CENOZOIC GEOMORPHIC EVOLUTION OF FLUVIAL LANDSCAPES IN THE BLACK HILLS, SD

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ABSTRACT

Watershed boundary adjustments have occurred throughout the Black Hills in response to post-Laramide fluvial incision within and peripheral to the Black Hills. Geologic field mapping and stream profile analyses have led to identification of two broad knickzones that separate three distinct fluvial geomorphic surfaces. The uppermost relict surface encompasses the central highlands of the uplift and records post-Laramide tectonic quiescence. Erosion of this surface extended throughout Oligocene time and has been paired with extensive deposition of the White River Group. The upper knickzone represents the extent of fluvial incision into the relict landscape and subsequent establishment of an intermediate surface below the upper knickzone. This period has been paired with sequences of Pliocene (~5.0 - 3.6 Ma) coarse-grained river gravels. Lower knickzone migration and incision into the intermediate surface occurred with the onset of crustal response to Pleistocene glaciation ~2.5-1.5 Ma. During this modern stage of erosion, glacio-isostatic surface adjustments in ice-peripheral regions altered river courses in the northern Great Plains from northeasterly to easterly flow. Associated river entrenchment of the modern erosion phase created multiple incision waves and terrace systems and drove formation of the present Cheyenne River (~660 Ka) which captured river flow out of the Black Hills. Numerous stream piracies have been preserved in the topography of the Black Hills, including evidence of reversed flow directions and abandoned channels. Watershed boundaries have adjusted to these tectonic and glacial drivers leaving evidence of a landscape that is out of equilibrium with modern processes.

Keywords

fluvial processes, knickzones, piracy, terraces

INTRODUCTION

Numerous studies of late Tertiary (~30 Ma to present) geologic history of the Black Hills have identified geomorphic features that define portions of the complex evolutionary processes that have dominated local landscape development (Darton 1909; Darton and Paige 1925; Fillman 1929; Plumley 1948; Harksen and Macdonald 1969; Kempton 1980; Straffin 1993 Gries 1996; Rahn 1996; Zaprowski 2001; Zaprowski et al. 2001; Stamm et al. 2013). These features include isolated Tertiary sediments at high-elevation that unconformably overly older tilted bedrock, large areas at high-elevation characterized by low local relief and disproportionally wide meandering headwater stream valleys, canyons and steep topography along the margins of the uplift, and several strath terrace benches in the lower elevations of incised watersheds. Primary conclusions of these studies indicated: 1) post-uplift deposition and subsequent removal of sediments in the Black Hills occurred in the Tertiary (~30 Ma to ~3.6 Ma) (Darton 1909; Darton and Paige 1925; Plumley 1948; Harksen and Macdonald 1969; Gries 1996), 2) the existence of an erosional surface at high elevation (Fillman 1929), 3) evidence for recent (late Tertiary through Quaternary) large-scale fluvial incision (Fillman 1929; Harksen and Macdonald 1969; Gries 1996; Rahn 1996), 4) association between these Black Hills features and post ~5 Ma widespread rejuvenation of the Northern Rocky Mountain uplift (Darton and Paige 1925; Harksen and Macdonald 1969; Gries 1996), and 5) glacial effects on Quaternary (~660 Ka) stream terrace formation (Kempton 1980; Harksen and Macdonald 1969; Zaprowski 2001; Zaprowski et al. 2001; Stamm et al. 2013). However, unresolved complexities include: 1) the magnitude, cause, and number of fluvial incision events, 2) the relationship between Tertiary depositional systems, potential erosional surfaces remaining, and fluvial incision events, and 3) the timing of these erosional features or incision events.

