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A revised provenance model for the Elk Mound Group in south-central Wisconsin based on detrital zircon analysis

Itai Bojdak-Yates

Abstract

The Late Cambrian Elk Mound Group consists of three supermature sandstone formations deposited in and along the shores of a shallow, tropical sea: the Mount Simon, Eau Claire, and Wonewoc formations, in ascending order. Workers have used detrital zircon (DZ) U-Pb analysis to constrain the sources of the sand grains and build a regional provenance model. This study considers new samples from the Mount Simon Sandstone in the context of previous DZ studies in Wisconsin and Illinois. The samples reveal a transition from Mesoproterozoic source provinces towards Late Archean source provinces over time, which is understood to represent a shift from sediments derived from the more local Wolf River Batholith and Penokean orogenies to sediments derived from the more distal Superior Province. Such a shift likely reflects rising sea levels, which drowned local provinces and prevented their erosion while leaving more distal provinces high and dry. Along with the DZ data, paleocurrent indicators derived from optical borehole image logs from wells across central Wisconsin suggest predominantly west- and southwest-flowing currents, providing some indication of the more immediate source and final transport of these sediments.

Introduction

The upper Midwestern United States (Minnesota, Wisconsin, Michigan, northern Illinois, Iowa) contains sequences of strata deposited in a shallow, tropical sea during the early Paleozoic (Ostrom, 1966; Runkel et al., 2007; Dott and Byers, 2016). This sea contained basins and arches that developed throughout the early Paleozoic, including the Wisconsin Arch, the northern reaches of the Transcontinental Arch in Minnesota, the Illinois Basin, and the Michigan Basin (Ostrom, 1966; Konstantinou et al., 2014). The arches formed highlands and islands which directed paleocurrents and provided sources of sediment to the sea, while the basins accumulated thick, deep strata. In addition to these major topographic and bathymetric features, the Upper Midwest contained resistant ridges of Mesoproterozoic quartzite, such as the Sioux, Baraboo, and Waterloo quartzites, which stuck out of the sea as islands (Dott and Byers, 2016). The sea covered much of the cratonic interior of Laurentia/North America such that at some sea level highstands even the Canadian Shield and the Superior craton, now situated under Lake Superior and northern and eastern Canada, were partially submerged (Michelson & Dott, 1973). As such, these Archean source provinces provided much of the sediment which filled the basins and became the strata that blanket the Upper Midwest today.

The oldest of these strata formed during the late Cambrian and are known in Minnesota, Wisconsin, and Illinois as the Elk Mound Group. The Elk Mound Group consists of three sandstone formations: the Mount Simon Formation, the Eau Claire Formation, and the Wonewoc Formation, in ascending order (Figure 1). The Mount Simon and Wonewoc formations are very similar to each other and represent more proximal depositional environments than the Eau Claire Formation, which was deposited more distally and is therefore more distinct from the other two (Ostrom, 1966; Clayton & Attig, 1990). That said, all three formations are quartz arenites noted for their extraordinary physical and chemical maturity. Because of this maturity, these formations have both fascinated and puzzled generations of geoscientists. In particular, the question of the provenance of the Elk Mound Group has remained a mystery thanks to a lack of chemical clues in the supermature sandstones (Dott, 2003; Konstantinou et al., 2014). However, recent detrital zircon (DZ) studies have shed new light on the

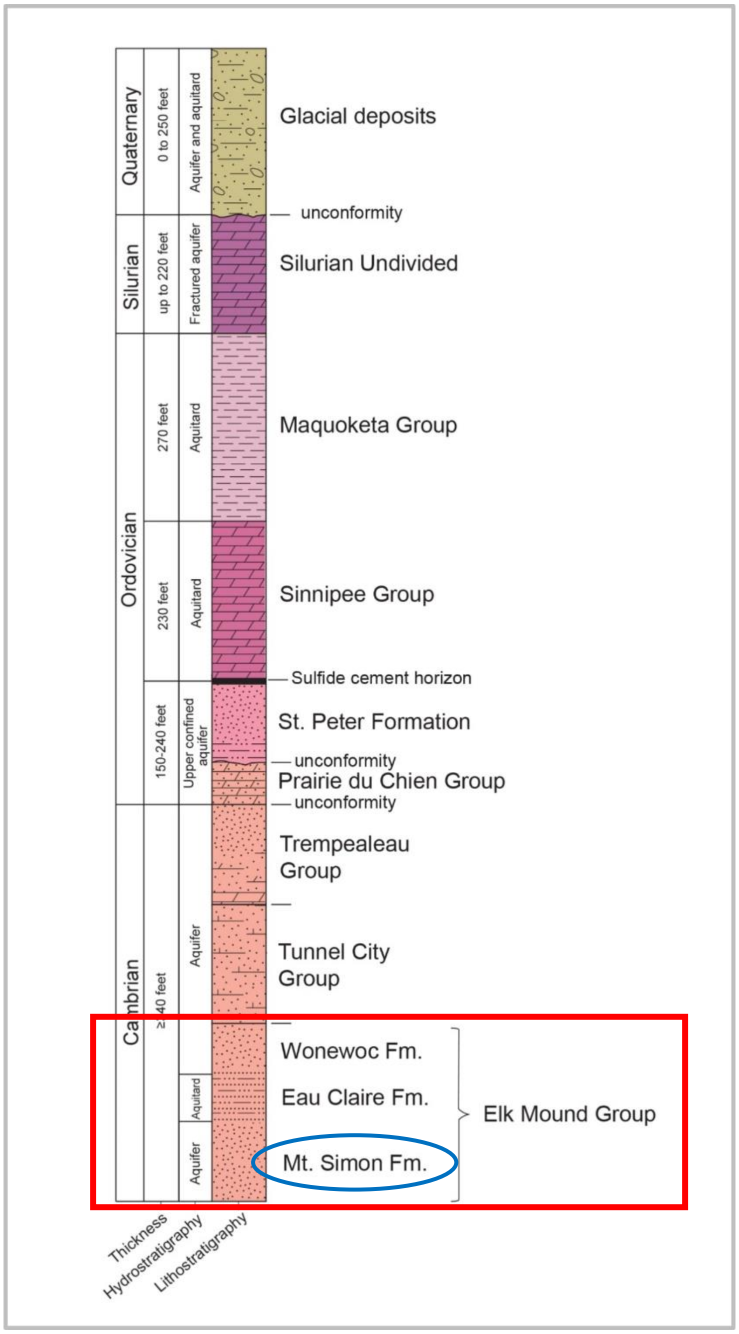

Figure 1: Phanerozoic stratigraphy of Wisconsin (modified from Stewart et al., 2021). The Elk Mound Group sits at the very base of the stratigraphic sequence (red box); the Mount Simon Formation sits at the base of the Elk Mound Group (blue oval).

origins of these sands, and workers have begun to piece together the paleogeography of the Laurentian interior in greater detail.

DZ research in Minnesota and Wisconsin has relied on outcrop samples, since the Elk Mound Group is well-exposed at the surface in these states. Research by Konstantinou et al. (2014)

sampled numerous outcrops in Wisconsin, Minnesota, northern Illinois, Missouri, and Michigan's Upper Peninsula, including most of the Cambrian and Ordovician formations in that region. They produced a wide-ranging analysis of the early Paleozoic sediments of the Upper Midwest and proposed that a river system with headwaters north or east of Lake Superior transported re-eroded sands from the Huronian, Animikie, and Midcontinent Rift (MCR) basins towards the modern west along what is now the north side of Lake Superior. In contrast, DZ work in Illinois has largely relied on drill core samples owing to the depth of the strata there. One result of this technique has been greater sampling detail within the Elk Mound Group, especially within the Mount Simon Sandstone (Lovell and Bowen, 2013; Freiberg et al., 2020; Freiberg et al., 2022). Such detail has revealed shifts in provenance in the lower portions of the Elk Mound Group, with earlier, proximal sources of sand being drowned by sediment and seawater and replaced by more distal sources. The combination of these studies and approaches has yielded a picture of sediment sources and transport through much of the Upper Midwest, with varying temporal resolution.

Despite this body of research, significant uncertainties remain. Detailed studies of the Elk Mound Group in Minnesota and Wisconsin have not been conducted, particularly from sites higher on the Wisconsin Arch. The absence of such research is significant because the Wisconsin Arch contains fluvial and aeolian sandstones (Dott et al., 1986), which may have different sources than the marine strata that surround and overlie them. Additionally, some major source provinces in

Minnesota and Wisconsin are poorly represented in the early Paleozoic sediments, including the Wolf River Batholith (WRB), formations associated with the Penokean Orogeny, and the Minnesota River Province. This lack of representation is surprising given that some of these formations would have been above sea level during parts of the early Paleozoic, and therefore should have been eroded into the sea during this time. The terrestrial sandstones of the Wisconsin Arch may provide some clues as to the current resting place of the sediment eroded from these formations.

In addition to DZ studies, researchers have examined crossbeds in early Paleozoic strata to understand paleocurrents in the area and possible directions of sediment transport. Such studies have found paleocurrents predominantly flowing in a southwesterly direction around the Wisconsin Arch, which implies transport from the Michigan Basin (Michelson & Dott, 1973; Guenther & Stewart, 2016). During the early Paleozoic, Laurentia sat in the tropics and was rotated about ninety degrees clockwise from its present orientation, so these paleocurrents would have flowed towards the paleo-northwest along the paleoshoreline. Given that Wisconsin was located about ten degrees south of the equator and squarely in the southern trade winds at the time, these paleocurrents would have followed the trades through shallow seas along the southern and western margins of a much smaller continent. This more immediate direction of transport suggests that sediment would have come from the modern east, although the influence of the arches and basins may complicate this interpretation.

This paper expands on the picture of the Cambrian landscape of the cratonic interior with a more focused examination of Elk Mound Group sandstones in central Wisconsin. The formations of the Elk Mound Group are relatively difficult to differentiate in central Wisconsin because the Wisconsin Arch forces the more distal Eau Claire Formation to pinch out, leaving a condensed section of shoreface and foreshore sediments (Ostrom, 1966; Clayton, 1989; Clayton & Attig, 1990). DZ analysis of samples from a variety of terrestrial environments near the Dells of the Wisconsin River provides greater temporal resolution for sandstones north of the Illinois Basin and illuminates differences in provenance between marine and terrestrial sandstones. Along with the DZ data, paleocurrent data from wells across central Wisconsin provides more detail on the immediate transport of the sand that formed the Elk Mound Group.

Regional Geology

As noted above, the Elk Mound Group was the first in a sequence of quartz arenites deposited in a shallow sea during the late Cambrian. The slope of the seafloor was exceptionally gradual, and the sediments form uniquely thin, laterally continuous layers in the Upper Midwest (Runkel et al., 2007). Cycles of sea level transgression and regression (rises and falls) created alternating layers of sediment. The earliest such cycle created the Eau Claire Formation, which predominantly formed below fair-weather wave base, in between the shoreface deposits of the Mount Simon and Wonewoc formations (Aswasereelert et al., 2008). These depositional patterns shift with the topography and bathymetry of the region. The Illinois Basin contains much thicker (hundred-meter-scale) formations and more variation within formations, while the Wisconsin Arch and the Hollandale Embayment to the west contains strata as little as a few dozen meters thick (Lovell and Bowen, 2013; Freiburg et al., 2022; Clayton, 1989). Additionally, as one moves onto the Wisconsin Arch, formations become more proximal in their depositional environment. As a result, more distal formations such as the Eau Claire Formation become totally indistinguishable from their surrounding formations or pinch out altogether, and marine deposits transition laterally to terrestrial ones (Ostrom, 1966; Dott et al., 1986; Zambito et al., 2017). Thus, the depositional environment and possible provenance of a formation vary spatially.

