Ontogeny of a flood plain

John A. Moody* *U.S. Geological Survey, M.S. 413, Box 25046, Denver Federal Center, Denver, Colorado 80225-0046*
James E. Pizzuto *Department of Geology, University of Delaware, Newark, Delaware 19716*
Robert H. Meade *U.S. Geological Survey, Box 25046, Denver Federal Center, Denver, Colorado 80225-0046*

ABSTRACT

The ontogeny of five flood-plain segments is described for a period of 18 yr following a major flood in 1978 on the Powder River in southeastern Montana. The flood plains developed on relatively elevated sand and gravel deposits left within the channel by the 1978 flood. In cross section, the flood plains resemble benches with well-developed natural levees. Flood-plain growth occurred as sediment was draped onto preexisting surfaces in layers of sand and mud a few centimeters to decimeters thick, resulting in some lateral, but mostly vertical accretion. Annual and biannual measurements indicated that, as the flood-plain segments grew upward, the annual rate of vertical accretion decreased as the partial duration recurrence interval for the threshold or bankfull discharge increased from 0.16 to 1.3 yr. It is clear that a constant recurrence interval for overbank flow cannot be meaningfully assigned to this type of flood-plain ontogeny.

These flood plains did not grow on migrating point bars, and vertical accretion at least initially occurred within the channel, rather than across the valley flat during extensive overbank flows. Sediments of these flood plains define narrow, elongated stratigraphic units that border the active channel and onlap older flood-plain deposits. These characteristics are considerably different from those of many facies models for meandering river deposits. Facies similar to those described in this paper are likely to be preserved, thereby providing important evidence in the geologic record for episodes of periodic channel expansion by ancient rivers.

INTRODUCTION

From a distance, the flood plain of a river may seem well-defined and obvious. Upon closer inspection, however, the flood plain is often found to be composed of several discrete surfaces of differing elevation that vary in their frequency of inundation. The complexities of flood plains have led to different definitions: some are based solely on recurrence intervals (1 yr interval, Wolman and Leopold, 1957; 1.5 yr interval, Leopold et al., 1964; 1.58 yr interval, Dury, 1973); and others are based on geomorphic criteria, which Nanson and Croke (1992) termed genetic classification and attributed the earliest use to Gilbert (1880). Nanson and Croke (1992, p. 460) defined the genetic flood plain as "the largely horizontal-bedded alluvial landform adjacent to a channel, separated from the channel by banks, and built of sediment transported by the present flow-regime." Following an analogy with biological classification, they grouped flood plains into classes, orders, and suborders based on the specific stream power and whether the alluvium of the flood plain is cohesive or noncohesive. Many different classes are found within the same river valley, often evolving in the downstream direction from one class to another class, depending upon the spatial variations of river slope, degree of confinement, and composition of alluvium.

In this paper we continue the biological analogy and document the ontogeny of several flood-plain segments along the Powder River in southeastern Montana. The geomorphic use of the term "ontogeny" was pioneered by Redfield (1965, 1967), who described the formation, growth, and evolution of a salt marsh based on detailed field observations. Redfield's concept of ontogeny as a detailed geomorphic history is important, because thorough observations are needed to clearly understand the spatial and temporal record of erosion and deposition that create and destroy flood plains and ultimately result in a preserved stratigraphy. In order to develop a detailed flood-plain ontogeny, frequent measurements spanning decades are typically required. However, previous studies have often been lacking either in frequency or duration of sampling. Periodic field-mapping studies in the past have often been relatively short in duration (Wolman and Leopold, 1957; Leopold, 1973; Costa, 1974), and although they may include some infrequent great floods (which may actually erode the flood plain), they rarely include more frequent moderate events that may be important processes in flood-plain ontogeny (Wolman and Miller, 1960; Leopold, 1973). Aerial mapping and stratigraphic studies (Schumm and Lichty, 1963; Lewin, 1983; Brakenridge, 1984; Nanson, 1986) can span a sufficient length of time, but the temporal resolution of these methods is rarely appropriate for measuring changes of 1 or 2 yr (and photographs may not indicate the extent of vertical accretion). Indirect methods such as tree rings and tree-tissue modification with their inherent variability (Everitt, 1968; Nanson and Beach, 1977) can be used to infer rates of vertical growth and lateral migration over decades, but cannot provide precise details at time scales of 1 or 2 yr.

This paper documents the ontogeny of a flood plain that is considerably different from the usual development of meandering river flood plains. Rather than observing lateral accretion on point bars or vertical accretion on the valley flat during overbank flows, the flood-plain segments described here grow by suspended-sediment deposition within the widened channel created by the 1978 flood. Flood-plain growth is primarily by vertical accretion, but with a significant lateral component as well, similar to the "oblique accretion" described by Nanson and Croke (1992). Our data document in detail how these in-channel flood plains accrete, a process that has previously been surmised from stratigraphic studies (Brakenridge, 1984; Macklin et al., 1992), but that has not been directly observed before.

ENVIRONMENTAL CONDITIONS

The Powder River is a northward-flowing river that drains 34 706 km^2 of northeastern Wyoming and southeastern Montana. It is unusual today in that no dams or other large engineering structures obstruct the flow or trap sediment. At the gaging station at Moorhead, Montana, near the Montana-Wyoming state line (Fig. 1), the Powder River dis-

*E-mail: jamoody@usgs.gov.

GSA Bulletin; February 1999; v. 111; no. 2; p. 291–303; 9 figures; 2 tables.

charges an average of 12.7 m^3/s (0.40 km^3/yr) and exceeds a discharge of 6 m^3/s about 50% of the time. The annual hydrograph for the Powder River, like that of many midlatitude nonmountain streams, is usually bimodal (Hodson et al., 1973). The first peak (~25 m^3/s) usually occurs between late February and early April, when snowmelt at low elevations (about 1000 m) in the southern part of the drainage basin is accelerated by late winter or early spring cyclonic rainstorms that cause the ice cover on the river to break up as the water flows northward. The ice often jams as it moves northward and causes local flooding, but we are not certain of the magnitude of the influence of such flooding on flood-plain development. The second peak (~45 m^3/s) usually occurs in mid-May to late June when the snowmelt from higher elevation (about 3000 m) in the Big Horn Mountains reaches the High Plains. The 1978 flood (peak discharge equal to 930 m^3/s, daily mean discharge of 779 m^3/s) that widened the channel (Moody and Meade, 1990; Pizzuto, 1994) occurred after a late spring snowstorm (May 4–7, 1978) had deposited 0.4 to 0.8 m of snow over much of central and eastern Wyoming. This snowstorm was followed by warm weather and a large cyclonic storm (May 16–19, 1978) that deposited 50 to 130 mm of rain over parts of the Powder River basin and melted snow at both high and low elevations (Parrett et al., 1984).

Local sources of sediment in the Powder River are the river bed and banks. In some locations, local outcrops of siltstone, shale, and sandstone units produce silt, clay, and sand; but the major source of sediment is reworked alluvial deposits that now exist as terraces throughout the watershed (Hembree et al., 1952). Powder River terraces in Wyoming were described by Leopold and Miller (1954), and we have also observed them in our study area in southeastern Montana. The lowest terrace is predominantly vegetated by cottonwoods (*Populus sargentii*, Everitt, 1968), the middle terrace is frequently cultivated as hay meadows and pastures, and the upper terrace is predominantly vegetated by grasses and sagebrush (*Artemisia cana*). This upper terrace blends into the colluvial slopes extending down from the surrounding badlands.

The river bed of the Powder River is sand and gravel, and the minimum elevation has been essentially constant through time at a particular cross section (Moody and Meade, 1990). The estimated average annual bed-load discharge (83 km upstream from Moorhead, Montana) is about 160 000 metric ton/yr (Hembree et al., 1952). It consists of about 3% silt and clay, 12% very fine sand (0.063–0.125 mm), 40% fine sand (0.125–0.250 mm), 30% medium sand (0.250–0.500 mm), and 15% coarse sand (0.500–4.00 mm) (Hembree et al., 1952, Fig. 29). Some

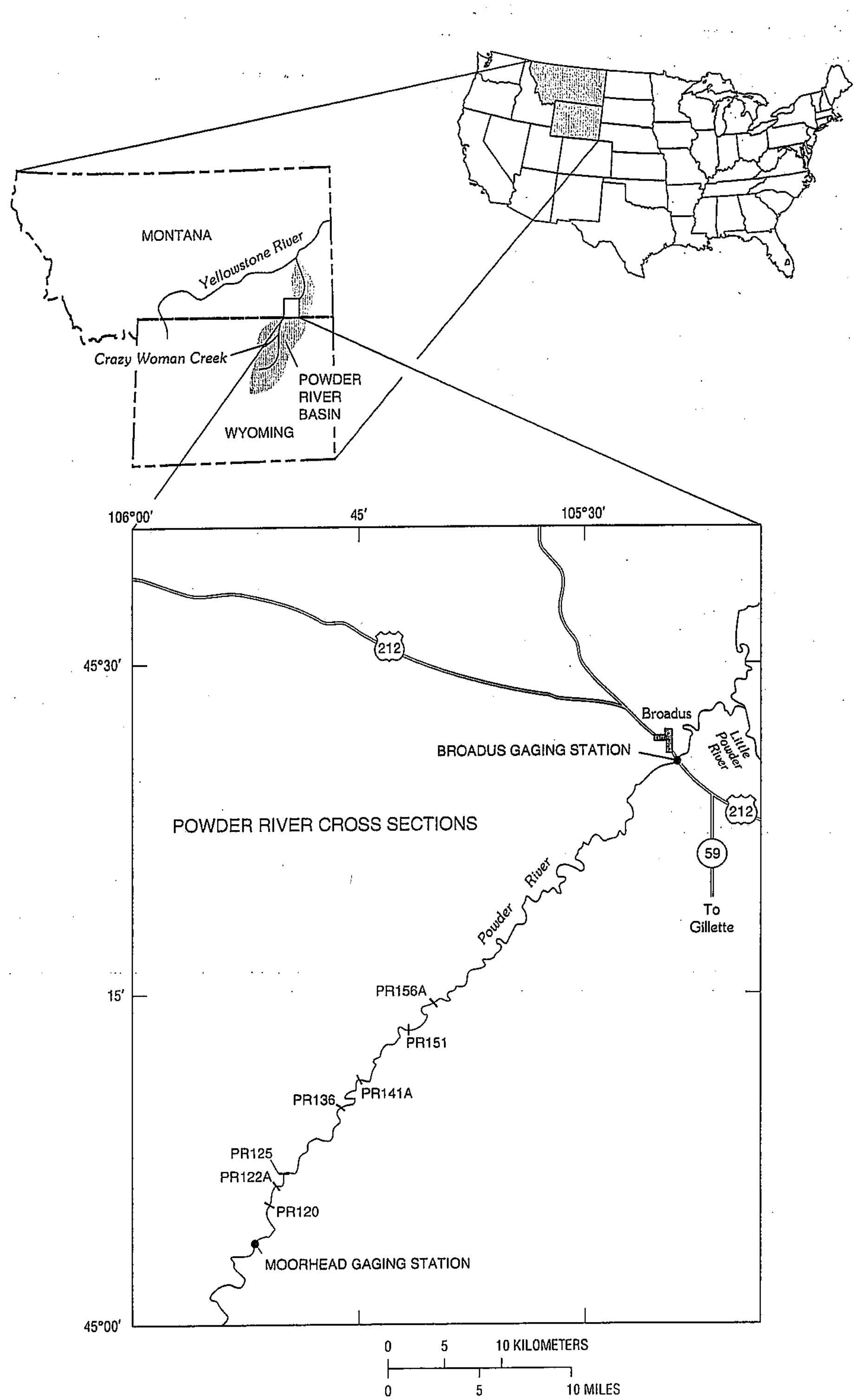

Figure 1. Location of the Powder River drainage basin and the study reach. Repeatedly measured cross sections (shown as short lines across the river) within the study reach are identified by PR and then by the distance in kilometers (measured in 1946) downstream from the confluence of Powder River and Crazy Woman Creek.

gravel probably is transported as well, but no measurements are available.