Timing of events are somewhat constrained by two fossil-based age groups of Tertiary sediments ~30 Ma and ~3.6 Ma (Darton and Paige 1925; Green and Gries 1963; Aho 1974; Redden and DeWitt 2008), however, these two separate lithologic units have not been well distinguished on maps and are often classified incorrectly. The most definitive age comes from a fossil of a right astragalus from a Pliocene camel *Gigantocamelus spatulus* (D. Pagnac, pers comm), excavated from a gravel pit in late Tertiary deposits in the Skyline Drive area of Rapid City (Green and Gries 1963). The weathering on the fossil suggested it was deposited, fossilized and subject to one or more fluvial reworking events allowing dating to at least the middle Pliocene (~3.6 Ma). Local relief of these deposits (~1150 m) exceeds reported thickness (up to 365 m) throughout the Northern Great Plains (Gries 1996). These sparse lines of evidence have resulted in an incomplete understanding of the late Tertiary (~30 Ma to present) geomorphic history of the Black Hills.

This paper investigates specific events defined by geomorphic drivers that have resulted in profound and significant alterations to the fluvial landscape of the Black Hills. Detailed fluvial analyses, including utilization of a novel method to analyze watersheds, have revealed two broad knickzone fronts in Black Hills streams. These knickzones, defined as broad convexities in channel profiles that occur over large distances, define an upper and lower bounding surface between major geomorphic events. Knickzones are subtle and undetectable through field observation (Zaprowski 2001) and are distinguished from a knickpoint, commonly defined as an abrupt change in stream slope identified by rapids or a waterfall (Whipple and Tucker 1999) often resulting from resistant bedrock (Ray and Rahn 1997).

METHODS

Through comprehensive fluvial analyses using 10-m digital elevation data from the United States Geological Survey National Elevation Dataset we evaluated the 19 major watersheds draining the Black Hills (Figure 1) and conducted de-

