Knickzone propagation in the Black Hills and northern High Plains: A different perspective on the late Cenozoic exhumation of the Laramide Rocky Mountains

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ABSTRACT

Geomorphic research in the Black Hills and northern High Plains poses an intriguing hypothesis for the Cenozoic evolution of this salient of the Laramide Rockies. Most recently, geologists have appealed to late Cenozoic epeirogenic uplift or climate change to explain the post-Laramide unroofing of the Rockies. On the basis of field mapping and the interpretation of long-valley profiles, we conclude that the propagation of knickzones is the primary mechanism for exhumation in the Black Hills. Long profiles of major drainages show discrete breaks in the slope of the channel gradient that are not coincident with changes in rock type. We use the term knickzones to describe these features because their profiles are broadly convex over tens of kilometers. At and below the knickzone, the channel is incising into bedrock, abandoning a flood plain, and forming a terrace. Above the knickzone, the channel is much less incised, resulting in a broad valley bottom. Numerous examples of stream piracy are documented, and in each case, the capture is recorded in the same terrace level. These observations are consistent with migrating knickzones that have swept through Black Hills streams, rearranging drainages in their wake. We demonstrate there are two knickzone fronts associated with mapped terraces. Preliminary field evidence of soil development shows that these terraces are time transgressive in nature. Our data strongly suggest that knickzone propagation must be considered a viable mechanism driving late Cenozoic fluvial incision and exhumation of the northern High Plains and adjacent northern Rocky Mountains.

Keywords: Black Hills, landscape evolution, terraces, stream gradients, fluvial erosion.

INTRODUCTION

Early workers held that late Cenozoic (<10 Ma) fluvial dissection and exhumation of the Laramide Rocky Mountains and adjacent High Plains resulted from the epeirogenic uplift of the entire western United States following a long period of tectonic quiescence (Davis, 1911; Love, 1970; Epis and Chapin, 1975). However, because the fluvial dissection is also coincident with the general transformation to Quaternary-like climates (Ruddiman and Raymo, 1988), numerous recent papers have appealed to river incision in response to climate-controlled changes in basin hydrology (Molnar and England, 1990; Small and Anderson, 1998; Dethier, 1999).

In contrast to these hypotheses, we present observations from the Black Hills and adjacent northern High Plains that argue strongly for a late Cenozoic exhumation of the northern Laramide ranges by a knickpoint migration mechanism. Traditionally, knickpoint migration (usually connected with changes in base level) has been underappreciated in terms of its ability, over very long time spans and large areas, to integrate drainages and exhume landscapes. Our insights into the evolution and propagation of knickpoints will be of broad interest to the geologic community, which is increasingly interested in how fluvial erosion unroofs rocks and influences tectonic processes at depth (see Zeitler et al., 2001).

BACKGROUND

The Black Hills are the easternmost uplift of the Late Cretaceous–Eocene Laramide orogeny (Fig. 1). The domed uplift is cored by Archean metamorphic and igneous rock, disconformably overlain by early Paleozoic sedimentary rocks and karstified Mississippian-Permian carbonate. Triassic redbeds of the Spearfish Formation, shallow-marine Jurassic siltstone of the Morrison and Sundance Formations, and well-sorted sandstone of the Cretaceous Inyan Cara Group unconformably overlie the carbonate. Cretaceous shale caps the stratigraphic sequence out in the surrounding High Plains. Laramide intrusive dikes and

