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Solving a Perplexing Scenic and Sage Creek Basin Drainage History Problem, Pennington County, South Dakota, USA

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Abstract

The escarpment-surrounded Sage Creek and Scenic Basins open in southeast directions toward the northeast and east oriented White River valley while their floors drain in a northwest direction to the northeast oriented Cheyenne River. Located in the South Dakota Badlands region the Sage Creek and Scenic Basins present an intriguing drainage history problem where key puzzle pieces also include the White and Cheyenne River valleys. The puzzle solution requires massive amounts of southeast oriented water to first erode as deep headcuts the east oriented White River valley segment and the two southeast-oriented Sage Creek and Scenic Basins prior to Cheyenne River valley headward erosion. The northeast oriented White River valley segment upstream from the east oriented White River valley segment (and from the Sage Creek and Scenic Basin location) next eroded headward across southeast oriented flow and was initiated by southeast oriented water flowing from the Scenic Basin that turned in a northeast direction to reach the east oriented White River downstream valley segment. Erosion of the Sage Creek and Scenic Basin headcuts abruptly ended when headward erosion of the northeast oriented Cheyenne River valley beheaded southeast oriented flow routes leading to the then actively eroding Sage Creek and Scenic Basin heacuts. Cheyenne River valley headward erosion in a southwest direction next captured massive southeast oriented flow then still moving to the newly eroded northeast oriented White River valley segment. Northwest oriented drainage developed on the Sage Creek and Scenic Basin floors when a flood surge or temporary dam caused water to fill the White River valley and to spill in a northwest direction across low points on the then abandoned Sage Creek and Scenic Basin headcut rims. This spillage eroded narrow northwest oriented valleys and drained water filling the two basins to the Cheyenne River valley while most of the ponded water drained in an east direction down the White River valley. The White River valley, Sage Creek and Scenic Basins, and the Cheyenne River valley were eroded by enormous quantities of southeast oriented water that also deeply eroded the entire South Dakota Badlands region.

Keywords: Badlands National Park, Cheyenne River, headcut, South Dakota Badlands, White River

1. Introduction

Drainage histories for some regions can be worked out by simply studying bedrock geology and structures, valley orientations, elbows of capture, barbed tributaries, and regional wind and water gaps, however some drainage history problems are not intuitively obvious. One such drainage history problem is found in the Sage Creek and Scenic Basin area of Pennington County, South Dakota adjacent to and straddling Badlands National Park. The two basins open in a southeast direction toward the northeast and east oriented White River valley while they are drained by narrow northwest oriented valleys cut into an upland surface with water flowing to the northeast oriented Cheyenne River. This unusual drainage arrangement raises perplexing questions the most puzzling of which are: What eroded the Sage Creek and Scenic Basins and why do escarpments surrounding the Sage Creek and Scenic Basins open in a southeast direction toward the White River valley while the two basins are drained in a northwest direction to the Cheyenne River valley? Just as puzzling are why does the White River change its direction just east of the Sage Creek and Scenic Basins and how was the Cheyenne River valley able to erode headward across multiple southeast oriented drainage routes that once led to the northeast oriented White River valley?

The Geologic Map of South Dakota (Martin et al, 2004) shows the northeast oriented Cheyenne River valley west of the Sage Creek and Scenic Basins to be eroded in Cretaceous age Pierre Shale while the northeast and east oriented White River valley is cut primarily in Tertiary age White River sediments. The more detailed King and Raymond (1971) map shows escarpments surrounding the Scenic Basin to be cut in Tertiary Brule Formation (clay, silt, sand, and volcanic ash containing channel sandstones, clastic dikes, and chalcedony veinlets). Stoffer (2003) in a United States Geological Survey (USGS) Open-File Report, which focuses on the Sage Creek basin region, states, "In most areas around Badlands National Park the bedrock consists of flat lying (or nearly flat lying) sedimentary strata…." The only structure of significance according to Stoffer is a Sage Creek anticline/fault system that parallels the Sage Creek Basin northeast rim. Tertiary and Cretaceous sediments making up the Badlands regional bedrock are easily eroded and with the possible exception of along the Sage Creek Basin northeast rim drainage routes appear to have developed independent of geologic or structural controls.

Figure 1 is taken from the United States Geological Survey (USGS) National Map Viewer website and shows the Sage Creek Basin and Scenic Basin relationship to the South Dakota Black Hills and to the northeast oriented Cheyenne River (identified by the letter "C") and the northeast and east oriented White River (identified by the letter "W"). Arrows have been added to indicate present day drainage directions and lines have been added to emphasize the Sage Creek and Scenic Basin escarpment rims. As seen in figure 1 the Sage Creek and Scenic Basins open in southeast directions, yet are drained in northwest directions to the Cheyenne River and are located on the Cheyenne-White River drainage divide near the point where the White River turns from flowing in a northeast direction to flow in an east direction. The Black Hills seen along the figure 1 western edge are an isolated Rocky Mountain outlier. The Cheyenne River begins west of the Black Hills as a southeast oriented river and turns in a northeast direction as it flows around the uplift's southern point. The Belle Fourche River is an important Cheyenne River tributary (not seen in figure 1), which begins west of the Black Hills as a northeast oriented river and then turns in a southeast direction as it flows around the Black Hills uplift's northern point.

