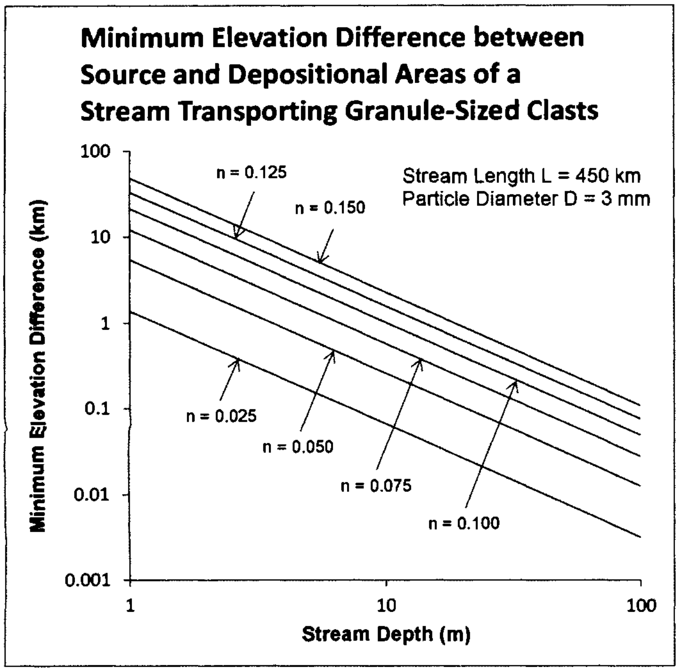


Fig. 5. The minimum elevation difference between the source and depositional areas of a stream transporting granule-sized clasts is calculated assuming the Hjulström curve for threshold velocity for transportation of particles of a given diameter, the Manning Equation for estimating stream velocity from slope and depth, stream length L = 450 km, particle diameter D = 3 mm, and the range of Manning roughness coefficients found in natural rivers (n = 0.025–0.150). Significant uplift (> 1 km) in the source area is required for stream depths less than 1 m (for n = 0.025) to less than 19 m (for n = 0.150).

Although there are a variety of empirical relations for the downstream decreases in slope and particle size (Knighton 1998), they are too poorly constrained for meaningful calculations. The minimum elevation difference was calculated assuming L = 450 km (see Fig. 2) and D = 3 mm (mid-range for granule-sized clasts). The greatest uncertainties are the stream depth and the Manning roughness coefficient n, which for natural rivers can range from n = 0.025 (clean, straight streams at full stage without riffles or deep pools) to n = 0.150 (streams with very weedy reaches or deep pools or floodways with heavy timber or underbrush) (Dingman 2009). Significant uplift (> 1 km) in the source area is required for stream depths less than 1 m (for n = 0.025) to less than 19 m (for n = 0.150) (see Fig. 5). Although the paleostream could have been sufficiently deep to transport granule-sized clasts without significant elevation drop, a Middle Pennsylvanian uplifted region in Minnesota – Wisconsin seems more likely than not.

It is interesting that Dr. Ron Blakey's North American Paleogeographic Map for the Late Pennsylvanian (300 Ma) (Colorado Plateau Geosystems 2012) shows highlands in Minnesota and Wisconsin, although this choice is not justified in his bibliography (Rich 1977). In an abstract Morgan (1980) argued in favor of the northeast – southwest motion of North America over a hotspot beginning in the Middle Devonian so that uplift progressively occurred from Colorado to Minnesota. An absolute plate motion of about 1.5 cm yr^{-1} would place the hotspot under Minnesota by the Middle Pennsylvanian. This concept was called hotspot epeirogeny (Neill 1976, Crough 1979) and has been applied to various areas of Phanerozoic uplift (Crough 1981, 1984, McHone 1981, Washington 1989, Morgan 1997, Sengor 2001). Unfortunately, there does not seem to have been any follow-up to Morgan's (1980) suggestion of a Devonian – Pennsylvanian North American hotspot track.

CONCLUSIONS

The vast majority of North American detrital zircon geochronology has been carried out in the Cordilleran, Rocky Mountain and Appalachian regions. This study has used detrital zircon geochronology in Iowa and Missouri to show evidence for an Early – Middle Pennsylvanian river originating in New England and entering Minnesota – Wisconsin from the northeast and for Middle Pennsylvanian uplift in the Minnesota – Wisconsin region. Prior to this study, the uplift was known only from relatively unsubstantiated suggestions and the major river was entirely unknown. It is hoped that this study will stimulate further research in detrital zircon geochronology in the mid-continent of North America.

ACKNOWLEDGEMENTS

This research was partially funded by a grant from the College of Science and Health Scholarly Activities Committee (Utah Valley University) and by the Department of Geological and Atmospheric Sciences (Iowa State University). The Arizona LaserChron Center is funded by National Science Foundation grant NSF-EAR 1032156. We are grateful to Carl Jacobson for suggesting the use of detrital zircon ages to address the problems described in this study.

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