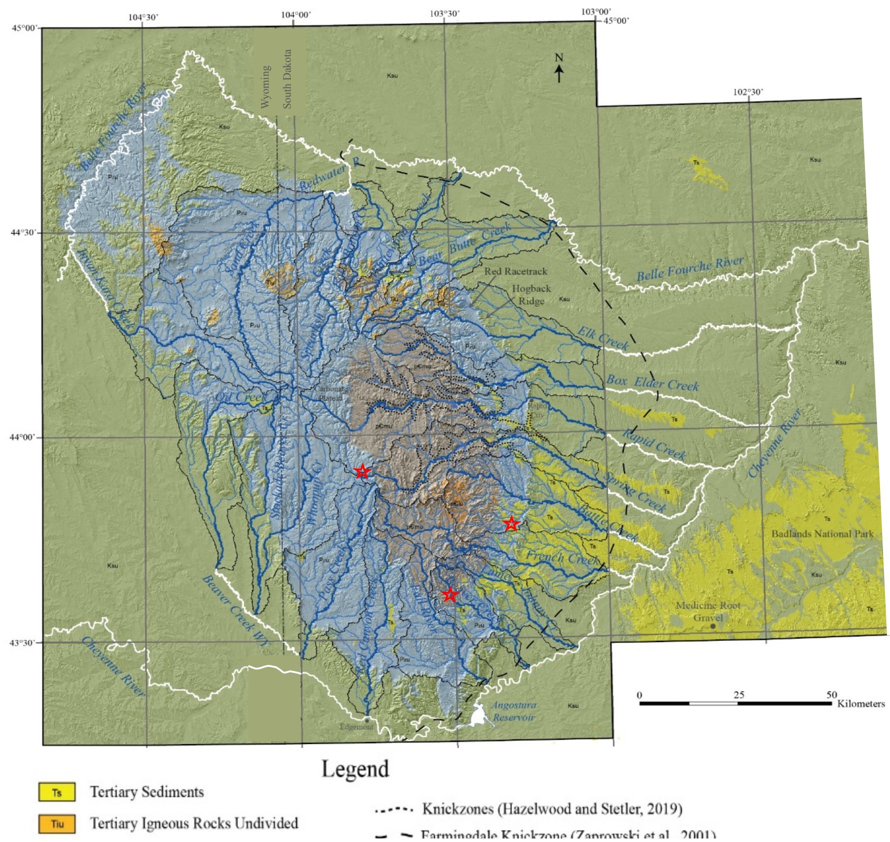

Figure 1. Shaded relief 10-m DEM of the Black Hills area showing generalized geology, topographic features, studied watersheds, and all profiled channels. Extent of the previously mapped knickzone fronts, including the Farmingdale knickzone (Zaprowski 2001), and the upper and lower knickzone fronts (Hazelwood and Stetler 2019) are dashed lines. Blue channels were those used in the 19 enhanced watershed-based analyses. Red stars represent the stream piracy events discussed below. Modified from Hazelwood (2019).

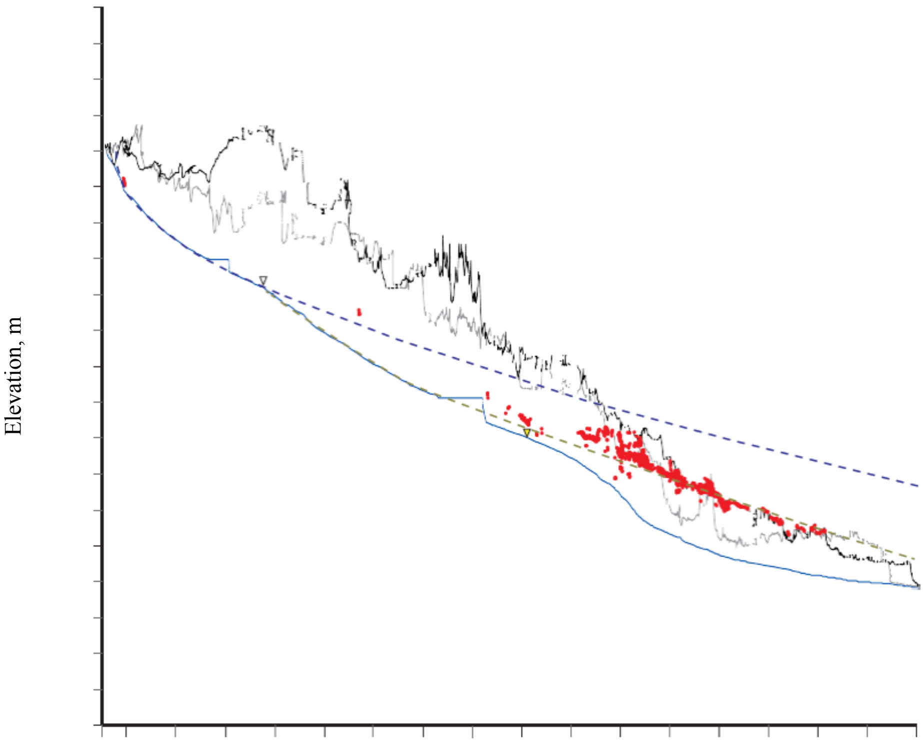

Figure 2. Enhanced longitudinal profile for the Rapid Creek watershed produced using watershed decomposition (Hazelwood and Stetler 2016). Similar profiles were generated for all 19 watersheds in the study (Hazelwood 2019). Knickzones are identified by the inverted triangles, and the tops of the Tertiary sediments are shown in red.

tailed field investigation of all Tertiary deposits (Hazelwood and Stetler 2016). Enhanced longitudinal profiles (Hazelwood and Stetler 2019) were generated for all trunk channels and tributaries (Figure 2) that contained all geomorphic characteristics of the watershed. These were used to identify past changes in fluvial architecture, piracy locations, and abandonment of previously balanced flow networks. These results have led to a better understanding of the driving forces, processes, and timing of major geomorphic alterations that have occurred in the post-Laramide fluvial landscape of the Black Hills.

