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Using Map Interpretation Techniques for Relative Dating to Determine a Western North Dakota and South Dakota Drainage Basin Formation Sequence, Missouri River Drainage Basin, USA

Eric Clausen[1]

[1] Jenkintown, PA (USA) 19046, USA

Correspondence: Eric Clausen, 100 west Ave D-17, Jenkintown, PA, 19046, USA.

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Abstract

Map interpretation techniques are used to determine the sequence in which western North and South Dakota erosion events occurred. The map interpretation techniques apply the principle of cross cutting relationships by studying asymmetric drainage divides, barbed tributaries, elbows of capture, drainage divide crossings, abandoned headcuts, and similar features on detailed topographic maps to determine the sequence in which drainage basins and valleys within those drainage basins formed. Detailed topographic maps covering western North and South Dakota show numerous closely spaced divide crossings along drainage divides separating the White, Bad, Cheyenne, Moreau, Grand, Cannonball, Heart, Knife, and Little Missouri Rivers. These divide crossings often form links between opposing northwest- and southeast-oriented tributary stream valleys and provide evidence of multiple closely spaced southeast-oriented flow channels that existed prior to formation of the deeper present day east-, northeast-, and north-oriented river valleys. Numerous barbed tributaries in the form of northwest-oriented tributaries to east- and northeast-oriented rivers (and major tributaries to the mentioned rivers) and southeast-oriented tributaries to the northeast- and north-oriented rivers (and tributaries to the mentioned rivers) suggest the deeper river (and tributary) valleys eroded headward across the southeast-oriented flow channels. Asymmetric drainage divides, barbed tributaries, abandoned headcuts, and elbows of capture demonstrate the southeast-oriented flow, which was most likely in the form of floods of ice-marginal melt water moving between the Black Hills uplift and a continental ice sheet's southwest margin, was captured in sequence by headward erosion of the White, Bad, Cheyenne, Moreau, Grand, Cannonball, Heart, Knife, and Little Missouri River valleys. This erosion event sequence and its probable cause, determined from the map evidence, has major implications related to what is commonly considered to have been a much larger pre-glacial Bell River system, which included segments of each of the studied river valleys, and for all geologic and glacial history interpretations based on a Bell River system pre-glacial age interpretation.

Keywords: abandoned headcuts, aligned drainage, Bell River, cross cutting relationships, deep erosion by continental ice sheets, drainage divide crossings, ice-walled and bedrock-floored canyons, Missouri Escarpment, topographic map interpretation

1. Introduction

The concept of relative dating because of its importance is repeatedly reinforced throughout undergraduate and graduate geology studies. Relative dating is simply the use of some type of observed evidence to arrange events (geological or other) in their sequence of occurrence. While geologists have developed a great variety of relative dating techniques only a small number of those techniques are widely used. Perhaps the four most commonly used relative dating techniques are superposition, where in undisturbed strata the oldest rock layer is at the bottom; cross cutting relationships, where a geological unit or feature cut by another geological feature or unit is older than the unit or feature that cuts it; faunal and floral succession, where animal and plant fossils are arranged according to their (hypothesized) evolutionary development; and (while often used without putting events in order) absolute dating techniques, where the time in years or some other unit before some reference point is determined.

Map interpretation techniques provide powerful, but rarely used relative dating tools. Most map interpretation relative dating techniques are based on the principle of cross cutting relationships and are best used with detailed topographic maps. For example, detailed topographic maps can be ideal tools for observing stream capture evidence, where headward erosion of a valley captures drainage that had been flowing in a different direction. Further, asymmetric escarpments and abandoned headcuts, also observable on detailed topographic maps, can be used to determine where one drainage basin has been eroded into another. In both cases the principle of cross cutting relationships is applied to determine which drainage system or drainage basin existed before the other. Detailed topographic maps can be used independently of other dating techniques and of previously interpreted geological evidence to determine sequences of drainage system and drainage basin formation, which not only provides valuable information about how the observed drainage systems and drainage basins formed, but which can also be used as powerful tests of the validity of assumptions some other age dating techniques use. This paper explores how map interpretation techniques are used to determine the relative sequence in which western North and South Dakota river valleys (see figure 1) were eroded and briefly discusses how the determined sequence challenges several commonly held and significant geology and glacial history interpretations.

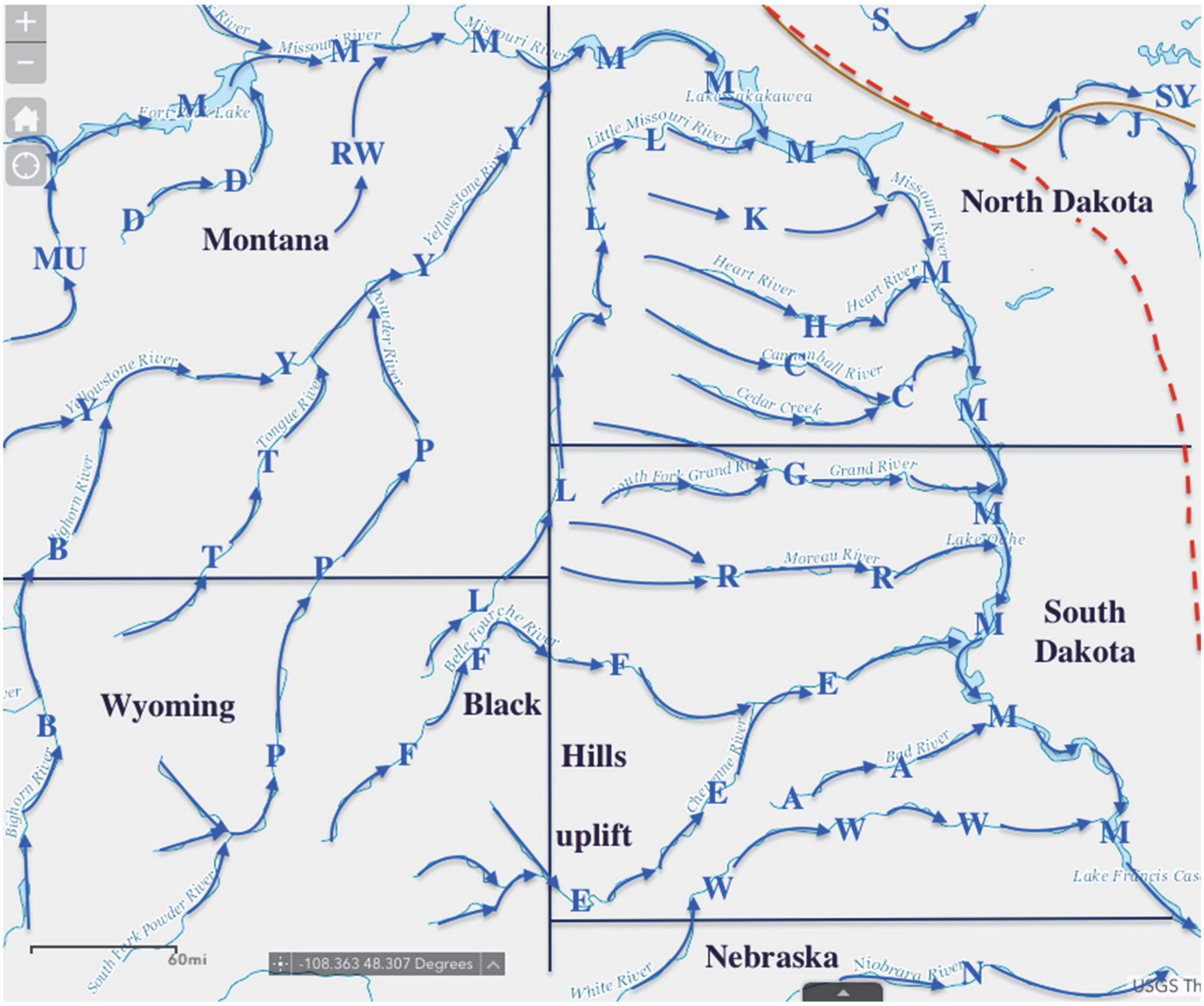

Figure 1. Modified map from United States Geological Survey (USGS) National Map website showing the Missouri River and tributaries in eastern Montana, northeast Wyoming, and western North and South Dakota. Blue arrows and letters show flow directions and identify drainage routes as discussed in the text. The red dashed line shows the Missouri Escarpment position and the brown line shows the present day north-south continental divide position. Scale bar in southwest corner represents 60 miles (97 kilometers)

1.1 Western North and South Dakota Drainage System

Figure 1 illustrates major North and South Dakota and adjacent Montana and Wyoming drainage routes identified as follows: “M” Missouri River, “A” Bad River, “B” Bighorn River, “C” Cannonball River, “D” Big Dry Creek, “E” Cheyenne River, “F” Belle Fourche River, “G” Grand River, “H” Heart River, “J” James River, “K” Knife River, “L” Little Missouri River, “MU” Musselshell River, “N” Niobrara River, “P” Powder River, “R” Moreau River, “RW” Redwater River, “S” Souris River, “SY” Sheyenne River, “T” Tongue River, “W” White River, and “Y” Yellowstone River. Note how several North and South Dakota rivers turn in northeast directions to join the south oriented Missouri River as barbed tributaries and how the north oriented Little Missouri River turns in an east direction before reaching the Missouri River. The North and South Dakota (and northeast Montana) Missouri River course roughly follows a former continental ice sheet margin and is joined by several east-, northeast-, and north-oriented tributary rivers. Approximately 30-50 miles (48-80 kilometers) north and east of the Missouri River is the northeast- and east-facing Missouri Escarpment, which is often referred to as a 300-600 foot (91-183 meter) step from lower plains to higher plains, which are found to the southwest and west (Thornbury, 1965). Between the Missouri River valley and the Missouri Escarpment is the Missouri Coteau, which is covered by thick fine- and coarse-grained glacially deposited debris. Coarse-grained glacial material is also found for as much as 100 kilometers (62 miles) to the south and west of the Missouri River valley, but in that region fine-grained glacially transported materials are almost completely absent. The distribution of glacial deposits and the Missouri Escarpment location have led many previous observers to suggest an ice sheet margin blocked a pre-glacial north-oriented drainage system forcing the water to flow along the ice sheet margin so as to form the Missouri River. Figure 1 illustrates why blockage of a north-oriented drainage system has been interpreted as the reason for the ice marginal Missouri River valley.