Suspended sediment is derived from the outcrops of bedrock in the upper river basin, as well as from terraces that form some of the banks. The average annual suspended-sediment discharge of the Powder River into the Yellowstone River is about 2–3 million metric tons (Moody and Meade, 1990). Concentrations reach 20 000 to 30 000 mg/L but typically are 1000 to 5000 mg/L and consist of about 47% clay (<0.004 mm), 35% silt (0.004–0.063 mm), 11% very fine sand, 6% fine sand, and 1% medium sand (based on 42 analyses of samples collected from 1975 to 1988 at Moorhead from discharges of less than 274 m^3/s).

In this paper we use the term "flood plain" not as a general reference to any surface that has been inundated at some time in the past (like the lower terraces), but in specific reference to the landforms that have developed with time within the channel widened by the flood in 1978 (Fig. 2). This flood plain has been called a low flood plain (Everitt, 1968) or a bench by other investigators (Leopold et al., 1964; Hickin, 1979; Woodyer et al., 1979; Page and Nanson, 1982; Pizzuto, 1994), but neither the height nor the morphology distinguishes this type of flood plain from other types that also exist within the study reach on the Powder River. Therefore, in this paper we refer to this type of flood plain as a channel-expansion flood plain, which attempts to identify it by a distinguishing characteristic.

METHODS

The primary method used to record the development of new flood plains within the widened channel was to measure the cross-sectional profile annually or biannually during low-flow conditions (usually August or September) over a period of 18 yr following the flood of 1978. The detailed survey method and annual elevation data from 21 cross sections spaced 3–8 km apart along a 93 km study reach of the river were described and presented by Moody and Meade (1990). At five cross sections, where the primary process has been vertical accretion, the recurrence interval was determined from the partial duration series, flood-plain sediment samples were collected to characterize the sediment, and water-surface elevations were measured at different stages to establish a stage-discharge relation for each cross section.

Recurrence Interval

The recurrence interval, R, of flood-plain–forming discharge is estimated from the partial-duration series of daily mean discharges (October 1, 1929, through September 30, 1995) greater than the mean-annual discharge of 12.8 m^3/s. R is equal to N/j, where N is the total number of years, and j is the rank of the floods, 1 being the highest (Langbein, 1949; Chow, 1950). The partial-duration series was used because flood-plain–building events do not just occur during annual floods, but during all floods greater than some threshold discharge. The daily-mean discharge was used because flood-plain building depends not only on the discharge but also on the duration of a flood event and thus the total volume of water. Although peak discharges may be very large, the duration may be only a few hours, whereas using the daily-mean discharge, the duration is at least 24 hr and therefore a better representation of the total volume of water or magnitude of a flood event.

Sediment Samples

Vertical composite samples consisting of flood-plain sediment deposited between 1978 and 1994 were collected during November 1994 at three to five locations across the new flood plain at cross sections PR120, PR125, PR136, PR151, and PR156A (Fig. 1). Square holes were dug with a shovel to a maximum depth of about 1 m and then a composite sample about 0.01 m thick and 0.1 m wide was collected from the side of the hole from top to bottom. Additional sediment samples were collected at cross section PR120 in 1992, 1994, and 1995. Six samples were collected in 1992 from the new flood-plain crest (Fig. 2) and four samples were collected across the flood-plain flat just downstream from the cross section. Six samples of sandy bed material were collected in 1994; five samples were from the stream channel near the flood plain at PR120 and one sample was from a midchannel sandbar about 50 m downstream from cross section PR141A. Sediment cores were obtained in 1995 (using an Eikelkampf hand-driven soil sampler) to help describe the stratigraphy of the flood plain. Particle-size distribution was determined using standard sieve and pipette methods (Guy, 1969), and a cubic-spline curve was fit to the cumulative sediment-size data assuming that there was no sediment finer than 0.00012 mm (R. F. Stallard, 1995, personal commun.).

Stage-Discharge Relation

Stage-discharge relations were developed for the five study sections (PR120, 125, 136, 151, and 156A) by measuring the water-surface elevation relative to the benchmark at each cross section (elevation is relative to National Geodetic vertical datum of 1929; see Moody and Meade, 1990), noting the time of the measurement and determining the corresponding discharge by the following indirect methods. For most of the annual or biannual field surveys, the discharge was low (0.2–4.0 m^3/s) but sufficiently steady so that the discharge at the Moorhead gaging station was assumed equal to the discharge at the surveyed section. This procedure gave numerous measurements, but all at low discharge. In 1993

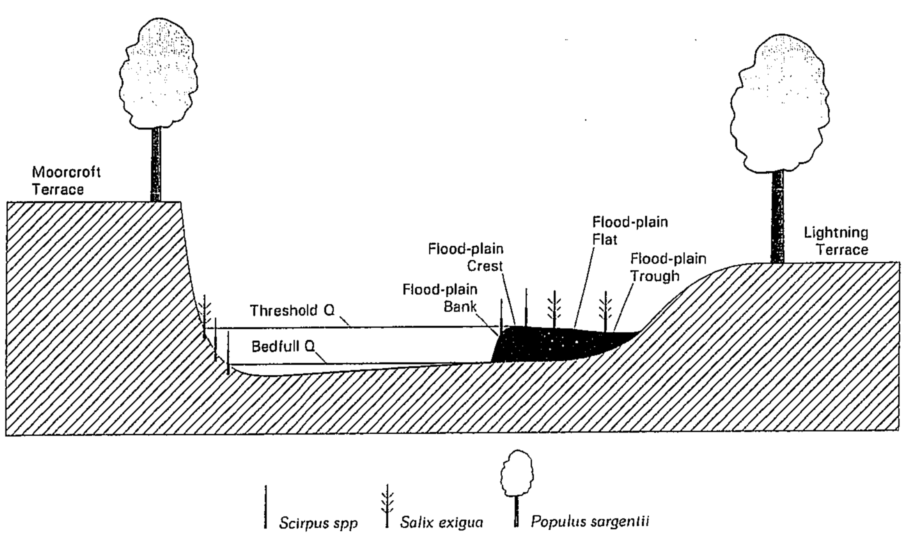

Figure 2. Schematic diagram of the flood plain and its setting. The solid black area is the new flood-plain deposit (1978–1996). The bed-full discharge, about 12 m^3/s, is the discharge required to fill the channel to the break in slope between the bank and channel bed. The threshold discharge is defined as the water discharge that corresponds to the elevation of the flood-plain trough. The terrace names are those used by Leopold and Miller (1954).

and 1994 a few measurements of water-surface elevation were made at higher discharges, but under conditions of unsteady flow corresponding to the propagation of a flood wave. For the latter measurements, therefore, the discharge at the Moorhead gaging station was routed downstream to each cross section with a wave celerity of 1.7 m/s (based on the distance and travel time of the wave between the gaging stations at Moorhead and Broadus, Montana). The discharge corresponding to the water-surface elevation at the cross section at time, T, was equal to the discharge at the Moorhead gaging station at a time, $T - \Delta T$, where ΔT is the river distance between the gaging station and the cross section divided by the wave celerity. A linear regression was determined for the logarithm of both the water-surface elevation, G, and the discharge, Q, which gave stage-discharge relations of the form:

$$G = c \cdot Q^{f} + e, \qquad (1)$$

where e was the minimum riverbed elevation for 1978 through 1994, and c and f are regression constants (Table 1). Only values of Q greater than 10 m^3/s were used so that the stage-discharge relation was not strongly influenced by numerous measurements at low discharge.

Threshold Discharge

The threshold discharge, Q_t, is defined in this paper as the discharge for a given year corresponding to the water-surface elevation that is equal to the elevation of either the flood-plain crest or the trough for a given year. Flood plains are three-dimensional, and the trough is often connected to the main channel at a low place in the crest near the downstream end of the flood-plain segment. The elevations of the trough and crest control two different flood-plain–building processes. One process is the deposition of fine sediment as water and sediment first flow upriver in the flood-plain trough. The second process is the deposition of coarse sediment as additional water and sediment flow over the crest.

The threshold discharge was computed from the stage-discharge relation, which was developed using primarily 1993 and 1994 data. The discharge, Q, is equal to the product of the top width, w, mean depth, H, and the mean velocity, $\bar{v}$. The mean velocity can be represented by the empirical Manning equation

$$\bar{v} = \frac{\sqrt{S}}{n} \cdot H^{\frac{2}{3}}$$

so that in general (for a rectangular channel with cross-sectional area $w \cdot H$)

$$Q = \frac{\sqrt{S}}{n} \cdot w \cdot H^{\frac{5}{3}}, \qquad (2)$$

where S is the water-surface slope, and n is the Manning roughness parameter. In order to use the stage-discharge relation to predict Q_t^y for any year, y, we must adjust for possibly different values of the top width, w_y, and the mean depth, H_y. We assumed that

$$\frac{\sqrt{S}}{n}$$

is constant for similar stages so that

$$\frac{Q_t^y}{w_y \cdot H_y^{\frac{5}{3}}} = \frac{\sqrt{S}}{n} = \frac{Q_t}{w \cdot H^{\frac{5}{3}}}, \qquad (3)$$

or

$$Q_t^y = Q_t \cdot \left\langle \frac{w_y}{w} \right\rangle \cdot \left\langle \frac{H_y}{H} \right\rangle^{\frac{5}{3}}, \qquad (4)$$

where H and w are 1994 values corresponding to the elevation of the flood-plain crest or trough in year, y. This assumption is justified because the changes in

$$\frac{\sqrt{S}}{n}$$

are small compared with changes in Q_t observed over 18 yr on the Powder River. For example, the change in

$$\frac{\sqrt{S}}{n}$$

is only 17% for a change in discharge of 900% (10 to 100 m^3/s), based on applying empirical results published by Osterkamp et al. (1983) to the Powder River with a width-to-depth ratio of about 50. Values of

$$\left\langle \frac{w_y}{w} \right\rangle \cdot \left\langle \frac{H_y}{H} \right\rangle^{\frac{5}{3}}$$

ranged from 0.85 to 1.07 and averaged 0.97 for the five sections.