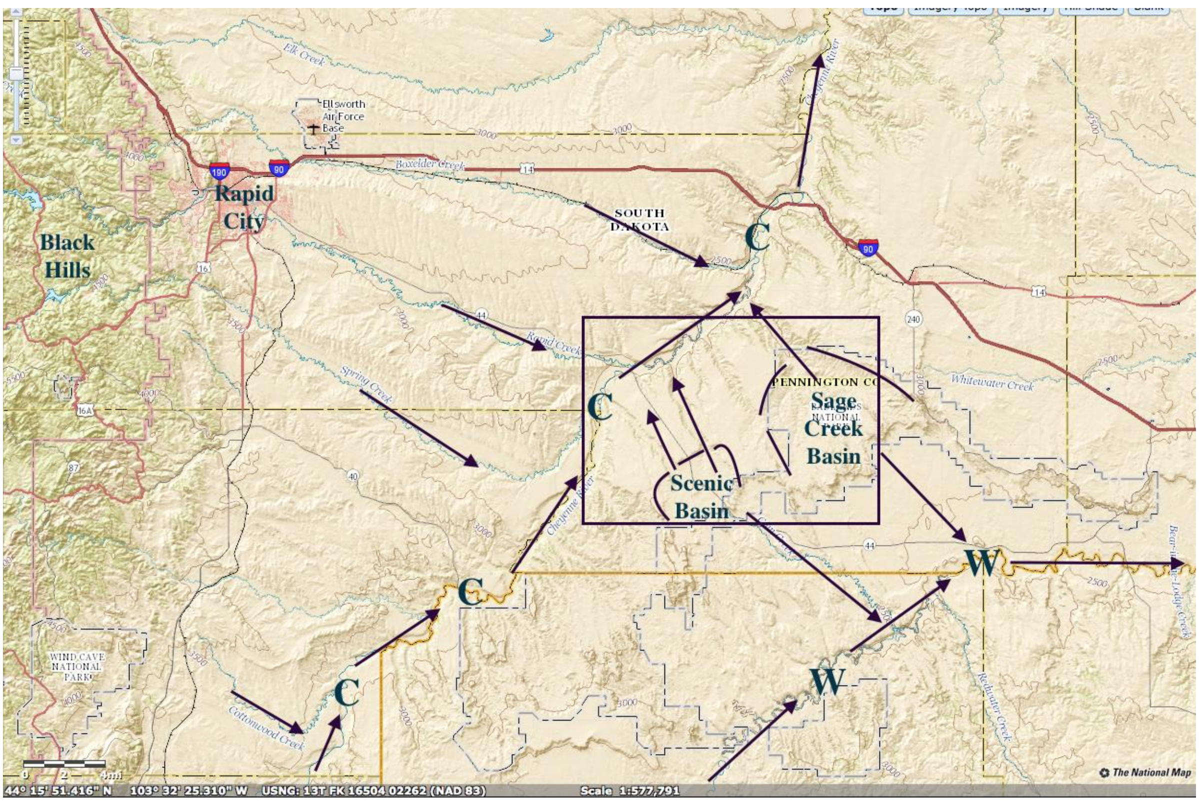

Figure 1. The Sage Creek and Scenic Basins are located east of the South Dakota Black Hills and are between the Cheyenne River (C) and the White River (W). Arrows indicate present day drainage directions. Scale bar in southwest corner represents 4 miles (6.4 kilometers)

Also important to this paper are surface alluvial deposits that Harksen (1966) named as the Medicine Root Gravel and that include alluvium Todd (1894) described as "an extensive deposit of boulders and gravel… found usually capping the high pinnacles of the Badlands between the Cheyenne and White Rivers." Eight years later Todd (1902) reported that at least some of the alluvial material was found capping areas in the White River drainage basin and had come from Black Hills source areas. While much of this alluvial material is in the form of lag deposits and was left after the easily eroded underlying bedrock surface had been lowered Harksen (1966) used *in situ* deposits to define the course of what he named the Medicine Root River. Harksen's Medicine Root River flowed in a southeast direction from the Black Hills across the modern day northeast oriented Cheyenne and White River valleys (a short distance south and west of the Sage Creek and Scenic Basin location) before turning in a northeast direction. While the nature of the Medicine Root River and its course can be debated Harksen's data provides convincing evidence that after Brule Formation deposition, but prior to erosion of the northeast oriented Cheyenne and White River valleys, large quantities of coarse-grained alluvium were transported from the Black Hills to the region east and south of the present day northeast and east oriented White River.