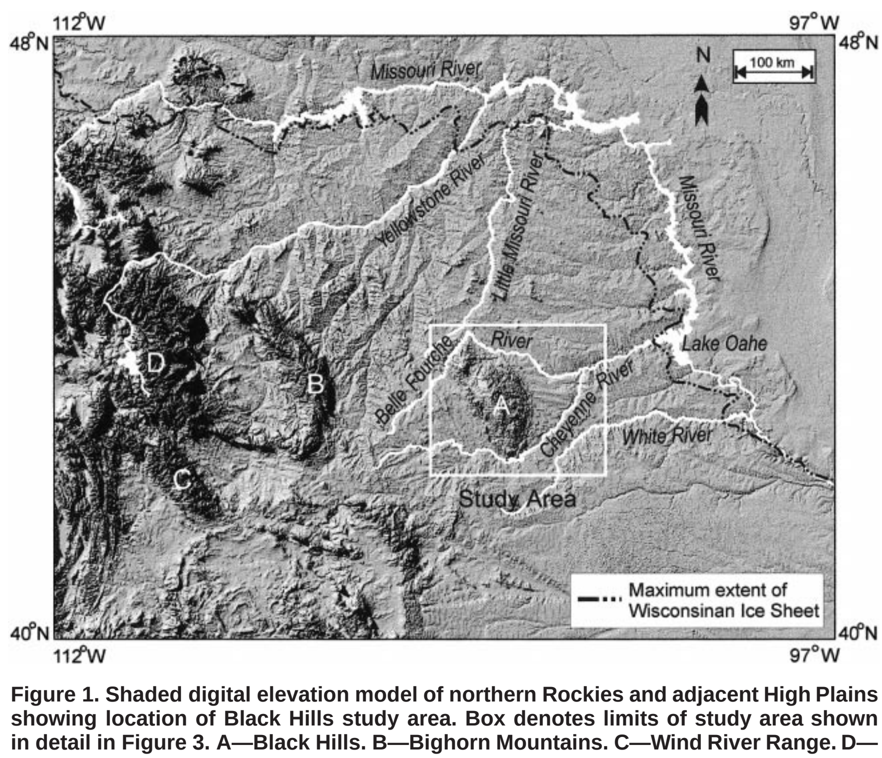

Figure 1. Shaded digital elevation model of northern Rockies and adjacent High Plains showing location of Black Hills study area. Box denotes limits of study area shown in detail in Figure 3. A—Black Hills. B—Bighorn Mountains. C—Wind River Range. D—Yellowstone National Park.

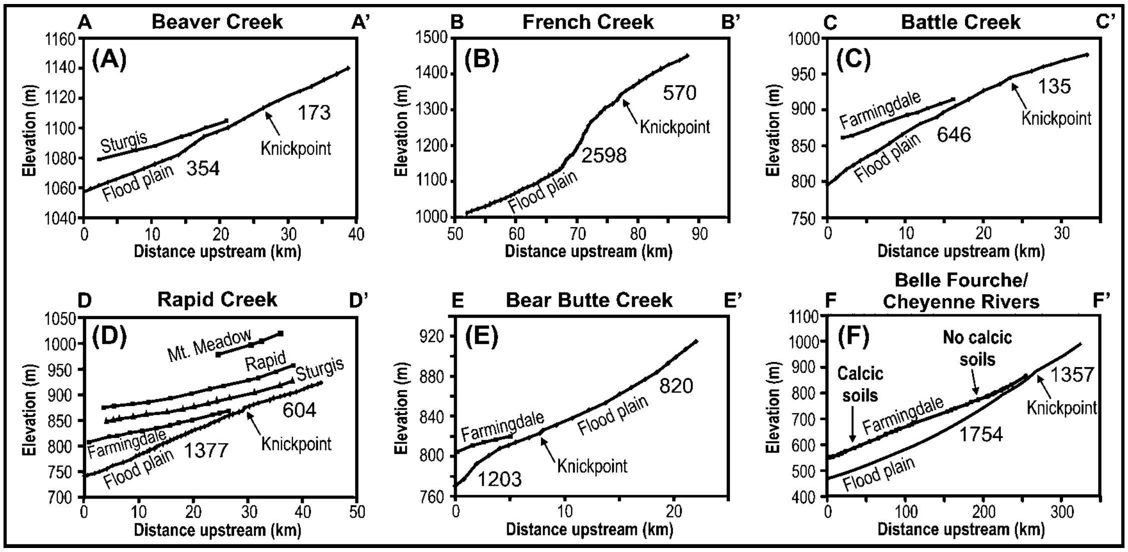

Figure 2. Long-valley profiles and terrace profiles from select drainages in and around Black Hills showing knickpoints and knickzones. Profile data were generated from 7.5 minute topographic sheets with 10 or 20 ft contour intervals. Each point represents contour crossing stream: x axis represents distance upstream from confluence with major channel. Terrace data are based on field mapping. Profiles A, C, D, E, and F are in shale, whereas profile B is in more resistant carbonate rocks. Only lowest terrace profiles are shown in A, C, E, and F. All four terraces are shown in D. See Figure 3 for location of each stream profile. Numbers below flood plain are average Hack Gradient Index above and below knickpoint.

volcanic necks crop out in the northern Black Hills.

Fluvial terraces are poorly preserved in the upper reaches of drainage basins underlain by Paleozoic carbonates where the streams tend to be incised into narrow canyons, but are laterally continuous and well preserved on the surrounding Triassic redbeds and adjacent High Plains shale. The ages of these fluvial deposits are not well known, and there is little agreement as to the regional correlation of terraces around the Black Hills. Most researchers have assigned Quaternary ages to these terrace deposits, except for the Mountain Meadow terrace, which is commonly cited as late Pliocene based on scant fossil evidence. The modern valley floors are typically Holocene in age (Straffin, 1993; Fredlund, 1996), but the precise age, stratigraphy, and sedimentology of the underlying fill are unknown.

