The Past, Present, and Future Mississippi River

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ABSTRACT

The Mississippi River Valley and its basin have undergone major changes since the Pliocene. Pliocene ancestral Mississippi River headwaters drained southern Alberta, Saskatchewan, Manitoba, and southwestern Ontario in a Pliocene drainage basin that was at least 30% greater than the modern Mississippi River basin. This large drainage basin is supported by Pliocene paleodrainage in Alberta and Saskatchewan and paleochannel analyses of Pliocene Mississippi River meander bends preserved in the Pliocene Mississippi River terrace sediments of the Upland Complex near Memphis, Tennessee. Near Memphis, the Pliocene discharge is calculated to have been six to eight times the discharge of the modern Mississippi River. The Pliocene Mississippi River drainage flowed east across Alberta and Saskatchewan, south across Paleozoic sedimentary rocks that covered the Canadian Shield in Manitoba and Ontario, and into North Dakota and South Dakota along the ancestral Red River. Early Pleistocene continental glaciation removed the sedimentary rocks covering the current Canadian Shield region of Manitoba and Ontario. Sea level declines of 120 m during the Pleistocene eroded central and southern Mississippi River Valley sediments of the Mississippi Embayment, and the base of Pliocene Upland Complex terrace remnants (Pliocene Mississippi River sediments) is now 70 m above the base of Holocene Mississippi River floodplain sediments near Memphis. This 70-m elevation difference is attributed to a +25-m Pliocene sea level and 45 m of Mississippi River Valley isostatic uplift caused by the Pleistocene denudation of the Mississippi River Valley. The erosion and isostatic uplift of the Mississippi Valley have influenced the state of stress in the valley and are in part responsible for reactivating Cambrian basement faults of the Reelfoot Rift and consequent earthquakes of the New Madrid seismic zone. Continuing Holocene glacial isostatic uplift of Manitoba and Ontario is returning the drainage of these provinces to their Pliocene southerly flow. We believe the north-flowing Red River, Lake Winnipeg, and southern 200 km of the Nelson River will reverse to a southerly flow to join the Mississippi River system between 6 and 8 ka if Canadian continental glaciation does not return.

Introduction

A fundamental principle of geology is "the present is the key to the past." Although certainly true, here we turn things around and propose that the past is the key to the present and future. In this article we illustrate that the Pliocene Mississippi River provides insights into the present and future Mississippi River.

The Mississippi River system during the Pliocene (~3.6 Ma) was a much larger river (figs. 1, 2), as estimated by river channel geometry measured from abandoned ancient meander bends in Pliocene Mississippi River terrace sediments of the Upland Complex (fig. 3), which is also regionally called the Mounds Gravel, Continental Deposits, and Preloess Terrace Deposits (Van Arsdale et al. 2007; Cupples and Van Arsdale 2014; Cox et al. 2014). The Upland Complex has been speculated to be Pliocene and/or early Pleistocene prior to available cosmogenic dating (Saucier 1994). Herein we accept the ~3.6 Ma $^{26}Al/^{10}Be$ age for the Upland Complex determined by Odom et al. (2020). Pliocene discharge of the Mississippi River was six to eight times (80,000–90,000 m^3/s) its current flow of 13,700 m^3/s at Vicksburg, Mississippi (Cox et al. 2014). Additionally, the base of Pliocene Mississippi River sediments is 70 m higher than the base of the Quaternary Mississippi River sediments near Memphis, Tennessee (fig. 2*B*).

The distribution of Pliocene Mississippi River terrace gravels suggests a floodplain at least 200 km wide at the latitude of Memphis, and its river's

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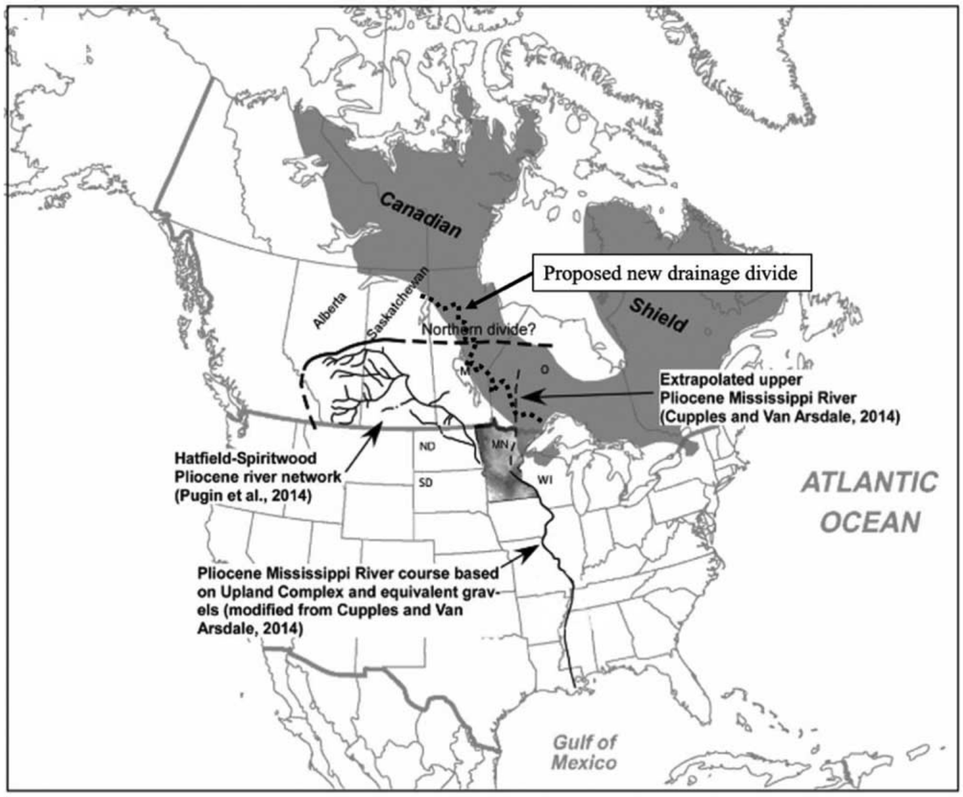

