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EVOLUTION OF CUTOFFS ACROSS MEANDER NECKS IN POWDER RIVER, MONTANA, USA

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ABSTRACT

Over a period of several decades, gullies have been observed in various stages of forming, growing and completing the cutoff of meander necks in Powder River. During one episode of overbank flow, water flowing over the down-stream bank of the neck forms a headcut. The headcut migrates up-valley, forming a gully in its wake, until it has traversed the entire neck, cutting off the meander. The river then follows the course of the gully, which is subsequently enlarged as the river develops its new channel. The complete process usually requires several episodes of high water: in only one of the five cases described herein was a meander cutoff initiated and completed during a single large flood. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: headward erosion; gullies; river meanders; cutoffs; ice-jam

INTRODUCTION

Most meander cutoffs in alluvial valleys form either by (1) progressive narrowing of a meander neck until the two limbs of the meander meet to complete the final breach, or (2) formation of a chute channel directly across a meander neck. Which of these two processes predominated in the formation of older cutoffs may be discerned from the shape of the oxbow lake left behind – whether the plan view is shaped like a teardrop or a horseshoe. The former usually is called a ‘neck cutoff’ and the latter a ‘chute cutoff’. Lewis and Lewin (1983) reserve the term ‘neck cutoff’ for cases in which the up-river and down-river limbs of a meander were less than a channel width apart at the time of breaching, and they use ‘chute cutoff’ for those cases in which a much longer breach channel was created. Erskine *et al*. (1992) use ‘chute cutoff’ where a stream reduced its length by cutting a new channel by following a swale or depression across the inside of a meander bend. Although chute cutoffs may be more common than neck cutoffs (Brice, 1977; Gagliano and Howard, 1984; Kulemina, 1973; Lewis and Lewin, 1983), neither process seems to be well described in terms of the detailed mechanisms by which the meander is actually cut off.

In published discussions of mechanisms, chute cutoffs have received less attention than neck cutoffs (Crickmay, 1960; Erskine *et al*., 1992; Gagliano and Howard, 1984; Ratzlaff, 1981). In what is perhaps the most detailed description and analysis of a neck cutoff, in the River Bollin in Cheshire, Mosley (1975) concluded that the process could be explained and perhaps even predicted (in a probabilistic sense) in terms of simple bank erosion of the insides of the converging limbs of the meander. In his discussion of chute cutoffs in the Lower Mississippi River, Matthes (1948) stated that ‘cutoffs usually occurred during very high stages when water scoured out channels across narrow necks of overdeveloped bends... These developments result from the gradual enlargement of shallow swales (which began during high stages) into channels deep enough to flow water even at low stages and, in time, the swales became main-river channels.’ In one of the most thorough descriptions of a chute cutoff, that in the River Irk in Lancashire, Johnson and Paynter (1967) favoured the hypothesis that the cutoff occurred ‘by piling up of water in the stream channel upstream of the meander so that

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Figure 1. Maps showing location of selected gullies and cutoffs in Moorhead-to-Broadus reach of Powder River in southeastern Montana, USA

the gradient of the water surface was steepened and raised to the level where the stream could flow across the lowest part of the floodplain, thus creating a meander chute.' Like Matthes (1948), however, Johnson and Paynter (1967) gave no further details to suggest just how such a meander chute might be created.

In this paper, we describe a specific mechanism for the formation of chute cutoffs: headcuts that form during floods in the down-river edges of meander necks and progress headward (up-river) across the necks eventually to complete the cutoffs. We begin by describing such a headcut that formed a gully part way across a meander neck in Powder River during March 1989, and which we were able to observe in its various phases of cutting. We then describe four more such headcuts, three of which actually cut off their meanders, and two of which we were able to observe during the cutoff process. The evidence we present ranges from anecdotal to inferential–anecdotal where we had opportunities to witness processes in action and landforms in the making, and inferential where we were able to reconstruct the sequences of recent events after the fact from aerial photography and terrestrial measurements.

Although the processes we have observed and will describe here seem to be common knowledge among some experienced practitioners of river engineering and fluvial geomorphology (S. A. Schumm, oral communication, 1995), we have not seen any previous detailed description of them in the published literature. The single exception may be a 1984 doctoral dissertation by A. Thompson which has been cited by Hooke (1995, p. 251) as showing that 'chute cutoffs take place by headward erosion of a gully or scour hole from the downstream side of the meander... such a cutoff initially produce(s) a cutoff channel of very irregular form.'

See the papers by Hooke (1995) and Hooke and Redmond (1992) for further insights into the major issues concerning meander cutoffs and other river-channel changes.