Cheyenne River tributaries seen in figure 1 flow in southeast directions from the Black Hills before joining the northeast oriented Cheyenne River as barbed tributaries and this relationship has caused a number of previous workers to suggest Cheyenne River valley headward erosion captured southeast oriented drainage that had been moving to the White River (e.g. Harkensen, 1966 and Stamm et al, 2013). Evidence for Cheyenne River capture of southeast oriented flow east of the Black Hills is overwhelming and suggests the Sage Creek and Scenic Basins were eroded before Cheyenne River headward erosion. If so, the two basins must have been eroded by large quantities of southeast oriented water flowing to a deep White River valley. Such a hypothesis explains why the Sage Creek and Scenic Basins open in a southeast direction, although it fails to explain why the basins are now drained in a northwest direction.

2. Method

The Sage Creek and Scenic escarpment-surrounded basins are a few of many intriguing landforms identified during the author's much larger Missouri River drainage basin landform origins research project. The Missouri River flows to the south oriented Mississippi River and drains much of the north central United States including most northern Great Plains and Rocky Mountain areas located east of the North American east-west continental divide and also some smaller areas in the Canadian provinces of Alberta and Saskatchewan. The author's multi-year Missouri River drainage basin landforms origins research project consisted of systematically studying detailed topographic maps of the entire Missouri River drainage basin and adjacent drainage basins to determine how major drainage divides within and surrounding North America's 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, and similar evidence to determine how the previous drainage routes were altered so as to become the drainage routes seen today. Unpublished evidence collected during that project suggested large floods of continental ice sheet melt water once flowed across the Wyoming Powder River Basin and around the Black Hills to reach the Sage Creek and Scenic Basin location. Approximately 550 unpublished and detailed project essays (or research notes) in blog format are on the geomorphologyresearch.com website (Clausen, 2011-2013).

Determining why the Sage Creek and Scenic Basins now open in a southeast direction, but are drained in a northwest direction was treated like a solvable puzzle. Each of the key puzzle pieces (i.e. the Sage Creek and Scenic Basins, the White River valley, the Cheyenne River valley, and the Sage Creek and Scenic Basin northwest drainage systems) was looked at separately to determine how that piece could develop in a way that fit with all other pieces. Topographic and geologic maps and literature descriptions of surface alluvial deposits were studied to determine how water, which flows in a downhill direction, could deposit the surface alluvium, erode the Sage Creek and Scenic Basins, erode the White River valley, erode the Cheyenne River valley, and yet create northwest oriented drainage systems on the Sage Creek and Scenic Basin floors. Also considered were orientations of southeast oriented streams draining as barbed tributaries from the Black Hills to the northeast oriented Cheyenne River. The method used was to conduct a thought experiment in which differing volumes of water were moved in various directions to erode the Sage Creek and Scenic Basins and White and Cheyenne River valleys and also to create the northwest oriented Sage Creek and Scenic Basin drainage systems. Based on the unpublished Missouri River drainage basin research project findings the possibility of immense melt water floods was considered. The thought experiment goal was to find the simplest way water could move across the region so as to create all puzzle pieces in a coherent sequence of erosion events that would result in the landforms seen today.

3. Results

3.1 What Eroded the Sage Creek and Scenic Basins?

The initial question asked in this study is what are the Sage Creek and Scenic Basins? Figure 2 was created using the USGS National Map Viewer website and illustrates the Sage Creek and Scenic Basins and their relationship to the northeast oriented Cheyenne River. Note how the divide between the northwest oriented drainage to the Cheyenne River and southeast oriented drainage to the White River is located southeast of the basins. The escarpment-surrounded Sage Creek and Scenic Basins both open in a southeast direction and their floors are today drained in a northwest direction through narrow northwest oriented valleys to the northeast oriented Cheyenne River, however the first step in determining the Sage Creek and Scenic Basin origins was to look at the basin shapes and to assume the basins had been eroded before the northwest oriented drainage systems developed. With that assumption shapes of the two basins suggest they probably originated as headcuts when large volumes of southeast oriented water flowed into the deep White River valley (not seen in figure 2), but that water must have come from somewhere and today no water source exists between the northeast oriented Cheyenne River valley and the two southeast oriented basins. If the two basins are not abandoned headcuts then spring sapping is the alternate mechanism usually proposed for escarpment retreat especially where no obvious surface water source exists (Higgins, 1990).

