CONCAVE-BANK BENCHES IN THE FLOODPLAINS OF MUSKWA AND FORT NELSON RIVERS, BRITISH COLUMBIA

Although concave-bank benches rarely occur in freely meandering rivers, they may constitute a significant proportion of the floodplain formed by the downvalley migration of the tight channel bends of confined meanders. This study reports the results of a field survey of the floodplains of Fort Nelson and Muskwa rivers, two of many northeastern British Columbian rivers whose meandering is confined between the resistant valley sides of former glacial meltwater channels. The formation and character of contemporary concave-bank benches and the morphology and sediments of the corresponding floodplain features are described. The concave-bank benches form lateral ribbons of deposition along the valley walls and constitute about one-third of the entire floodplain.

This paper is concerned primarily with floodplain features deposited in separated flow on the concave side of river bends of tight curvature. Carey (1963, 1969) first recognized the importance of such separation zones in the formation of river floodplains and documented several cases of 'eddy accretions' associated with 'abrupt-angle configuration' of the channel planform of the Mississippi River.

Woodyer (1975), Taylor and Woodyer (1978), and Woodyer, Taylor, and Crook (1979) subsequently described similar depositional environments on the contorted bends of the Barwon River in eastern Australia and termed the low attached bar of eddy accretion deposits a 'concave-bank bench.' I have also described the character and sedimentation dynamics of concave-bank development on tightly curved bends of the Squamish River near Vancouver, in British Columbia (Hickin 1979). Although these features seem to be most commonly associated with downvalley migration of meander trains that impinge on resistant bluffs, they also occur (much less commonly) in any zone of flow expansion in which the accompanying steep pressure gradients promote flow separation at the concave bank. For example, flow will readily separate to isolate bank scallops produced by flood scour or a protruberance caused by bank slumping.

An important notion implicit in these accounts is that the eddy accretion and the resulting concave-bank bench are relatively unimportant in the general context of floodplain deposition. They may constitute an important feature on a particular channel bend, but they remain a local effect ranking well below point bar accretion and overbank deposition as a mechanism of point bar and floodplain construction in general.

More recent studies by Nanson and Page (1982) and Page and Nanson (1982), however, challenge the
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Eddy accretion deposits forming concave-bank benches
Separated flow at the concave bank

Figure 1
The effect of valley confinement on the planform of meanders and potential sites of concave-bank bench development and preservation

universality of this notion. Nanson's recent field investigations in British Columbia have confirmed that there is a particular circumstance in which concave-bank benches may be preserved, resulting in as much as one-third of the floodplain being eddy accretion deposits: the case of confined meanders. He identifies those of the Fort Nelson River in northeastern British Columbia as the type example (Page and Nanson 1982). The effect of confinement of meander planform has been noted elsewhere (see Lewin and Brindle 1977) and is shown in Figure 1. The natural curve of the bends is truncated and the meander train is distorted to a saw-tooth sequence of curves, convex to the direction of flow and channel migration. These bends meet at the valley walls, forming abrupt angles and ideal sites for eddy accretion and for the formation of concave-bank benches. As the meander train migrates downstream, it leaves behind lateral ribbons of eddy accretion deposits along the valley walls. An examination of aerial photographs of the many cases of confined meanders in northeastern British Columbia and Alberta indicates that this type of planform distortion is most pronounced when the ratio of valley width to channel width is between 3 and 5. A smaller ratio suppresses meandering, and a larger ratio allows too great a degree of free meandering for the systematic formation of concave-bank benches.

Clearly, the genesis, morphology, and sedimentology of confined meander floodplains may be fundamentally different from those associated with free meandering. The fact remains, however, that this notion largely is speculative, based as it is on aerial photograph interpretation and on almost no field data. The present paper addresses this problem by reporting the results of a recent field survey of the floodplains of Fort Nelson and Muskwa rivers by the writer.