Not seen in figure 1 are valleys (partially filled with glacially transported materials) aligned with the east, northeast, and north oriented Missouri River tributary valleys and traceable in northeast directions into Canada. North and South Dakota and eastern Montana Missouri River tributary valleys and the partially filled valleys aligned with them are often used to suggest the existence of a major pre-glacial north-oriented river system (commonly named the Bell River system) that drained the figure 1 map area to the Labrador Sea (e.g. McMillan, 1973 and Sears, 2013). The partially filled valleys exist and the glacially deposited sediments in them are often cited to support the Bell River system’s hypothesized pre-glacial age, which is then cited as evidence the North American ice sheets did not deeply erode the North American continent (e.g. Sugden, 1976). While much published geological literature supports the pre-glacial Bell River system age a serious problem exists. White (1972, 1988) has asked why ice sheet erosion did not destroy the pre-glacial valleys, especially those partially filled valleys now found in easily eroded bedrock materials located throughout much of North and South Dakota and in many of the adjacent Canadian areas immediately to the north? If the partially filled Bell River system of valleys did not originate prior to North American ice sheet formation then continental ice sheet erosion may have been much deeper than is commonly claimed. Determining the sequence in which North and South Dakota Missouri River tributary drainage basins formed may help determine the Bell River valley system age and origin.

1.2 Previous Western North and South Dakota Drainage Basin Interpretations

Thornbury (1965) credits G. K. Warren (1868) as being the first geologist to suggest an ice sheet blocked north-oriented drainage routes and diverted the water along the ice sheet margin. Todd (1914) further developed the idea by suggesting that prior to glaciation northern Wyoming, eastern Montana, and North and South Dakota drainage had been to Hudson Bay and the present day Missouri River developed when the pre-glacial north-oriented drainage system was blocked and diverted to flow along an ice sheet margin. Todd placed the pre-glacial north-south continental divide between the White and Niobrara Rivers with the White River draining to Hudson Bay and the Niobrara River to the Gulf of Mexico. Flint (1949, 1955) suggested the north-south continental divide was further north with the pre-glacial Cheyenne River being the southernmost of the Hudson Bay drainage routes. Evidence cited by Todd (1914) and subsequent workers to support the pre-glacial Hudson Bay oriented drainage system (now referred to as the Bell River system) included valleys (partially filled with glacially deposited sediments) located north and east of the present day Missouri River. Subsequent workers including McMillan (1973) and Sears (2013) interpreted the Missouri River tributaries and partially filled valleys as components of an extensive north-oriented Tertiary age drainage system. Leonard (1916) and Bluemle (1972) have also suggested the north-oriented Bell River drainage system included some modern day Missouri River valley segments.

Aligned drainage in western South Dakota and elsewhere, primarily in minor tributaries to larger Missouri River tributaries seen in figure 1, has also interested previous researchers. For example Russell (1929) observed a marked drainage alignment that could not be produced by normal drainage development or by regional tilting. Based on the alignment of southwest Nebraska sand deposits attributed to deposition by northwest-to-southeast oriented winds, Russell suggested “the alignment elsewhere had been produced in the same manner, and the sand deposits removed by erosion.” Flint (1955) determined eolian control was most likely, but the mechanism was not apparent. White (1961) concluded that “NW-SE stream alignment in western South Dakota coincides with the prevailing wind direction. This alignment appears to be due to the periodic accumulation of locally derived eolian sediments in drains, which are not aligned. Because of this deposition, unaligned drains are not elongated by water erosion as rapidly as those which are aligned.” An alternate wind related hypothesis proposed by Harksen (1968) and Clayton (1975) suggests a relationship between the drainage alignment and bison trails, with the trails being oriented in the prevailing wind direction. Wayne (1991) suggests that “Yardang-like topography beyond the limit of Wisconsin till across central South Dakota and northeastern Nebraska, is further evidence of exceptionally strong winds parallel to the ice margin during the late Wisconsin glacial maximum, between 22 and 18 ka.”

Western South Dakota northwest-to-southeast oriented aligned drainage has also been attributed to causes other than the prevailing wind direction. Toepelman (1925) presented evidence for deep northwest-to-southeast oriented post-Oligocene or pre-Miocene canyons and suggested the canyons had been eroded along surface joints or fractures. Gill (1962) mapped “fossil” slump blocks along deep latest Oligocene or earliest Miocene northwest-to-southeast oriented valleys and also suggested that pre-Oligocene joints and fractures had determined valley orientations. Crandell (1958) however concluded joint control did not explain aligned drainage in the Pierre, South Dakota area. Lillegraven (1970) reported he could find no evidence for the “presence of a latest Oligocene or earliest Miocene stream system capable of cutting the deep valleys necessary to accommodate and to preserve” large slump-blocks, but recognized the presence of regional structures. Clausen (1989) found rounded cobbles and small boulders associated with Gill’s mapped slump blocks and regarded Lillegraven’s rejection of the Toepelman and Gill deep canyon hypotheses as being premature. Shurr (1982) used Landsat imagery of aligned drainage regions to map what he and others consider to be northwest-to-southeast oriented surface lineaments in regions surrounding the Black Hills. Guo and George (1999) summarize literature in which northeast and northwest trending Mid Continent Region surface lineaments have been correlated with subsurface lineaments and fractures as a tool to assist in oil and gas exploration. Guerrero (2012) describes an attempt to correlate southwest North Dakota surface lineaments with deep subsurface lithofacies.

Most recently Clausen (2017a and 2017b) suggested that massive southeast-oriented ice marginal melt water floods flowed across western South Dakota and adjacent regions. The 2017a paper describes evidence indicating the northeast-oriented White River and Cheyenne River valleys eroded headward across western South Dakota during a massive southeast-oriented flood flow event with White River valley headward erosion occurring prior to Cheyenne River valley headward erosion. The subsequent paper (Clausen, 2017b) presents evidence that what was probably southeast-oriented melt water flow in northwest South Dakota to the North Fork Moreau River valley was beheaded in sequence by headward erosion of the South Fork Grand River valley, the north-oriented Little Missouri River valley, two northeast-oriented Little Missouri River tributary valleys, and the north-oriented Powder River valley. That paper also suggests the North Fork Grand River valley beheaded flow to the South Fork Grand River valley

2. Research Method

This paper reports on a few findings from the author’s much larger and unpublished Missouri River drainage basin landform origins research project. The multi-year Missouri River drainage basin landforms origins research project consisted of systematically studying detailed United States Geologic Survey (USGS) topographic maps of the entire Missouri River drainage basin and adjacent drainage basins to determine how major drainage divides within and surrounding the large and complex Missouri River drainage basin originated. Drainage divide origins were determined by using divide crossings (through valleys, wind gaps, etc.) as evidence of previous drainage routes and then using barbed tributaries, elbows of capture, asymmetric drainage divides, abandoned headcuts, and similar evidence to determine how many thousands of capture events altered earlier drainage routes so as to produce the present day Missouri River drainage basin drainage routes. Approximately 550 unpublished and detailed project essays (or research notes) can be found in blog format on the author’s geomorphologyresearch.com website.

The project determined that all major Missouri River tributary drainage basins evolved in identifiable sequences, however this paper focuses on western North and South Dakota areas underlain by gently dipping or nearly horizontal and easily-eroded late Cretaceous and Tertiary sediments so as to avoid complications created by more erosion resistant bedrock units and geologic structures. The study reported here investigated western North and South Dakota map evidence for the Bad, Cannonball, Cheyenne, Grand, Heart, Knife, Little Missouri, Moreau, and White River drainage basins and drainage divides surrounding those drainage basins to determine the sequence in which those drainage basins had formed. Map interpretation techniques applied in this study made use of asymmetric drainage divides, barbed tributaries, divide crossings, elbows of capture, and abandoned headcuts to determine erosion event sequences. Each of the study region’s major drainage divides was analyzed independently of other study region drainage divides using whichever map interpretation techniques best fit the observed evidence. The independent drainage divide analyses were then combined in the summary below to construct the identifiable western North and South Dakota drainage basin formation sequence.

3. Results

3.1 Bad River-White River Drainage Divide

The Bad River is located between the east oriented White River downstream segment (east of the Black Hills) and the northeast oriented Cheyenne River segment (northeast of the Black Hills). Upstream from the Bad River headwaters there is no northeast oriented river or stream located between the northeast-oriented Cheyenne and White Rivers. Clausen (2017a) analyzed that upstream drainage divide and determined northeast-oriented Cheyenne River valley headward erosion captured southeast-oriented drainage that had been moving to what was interpreted to be a newly eroded northeast-oriented White River valley. The Bad-White River drainage divide segment analyzed here is located at the western end of the northeast-oriented Bad River valley and north and east of the previously analyzed Cheyenne-White River drainage divide. Further to the east is east-oriented Medicine Creek located between the Bad and White Rivers and the Bad River-Medicine Creek and Medicine Creek-White River drainage divides were analyzed independently.

West of the east-oriented Medicine Creek headwaters the Bad-White River drainage divide is asymmetric with short south- and southeast-oriented White River tributaries draining from a southeast- and south-facing escarpment that in places merges with the White River north valley wall. Longer north- and northeast-oriented tributaries drain higher elevation areas north of the escarpment rim to the northeast-oriented Bad River valley and are joined by many shorter southeast- and northwest-oriented tributaries with some of the northwest-oriented tributaries originating at or near the escarpment rim (although northeast-oriented Bad River tributaries also drain from relatively short southwest-facing escarpment segments). Figure 2 illustrates a Bad-White River drainage divide segment located east of Badlands National Park and west of Kadoka (SD). The White River meanders in an east-northeast direction across the figure 2 southeast quadrant and the brown line marks the drainage divide between southeast-oriented drainage to the White River and north-oriented drainage to northeast- and north-oriented Bad River tributaries.