FLOOD-PLAIN MORPHOLOGY

The channel-expansion flood plains described here are discontinuous features that have developed on surfaces left by the 1978 flood. These surfaces were bare sand and gravel bars (either in midchannel or adjacent to the 1978 bank), or simply elevated sloping surfaces at the channel margins. All of these features inherited from the 1978 flood appear white in the aerial photograph taken four months after the flood (Fig. 3A).

We selected five segments of flood plains that have developed on these surfaces by mostly vertical accretion: two evolved on the right bank (PR120 and PR 156A), two evolved on the left bank (PR125 and PR151), and one evolved into an island (PR136). These flood-plain surfaces have since been colonized by vegetation and thus

TABLE 1. PARAMETERS FOR THE DISCHARGE-STAGE RELATION USED AT FIVE CROSS SECTIONS ON THE POWDER RIVER NEAR THE GAGING STATION AT MOORHEAD, MONTANA

Cross section	Distance downstream from Moorhead gaging station (km)	Minimum river-bed elevation, e (m above NGVD)	Standard deviation of the minimum river-bed elevation (m)	Coefficient c	Exponent f	Coefficient of determination r^2	Number of measurements used in the regression*
Moorhead gaging station†	0.00	1016.97§	N.A.	0.045	0.68	0.994	34
	0.00	1016.97§	N.A.	0.041	0.71	0.999	4#
PR120	4.61	1010.63	0.03	0.15	0.49	0.996	12
PR125	8.59	1004.17	0.10	0.27	0.41	0.996	12
PR136	19.65	991.09	0.10	0.28	0.38	0.780	11
PR151	34.31	973.76	0.06	0.20	0.43	0.884**	9
PR156A	39.14	969.13	0.06	0.14	0.49	0.880††	8

Notes: Discharge-stage relation has the form $G = c \cdot Q^{f} + e$; where G is the water elevation, Q is the water discharge, and e, c, and f are given above. NGVD—National Geodetic vertical datum. N.A.—not applicable.

*Only discharges greater than 10 m^3/s were used.

†The equation developed in this paper is not necessarily the same as the equation used to calculated the official U.S. Geological Survey discharges reported in the Water-Resources Data for Montana.

§This value was not measured but determined as the value which gave the best fit of the rating curve to the data.

#The water discharge was greater than 66 m^3/s for these four measurements.

**This is the value for the linear regression curve (c = 0.20, f = 0.42) that did not fit the data as well as one drawn by eye using the values of c and f in this table.

††This is the value for the linear regression curve (c = 0.39, f = 0.24) that did not fit the data as well as one drawn by eye using the values of c and f in this table.

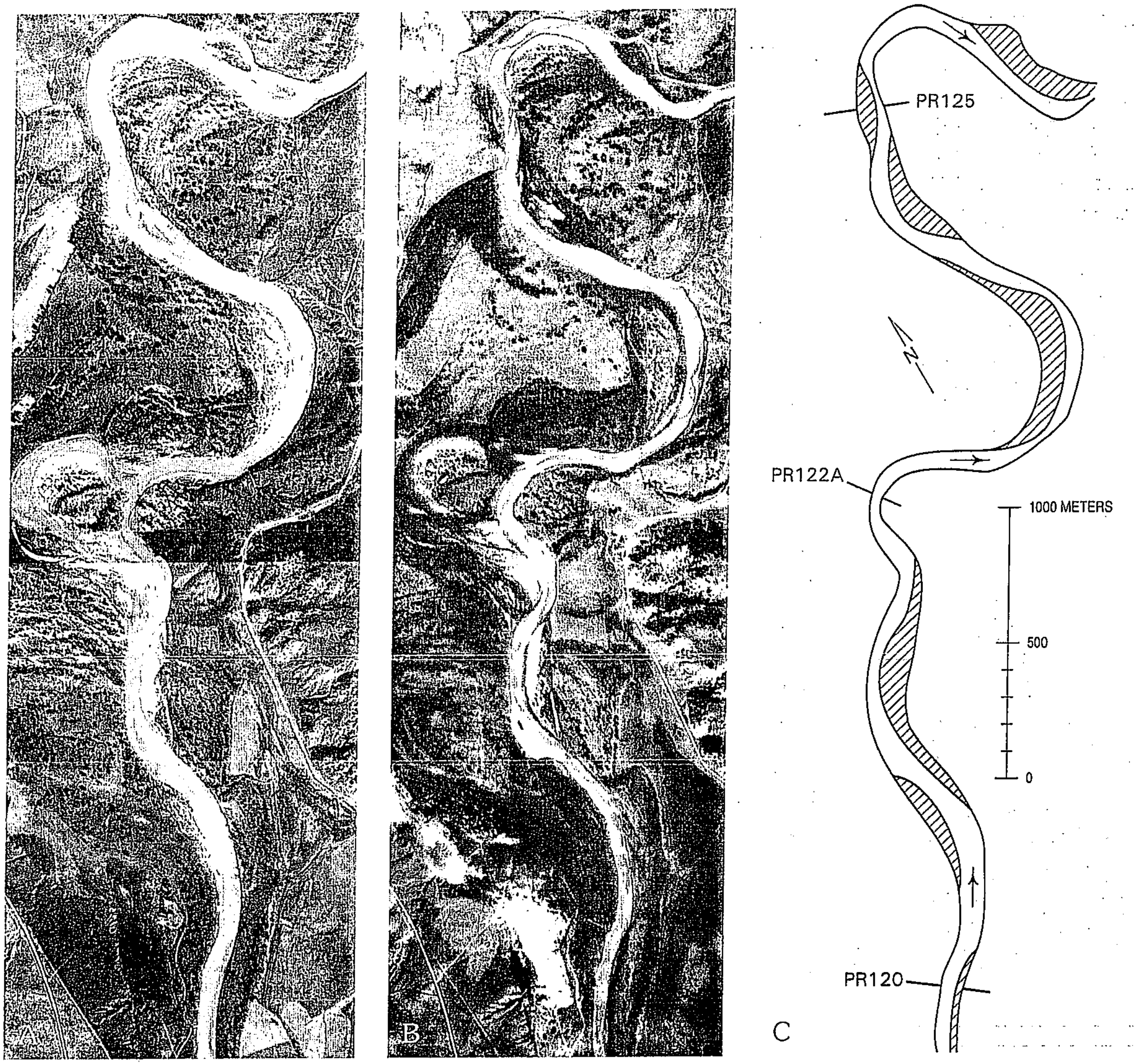

Figure 3. Plan view of a reach of Powder River from section PR120 to PR125. (A) Aerial photograph taken on September 24, 1978, four months after the flood of 1978, showing sand and gravel bars left by the flood as white areas within the widened channel. (B) Aerial photograph taken August 30, 1991, showing the formerly white areas covered by dark vegetation. (C) Diagram of the same reach shown in A and B with the new flood plains outlined by hachures. Photograph A was taken by W. E. Woodcock, Miles City, Montana (original scale is 1:10 000), and B was taken by U. S. Department of Agriculture, Agricultural Stabilization and Conservation Service, Salt Lake City, Utah (original scale is 1:40 000).

appear dark in the aerial photograph taken 13 yr after the flood (Fig. 3B). The length of these five flood-plain surfaces ranges from 150 to 450 m, and the maximum width ranges from 20 to 40 m. The vertical accretion on these surfaces has been about 1 m over a period of 18 yr.

Cross sections of the new flood plain show a nearly level surface resembling a bench (Fig. 4). As of 1996, the elevation of the surface climbs gradually (slopes range from 2% to 7%) from a trough near the old bank toward a crest near a steep new bank. The slope of the new bank ranges from 9% to 28% and is colonized by sedges (*Scirpus* spp.), which begin at the break in slope between the bank and the channel bed. The average discharge corresponding to the water-surface elevations at this break in slope we define as bed-full discharge (see Osterkamp and Hedman, 1982, Fig. 2, for a similar definition). The bed-full discharge has a mean value of 12 m^3/s with a standard deviation of 5 m^3/s. The river flowed within the range of the bed-full discharge (7–17 m^3/s) about 32% of the time between 1979 and 1994, of which 20% was during the growing season from April through September. Willows (*Salix exigua*) begin to grow near the crest of the flood plain so that from late fall to spring the crest appears red from a distance because of the reddish willow branches. The elevation of the crest of the flood plain, between PR120 and PR125, ranges from 0.66 to 1.38 m above bed-full discharge. Although not clearly illustrated in Figure 3, flood plains have formed on both the outside and inside of meander bends; flood plains are on average higher on the outside (1.15 m) than on the inside (0.88 m) of bends between PR120 and PR125. Cottonwood seedlings (*Populus sargentii*) frequently grow on the flood-plain crest but are more numerous across the flat; they decrease in density as they increase in size, and are the largest near the trough and old bank (Fig. 2). Other plants such as tamarisk (*Tamarix ramosissima*), cocklebur (*Xanthium strumarium*), and American licorice (*Glycyrrhiza lepidota*) are also present. A variety of grasses (the most common have been tentatively identified as *Agropyron repens*,