RESULTS

Two distinct knickzone fronts, an upper and a lower zone, were identified by evaluating the 295 individual knickzones identified within all 19 major watersheds. The upper knickzone was delineated by 160 individual knickzones that were located predominantly in the upstream reaches of each watershed. These mostly occurred across Paleozoic and Precambrian metasedimentary units. Underlying bedrock was steeply-dipping (~70° to ~90°) metamorphic lithologies and shallow-dipping (~1° to ~3°) Paleozoic strata. Knickzone elevations ranged between ~1450 and ~1980 m and showed a normal distribution around a median elevation of ~ 1700 m across all 19 watersheds.

The lower knickzone was delineated by 135 knickzones that occurred in the lower trunk channel of every watershed, but were most pronounced in north and east draining streams. Approximately 8% of total occurrences were located just upstream of the lithological contact between Paleozoic sedimentary and Precambrian metasedimentary bedrock. The remaining ~70% occurred over moderately dipping (~10° to ~15°) Paleozoic sedimentary units in the peripheral Black Hills. In all cases, the lower incision front had penetrated the Cretaceous hogback ridge.

In addition, the Farmingdale knickzone front (Zaprowski 2001) was identified in the regional longitudinal profile of the study area (Figure 1) and occurred inboard of the Cheyenne and Belle Fourche Rivers between Edgemont northward to roughly Spearfish, SD.

The occurrence of both the upper and lower knickzones at uniform elevations across all channels (Figure 1) confirmed that they define propagating fronts of transient stream incision in response to altered fluvial bounding conditions (Hazelwood and Stetler 2019). This indicates that the present Black Hills topography represents a non-equilibrium landscape containing a long-lived slowly eroding relict landscape at high elevation (upstream of upper knickzones), an intermediate landscape at lower elevation (upstream of lower knickzones), and a modern landscape downstream of the lower knickzone. The two knickzones represent the mobile boundary between relict, intermediate, and modern landscape development phases of adjustment which can be defined from the extent of these features throughout the Black Hills.

During extrapolation of erosion fronts, we discovered several stream piracy events. These piracy locations provided additional and significant insight into drainage pattern changes that have occurred throughout the major landscape adjustment periods. Some of the prominent examples include a piracy between Battle and French Creeks at the intersection of Highway 16A and Wildlife Loop Road in Custer County, SD (Figure 1, eastern red star), abandonment of an east to west stream channel near Pringle, SD (Figure 1, southern red star), and a watershed boundary shift via stream capture of Spring Creek by Whoopup Creek (Figure 1, western red star).

At Highway 16 – Wildlife Loop Road, an abandoned valley sits ~20 m higher than the present-day channel, marking the location of the capture (Figure 3). The captured area was originally part of the French Creek watershed which drained to the southeast. Currently, it is part of the Battle Creek watershed draining to the northeast, a change in flow-direction of ~80°. This piracy was studied in detail by reproducing its pre-piracy state in the longitudinal profile of French Creek and comparing it to its modern position in the profile of Battle Creek (Figure 3). This was accomplished by constructing an artificial digital elevation model (DEM) dam at the piracy location and producing a longitudinal profile for both the dammed and undammed versions of the DEM. The subsequent longitudinal profile (Figure 3) indicated that the capture occurred in an actively adjusting lower knickzone reach that was moving upstream through the French Creek watershed. The lower knickzone in the French Creek watershed was outpaced by the lower knickzone in the Battle Creek watershed, which reached the watershed boundary of French Creek and captured the area at the present piracy location. Figure 4 is a Google Earth image of the capture zone using 3x vertical exaggeration. The original and abandoned channel to the southeast is clearly identifiable at a higher elevation than the current stream valley flowing northeast. The profile details the ~20 m elevation difference between the two channels.

Many other similar piracies exist, mainly in the eastern flanks of the Black Hills and were observed to directly correlate with the lower knickzone front. Many of those piracies in the eastern Black Hills, including the French Creek piracy, were associated with a significant change in drainage flow direction from southeast to northeast (~80°). This same northward shift was identified in Box Elder and Rapid Creek, but stream piracy evidence was missing, presumably due to erosion and channel adjustment processes.