Figure 1. Preglacial Pliocene Mississippi River basin northern divide (solid and dashed line; after Cox et al. 2014). The interpretation herein places the Pliocene Mississippi River drainage divide in Manitoba and western Ontario along the northwest-trending dotted line. The greater depth to bedrock in Minnesota indicated by dark shading is interpreted to have been the southern continuation of the Pliocene Red River to the Mississippi River. M = Manitoba; O = Ontario; ND =North Dakota; SD = South Dakota; MN = Minnesota; WI = Wisconsin.

drainage basin, like today, extended from the eastern side of the Rocky Mountains to the western side of the Appalachian Mountains. However, to accommodate a river with a discharge of six to eight times that of the modern Mississippi River, with no indication of increased rainfall during the Pliocene, requires a much larger drainage basin (Cox et al. 2014; Cupples and Van Arsdale 2014). The only way to reconstruct a Pliocene drainage basin that is larger is to extend the Pliocene drainage basin north into Canada from its current location along the United States–Canada border (fig. 1).

Other investigators (Galloway et al. 2011; Carson et al. 2018; Blum 2019) have argued that the northern divide of the Pliocene Mississippi River was approximately along the United States–Canada border. These authors base their arguments on provenance studies of Pliocene sediments in the northern Gulf of Mexico and assume that Precambrian igneous and metamorphic rocks were at the surface of the Canadian Shield in southern Canada during the Pliocene. However, Canadian field investigations conclude that the Canadian Shield of Manitoba and western Ontario was covered by Paleozoic limestones and sandstones during the Pliocene prior to ice sheet advance (Shilts et al. 1987; Dredge and Cowan 1989), and thus this region of Canada would not have a Canadian Shield signature in Gulf of Mexico provenance data.

Mississippi River Puzzles

Three Pliocene Mississippi River Puzzles. Three puzzles emerged from our mapping of the Pliocene Mississippi River floodplain. First, the base of the Mississippi River and its associated floodplain is controlled by sea level, as reflected by the fact that 50 km north of Memphis the base of the Pleistocene Mississippi River alluvium is 20 m below modern sea level, as shown in figure 2*B* (Van Arsdale et al. 2014). So why is the base of the Pliocene Mississippi River terrace (Upland Complex) 70 m higher than current sea level (fig. 2*B*)? Sea level during the Pliocene was 25 m above modern sea level (Winnick and Caves 2015), so there is 45 m of elevation difference that must be explained. The

