SEDIMENTATION IN COARSE-GRAINED SAND-BEDDED MEANDERS: DISTINCTIVE DEPOSITION OF SUSPENDED SEDIMENT

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Abstract. Sedimentological processes in coarse-grained sand-bedded meanders, which are typical in reaches downstream of alluvial fans, were investigated in two different-sized rivers, one with low sinuosity and one with intermediate sinuosity. Following detailed descriptions of the morphology and stratigraphy of each river, mechanisms of formation of natural levee and ridge-and-swale topography are discussed. Downstream migration of a meander causes a stratigraphic sequence of successively higher deposits of the channel bed, bank slope, floodplain, and natural levee. Deep deposition of suspended sediments forms the upper three units, in which grains larger than 0.5 mm in diameter are rarely observed. High variability of water discharge and high suspended sediment transport seem to favor sedimentation of overbank mud or undivided top stratum, which overlies the point bar deposits of many previous depositional models. The flood flow loses its coarse load once it leaves the channel. Natural levees develop over the outer bank of the channel, where the in-channel water with abundant intermittent suspended load first exits the channel. Inversely graded beds make up natural levee deposits. The foundation of floodplain scrolls is the bank bench which occurs in the gentle slopes of the inner accretionary bank. Flow separation in a meander bend is possibly an instrument for the excessive supply of fine and very fine sand there, which is preserved as climbing-ripple laminations among deep bank slope deposits.

1. Context

The simplest classification of fluvial deposits is the one which distinguishes between lateral accretion and vertical accretion (MACKIN, 1937; FISK, 1947; LEOPOLD et al., 1964). In meandering rivers, these two fundamental types of deposits have very often been described as point bar deposits and overbank deposits.

Many have shown a great interest in the stratigraphy of meandering rivers (reviewed in ALLEN, 1965; MIALL, 1978, 1987; REINECK and SINGH, 1980), and a number of different types of depositional models have been proposed in relation to geomorphological features of floodplains (e.g., HARR et al., 1940; ALLEN, 1964, 1965), types of channel evolution (BRIDGE, 1975), and hydrodynamic processes of river bends (ALLEN, 1970a, b; JACkSON, 1975, 1976a). Most of models have revealed that the proportion of overbank deposits is very small in a vertical profile of fluvial sediments deposited within meander belts during point bar migration, as WOLMAN and LEOPOLD (1957) demonstrated the lower importance of the overbank deposits for the formation of floodplains in the Watts Branch.
However, we have observed that deposits of suspended load during high flows constitute distinctive sedimentary sequences on upper point bar deposits in many Japanese sand-bed rivers. The channel and floodplain morphology of these rivers can be commonly divided into three major units: 1) channel bed, 2) channel bank, and 3) floodplain. Both bank slope and floodplain deposits are responsible for forming floodplain morphology. These two units are clearly distinguished from channel deposits, not only in sedimentary structure but also in grain size.

We have investigated both floodplain stratigraphy and morphology in two different-sized rivers, and also made some hydraulic measurements of channel processes. This paper will endeavor to describe sedimentological processes operating in both rivers, and discuss mechanisms of formation of natural levees and ridge-and-swale topography.

2. Overview and Terminology

Japanese fluvial lowlands have been traditionally classified into three areas from upstream to downstream—the alluvial fan, the natural levee, and the delta (e.g., Kaizuka et al., 1963)—through which a river shows successive changes in grain size, stream pattern, and adjacent floodplain morphology. Coarse-grained sand-bedded meanders, which this paper deals with in detail, occur in the natural levee areas downstream of alluvial fans, where braiding is the most common stream pattern.

In natural levee areas, most floods are due to heavy rainstorms in the typhoon season, when flow rapidly increases to a few tenfold, or sometimes a hundredfold, of the usual low flow within one or two days (e.g., Tokyo Astronomical Observatory, 1985, p. 642–643). Flooding persists not more than a few days, even in the largest river, the Tone. Besides, flood flows transport extremely high concentrations of suspended fines, the so-called 'wash load'. Concentration commonly peaks at the rising limb of the flood hydrograph (Kikkawa, 1954; Iseya, 1979, 1982; Kinoshita, 1984, his Fig. 1). High variability of water discharge and suspended sediment supply seem to favor the sedimentation of overbank mud, or the undivided topstratum of Allen (1965).