POWDER RIVER: THE SETTING

Powder River collects water from the eastern slopes of the Bighorn Mountains of north central Wyoming, flows onto the western edge of the northern Great Plains, and turns north-northeast to flow 400 km (valley distance) to join the Yellowstone River in eastern Montana (Figure 1). The reach of Powder River with which this paper is concerned lies between Moorhead and Broadus, Montana; it drains an area of about 21 500 km^2 and discharges an average of 13 $m^3\ s^{-1}$ of water and $2–3\times10^6$ tons of suspended sediment per year. The average river slope through the reach is 1 m km^{-1}. Bankfull width at mean annual high flow averages about 50 m. No mainstem reservoirs or other large works of river engineering such as dykes, levees, or bank-protection devices inhibit the natural processes of the river. The only significant anthropogenic influence on Powder River is the withdrawal of irrigation water, mostly to grow alfalfa for cattle feed. Further details of the geology and hydrology of Powder River drainage basin are given by Hembree *et al*. (1952) and Hubert (1993).

Powder River is an actively meandering stream. Sinuosity measured on aerial photographs taken at six different times between 1939 and 1978 averaged 1·40 to 1·50 between Moorhead and Broadus. Fifteen meander bends were cut off during the same 40 year period. The length of the reach increased from 105·3 km in 1939 to 110·3 km in 1978, showing that the reach-averaged rate of shortening by meander cutoff was less than the rate of lengthening by meander growth. These and other details on the geomorphology of the Moorhead–Broadus reach were discussed at greater length by Martinson (1984), Martinson and Meade (1983), and Pizzuto (1994).

Two types of flood prevail in Powder River: ice-jam floods during the colder months, and rainfall/snowmelt floods during the warmer months. Powder River is especially susceptible to ice jams because (1) it flows northward across a sufficiently large range of latitude (43–46°N) that upstream reaches may thaw more rapidly than downstream reaches, and (2) its sinuosity provides numerous tight bends where ice can lodge. The extent of the changes in channel morphology wrought by ice jams depends on whether the river banks are frozen at the time of the flood. In any event, any given ice-jam flood usually affects only a few kilometres of river. Rainfall/snowmelt floods, on the other hand, are more pervasive. The largest and second-largest floods of record on Powder River came during the warmer months of September/October 1923 and May 1978. The flood of May 1978, some of whose effects will be discussed below, was the result of two 100 mm rainfall episodes within a period of two weeks.

HEADCUT AT GAY RANCH

We first describe the formation of a headcut and chute channel across a meander neck that did not result in a complete cutoff, which two of us were able to observe in process (see 'Attributions and Acknowledgements' section). On 13 March 1989, an ice jam had formed in the bend of Powder River in Sections 28–29 of T7S, R49E, about 1500 m south-southeast of the main buildings of the Gay Ranch. The ice had dammed the main channel of the river, and water was flowing across the neck of the bend. By the time we first noticed the water flowing across the neck (08.00–09.00 hours), several small headcuts had already formed on the down-valley side of the neck and had receded 3–6 m into the river bank.

The floodplain/terrace deposits of which the neck was formed (possibly corresponding to the Lightning terrace of Leopold and Miller (1954) were not frozen. The material eroded by the headcuts consisted of sod 10–20 cm thick over an unconsolidated sand layer about 0·5 m thick that lay atop a gravel layer about 1 m thick. The gravel lay on top of bedrock, a shaly layer (locally called 'blue shale') of the Fort Union Formation of Paleocene age.

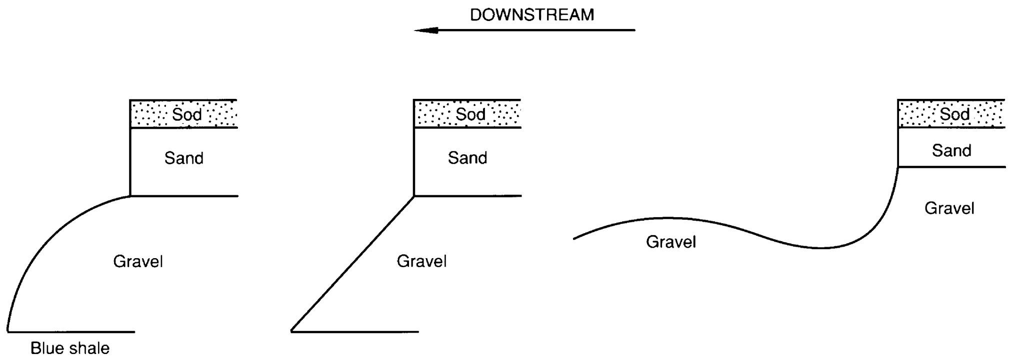

Figure 2. Schematic sketches of profiles of headcuts observed in March 1989, during the progressive formation of the gully across a meander neck on Powder River at Gay Ranch, NE corner of Section 29 of T7S, R49E. Left: initial profile. Centre: profile during most of the headcutting. Right: profile as it formed near the upper end of headcut