Map interpretation techniques used in studying the Bad-White River drainage divide included looking for through valleys (divide crossings) that cross what is now the south-facing escarpment rim. These divide crossings are seen in the form of notches cut into the escarpment rim and link south-oriented White River tributaries with north-oriented Bad River tributaries. In figure 2 two such notches have been given names with Chamberlain Pass being found at location 1 and Hughes Pass at location 4. These and numerous similar notches suggest water once flowed across the present day drainage divide with the most probable flow direction being from the higher elevation Bad River drainage basin to the lower elevation White River drainage basin. The large number of such notches suggests great quantities of such south-oriented water eroded the south-facing escarpment seen in figure 2. Since the area to the north of figure 2 is today the Bad River headwaters area and the Bad River valley floor is lower in elevation than the escarpment rim the interpretation is made that the south-oriented water flowed across what is now the Bad River drainage basin and eroded the White River north valley wall headward in a northwest direction. In other words at that time the northeast-oriented Bad River headwaters valley did not exist, but the White River valley did exist.

More detailed study of figure 2 drainage routes on either side of the escarpment rim suggests many channels moving water across the present day drainage divide were probably oriented in a northwest-to-southeast direction. Numerous southeast-oriented White River tributaries can be seen originating at or near the escarpment face and numerous northwest-oriented Bad River tributaries can be seen originating at or near the escarpment rim. The northwest-oriented Bad River tributary valleys were probably originally eroded by southeast-oriented flow that was beheaded and reversed by headward erosion of deeper northeast-oriented Bad River headwaters valleys. The many northwest-to-southeast oriented tributaries suggest the southeast-oriented flow may have initially moved in extensive sheets of water that eroded the escarpment face headward from the east-northeast oriented White River valley wall. The deep White River valley provided a lower base level, which then enabled the water to erode shallow southeast-oriented channels headward across the region. The southeast-oriented flow was captured when headward erosion of northeast-oriented Bad River headwaters valleys beheaded and reversed flow in those channels to create the present day Bad River-White River drainage divide and the northwest-oriented Bad River tributaries.

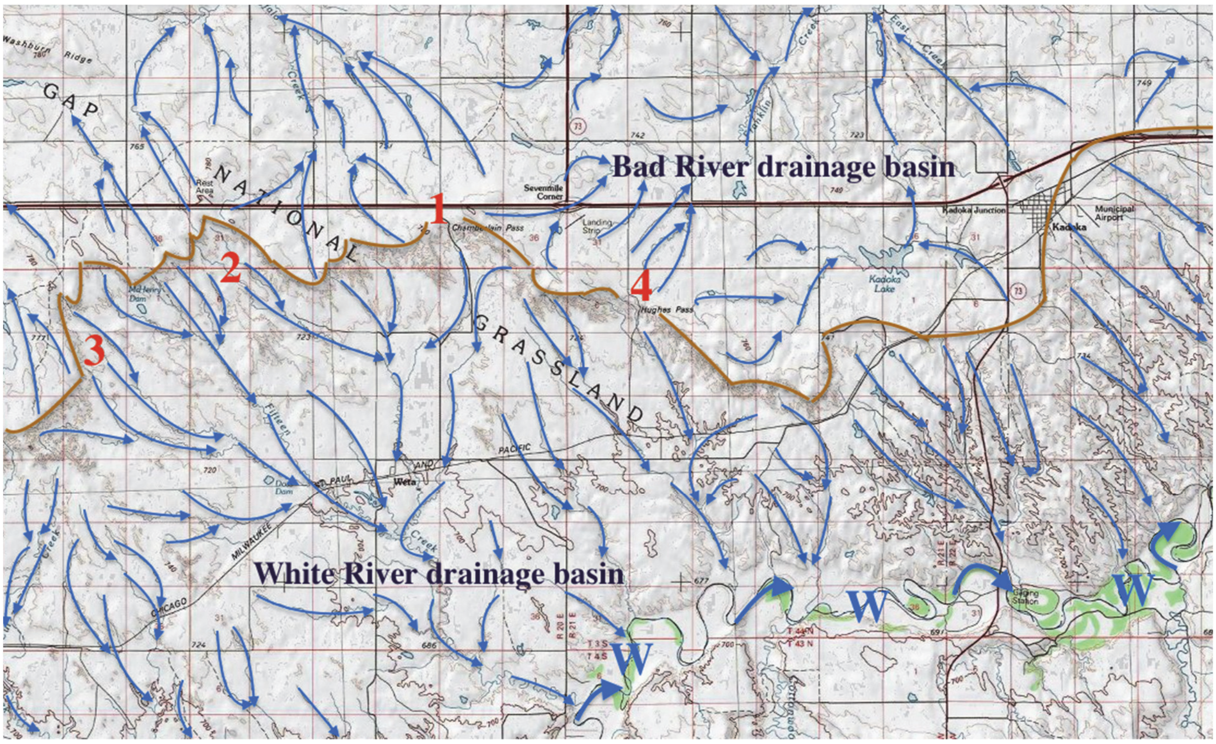

Figure 2 Modified section of a USGS topographic map from the USGS National Map website showing the Bad-White River drainage divide area. The contour interval is 20 meters (66 feet). Sides of squares in the grid are 1 mile (1.6 kilometers) in length.

Additional evidence supporting an interpretation that large volumes of southeast-oriented water eroded the White River north valley wall can be seen in figure 3, which provides a detailed map of the escarpment-surrounded basin or abandoned headcut located immediately south of Chamberlain Pass (location 1 in figures 2 and 3). Southeast-oriented water that eroded Chamberlain Pass also eroded the escarpment-surrounded basin headward (or in a northwest direction) into the easily eroded bedrock from the White River valley wall toward Chamberlain Pass. Headcut erosion ended when headward erosion of the northeast-oriented South Fork Bad River (north of figures 2 and 3) beheaded and reversed southeast-oriented flow through Chamberlain Pass to initiate the northwest-oriented Bad River tributaries seen in figures 2 and 3 and to leave the escarpment-surrounded basin as a large abandoned headcut.

Such escarpment-surrounded basins or abandoned headcuts are common along the Bad River-White River divide and throughout this paper's study region. These abandoned headcuts provide evidence that large volumes of water flowed across the region, and can also be used to identify the flow directions. In the case of the Bad River-White River drainage divide a larger escarpment-surrounded basin is found at locations 2 and 3 in figure 2 and the southwest-facing escarpment segment seen in figure 2 (and partially seen in figure 3) is probably one wall of an even larger southeast-facing escarpment-surrounded basin. The divide crossings and escarpment-surrounded basins provide evidence extensive sheets of southeast-oriented water (perhaps also moving in complexes of shallow southeast-oriented channels across the present day drainage divide) flowed into the deeper White River valley, which probably had previously been eroded headward in a west direction as it captured the massive southeast-oriented flow.

Two drainage divides are present in the eastern half of the Bad River-White River drainage divide area. One divide is between the northeast-oriented Bad River and east and north-oriented Medicine Creek and the other divide is between Medicine Creek and the White River. Medicine Creek is an east- and north-oriented Missouri River tributary. Figure 4 provides a topographic map illustrating Medicine Creek where it turns from flowing in an east direction to flow in a north direction. Northwest-oriented tributaries join the east-oriented Medicine Creek segment as barbed tributaries while southeast-oriented tributaries join the north-oriented Medicine Creek segment as barbed tributaries. Orientations of Medicine Creek tributaries seen in figure 4 suggest the Medicine Creek valley eroded headward across southeast-oriented water moving in shallow and low gradient southeast-oriented flow channels. Headward erosion of the deep Medicine Creek valley initiated the northwest-oriented Medicine Creek tributary valleys by reversing the flow direction on the downstream ends of beheaded flow channels, which enabled water south and east of the newly eroded Medicine Creek valley to flow toward the newly eroded and deep Medicine Creek valley. Divide crossings and abandoned headcuts similar to those seen in figures 2 and 3 and the northwest- and southeast-oriented Medicine Creek tributaries seen in figure 3 provide strong evidence that headward erosion of the Medicine Creek valley captured large volumes of southeast-oriented water moving to the White River valley and that headward erosion of the northeast-oriented Bad River valley next captured southeast-oriented water moving to the newly eroded east- and north-oriented Medicine Creek valley.