Point bars are the most conspicuous morphological features in meandering rivers. Figure 1(a) sketches a typical point bar. A point bar is the deposit formed around the inner or convex bank of a bend. It usually has the greatest width just downstream at the position of maximum curvature, or the bend apex. The top of the point bar is very often at the height of the floodplain, and thus the floodplain on the convex side has no distinctive bank slope.

However, this type of point bar is seldom seen in coarse-grained sand-bed rivers we have investigated, and well-defined banks always constrain meanders. Figure 1(b) illustrates this type of meander, and designates terminology used in this paper. The shallowest part of a bar characteristically occurs along the upstream limb of the concave bank, and the bar tail is at the vicinity of the bend apex. Because of the relatively planar surface of these areas, we call this the "point bar platform". This feature can be compared to the 'supra-bar platform' of the River Endrich (Bluck, 1971). The channel bank to the inside of the point bar platform accelerates laterally by deposition of suspended sediments. We call this bank the "inner bank" or "inner accretionary bank". It commonly merges upstream and downstream with a steep "outer bank".

The term 'meander' in this paper is not defined precisely, but just refers to the plan form of a channel with slightly rounded curves.
3. Morphology and Stratigraphy of a River with Low Sinuosity

3.1 Sakura River

The Sakura River is a main stream flowing into Kasumiga-Ura lake, central Japan (Fig. 2). The upper course of the Sakura has a narrow, low-sinuosity channel with a gradient of approximately 1/1000. Bankfull width and depth are 15–20 m and 1.5–1.8 m, and thus the width-depth ratio averages about 10. Over 85% of the bed material is made up of granules (2–4 mm in diameter) and coarse-sand (0.5–1 mm) grains; the median diameter is about 1.5 mm. These coarse grains originate from deeply weathered and coarse-grained granitic rocks of low mountains in the upper drainage basin.

Mean annual precipitation for the last twenty years is about 1,500 mm. Intense rain from typhoons causes large floods that leave thick deposits on the floodplain. High flow, up to bankfull discharge, occurs at least two or three times a year. The flood hydrograph shows a rapid increase or decrease of water height within two or three days (see ISEYA, this volume). Water discharge and mean flow velocity at the bankfull stage of the study site (Fig. 3) are about 12 m³/sec and 0.5–0.6 m/sec, and the maximum surface velocity attains 1.2–1.3 m/sec.

3.2 Field methods

We investigated flood deposits over the floodplain all along the upper course shown in Fig. 2 soon after some floods, before the deposits were disturbed by grasses, moles, earthworms, or human activities. Over several short distances, sedimentary sequences, vertical grain size change, and rate of deposition were investigated in relation to microfeatures of the floodplain. We also observed sedimentary structures of the floodplain at many bank exposures and some trenches.
Fig. 2. Geological setting and contour map (unit: m) of the Sakura River.

For further detailed study, we measured cross profiles of the channel every ten meters in 1977 and 1982 at the reach shown in Fig. 3, and drew plan views of the channel (Fig. 4). We also made hydraulic measurements of some floods in 1977 (ISEYA, 1979, 1982). The measurements focused on two problems to explain the origin of distinctive inverse grading of natural levee deposits: the temporal relationship between suspended sediment concentration and the flood hydrograph, and the maximum grain size of suspended sediments.

3.3 Channel and floodplain morphology

In the study site, the micro relief of the floodplain is well preserved in a very narrow width along the stream, while the main area of the floodplain has been cultivated as rice fields (Fig. 3). An artificial low ridge defines the boundary. Three units of the channel and floodplain morphology are described below.

Channel bed: The channel bed was composed of granules to coarse sand. Obscure thalwegs run alternately along both banks at low water stages, reflecting alternate bars with small relief (Fig. 4(a), (b)). The highest parts of bars were exposed to form point bar platforms. An echo-sounding survey showed that the bed surface was always covered with dunes during high flows (ISEYA, 1982). The length and height of dominant dunes were about 2–3 m and 0.2–0.4 m.

Channel banks: Channel banks were clearly distinguished from the stream bed, because coarse-grained channel deposits abruptly met fine muddy sediments at the foot of the bank. Cross profiles and plan views of Fig. 4 indicate that two different kinds of bank, one steep and one gentle, define the channel margin.
Steeply sloping banks were at the stoss side of a meander or at the outer bank, which was directly attacked by high flow velocities and subject to erosion. A few bank failures were observed in 1982, but most banks were protected by dense vegetation (reeds and willow trees).