The profiles of the headcuts themselves changed in the course of the cutting. At first the sod and sand layers formed a near-vertical face over an outward-curving gravel slope (Figure 2, left). Soon the face took on a profile in which the sod and sand layers formed a vertical face and the gravel face sloped down-river in a more rectilinear configuration (Figure 2, centre). This second profile was maintained for some hours and 'moved' up-gully many tens of metres during the course of the headcutting. As the water poured over the cutting face (Figure 3), the sod would fail in blocks, presumably because the falling water was first washing out the less cohesive sand underneath. The headcut migrated across the neck in the up-river direction to where the thickness of the sand layer had diminished and the top of the gravel lay closer to the surface. The profile then took on the shape shown on the right of Figure 2, in which the trench was deepest just down-gully of the cutting face.

The headcutting proceeded at a variable rate. Most of the trench (the first 150 m) was cut during the first day, 13 March (Figure 3). The maximum observed rate of knickpoint migration was on the order of 10 m h^{-1}. The cutting rate was slowed in places by the roots of mature cottonwood trees (*Populus sargentii*) growing on the neck. Early in the cutting, the gully widened as it was being cut back, but eventually the width stabilized at about 5–6 m.

At the outset, several headcuts seem to have started, more or less simultaneously, on the down-river edge of the neck. After they had cut back about 40 m from the down-river edge, two of the larger headcuts joined and formed a single wide cut that then became the main headcut. The water flowing across the neck eventually began flowing laterally into this single gully instead of flowing completely across the neck in its original down-river direction. At some stage the principal gully acquired tributaries that enhanced its interception of water flowing across the meander neck. The tributaries stopped the flow of water into (and hence the continued headward erosion of) some of the smaller headcuts on the down-river edge of the neck. This sequence is shown diagrammatically in Figure 4.

On the night of 13 March, temperatures fell below the freezing mark, snow fell, and the river level dropped. At this lowest river level, the flow across the meander neck continued but was substantially reduced. Even at these flows, however, the headcut advanced in the up-river direction, but at a much slower rate than earlier. The elevation of the gully floor became higher as the headcut advanced up-river, at least partly because the top of the underlying gravel layer is higher in the up-river part of the meander neck.

The ice dam finally broke about two weeks later, at which time water completely stopped flowing across the neck. By the time it had stopped, the headcut had progressed about 250 m in the up-river direction and had come within about 70 m of cutting completely through the meander neck. The configuration of the gully at the close of this episode of cutting is shown in Figure 5.

MEANDER CUTOFF NEAR PLUM CREEK

Some years ago, a meander of Powder River was cut off in Section 7 of T8S, R49E, near its confluence with Plum Creek (Figure 6). This meander was cut off in late spring or early summer in association with the June rise

Figure 3. Three photographs taken 13 March 1989, during the formation of a gully across the neck of a meander on Powder River at Gay Ranch, NE corner of Section 29 of T7S, R49E; and one photograph taken several weeks later, after ice jam had broken and river level had fallen. Upper left: up-river view of flow across meander neck and of the active headcut after it had cut 10–20 m into the down-river edge of the neck. Upper and lower right: successive views, taken about 2 h apart, of active headcut at distances 70–80 m up-river of the down-river edge of the neck. lower left: approximately same view as in upper left, taken several weeks later; depth of gully about 2 m

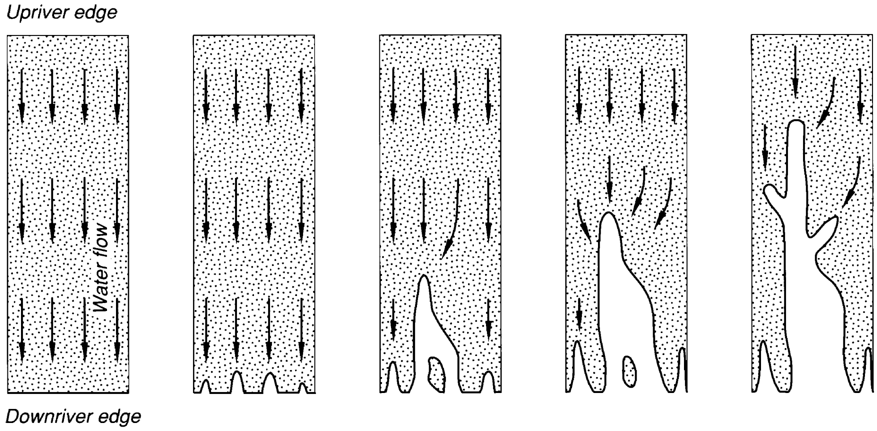

Figure 4. Diagrammatic plan views of successive stages (sequence from left to right) of the growth of a headcut of the type that formed across the meander neck on Powder River at Gay Ranch during March 1989