The Study Area

The Fort Nelson River, a major tributary of the Liard River and thus part of the Mackenzie River system, carries Arctic-bound runoff from the Interior Plains and Rocky Mountain Foothills of northeastern British Columbia (see Figure 2). Field sites are located along the one hundred kilometres of river floodplain immediately downstream of the town of Fort Nelson on the Alaska Highway. The hydrologic and sediment supply characteristics of the river at the field sites reflect the interaction of the two rather contrasting sub-basins, each of which forms about half of the 40,000 km² of drainage area upstream of Fort Nelson. The eastern sub-basin, occupied by the Sikanni Chief, Fontas, and Fort Nelson rivers, is largely formed in gently southward-dipping
Tertiary and Cretaceous sediments of the Alberta Plateau. These thick sequences of weak shales and intercalated sandstone members contribute substantial quantities of sediment for river transport. Here the upland surface of the Alberta Plateau is relatively flat or gently rolling and lies between 1,000 and 1,500 meters above sea level (m.a.s.l.). Drainage is poorly organized, and there are large areas of muskeg through which tributaries tortuously meander to their incised trunk streams. In the Fort Nelson catchment, little of the Alberta Plateau surface remains uneroded, and much of the resulting Fort Nelson Lowland is below 700 m.a.s.l. Only the Sikanni Chief River taps the higher and steeper regions (up to 2,900 m.a.s.l.) of folded and faulted Palaeozoic and Mesozoic sediments of the Rocky Mountain Foothills.

In contrast, the western sub-basin is largely formed in the highest part of the Alberta Plateau (up to 1,700 m.a.s.l.) or in the adjoining Rocky Mountain Foothills (up to 2,350 m.a.s.l.) and the Muskwa Ranges of the Rocky Mountains (peaking at 3,200 m.a.s.l.). Here the rugged Muskwa Ranges are formed in Palaeozoic and Proterozoic limestones and metasediments.

The entire area was heavily glaciated during the Pleistocene, and the higher areas of the western sub-basin today still support glaciers and small icefields. Precipitation, about half of which is snow, increases up the elevation gradient from the eastern sub-basin (about 50 cm/yr) to that in the west (about 80 cm/yr). The effect of these environmental controls on the hydrology of the Lower Fort Nelson River is summarized in Figure 3. The annual hydrograph shows a steep rising snowmelt limb from ice-break-up in late April to a pronounced peak in mid- to late June and a subsequent rapid decline in discharge to winter low-flow levels. The eastern sub-basin also peaks in mid- to late June, but is considerably less than the flow peak from the western basin, which typically occurs about four weeks later. During the geomorphologically active months of May to October, about 60 per cent of the flow in the Lower Fort Nelson River is derived from the western sub-basin and the remainder comes from the
eastern sub-basin. Nevertheless, the timing of the peak flow on the Lower Fort Nelson is controlled by the hydrologic events of the eastern sub-basin. The annual instantaneous peak flow on Muskwa and Fort Nelson rivers is related to summer rainstorm events, a recent example of which is described by Smith (1975). There may also be some flood enhancement by river-ice processes during break-up (Smith 1979).

Figure 3a shows predictably contrasted suspended-sediment load/discharge relations for the two sub-basins. Sediment concentrations from the eastern sub-basin are an order of magnitude greater than those from the western sub-basin for given discharges. The substantial scatter characterizing these relations, particularly in the case of the western sub-basin, indicates that sediment supply likely is much influenced by changing within-channel sediment storage and by discrete geomorphic events such as bank slumping and cut-off formation (Sherstone 1983). Integration of the hydrologic and sediment concentration record indicates that, at the mean annual flood of 2,500 m$^3$s$^{-1}$ on the Lower Fort Nelson River (see Figure 3c), the suspended sediment concentration is about 7,000 mg$^{-1}$ and the equivalent load is 1.512 million tonnes per day. A detailed review of hydrologic and sediment transport data is available in Grey (1981). Unfortunately, no data...
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15

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m

Fort Nelson River
near Fort Nelson

W = 115 Q^0.08

100.0

10.0

m

0.1

m. ms^-1

10

100

1000

10,000

Q, m^3 s^-1

Mean annual flood

Figure 4

Hydraulic geometry of Fort Nelson River at Fort Nelson based on Water Survey of Canada data for gauging station 10cc001.