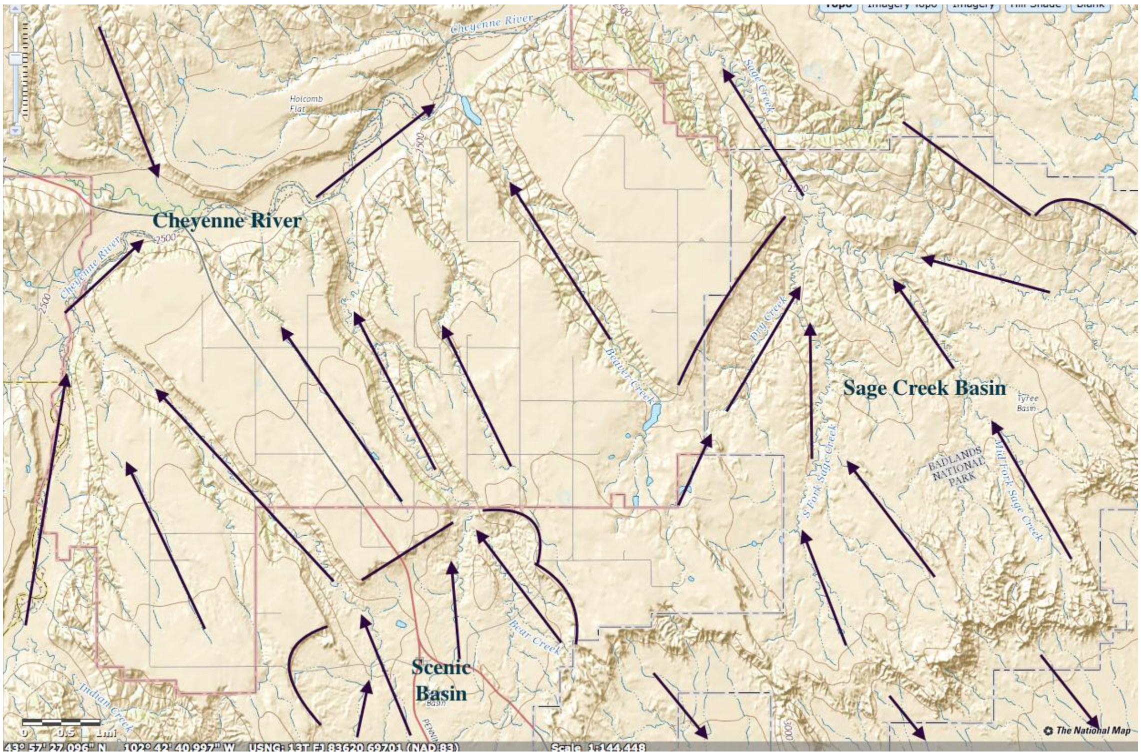

Figure 2. Map showing the Sage Creek and Scenic Basins and their relationship to the Cheyenne River. Lines have been added along escarpment rims surrounding the basins and arrows show present day drainage directions. The contour interval is 100 feet (30.5 meters) and the scale bar represents 1 mile (1.6 kilometers)

The American Geological Institute 1972 *Glossary of Geology* defines a headcut as being “a vertical face or drop on the bed of a stream channel, occurring at a knickpoint.” Small-scale and temporarily abandoned headcuts are found throughout the South Dakota Badlands region and can be used for comparison purposes. The Badlands of South Dakota according to Howard (1999) “originated due to downcutting by the White River through Cenozoic shale and mudstone. These badlands have gradually advanced over thousands of years as a steep erosional front consuming a rolling, grassy upland.” Howard suggested erosion of at least some of the smaller regional headcuts was “triggered by late Pleistocene downcutting of the master drainage, probably aided by a drier Holocene climate that has reduced vegetation cover.” During periods of heavy rainfall water moving on visible flow routes still erodes most of the smaller South Dakota Badlands headcuts. However, if the Sage Creek and Scenic Basins are abandoned headcuts they were eroded by large volumes of water moving along flow routes that no longer exist. The best examples of previously recognized abandoned headcuts are found in the Channel Scabland area of Washington State (USA). Figure 3 shows two of several headcuts found at Dry Falls, Bretz (1928) described Dry Falls as an abandoned cataract formed during an immense glacial flood. Baker (1978) describes how the Dry Falls headcut eroded headward through basalt bedrock for 32 kilometers before being abandoned.