Fillman (1929) was the first to map and describe terraces in the northern and eastern Black Hills. She named the three highest terrace surfaces—Mountain Meadow, Rapid, and Sturgis (oldest to youngest, respectively)—and suggested that diastrophic uplift, climatic change, or glacial damming downstream at the Missouri River might have caused river incision and the subsequent terrace formation. Plumley (1948) identified two additional younger terrace surfaces: Bear Butte (older) and Farmingdale (younger) and the presence of knickpoints on the Bear Butte, Rapid, and Battle Creeks. Plumley suggested that terrace formation was caused by a localized base-level fall event downstream on the Missouri River, propagating knickpoints upstream; this view is consistent with our observations. Harksen and MacDonald (1969) studied gravel deposits in the plains of South Dakota and argued for epeirogenic uplift of the northern Great Plains in the Quaternary with tilting to the southwest to explain the incision. Straffin (1993) suggested that terrace formation was linked to climate variability and proposed that flood plains are synchronously incised during drier interglacial periods and stable during wetter glacial periods.

TERRACE DESCRIPTIONS

Terraces in and around the Black Hills share similar morphologic and stratigraphic characteristics (Fillman, 1929; Plumley, 1948; Kempton, 1980; Straffin, 1993). On the redbeds, terraces are paired and have 2–10 m of fluvial silt, sand, and gravel overlying relatively flat bedrock straths. The fluvial deposits gradually decrease in thickness downstream. In the surrounding High Plains, the terraces are paired and have 2–4 m of fluvial sediments overlying relatively flat straths. On the flanks of the Black Hills and on the High Plains, older terrace treads have been greatly modified and rarely contain fine-grained deposits, whereas the younger terraces have flat treads and a 1–2-m-thick fine-grained component of both alluvial and eolian (loess) origin. The valley bottoms have large flood plains, and small inset cut and fill terraces proximal to the modern drainages. Alluvial deposits under the flood plains can be 5–30 m thick, but generally thin away from the uplands of the Black Hills. We use tread relief, strath relief, grain size, and relative pedogenesis to identify four terraces in the Black Hills and surrounding High Plains (from highest to lowest): Mountain Meadow, Rapid, Sturgis, and Farmingdale. We believe that the Bear Butte terrace of Plumley (1948) is equivalent to the Sturgis terrace of our nomenclature. The Farmingdale terrace has a weakly developed to nonexistent calcic soil, consistent with a youthful age not likely older than late Pleistocene. In contrast, the Sturgis and older terraces have complicated, polygenetic calcic soils consistent with an advanced age; these terraces have been in the landscape for tens of thousands if not hundreds of thousands of years.

LONG-VALLEY PROFILES

We plotted long-valley profiles of all the major drainages in the Black Hills (Fig. 2) using 1:24 000 topographic maps. Knickpoints were identified on all major drainages along the northern and eastern flanks of the Black Hills (Fig. 3). The change in gradient downstream of these knickpoints is small, but can extend over tens of kilometers. Therefore, we use the term knickzones to describe these features because the channel gradient change is expressed across a broad convexity (Fig. 2). The average Hack Gradient Index (SL index; Hack, 1973) was calculated for reaches above and below the knickpoint, and in every case, the value below the knickpoint was always significantly higher than above (Fig. 2). The long-valley profiles on both flanks of the