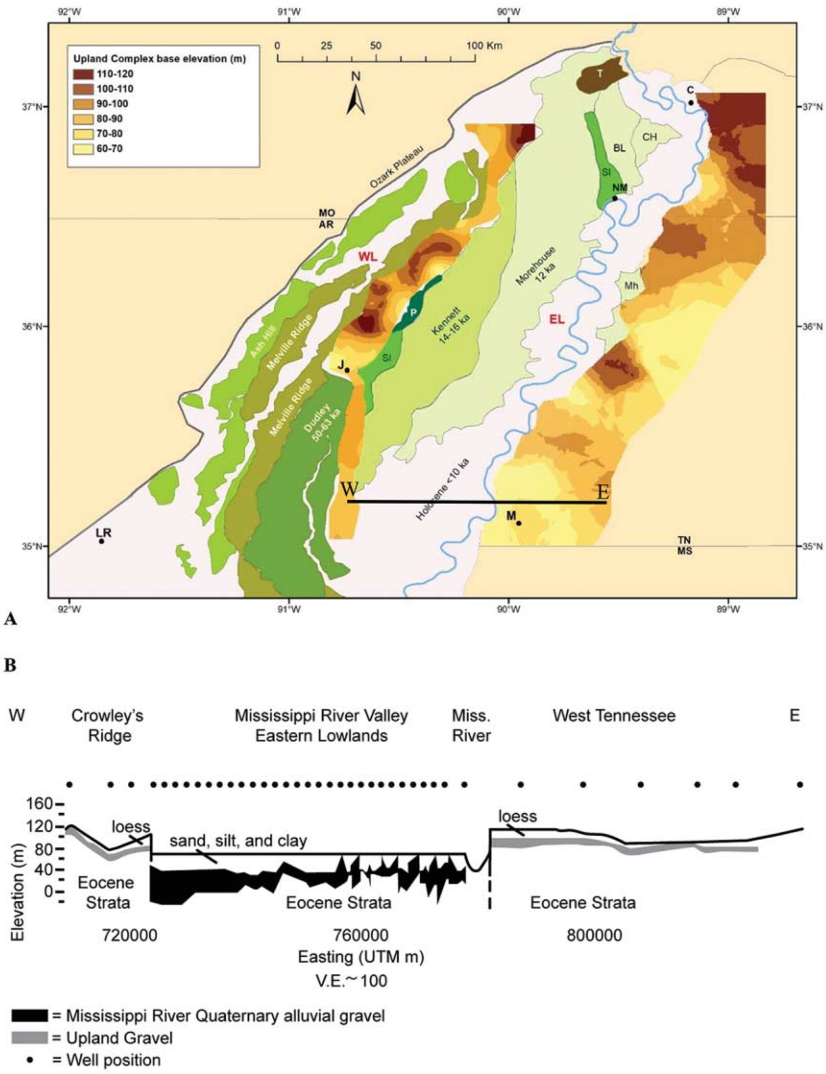

Figure 2. *A*, Base of the Pliocene Mississippi River terrace called the Upland Complex (also called the Upland Gravel; yellow to brown), which extends from Illinois south into Louisiana with the Arkansas, Kentucky, and Tennessee portions shown here. Pleistocene Mississippi River terraces (greens), the Holocene floodplain of the Mississippi River (beige), and Uplands (tan); from Rittenour et al. (2007) and modified by Van Arsdale and Cupples (2013). Mh = Morehouse terrace (12 ka); BL = Blodgett terrace (13 ka); CH = Charleston terrace (14 ka); SI = Sikeston terrace (17–19 ka); Ash Hill = Ash Hill terrace (24–27 ka); Melville Ridge = Melville Ridge terrace (34–41 ka); P = Paragould terrace (85 ka); C = Cairo; CR = Crowley's Ridge; T = Tertiary uplands; EL = Eastern Lowlands; WL = Western Lowlands; LR = Little Rock; J = Jonesboro; M = Memphis; MR = Mississippi River; NM = New Madrid. *B*, West-to-east geologic cross section, 50 km north of Memphis, Tennessee (Van Arsdale et al. 2007). Circles show wells used in cross-section construction and approximate the estimated original Pliocene Mississippi River floodplain surface elevation of 176 m. The current average elevation of the top of the Upland Complex is ~80 m. Thus, there has been ~96 m of average landscape elevation reduction in the Western and Eastern Lowlands over the past ~2.5 My.

second puzzle involves the northern boundary of the Pliocene Mississippi River basin. Modern drainage flows north to Hudson Bay in South Dakota, North Dakota, western Ontario, and Manitoba primarily within the Red River–Lake Winnipeg–Nelson River drainage basin. If the Pliocene Mississippi River drainage basin extended into southern Canada, then the Pliocene Red River, Lake Winnipeg basin, and perhaps the southern portion of the Nelson River ancestral drainage system must have flowed south to the Mississippi River. The second question thus is: did the ancestral Red River–Lake Winnipeg–southern Nelson River system flow south during the Pliocene? Our third puzzle involves the composition of the Pliocene Mississippi River terrace sediments called the Upland Complex preserved in the central United States. The Upland Complex consists of chert gravel and quartz sand that were derived from the weathering of lower Paleozoic limestone and sandstone (Potter 1955; Lumsden et al. 2016). The modern surface geology of Manitoba and western Ontario primarily consists of Precambrian igneous and metamorphic rock of the Canadian Shield (fig. 1) with a thin veneer of Pleistocene glacial sediments with Precambrian igneous and metamorphic rock fragments. The question thus arises: if the Pliocene Mississippi River drained Manitoba and western Ontario, why are there almost no igneous or metamorphic rock fragments downstream in the sand and gravel of the Upland Complex in the central United States (Lumsden et al. 2016)?

Mississippi River Valley Observations Needing Explanation. We start by making some geologic observations. The Mississippi River Valley has undergone erosion during the last ~2.5 My. This is manifest by the ~3.6 Ma Pliocene (Odom et al. 2020) Mississippi River Upland Complex terrace remnants preserved in western Kentucky, Tennessee, Mississippi, and eastern Arkansas. The elevation of the base of the Upland Complex tells us that the Mississippi River system entrenched and eroded at least 70 m of valley sediment since the terrace formed at ~3.6 Ma. We also note that since Pliocene sea level was only 25 m higher than today, the lower Mississippi River Valley and its terraces were raised 45 m since the deposition of the terrace at 3.6 Ma. There is no evidence of Quaternary tectonic compression and resulting uplift of the Mississippi River Valley, and therefore we invoke isostasy (Burbank and Anderson 2012) as the method of lifting the Mississippi River Valley (Van Arsdale et al. 2019). Deposition and erosion of sediments can respectively cause crustal subsidence or uplift through isostatic adjustment (Molnar and England 1990; Watts 2001).

We believe that extensive erosion of the Mississippi River Valley and coincident isostatic uplift is the best explanation for the origin of the modern Mississippi River Valley (Van Arsdale et al. 2019). The sequence of events initiated with formation of

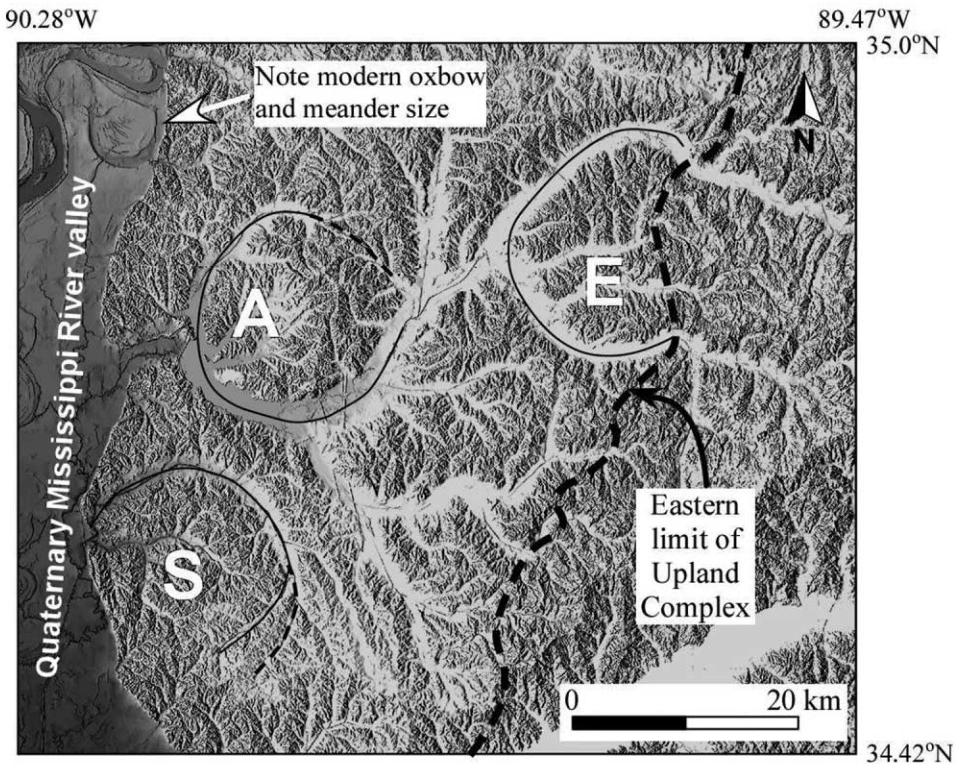

Figure 3. Shaded relief map showing the three arcuate valleys (A, S, and E) in northwest Mississippi within the Pliocene terrace sediment called the Upland Complex (from Cox et al. 2014). Arc A contains Arkabutla Lake. Cross-bed measurements within the Upland Complex arcs reveal meander bedform (Cox et al. 2014). Note the contrast in the size of the putative paleomeanders (arcuate valleys) compared with the size of the present Mississippi River meanders and oxbows in the northwest corner of the map.