The Elk Mound Group overlies the Great Unconformity, and the underlying rocks provide a wealth of potential zircon sources (Figure 2). The oldest rocks in the region comprise the Superior Province, a set of granite-greenstone terranes with ages ranging from 2600-3000 million years ago (Ma) and modern exposures in Minnesota and Ontario. The next oldest igneous provinces in the region formed from the Penokean and Yavapai orogenies. The Penokean Orogeny occurred between 1830 and 1890 Ma, when the recently formed island arcs of the Pembine-Wausau Terrane and the Archean-age Marshfield Terrane collided with the Superior Province (Schulz & Cannon, 2007). The Yavapai Orogeny occurred around 1700 Ma, when the 1700-1800 Ma Yavapai Province accreted to the continent from the modern south. The accretion of the Yavapai Province manifested

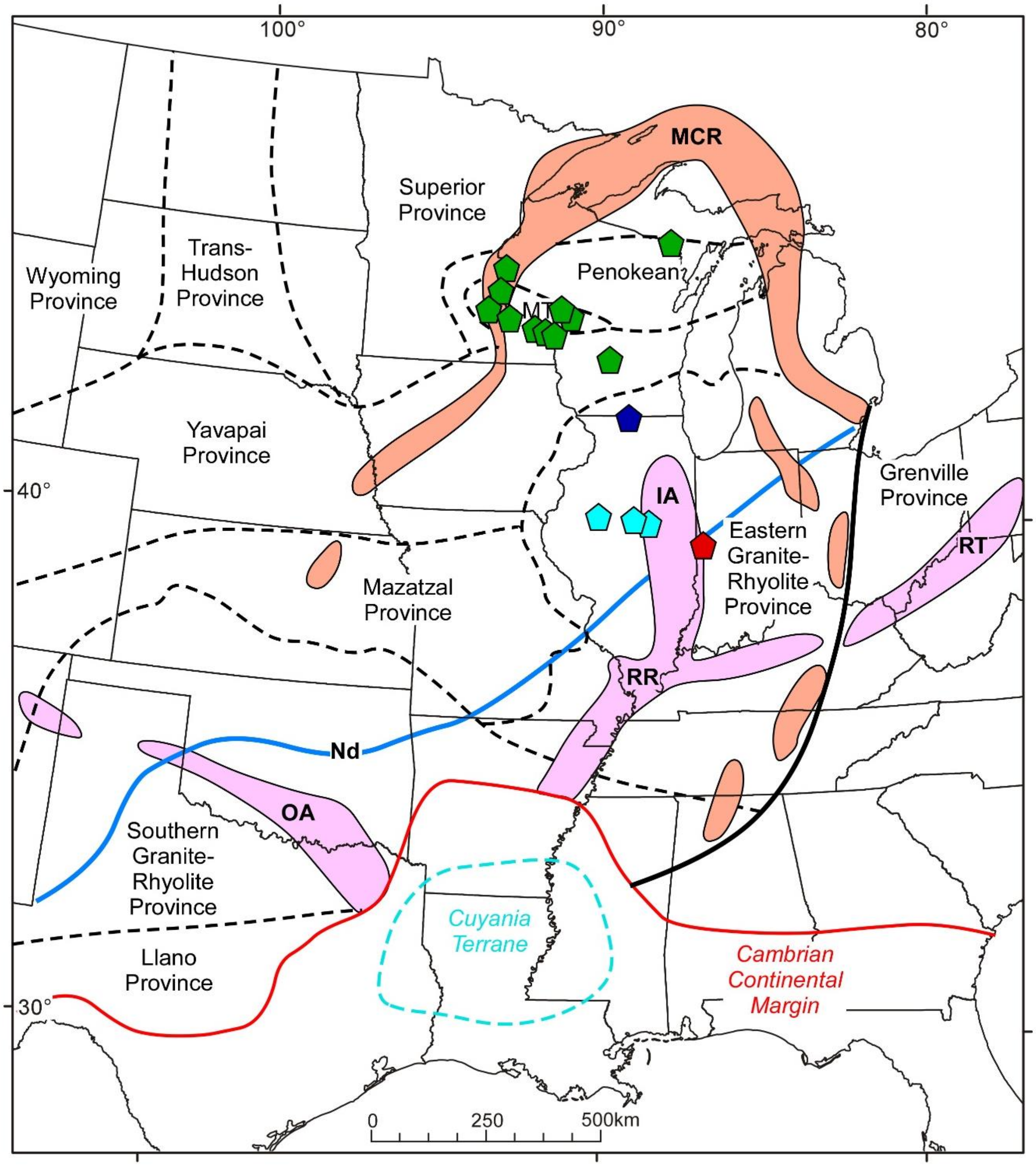

Figure 2: Archean and Proterozoic terranes of Laurentia (copied from Freiburg et al., 2022). The dark blue pentagon indicates the location of the UPH cores; the green pentagon immediately above it indicates the location of the Wonewoc samples used by Konstantinou et al. (2014) MCR refers to the Midcontinent Rift, while MT refers to the Marshfield Terrane. The Wolf River Batholith is unmarked but located under and just south of the second half of the word "Penokean".

itself in Wisconsin as the Red Granite Interval, when batholiths of red granite formed under much of the state. In the several hundred million years after the Yavapai Orogeny, a series of granite-rhyolite provinces formed (Whitmeyer & Karlstrom, 2007). These provinces largely formed south of Wisconsin and thus lay further out to sea during the late Cambrian, but some may have provided sediment sources before the sea rose to cover much of the continent. In addition, the Wolf River Batholith formed in northeast Wisconsin between 1460 and 1510 Ma (Van Schmus et al., 1975) and was also a potential source of sediment to the Elk Mound Group. Finally, the most recent igneous provinces identified as potential sediment sources are the Grenville Province and the Midcontinent Rift (MCR). The former contains formations of various ages ranging from 950 Ma to 1300 Ma (Whitmeyer & Karlstrom, 2007). While these formations lie under the northeastern United States, far from the Upper Midwest, the Grenville Orogeny produced huge mountains that shed sediment across Laurentia. The MCR formed far closer to the Elk Mound Group and arcs through the Upper Midwest (Figure 2). It formed between 1125 and 1085 Ma as a failed rift system and contains large basaltic provinces and scattered rhyolites, which could have provided quartz to the Cambrian sandstones (Whitmeyer & Karlstrom, 2007).

In addition to primary igneous sources, older sedimentary formations may have been eroded and redeposited to form the Elk Mound Group. Such sediment recycling is especially likely given the physical maturity of the sandstones (Dott, 2003). Basins that could have contributed sediment include the Huronian, Animikie, and MCR sediment basins. The Huronian basin formed between 2200 and 2500 Ga and primarily contains Superior-age sediments from 2600-2700 Ma. The Animikie Basin formed during the Penokean Orogeny and contains a wide range of sediment ages, although the two most prominent peaks date to the Penokees themselves (1850 Ma) and the Superior Province (2600 Ma, among other ages; Craddock, Rainbird, et al., 2013) The MCR contains sediments deposited after igneous activity ceased (between 1050 and 1090 Ma). These sediments largely date to the rift itself and the Grenville Province to the east but include sediments from the Penokees, granite-rhyolite suites, and Superior Province as well (Craddock, Konstantinou, et al., 2013; Malone et al., 2020). In addition to these basins, the quartzite ridges of the Upper Midwest could have contributed sediment as well. The quartzite formed from sandstones deposited around 1600-1700 Ma, and it consists predominantly of Penokean- and Yavapai-age, 1750-1900 Ma zircons with a smattering of Superior-age, 2400-2840 Ma zircons (Stewart et al., 2021). Sedimentary and meta-sedimentary sources can be difficult to detect because any zircons eroded from these sources retain the ages of the igneous provinces from whence they originally eroded. Thus, attempts to pin down sedimentary basins as sources of sediment must rely on physical and chemical characteristics of the grains, along with more complex statistics. Some papers (Konstantinou et al., 2014) have rigorously tackled this problem, while others have left open the issue of redeposited, secondary sediment.

Methods

DZ sample locations

This study considers six previously unpublished DZ samples. Of these six, four were collected by the author from outcrops – two about 2.3 km north of Wisconsin Dells, WI, in the Dells of the Wisconsin River State Natural Area (SNA) along the Chapel Gorge Trail, and two about 5.5 km south of Wisconsin Dells on the northwest bank of Mirror Lake. Two additional samples were collected by Esther Stewart, a geologist at the Wisconsin Geological and Natural History Survey (WGNHS), from cores drilled by the WGNHS. One core, the Triemstra core, was drilled in Belle Fountain, WI, about 42 km east of Wisconsin Dells. The other core, the UPH-1 core, was drilled in Winslow Township, IL, just south of the WI-IL state line (Figure 3). The Mirror Lake samples

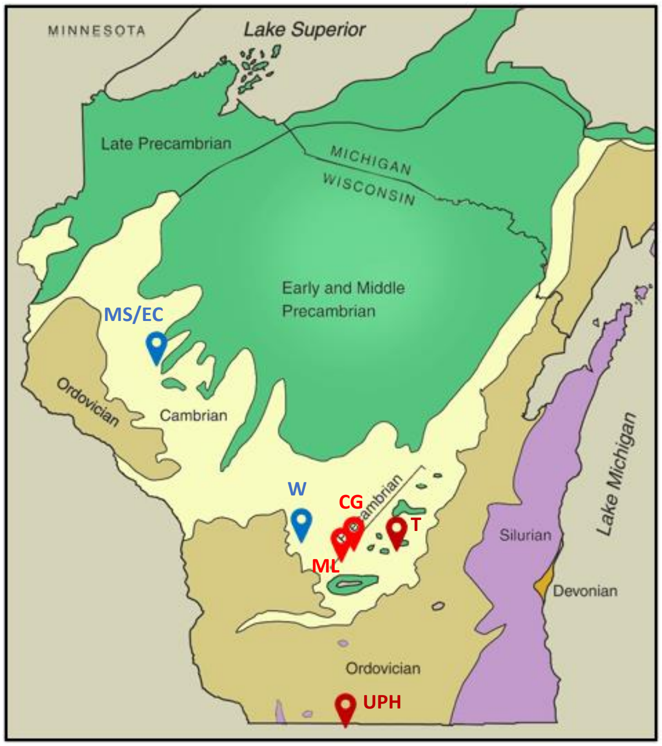

Figure 3: Zircon sample locations (modified from Dott and Attig, 2004). Light red icons indicate outcrop locations near Wisconsin Dells (CG for Chapel Gorge samples, ML for Mirror Lake samples); dark red icons indicate the locations of the Triemstra (T) and UPH cores. The UPH-1 and UPH-3 cores were drilled within a couple of kilometers of each other. Blue icons indicate samples from the Elk Mound Group analyzed by Konstantinou et al. (2014) (MS/EC for the Mount Simon and Eau Claire samples, W for the Wonewoc sample). The Wisconsin Arch extends down through the center of Wisconsin and splits formations around it to the east and west.

were collected about 10 vertical meters apart, while the Chapel Gorge samples were collected about 15 vertical meters apart. Both the Mirror Lake and Chapel Gorge sample pairs were collected within a couple hundred horizontal meters of each other to record temporal shifts rather than spatial ones. The core samples were both collected near the base of the Elk Mound Group in their respective cores, just above the Precambrian basement. These sample locations represent depths of about 180 meters below the surface in the Triemstra core and 600 meters in the UPH-1 core.