Field and Laboratory Work

Channel planforms and general survey data for this study are based largely on photogrammetric analysis of BC government photographs. Topographic detail on the floodplain surface was obtained from theodolite ground transects, and channel cross-sections are based on echo-depth profiles recorded by a Raytheon De719b fathometer. Sediment was sampled from the channel bed by extracting cores in a 2.5 cm x 2 m coring tube. Sediment was sampled at depth in the floodplain by using natural exposures (bank cuts on the main channel and in tributaries) and digging shallow pits (1–2 m in depth). Samples were mechanically analysed in the laboratory using a combination of sieving (at 1/2 \( \phi \) interval) and a Micromeritics Instrument Corporation Sedigraph 50000 for material in the silt and clay size range. The conventions of Folk and Ward (1957) are followed in determining mean and median particle size (\( D^* \), \( D_{50} \)) and sorting coefficient (So) from graphical analysis.

About forty actively forming concave-bank benches were examined in the field although detailed morphologic and sedimentological data for only seven cases are presented here. These particular bends were selected because together they display the full range of geomorphic characteristics exhibited in the study reach in its entirety; they are shown in Figure 5.

Contemporary Fluvial Sedimentation

The morphology and sedimentology of the Fort Nelson River floodplain can be interpreted in terms of fluvial processes observed in the contemporary channel. The floodplain is formed and destroyed simultaneously at the rate at which the confined meander train migrates downvalley (about 5–7 m/year; see Hickin and Nanson 1984). Meander wave-lengths typically are about 3,500 m, and the age of the floodplain material therefore rarely exceeds about 400 years in most reaches at the downstream limit of the 100 km-long study reach.

Fort Nelson River has deposited its ribbon of floodplain on the floor of an abandoned glacial meltwater channel. This palaeochannel forms a 1.5-to-2.0-km-wide valley incised 70 to 80 m into the surrounding muskeg plateau. The palaeochannel sediments form steep bluffs containing cobbles up to 1 m in diameter. These coarse sediments are contributed directly to the present channel at points of river impingement where there is consequent erosion of the bluffs.
Figure 5
Examples of concave-bank benches on Muskwa (M) and Fort Nelson (FN) rivers (BC Government aerial photographs); site location in river kilometres downstream from the Muskwa/Fort Nelson confluence are (A) M, -13km; (B) M, -8km; (C) M, -1km; (D) FN, -13km; (E) FN, -14km; (F) FN, +82km; (G) FN, +63km; (H) FN, +75km.
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In all cases concave-bank benches form as bars attached to the concave bank of a tight river bend, so distorted because the channel has impinged on the steep valley wall of the meltwater channel (see Figure 5). This point of impingement marks the downstream limit of the concave-bank bench, and the upstream limit is less well-defined where it merges with the downstream tail of the point bar. The concave-bank bench is deposited almost entirely upstream of the bend apex, a relationship also noted by Page and Nanson (1982) on the Murrumbidgee River.

The active concave-bank is identified easily on aerial photographs because it supports little or no vegetation, contrasting with the willow, alder, cottonwood, and spruce tree-covered bars in the older part of the succession beyond it (upvalley).

In general, the more severe the bend distortion the more extensive and better developed is the active concave-bank bench. For example, the more open bends in Figure 5A and C have distinctly less obvious benches than do those in the hairpin bends depicted in Figure 5D, E, and F.