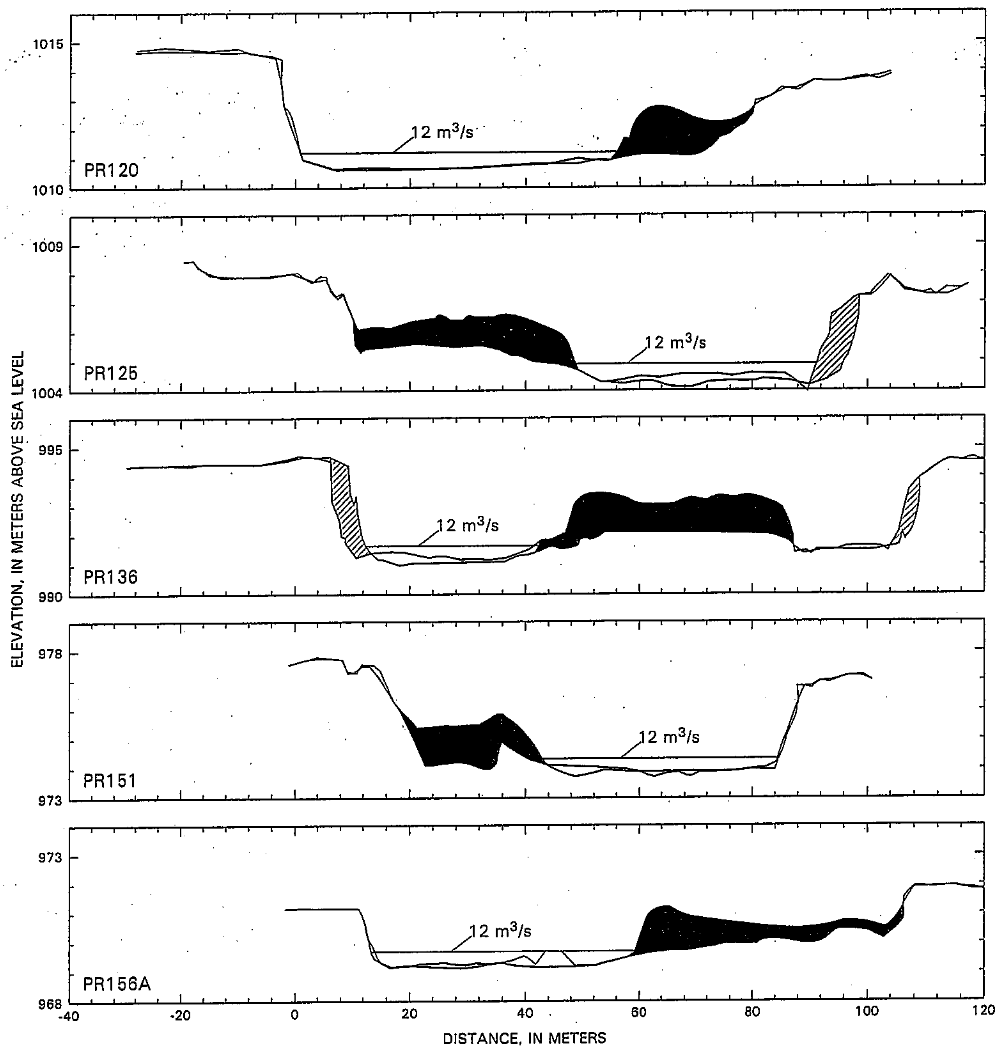

Figure 4. Five examples of flood plains that have evolved by mostly vertical accretion in the flood-widened channel of the Powder River. The 1978 and 1996 surfaces are shown as solid lines. The hachured areas represent net erosion, and the solid black areas represent net deposition.

Agropyron pauciflorum, *Bromus inermis*, *Elymus canadenis*, *Spartina pectinata*, and *Spartina cynosoroides*; Hitchcock, 1935) cover the surface of the flood plain and have stem diameters of 1–5 mm and densities ranging from 1 to 320 stems per square meter.

FLOOD-PLAIN SEDIMENT SIZE

The particle-size characteristics of the suspended-sediment source are quite different from those of the bed-sediment source (Fig. 5A). The particle sizes of the five flood plains decrease from predominantly fine and very fine sand near the edge of the river to silt and clay in the trough. When the particle sizes for all five flood plains are averaged, sand represents about 55% of the total sediment at the crest and decreases to about 10% in samples collected in the trough, whereas clay represents 40% of the total sediment in the trough and decreases to 10% at the crest (Fig. 5B). At most of the sections, the silt content (about 45%) is nearly constant. The size distribution of newly deposited surface sediment (collected about two weeks after a flood event with a maximum daily mean discharge of 205 m^3/s on October 19, 1994) was similar to the distribution for earlier composite sediment samples, but had a higher percentage of sand (80%) about midway down the bank and 50% sand at the crest. The sand on the bank was not stabilized and some already had been eroded during lower stages. We speculate that newly deposited sand is often eroded before it can be stabilized by vegetation, which would decrease sand percentage from 80% to the typical 50% found in composite samples collected midway down the bank. The sediment in the troughs contains mostly silt and clay, and the particle-size distribution closely resembles the size distribution of the suspended-sediment samples collected at the Moorhead gaging station (Fig. 5). The size distribution of sediment in the crests is only slightly finer than that of the bed material from sandbars; the crest accumulates some coarse silt but very little of the fine silt or clay.

FLOOD-PLAIN ONTOGENY

The flood of 1978 left a legacy of sloping sand and gravel surfaces that acted as substrates upon which the channel-expansion flood plain subsequently developed. Development was monitored annually or biannually so that the net change could be determined from the difference between two successive profiles and the surfaces of the flood plain could later be related to the stratigraphy of the deposits.

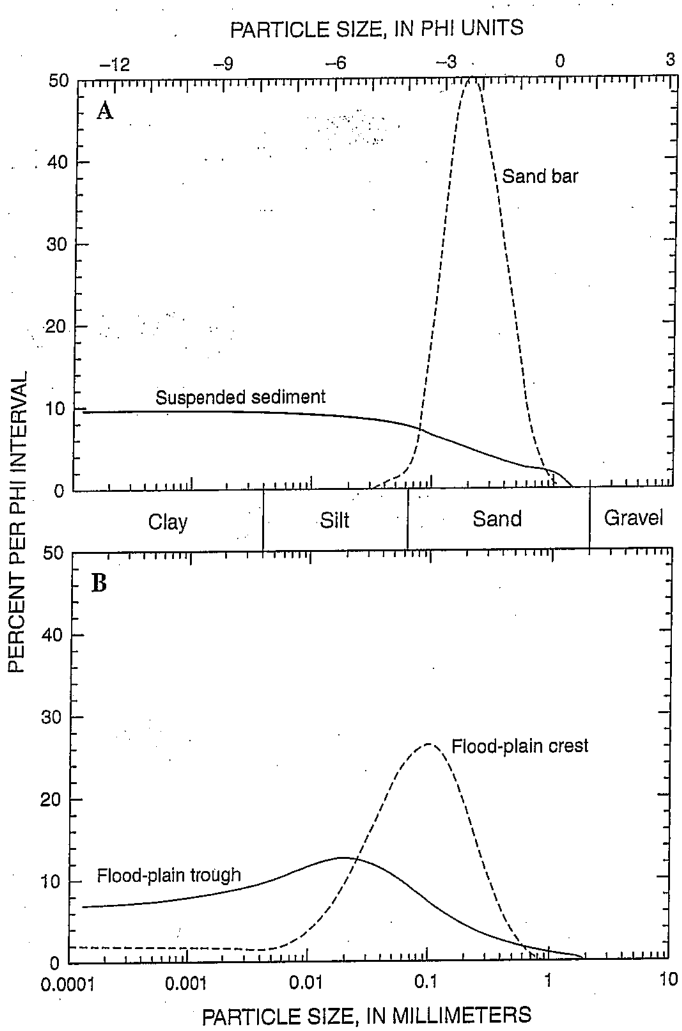

Figure 5. Average sediment-size distribution. (A) Sediment sources: suspended sediment samples (solid line) collected at Moorhead, Montana, from 1975 to 1988 (42 samples), and bed samples (dashed line) collected from sandbars near PR120 (5 samples) and PR141A (1 sample). (B) Flood-plain sediment: trough samples (solid line, 5 samples, no sample from PR136) and crest samples (dashed line, 6 samples) from each section. A cubic spline curve was fit to the cumulative data assuming that there was no sediment finer than 0.00012 mm in the <0.004 mm size class.

Deposition and Erosion Patterns

The ontogeny of the flood plain was similar at all five locations, so only the development at cross section PR120 is described in detail. The flood plain began to grow between October 1980 and September 1982. At PR120 a definite bench-like feature (Fig. 6) was probably deposited by five flood events (with maximum daily mean discharges of 87, 97, 148, 48, and 73 m^3/s) before September 30, 1982. The surface grew vertically by 10–20 cm between stations 63 and 76 m, and the new bank was eroded along its base as a result of four flood events from October 1982 through September 1984. One event had a maximum daily mean discharge of 125 m^3/s and a duration of about a month. Sediment was redeposited over the bank and 2–3 cm was eroded from a broad 4-m-wide crest during the 1985 water year, but during the 1986 water year about 5 cm of new sediment was deposited on the broad crest. New sediment was deposited across the entire flood plain during the 1987 water year such that the bank grew laterally about 2 m toward the river channel and the crest grew vertically about 30 cm and became more pronounced. The crest shifted toward the river to station 64 m from its previous position at station 67 m. The profile changed very little during the 1988 and 1989 water years. Sediment was primarily deposited on the sloping bank again during the 1990 water year, raising the height of the flood plain and extending the bank face outward into the stream channel. This bank face was eroded somewhat in the 1991 and 1992 water years. Several flood events in May–June 1993 added sediment across the entire flood plain with the greatest thickness over the bank and crest (about 30 cm) and lesser thickness over the trough (about 10 cm). Between the surveys in September 1993 and 1994, 2–5 cm of new sediment was deposited. A significant thickness of new sediment (20–30 cm) was added between stations 60 and 78 during the 1995 water year; some previously deposited material was eroded from the sloping bank, and the crest shifted away from the river. In 1996, some of the previously eroded material was redeposited between stations 58 and 59 m. Between 1980 and 1996, deposits were generally thickest near the crest and tapered toward the trough such that the flood plain grew both upward and outward into the river channel.

Both deposition and erosion were important at all five sections. The average net sediment deposition and erosion across the flood plain were calculated for the intervals between annual or biannual surveys for all five flood-plain segments (only PR120 and PR156A are listed in Table 2). The years of greatest activity (1981 and 1982, 1987, 1993, and 1995 water years) were the same at all five segments. Using either the changes of the elevation of the flood-plain crest or flood-plain trough, the rate of growth of the flood plain was very similar at all five sections (Fig. 7) and ranged from 3 to 8 cm/yr for the crest and 2 to 8 cm/year for the trough.

Vegetation took root on the new surface, at first sporadically and eventually more systematically, as the flood plains developed. During the first 1–3 yr following the flood of 1978, the areas on which the new flood plain would eventually accrete were populated fairly sparsely by a variety of opportunistic species that included tamarisk (*Tamarix ramosissima*), cocklebur (*Xanthium strumarium*), American licorice (*Glycyrrhiza lepidota*), and sweet clover (*Melilotus* spp.). Of the three plants that would dominate the floral assemblage (sedge, *Scirpus* spp.; willow, *Salix exigua*; and cottonwood, *Populus sargentii*), the first to form dense clusters was sedge. Eventually, as the flood plain rose by successive layers of accreting sediment, the sloping bank nearest the river was vegetated mostly by sedge, and the upper flatter surface became densely populated by willow and, to a lesser extent, cottonwood. Between October 1985 and September 1990, the plants became sufficiently established that the successively deposited layers of new sediment could accumulate around their stems without damaging them seriously.