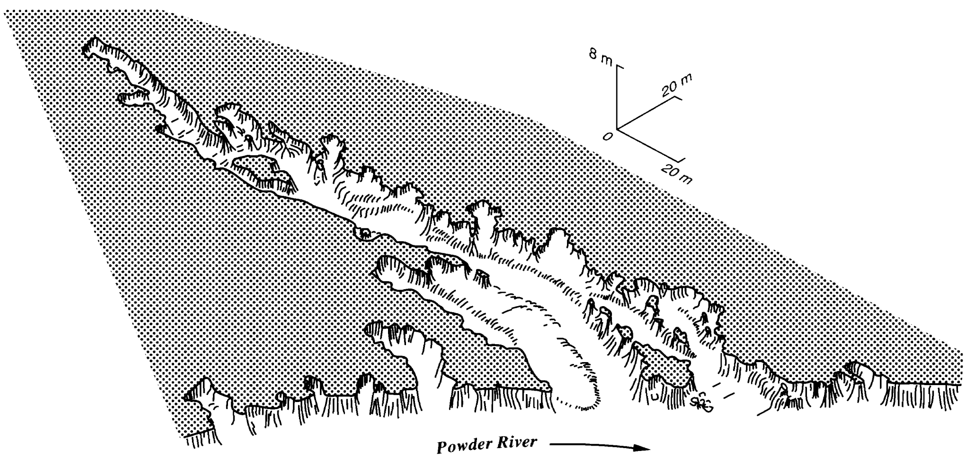

Figure 5. Isometric drawing of headcut that formed during March 1989 on meander neck on Powder River at Gay Ranch, based on level surveys and field sketches made during September 1989 and September 1990

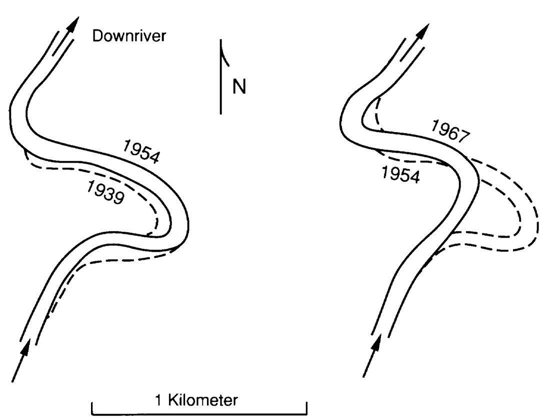

Figure 6. Map showing progression and cutoff of meander in Powder River near Plum Creek, Section 7 of T8S, R49E (Martinson and Meade, 1983, sheet 1)

rather than with an ice jam. Although we cannot recall the exact year, aerial photographs indicate that it happened between 1954 and 1962. The cutoff channel appears in a photograph taken in July 1962 and the old channel still looked fairly fresh and unvegetated on a photograph taken in 1967.

For several years prior, we had anticipated that the neck of the meander would be cut through. High water had been leaving sand and debris on the neck, and small headcuts already had started on the down-river side. One morning during late spring or early summer, while high water was flowing across the neck in many places, we noticed that at least one prominent headcut had formed, and that a small gully had been cut back up-river at least 10 m from the down-river edge of the neck. When we returned (the next day, as we recall), the gully had cut all the way through the neck, and the river was flowing through the newly made cutoff channel. When the water level fell, the entire flow of the river went down the new channel. The new channel was fairly narrow at first, but it widened substantially during or after the next high-water episode. During the next several floods, some water continued to flow into the old channel which became filled with sediment within a few years.

During the cutoff event itself, the channel up-river deepened by nearly 1 m, exposing several ledges of sandstone bedrock. One such ledge, exposed about 1 km up-river of the cutoff, was an excellent place to water cattle. Another such sandstone ledge was exposed about 700 m up-river of the first ledge. Within a few years, however, these ledges were again covered with sand and hidden from view.

HEADCUT AND MEANDER CUTOFF NEAR BLOOM CREEK

The headcut gully across the large meander neck in the southwest corner of Section 29 of T7S, R49E (Figure 7, upper left) might have been started during the great flood of 1923: we remember it as having been there since that time. It is visible on the first aerial photographs taken of this reach of Powder River during 1939 and in all subsequent aerial photographs taken through 1976.