Not revealed on aerial photographs, but evident on Raytheon sonar records, is incipient concave-bank bench formation beneath the water surface and streamward of the active bench. Depending on their stage of development, these bars can vary in size from insignificant features to major mid-channel bars. For example, Figure 6 shows the Raytheon profiles across the incipient concave-bank benches on the bends photographed as H, E, and F in Figure 5. In each case the bars eventually will build to the level of the floodplain surface. The process at bend F is almost complete, and the channelward growth of a small but longitudinally continuous bar in about 4.0 m of water probably signals the initiation of a new bench in the downvalley succession.

Flow over the concave benches is separated from the main flow and takes the form of a large elongated eddy centred over the features. At the streamward boundary of the concave-bank bench the separation envelope is highly unstable and was observed to break down continually and re-form locally as parcels of water were advected from the main flow to the separation zone over the bench. Once these smaller eddies are captured by the separated flow they rapidly dissipate, presumably allowing their load of suspended sediment to settle out in the relatively quiescent water over the central part of the bench. At the downstream end of the concave bench the flow reverses direction and returns along the channel bank to reverse again at the upper end of the feature, thus completing the primary circulation of the large eddy. The reverse flow near the channel bank is sufficiently strong (maximum measured velocities up to 0.75 m s\(^{-1}\)) to keep scoured a gutter separating the bench from the bank. This gutter eventually may be preserved in the floodplain as a swale separating ridges (over benches) one from the other. Ripples and dunes formed on the bed of this gutter leave sedimentary structures consistent with the "reversed" direction of flow.

Undisturbed near-surface samples of sediment were obtained in short cores extracted from several actively forming concave-bank benches. These samples are remarkably similar in particle size characteristics, and three representative sets, respectively from bends E, D, and F (in Figure 5) are shown in Figure 7A, B, and C. Samples were obtained from the upstream zone (samples E-1, D-1, and F-1), the centre (samples E-2, D-2, and F-2), and the downstream zone (samples E-3, D-3, and F-3) of each concave-bank bench. All nine samples have been combined to produce a composite particle size distribution in Figure 7D.
The concave-bank bench material is silty sand with the modal class in the very fine sand range; in the composite sample, $D_{50} = 0.03$ mm, $D^{*} = 0.69$ mm, and $S_o = 1.00$. It is moderately to poorly sorted depending on the relative amounts of silt and coarse clay present. These low-energy deposits contrast markedly with the sandy gravel of the basal sediments in the adjacent point bars.

There is no pronounced gradation of particle size along the concave-bank benches, although that at bend F (in Figure 7c) indicates that there material fines toward the centre of the bench, a trend consistent with the observed pattern of flow intensity within the separation zone.

The relation of the particle-size distribution of the concave-bank bench material to that of the sediment suspended in the flow is shown in Figure 7d. The bulk of the bench material (90 per cent) is in the very fine sand to coarse silt range and is extracted from the coarsest 36 per cent of the suspended sediment in the flow. Three-quarters of the suspended sediment is in the silt range; most of it appears to remain in suspension and thus is transported through the system. The suspended-sediment particle size data are for samples collected by the Water Survey of Canada in May 1982 from the Fort Nelson River just upstream of the Muskwa River junction (discharge at the time was 1,020 m$^3$s$^{-1}$).

Figure 7 shows a series of shallow exposure logs for the well-developed but actively forming concave-bank bench on bend H (see Figure 6). Again, the most striking feature of these records is the remarkable uniformity in the size of the material. It is very fine sand throughout with some upward fining to silt near the surface. There are few internal structures other than horizontal laminations, although small trough sets of climbing ripples are evident in some sections. In most cases these structures are regressive ripples in the sense that, although they indicate flow directions consistent with the circulation of the separated flow, they face upstream with respect to the flow through the main channel. Localized concentrations of organics in the form of lenses of leaf litter commonly are associated with horizontally bedded very fine sand and silt.

There is a strong tendency for the organic content of this bar to increase toward the surface of the feature.

The exposures shown in Figure 8 were readily accessible because the downstream and streamward margins of the concave-bank bench had been eroded by the low flow to produce vertical scarps. Erosional margins of bars are common and suggest that concave-bank benches may be formed during high flows and slowly destroyed during intervening low-flow periods. If this is the case then, clearly, preservation of the contemporary features in part depends on the relative dominance of the constructional phase of the annual flood over the destructive low flows.