This study considers the new data in the context of data gathered by Konstantinou et al. (2014) and Lovell and Bowen (2013). Konstantinou et al. (2014) analyzed one sample from each of the three formations in the Elk Mound Group. They gathered the samples from the type sections of these formations near Wonewoc, WI, (about 36 km west of Wisconsin Dells) and Eau Claire, WI (Figure 3). (The type sections of both the Mount Simon and Eau Claire formations are near the city of Eau Claire, about 190 km northwest of Wisconsin Dells.) Lovell and Bowen (2013) analyzed the UPH-3 core, drilled near the UPH-1 core in northern Illinois. They collected five DZ samples from the Mount Simon Formation in this core at depths of about 410, 460, 540, 580, and 640 meters. Lovell and Bowen (2013) also provided sedimentological and compositional descriptions of the UPH-3 core to accompany their DZ data. Thus, the data provided by Lovell and Bowen (2013) provides key context for the UPH-1 sample, while the data provided by Konstantinou et al. (2014) contributes to interpretations of the outcrop and Triemstra samples in central Wisconsin.

DZ processing methods

The following description of DZ processing is adapted from personal communication with Dr. David Malone, Professor of Geosciences at Illinois State University. An exact copy of what he wrote (with more detail) can be found in Appendix A.

The outcrop samples were separated by Dr. Malone at Illinois State University in late 2022 and dated at the Arizona LaserChron Center (ALC) by Dr. Malone and a team of undergraduates (including the author) in early 2023. Zircon crystals were extracted from the samples using traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples were processed such that all zircons were retained in the final heavy mineral fraction. Hundreds of these zircons were then incorporated into a 1" epoxy mount together with zircon crystals of known ages as calibration standards. Prior to isotopic analysis, the mounts were sanded down to a depth of ~20 microns, polished, imaged, and cleaned. Grains of interest were imaged to provide a guide for locating analysis pits in optimal locations and to assist in interpreting results.

Methods for U-Pb geochronology have been described by Gehrels et al. (2006, 2008), Gehrels and Pecha (2014), and Pullen et al. (2018). The analyses involved ablation of zircons with a Photon Machines Analyte G2 excimer laser equipped with a HelEx ablation cell using a spot diameter of 20 microns. The ablated material was carried in helium into the plasma source of an

Element2 HR ICPMS (inductively coupled plasma mass spectrometer), which sequenced rapidly through the U, Th, Pb, and Hg isotopes. Signal intensities were measured with an SEM that operated in pulse counting mode for signals less than 50,000 cps, in both pulse-counting and analog mode for signals between 50K and 4M cps, and in analog mode above 4M cps. The calibration between pulse-counting and analog signals was determined line-by-line for signals between 50K and 4M cps and applied to >4M cps signals.

With the laser set to an energy density of ~5 J/cm^2, a repetition rate of 8 Hz, and an ablation time of ~10 seconds, ablation pits were ~10 microns in depth. Sensitivity with these settings was approximately ~58,000 cps/ppm. Each analysis consisted of 8 seconds on peaks with the laser off (for backgrounds), 10 seconds with the laser firing (for peak intensities), and an 8 second delay to purge the previous sample and save files.

Following analysis, data reduction was performed with an in-house Python decoding routine and an Excel spreadsheet (E2agecalc). E2agecalc performed a series of calculations to obtain signals for various isotopes of U, Th, Pb, and Hg. These signals were then compared to determine ratios of Pb-206/U-238, Pb-207/U-235, and Pb-206/Pb-207, which were in turn employed to determine ages and error margins for individual zircon crystals. Some crystals were discarded due to heterogeneities, discordance, or error bounds greater than 10%. However, the remaining zircons were considered representative of the ages of the source provinces of the sediments from which they were derived. The zircon ages calculated from the Pb-206/Pb-207 ratio were used as the definitive ages of the crystals since this ratio generally returns the best ages for zircons older than about 950 Ma.

The core samples were broken up into fist-sized pieces, crushed and separated by ZirChron LLC using standard methods, and dated at the ALC using the methods described above. These samples were separated, dated, and analyzed in 2013. Esther Stewart managed this process.

Sample sizes

DZ studies analyze a representative sample of the formations of interest to understand what percentage of the sediment falls into which age ranges. These age ranges in turn are matched to distinct igneous and metamorphic provinces and older sediment basins, which are understood to represent the source of the sediment. Such analysis relies on statistics and large sample sizes to ensure that no source province is over- or under-represented in the zircon sample. However, various factors constrain the maximum number of zircons that can be reasonably analyzed, including time, funding, sample availability, and zircon richness in the formation(s) of interest. Given these constraints, studies have attempted to determine an optimal number of zircons for statistically rigorous results. Vermeesch (2004) determined that a sample size of 117 would enable researchers to be 95% confident they had at least one zircon from any province providing at least 5% of the sediment in a formation. This standard has been the target of this study. All but two samples missed this mark due to elimination of crystals for discordance or heterogeneities, and the paucity of detrital zircons in supermature arenites further constrained sample sizes. However, every sample provided at least 97 reliable ages, so sample sizes remain reasonably robust.

Sedimentology

Sample sedimentology was analyzed through observations of outcrops, cores, photographs of cores, and optical borehole image (OBI) logs. OBI logs were the least reliable of these methods, as the logs' image quality was often too low to accurately assess colors or grain sizes. In addition to these observations, previously published reports on the sedimentology of the formations of interest were considered, especially Dott et al. (1986) in the Wisconsin Dells area and Lovell and Bowen (2013) in northern Illinois. Direct observations in the field generally corroborated the published reports.

Paleocurrent indicators

Paleocurrent data were collected from crossbeds in wells across central Wisconsin using OBI logs and WellCAD software, in a similar manner to that used by Guenther and Kingsbury Stewart (2016). Borehole images were captured using downhole rotating cameras, which recorded imagery that could then be "unwrapped" and viewed as a two-dimensional section of the well. These images were examined for sine curves in the bedding characteristic of slanted planes (crossbeds), and such curves were marked as structures to record their strike and dip (Figure 4). Care was taken to filter out faults and veins, along with beds with dip angles greater than sand's angle of repose. Crossbeds were corrected for deviations in the well path using WellCAD. Compass directions were recorded

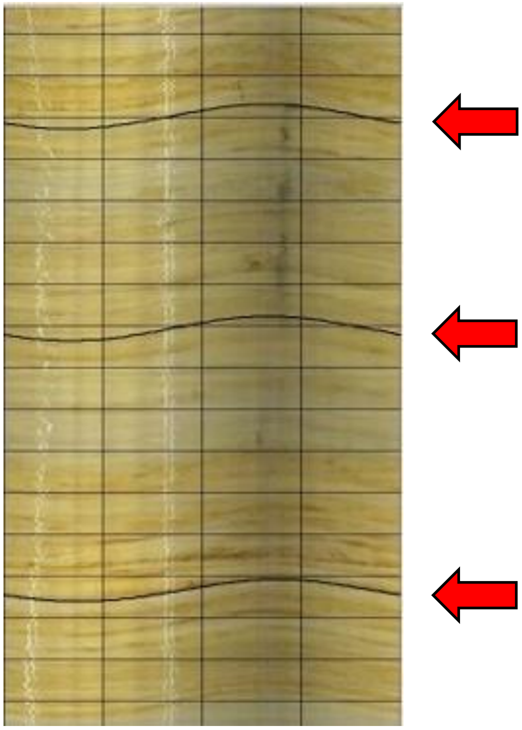

Figure 4: Screenshot of an OBI log in WellCAD software. The sine-curve-shaped bedding indicates tilted planes in the sandstone, here taken to be crossbeds. Black lines indicate planes that were marked and recorded for analysis (arrows).

in the original OBI logs. Crossbed strike and dip were entered into the free application Stereonet to calculate mean vectors with error bounds and to build rose diagrams. Given the difficulty of differentiating the formations of the Elk Mound Group on the Wisconsin Arch, crossbeds were gathered from throughout the Elk Mound Group, and in some cases from parts of the Tunnel City Group immediately above. In certain wells, geochemical signatures could be used to discern boundaries between formations. A total of 21 distinct wells were ultimately considered from across Juneau, Adams, Sauk, Columbia, Dodge, and Fond du Lac counties in central Wisconsin. In addition, crossbeds were measured in outcrops at Chapel Gorge in the Dells of the Wisconsin River SNA. The number of crossbeds obtained at each location varied, but the well crossbeds ranged from 50 to 223 per well, providing reasonably robust sample sizes.

Results

Zircon ages

Almost every zircon analyzed for this project fell between 1000 Ma and 2800 Ma in age. Within this range, most zircons fell between 1000 and 1500 Ma, 1600 and 1900 Ma, or 2600 and 2800 Ma. Older samples from lower in the section generally contained a mix of zircons from the different age bins, while younger samples from higher in the section almost exclusively contained zircons from 2600-2800 Ma.

In the samples from central Wisconsin, the older samples contained a mixture of zircons from the 1000-1500 Ma range and the 2600-2800 Ma range. The middle samples contained samples from the 1800-1900 Ma range as well. The younger samples mostly consisted of 2600-2800 Ma zircons (Figures 5; also Figure 1A). The basal Triemstra core contained a peak around 1450 Ma and a spike around 2720 Ma. The lower Chapel Gorge core contained similar peaks, as well as a peak around 1050 Ma and a small peak around 1840 Ma. The upper Chapel Gorge core contained a larger peak around 1830 Ma, as well as peaks around 1050 Ma, 1470 Ma, and 2710 Ma. The lower Mirror Lake sample showed a similar pattern, albeit with more sub-peaks around 1150 Ma and 1210 Ma. The upper Mirror Lake sample contained a dominant peak around 2680 Ma, with smaller peaks around 1430 Ma and a smattering of zircons between 950-1500 Ma and 1700-1900 Ma. Finally, the Wone-