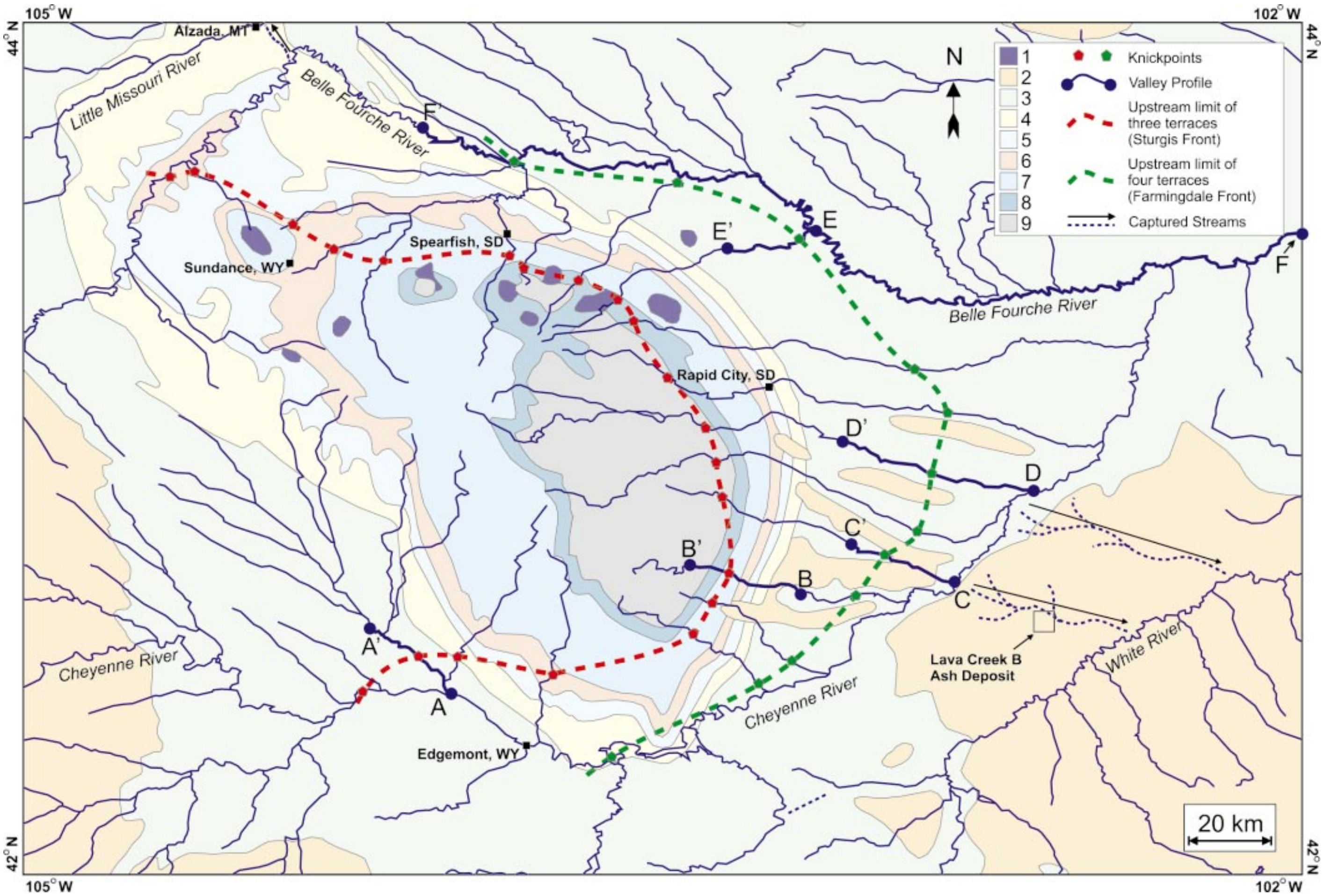

Figure 3. Geologic map of Black Hills and surrounding High Plains showing location of valley profiles from Figure 2. A-A′—Beaver Creek, B-B′— French Creek, C-C′— Battle Creek, D-D′—Rapid Creek, E-E′— Bear Butte Creek. Geologic units: 1—Tertiary intrusives; 2—Tertiary sands, silts, and mudstones; 3—Cretaceous shales; 4—Cretaceous sandstones; 5—Jurassic siltstones; 6—Triassic redbeds; 7—upper Paleozoic carbonates; 8—lower Paleozoic clastics; 9—Precambrian igneous and metamorphic rocks. Approximate location of captured streams is based on figures in Darton (1909) and Wanless (1923). Original captured stream paths are inferred from location of fluvial deposits. Location of Lava Creek B ash deposit is from Straffin (1993).

Black Hills were field checked and no significant knickpoints associated with obvious changes in rock type were observed. The presence of knickzones on the eastern flanks does not appear to be related to differences in drainage basin size, hypsometry, or climatic gradient between the eastern and western flanks of the Black Hills. However, the upstream position of these knickzones is strongly dependent on the size of the drainage basin in which they are located. Knickzones on the large Belle Fourche and Cheyenne Rivers are positioned much further upstream than knickzones on the smaller intermittent tributaries (Fig. 3).

In the Cretaceous shale of the High Plains, the knickzones have a very gentle gradient and extend over several tens of kilometers (Fig. 2, A, C–F). Here, the streams are meandering alluvial channels armored with gravel. In contrast, streams in the crystalline uplands of the Black Hills have much steeper knickzones, only 10–20 km long (Fig. 2B); the streams meander much less, and typically flow through narrow canyons.