In contrast, gently sloping banks were formed at the inner accretionary side. The gentle slopes along the left bank from 90 to 130 were good examples. Their slope angles were 14–18 degrees. The channel bed graded into the bank slope, which graded into the floodplain, without a sharp break in profile.

Floodplain with natural levees: The floodplain of the Sakura has natural levees that are discontinuous and occur alternately along either side of the river. A prominent ridge developed parallel to the outer bank (Fig. 4). In profile, a natural levee was highest next to the steep bank and fell gradually away from the bank. High natural levees on the outer bank were always accompanied by low banks on the opposite side, which were even with the floodplain (Fig. 5). The difference in elevation between opposite banks was nearly as large as 1 m.

3.4 Channel changes

Although the streambed elevation was stable for 5 years, concurrent deposition over the banks, the floodplain and the natural levee changed a wide, shallow channel into a deep narrow one (Fig. 4(c)). The bank heights were 1–1.5 m above the bed surface in 1977 except where natural levees developed. Almost all floodplains were higher than 1.5 m in 1982, and natural levees were higher than 2 m. The average rate of vertical accretion during the 5 years was 30 cm.

The cross profile at 170 shows that the channel moved laterally about half a width over 5 years. This change resulted only from the downstream migration of the channel, and not from a change in channel geometry.
Fig. 4. Changes of channel and floodplain morphology between 1977(a) and 1982(b). Sketch maps of (a) and (b) are based on cross profiles of (c) taken at 10 m intervals. Cross profiles were surveyed with a level on May 8 of 1977, and on April 22 of 1982. A closed circle and a solid line of (b) show locations of the sedimentary log of Fig. 6 and the sedimentary structure of a natural levee of Fig. 8, respectively. Flow is from bottom to top.
3.5 Sedimentary sequences

A sedimentary log of Fig. 6 is a fully developed depositional sequence of the Sakura. The fluvial deposit is obviously divided into three different units: (1) channel bed deposits (CB), (2) bank slope deposits (BS), and (3) floodplain deposits (FP), including natural levee deposits (NL). Each of these is formed under different sedimentary subenvironments corresponding to the channel and floodplain morphology described above.

Channel bed deposits (CB): Granule to coarse-grained sand particles were at the lowest part of the sequence. The top of CB usually coincided with that of the subaqueous portion of alternate bars. CB sometimes had trough-cross stratification, indicating that they were formed by migrating dunes in the stream bed. A trench for a drainage canal in a rice field indicated that the total thickness of CB was not more than 1 m, and usually several decimeters. This approximately equals the difference in elevation between the deepest and shallowest parts of the stream bed.

Bank slope deposits (BS): The finest materials made up the middle part of the sequence. The thickness of this unit was usually less than 1 m. Grain size analyses every 5 cm show that the lower half contains over 50% silt-clay (<0.063 mm), and the proportion of fine sand (0.125–0.25 mm) increases upward (Fig. 6). The primary sedimentary structure of the layer was extensively disturbed, partly by roots and animal burrows, but mostly by desiccation
Fig. 6. A fully developed depositional sequence of the Sakura. The log was taken at the closed circle of Fig. 4(b). A settling tube system was used for grain size analysis. Settling velocity was converted into settling grain diameter by an equation from Gibbs et al. (1971).
and compaction, which caused loosely deposited mud to form a cohesive body. However, a conspicuous thin layer of clay was sometimes seen in the upper half. The thin layer dipped toward the stream and was parallel to a gentle bank slope (cf., Fig. 8).

These clayey and silty sediments have been deposited on the gentle slope of an inner accretionary bank. Stagnant flows at the lee side of a meander would promote deposition of suspended fines. Actually, muddy sediments with abundant organic debris were commonly deposited not only by large floods but by small rises in discharge. When a man stood carelessly on the toe of the bank slope soon after high flows, his feet were easily submerged into water-saturated mud.

**Floodplain deposits (FP) and natural levee deposits (NL)—repeated sequences of inverse grading:** Deposition of suspended sediments from flood waters promote vertical accretion of natural levees and floodplains. Such an overbank deposit always has inverse grading, as ISEYA (1979) first described. A sedimentation unit of a single flood is characterized by two beds that both show upward-coarsening, a lower muddy one and an upper sandy one. The inverse grading is mainly produced by an extremely high concentration of suspended fines at the very beginning of flooding. This depositional process is reviewed by ISEYA (this volume).