Another piracy example is an abandoned eastward flowing stream valley along the intermediate-modern landscape boundary (Figure 3, southern red star). The abandoned stream valley meandered ~eastward from a flat area west of Pringle, SD, into the "Red Racetrack" in Wind Cave National Park, crossing what is now

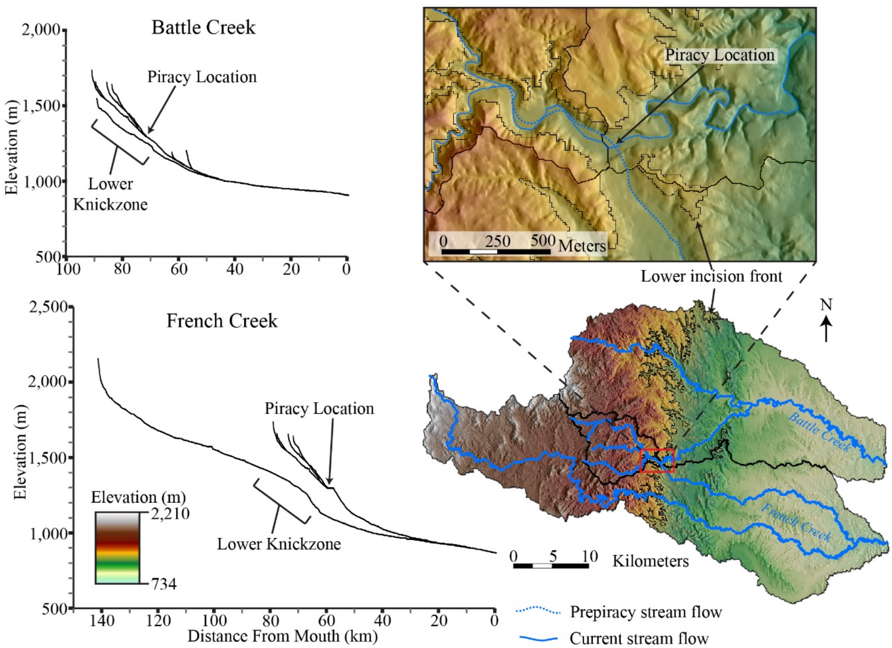

Figure 3. Piracy area between French and Battle Creeks (location in Figure 1, eastern red star) and associated longitudinal profiles. The pirated area is included in both profiles, showing its association with the lower incision front. The pirated area was originally part of the French Creek watershed, but is now part of the Battle Creek watershed and now represents a drastic (~80°) shift in flow direction to the north.

the modern southward flowing trunk channels of Fall River and Beaver Creek (Figure 5). The headwaters of Fall River and Beaver Creek would have joined with this abandoned stream valley during the intermediate landscape stage, making sharp turns to the east instead of continuing southward as they do today. Incision into the intermediate landscape has since caused abandonment of this east to west route in favor of more direct and southward routes of the affected streams to the Cheyenne River. These stream piracies indicate that many drainage rearrangements were associated with the lower knickzone front, and that drainage patterns on the intermediate landscape were potentially vastly different than drainage patterns of the modern landscape.

The only piracy event identified on the relict landscape was located between the eastward draining Spring Creek and westward draining Whoopup Creek near the center of the relict landscape (Figure 1, western red star). This piracy occurred via drastic changes in channel routes in the headwaters of Spring Creek. Prior to the capture event, channels that are currently in the eastward flowing Spring Creek