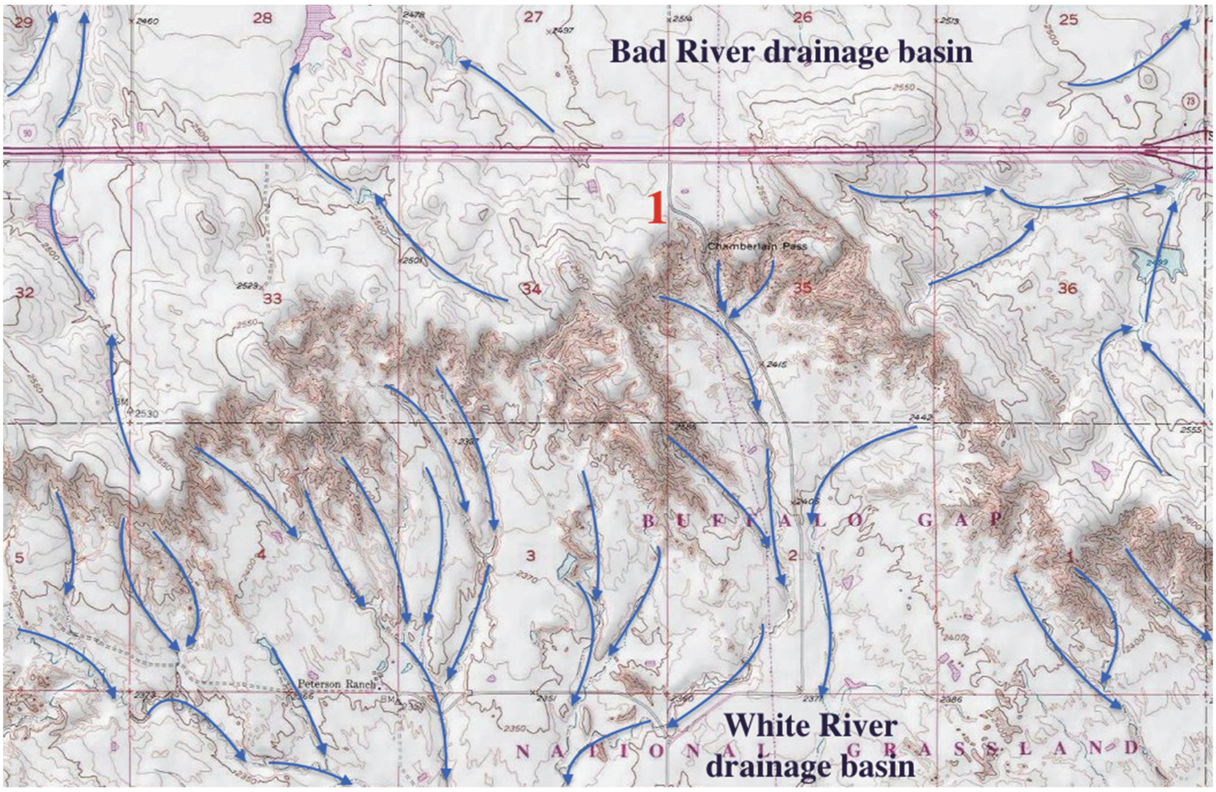

Figure 3. Modified USGS topographic map of the Chamberlain Pass area from USGS National Map website. Contour interval is 10 feet (3 meters) and sides of squares in the grid are 1 mile (1.6 kilometers) in length. The number 1 identifies Chamberlain Pass

3.2 Cheyenne River-Bad River Drainage Divide

When observed on detailed topographic maps the Cheyenne River-Bad River drainage divide is in many places a ridge notched with numerous closely spaced divide crossings (similar to divide crossing seen in figure 3) that link northwest-oriented Cheyenne tributary headwaters valleys with opposing southeast-oriented Bad River tributary headwaters valleys (figure 5 illustrates deeper divide crossings near the west end of the Cheyenne River-Bad River drainage divide). The divide crossings suggest southeast-oriented water first flowed across what are today deep Cheyenne River and Bad River valleys to a newly eroded White River valley and subsequently was captured by headward erosion of the northeast-oriented Bad River valley and later by headward erosion of the deep northeast-oriented Cheyenne River valley.

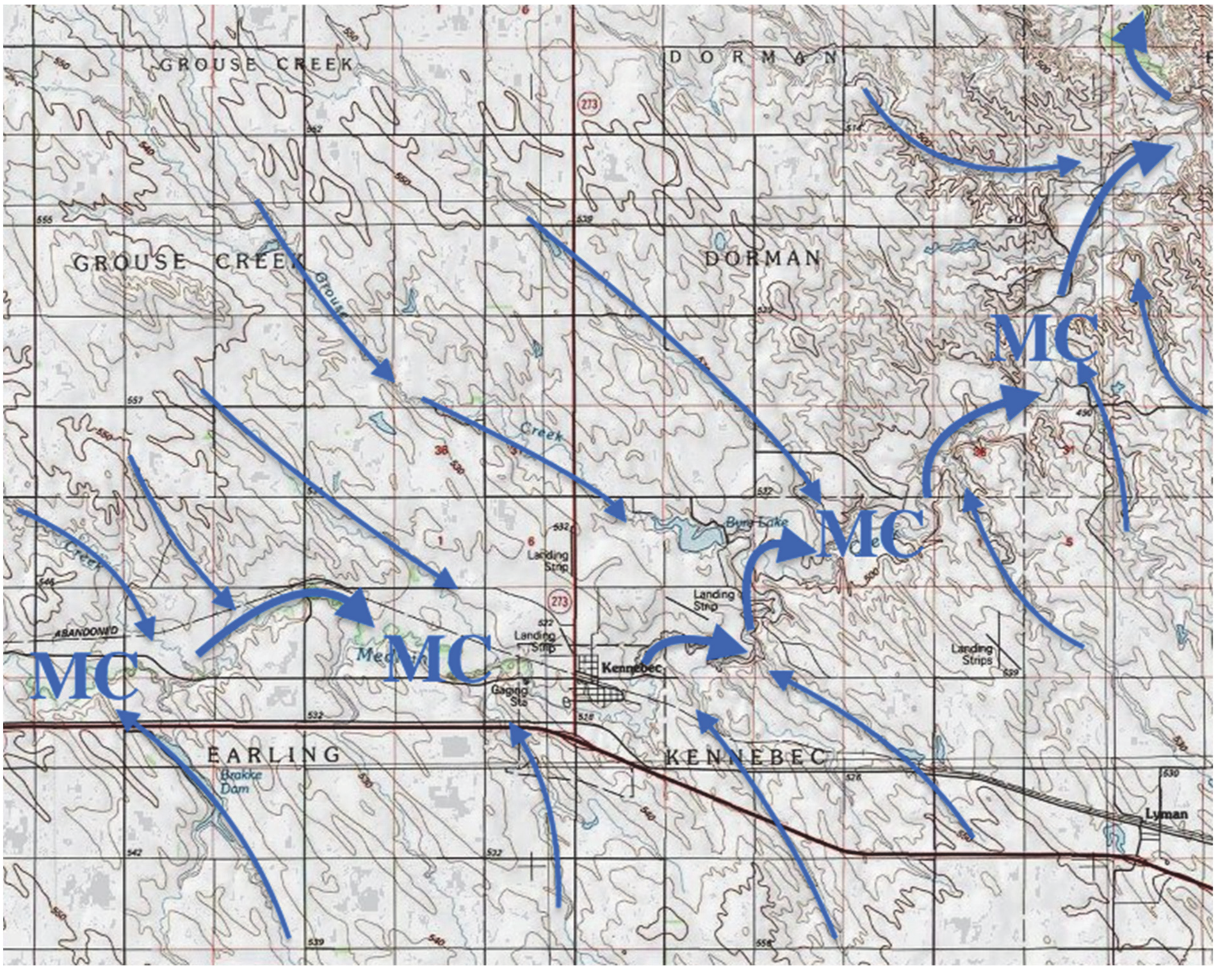

Figure 4. Modified USGS topographic map from the USGS National Map website illustrating tributaries flowing to east- and north-oriented Medicine Creek (MC). The contour interval is 10 meters (33 feet) and sides of grid squares are 1 mile (1.6 kilometers) in length

If so headward erosion of the deep Cheyenne River valley must also have been across multiple southeast-oriented flow channels and the Cheyenne River should today have many northwest-oriented tributaries from the south similar to those seen in figure 4. While joined by many shorter northwest-oriented tributaries as predicted the Cheyenne River, like the Bad River, is also joined by several longer north oriented tributaries. Numerous southeast- and northwest-oriented tributaries join those north-oriented Cheyenne River tributaries. One tributary, Plum Creek, like Medicine Creek in figure 4, has significant east-, north-, and northeast-oriented valley segments. Like with Medicine Creek northwest- and southeast-oriented tributaries join the east-, north-, and northeast-oriented Plum Creek valley segments suggesting the deep Plum Creek valley also eroded headward across massive southeast-oriented flow.

Figure 5 is a detailed topographic map illustrating some of the deeper divide crossings (approximately 200 feet or 61 meters deep) linking northwest- and north-oriented headwaters of Cheyenne River tributaries with opposing southeast-oriented Bad River tributary headwaters. Most other divide crossings along the Cheyenne-Bad River divide are shallower and generally are less than 100 feet or 30 meters deep. The divide crossings suggest headward erosion of the deep northeast-oriented Cheyenne River valley captured southeast-oriented water moving across what is now the Cheyenne River-Bad River drainage divide to reach what must have been actively eroding southeast-oriented Bad River tributary valleys, which were eroding headward from what must have been a newly eroded northeast-oriented Bad River valley.