From 1923 to 1978, the gully was cut headward across the meander neck a short distance at a time. During at least some of these small headcutting episodes, sand was washed out from under the overlying sod, leaving the sod behind in large collapsed blocks. Although the gully did not cut completely across the meander neck before 1978, an aerial photograph taken during September 1976 shows the gully headcut to be only about 20 m from the up-river edge of the meander neck.

During the flood of May 1978, the meander neck was breached, and the new cutoff channel followed the course of the old headcut gully. As we were watching, we were unable to see the actual completion of the cutoff because the whole meander neck and loop of the river were under water. The first thing to appear above the receding water was a large sand-and-gravel bar that had formed across the upstream end of the loop of the channel that was cut off. We then noticed that the water in the old meander loop had gone slack while water continued to flow rapidly across the neck. Whether the large sand-and-gravel bar formed mostly before or after the cutoff channel had completely breached the meander neck was not possible for us to observe.

The cutoff breached the meander neck sufficiently early in the course of the 1978 flood that time and hydraulic energy were available to mould the cross-section of the chute into the markedly asymmetrical profile of a mature channel cross-section at the crest of the bend. The cutbank on the concave side of the new bend apparently was eroded laterally about 100 m between the time the neck was initially cut off and the time the flood waters receded. On the convex side of the new bend a large gravel-and-sand point bar developed, approximately 100 m wide in the cross-channel direction (Figure 7, upper right).

The channel up-river of the meander cutoff was deepened by about 1·5 m for a distance upstream of about 1 km (Figure 7, middle and lower right). The up-river progress of the downcutting apparently was halted by a large riffle of coarse gravel, which may be underlain by a ledge of bedrock. This riffle was covered with sand before 1978. Since the flood of 1978, when the gravel was swept clean of sand, the top of the riffle has been used extensively as a fording place by local ranchers.

MEANDER CUTOFF NEAR FLOOD CREEK

During the flood of 1978, a cutoff breached the neck of a meander in Section 28 of T8S, R48E that had been migrating down-river and becoming smaller in radius at least since the time of the first land surveys of 1890