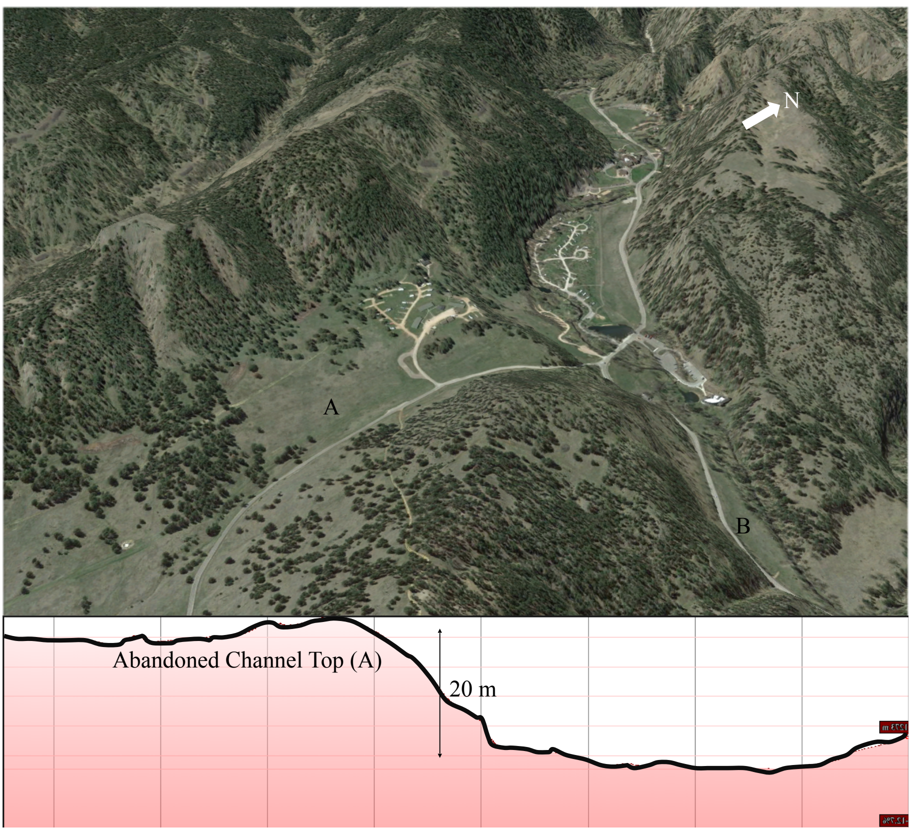

Figure 4. Stream piracy near the Wildlife Loop Road viewed in 3D from Google Earth. The original stream flowed from the top of the view and exited at the lower left side (A) where the current flow is from the top to the bottom of the image (B) and at an elevation ~20 m lower than the abandoned channel. The lower profile shows the elevation difference from the lower modern channel to the abandoned channel.

watershed originally flowed to the west (~260°) but now flow to the east (~80°) at the eastern limit of the Carbonate Plateau. The eastern edge of the Carbonate Plateau consists of a prominent weathered ridge, dominantly formed by the Pahasapa Limestone, providing the relict landscape with its largest topographic feature. Rather than representing a border between differing external bounding conditions, this ridge and piracy event were likely established due to vast differences in hydrology (steeper gradients to the east) between the crystalline Precambrian rocks of the central uplift and the carbonates of the plateau (Carter et al. 2002). This hydraulic boundary would have allowed faster headward erosion rates of the eastward flowing streams, progressively removing the Carbonate Plateau in a westward direction through time. This process likely originated during the erosive breach into the Precambrian metamorphic rocks and continued during the maturation of the relict landscape to its present extent. Boulders of crystalline Precambrian vein quartz (Figure 6) occur in the upper watershed of Whoopup Creek that originated from the Precambrian central core of the Black Hills during a time when these rocks were part of the upper Whoopup Creek watershed. The capture of the upper Whoopup Creek channels by Spring Creek has resulted