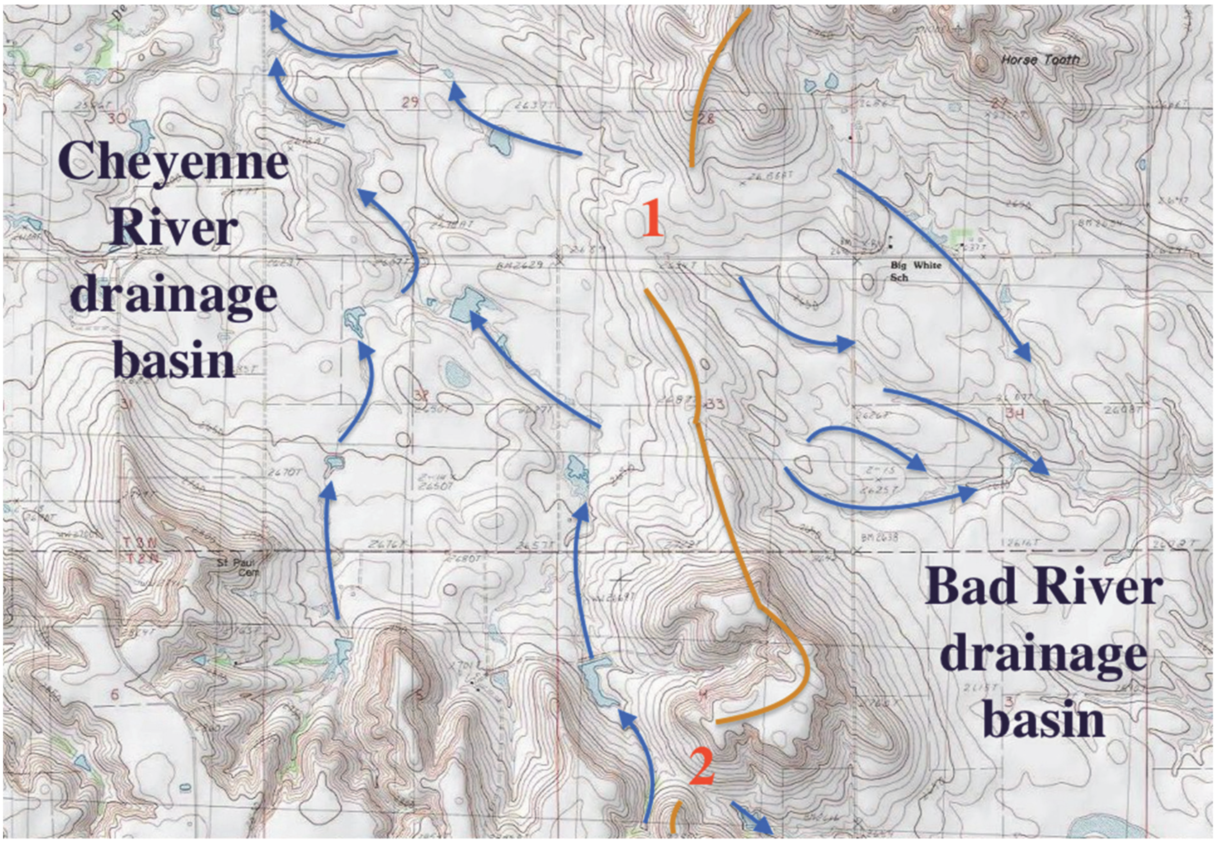

Figure 5. Modified USGS topographic map from the USGS National Map website showing divide crossings notched into the Cheyenne-Bad River drainage divide. Red numbers 1 and 2 identify deep divide crossings linking the two drainage basins. The contour interval is 10 feet (3 meters) and sides of larger grid squares are 1 mile (1.6 kilometers) in length

3.3 Moreau River-Cheyenne River Drainage Divide

Similar map evidence can be interpreted to demonstrate southeast-oriented water flowed across what is today the Moreau River valley to reach the northeast-oriented Cheyenne River valley. Near the Missouri River the rim of a steep southeast-facing escarpment is the divide between the northeast-oriented Moreau River valley and the northeast-oriented Cheyenne River valley to the south. Further to the west several southeast-, east-southeast-, and east-oriented tributaries flow to the northeast-oriented Cheyenne River and northeast-oriented tributaries flow to the east- and northeast-oriented Moreau River (which also has North and South Forks) and these tributary valleys are located between the east- and northeast-oriented Moreau River and the northeast-oriented Cheyenne River. Shallow divide crossings linking opposing northwest- and southeast-oriented streams are notched into many, but not all, segments of the Moreau River-Cheyenne River drainage divide and of drainage divides between the southeast-, east-southeast-, and east-oriented Cheyenne River and northeast-oriented Moreau River tributaries. The nature of these divide crossings varies from place to place, but the divide crossings like those in figure 6 provide evidence that multiple closely spaced channels moved large quantities of water across what are now east-, east-northeast-, and northeast-oriented drainage divides to reach the deep northeast-oriented Cheyenne River valley.

Figure 6 illustrates divide crossings on a short segment of the asymmetric Red Owl Creek-Cheyenne River drainage divide. Note the short northwest-oriented tributaries to northeast-oriented Red Owl Creek, which flows to east- and southeast-oriented Cherry Creek (which then flows to the northeast-oriented Cheyenne River) and the longer southeast-oriented tributaries to the northeast-oriented Cheyenne River. Prior to headward erosion of the northeast-oriented Red Owl Creek valley the divide crossings indicate water flowed in a southeast direction across this region. Continuing in a north or northwest direction from figure 6 there are drainage divides between east-oriented Cherry Creek and northeast-oriented Red Owl Creek, between Cherry Creek and northeast-oriented Flint Creek (which flows to the Moreau River), between Flint Creek and east-oriented Deep Creek, and between

Deep Creek and the Moreau River. Divide crossings notched into all of these drainage divides indicate southeast oriented water moving to the deep northeast-oriented Cheyenne River valley was captured in sequence by headward erosion of the northeast-oriented Red Owl Creek valley, the east-oriented Cherry Creek valley, the northeast-oriented Flint Creek valley, the east-oriented Deep Creek valley, and the east-oriented Moreau River valley.

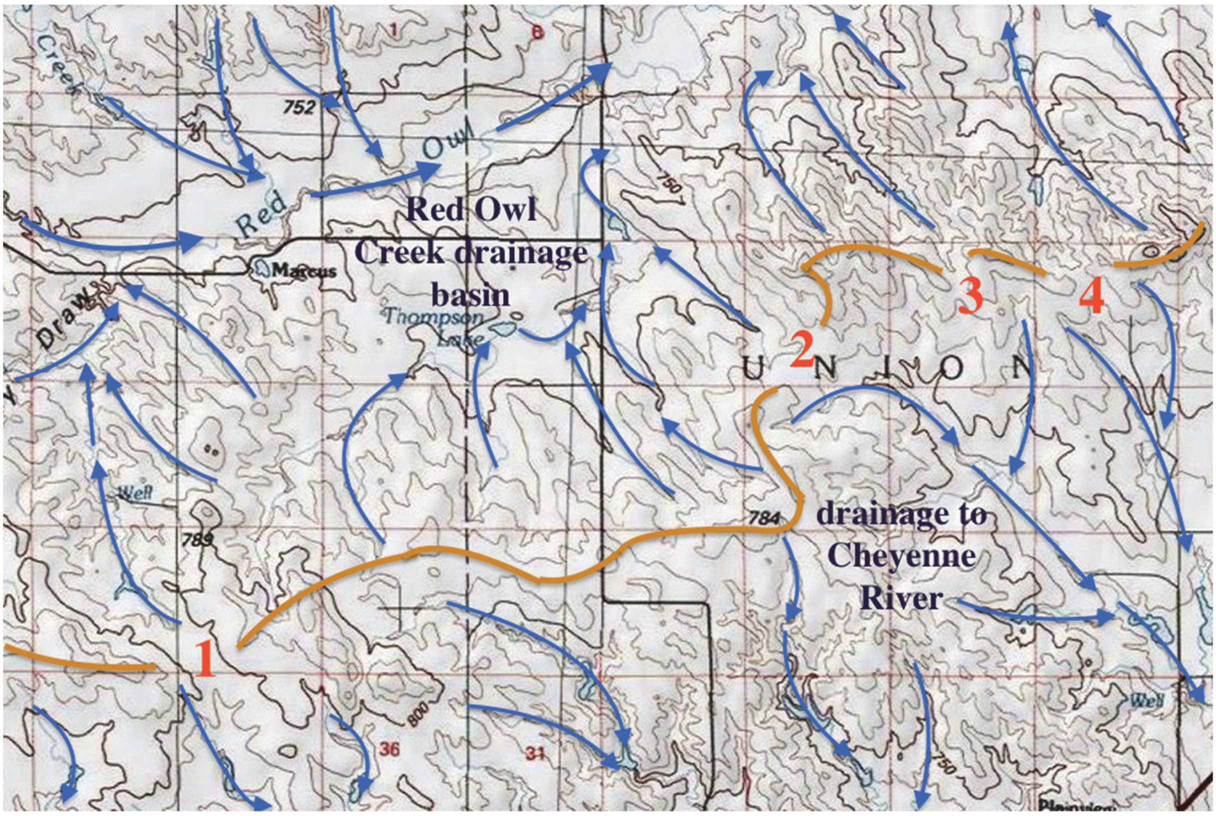

Figure 6. Modified USGS topographic map from USGS National Map website showing a Red Owl Creek-Cheyenne River drainage divide segment. The brown line follows the drainage divide. The contour interval is 10 meters (33 feet) and squares in the grid have sides that are 1 mile (1.6 kilometers) in length

3.4 Grand River-Moreau River drainage divide

Like the Moreau River the Grand River has North and South Forks. The South Fork Grand River begins as a northeast-oriented stream before turning in an east and then northeast direction to join the southeast-oriented North Fork. Figure 7 is a modified section of the USGS 1:250,000-scale Lemmon (SD) topographic map showing the region where the northeast-oriented South Fork Grand River headwaters turn to flow in an east direction. The brown line in figure 7 follows the Grand River-Moreau River drainage divide with the north-to-south segment of that drainage divide being located along the top of Slim Buttes, which has an erosion resistant cap rock (Slim Buttes area stratigraphy is described in detail in Lillegraven's 1970 paper). Red numbers on figure 7 identify gaps notched into the Slim Buttes crest with the deepest notches being located in the Reva Gap area (numbers 1 and 2). Note how today east and southeast oriented Moreau River tributaries originate at or near those gaps with a northwest-oriented South Fork Grand River tributary originating near the deep Reva Gap area at numbers 1 and 2.