the Pliocene Mississippi River floodplain whose base formed 25 m higher than modern sea level. During Pleistocene continental glaciations, sea level declined as much as 120 m, resulting in multiple periods of river erosion and entrenchment in the Mississippi River Valley. We can estimate the thickness of sediment removed by erosion using isostatic relationships (Van Arsdale et al. 2019). This isostatic calculation shows that to raise the Pliocene Mississippi River Upland Complex terraces to their current elevation, a total of ~141 m of sediment must have been removed by erosion from the Upland Complex. A consequence of erosion is concurrent isostatic uplift, and indeed there is geologic evidence of the Mississippi River Valley rising during the Pleistocene. Specifically, near the center of the Mississippi River Valley is Crowley's Ridge in eastern Arkansas (fig. 2). This ridge is an erosional remnant that formed when the Pleistocene Mississippi River flowed south through the Western Lowlands, west of the ridge, and the Pleistocene Ohio River flowed south through the Eastern Lowlands, east of the ridge, and the two rivers merged near Helena, Arkansas. During the Pleistocene, the point of confluence of the Pleistocene Mississippi and Ohio Rivers moved north by river capture from Helena ultimately to Thebe's Gap, Illinois, to form today's Mississippi River Valley. Crowley's Ridge is also bounded by faults, and thus it has been lifted relative to the lowlands on its eastern and western sides during isostatic adjustment (Van Arsdale et al. 1995; Thompson Jobe et al. 2020). A manifestation of this Quaternary uplift of Crowley's Ridge is the distribution of Pleistocene terraces and the location of the modern Mississippi River (Adams 1980). Pleistocene terraces on either side of Crowley's Ridge become progressively younger to the east and west of Crowley's Ridge, moving away from the ridge center (fig. 2). This indicates that the ancestral Mississippi and Ohio Rivers shifted to the west and east, respectively, during Pleistocene erosional entrenchment. A good example for the eastward shift of the Mississippi River is the segment of the modern Mississippi River between Hickman, Kentucky, and Memphis, which sits against the eastern side of its floodplain, with its only excursion from the floodplain margin being around the actively uplifting Reelfoot fault system near New Madrid, Missouri (fig. 2).

This Pleistocene and Holocene erosion has also contributed to earthquake activity in the central Mississippi River Valley. Specifically, the New Madrid seismic zone and other Reelfoot Rift faults in the valley have "turned on" during the Pleistocene (Van Arsdale and Cupples 2013). The vast erosion within the Mississippi River Valley diminished the vertical stress, which released the elastic strain energy stored around the faults of the New Madrid seismic zone, causing the faults to slip (Van Arsdale et al. 2007, 2014, 2019; Calais et al. 2010). The fault slippage caused the >7-magnitude New Madrid earthquakes (Cramer and Boyd 2014) that rocked the Mississippi River Valley and much of the eastern United States in 1811–1812, with small earthquakes continuing today.

To summarize to this point, the geology of the Mississippi River Valley reveals a huge Pliocene Mississippi River that produced a vast floodplain with sediments reaching a total thickness of ~151 m (fig. 4). Decline in sea level during many Pleistocene glaciations over the past 2.5 My resulted in eroding most of this Pliocene sediment plus erosion within the current floodplain area of the Mississippi River that extends down into Eocene strata below the Pliocene terrace (Upland Complex; fig. 2*B*). The ~141 m of eroded Upland Complex plus the ~10 m of remaining Upland Complex indicates that the original Upland Complex was ~151 m thick. Although this is indeed a large thickness, we must note that the Quaternary Mississippi River alluvium immediately east of Crowley's Ridge is ~110 m thick (fig. 2*B*). The estimated total amount of sediment eroded out of the Mississippi River Valley and deposited in the northern Gulf of Mexico during Pleistocene erosion is >11,500 km^3 (Van Arsdale et al. 2019). Continued erosion and isostatic rebound in the Mississippi River Valley appear to be major factors in the ongoing seismicity (Van Arsdale et al. 2007, 2014, 2019; Calais et al. 2010).

Pliocene Mississippi River Drainage Basin. We propose a much larger Mississippi River drainage basin during Pliocene precontinental glaciation (Cupples and Van Arsdale 2014; Cox et al. 2014). Coincident with our research, Pugin et al. (2014) mapped a now-buried preglacial Pliocene Hatfield-Spiritwood River that flowed east in Alberta, Saskatchewan, and Manitoba and turned south into North Dakota (fig. 1). When combining their Canadian Pliocene Mississippi River drainage basin with the proposed drainage basin in Manitoba and Ontario (Cupples and Van Arsdale 2014; Cox et al. 2014), the resulting area of the Pliocene Mississippi River drainage basin would have been at least 30% larger than today (fig. 1). Since the northern limit of the Pliocene Mississippi River drainage basin in Saskatchewan and Alberta is not known—nor is the eastern limit in Ontario—the Pliocene drainage basin could have been 50% larger than today. So the question remains: what is the evidence for