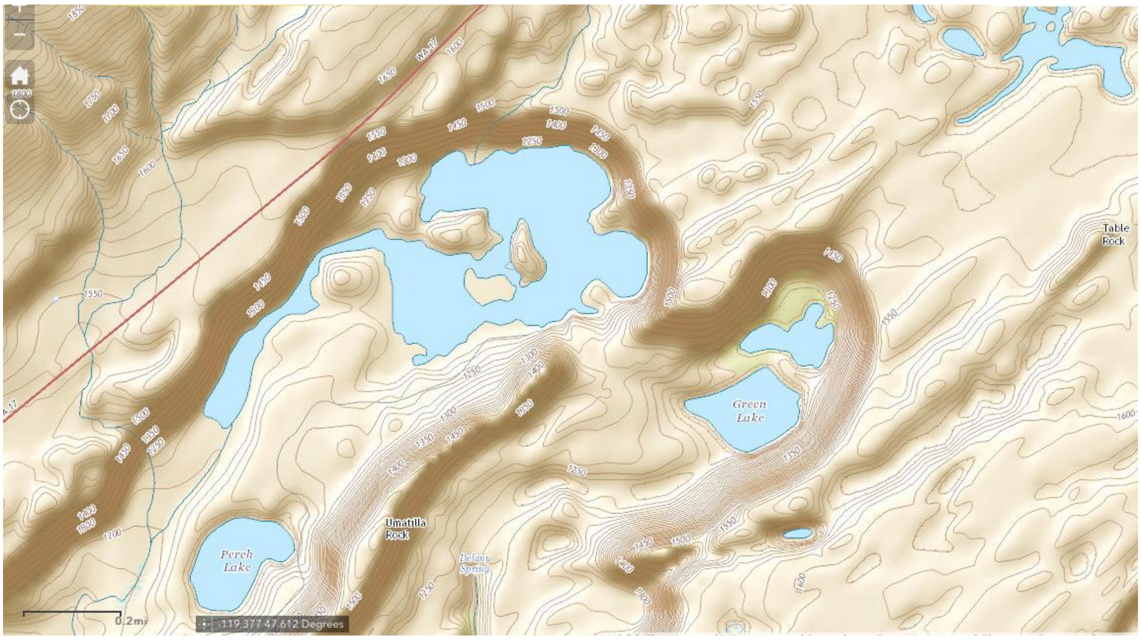

Figure 3. Topographic map taken from the United States Geological Survey National Map website showing two abandoned headcuts at the larger Dry Falls area in Washington State. Scale bar represents .2 miles (.32 kilometers) and contour interval is 50 feet (15.24 meters)

Figure 4 shows a detailed topographic map of escarpments bounding the Scenic Basin northwest end at a scale similar, but not identical to that used in figure 3. Without the two narrow northwest oriented valleys cut into the southeast-facing escarpment the Scenic Basin has some similarities in shape with the Dry Falls headcuts, but is somewhat larger than the two Dry Falls headcuts seen in figure 3 (the entire Dry Falls cataract area is larger than the Scenic Basin). The Dry Falls headcut height is 400 feet (120 meters) while the Scenic Basin escarpment height is 120 feet (37 meters). Differences in bedrock characteristics and resistance to erosion probably account for differences seen between figures 3 and 4. For example, there are no plunge pools at the bases of either the Sage Creek or the Scenic Basin escarpments, yet evidence of plunge pools is not seen at the base of many small-scale badlands headcuts. In addition northwest oriented drainage on the Sage Creek and Scenic Basin floors indicates one or more additional erosion events took place in both the Sage Creek and Scenic Basins after the southeast oriented flow had ended (and the headcuts had been abandoned), although no evidence of further erosion events is seen at Dry Falls, where floors of the escarpment-surrounded basins are drained in the same southwest direction that the Dry Falls escarpment-surrounded basins open. Also upstream from the Dry Falls headcuts linear grooves can be seen eroded into the basalt bedrock. While evidence for similar grooves upstream from the Sage Creek and Scenic Basin headcuts is not seen in figures 2 or 4 it is possible the narrow northwest oriented valleys were eroded headward from the Cheyenne River valley along alignments of similar grooves.

If the Sage Creek and Scenic Basins are not abandoned headcuts then something else eroded them. Spring sapping is often claimed to be the escarpment retreat mechanism where no visible surface water source exists. But spring sapping does not create escarpments and in horizontal sediments can only provide a retreat mechanism for escarpments that already exist. While headward erosion of the White River valley did create an escarpment face or at least a steep slope from which the Sage Creek and Scenic Basin escarpments could have retreated there is no reason why spring sapping would cause that escarpment face to retreat in a northwest direction so as to produce the escarpment-surrounded Sage Creek and Scenic Basin shapes seen in figures 2 and 4. Another problem posed by the spring sapping hypothesis is how was debris from the retreating escarpment removed. The two basins are drained in a northwest direction by streams that do not now flow along the escarpment bases. Removal of debris caused by spring sapping adds significant complications to an already complicated drainage history. In addition the spring sapping hypothesis has a significant ground water source problem, almost as serious as the abandoned headcut hypothesis water source problem. To cause Sage Creek and Scenic Basin escarpment retreat ground water must be moving (or have moved) in a southeast direction, yet the surface drainage in both basins is in a northwest direction and the northeast oriented Cheyenne River valley floor is lower in elevation than either of the two basin floors. The spring sapping hypothesis results in a significantly more complicated drainage history puzzle solution than the abandoned headcut hypothesis and is rejected for that reason.