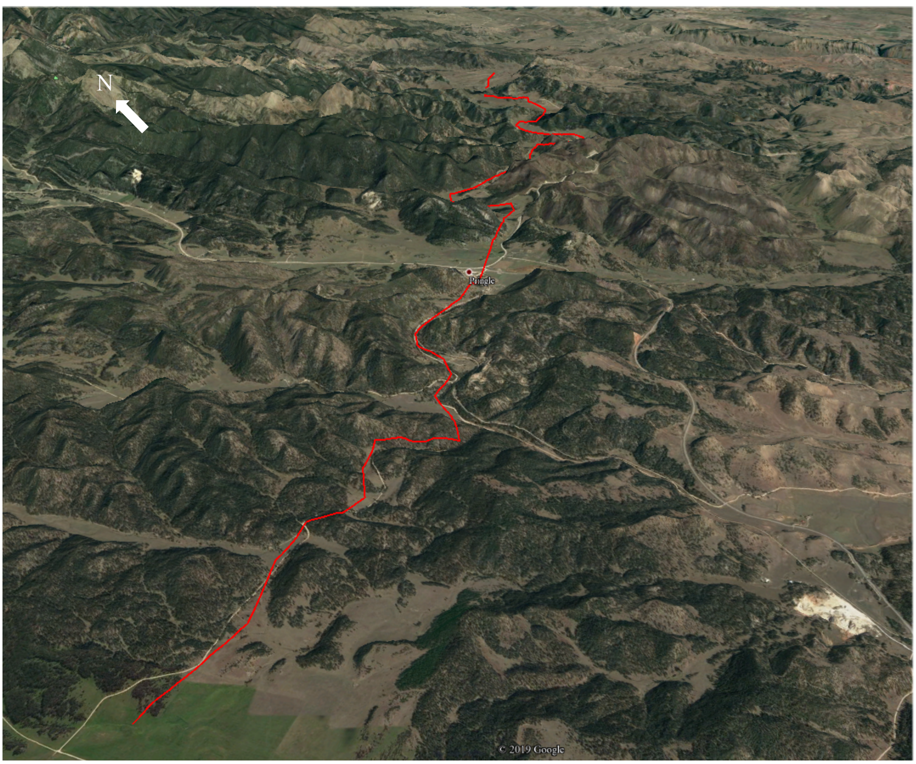

Figure 5. Abandoned stream channel (red) that had flowed in an easterly direction through the town of Pringle and into the red valley near Wind Cave. Current channels flow north to south as a function of the radial flow in the Black Hills and have captured the eastward flow redirecting these flows southward. Google Earth image in 3D mode.

Figure 6. Precambrian vein quartz clasts from gravel deposits in upper Whoopup Creek. The large singular crystals (left, center) contain zoning matching those of Harney Peak Pegmatites. (Figure 1, western red star). Modified from Hazelwood (2019).

in the existence of boulders that have no compositional source upstream of their occurrence in the present watershed.

DISCUSSION

Geomorphic watershed adjustments in the Black Hills have been age-constrained based on fluvial sedimentation and fossil evidence. Two major knickzones are evidenced in all 19 watersheds draining the Black Hills. Above the highest elevation knickzone is a broad, relatively low relief, subdued landscape where rocks have been exposed to erosion since at least the end of the Laramide orogeny. At the margins of the subdued topographic zone, streams rapidly incise into steep-sided and deep canyons. At lower elevations, more peripheral to the margins of the Black Hills is a second knickzone that contains a similar lower boundary marked by incised river channels in steep canyons. The modern equilibrium landscape lies mainly outboard of this lower knickzone. The steepness of the two knickzones suggests that forces causing incision were rapid and that at progressively higher elevations, the landscape is more removed from current geomorphic processes.

Future research should address age-dating of these surfaces to define timing of the geomorphic changes that have occurred. These ages would provide the exact timing and much of the needed insight into the causes for knickzone progression. Additional research should focus on prominent stream channel pattern evolution where they emerge from the Black Hills and begin to flow out onto the prairie. Observation suggests some adjustments could be due to Pleistocene glaciation, such as crustal warping and subsequent changes to base level, but more age data are required to confirm this.

The Black Hills has experienced a dynamic past including punctiliar deep-seated and shallow, plutonic and volcanic activity, continental-scale uplift, and multiple erosion periods. These events have been captured in the geomorphologic and sedimentary record that has been, thus far, inadequately explored and researched. The efforts reported here seek to reduce the unknowns of Black Hills geomorphic evolution.

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