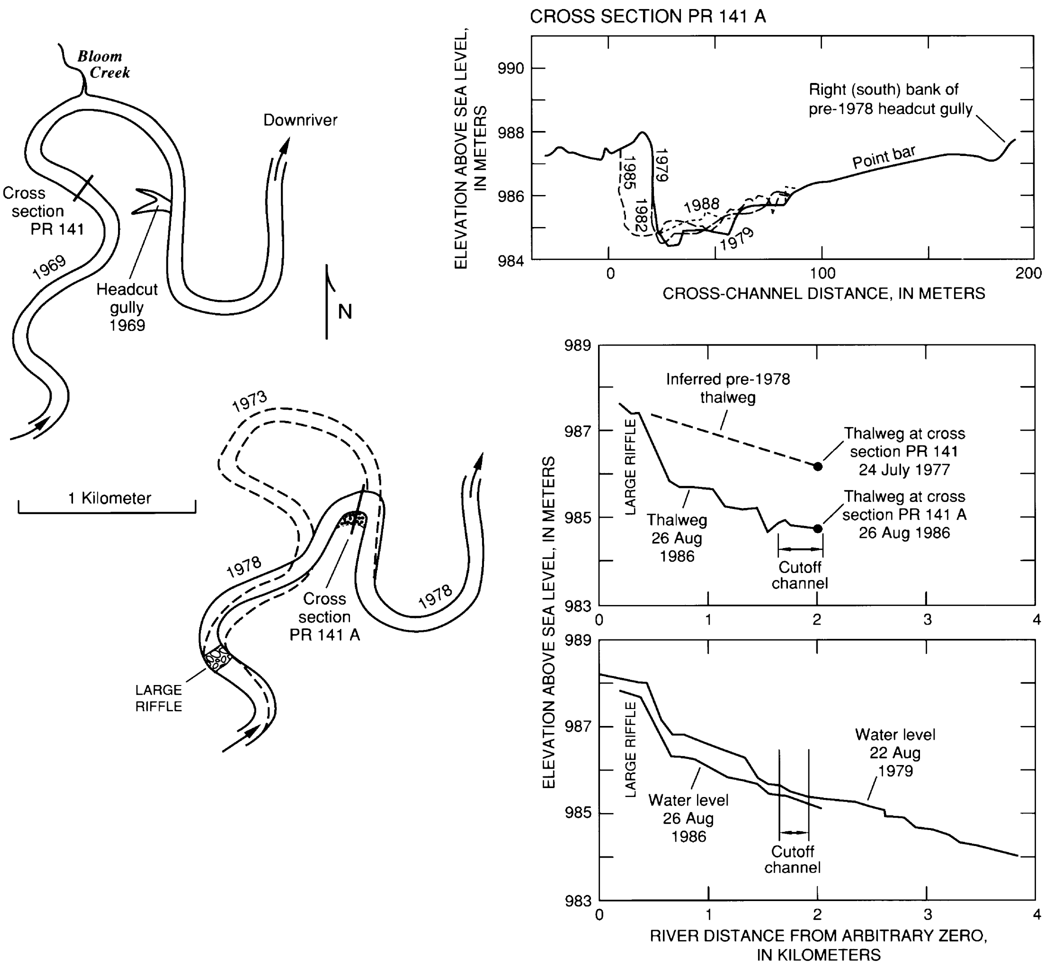

Figure 7. Meander, headcut gully, and cutoff in Powder River near Bloom Creek, SW corner of Section 29 of T7S, R49E. Upper left: meandering channel and headcut gully across meander neck prior to flood of 1978, from US Geological Survey Bloom Creek and Huckins School Quadrangle Maps (scale 1:24 000), based on aerial photographs taken in 1969. Lower left: cutoff channel following flood of 1978 (Martinson and Meade, 1983, sheet 1). Upper right: cross-sections of cutoff channel, 1979–88, showing mature profile (as measured in 1979) of the section as it developed during the flood of 1978, and the relative stability (notwithstanding some erosion of the concave left bank between 1982 and 1985) during subsequent years (Moody and Meade, 1990, p. 114–115). Middle right: thalweg profiles before and after meander cutoff of 1978. The post-cutoff thalweg profile was measured on 26 August 1986 (with assistance from Jean Hough); the similarity of this profile to one that might have been surveyed soon after the flood is suggested by the similarity of two water-level profiles (lower right) surveyed through this reach on 22 August 1979 and 26 August 1986, both of which clearly show a steep drop of more than 1 m below the large riffle

(Figure 8, upper left). No headcuts, incipient or otherwise, were noticed on the ground or were visible in aerial photographs taken before the 1978 flood. But when the flood waters receded, not only had a cutoff channel formed completely across the neck of the meander, but we could see that several smaller headcut gullies had formed nearby, more or less parallel to the cutoff channel. The smaller gullies had cut no more than halfway across the former meander neck.

From these observations and from those described above at the other cutoff sites, we infer the following sequence of events during the 1978 flood: (1) at least three headcuts began cutting into the down-river edge of the meander neck; (2) the headwalls continued to cut up-river across the meander neck until (3) the most prominent headcut completed the breach, and (4) the flow of the river was diverted through the cutoff channel. That this process was completed fairly late in the flood is suggested by the rather constricted cross-sectional