The failure of spring sapping to satisfactorily explain the Sage Creek and Scenic Basins means large volumes of southeast oriented water flowing into the deep northeast and east oriented White River valley most likely eroded the two basins. Sage Creek and Scenic Basin widths suggest enormous volumes of southeast oriented water flowed across the region with the most concentrated flow moving across the retreating Sage Creek and Scenic Basin headcut faces to the White River valley. If so the east oriented White River valley already existed or was also being eroded when the Sage Creek and Scenic Basins erosion occurred, but the northeast oriented Cheyenne River valley had not yet been eroded. Also, if the Sage Creek and Scenic Basins are abandoned headcuts something abruptly ended their erosion, which was most likely capture of the southeast oriented flow by headward erosion of the deep northeast oriented Cheyenne River valley. Following capture of the southeast oriented flow (by the Cheyenne River valley) an additional erosion event must have created the basin floor northwest oriented drainage systems and the northwest oriented valleys that now cut the southeast-facing escarpments. The problem of how running water eroded northwest oriented valleys across high escarpments and captured drainage on the floors of the two abandoned southeast-facing basins is left unanswered here and is addressed in section 3.4.

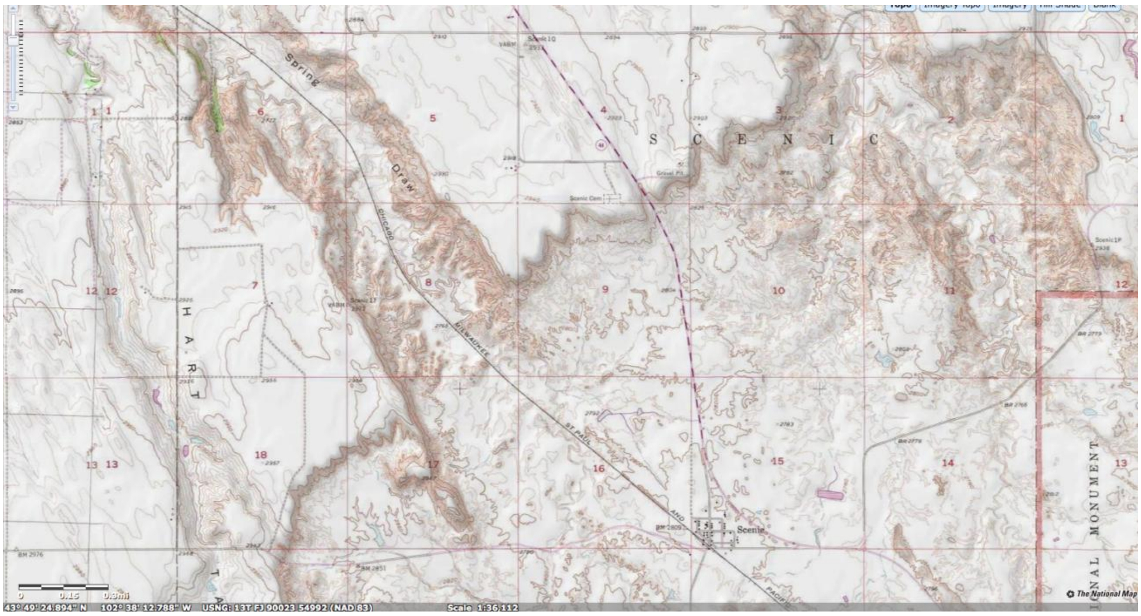

Figure 4. USGS topographic map showing escarpments at the Scenic Basin northeast end. Scale bar represents .3 miles (.48 kilometers) and contour interval is 10 feet (3.05 meters).

3.2 Why does the White River Change Its Direction?

The Sage Creek and Scenic Basin headcuts eroded headward in a northwest direction from what at that time must have been a deep east oriented White River valley, which probably eroded headward into the region as a deep headcut similar to the Sage Creek and Scenic Basin headcuts. In their report on mineral resources of the South Dakota Pine Ridge Indian Reservation Raymond et al (1976) show hypothesized pre-Cheyenne River (and also pre-White River) drainage routes coming from the Black Hills area that deposited Medicine Root and Thin Elk gravels in regions south and east of today's White River. The high level Thin Elk gravels were deposited by southeast oriented drainage that crossed the present day northeast oriented White River valley and then continued in a southeast direction. The river that deposited the Medicine Root gravels at somewhat lower elevations, but still 650 feet (200 meters) above today's White River, flowed in a southeast direction across the modern day northeast oriented White River valley before gradually turning in a northeast direction toward what is now the east oriented White River valley. The shift of drainage direction between Thin Elk gravel and Medicine Root gravel deposition suggests the southeast oriented drainage was being captured and diverted in a northeast direction as the deep White River valley eroded headward in a west direction toward the present day White River direction change.