**Floodplain Morphology and Sedimentology**

Behind each actively forming concave-bank bench is an upvalley succession of increasingly older benches (see Figure 5). Although those benches nearest the channel may produce an undular topography of bench and swale, the floodplain surface quickly changes away from the river to a sensibly flat topography. Clearly, overbank accretion rapidly obscures the initial forms of each concave bench as a distinct and separate bar. This circumstance contrasts with the well-defined ridges and swales on adjacent point bars (also see Hickin and Nanson 1975; Nanson 1980). Nevertheless, the general alignment of these older ridges remains clearly visible on aerial photographs because it is reflected in vegetation zoning, apparently sensitive to very small
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0.013 > D50 (mm) for sample at this point

- Silty sand: plane beds
- Silty sand: type B ripples
- Silty sand: type A ripples
- Silty sand: troughs
- Sandy silt: plane beds
- Sandy silt: plane beds (sinusoidal waves)
- Sandy silt: plane beds

Figure 8
Section logs showing sedimentary structures and particle size for sediments in an active concave-bank bench on Fort Nelson River (bend H)

variations in soil moisture and localized drainage conditions.

Contrary to expectations set by Carey’s work on the Mississippi River, the general elevation of the concave-bank deposits in the floodplain is not distinctly lower than the surface of the point bar material, although locally such a difference may exist. Concave-bank benches appear to be lower on aerial photographs because the floodplain vegetation is commonly more open here in contrast to the heavily timbered point bars.

The concave-bank benches on the Fort Nelson River apparently are able to build rapidly to the general floodplain elevation because of the abundance of suspended sediment in the fine sand and silt size range. The first five metres of concave bank sedimentation correspond with the downvalley translation of about half the channel width, or about 100 m (see Figure 6). The bend migration rate of 5-7 m/yr therefore implies an average rate of vertical accretion for the first 5 m of concave-bank bench material of about 25-35 cm/yr. These rates accord with those measured by Nanson (1980) for rates of the first few metres of point-bar accretion on the nearby Beatton River.

The upper 5 m of concave-bank bench deposits are laterally contiguous with the overbank deposits of the adjacent point bar and therefore can be taken as contemporaneous and governed by the same processes of sedimentation.

Several representative bore logs for upper concave-bank bench deposits are shown in Figure 9. In general, they are indistinguishable from logs of overbank accretion elsewhere on the point bar. Three particular characteristics are typical of the concave-bank bench material, however, and are worthy of note.

First, the upper concave-bank bench deposits structurally are dominated by alternating silts and sands. Following Nanson (1980) these are taken to be flood cyclothems. A complete cyclothem consists of a basal unit of horizontal to sinusoidal ripple lamination in silts overlain by a sandy unit of type B to type A ripple drift cross lamination (after the classification of Jopling and Walker 1968) and capped by another silty unit similar to the lower bounding structures. This fine-to coarse to fine coset can be interpreted as a response to increasing velocity and traction loads, and their subsequent decline associated with the passage of a flood event. This type of internal structure also is found in the overbank floodplain deposits here and elsewhere (see Nanson 1980). In the concave-bank bench flood cyclothems, however, there is a distinctive and distinguishing characteristic: the ripple structures normally are regressive with respect to the flow direction in the main channel on the downvalley or depositing side of the migrating channel bend. On the eroding side of the bend, of course, the ripple orientation only appears to be consistent with the main flow direction.
Flood cyclothems often are incomplete but are well developed in the core shown for bend F in Figure 9 where, for the first metre, they average about 10 cm in thickness. Their thickness increases with depth as does the median grain size of the concave-bank bench material (Figure 8).