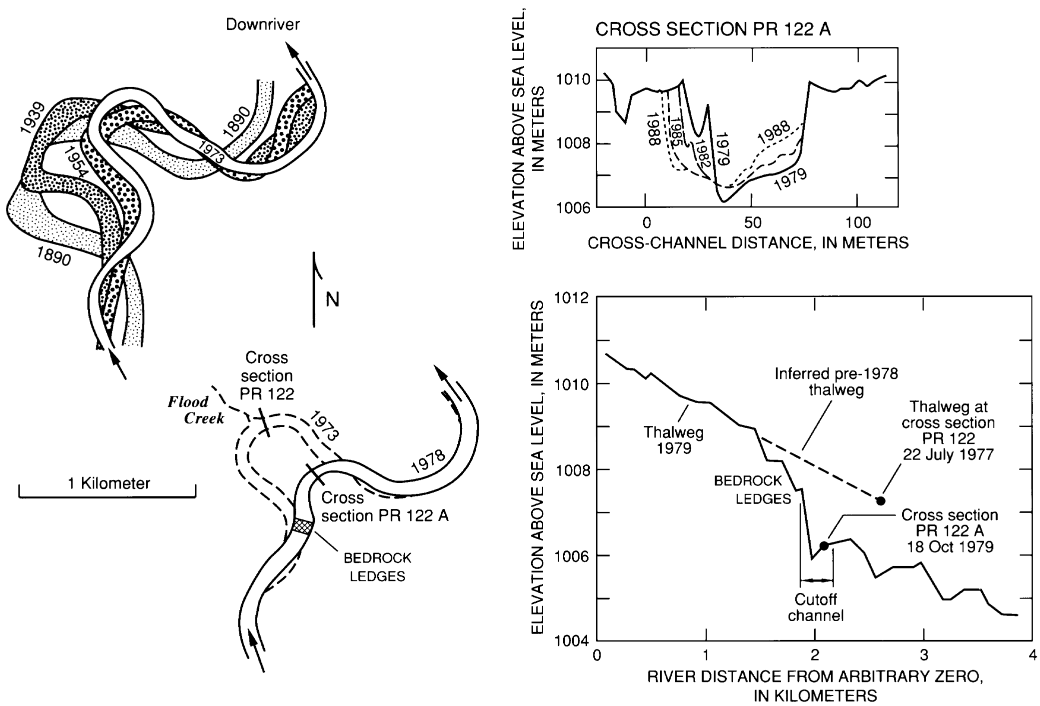

Figure 8. Meander and cutoff in Powder River near Flood Creek, Section 28 of T8S, R48E. Upper left: down-valley migration and narrowing of meander neck, 1890–1973 (Martinson and Meade, 1983, sheet 1), prior to flood of 1978. Lower left: cutoff channel of 1978. Upper right: cross-sections of cutoff channel, 1979–88, showing progressive erosion of concave left bank and deposition of point bar in right side of channel (Moody and Meade, 1990, p. 66–67). Smaller headcut gullies that formed during the 1978 flood but did not cut completely across the meander neck are shown crossing the 1979 section at cross-channel distances of –10 m and +28 m. Lower right: thalweg profiles before and after meander cutoffs of 1978. Thalweg elevations of 1979 measured on 17 October (distances 2·3–4·0 km) and 18 October (0–2·3 km)

profile of the cutoff channel. In contrast to the one that developed near Bloom Creek, the cutoff channel here was narrow and deep, with no visible point bar, when the flood waters receded. During the subsequent years of more average water discharges, the cutoff channel has gradually been widened by erosion of its concave (left) bank, and a point bar has developed on the convex (right) bank of the channel (Figure 8, upper right). The headcut did not continue up-river of the cutoff, deepening the channel as it went, as it did above the cutoff near Bloom Creek. Prominent ledges of sandstone and coal (Fort Union Formation) at the up-river end of the channel cutoff blocked any further progress of the headcut (Figure 8, lower right).

HEADCUT NEAR DAILY RANCH

During an ice-jam flood near the beginning of April 1985, water flowed across the narrow neck of a large meander in the northeast corner of Section 28 of T6S, R50E, 1700–1800 m southwest of the main buildings of the John Daily ranch. During at least the years since 1939 (when the first aerial photographs were taken), the meander neck had become more constricted until, by 1985, the distance across the neck at its narrowest point was only about 200 m (Figure 9, upper left). During the ice-jam flood of 1985, a headcut formed that eventually migrated about one-fourth of the way across the meander neck, beginning, as usual, at the down-river end. Other smaller headcuts also began cutting into the down-river edge of the meander neck (Figure 9, right). Before any of the headcuts was able to complete the breach, however, water stopped flowing across the neck. Like the large headcut gully at Gay Ranch, this gully waits for the next overbank flood to reactivate it and perhaps complete the cutoff process (Figure 10).

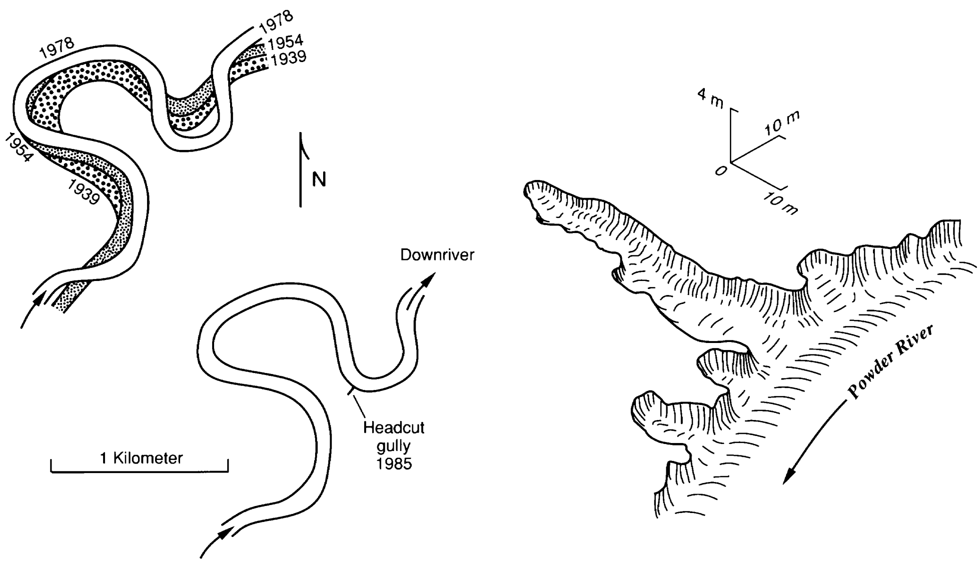

Figure 9. Meander and headcut gully, Powder River near Daily Ranch, Section 28 of T6S, R50E. Upper left: narrowing of meander neck, 1939–78 (Martinson and Meade, 1983, sheet 2). Lower left: location of headcut gully that formed in 1985 on down-river side of meander neck. Right: isometric drawing of headcut gully, based on plane-table survey made on 25 September 1988

Annual high flows in Powder River during the years following 1985, all of which have been less than bankfull, have actually begun filling the down-river end of the gully with sediment, by laying a low berm of sand across the gully mouth and partially flooding the gully floor behind the berm with mud-laden waters.