The White River today flows to the Missouri River valley, which according to Todd (1914) was eroded along a continental ice sheet margin. What triggered headward erosion of the deep east oriented White River valley is not the subject of this paper, but was probably related in some way to Missouri River valley headward erosion events. Once initiated the east oriented White River valley most likely eroded headward across southeast oriented ice-marginal melt water flow with north oriented tributary valleys being eroded by yet to be captured southeast oriented water that was flowing west of the actively eroding east oriented White River valley head. Such water reached areas south of the actively eroding White River valley and then had to turn in a north direction to reach the much deeper White River valley. Evidence for such captures is found in the high elevation Medicine Root River course mapped by Harksen (1966) and shown by Raymond et al (1976) that crossed the present day northeast oriented White River valley in a southeast direction and then turned in a northeast direction to flow toward the east oriented White River valley. Additional evidence is found where the White River direction now turns from flowing in a northeast direction to flow in an east direction. As seen in figure 1 the Scenic Basin opens toward the northeast oriented White River valley upstream (or southwest) from where its direction changes and the water that eroded the Scenic Basin must have turned from flowing in a southeast direction to flow in a northeast direction so as to reach the end of the deep east oriented White River valley.

Headward erosion of the large southeast oriented Sage Creek and Scenic Basin headcuts abruptly ended when headward erosion of the northeast oriented Cheyenne River valley captured the southeast flow. However, southeast oriented flow continued across the region south and west of the actively eroding Cheyenne River valley head and still could be captured by the actively eroding northeast oriented White River valley head. The White River direction change was initiated when water eroding the Scenic Basin turned in a northeast direction to reach the deep east oriented White River valley and was maintained because the actively eroding White River valley head was still capturing southeast oriented flow that was moving south and west of the actively eroding Cheyenne River valley head. In this manner the White River valley was able to erode headward in a southwest direction before Cheyenne River valley headward erosion captured the flow. This interpretation requires that headward erosion of the northeast oriented White River valley segment occurred at least slightly in advance of Cheyenne River valley headward erosion and also requires enormous volumes of water to erode both deep valleys during the same erosion event.

3.3 How did the Cheyenne River Valley Erode Across Southeast Oriented Drainage?

Bishop (1995) argues, "The key process in stream capture, namely, drainage head retreat, is difficult to envisage as a normal part of drainage net evolution…. Stream capture may therefore be a relatively rare event in drainage net evolution…[and] should not be routinely invoked in interpretations of long-term drainage evolution." Yet the northeast oriented Cheyenne River east of the Black Hills (seen in figure 1) did not exist at the time large volumes of southeast oriented water eroded the Sage Creek and Scenic Basins. What must have been an abrupt abandonment of southeast oriented flow to the Sage Creek and Scenic Basins suggests Cheyenne River valley headward erosion captured the southeast oriented flow eroding the two headcuts. Further, southeast oriented Cheyenne River tributaries seen in figure 1 (and a more detailed map shows even more) suggest the Cheyenne River valley eroded headward across multiple southeast oriented drainage routes moving water to the newly eroded northeast oriented White River valley. Something abnormal was enabling the Cheyenne River valley to erode headward across the region.

Like the White River the Cheyenne River is today a Missouri River tributary and events related to development of the ice-marginal Missouri River valley may in some way have helped trigger Cheyenne River valley headward erosion. However other possibilities exist. Todd (1914) and others have interpreted the northeast oriented Cheyenne River valley to have been part of a pre-glacial north oriented drainage system leading to Hudson Bay. If so headward erosion of the Cheyenne River valley may have begun in pre-glacial time, but drainage at that time should have developed in a normal fashion, making stream capture difficult to achieve. However, more recent literature includes other possibilities. Zaprowski et al (2001) and Zaprowski and Floyd (2005) suggest the possibility that glacial isostatic rebound may have played a role in Cheyenne River valley erosion. In unpublished research notes (or essays) available in blog format (Clausen, 2011-2013) suggests Cheyenne River valley headward erosion may have been triggered when north oriented drainage routes developed on a decaying ice sheet floor and captured southeast oriented ice-marginal drainage. The latter two hypotheses suggest the Cheyenne River drainage system may have developed when a continental ice sheet was located nearby and that large quantities of glacial melt water may have been moving in a southeast direction across the adjacent ice marginal regions.

Whenever and however headward erosion of the deep northeast oriented Cheyenne valley was initiated the same erosion processes that eroded the southeast oriented Sage Creek and Scenic Basin headcuts and the northeast oriented White River valley segment also were responsible for Cheyenne River valley headward erosion. Bedrock in the region is nearly flat lying and easily eroded and the size of the Sage Creek and Scenic Basin headcuts indicates massive amounts of southeast oriented water eroded them. Under such conditions Sage Creek and Scenic Basin headward erosion was rapid. How rapid is not known, but the time interval between when headward erosion of the headcuts from the deep White River valley began and when floodwaters ceased to erode the headcuts was short. The short time interval between the initiation and abandonment of the Sage Creek and Scenic Basin headcuts suggests the time interval between headward erosion of the northeast oriented White River valley and the subsequent headward erosion of the northeast oriented Cheyenne River valley was also short. Whatever its source the flood event that eroded the Sage Creek and Scenic Basins also eroded both the northeast oriented White River valley and the northeast oriented Cheyenne River valley in addition to deeply eroding the entire regional bedrock surface.