A key observation made in the field was the presence of a paired strath terrace downstream of each knickpoint. There is a demonstrable genetic relationship between the knickzones and the Sturgis (Fig. 2, A and B) and Farmingdale (Fig. 2, C–F) terraces in the Black Hills and surrounding High Plains. When the fluvial terraces along these streams are plotted on a long-valley profile, the terrace tread downstream of the knickzone merges with the upstream flood plain at the knickpoint. These knickpoints, when plotted on a map, can be contoured to represent the number of terraces along streams in the Black Hills and surrounding High Plains (Fig. 3). Preliminary field observations show that the terraces are time transgressive in nature (Fig. 2F). Farmingdale terraces on the Cheyenne River, downstream near Lake Oahe (see Fig. 1), have late stage I calcic soils, whereas Farmingdale terraces upstream near the knickpoint have no calcic soil development.

STREAM PIRACY

Many authors have noted major stream captures in the Black Hills. For example, Todd (1902) and Wanless (1923) demonstrated that streams in the southeastern Black Hills formerly flowed along a path to the White River before being truncated by the Cheyenne River (Fig. 3). A Lava Creek B ash deposit overlying a fluvial terrace between the White and Cheyenne Rivers yields a minimum age of ca. 610 ka for this capture event (Straffin, 1993). In another example, the Belle Fourche River truncated a major tributary of the Little Missouri River (Darton, 1909) near the town of Alzada, Montana, diverting flow to the east (Fig. 3). In each case, the piracies occurred because the capturing stream is a shorter distance upstream from the Missouri River base level, at the point of capture, than the captured stream. Additional geomorphic evidence for stream piracies in the Black Hills is consistently preserved in the Rapid terraces. The best way to accommodate these stream capture events is with a Rapid knickzone migrating upstream from the Missouri River. Conceivably, headward erosion of the shorter, steeper streams was fostered by the knickpoints, favoring them to capture longer streams. In addition, the capturing streams must also have had enough of an advantage over the larger, higher discharge rivers, and presumably faster migrating knickpoints, for piracy to occur.

DISCUSSION AND CONCLUSIONS

What is not clear to us at this time is the mechanism by which these knickzones are created and propagated over long distances through easily erodible, flat-lying, fissile Cretaceous shales. Flume studies in homogeneous materials (Begin et al., 1980; Gardner, 1983) suggest that knickpoints both recline and retreat rapidly over time, removing the knickpoint from the channel profile. Miller (1991) presented compelling evidence to show how knickzones for streams in the humid Midwest are overwhelmingly controlled by even subtle changes in rock type. In contrast, there are field data demonstrating not only the existence of knickpoints in homogeneous rock types, but also the ability for knickpoints to be propagated and maintained as steep features a great distance upstream from the point of initiation (Wohl, 1993; Young and McDougall, 1993; Fabel et al., 1996; Seidl et al., 1997).

Although our data are not well suited to investigate the relative roles of climate or tectonics, our findings suggest that base-level fall is most likely responsible for knickzone formation. The genetic relationship between the knickzones and the terraces, the relationship between the basin size and the upstream location of the knickzones, and the change in knickzone character across different rock types are strongly indicative of features propagating upstream from some unspecified base-level fall. Computer models of base-level knickpoint propagation suggest that knickpoints behave like diffusive waves in easily erodible rocks, but act like kinematic waves in more resistant rock. This model matches our field data well and strengthens our assertion that knickzone propagation is caused by base-level fall.

We believe that the geomorphic evolution of the Black Hills and surrounding northern Great Plains during the Quaternary and at present can best be explained by the migration of four knickzones upstream from the Missouri River. The two younger knickzones, when connected on a map, represent erosional fronts migrating up the Cheyenne and Belle Fourche Rivers and each subsequent tributary encountered, leaving the Farmingdale and Sturgis terraces in their wake (Fig. 3). Given the similarity in geomorphology and long profiles of the older Mountain Meadow and Rapid terraces to the younger Farmingdale and Sturgis terraces (Fig. 2D), we have no basis to appeal to a mechanism other than knickpoint migration for their genesis. The Cheyenne River piracy demonstrates that a knickzone migration process has been active in the Black Hills for at least 600 k.y., and probably longer.

We believe that our data suggest that a knickzone propagation process is capable of significant amounts of landscape incision and headward erosion over long time spans. If our observations are representative of the northern Rocky Mountains in general, knickpoint migration must be entertained as a viable mechanism for ultimate exhumation of the Laramide Rockies during the late Cenozoic.

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