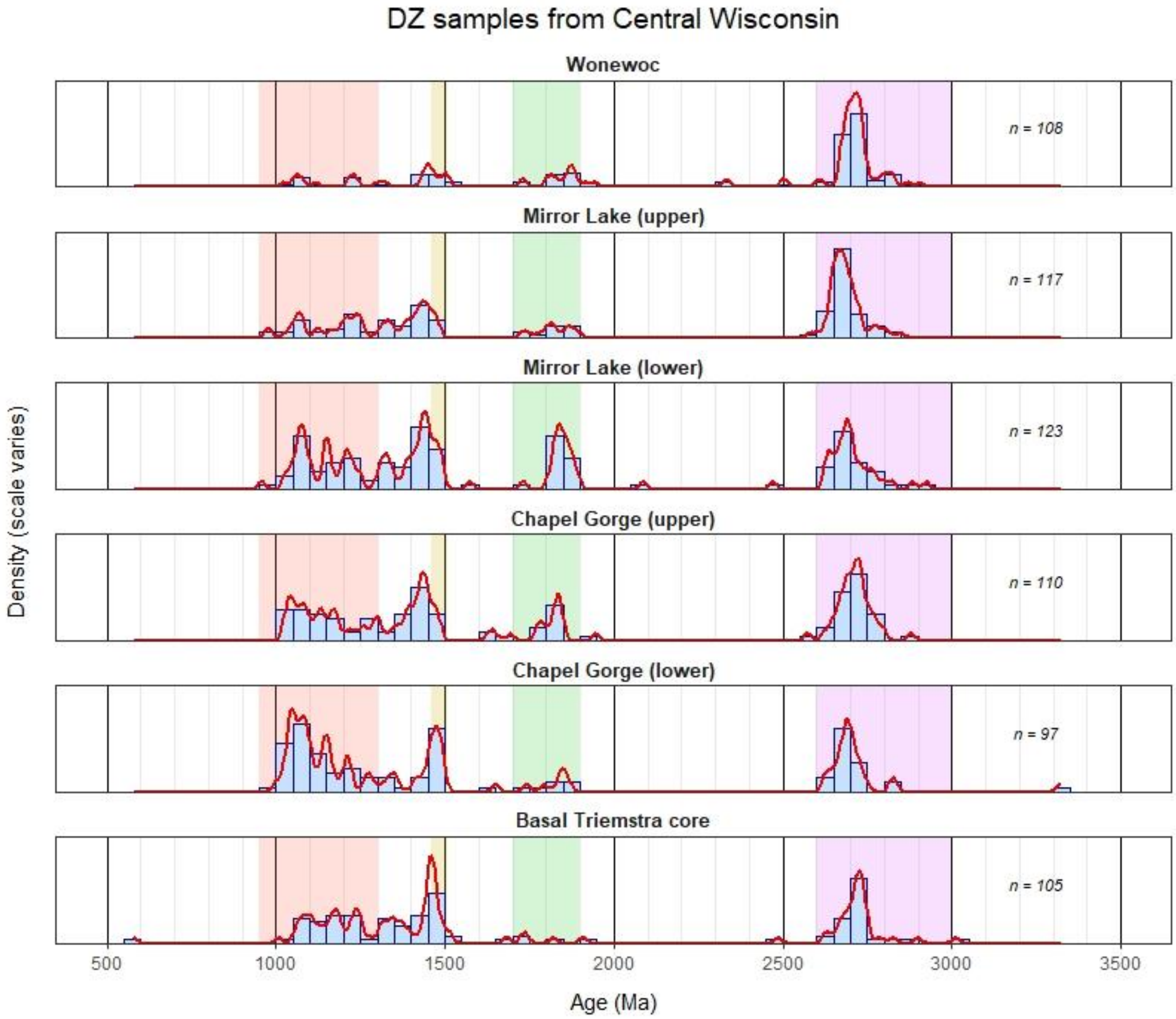

Figure 5: Samples from central Wisconsin, organized in stratigraphic order (and, incidentally, roughly from east to west as one ascends through the figure). Colored and shaded bands indicate the age ranges of the Grenville, Wolf River, Penokean-Yavapai, and Superior provinces, named from left to right (ascending age). See Figure 1A (appendix) for an alternative visualization of this data.

woc sample (collected by Konstantinou et al., 2014) showed a similar pattern to the upper Mirror Lake sample, albeit with a more dominant Late Archean peak around 2710 Ma.

The samples from the UPH wells in northern Illinois contain more zircons in the 1700–1900 Ma range, but otherwise show similar patterns to the central Wisconsin samples (Figure 6; also Figure 2A). The deepest sample, which was gathered and analyzed by Lovell and Bowen (2013), contains a

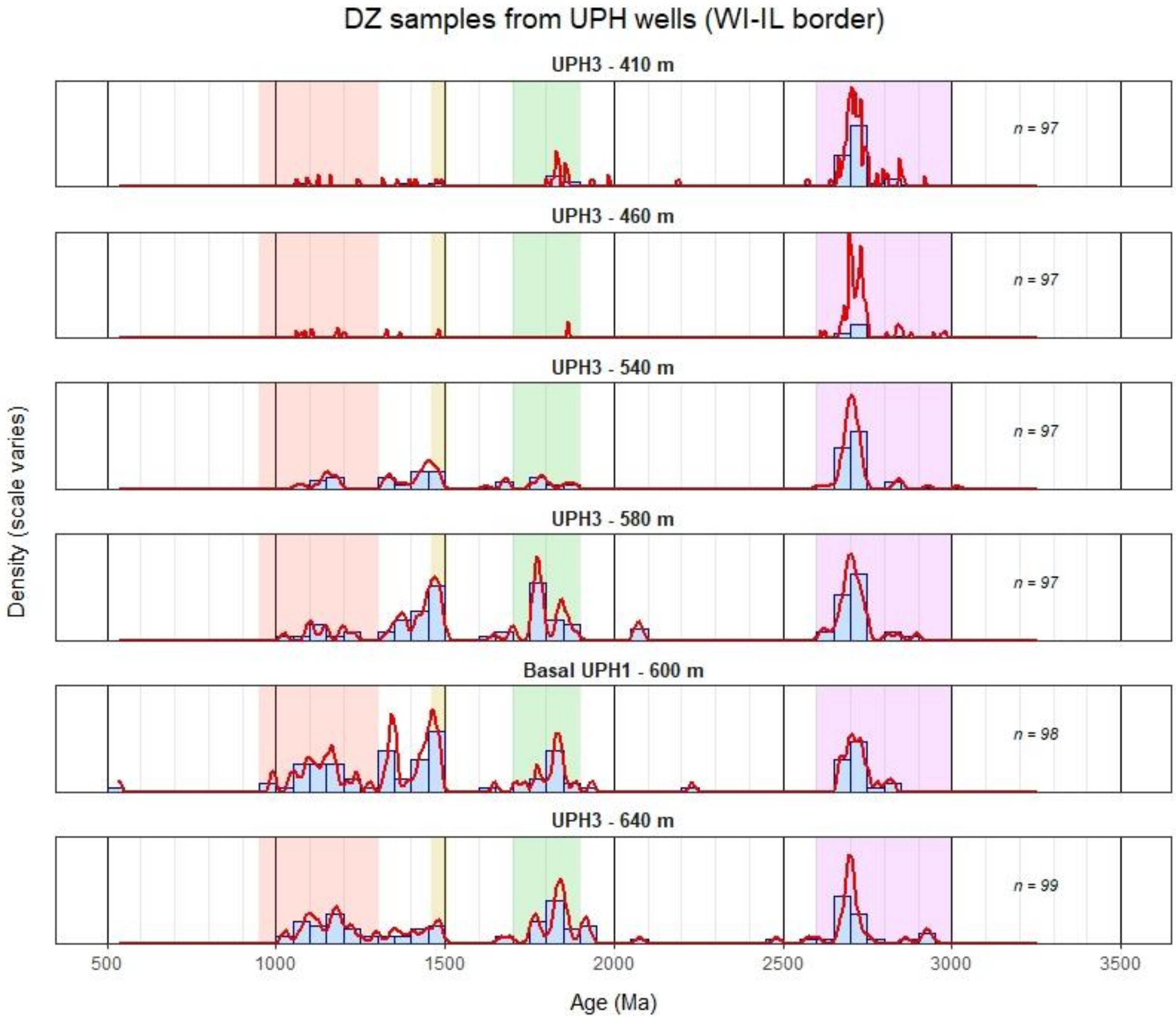

Figure 6: Samples from the UPH wells in northern Illinois, organized in stratigraphic order. The depth of each sample below the modern land surface. is noted in the title of that panel. Colored and shaded bands are copied from Figure 5. See Figure 2A (appendix) for an alternative visualization of this data.

peak at about 2700 Ma, as well as peaks at 1830 Ma, 1760 Ma, and 1920 Ma and a spread of zircons between 1000 and 1500 Ma. The sample from UPH-1, which is the next deepest, contains a smaller peak at 2700 Ma, sharp peaks at 1340 Ma and 1450 Ma, a peak around 1820 Ma, and a diffuse peak at 1170 Ma. (After this sample, all the remaining samples come from the UPH-3 core, analyzed by Lovell and Bowen, 2013.) The next sample up shows a sharper peak again at 2700 Ma, a similarsized peak at 1780 Ma, a peak at 1460 Ma, and smaller peaks at 1830 Ma and elsewhere. The top three samples are all dominated by peaks at 2700 Ma and contain very few zircons from the Proterozoic.

Paleocurrent indicators

Paleocurrent patterns vary across central Wisconsin, but generally point in a westerly or southwesterly direction (Figure 7). This trend is most pronounced in Columbia and Dodge counties (east of the Baraboo Hills), where paleocurrents from 9 out of 12 sites show a westerly or southwesterly direction of transport. Of the three exceptions, two point northwest and the other points northeast. Most of these sites show unimodal currents, although some show a more diffuse spread, one shows a roughly bimodal distribution, and one plots as a starburst of currents.

Around the Baraboo Hills (which stood as islands in the Cambrian sea) the paleocurrents vary more in their directions of transport. Two roughly bimodal sites around the Dells show primary transport to the southeast and secondary transport to the northwest. One of the northwesterly indicators in Columbia County lies near the Baraboo Hills and points towards the hills. Two more sites on either side of the Baraboo show a bimodal pattern with modes pointing southwest and northwest at 90-degree angles to each other, while another site south of the Baraboo gives a chaotic signal with the most prominent mode pointing to the northeast. These six wells thus show some variation in their transport direction relative to the clearer signal given further east. The four paleocurrent sites north of the Dells vary between chaotic and bimodal signals, thus also breaking the pattern presented in Columbia and Dodge counties.