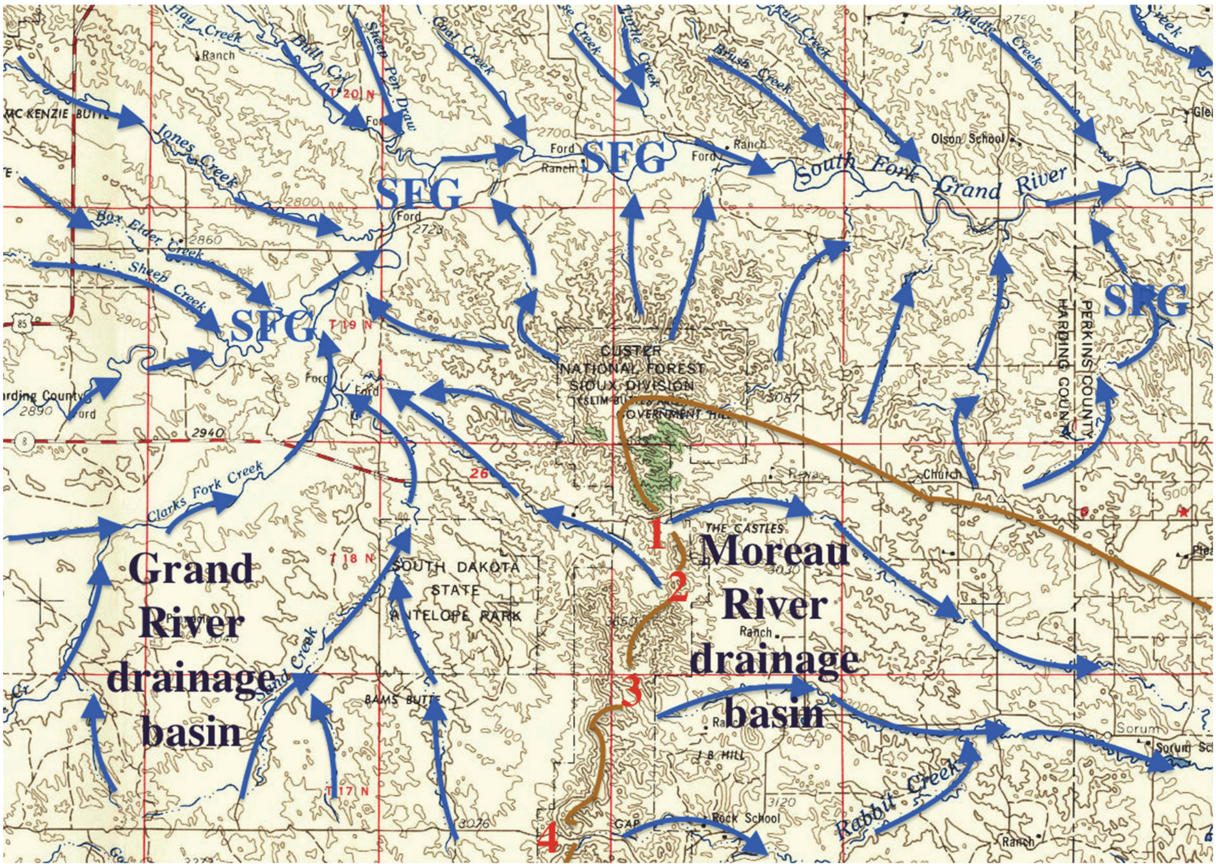

Figure 7. Modified section of USGS 1:250,000-scale Lemmon (SD) topographic map from the USGS Historical Map Collection website. The brown line follows the Grand River-Moreau River drainage divide. Red numbers identify gaps notched into the crest of Slim Buttes as discussed in the text. Blue arrows emphasize present day drainage and "SFG" identifies the South Fork Grand River. The contour interval is 100 feet (30 meters) and red grid lines are 6 miles (9.6 kilometers) apart

Toeplelman (1925) and Gil (1962 interpreted structures in the Reva Gap area to be late Oligocene or early Miocene landslide or slump blocks that had formed along the walls of deep northwest-to-southeast oriented valleys, although Lillegraven (1970) interpreted the structures differently. Whatever the structures are the map evidence seen in figure 7 suggests headward erosion of a deep northeast-oriented South Fork Grand River valley and its north-oriented tributary valleys beheaded and reversed southeast oriented flow that was moving through the Reva Gap area to the Moreau River valley. Note how northwest-oriented drainage from the Reva Gap area is met at the South Fork Grand River by southeast-oriented streams from the northwest. Interestingly north and west of figure 7 northeast-oriented North Fork Grand River headwaters streams appear to have beheaded the southeast-oriented South Fork Grand River tributaries. West and south of figure 7 is the Jump-off escarpment-surrounded basin which Clausen (2017b) interpreted as an abandoned headcut formed when headward erosion of the South Fork Grand River headwaters valley beheaded southeast-oriented flow moving to the southeast oriented North Fork Moreau River headwaters area.

While not map evidence this author has previously observed field evidence suggesting water flowed in a southeast direction across the region just east of figure 7. A trail of coarse-grained alluvium (including distinctive rock types from the Montana Beartooth Mountains located south of the Yellowstone River and west of the figure 1 west edge) extends from the North Fork Grand River valley in a southeast direction across the region east of figure 7. The alluvium, which includes cobble-sized material, forms an identifiable band extending across the North Fork Grand River-South Fork Grand River drainage divide and then across the South Fork Grand River-Moreau River drainage divide and into the southeast-oriented Thunder Butte Creek valley (Thunder Butte Creek is a southeast-oriented Moreau River tributary). Water that deposited this alluvium band flowed in a southeast direction on a surface at least as high as the present day North Fork-South Fork Grand River and South Fork Grand River-Moreau River drainage divides and eroded the southeast-oriented Thunder Butte Creek valley headward in a northwest direction. Headward erosion of the South Fork Grand River valley first captured this southeast-oriented flow with headward erosion of the North Fork Grand River valley subsequently capturing the southeast-oriented flow.

3.5 Cannonball River-Grand River Drainage Divide

The Cannonball River originates as a southeast-oriented stream, but turns at an elbow of capture to flow in a northeast direction to join the south oriented Missouri River as a barbed tributary. Elbows of capture, like the Cannonball River elbow of capture, represent another type of easily observed map evidence useful in determining drainage route histories. As seen in figure 1 the elbow of capture is located where a southeast- and northeast-oriented tributary (Cedar Creek-shown, but not labeled in figure 1) joins the Cannonball River. The elbow of capture is interesting as it suggests headward erosion of the northeast-oriented Cannonball River valley segment captured not only southeast-oriented flow on the present day Cannonball River alignment, but also southeast-oriented flow on the Cedar Creek alignment. Timber Creek is a north-oriented tributary joining Cedar Creek near its elbow of capture and Hay Creek is a northeast- and north-oriented tributary joining Cedar Creek about 6 miles (9.6 kilometers) further to the west. Figure 8 illustrates a section of a detailed topographic map showing the Cedar Creek (Cannonball River)-Moreau River drainage divide immediately to the southwest of the northeast- and north-oriented Hay Creek valley and to the southeast of the north-oriented Timber Creek valley.

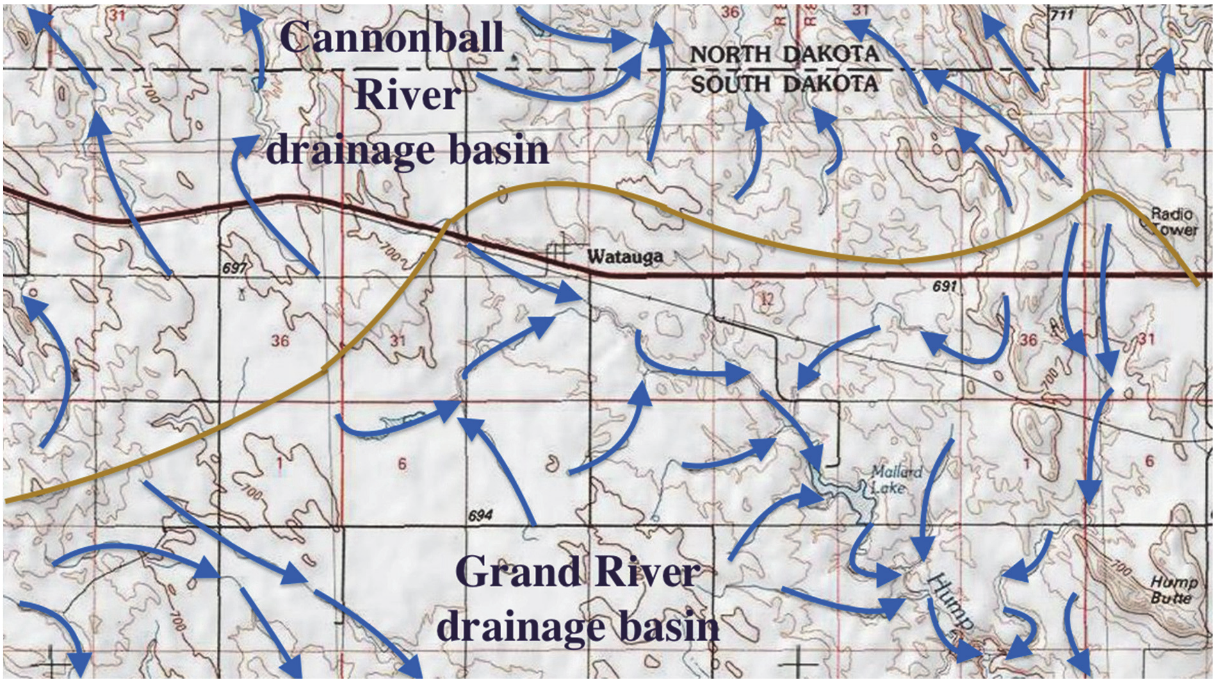

Figure 8. Modified USGS topographic map from USGS National Map website showing a segment of the Cannonball-Grand River drainage divide. The brown line follows the drainage divide. The contour interval is 10 meters (33 feet) and sides of the grid squares are 1 mile (1.6 kilometers) in length

In figure 8 the north-oriented drainage flows to north- and northeast-oriented Cedar Creek tributaries with Cedar Creek flowing in an east and northeast direction to join the northeast-oriented Cannonball River segment. Hump Creek is the southeast-oriented stream in the figure 8 southeast quadrant and flows to the east-oriented Grand River. Note the broad lowland on which the small town of Watauga is located. Low hills located in the southeast and southwest corners of figure 8 suggest the intervening lowlands form the floor of a 6-mile (9.6-kilometer) wide northwest-to-southeast oriented 50-foot (15-meter) deep valley. This lowland suggests the southeast oriented Hump Creek valley was eroded headward when a sheet of water flowed in a southeast direction from the upstream Cedar Creek alignment to the present day Grand River valley. Headward erosion of the southeast-oriented Hump Creek valley ended when headward erosion of the east- and northeast-oriented Cedar Creek valley beheaded and reversed the flow.