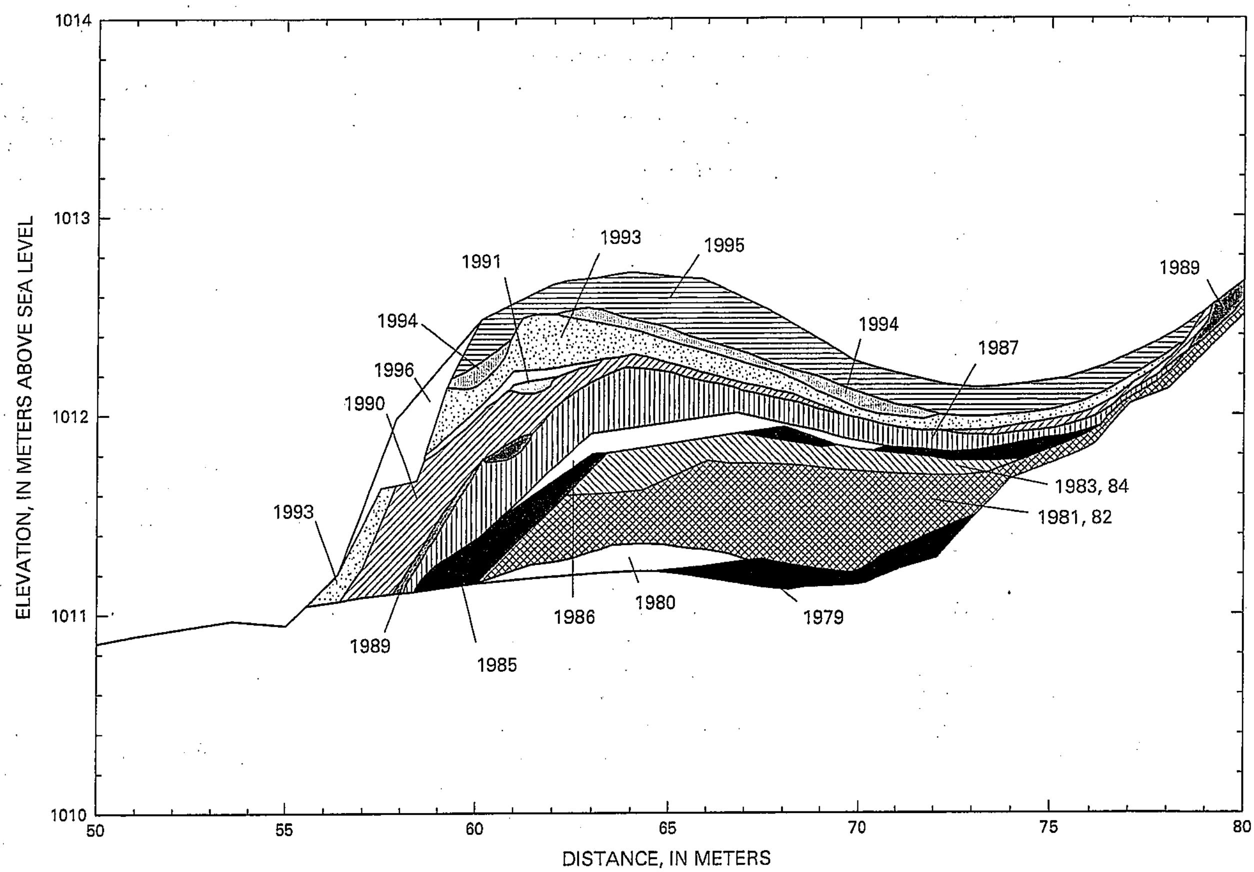

Figure 6. Annual and biannual net sediment accumulation at cross section PR120 for those water years when the water level exceeded the crest of the flood plain.

TABLE 2. DEPOSITION, EROSION, THRESHOLD DISCHARGE, RECURRENCE INTERVAL, AND SUMMARY OF THE MAGNITUDE OF FLOOD EVENTS AT TWO CROSS SECTIONS OF THE POWDER RIVER BETWEEN MOORHEAD AND BROADUS, MONTANA

	PR120 55–85 m							PR156A 60–105 m						
Water year	D (cm)	E (cm)	Q_t (m^3/s)	R (y)	*m*	v (m/s)	M (tons)	D (cm)	E (cm)	Q_t (m^3/s)	R (y)	*m*	v (m/s)	M (tons)
1979	5.2	0.1	13	0.16	3	0.6	210	3.0	1.0	50	0.52	1	1.1	0.3
1980	2.9	1.1	14	0.18	6	0.6	320	3.0	3.4	46	0.49	2	1.1	27
1981			16	0.21	3	0.8	640			27	0.33	3	1.0	290
1982	18.6	1.4	*32	0.37	5	0.9	1300	12.8	1.3	*46	0.49	4	1.3	740
1983			48	0.50	2	0.9	98			65	0.65	1	1.5	5
1984	5.9	2.6	*56	0.56	2	1.1	370	5.1	0.5	*62	0.61	2	1.6	300
1985	3.6	0.7	64	0.64	0	1.2	0	3.0	0.2	60	0.59	0	1.6	0
1986	2.5	0.7	66	0.66	2	1.2	80	3.2	0.8	61	0.61	2	1.6	100
1987	11.9	<0.1	66	0.66	4	1.2	260	8.4	0.0	60	0.59	4	1.6	300
1988	0.3	2.3	79	0.82	0	1.4	0	0.6	1.1	70	0.71	0	1.8	0
1989	1.7	0.3	78	0.82	1	0.3	0.1	2.3	0.8	65	0.65	1	1.7	0.3
1990	8.8	0.3	78	0.82	2	1.5	47	3.6	1.2	62	0.61	2	1.6	59
1991	0.5	2.0	79	0.82	4	1.6	230	1.2	0.4	87	0.94	4	1.9	130
1992	2.2	0.6	79	0.82	3	1.5	10	0.6	0.8	66	0.66	3	1.6	58
1993	8.5	0.1	79	0.81	7	1.5	590	9.5	0.1	74	0.72	7	1.8	680
1994	2.6	0.4	102	1.0	1	1.7	7	1.5	0.5	81	0.85	1	1.8	11
1995	11.4	1.9	94	1.0	3	1.8	1200	12.8	0.2	78	0.82	3	2.0	1500
1996	0.9	0.2	112	1.3	2	1.8	98	0.2	0.8	97	1.1	2	2.0	150

Note: The station distances in meters given below the section numbers are the beginning and ending stations for calculating the net deposition, D, and net erosion, E; the threshold discharge, Q_t, is for the flood-plain trough and for September or October; the recurrence interval, R, is based on the partial duration series of 429 floods greater than the mean annual discharge of 12.8 m^3/s recorded at the Moorhead gaging station from October 1, 1929, through September 30, 1995; m, the number of events; v, cross-sectional mean velocity for the threshold discharge; M, the annual or biannual magnitude in thousands of metric tons is the sum of all events magnitudes during interval between surveys; the event magnitude is equal to the hourly discharge minus threshold discharge for the flood-plain trough, times the duration of the event, times the mean sediment concentration.

*Values are interpolated between 1980 and 1982 and between 1982 and 1984.

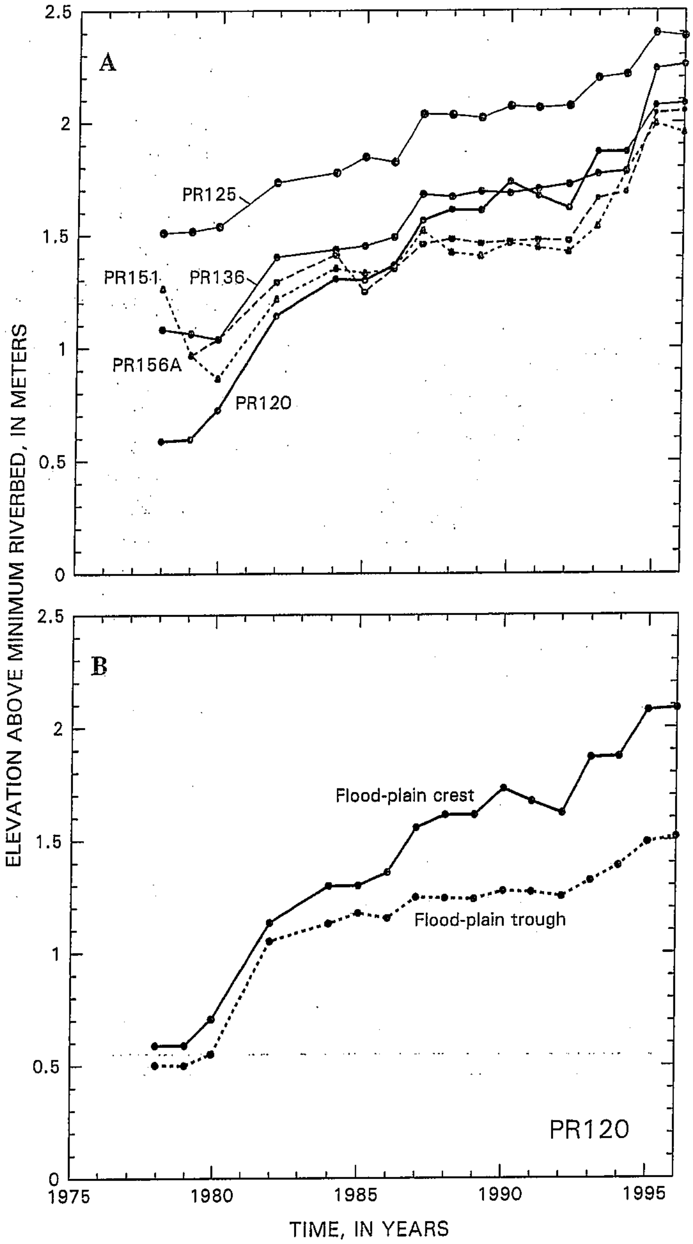

Figure 7. (A) Measured growth curves of the flood-plain crest at five locations on the Powder River between Moorhead and Broadus, Montana, from 1978 to 1996. (B) Measured growth curves of the flood-plain crest and trough at section PR120.

Stratigraphy

The channel-expansion flood plains are composed of interbedded sand and mud that abruptly overlies sand and gravel deposited by the 1978 flood (Fig. 8). On the landward sides of the crests (away from the river channel), bedding planes are parallel to the annually surveyed surfaces. On the riverward sides of the crests, the bedding planes and surveyed surfaces are not parallel and they often intersect each other, demonstrating that periods of erosion occurred as these beds were being created. In the example shown in Figure 8, thin mud layers dip away from the river; they were deposited behind the crest of the flood plain on the flood-plain flat and trough, onlapping the river bank created by erosion during the 1978 flood. Thicker mud layers were deposited near the base of the bank, and the thickest sand layers were deposited near the crest and on the bank of the flood plain, similar to a model described by Zwolinski (1992).

The preserved flood-plain deposits, however, do not fully reveal the original form of the layers because 18%–54% of the accumulation has been eroded from the bank region and 5%–7% has been eroded from the flat and trough region. These stratigraphic relationships reinforce the conclusion drawn from the annual and biannual survey data (Table 2, Fig. 6), that localized bank erosion has been important in shaping the flood plain.