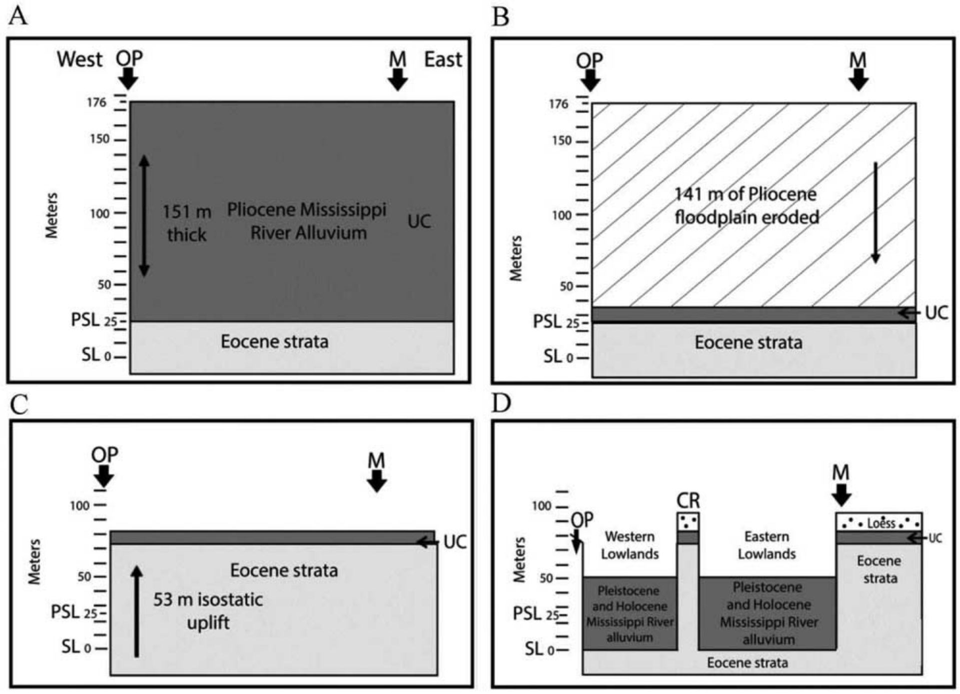

Figure 4. Modeled erosional and isostatic history of the Pliocene terrace called the Upland Complex (UC) since its deposition at ~3.6 Ma at the latitude of Tennessee (from Van Arsdale et al. 2019). Sea level during the Pliocene (PSL) was +25 m. *A*, At ~3.6 Ma, the Pliocene Mississippi River alluvium was ~151 m thick. *B*, Pleistocene erosion of 141 m of the UC alluvium. *C*, 53 m of isostatic uplift due to erosion of most of the UC alluvium. *D*, Entrenchment of the Western Lowlands by the ancestral Mississippi River, entrenchment of the Eastern Lowlands by the ancestral Ohio/Mississippi River, and 15 m of Pleistocene glacial loess deposition. *B–D* represent Pleistocene time and are largely concurrent. CR = Crowley's Ridge; M = Memphis; OP = Ozark Plateau (Paleozoic bedrock). The calculation for determining the thickness of sediment removed by erosion is Δthickness = Δelevation × [density of mantle/(density of mantle − density of crust)] (i.e., 141 m = 53 m × [3.2 g/cm^3/(3.2 g/cm^3 − 2.0 g/cm^3)]).

south-flowing Pliocene Mississippi River drainage in Manitoba and western Ontario?

The modern principal drainage in North Dakota, western Ontario, and Manitoba flows northerly to Hudson Bay through the Red River–Lake Winnipeg–Nelson River system (fig. 5). This river system grew northward as the most recent continental ice sheet melted and glacial Lake Agassiz drained. During Pleistocene ice advances, a thick layer of ice covered much of Canada and north-central United States. Because of this imposed weight, the crust of Canada isostatically subsided. The northerly slope of the river system was, and is, due to isostatic subsidence from the Canadian glacial ice sheet load and to increased elevation along the southern perimeter of the ice sheet due to deposition of glacial sediments and glacial forebulge. To determine the direction of drainage in Manitoba and western Ontario during the Pliocene required another isostatic consideration (Van Arsdale and Kwon 2022).

Currently, Ontario and Manitoba are undergoing postglacial isostatic uplift (Roy and Peltier 2017). The Canadian crust is rising at a rate of ≥10 mm/y along the southern margin of Hudson Bay and diminishes to zero near the United States–Canada border (Henton et al. 2006; Sella et al. 2007). Andrews (1968) calculated that the southwestern shore of Hudson Bay locally has 120 m of remaining isostatic uplift. We thus calculated the remaining uplift that will occur in Manitoba and western Ontario by assuming a linear uplift from the current point of no isostatic uplift near the United States–Canada border increasing northward to the southwest margin of Hudson Bay (Van Arsdale and Kwon 2022).

The results of this "tilting" of the bedrock surface indicates that with only 60 m of future uplift along the southwestern margin of Hudson Bay, the northern portions of the profiles in figures 6 and 7 continue to slope north into Hudson Bay but the southern portions of the profiles begin to slope south. We interpret this southerly sloping (tilted) isostatically rebounded bedrock surface of Manitoba and western Ontario to be the Pliocene bedrock landscape that controlled Pliocene drainage in this region.

The proposed Pliocene Mississippi River drainage divide trends northwest through central Manitoba and projects beneath the Nelson River ~200 km north of Lake Winnipeg (fig. 6). Our interpretation of the Pliocene Mississippi River drainage necessitates a reversal in the modern flow direction of the Red River–Lake Winnipeg–southern portion of the Nelson River (Van Arsdale and Kwon 2022). If the Manitoba landscape is currently tilting southerly because of glacial rebound, this should be evident in the modern flow of the Red River. Indeed, the north-flowing Red River has decreased in slope by 60% in the last 8000 y, and this uplift has contributed to the southward expansion of Lake Winnipeg (Brooks et al. 2005; Henton et al. 2006; Brooks 2017). It is also apparent that the continued southerly isostatic tilting of Manitoba and western Ontario will result in a south-sloping Red River–Lake Winnipeg basin–southern 200 km of the Nelson River (fig. 8). Additionally, the northern United States is subsiding due to glacial forebulge collapse that contributes to a southerly slope of the bedrock surface south of the United States–Canada border (Henton et al. 2006; Sella et al. 2007). We are thus led to the conclusion