3.6 Heart River-Cannonball River Drainage Divide

The Heart River begins almost at the deep north-oriented Little Missouri River valley rim and flows across a gently sloping surface in an east direction to where the southeast-oriented Green River joins it. From its confluence with the Green River the Heart River then flows in a southeast direction for a considerable distance before turning in a northeast direction to join southeast-oriented Muddy Creek (flowing in the southeast-oriented Curlew Valley). From its confluence with Muddy Creek the Heart River then flows for a short distance in a southeast direction before turning abruptly at an elbow of capture to flow in a north-northeast direction and eventually joins the south-oriented Missouri River as a barbed tributary. Figure 9 illustrates the northeast-oriented and southeast-oriented Heart River (labeled H) segments located just upstream from the elbow of capture. Also seen in figure 9 is the southeast-oriented Muddy Creek valley (MC) and a south-southeast oriented abandoned valley (AV) south of the Heart River elbow of capture.

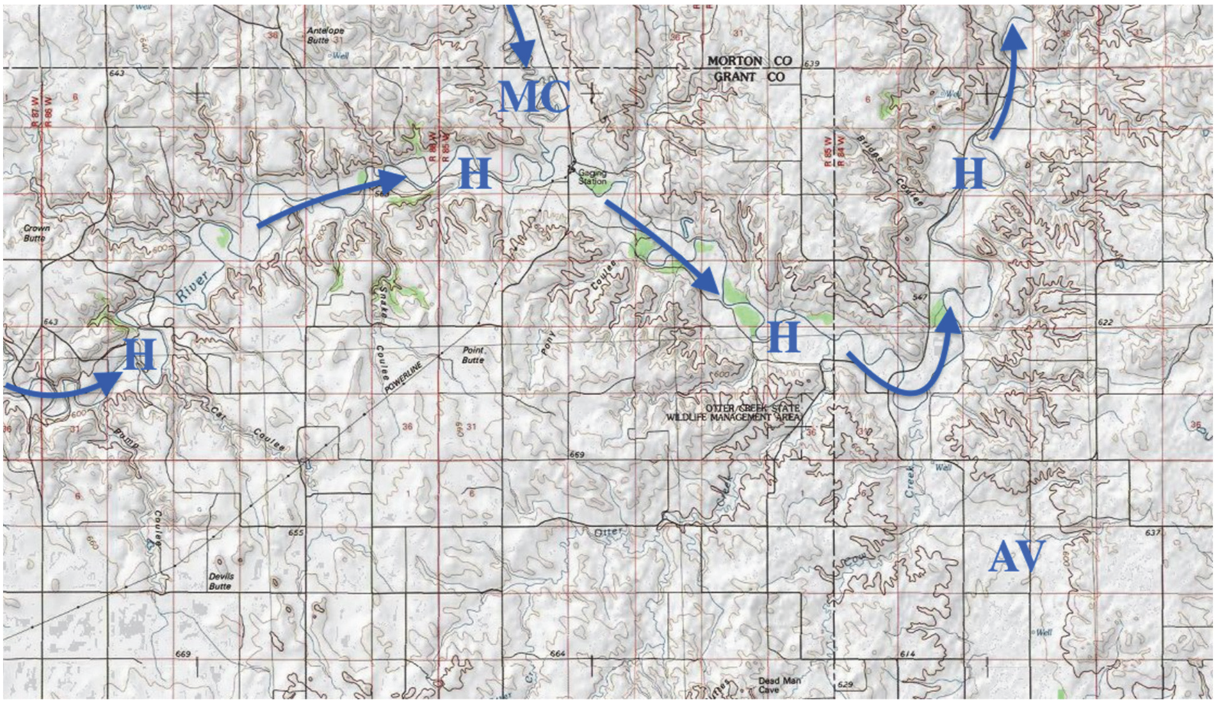

Figure 9. Modified USGS topographic map from USGS National Map website showing the Heart River elbow of capture area. Blue arrows show present day flow directions and letters identify features as follows: "H" Heart River, "MC" Muddy Creek, and "AV" abandoned valley. The map contour interval is 20 meters (66 feet). Sides of squares in grid are 1 mile (1.6 kilometers) in length

The southeast-oriented Muddy Creek and Heart River valley and the abandoned valley segment seen in figure 9 represent a small section of a much longer southeast-oriented abandoned river channel shown on the Geologic Map of North Dakota (Clayton, 1980) and on the earlier Preliminary Glacial Map of North Dakota (Colton et al, 1963). The channel contains outwash sediments and both maps show the channel extending across a region where glacial erratic material is present and across the present day Knife, Heart, and Cannonball River valleys. As seen in figure 9 headward erosion of the north- and northeast-oriented Heart River valley captured southeast-oriented water (probably glacial melt water) that was moving in this much longer southeast-oriented river channel, which means the southeast-oriented river channel (used by glacial melt water) predates the north-northeast oriented Heart River valley segment, although both valleys could have been eroded at approximately the same time. Likewise the northeast-oriented Cannonball River valley segment and the southeast- and northeast-oriented Knife River valley cannot be older than the longer southeast-oriented river channel, which they cut.

3.7 Knife River-Heart River Drainage Divide

The Knife River as seen in figure 1 originates as an east-southeast oriented stream, which like the Cannonball River turns to flow in a northeast direction to join the south-oriented Missouri River as a barbed tributary. A prominent north- and northeast-facing escarpment locally known as the Russian Spring Escarpment forms the boundary between the southeast-oriented Knife River headwaters drainage basin and the Heart River drainage basin to the south. The Russian Springs Escarpment originates at an east-oriented escarpment-surrounded basin or abandoned headcut located south of the Knife River headwaters area seen in figure 10, but is much better seen on more detailed topographic maps. The east-oriented escarpment-surrounded basin suggests the southeast-oriented Knife River drainage basin was eroded headward into what had previously been the Heart River drainage basin.

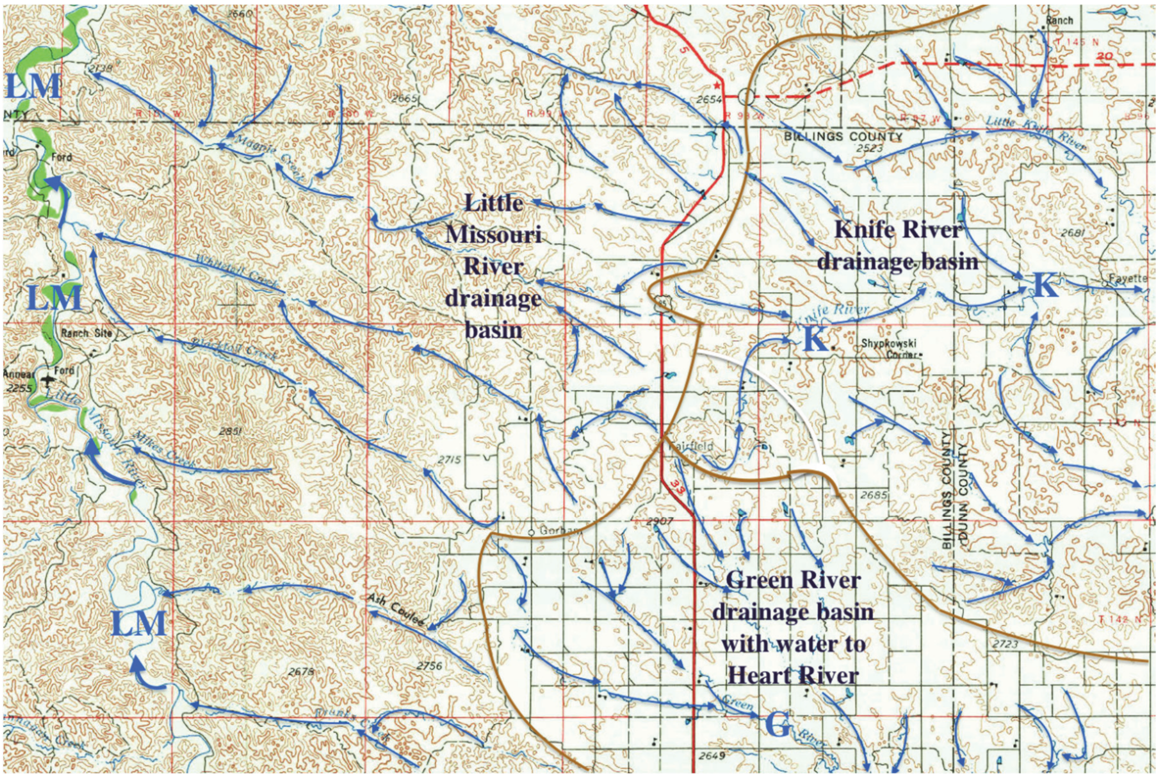

Figure 10. Modified section of USGS 1:250,000-scale Watford City (ND) topographic map from USGS Historical Map Collection website showing where the Heart, Knife, and Little Missouri River drainage basins meet. The brown lines show approximate drainage divide locations and blue arrows identify key drainage routes and directions with blue letters identifying rivers as follows: “G” Green River, “K” Knife River, and “LM” Little Missouri River. The contour interval is 100 feet (33 meters) and sides of squares in the red grid are 6 miles (9.6 kilometers) in length

Figure 10 provides a modified topographic map of the Knife River headwaters area. Near the west edge of figure 10 is the deep north-oriented Little Missouri River valley, which north of figure 10 turns in an east direction to reach the Missouri River (see figure 1). To the southwest of the Knife River headwaters are southeast-oriented Green River headwaters with the Green River being a southeast-oriented tributary flowing to the east- and southeast-oriented Heart River. While much better seen on more detailed topographic maps a large east-oriented escarpment-surrounded basin is located east and south of the present day Knife River headwaters stream (approximately where the vertical Billings and Dunn County names are located on either side of the north-to-south oriented county line). This escarpment-surrounded basin or abandoned headcut suggests large volumes of east- or southeast-oriented water flowed across the present day deep north-oriented Little Missouri River valley to the southeast-oriented Green-Heart River drainage basin and was being captured by headward erosion of the deeper east-southeast oriented Knife River drainage basin just before headward erosion of the even deeper north-oriented Little Missouri River valley captured the east- and southeast-oriented water and diverted that water in a north and then east direction.