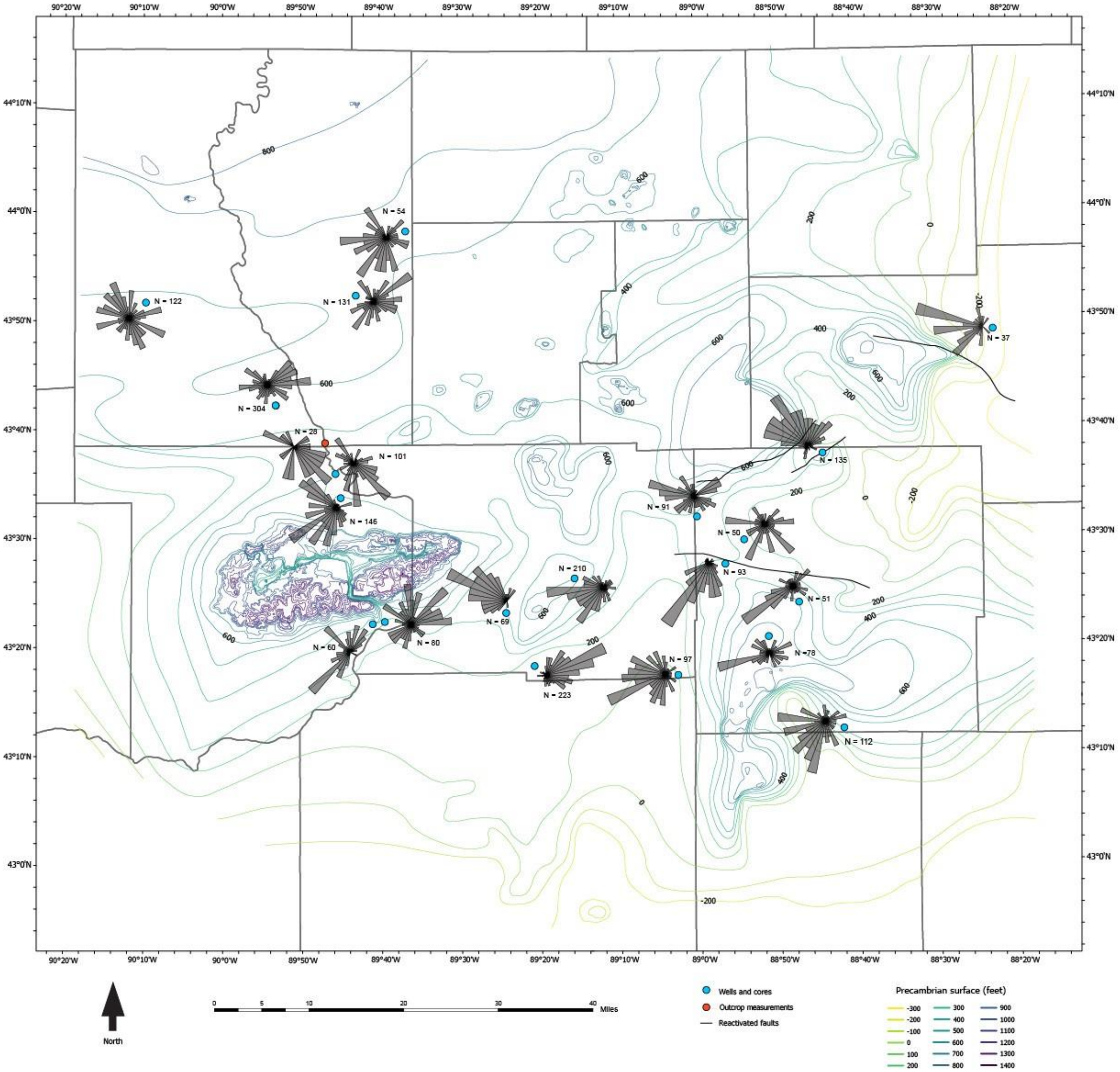

Figure 7: Map of paleocurrents on the modern topography of the Precambrian basement. The Precambrian topographic base map was modified from Stewart et al. (in press). County outlines are shown in gray. Wisconsin Dells sits near the red dot, and the Baraboo Hills can be seen as a purple ellipsoid mass on the west side of the map. Blue and red dots indicate the actual locations of the wells from which nearby rose diagrams were collected. The yellow lines on the southern and eastern sides of the map mark the southern limit of the Wisconsin Arch.

Sedimentology of sample locations

All four outcrop samples come from the Dells of the Wisconsin River and related gorges. The sandstone walls of the gorges were deposited as aeolian dunes, which gradually transitioned to a braided river environment before being submerged by the sea (Dott et al., 1986). The lower Chapel Gorge sample came from decimeter-scale, slightly hummocky crossbeds of pale, medium- to coarse-grained sandstone close to the level of the Wisconsin River (Figure 8.a). Outcrops immediately upstream show evidence of grainflow and adhesion structures, while outcrops across the river show the classic, meter-scale crossbeds of the Dells (Figure 8.c), all indicative of an aeolian dune environment with some slight reworking by river systems. The upper Chapel Gorge sample came from flaggy, slightly dipping, cm-scale beds, which sit just above thick, steep, truncated crossbeds and just below a topographic bench (Figure 8.b). The sand grains are poorly sorted, pale, and fine- to coarse-grained, with some mm-scale laminae visible. Some scour marks and uneven bedding planes are visible slightly to the west (Figure 8.d). These characteristics suggest a river-dominated system, with a mixture of well-defined channel banks forming the thick, steep crossbeds and sheet floods forming the thin, flaggy beds. While the Elk Mound Group is nearly impossible to subdivide this high on the Wisconsin Arch, both Chapel Gorge samples likely came from the Mount Simon Formation (or were at least laid down at the same time as the Mount Simon Formation) based on extrapolated layer thicknesses (Clayton, 1989).

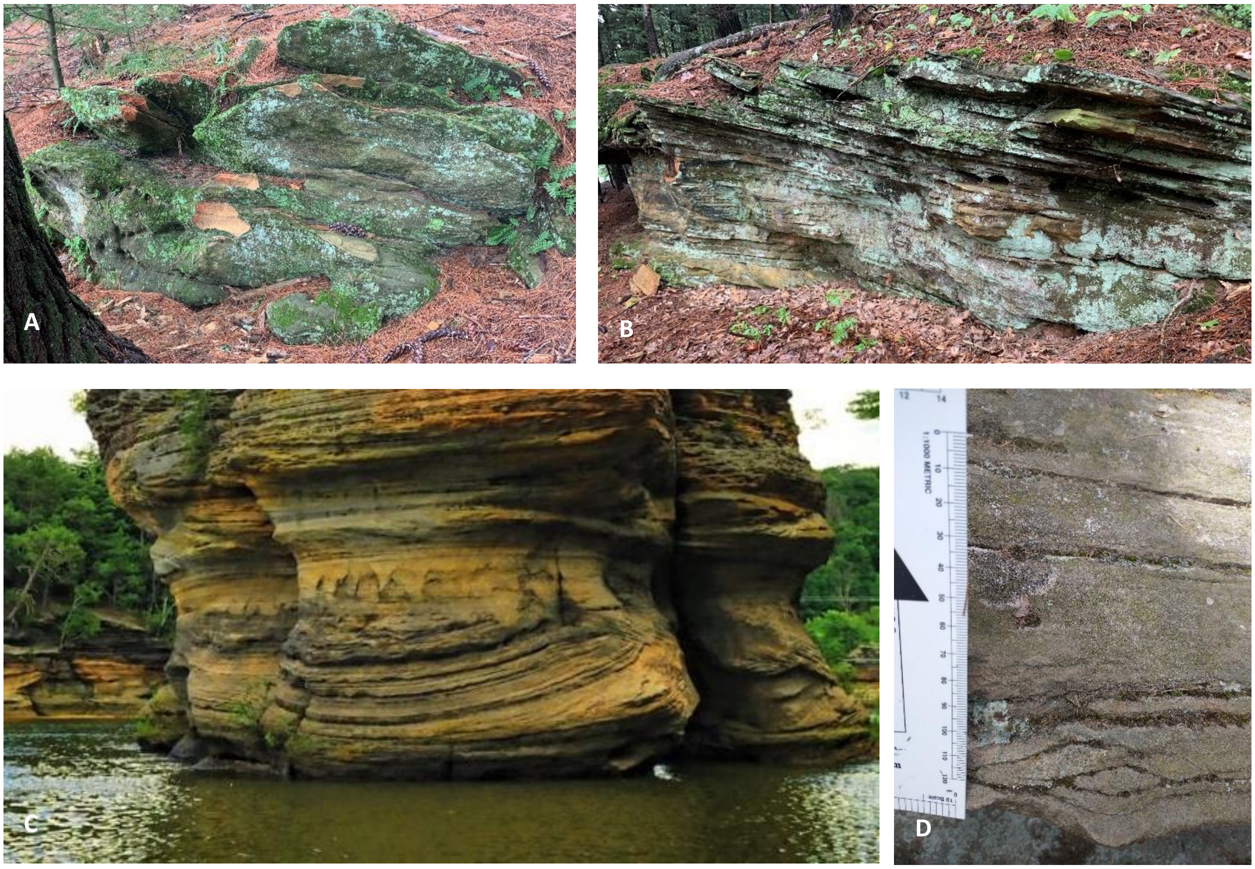

Figure 8: Sedimentology of the Chapel Gorge samples. A) Sample location for the lower Chapel Gorge sample. B) Sample location for the upper Chapel Gorge sample. C) Crossbeds in the Wisconsin Dells produced by aeolian dunes. D) Finely laminated bedding and scour marks near the upper Chapel Gorge sample site.

The lower Mirror Lake sample came from pale, medium- to coarse-grained sandstone with hummocky and steeply curved beds. Cm-scale lenses and wedges are visible (Figure 9.a). Some portions contain mm-thick laminae alternating between well-sorted coarse and fine grains. Just above this exposure sits poorly sorted, flaggy, waffle-patterned sandstone with crisscrossing beds (Figure 9.b). These exposures sit a few meters above the level of Mirror Lake and likely formed at the reworked toe of a dune, with the flaggy sandstone just above the sample source representing more sheet floods. The upper Mirror Lake sample came from a unique layer within the Elk Mound Group. This thin (about one meter thick) layer appears darker and reddish and contains mm-thick

Figure 9: Sedimentology of the Mirror Lake samples. A) Sample location for the lower Mirror Lake sample, including hummocks and lenses. B) Waffly bedding just above the location in A. C) Sample location for the upper Mirror Lake sample, with anastomosing hematite bands visible. D) Hand sample from the root hole in C showing fine laminae of red silt and white kaolinite.

patches of silt. It also contains mm- to cm-thick bands of hematite cement and thin, white clasts of kaolinite (Figure 9.c-d). The sand grains are poorly sorted and darker in color. Bedding planes are generally flat-lying, although one sample from the layer contained cm-scale ripples. This layer can be found in numerous locations around the Dells and the surrounding countryside, and it frequently forms a slight topographic bench. Between and around the silt, hematite, and kaolinite, this layer consists of pure, poorly sorted quartz arenite. The silty layer likely formed in quiet backwaters or ephemeral pools in a dune- and river-dominated setting. The quiet backwaters would have allowed silt and kaolinite to settle in fine laminae, while shifting rivers and dunes could have buried these finer layers in poorly sorted sand. The layer has previously been interpreted as a distal deposit of the Eau Claire Formation, and while this paper does not wholly accept that conclusion (partially because of the sedimentology of the layer; for a full explanation, see the author's Geoscience capstone paper), it concurs that, based on layer thicknesses, the silty layer sits at the level of the Eau Claire Formation. Thus, the upper sample from Mirror Lake likely comes from the Eau Claire Formation, while the lower sample comes from the Mount Simon Formation.

Less detail can be gathered about the sedimentology of the core samples. The basal Triemstra sample contains pale, crossbedded, medium- to coarse-grained sandstone with some larger (mm-scale) rounded quartz grains and small silt drapes. The basal UPH-1 sample also contains crossbedded, medium- to coarse-grained sandstone, which varies in color from beige to purple. Millimeter-scale pebble lags and sub-cm-diameter, subangular pebbles can also be seen. Both samples come from just above the Precambrian basement, and therefore represent the basal Mount Simon Formation. The basal UPH-1 sample likely formed in a braided river system. Evidence for such a system can be seen in the crossbedded sandstone and pebble lags, as well as its spatial and temporal proximity and sedimentological similarity to the lower reaches of the UPH-3 core, which Lovell and Bowen (2013) interpret the same way. The basal Triemstra core likely formed in a similar environment, with larger grains and silt drapes representing occasional surges or drops in flow velocity associated with floods.

All six of the newly presented samples in this paper thus formed in fluvial or aeolian settings. The samples presented by Lovell and Bowen (2013) from the UPH-3 core were also interpreted as forming in fluvial settings, with the lower samples from that core forming in a braided river system and the upper samples forming in a tidally influenced delta. The UPH-3 core thus records a transition towards increasingly marine samples. The type sections in the Elk Mound Group collected by Konstantinou et al. (2014) are interpreted as proximal marine deposits, mostly either above fair-weather wave base or between fairweather and storm wave base (Ostrom, 1966; Aswasereelert et al., 2008). These samples thus represent marine deposits, which contrast with the terrestrial deposits represented by the rest of the samples discussed in this study. Whether their ultimate place of deposition was a marine or terrestrial setting, the zircon crystals would have shared long-distance transport paths.