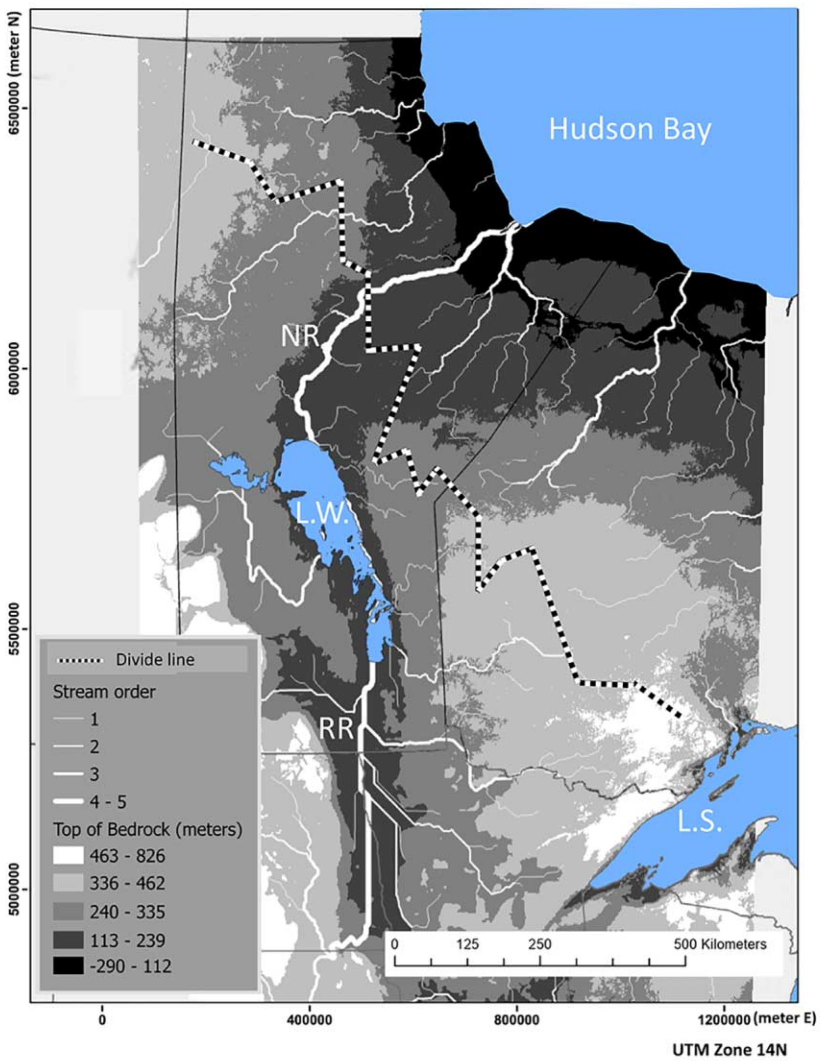

Figure 5. Top-of-bedrock map of Manitoba, northwestern Ontario, northeastern North Dakota, northeastern South Dakota, northern Minnesota, and northwestern Wisconsin (from Van Arsdale and Kwon 2022). RR = Red River; L.W. = Lake Winnipeg; NR = Nelson River (all of which are connected and drain north); L.S. = Lake Superior. The dashed line represents the Pliocene Mississippi River drainage divide, as determined in figures 6 and 7.

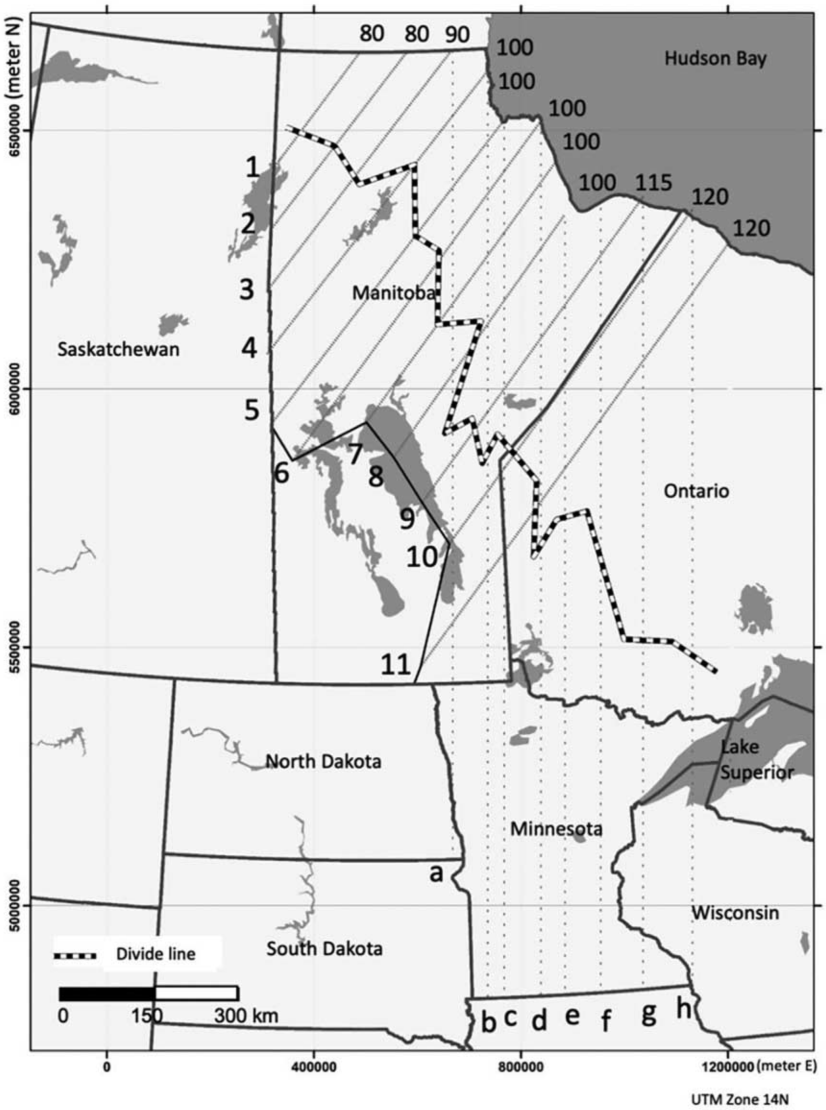

Figure 6. Northeast (solid) and north-trending (dotted) top-of-bedrock profiles (from Van Arsdale and Kwon 2022). Only profiles a–f are shown in figure 7. Numbers at northern ends of profiles are the estimated remaining glacial isostatic uplift in meters at that location, as calculated by Andrews (1968). The diagonal checkered line represents the drainage divide across which the bedrock slope changes from southwest on the southwestern side to northeast on the northeastern side.