Maps constructed from aerial photographs and field observations suggest that these flood plains form narrow, elongated stratigraphic units bordering the river channel (Fig. 3). Although the data are not presented here, we have verified this hypothesis for the flood-plain site PR120 by observing sedimentary facies in more than 50 hand-driven borings. A similar alluvial architecture of vertically accreted flood-plain deposits along the Duck River in Tennessee was described by Brakenridge (1984).

FLOOD-PLAIN FORMING DISCHARGE EVENTS

Flood plains grow by the deposition of sediment, which occurs only if the water is high enough to cover them. As the flood plains grew following the 1978 flood, the threshold discharge of the crest and trough also increased (Fig. 7, Table 2). The threshold discharge of the trough is used in the remainder of this paper because it represents the lowest limit that must be exceeded before any sediment can be deposited on the flood plain. At PR120, the threshold discharge was only 13 m^3/s in October 1978, but by 1996, the threshold discharge had increased to 112 m^3/s. Averaged over all five cross sections, the threshold discharge increased by a factor of about 3.7 from October 1978 to September 1996. In 1979, the recurrence interval for threshold events averaged about 0.46 yr, so that flood-plain–building events occurred about twice as often as the 1.00 yr partial-duration series recurrence interval (equivalent to the 1.58 yr interval for the annual series) suggested by Dury (1973). The average recurrence interval for the Q_t at the end of the 1995 water year for all five cross sections was about 1.3 yr.

The event magnitude is defined as the total transported suspended sediment in flood waters that exceed the minimum elevation of the flood plain. It is calculated by multiplying the discharge excess (hourly discharge minus the threshold discharge of the trough) times the duration of the event, times the average concentration of suspended sediment during the event, and is a parameter or variable that may be correlated with the average deposition across the flood plain. This does not include an estimate of sediment contributed by bed load because the annual bed-

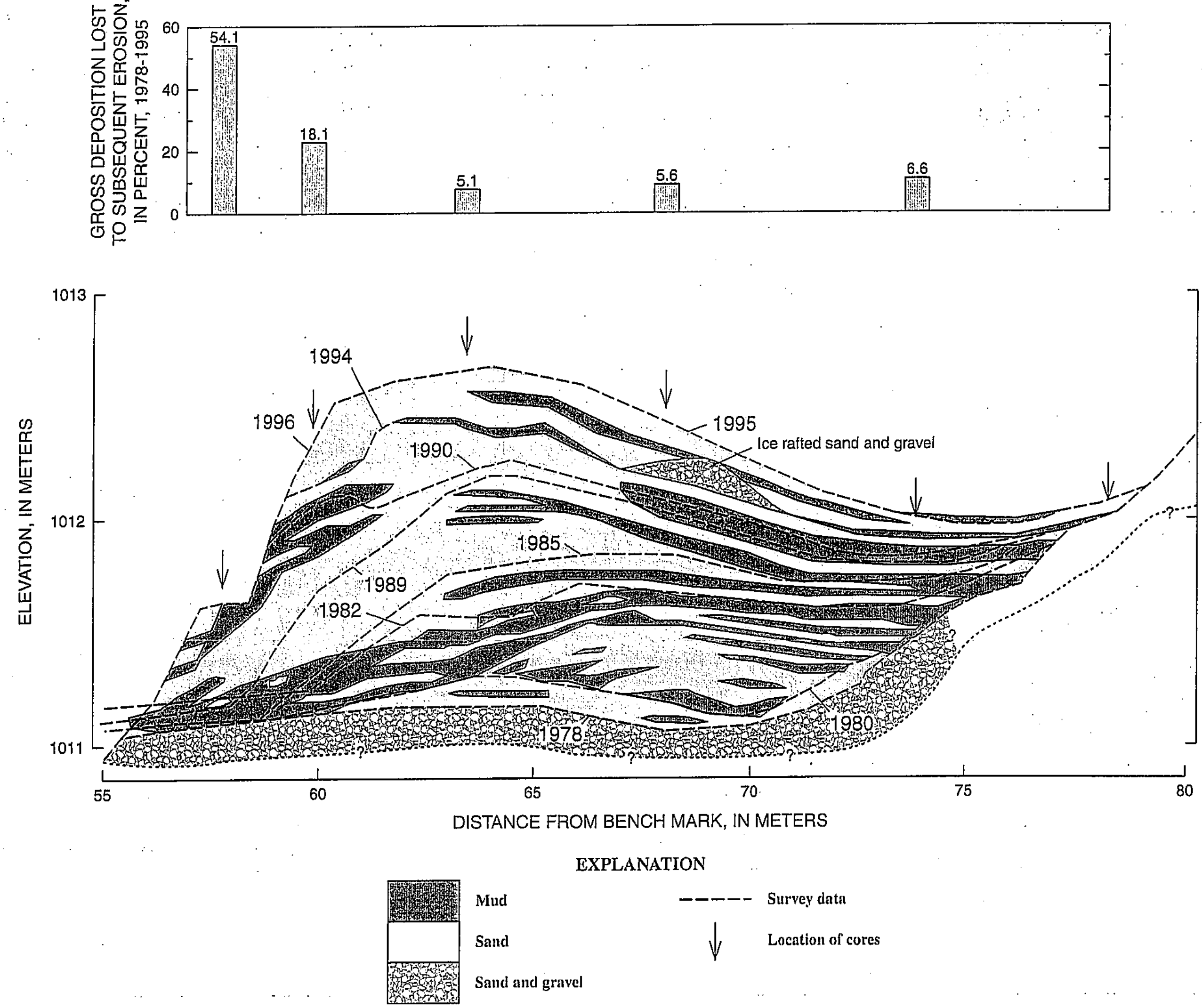

Figure 8. Stratigraphic cross section of the flood plain at section PR120 across the Powder River near Moorhead, Montana. The mud is shown as solid black areas and the sand as gray areas. Some of the annual and biannual surveyed surfaces (see Moody and Meade [1990] for data from 1975 to 1988) are labeled and the arrows indicate the locations of cores.

load discharge is much less than the suspended-sediment discharge. The annual or biannual magnitude is the sum of the event magnitudes of all the flood events that occurred during the interval between surveys.

An event at one section did not necessarily have the same event magnitude at other sections. For example, the longest flood event started on May 14, 1984, and its duration was 811 hr at PR120, 1034 hr at PR125, 656 hr at PR136, 343 hr at PR151, and 613 hr at PR156A. The May 14 event magnitude was different at each section: 350, 580, 320, 109, and 290 thousand metric tons at PR120, PR125, PR136, PR151, and PR156A. The event with the largest peak discharge (242 m^3/s) occurred on July 17, 1987. The largest flood event (except at PR125) started on May 10, 1995, but it was not the longest nor the one with the largest peak discharge. It had a duration of 43–58 hr, a peak discharge of 227 m^3/s, and magnitudes of 464, 436, 382, 464, and 587 thousand metric tons at PR120, PR125, PR136, PR151, and PR156A.

The annual and biannual event magnitudes, M, are correlated with the average net sediment deposition, D (Table 2) across the flood plain (Fig. 9). The correlation is positive and definitely nonlinear ($D = 0.27 \cdot M^{0.24}$, $r = 0.57$); however, 11 points with deposition less than 4.3 cm per water year and corresponding to event magnitudes of zero (see discussion for explanation) cannot be shown on this type of plot. The event magnitude is an estimate of the suspended sediment available for flood-plain growth but does not measure the possible bed-load transport that may also contribute sediment to the flood plain even when the sediment magnitude is zero. Certainly much more sediment was deposited during flood events, but the annual and biannual surveys measure only the net deposition. The scatter in Figure 9 reemphasizes that the magnitudes and the extent of deposition vary significantly among sections for the same event and at the same section for different events. The average deposition across the flood plain, shown in Figure 9, is often the cumulative thickness from several events, so that when the deposition per event is calculated, the range of values is less (0.1–9.0 cm per flood event) than the average deposition between surveys. The mean measured deposition of sediment across the flood plain at

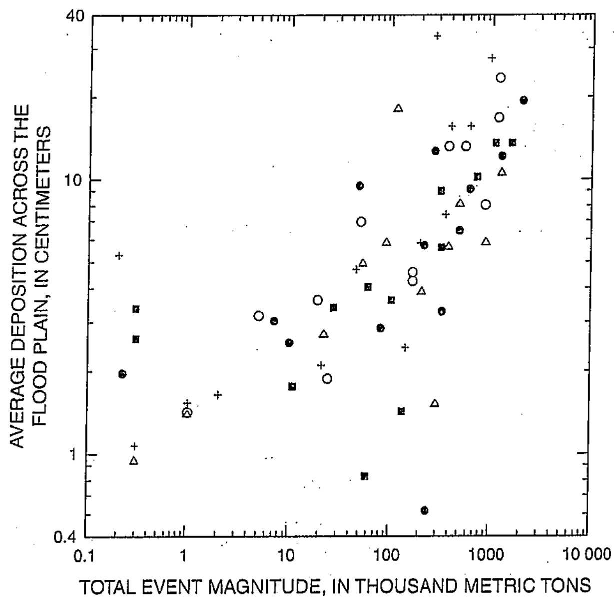

Figure 9. Average net deposition of sediment across the flood plain compared to the annual and biannual event magnitude. The data for PR120 are solid circles, for PR125 are open circles, for PR136 are plus symbols, for PR151 are open triangles, and for PR156A are solid squares.

sections PR120, PR125, PR136, PR151, and PR156A during the 17 yr of the study was 1.8, 2.3, 2.8, 1.8 and 1.8 cm per flood event.

DISCUSSION

Processes of Annual Flood-Plain Accumulation

The growth curves for the channel-expansion flood plains along the Powder River (Fig. 7A) represent the initial phase of the flood-plain ontogeny. The slopes of the growth curves in Figure 7 seem to decrease with time, an asymptotic pattern that may be explained by the decrease in flood frequency associated with a threshold discharge that increased by almost a factor of 10 at some sites (Everitt, 1968; Nanson and Beach, 1977; Pizzuto, 1986, 1987). These curves (Fig. 7A) represent just one realization of many possible random sequences. The order of the flood events can produce very different impressions of the ontogeny of a flood plain. The examples given here along the Powder River give the impression that this type of flood plain grows by slow accretion at a decreasing rate, similar to observations by Ritter et al. (1973). If, however, the events during 1995 had occurred in 1979, when the elevation of the flood-plain segments was lower, and if the results of the 1995 flood were the same, the impression might have been that flood plains grow rapidly and that the development of the flood plain was an episodic process.