Discussion

Central Wisconsin provenance

Given the depositional environments of the samples, the question arises of how these environments might have influenced the provenance of the sands based on DZ analysis.

The basal Triemstra sample shows the strongest spike from the Mesoproterozoic WRB of any sample. Given that it formed relatively close to the WRB and just above the Precambrian basement (i.e., before sand could bury the underlying igneous formations), this spike may reflect direct erosion from the WRB. The rest of the sand from this sample appears to originally come from the Grenville and Superior provinces. The Grenville zircons persist through the Chapel Gorge and lower Mirror Lake samples, suggesting continued transport from the source of these sediments. Given the distance to the Grenville Province, such sediments likely flowed down from sedimentary deposits in the MCR on the rivers whose presence these same sandstones record. However, given the direction of the trade winds and the lack of vegetation to hold down sand on the Cambrian land surface, it may also be that some sand blew across the continent directly from the Grenville Province. The MCR itself contains relatively little quartz, so it likely contributed little sediment to the Cambrian sandstones. That said, scattered rhyolites and granites associated with the MCR may have contributed sediment. Multiple subpeaks between 1000 Ma and 1300 Ma further suggest that the zircons came from the multistage Grenville Province rather than the temporally compact MCR, especially given a relative lack of peaks around 1100 Ma. Some of the WRB sediments likely come from the same deposits since the WRB and related granite-rhyolite provinces contributed a portion of the sediment in the MCR basins. Based on the extreme physical maturity of the sand grains, this explanation seems more likely than primary erosion from the WRB itself (Dott, 2003). That said, the WRB did not contribute a particularly large portion of the sediments in the MCR, so some of the larger spikes of WRB age may require direct erosion from the WRB as well. Sediments directly eroded from the Grenville Province, in contrast, might have weathered enough while blowing across

Laurentia that they did not require secondary erosion and deposition. That said, if WRB sediments were eroding from the MCR, Grenville sediments would have eroded with them.

Both Chapel Gorge samples and the lower Mirror Lake sample show similar patterns to the basal Triemstra sample. Additionally, these three samples show an increasing peak in Penokean-age zircons, especially those that formed around 1830 Ma. Such a peak suggests delivery from the Animikie Basin, which has a substantial proportion of Penokean-age zircons owing to its formation in the shadow of the Penokee Mountains. Given the sedimentological similarity of the upper Chapel Gorge and lower Mirror Lake samples, it seems plausible that this shift in provenance reflects the input of a new river system transporting sediment from the Animikie Basin, with accompanying changes in the local depositional environment. The Animikie Basin also contains a large portion of Superior-age zircons, so it could easily have supplied this peak as well. However, the MCR clearly continued to provide sediment based on the continued presence of Grenville- and WRB-age zircons in the mix (which could not have come from the circa-1800 Ma Animikie Basin since the Animikie formed 300 My before the WRB).

The Baraboo Range and other quartzites in the area could have provided the surge in Penokean zircons as well. However, such a sediment source seems unlikely because of the physical toughness of the Baraboo Quartzite. The Baraboo and other similarly-aged quartzites are incredibly resistant to erosion (as evidenced by their continued existence today, well over a billion years after they metamorphosed), so it seems unlikely that such physically mature grains as those of the Elk Mound Group could have formed from such resistant and proximal sources. Purple pebbles in the UPH-1 core may come from the Baraboo (which is famously purple), and deposits very close to the Baraboo may contain more Baraboo sediment, but the Elk Mound Group as a whole likely contains no significant fraction of Baraboo-derived sediment. Such a conclusion is further supported by the lack of Penokean zircons in the Wonewoc sample. Since this sample was collected west of the Baraboo and represents a marine sample, it should have received any sediment from the Baraboo, especially sediment broken off by waves in the sea. The fact that this sample contains almost no Penokean zircons suggests a relative lack of Baraboo-derived sediment.

The upper Mirror Lake sample records a drop in the portion of Penokean-, WRB-, and Grenville-age zircons. This decline continues in the Wonewoc sample, such that virtually all the zircons in this sample come from the Superior Province. Since the Wonewoc sample comes from marine deposits, the dominance of the Superior Province may reflect a sea in which most of the sediments came from the Canadian Shield. However, since the Wonewoc sample formed as a shoreface deposit very close to land, one would expect its sediments to reflect those found in river systems. Thus, one can reasonably conclude that the rivers flowing into this area at the time were mostly delivering sediments originally eroded from the Superior Province. It therefore seems likely that the Animikie and Huronian basins had grown dominant as sources of sediment by this time, while the MCR was either eroding to a different location or had itself been drowned by the sea.

The Mount Simon and Eau Claire samples from Konstantinou et al. (2014) appear very similar to the Wonewoc sample (Figure 10; also Figure 3A). These samples were also collected from marine deposits. The Mount Simon sample came from shoreface deposits like those of the Wonewoc sample, whereas the Eau Claire sample came from more distal deposits below fair-weather wave base. The fact that all three samples consist almost exclusively of Superior-age zircons lends credence to the idea that the sediments moving through the sea were rich in such zircons, possibly because of delivery from a different river system than the one feeding central Wisconsin (Konstantinou et al., 2014). It should be noted that these Mount Simon and Eau Claire samples came from well to the

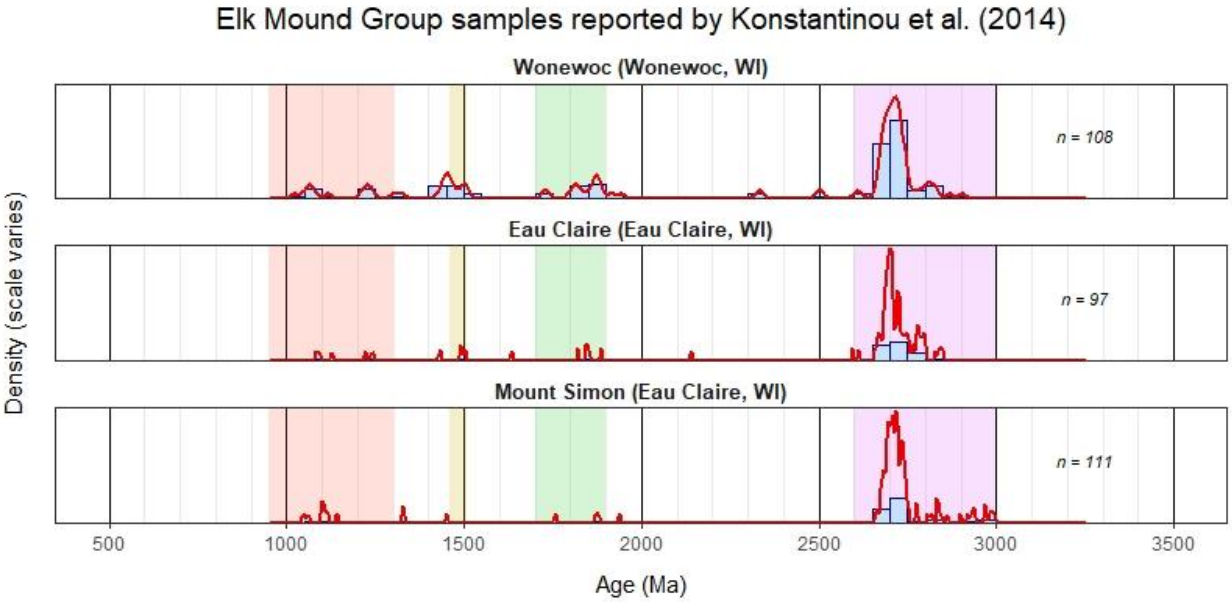

Figure 10: Elk Mound Group samples gathered and analyzed by Konstantinou et al. (2014), arranged in section order. See Figure 3A (appendix) for an alternative visualization of this data.

northwest of the samples from central Wisconsin and that they formed further off the Wisconsin Arch. The three samples were therefore probably fed by distinct river systems. There may also have been a different mix of zircons in that part of the sea than at the base of the Wisconsin Arch. However, since they formed in the same depositional environment as the Wonewoc sample, any differences in sediments between different parts of the sea were probably negligible and the sea likely delivered a large proportion of Superior-age zircons across the shoreline of the Wisconsin Arch.

UPH provenance

The UPH samples show a similar pattern to the samples from central Wisconsin. However, the UPH samples contain fewer zircons from the Grenville Province and WRB and more zircons from the Penokees, especially in older samples. Additionally, the shift towards almost exclusively Archean zircons occurs earlier in the UPH cores than in the central Wisconsin samples. The increased Penokean fraction and decreased Grenville fraction suggest more transport of sediment from the Animikie Basin instead of the MCR. As the sandstones of the UPH cores were deposited contemporaneously with the Mount Simon sandstone in central Wisconsin, this difference in provenance could mean that a different river system flowed from the Animikie Basin through eastern or western Wisconsin and down to Illinois. A river through eastern Wisconsin could explain why the UPH wells retain a high fraction of WRB-age zircons, which may have been picked up by a river system flowing over the WRB instead of re-eroded sediments from the MCR. The Mount Simon

Formation of the Illinois Basin is not as supermature as in Wisconsin, making such primary erosion plausible (Lovell & Bowen, 2013; Freiburg et al., 2020). However, far more data would be needed to fully support such a pattern, including DZ and sedimentological studies of buried Mount Simon deposits in eastern Wisconsin. Alternately, the northern Illinois sediments could come from the same river system as the central Wisconsin sediments, but the sediments did not accumulate in Wisconsin until the sea rose further and environmental conditions changed. Thus, the surge in Penokean sediment was not recorded as strongly in Wisconsin.

Another difference between the UPH samples and central Wisconsin samples is the presence of a significant peak around 1340 Ma in the UPH-1 sample. A smaller version of this peak can be seen in the 580- and 540-meter samples from UPH-3, as well as the lower Mirror Lake sample. These age ranges are best matched to the Eastern Granite-Rhyolite Province (EGRP; see Figure 2 and Freiburg et al., 2020) underlying Phanerozoic strata in much of Illinois and Indiana. However, such formations were downstream/more distally located than both the UPH locations and central Wisconsin, so any claim that the EGRP provided these zircons must account for how the sediment essentially moved upstream. Other formations of similar age could have formed higher on the continent and eroded down into the MCR or directly to the Mount Simon Formation. It may also be that a highland existed at the EGRP which allowed sediments to flow downstream from Illinois and Indiana towards the Mount Simon Formation prior to the advance of the Cambrian sea.

The relatively rapid shift to exclusively Archean zircons in the UPH samples can be explained more easily. Northern Illinois was submerged more quickly than central Wisconsin by any sea level rises moving up the continent, and those seas would have radically altered the provenance of zircons in the area by providing a wash of marine sediment from the extraordinarily gentle slope of the continental shelf. Sedimentological data from the UPH-3 core supports such an interpretation (Lovell & Bowen, 2013, especially Figure 3 in their paper). The three higher samples from the UPH-3 core formed in fluvial and deltaic environments that were later reworked by marine forces before lithifying. Thus, they could easily have been flooded with sand from the Superior Province, creating a mostly Archean DZ signal. Such an interpretation fits well with the predominantly Archean signal from the marine deposits in Wisconsin analyzed by Konstantinou et al. (2014).