The previously mentioned southeast-oriented abandoned river channel crosses the present-day east-southeast oriented Knife River valley before now being used by southeast-oriented Muddy Creek, which as seen in figure 9 flows to the Heart River. Assuming the Geologic Map of North Dakota (Clayton, (1980) implication that southeast-oriented melt water once flowed from north of the Knife River valley across the present-day Knife, Heart, and Cannonball River valleys to reach the south-oriented Missouri River (near the North-South Dakota border) is correct the present-day east-southeast oriented Knife River headwaters valley is probably younger than or about the same age as the former southeast-oriented melt water channel. The southeast-oriented former river channel contains glacial outwash sediments and is located near, but north and east of, the southwest margin of glacial erratic materials, which suggests glacial melt water may also have eroded the east-southeast oriented Knife River headwaters area.

3.8 Asymmetric Little Missouri River-Missouri River Drainage Divide

The Little Missouri-Cannonball River and the Little Missouri-Heart River drainage divides in southwest North Dakota are similar to the Little Missouri–Knife River and Little Missouri-Green (Heart) River drainage divides seen in figure 10 with the southeast- and east-oriented Cannonball and Heart Rivers headwaters also originating near the rim of the deep north-oriented Little Missouri River valley. This asymmetric drainage divide strongly suggests headward erosion of the north-oriented Little Missouri River valley captured east- or southeast-oriented flow moving to the Knife, Heart, and Cannonball River drainage basins. Further south in South Dakota the Little Missouri River valley is much shallower and Clausen (2017b) has described the drainage divide there. While not seen in figure 10, but illustrated in Clausen's paper numerous southeast-oriented and barbed tributaries join the Little Missouri River from the west and short northwest-oriented tributaries join the Little Missouri River from the east suggesting the north-oriented Little Missouri River valley eroded headward across multiple southeast-oriented flow channels.

4. Summary and Discussion

Map interpretation techniques when applied using detailed topographic maps provide evidence that large volumes of southeast-oriented water moving in closely spaced channels and sometimes even as sheets of water crossed western North and South Dakota drainage divides and eroded river valleys in an identifiable sequence. Headward erosion of the east-oriented White River valley first captured the southeast-oriented flow. Headward erosion of the northeast-oriented Bad River valley next captured the flow with headward erosion of the northeast-oriented Cheyenne River valley subsequently capturing the flow. Headward erosion of the Moreau River valley then captured southeast-oriented flow to the northeast-oriented Cheyenne River valley and Grand River valley headward erosion subsequently captured southeast-oriented flow to the Moreau River valley. Next headward erosion of the northeast-oriented Cedar Creek-Cannonball River valley captured the southeast-oriented flow and headward erosion of the north-northeast oriented Heart River valley segment captured southeast-oriented flow to the Cannonball River valley. Finally Knife River valley headward erosion captured southeast-oriented flow to the Heart River drainage basin and headward erosion of the north-oriented Little Missouri River valley beheaded southeast-oriented flow routes to the Knife, Heart, Cannonball, Grand, Moreau, and Cheyenne River drainage basins (in that order).

Western North and South Dakota drainage basins studied here are located between the Black Hills uplift and a continental ice sheet's southwest margin and each of the studied rivers flows from non-glaciated areas into glaciated areas. Most published regional geologic histories are based on the assumption that western North and South Dakota east-, northeast-, and north-oriented river valleys are pre-glacial in origin, which in turn leads to the assumption that continental ice sheets moved across a topographic surface similar to the modern day surface. In addition continental ice sheets as commonly described, while containing enough frozen water to produce (when they melt) massive ice-marginal melt water floods would have melted in ways that would not resulted in the headward erosion of deep east-, northeast-, and north-oriented valleys from glaciated areas into non-glaciated areas. Yet that is what topographic map evidence says happened. Something produced the massive southeast-oriented floods responsible for eroding the sequence of river valleys described here and large volumes of ice-marginal melt water flowing in a southeast direction between a continental ice sheet's southwest margin (to the north and east) and the Black Hills (to the southwest) is the most logical water source. There is no known pre-glacial source of water capable of eroding the region as described. If the southeast-oriented flow was continental ice sheet melt water then the Bell River system of north-oriented valleys is not pre-glacial in age as is commonly claimed, but instead was eroded late during a large North American continental ice sheet's history.

Further complicating the situation, North American continental ice sheets, as already mentioned and as commonly described, melted in ways that would have prevented a major north-oriented drainage system from flowing across their floors. Yet that is what map evidence says happened, which means the continental ice sheet that produced the massive southeast-oriented melt water floods must have had characteristics causing it to melt in ways the geologic literature has yet to describe. Perhaps glacial geologists have been too quick to reject White's (1972, 1988) deep erosion by continental ice sheets hypothesis. What would happen if the continental ice sheet that produced the massive southeast-oriented floods and which eroded the sequence of western North and South Dakota valleys described here had deeply eroded the North American continent so as to produce and occupy a deep “hole” as White predicted? If White was correct and a large continental ice sheet did create and occupy a deep “hole”, and if during that ice sheet’s melt down melt water rivers flowing on the ice sheet’s surface sliced deep ice-walled canyons into the ice sheet’s surface, then the valley erosion sequence described here can be explained.

North and east of the Missouri River in North and South Dakota, southwest Minnesota, southwest Manitoba and southern Saskatchewan is a network of poorly explained broad escarpment-bordered lowlands. An ice-walled and bedrock-floored canyon network that had been sliced into a decaying ice sheet’s surface would have left some evidence of its existence and those escarpment-bordered lowlands are probably that evidence. Of importance to this paper is the Missouri Escarpment (red dashed line in figure 1). The Missouri Escarpment is a 100-200 meter (328-656 foot) high northeast- and east-facing rise and probably is a remnant of an ice-walled and bedrock-floored canyon’s (named here as the Midcontinent Trench) southwest and west wall. In South Dakota the broad lowland at the Missouri Escarpment base is today drained by the south-oriented James River and is bordered on the east by the west-facing Prairie Coteau escarpment (east of figure 1), which is probably a remnant of the ice-walled and bedrock-floored canyon’s eastern wall. Melt water flowed from the mouth of this southeast- and south-oriented ice-walled and bedrock-floored canyon to southeast South Dakota and probably eroded the lower Missouri River valley.

Assuming similar North and South Dakota, southwest Minnesota, southwest Manitoba, and southern Saskatchewan escarpments also indicate former ice-walled and bedrock-floored canyon wall locations the melt down history of a continental ice sheet that had deeply eroded the North American continent can partially be reconstructed. Initially during the ice sheet’s melt down history water carving the Midcontinent Trench flowed in a south direction toward what is today southeast South Dakota’s southeast- and south-oriented Missouri River valley and water in an eastern ice-walled and bedrock-floored canyon flowed in a south direction along the present day North Dakota-Minnesota border to what is today the southeast-oriented Minnesota River valley and then to the south-oriented Mississippi River valley. As the Midcontinent Trench sliced through the ice sheet surface to become a bedrock-floored valley the elevation of its floor was lowered below the elevation of southeast-oriented ice-marginal melt water floods and at the same time the Midcontinent Trench gradually detached the ice sheet’s southwest margin. This created a situation where ice-marginal melt water floodwaters could spill across the ice sheet’s detached southwest margin and into the deeper Midcontinent Trench. These spillages probably first occurred near the south end of the ice sheet’s detached southwest margin (just east of where the White River now joins the Missouri River) and then progressed in a north and northwest direction as the ice sheet’s detached margin gradually decayed.

These spillages of ice-marginal melt water floodwaters across the ice sheet’s detached and decaying southwest margin occurred in a progressive sequence, which initiated erosion of the east-, northeast-, and north-oriented valleys as discussed in this paper. As the continental ice sheet decayed the network of ice-walled and bedrock-floored canyons chopped the ice sheet (at least in the area where the poorly explained escarpments now exist) into smaller detached ice sheets of various sizes and shapes with large melt water rivers flowing on floors of broad ice-walled and bedrock-floored canyons between them. As shorter routes to the Atlantic Ocean opened up, first through the present day Saint Lawrence River drainage basin and later to the Hudson Bay area and the Labrador Sea, headward erosion of the east-, northeast-, and north-oriented western North and South Dakota tributary valleys and their tributary valleys as described here (and also north-oriented Montana Missouri River tributary valleys seen in figure 1) systematically captured the massive southeast-oriented ice-marginal melt water floods moving between the Rocky Mountains and the ice sheet’s southwest margin and diverted that melt water northward to the Labrador Sea and in the process eroded the Bell River system of valleys. Finally, climate change, perhaps triggered by diversion of melt water floods from the south to the north, froze the north-oriented melt water rivers between the decaying and detached ice sheet masses to produce a new thinner and very different type of ice sheet.

In conclusion the sequence in which western North and Dakota river drainage basins formed has been determined by study of drainage divide crossings on detailed topographic maps and by use of map interpretation techniques involving the principle of cross cutting relationships. The determined drainage basin formation sequence strongly suggests the north-oriented drainage system, commonly referred to in the literature as the Bell River system, evolved late during the melt down of a thick North American continental ice sheet that had deeply eroded the continent’s surface and not during pre-glacial time as is commonly reported. A subsequent different and much thinner continental ice sheet then formed probably when rapid climate change caused melt water floods to freeze on the floors of deep ice-walled and bedrock-floored canyons that had chopped the decaying thick continental ice sheet up into many detached ice sheet masses. This subsequent thinner ice sheet was responsible for blocking the previously formed north-oriented melt water river valleys, which caused water in those valleys to overflow drainage divides so to create final segments of the present day North and South Dakota Missouri River course and also for depositing glacially transported sediments now found in some of the Bell River system valley segments.

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