The large volumes of water that eroded the northeast oriented Cheyenne River valley were from the same flood event(s) that also eroded the northeast oriented White River valley. Southeast oriented streams flowing today to the northeast oriented Cheyenne River as barbed tributaries provide evidence of multiple captures, but also pose an unanswered question. Today many of those tributaries head at high elevations in the Black Hills uplift area and their discharges, even during the largest known historic flood events, are not large enough to account for the deep regional erosion and the very significant drainage rearrangement that occurred as the northeast oriented White River and Cheyenne River valleys were eroded headward across the region. Volumes of water moving from the Black Hills uplift area across the figure 1 map area must have been many times greater than they are today. Where that water came from is beyond the scope of this paper, but may in some way be related to the presence of a nearby continental ice sheet.

3.4 Why are the Sage Creek and Scenic Basins now drained in a Northwest Direction?

Perhaps the most confusing evidence discussed here is the northwest oriented drainage on the southeast-facing and escarpment-surrounded Sage Creek and Scenic Basin floors. Headward erosion of the northeast oriented Cheyenne River valley created the Cheyenne-White River drainage divide, which initially was located along the southeast-facing Sage Creek and Scenic Basin escarpment rims. Clausen (2017) described how headward erosion of deep valleys across low gradient flood formed anastomosing channels in southeast Pennsylvania caused reversals of flow on downstream ends of the beheaded channels, however while such a mechanism may account for some northwest oriented tributaries to the northeast oriented White and Cheyenne River valleys it does not explain how the reversed flow could erode deep reversed flow valleys into a headcut escarpment face and completely reverse all drainage on the headcut basin floor. Yet that is what drainage patterns seen in figure 2 show must have happened.

The simplest solution to the Sage Creek and Scenic Basin northwest oriented drainage problem is the White River valley including the Sage Creek and Scenic Basins was temporarily filled with water to a high enough level that water spilled in a northwest direction across the newly formed drainage divide into the Cheyenne River valley. Landslides and/or ice jams could have created temporary dams in what at that time was still a newly eroded downstream east-oriented White River valley or a surge of flood water may have moved down the newly eroded upstream and northeast oriented White River valley. If the deep White River valley was temporarily filled to overflowing the Sage Creek and Scenic Basin headcuts provided low points along the Cheyenne-White River drainage divide where water could spill in a northwest direction into the Cheyenne River valley. Such spillage could rapidly erode narrow northwest oriented valleys into the easily eroded bedrock and drain water filling the two southeast-facing basins to the Cheyenne River valley while at the same time the White River valley was rapidly draining most of the ponded floodwater.

4. Conclusions

Headward erosion of deep valleys into a region being crossed by vast quantities of southeast oriented water solves the perplexing drainage history problem that the Sage Creek and Scenic Basins, White River valley, Cheyenne River valley, and related features pose. First enormous volumes of southeast oriented water eroded the east oriented White River valley segment headward into the region and then the large southeast facing Sage Creek and Scenic Basins headcuts eroded headward from that east oriented White River valley in a northwest direction. Southeast oriented water eroding the Scenic Basin turned in a northeast direction to initiate the northeast oriented White River valley, which then continued to erode headward in a southwest direction across the southeast oriented flood flow. Cheyenne River valley headward erosion next captured the southeast oriented flow that had been eroding the Sage Creek and Scenic Basin headcuts causing the two large headcuts to become abandoned escarpment-surrounded basins opening in southeast directions toward the White River valley.

Headward erosion of the northeast oriented Cheyenne River valley then proceeded in a southwest direction as it captured southeast oriented flow that was moving to the then newly eroded northeast oriented White River valley. Ponding of water in the White River valley, due either to a flood surge or to some type of temporary blockage, next enabled water to spill across the newly created Cheyenne-White River drainage divide at Sage Creek and Scenic Basin low points and to drain the two basins in a northwest direction while most of the ponded water drained down the White River valley.

The Sage Creek and Scenic Basin drainage history problem solution presented here requires tremendous volumes of southeast oriented water to have flowed across the region at the time the White River valley, Sage Creek and Scenic Basins, and the Cheyenne River valleys were eroded. These vast quantities of water also deeply eroded the entire region, although the flood source cannot be determined from the Sage Creek and Scenic Basin area landform evidence. Further, the landform evidence as determined from topographic maps cannot be used to determine when the regional erosion occurred, although it can be used to determine that the White River valley, Sage Creek and Scenic Basins, and Cheyenne River valley were all eroded during the same deep erosion event. The lack of study region evidence for significant subsequent erosion suggests the immense flood(s) occurred late in geologic time, probably in the late Cenozoic at a time when the southwest margin of a large North American ice sheet was nearby and immense volumes of melt water were flowing in a southeast direction along that continental ice sheet's southwest margin.

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