that the Red River–Lake Winnipeg basin–southern Nelson River system will flow south, ultimately to drain east into the Mississippi River across southern Minnesota (dark bedrock low in fig. 1), as it did during the Pliocene (Cox et al. 2014; Van Arsdale and Kwon 2022). When will this reversal of flow to a southerly direction occur? The anticipated uplift of 100–120 m along the southern margin of Hudson Bay is projected to occur in the next ~10,000 y (Andrews 1970). However, considering that uplift decay follows a logarithmic pattern and a minimum uplift of 60 m is necessary to trigger a flow reversal in the Red River–Lake Winnipeg–southern Nelson River, we estimate that the reversal of flow direction will occur within the next 6000 to 8000 y. For a better determination of when the Red River–Lake Winnipeg basin–southern 200 km of the Nelson River will reverse flow, a geophysical survey of the remaining isostatic rebound of the Pliocene divide area in Manitoba and western Ontario identified in figure 6 should include both remaining glacial isostatic rebound and an estimate of the isostatic response of Pleistocene erosion of Paleozoic strata from the Canadian Shield. Regardless of when this

Red River slope reversal occurs, the ongoing decreasing northerly gradient of the Red River will increase its flood hazards (Brooks et al. 2005; Brooks 2017).

As a final thought on this proposed future Red River flow reversal, we may be in an interglacial period and our current interglacial period may be nearing its end (Marshak 2016), ignoring global warming. If so, then the necessary time for Red River flow reversal may exceed our present interglacial period. The short duration of previous Pleistocene interglacial periods (~10,000 y) may explain why there is no evidence of a south-flowing Red River in the United States during previous interglacial periods.

Pliocene Upland Complex Sand and Chert Gravel Provenance. One puzzle remains. Why does the high-level terrace of the Pliocene Mississippi River (Upland Complex) in the central Mississippi River Valley not contain Precambrian igneous and metamorphic rock fragments of the Canadian Shield (fig. 1)? Our explanation for this is that during the Pliocene, the Precambrian Shield rocks of south-central Canada were covered by a relatively thin

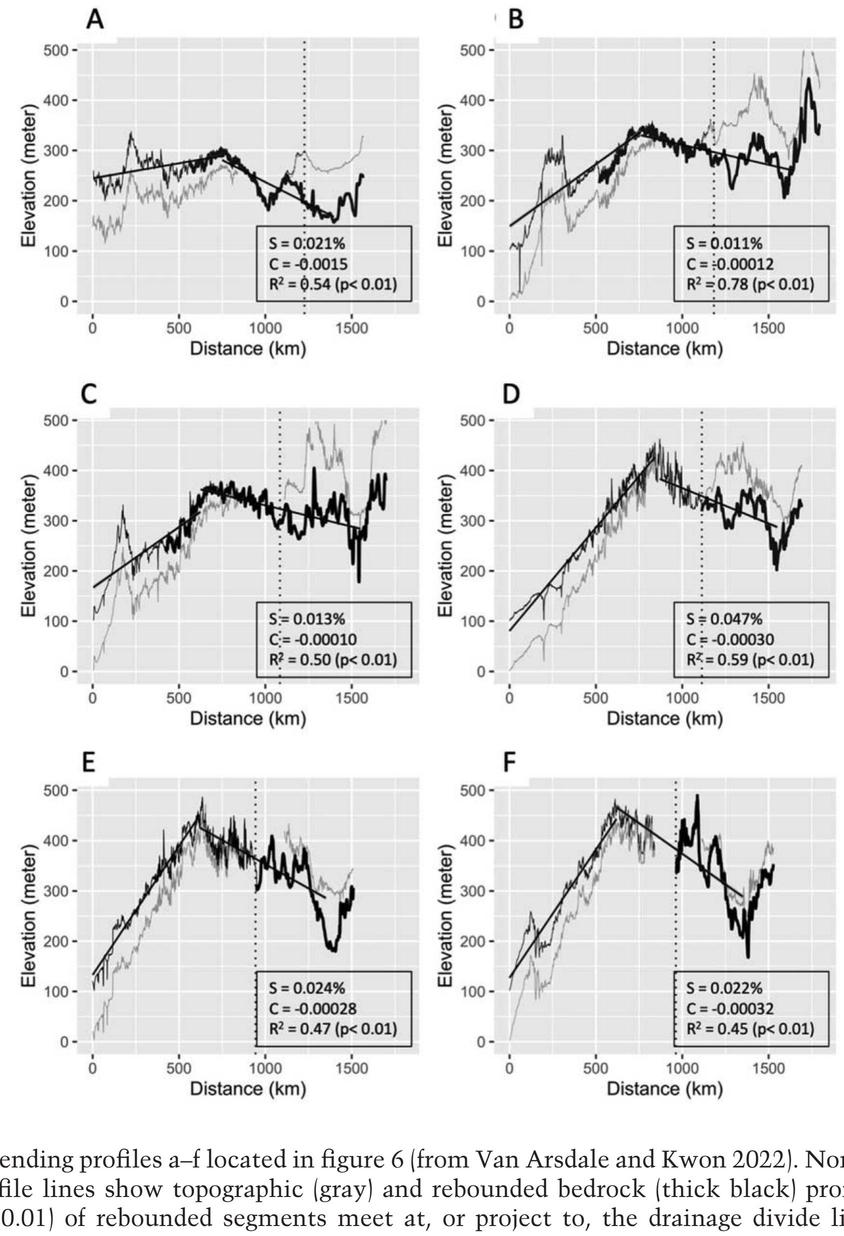

Figure 7. North-trending profiles a–f located in figure 6 (from Van Arsdale and Kwon 2022). North is on the left side of the profiles. Profile lines show topographic (gray) and rebounded bedrock (thick black) profile lines. Linear regression lines ($p < 0.01$) of rebounded segments meet at, or project to, the drainage divide line in figure 6. The vertical dotted line is the United States–Canada border. Vertical exaggeration is ×2750. S = slope of southern regression line; C = coefficient of southern slope regression line; R^2 = goodness-of-fit value of southern regression line.