Paleocurrents

As noted above, the paleocurrents indicators considered in this study indicate a southwest-directed current system in central Wisconsin at the time that the Elk Mound Group was deposited. This interpretation fits with the paleoceanography of the area. Laurentia was rotated about ninety degrees clockwise from its present orientation and situated in the southern trades, so the paleoshoreline in central Wisconsin would have aligned with the southeasterly prevailing winds. Given that the continental shelf in the area had such a gradual slope, the water in this area would have been quite shallow. As a result, tidal currents and longshore drift would have dominated, and any non-tidal currents would have closely followed the wind. Thus, sediment would have been transported to the paleo-northwest (modern southwest) along the coast, matching the paleocurrents recorded. However, several anomalous rose diagrams in the area need to be explained.

Many of the rocks from which paleocurrent directions were determined were deposited higher on the Wisconsin Arch (Figure 7) and record fluvial or aeolian deposits. These deposits would not have recorded consistent current directions in the manner of marine deposits, especially in the shifting, pre-vegetated sands of the Cambrian land surface. Thus, the more variable rose diagrams likely indicate these shifting patterns in the terrestrial highlands. This interpretation seems particularly valid for currents north of the Dells, which would have been much higher on the Wisconsin Arch than currents further south. Closer to the Baraboo Hills, paleocurrents tend to point either towards the hills or along the side of the range. Currents pointing towards the hills likely reflect the general westward trend of currents in the area if they sit south of the hills, or they likely preserve rivers flowing from the Arch if they sit north of the hills. Currents running along the hills suggest that the hills altered the direction of currents in the area, which seems likely for a resistant ridge amidst flat-lying sands.

Some of the currents show a bimodal distribution in which the modes point in opposite directions. Such a distribution commonly indicates tidal forces, but many of these currents seem to be aligned with the paleoshoreline rather than perpendicular to it. Given the complex topography of the area, the tidal currents may not have flowed directly on- and offshore but could have flowed in different directions around the region. Additionally, some of these currents likely represent deposition in terrestrial environments, perhaps by variable winds. Finally, the rose diagrams portrayed above compile paleocurrents from across the Elk Mound Group, and in some cases into the Tunnel City Group above. A more temporally detailed analysis may reveal shifts in current direction over time, perhaps indicating the reversal of a river system or a shift from terrestrial to marine currents. Thus, the bimodal distributions may have a variety of explanations.

Regardless of anomalies, the currents above indicate generally westward transport, which suggests that sediment in the area came most immediately from eastern Wisconsin or the Michigan Basin. This interpretation implies that any river systems in the area likely flowed either straight down the Arch to the sea or east along the Wisconsin Arch towards the Michigan Basin before moving west along the shoreline. However, the Michigan Basin had already begun to subside by the late Cambrian, and sediment would not have easily flowed out of the basin and around the Wisconsin Arch. This paper therefore posits a river system flowing directly to the modern south down the Wisconsin Arch and into the sea. Once the sea rose and submerged the area, paleocurrents reshuffled the sand and flooded the area with Superior-derived sediment.

Conclusion

The data presented here largely align with previous publications, but they also contribute new and significant details to the understanding of the sources of the Elk Mound Group in central Wisconsin. River systems flowed down the length of the Wisconsin Arch, initially transporting sediment from the MCR but later shifting their headwaters or areas of dominant erosion eastward towards the Animikie Basin. Sediments in the sea clearly came from the Superior Province, and they may have come from river systems further to the west or east. However, paleocurrent data suggests transport from the east, implying river systems from the Canadian Shield and Huronian Basin that flowed east of the Wisconsin Arch. As the sea rose, it first drowned the depositional environments in a slew of Superior sediment, then drowned the source provinces themselves and prevented further erosion from proximal sources.

Of course, many questions remain from this work. What sort of river systems flowed along western and eastern Wisconsin? Could sediment have flowed out of the nascent Michigan and Illinois basins and onto the Wisconsin Arch? What precise mix of basins did sediment come from at different points in time? How did paleocurrents change with time and depositional environments? These questions can be approached with the data and methods discussed above, but they lie beyond the scope of this paper. DZ analysis of the Elk Mound Group elsewhere in Wisconsin and beyond, detailed statistical analysis of zircon ages and comparison to potential source basins (akin to analysis by Konstantinou et al., 2014), and more detailed analysis of paleocurrents in different formations and sedimentological contexts would all contribute greatly to the work discussed above. These avenues of further research and others should be pursued so that the paleogeography of the Upper Midwest can be further understood and our images of ancient landscapes and worlds can become more complete.

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Appendix

Detailed methodology for DZ separation, dating, and analysis

The text below is copied from personal communication with Dave Malone, who relied on personal experience and the ALC website for his information. Other than minor typographical and grammatical edits, the words are his.

Zircon crystals are extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table, heavy liquids, and a Frantz magnetic separator. Samples are processed such that all zircons are retained in the final heavy mineral fraction. For detrital analyses, a large split of grains (generally thousands of grains) is incorporated into a 1" epoxy mount together with fragments or loose grains of Sri Lanka, FC-1, and R33 zircon crystals as the zircon standards. For igneous samples, ~50 high-quality grains are selected and mounted with standards, generally with four samples per mount. The mounts are sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis. Grains of interest are imaged to provide a guide for locating analysis pits in optimal locations, and to assist in interpreting results. BSE and color CL Images are generated with a Hitachi 3400N SEM and a Gatan CL2 detector system (www.geoarizonasem.org).

Methods for U-Pb geochronology have been described by Gehrels et al. (2006, 2008), Gehrels and Pecha (2014), and Pullen et al. (2018). The analyses involve ablation of zircon with a Photon Machines Analyte G2 excimer laser equipped with HelEx ablation cell using a spot diameter of 20 microns. The ablated material is carried in helium into the plasma source of an Element2 HR ICPMS, which sequences rapidly through the U, Th, Pb, and Hg isotopes. Signal intensities are measured with an SEM that operates in pulse counting mode for signals less than 50K cps, in both pulse-counting and analog mode for signals between 50K and 4M cps, and in analog mode above 4M cps. The calibration between pulse- counting and analog signals is determined line-by-line for signals between 50K and 4M cps and is applied to >4M cps signals.

One intensity is determined on each mass, with dwell times as follows:

- Hg202 0.021 sec
- Hg+Pb204 = 0.031 sec
- Pb206 = 0.081 sec
- Pb207 = 0.150 sec
- Pb208 = 0.010 sec
- Th232 = 0.010 sec
- U235 = 0.150 sec

Total scan time is approximately 10 sec including all dwell and settle times. Data are acquired an acquisition that consists of during 56 scans. With the laser set an energy density of ~5 J/cm^2, a repetition rate of 8 Hz, and an ablation time of ~10 seconds, ablation pits are ~10 microns in depth. Sensitivity with these settings is approximately ~58,000 cps/ppm. Each analysis consists of 8 seconds on peaks with the laser off (for backgrounds), 10 seconds with the laser firing (for peak intensities), and an 8 second delay to purge the previous sample and save files.

Following analysis, data reduction is performed with an in-house Python decoding routine and an Excel spreadsheet (E2agecalc). The first step is to extract the measured ion intensities from the Thermo output (.dat) files utilizing a decoder that was written by John Dr. Hartman (University of Arizona). Details of this decoding routine are available from the Dat File Decoder link on the ALC web page (under Tools). This decoding routine generates a .csv file that includes all ion intensities for each scan. These ion intensities and the list of spot names are imported into E2agecalc.

U-Th-Pb Data Reduction and Interpretation

Following are the calculations performed by E2agecalc to reduce U-Th-Pb data.

1. Calculates background intensities for each mass based on the average of the ion intensities during the first ten seconds (with no laser firing) of each analysis.
2. These backgrounds are subtracted from the intensities measured while the laser is firing.
3. Subtracts 204 Hg from the measured 204 signal (using natural 202 Hg/ 204 Hg of 4.3) to generate intensities for 204 Pb. This Hg correction is not significant for most analyses because our Hg backgrounds are low (generally ~150 cps at mass 204).
4. Calculates a preliminary 206/238 age to determine the composition of common Pb based on Stacey and Kramers (1975).
5. Subtracts common Pb from 206, 207, and 208 based on the measured 206/204 and the Stacey Kramers composition.
6. Calculates preliminary 206/238, 206/207, and 208/232 ratios
7. Compares measured and known ratios for the three standards to determine fractionation factors for 206/238, 206/207, and 208/232. These correction factors are generally <5% for 206/238, <2% for 206/207, and <20% for 208/232.
8. Determines an overdispersion factor if the standard analyses show greater dispersion than expected from measurement uncertainties.
9. Uses a sliding-window average to apply fractionation factors to unknowns (generally averaging 8 standard analyses)
10. Calculates fractionation-corrected 206/238, 206/207, and 208/232 ratios and ages for standards and unknowns.

11. Propagates measurement uncertainties for 206/238 and 208/232 that are based on the scatter about a regression of measured values. Uncertainties for 206/207 and 206/204 are based on the standard deviation of measured values since these ratios generally do not change during an analysis. The sum of this uncertainty and any overdispersion factor is reported as the internal (or measurement) uncertainty for each analysis. These uncertainties are reported at the 1-sigma level.
12. Calculates the down-hole slope of 206/238 to highlight analyses in which 206/238 is compromised due to heterogeneity in age (e.g., crossing an age boundary) or intersection of a fracture or inclusion.
13. Calculates concentrations of U and Th for unknowns based on the measured intensity and known concentrations of FC-1.
14. Calculates the external (systematic) uncertainties for 206/238, 206/207, and 208/232, which include contributions from (a) the scatter of standard analyses, (b) uncertainties in the ages of the standards, (c) uncertainties in the composition of common Pb, and (4) uncertainties in the decay constants for 235 U and 238 U.
15. Determines a "Best Age" for each analysis, which is generally the 206/238 age for <900 Ma ages and the 206/207 age for >900 Ma ages.
16. Provides preliminary filters that highlight analyses with >20% discordance, >5% reverse discordance, or >10% internal (measurement) uncertainty.
17. Creates publication-ready datatables with concentrations, isotope ratios, and ages. All uncertainties are reported at 2-sigma. Separate tables are created for unknowns and standards. For detrital analyses, the ages are shown on Pb-U concordia diagrams and relative age-probability diagrams using the routines in Isoplot (Ludwig, 2008). The age-probability diagrams show each age and its uncertainty (for measurement error only) as a normal distribution and sum all ages from a sample into a single curve. Composite age probability plots are made from an in-house Excel program (see Analysis Tools for link) that normalizes each curve according to the number of constituent analyses, such that each curve contains the same area, and then stacks the probability curves.