DISCUSSION AND CONCLUSIONS

Years of directly observing Powder River in southeastern Montana allow us to piece together a coherent composite picture of at least one mechanism by which meander necks are breached. Fifteen meander necks were cut off in a 110 km reach of the river between 1939 and 1978, most of them by the mechanisms we describe.

The cutoff process begins when, because of an ice jam or because of a general raising of the river level by rainfall or snowmelt, water flows across the neck of a meander. At least half of such cross-neck flows in Powder River might be strictly local events caused by ice jams. Meanders with the tightest curvature are the most susceptible to ice jams and, consequently, to this kind of overflow. Small headcuts form on the down-river side of the neck, where the overflowing waters rejoin the main channel by flowing down the bank. These small headcuts are likely to form at first where swales or other low-lying areas intersect the down-river bank; some may follow the notched trails worn down by beavers that inhabit the banks of Powder River.

The headcuts propagate up-river by what Stein and Julien (1990) refer to as dominant down-stream erosion; that is, the erosion occurs on the down-stream side of the headcut. This is especially applicable to sequences of material, common in meander necks in Powder River and studied in a laboratory flume by Stein and Julien, in which a surface layer of cohesive soil is underlain by a layer of non-cohesive sand. The sand is readily removed by the water plunging over the face of the headcut, leaving cantilevered blocks of overlying sod that eventually collapse into the plunge pool. The rates of headcut propagation depend strongly on rates of cross-neck flow and on whether or not the soil and underlying layers are frozen.

Regardless of how the gullies may be initiated or sustained, they continue to cut headward so long as significant quantities of water continue to flow across the neck. Several of the small gullies may eventually converge headward into a single large gully. A headward-cutting gully may breach a meander neck during a single flood. More often, several flooding episodes – usually successive ice jams separated by periods of dormancy that last for years or even decades – are required to complete the breach.

Figure 10. Photographs taken 20 August 1986 of gully that formed in April 1985 near Daily Ranch, Section 28 of T6S, R50E. Upper: up-valley view showing headcut and blocks of collapsed sod. Lower: down-valley view showing mouth of gully and Powder River (in distance). John Moody, 2 m tall, is standing in same location in both photographs

After the neck has been breached, the headcut continues up-river, following and deepening the thalweg, until its headward progress is stopped by a bedrock outcrop or a large riffle. Many annual cycles of rise and fall, freeze and thaw, may be required for a cutoff channel to develop the typical cross-sectional channel geometry of the more average reaches of Powder River.

ATTRIBUTIONS AND ACKNOWLEDGEMENTS

This paper is a product of two decades of discussions between us. The Gays have lived and ranched along the banks of Powder River their entire lives (since 1918, in Hubert's case), and have observed changes in the river from the ground and, since 1951, from a small airplane. When Meade initiated geomorphic studies on Powder River in 1975, he immediately began exploiting this wealth of observations and insights into riverine processes. Discussions continued during annual or biennial visits by Meade (since 1975), Moody (1978, and since 1984), and Martinson (1979) until, in 1989, the formation of the headcut at Gay Ranch provided the impetus to focus some of our previous observations and ideas. Actual observations of headcutting in progress were all made by the Gays. Channel-slope and cross-sectional surveys during 1979 were made by Martinson and Meade. All other field mapping of the gullies was done by Moody and Meade. Meade wrote the paper. Authors are listed alphabetically because, after so many years of active and freewheeling discussion, it is impossible to sort out the specific provenances of many of the various contributions to the paper.

We thank Mary Gay, for providing the congenial ambience for our ongoing discussions, as well as for her part in them; Mike Karlinger and Shirley Hamamoto, for helping collect the 1982 cross-section data; Jean Hough, for serving as extra rodperson on some of the field surveys; neighbouring ranchers and landowners, especially Howard Best; Jim Sr, Jim Jr and Tom Bowers; John Daily; George and Hugh Fulton; Amory Hubbard; Bunk, Philip, Floyd and Gary Huckins; Randall Perry; Doug, Craig and Lucille Randall; Shirley, John and Diane Stuver; Virginia Williams; J. L. and Dick Wilson, for their observations and for allowing us repeated access across their lands to the river; Jim Pizzuto, Gar Williams, and two anonymous referees for reviewing the manuscript.

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