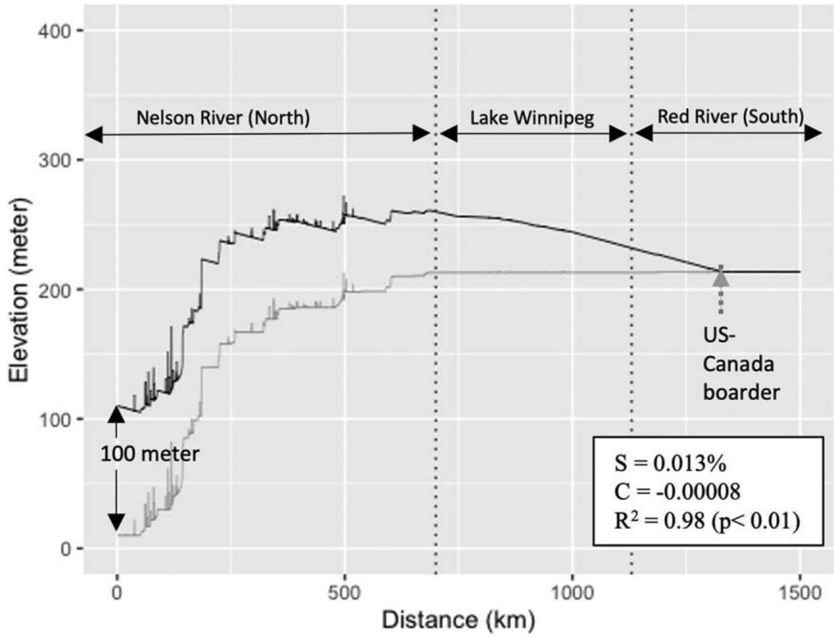

Figure 8. Bedrock topographic profile of the modern Red River/Lake Winnipeg/Nelson River (fig. 5) in lower profile (gray) and with future glacial isostatic rebound in upper profile (black; from Van Arsdale and Kwon 2022). S = southerly slope of tilted river profile consisting of the Red River, Lake Winnipeg, and the southern 200 km of Nelson River; C = coefficient of southern slope; R^2 = goodness-of-fit value of southern regression line. Vertical exaggeration is ×3700.

layer of lower Paleozoic limestones and sandstones (Shilts et al. 1987; Dredge and Cowan 1989; Cupples and Van Arsdale 2014). These Paleozoic strata were the source of the quartz sand and chert gravel in the Upland Complex of the southern Mississippi River Valley (Potter 1955; Lumsden et al. 2016). The Paleozoic rocks were subsequently stripped off by the continental ice sheets that moved south across Manitoba and Ontario during the early Pleistocene. Till provenance in the United States also indicates that Paleozoic strata overlaid the Manitoba and Ontario Shield during the early Pleistocene. The oldest Pleistocene tills in the United States are dominated by sedimentary rock clasts (Horberg 1954; Boellstorff 1978; Schreiner 1990; Roy et al. 2004; Rovey and Spoering 2020), suggesting that early Pleistocene glaciations stripped Paleozoic sedimentary strata from the shield, exposing Archean rocks as a major source of clasts in middle and late Pleistocene glacial tills (Meneley 1964). These observations thus introduce the possibility that the Upland Complex is both Pliocene and early Pleistocene.

Conclusions

Our research in the Mississippi River Valley reveals a fascinating history that also has strong implications as to how the North American landscape will evolve. We believe our research, summarized and integrated in this article, supports the following conclusions.

1. The Pliocene Mississippi River had a discharge six to eight times greater than the modern Mississippi River.
2. Headwaters of the Pliocene Mississippi River were in southern Canada, with its northern divide trending east across Alberta and Saskatchewan and southeast across central Manitoba and southwestern Ontario.
3. The Pliocene Mississippi River drainage basin area was at least 30% greater than today and was probably 50% greater.
4. Paleozoic sedimentary rocks covered the Canadian Shield of Manitoba and western Ontario during the Pliocene, with continental glaciation removing the Paleozoic strata during the early Pleistocene.
5. Pleistocene glaciation in southern Canada buried the Pliocene Canadian headwaters of the Mississippi River and depressed the crust, ultimately locating the Mississippi River northern drainage divide to its location near the United States–Canada border.
6. Pleistocene sea level declines and resulting erosion in the lower Mississippi River Valley vertically removed ~141 m of sediment, which resulted in 45 m of isostatic uplift that continues in the Holocene.

7. Pleistocene and Holocene erosion in the Mississippi River Valley caused isostatic uplift and reduced the vertical stress on basement Cambrian Reelfoot Rift faults, thereby promoting Quaternary fault movement and earthquakes.

8. Manitoba and Ontario are isostatically rebounding to return to a Pliocene drainage configuration.

9. The Red River, Lake Winnipeg, and the southern 200 km of the Nelson River sloped south during the Pliocene and will flow south again within ~6000 y, when glacial isostatic adjustment of >60 m is restored along the southern margin of Hudson Bay and if Canadian continental glaciation does not return.

10. Our above conclusions support the interpretation of Cupples and Van Arsdale (2014) and Cox et al. (2014) that a very large Pliocene Mississippi River flowed south to the Gulf of Mexico.

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