Although the annual rates of accumulation generally decrease with time, these rates are highly variable. We have attempted to explain this variability using the event magnitudes (Fig. 9), a variable that only represents the potential for deposition. However, the relatively poor correlation illustrated in Figure 9 suggests that processes other than deposition should be considered. For example, many deposits (particularly those along the banks) are partially eroded soon after deposition. Furthermore, flood plains must also be considered as three- and not two-dimensional features, because in each of the five segments discussed in this paper, the trough was connected to the river at some low point through the crest downstream from the cross section. This means that as the water level rises, water with suspended sediment can back up into the trough and deposit sediment even though the discharge does not exceed the level of the crest. Local ice jams will raise the water locally and deposit sediment, but will not raise the water level at the gage that was used to predict the threshold discharge. Thus, the three-dimensional architecture of the flood plain, local ice jams, and errors in predicting the local elevation of the water (based on the elevation at the gaging station upstream) may explain why there was some annual net deposition even though the event magnitude was zero. Vegetation is clearly another important process because it strongly influences erosion and deposition (Hadley, 1961; Schumm and Lichty, 1963; Smith, 1976; Graf, 1978; Pizzuto, 1984) and definitely influenced the patterns of accumulation documented by our surveys.

Sediment deposition by ice is an additional complicating process, the importance of which has not yet been quantified. In some years, local ice-jam floods have lifted blocks of sediment-laden ice onto the flood plain, and when these blocks melt, decimeters of sediment have been deposited (Fig. 8; Moody, unpubl. data). Ice-jam floods do not necessarily occur during high discharges and could be a source of some of the unexplained variability in Figure 9.

Comparison with Other Ontogenies of Meandering River Alluviation

It is useful to compare our observations of flood-plain formation on the Powder River with two classes of meandering river flood plains defined by Nanson and Croke (1992) in their genetic classification: medium-energy, meandering river, lateral-migration flood plains (order B3), and high-energy, unconfined vertical accretion sandy flood plains (order A3). Meandering river lateral migration flood plains form by quasi-steady point-bar migration, with vertical accretion on the valley flat during floods (Allen, 1965). Unconfined vertical accretion sandy flood plains form by similar processes, but they are occasionally almost completely destroyed by extreme events (Schumm and Lichty, 1963). After an episode of flood-plain destruction, the flood plains of order A3 reform primarily by vertical accretion, but also by island deposition and abandoned channel accretion.

Nanson and Croke (1992) explained the differences between lateral migration flood plains (order B3) and unconfined vertical accretion sandy flood plains (order A3) in terms of the relation between available stream power and the resistance of the flood plain to erosion. Order B3 flood plains have moderate values of stream power and flood-plain sediments are relatively resistant to erosion. Thus, moderate-discharge events tend to control the evolution of order B3 flood plains, and extreme floods are not significant. Order A3 flood plains are subject to high values of stream power that greatly exceed the resistance of the flood plain to erosion, leading to their periodic destruction and subsequent rebirth.

The Powder River probably occupies an intermediate position along the continuum of stream power and erosion resistance represented by order A3 and B3 flood plains. For example, the 1978 flood caused dramatic channel widening. After the flood, new flood plains grew on an unconformable erosion surface, similar to flood-plain recovery in order A3 flood plains. However, the entire flood plain was not destroyed, and as a result, the five flood plains described in this paper formed within the widened channel, rather than across a scoured valley flat. During the past 20 yr, however, we have also documented reaches where flood plains form primarily by lateral meander migration (Moody and Mead, 1990), although these are not described herein. Thus, our observations suggest that flood-plain–forming processes along the Powder River have characteristics in common with both order A3 and B3 flood plains: along some reaches of the river, the channel expands significantly during high discharges, but along other reaches much of the flood plain remains intact. On the former, vertical accretion is the dominant process of flood-plain formation, while on the latter, meander migration is more important.

Stratigraphic Implications

Order B3 flood plains form characteristic deposits that are widely represented in available facies models (Allen, 1970). Order A3 flood plains, although not as well-documented, probably also create distinctive flood-plain deposits. Order B3 flood plains are composed of point-bar and channel deposits overlain by laterally extensive, horizontally bedded, fine-grained overbank deposits. Order A3 deposits are probably composed of channel facies (without extensive point-bar deposits) that are also overlain by laterally extensive horizontally bedded overbank deposits (Schumm and Lichty, 1963).

Despite the transitional nature of flood-plain–forming processes along the Powder River, the deposits described in this paper are significantly different from those of either order A3 or B3 flood plains. Although it has not been described in detail in this paper, the channel facies at the base of the flood-plain sequence often consist of midchannel bar or channel lag deposits, rather than point-bar deposits. Vertically accreted facies consist of interbedded sands and muds similar to those described on natural levees or benches (Allen, 1965; Coleman, 1969; Taylor and Woodyear, 1978). Unlike the laterally extensive deposits of both order A3 and B3 flood plains, the flood-plain deposits described in this paper onlap the margin of the active channel (a geometry nearly identical to that of flood-plain deposits described by Brakenridge [1984]).

Will these deposits represent a significant percentage of the stratigraphic record? The preservation of these deposits will depend on the extent to which they are reworked by future floods and by lateral meander migration, processes that are nearly impossible to predict. However, we have observed facies similar to those described in this paper in a least one cutbank along the Powder River, so apparently some of these flood-plain deposits are preserved. Furthermore, similar deposits have been observed by others (Fujita et al., 1995; Macklin et al., 1992), and Brakenridge (1984) described essentially an entire Quaternary valley fill along the Duck River in Tennessee that formed by periodic channel expansion processes broadly similar to those described herein. Thus, channel-expansion flood plains should be represented by distinctive sedimentary facies in the geologic record. These facies, if correctly interpreted, could provide important evidence for episodes of periodic channel expansion by ancient rivers.

SUMMARY AND CONCLUSIONS

We have described the initial ontogeny of five examples of unconfined, vertical-accretion sandy flood plains that developed on sloping sand and gravel deposits left by the 1978 flood on the Powder River. Soon after their inception, these flood plains developed a cross-sectional profile resembling a bench that sloped gradually (2%–7%) from a crest near the river to a trough near the old bank. Sediment deposited near the crest averaged 55% sand, 35% silt, and 10% clay; in the trough it averaged 10% sand, 50% silt, and 40% clay. This sediment was deposited as layers a few centimeters to decimeters in thickness; beds paralleled time lines on the flood-plain flat and trough, but cut across time lines on the banks. Sediment preserved in the flood plains reflects not only deposition, but also periodic erosion: 18%–54% of the deposition on the bank region has been eroded, while only 5%–7% of the deposition on the flat and trough region has been eroded. By 1985, vegetation was well-established and probably had a significant influence on the subsequent growth of the flood plain.

The 1978 flood had an event magnitude of 5.3 million metric tons, and was both an erosive event widening the channel and a depositional event leaving sediment on the Lightning terrace and in the widened channel. This flood is recorded in the overbank deposits on the terraces and in the locations of the new flood plains. The flood-plain–building events, which followed the 1978 flood, were moderate flood events with maximum event magnitudes ranging from 200 to 1 500 000 metric tons. In 1979, the recurrence intervals for these moderate events were about 0.46 yr, so that flood-plain–building events occurred about twice as often as the 1.00 yr partial duration flood often quoted in the literature. The flood plain grew vertically at an average rate of 2–8 cm/yr, and the average threshold or bankfull discharge for five sections increased from 43 m^3/s at the beginning of the flood-plain building after the 1978 flood to 114 m^3/s at the end of the 1996 water year.

Our results demonstrate that flood plains on meandering rivers can form by vertical accretion within the boundaries of a widened channel. This process creates deposits with a distinctive three-dimensional alluvial architecture and characteristic sedimentary facies. We have speculated that these deposits should be preserved in the stratigraphic record, thereby providing important evidence for episodic channel expansion by ancient rivers.

ACKNOWLEDGMENTS

The Powder River sections are on private ranch land in Montana. The owners, Jim and Ellie Bowers, Jim and Cathy Bowers, Tom and Carla Bowers, Harold Crocker, George and Evelene Fulton, Hugh and Cheri Fulton, Hubert and Mary Gay, Bill and Dina Gay, Glenn Gay, Bunk Huckins, Floyd and Dora Huckins, and Gary Huckins gave us annual access to the sections. The Gay family also related valuable information about the river that only comes from living each day next to the river and also from the innate ability to make and connect observations of river processes. George and Hugh Fulton collected suspended-sediment samples at the Moorhead, Montana, gaging site just upstream from their ranch headquarters. Bob Stallard wrote the spline-fitting program, which enabled us to present graphic comparisons of the sediment size data. Jean Hough, Holly Martinson, Mike Fitzgerald, Mike Karlinger, and Shirley Stewart helped with the annual surveys. Ideas arising from discussions with Koh-ichi Fujita, Jim Smith, and Nicola Surian coupled with the observations and ideas of the Gay family were probably incorporated into the ideas expressed in this paper. Reviews of a previous version by Robert Brakenridge, an anonymous reviewer, and Associate Editor Peter Patton led to important improvements.

REFERENCES CITED

Allen, J. R. L., 1965, A review of the origin and characteristics of recent alluvial sediments: Sedimentology, v. 5, p. 89–191.

Allen, J. R. L., 1970, Studies in fluvial sedimentation: A comparison of fining-upward cyclothems, with special reference to coarse-member composition and interpretation: Journal of Sedimentary Petrology, v. 40, p. 298–323.

Brakenridge, G. R., 1984, Alluvial stratigraphy and radiocarbon dating along the Duck River, Tennessee: Implications regarding flood-plain origin: Geological Society of America Bulletin, v. 95, p. 9–25.

Chow, V. T., 1950, Annual floods and the partial duration flood series: Discussion: Eos (Transactions, American Geophysical Union), v. 31, p. 939–941.

Coleman, J. M., 1969, Brahmaputra River: Channel processes and sedimentation: Sedimentary Geology, v. 3, p. 122–239.

Costa, J. E., 1974, Response and recovery of a piedmont watershed from tropical storm Agnes, June 1972: Water Resources Research, v. 10, p. 106–112.

Dury, G. H., 1973, Magnitude-frequency analysis and channel morphometry, *in* Morisawa, M., ed., Fluvial geomorphology: Binghamton, State University of New York, p. 91–121.

Everitt, B. L., 1968, Use of the cottonwood in an investigation of the recent history of a flood plain: American Journal of Science, v. 266, p. 417–439.

Fujita, Koh-ichi, Moody, J. A., and Meade, R. H., 1995, Flood plain formation and channel narrowing after forced widening of a channel: Comparison between the Powder River case in the US and the Sendi River case in Japan, *in* Nakao, T., ed., Proceedings of the Third PWRI-USGS Workshop on Hydrology, Water Resources and Global Climate Change: PWRI Technical Memorandum no. 3373, chapter 2.

Gilbert, G. K., 1880, Report on the geology of the Henry Mountains (second edition): Washington, D.C., U.S. Geographical and Geological Survey of the Rocky Mountain Region.

Graf, W. L., 1978, Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region: Geological Society of America Bulletin, v. 89, p. 1491–1501.