A second distinctive but less common characteristic of the internal structures of these concave-bank bench deposits is the presence of substantial beds of organics, largely in the form of leaf litter. The organic content in general, however, is considerably less than the expectation set by the results of other studies (cf. Carey 1963, 1969; Nanson and Page 1982; Page and Nanson 1982; Hickin 1984). Logs commonly accumulate on the surface of the upvalley parts of concave-bank bench deposits (see Hickin 1984) but do not appear to be incorporated at depth.

The third distinctive characteristic of the concave-bank bench material is the occasional presence of coarse sand and gravel splays in the record. These splays are most common in the upper sections of the concave-bank bench on the upvalley side of the channel bend. Much less commonly they may extend from channel to channel across the neck of the confined meander bend. In this case there is a potential for some of this coarser material to be incorporated at depth in the downvalley portion of the bench. Only surficial splays were observed (within 1 m of the bench surface) in the bore logs obtained in this study, however, so that this potential preservation remains unconfirmed.

The contrast between concave-bank bench material and that in the adjacent point bar is nowhere clearer than in the bank exposures near the water surface. Figure 10 shows the median diameter of sediment sampled along longitudinal bank transects of five bends. In the banks of the concave-bank bench the sediment largely is coarse silt and very fine sand that tends to fine upstream toward the point bar. The point bar sediments, in contrast, consist of a veneer of medium to coarse sand and granules overlying a basal gravel platform of pebbles and cobbles. Between these two environments is a transition zone in which median particle size abruptly increases upstream of the concave-bank bench and increases again more abruptly where it meets the coarser point bar deposits further upstream. The transition zone is one in which lenses of fine concave-bank bench material are sandwiched between stringers of coarser material marking the downstream limit of the point bars. These sands and silts are intercalated both vertically and horizontally and may have a surface morphological expression as overlapping ridges and swales. Variability in this overlap indicates that the relative do-
mains of the concave-bank bench and point bar materials have varied over time. It seems likely that large and prolonged floods favour upstream extension of the separation zone and, thus, of the concave-bank bench deposits, and the smaller overbank flows probably favour point bar development in the transition zone. In general, however, up to one-third of the surface geomorphology of the floodplain of these confined meanders reflects the presence of concave-bank bench deposits (cf. Nanson 1980).

Summary and Conclusion

The geomorphic and sedimentologic relations described in the previous sections are summarized schematically in Figure 11.

In the absence of drill core and seismic data, the deep subsurface detail in Figure 11 must remain speculative. Nevertheless, the known surface dynamics of lateral river migration, point bar formation, and concave-bank bench deposition, in particular, lead inevitably to the subsurface model proposed in Figure 11.

The floodplain morphology and surficial sedimentology, however, provide a clear and consistent view of the origin of this type of confined meander floodplain. Downstream migration of the confined meanders of the Fort Nelson and Muskwa rivers forms floodplains of two markedly contrasted styles of deposition and consequent sediment types: coarse point bar material
and relatively fine concave-bank bench deposits. The point bars, consisting of a gravel and sand platform underlying silty sands of overbank accretion, conform to Nanson’s (1980) model of deposition for the nearby Beatton River. The concave-bank benches form in separated flow and consist of a relatively uniform deposit of silt and fine sand with regressive internal structures and are relatively rich in organics; there is no evidence of a gravel basement at the level corresponding to that in the adjacent point bar. The upper concave-bank bench material forms two wide ribbons of deposition along each confining valley wall and may constitute up to one-third of the entire floodplain deposit.

These observations suggest that concave-bank bench deposits likely are typical of floodplains associated with confined meanders. They clearly should be considered for inclusion in any comprehensive floodplain facies model. They also suggest a cautionary note in reading the rock record. In these circumstances a low-energy depositional environment is contemporaneously and spatially associated with deposits of a high-energy gravel and sand-bed river. Further, any reconstruction of regional flow direction must allow for the abundance of regressive flow structures in the fine-grained concave-bank bench deposits.

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Figure 11
An idealized model of the associations among confined meander planform, point bar, and concave-bank bench deposits