Cumulative probability plots of DZ ages

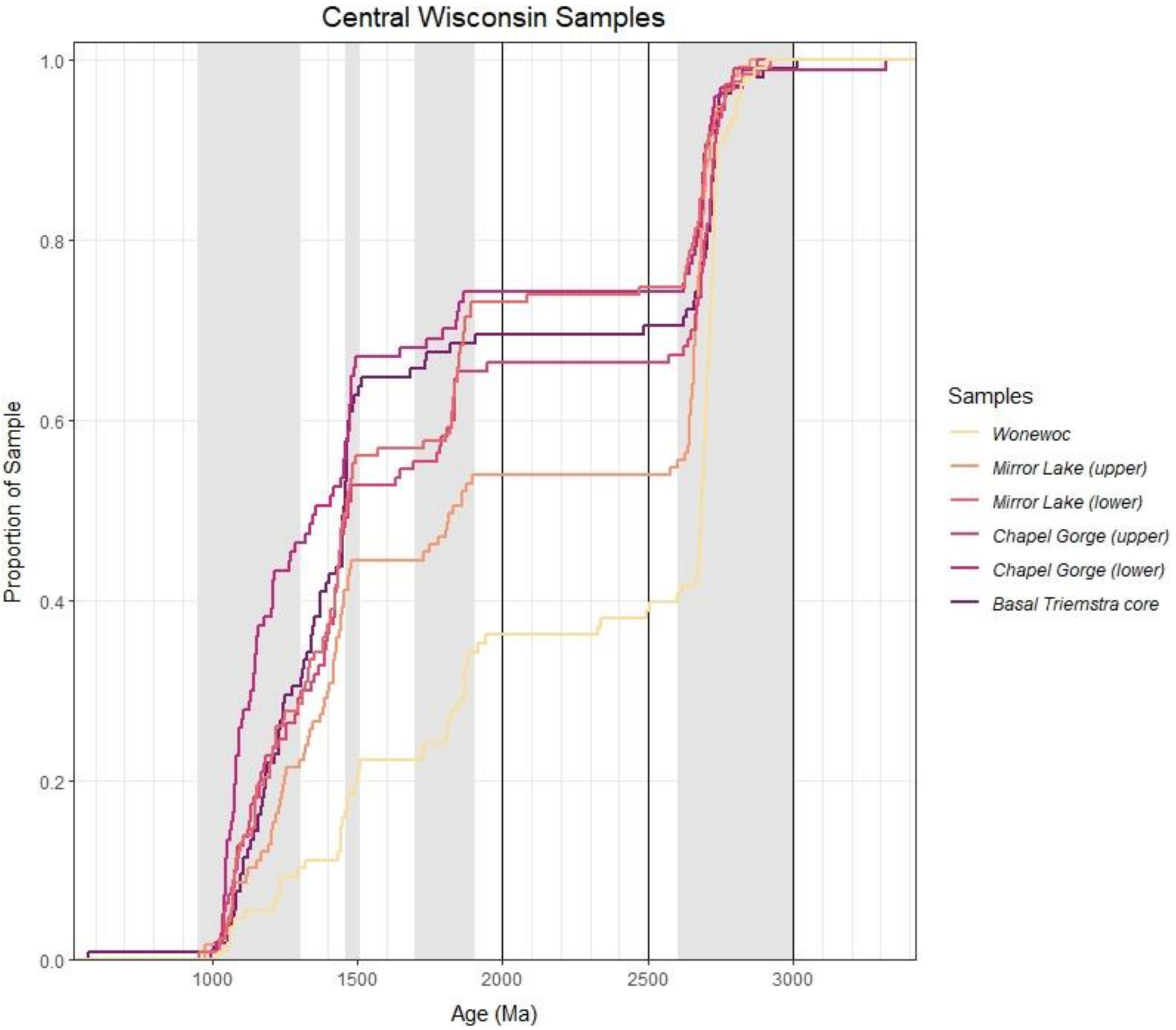

Figure 1A: Cumulative probability plot of detrital zircons from central Wisconsin. Each line shows the proportion of zircons from a given sample that are as young or younger than any given age. In other words, this figure plots the integral of the probability density function in Figure 5 (the red line) for each sample. Gray bars represent the age ranges of the Grenville, Wolf River, Penokean-Yavapai, and Superior provinces, going from left to right. The legend lists samples in section order, with the youngest samples on top.

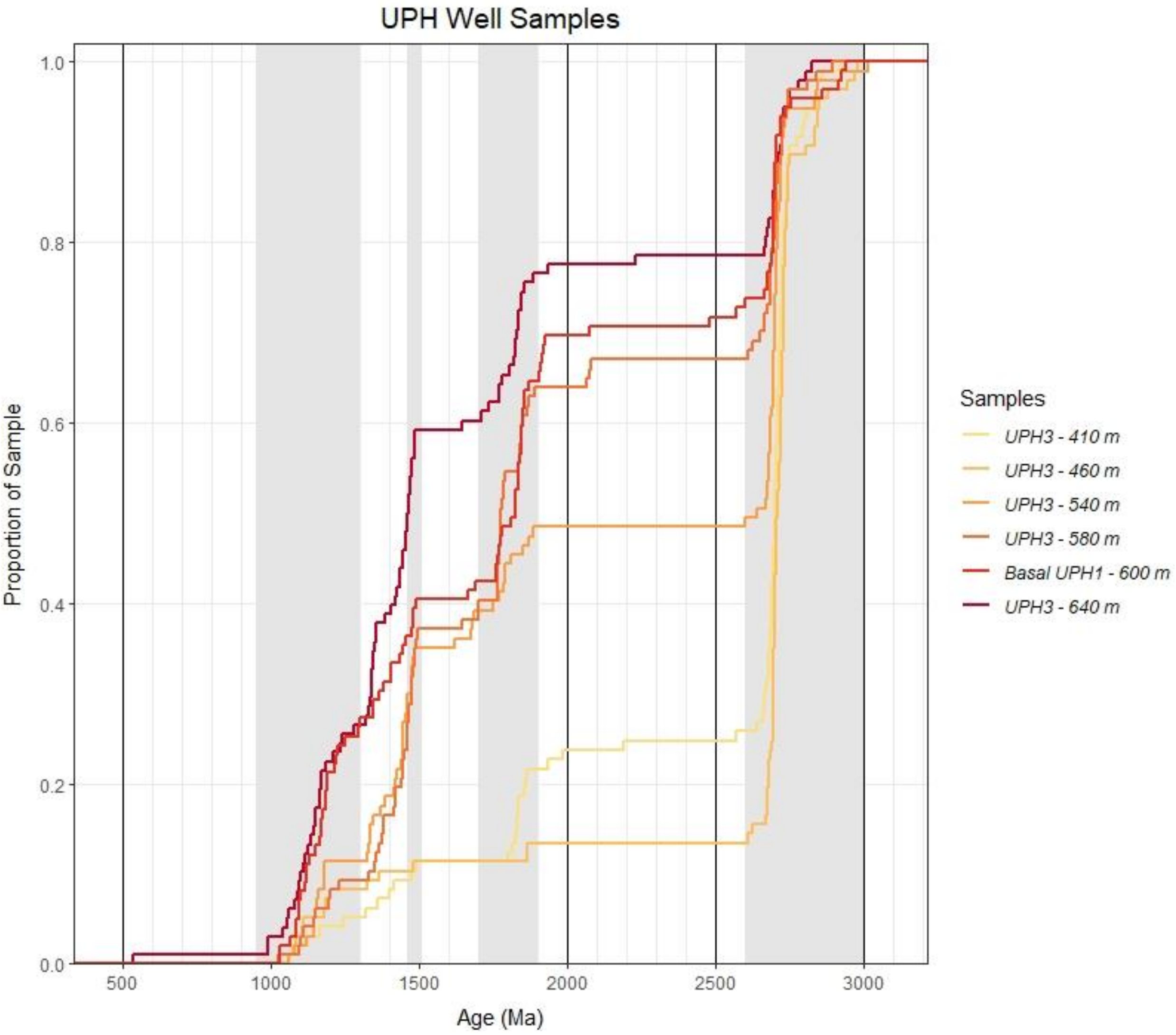

Figure 2A: Cumulative probability plot of detrital zircons from the UPH wells. This figure works the same way as Figure 1A, except it uses the UPH data portrayed in Figure 6.

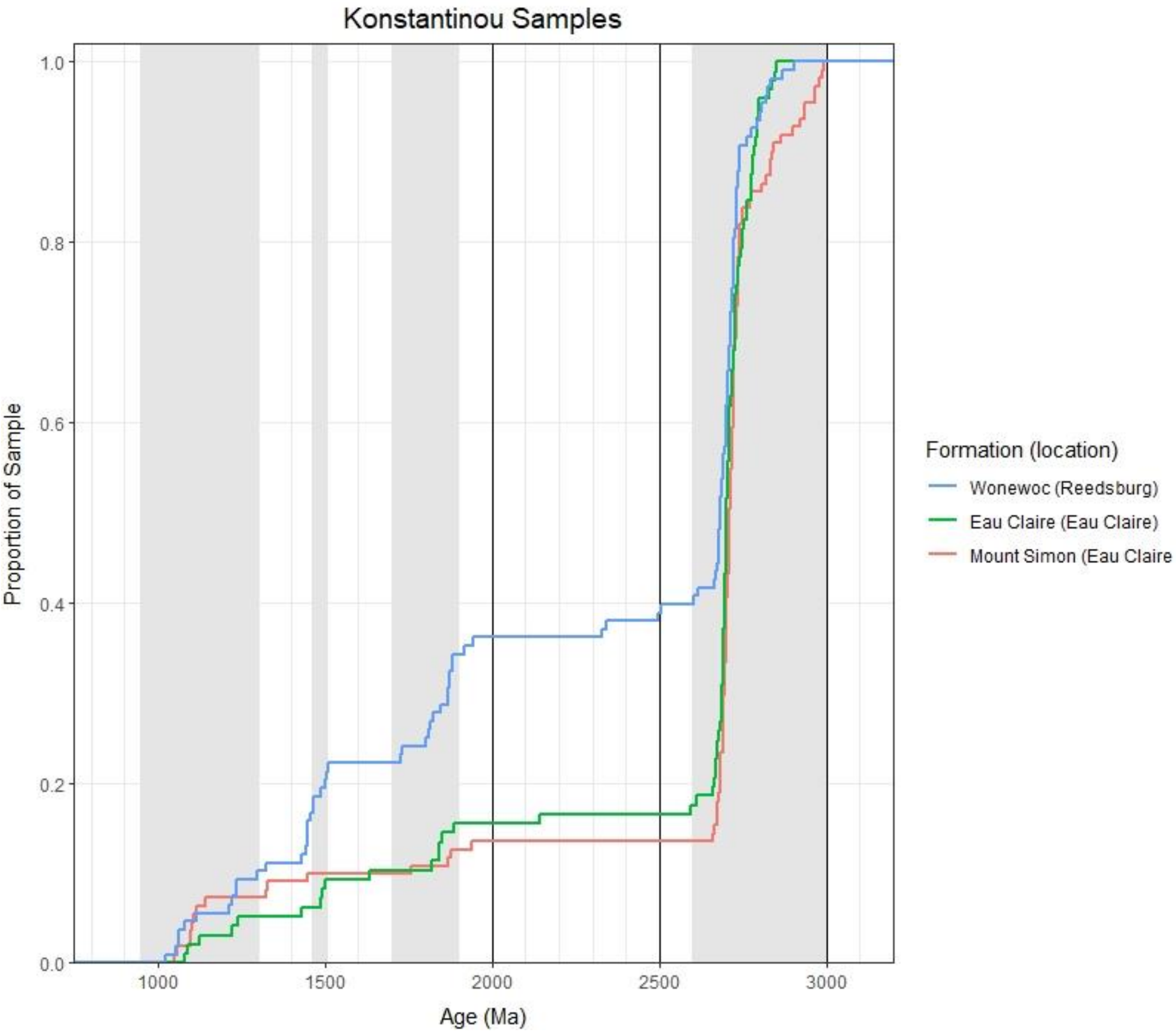

Figure 3A: Cumulative probability plot of detrital zircons from the Elk Mound Group samples gathered and analyzed by Konstantinou et al. (2014). This figure works the same way as Figure 1A, except it uses data from Konstantinou et al. (2014) and portrayed in Figure 10.