Guy, H. P., 1969, Laboratory theory and methods for sediment analysis: Techniques of Water-Resources Investigations of the United States Geological Survey, chapter C1, book 5, 58 p.

Hadley, R. F., 1961, Influence of riparian vegetation on channel shape, northeastern Arizona: U.S. Geological Survey Professional Paper 424-C, p. C30–C31.

Hembree, C. H., Colby, B. R., Swenson, H. A., and Davis, J. R., 1952, Sedimentation and chemical quality of water in the Powder River drainage basin Wyoming and Montana: U.S. Geological Survey Circular 170, 92 p.

Hickin, E. J., 1979, Concave-bank benches on the Squamish River, British Columbia, Canada: Canadian Journal of Earth Sciences, v. 16, p. 200–203.

Hitchcock, A. S., 1935, Manual of the grass of the United States: United States Department of Agriculture Miscellaneous Publication 200, p.39–491.

Hodson, W. G., Pearl, R. H., and Druse, S. A., 1973, Water resources of the Powder River basin and adjacent areas, northeastern Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA-465.

Langbein, W. B., 1949, Annual floods and the partial-duration flood series: Eos (Transactions, American Geophysical Union), v. 30, p. 879–881.

Leopold, L. B., 1973, River channel changes with time: An example: Geological Society of America Bulletin, v. 84, p. 1845–1860.

Leopold, L. B., and Miller, J. P., 1954, A postglacial chronology for some alluvial valleys in Wyoming: U.S. Geological Survey Water-Supply Paper 1261, 90 p.

Leopold, L. B., Wolman, M. G., and Miller, J. P., 1964, Fluvial processes in geomorphology: San Francisco, W. H. Freeman and Company, 522 p.

Lewin, J., 1983, Changes of channel patterns and floodplains, *in* Gregory, K. J., ed., Background to palaeohydrology: A perspective: Chichester, United Kingdom, John Wiley and Sons, p. 303–319.

Macklin, M. G., Rumsby, B. T., and Newson, M. D., 1992, Historical floods and vertical accretion of fine-grained alluvium in the lower Tyne Valley, northeast England, *in* Billi, P., Hey, R. D., Thorne, C. R., and Tacconi, P., eds., Dynamics of gravel rivers: Chichester, United Kingdom, John Wiley and Sons, p. 573–592.

Moody, J. A., and Meade, R. H., 1990, Channel changes at cross sections of the Powder River between Moorhead and Broadus, Montana, 1975–88: U.S. Geological Survey Open-File Report 89-407, 252 p.

Nanson, G. C., 1986, Episodes of vertical accretion and catastrophic stripping: A model of disequilibrium flood-plain development: Geological Society of America Bulletin, v. 97, p. 1467–1475.

Nanson, G. C., and Beach, H. F., 1977, Forest succession and sedimentation on a meandering river floodplain: Journal of Biogeography, v. 4, p. 229–251.

Nanson, G. C., and Croke, J. C., 1992, Genetic classification of floodplains: Geomorphology, v. 4, p. 459–486.

Osterkamp, W. R., and Hedman, E. R., 1982, Perennial-streamflow characteristics related to channel geometry and sediment in Missouri River basin: U.S. Geological Survey Professional Paper 1242, 37 p.

Osterkamp, W. R., Lane, L. J., and Foster, G. R., 1983, An analytical treatment of channel-morphology relations: U.S. Geological Survey Professional Paper 1288, 21 p.

Page, K., and Nanson, G. C., 1982, Concave-bank benches and associated flood plain formation: Earth Surface Processes and Landforms, v. 7, p. 529–543.

Parrett, C., Carlson, D. D., and Craig, G. S., Jr., 1984, Floods of May 1978 in southeastern Montana and northeastern Wyoming: U.S. Geological Survey Professional Paper 1244, 74 p.

Pizzuto, J. E., 1984, Bank erodibility of shallow sand-bed streams: Earth Surface Processes and Landforms, v. 9, p. 113–124.

Pizzuto, J. E., 1986, Flow variability and the bankfull depth of sandbed streams of the American Midwest: Earth Surface Processes and Landforms, v. 11, p. 441–450.

Pizzuto, J. E., 1987, Sediment diffusion during overbank flows: Sedimentology, v. 34, p. 301–317.

Pizzuto, J. E., 1994, Channel adjustments to changing discharges, Powder River, Montana: Geological Society of America Bulletin, v. 106, p. 1494–1501.

Redfield, A. C., 1965, Ontogeny of a salt marsh: Science, v. 147, p. 50–55.

Redfield, A. C., 1967, The ontogeny of a salt marsh estuary, *in* Lauff, G. H., ed., Estuaries: American Association for the Advancement of Science Publication 83, p. 108–114.

Ritter, D. F., Kinsey, W. F., III, and Kauffman, M. E., 1973, Overbank sedimentation in the Delaware River Valley during the last 6000 years: Science, v. 179, p. 374–375.

Schumm, S. A., and Lichty, R. W., 1963, Channel widening and flood-plain construction along Cimarron River in southwestern Kansas: U.S. Geological Survey Professional Paper 352-D, 88 p.

Smith, D. G., 1976, Effect of vegetation on lateral migration of anastomosed channels of a glacial meltwater river: Geological Society of America Bulletin, v. 87, p. 857–860.

Taylor, G., and Woodyer, K. D., 1978, Bank deposition in suspended-load streams, *in* Miall, A. D., ed., Fluvial sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 257–275.

Wolman, M. G., and Leopold, L. B., 1957, River flood plains: Some observations on their formation: U.S. Geological Survey Professional Paper 282-C, 107 p.

Wolman, M. G., and Miller, J. P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54–74.

Woodyer, K. D., Taylor, G., and Crook, K. A. W., 1979, Depositional processes along a very low-gradient, suspended-load stream: The Barwon River, New South Wales: Sedimentary Geology, v. 22, p. 97–120.

Zwolinski, Z., 1992, Sedimentology and geomorphology of overbank flows on meandering river floodplains: Geomorphology, v. 4, p. 367–379.

MANUSCRIPT RECEIVED BY THE SOCIETY MARCH 7, 1997
REVISED MANUSCRIPT RECEIVED MARCH 19, 1998
MANUSCRIPT ACCEPTED MARCH 25, 1998

Printed in U.S.A.

Importance of mechanical disaggregation in chemical weathering in a cold alpine environment, San Juan Mountains, Colorado

Anthony R. Hoch* }
Michael M. Reddy } *U.S. Geological Survey, 3215 Marine Street, Boulder, Colorado 80303*
James I. Drever *University of Wyoming, P.O. Box 3006, Laramie, Wyoming 82071*

ABSTRACT

Weathering of welded tuff near the summit of Snowshoe Mountain (3660 m) in southwestern Colorado was studied by analyzing infiltrating waters in the soil and associated solid phases. Infiltrating waters exhibit anomalously high potassium to silica ratios resulting from dissolution of a potassium-rich glass that occurs as a trace phase in the rock. In laboratory experiments using rock from the field site, initial dissolution generated potassium-rich solutions similar to those observed in the field. The anomalous potassium release decreased over time (about 1 month), after which the dominant cation was calcium, with a much lower potassium to silica ratio.

The anomalous potassium concentrations observed in the infiltrating soil solutions result from weathering of freshly exposed rock surfaces. Continual mechanical disaggregation of the rock due to segregation freezing exposes fresh glass to weathering and thus maintains the source of potassium for the infiltrating water. The ongoing process of creation of fresh surfaces by physical processes is an important influence on the composition of infiltrating waters in the vadose zone.

INTRODUCTION

Chemical weathering is a primary source of solutes in surface and ground water and is also an important source of mineral nutrients in soils for plants and microorganisms. Processes and kinetics of chemical weathering are of interest to the geochemical community because of efforts to understand and model soil development (Sposito, 1985), buffering of watershed acidification (Mast and Drever, 1987), and global chemical cycles (Berner et al., 1983). Accompanying the effort to quantify chemical fluxes from weathering has been a debate over how to use results of dissolution experiments in modeling of natural processes (Sverdrup and Warfvinge, 1995). At the center of the debate is the observation that experimentally determined rock- and mineral-dissolution rates are often several orders of magnitude faster than rates calculated on the basis of field data.

Discrepancies in laboratory- and field-determined weathering rates have been attributed to various factors including experimental mineral preparation (Holdren and Berner, 1979), differences in mineral wetting (Swoboda-Colberg and Drever, 1992), and variations in solution compositions (Burch et al., 1993). Minerals prepared for experiments by grinding and sieving exhibit two distinct stages of dissolution-driven solute flux. The first is the initial, rapid release of solutes to solution, which is associated with freshly created, high-energy surfaces, followed by a much slower approach to steady-state dissolution (Holdren and Berner, 1979). In experimental systems, the rapid "pre–steady-state" dissolution is nearly impossible to quantitatively reproduce (Eggleston

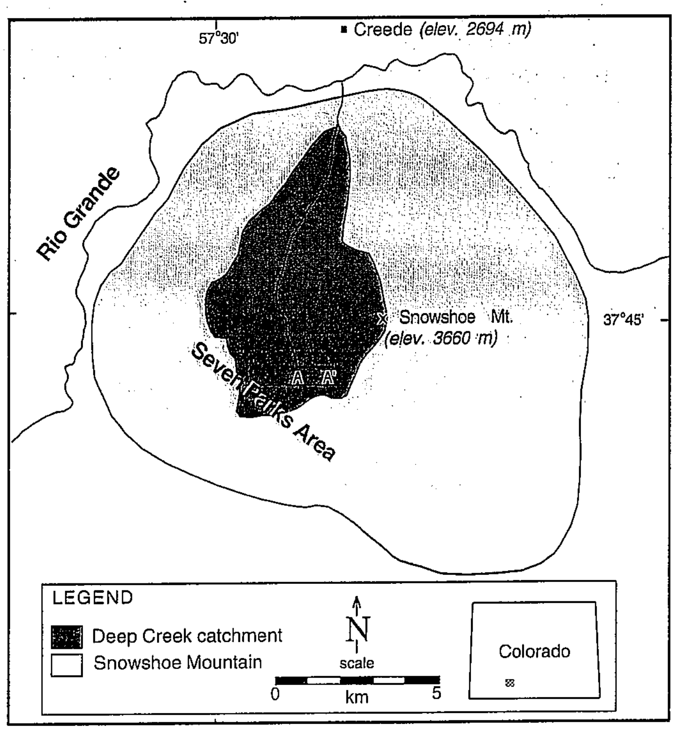

Figure 1. Location map of the Seven Parks study area. Darker shaded area is the Deep Creek drainage on Snowshoe Mountain (after Claassen et al., 1986). The Seven Parks area is at the head of Deep Creek. The cross-section trace at A–A′ includes sampling sites and is shown in Figure 2.

*E-mail: tonyhoch@usgs.gov.

GSA Bulletin; February 1999; v. 111; no. 2; p. 304–314; 9 figures; 6 tables.