The upper half of the sedimentary sequence of Fig. 6 was made up of many sandy layers. Each layer clearly displayed inverse grading structure. In a vertical profile, sedimentation units were thin in the lower part (2–4 cm), and become as thick as 15 cm toward the surface. Mud beds which defined the bottom of the inverse grading were commonly obscure in the upper part.

This succession was produced by the increasing height of the floodplain, which was equivalent to the spatial distribution of overbank deposits on the present floodplain surface. Overbank deposits on low floodplain surfaces had a distinctive mud bed (Fig. 7), because those areas were first covered with flood waters with abundant suspended fines. Such mud beds were commonly 1–2 cm, and as much as 10 cm, in thickness. In contrast, the lowermost muddy part was indistinct in natural levee deposits (NL), mostly because the natural levee was submerged by flood waters after wash load concentration decreased. A deep sand bed, as thick as 18 cm, commonly displayed no internal structure, but very occasionally showed parallel or ripple laminations.

Except for CB, natural levees contain the coarsest material. Medium (0.25–0.5 mm) to fine (0.125–0.25 mm) sand comprise 80–90% of each deep sand bed. Of considerable importance here is the fact that grains larger than 0.5 mm (1 phi) never occur in FP and NL. This is very consistent with results of hydraulic measurements within the channel, in which the maximum grain of suspended sediment, certainly originating from intermittent suspension, was almost always smaller than 0.5 mm (ISEYA, 1982).

### 3.6 Formation process of floodplain stratigraphy

Figure 8 was constructed from detailed structural analyses of NL. The inverse grading structure provides a very effective tool in constructing the history of natural levee development, although the primary sedimentary structure has often been bioturbated. A mud bed, having a sharp contact with the lowerlying bed and grading into the upper sandy part, is sometimes well preserved among sequences and provides a conspicuous time marker.

When a high flow overtops the bank, the coarsest sediment is deposited near the channel, and both the grain size and the rate of deposition rapidly decrease away from the channel. This process forms a natural levee over a flat floodplain surface. Initial construction of the levee was accomplished by only two floods, marked by sedimentation
Fig. 7. Repeated cycles of inverse grading structure at various points over the floodplain. A pair of mud and sand beds are caused by a single flood. Deep mud beds are distinctive on low floodplains, whereas deep sand beds occur on natural levees. Logs were investigated in May, 1982. Flow is from bottom to top.
units Nos. 21 and 20. The height of the natural levee increased until sedimentation unit No. 12 was deposited. After No. 10 was deposited, the deepest deposition gradually moved away from the channel. Figure 8 indicates as a whole that sedimentation on the floodplain accelerates toward intermediate heights of the levee and decelerates at greater heights.

We'll summarize here how the downstream migration of the channel could produce the full cycle of the vertical sedimentary sequence shown on Fig. 6. Such a sedimentary process possibly took place at the left bank at 130, in which a gentle slope changed into a natural levee during a 5-year observation (Fig. 4).

1) The channel bed adjacent to the accretionary inner bank is gradually covered with fine cohesive materials (BS), which makes a footing for the deposition of suspended fines, and thus 2) a gentle bank slope grows laterally. 3) Repeated sedimentation on a gentle bank slope gradually forms a low floodplain, which offers a plane surface for overbank deposition (FP). This is followed by downstream movement of a meander, and therefore the depositional environment becomes one of an outer convex bank. 4) A few floods leave thick overbank deposits (NL) adjacent to the bank, which initiates natural levee formation. 5) Subsequent floods accelerate natural levee construction. 6) The rate of vertical accretion on the natural levee slows down. 7) Finally, the site becomes exposed to bank erosion.

3.7 Concluding remarks

Sedimentological and geomorphological characteristics of a low-sinuosity meander are all involved in Fig. 6:

1) Downstream migration of a meander creates, from bottom to top, channel deposits (CB), bank slope deposits (BS), floodplain deposits (FP) and natural levee deposits (NL). CB and BS are lateral accretion or within-channel deposits, and FP and NL are vertical accretion or overbank deposits.

2) Only CB are formed by bedload transport. BS, FP, and NL are composed of suspended sediments. The grain size abruptly changes at the foot of the channel bank. Therefore, CB and BS have a very sharp contact. It is quite a significant fact that grains larger than 0.5 mm in diameter are absent in suspended load deposits.
3) The thickness of CB is usually small, less than 1 m. This is equivalent to the difference between the maximum and minimum heights of the channel bed. In contrast, the total thickness of BS, FP and NL reaches approximately 2 m, which is equivalent to maximum bank height. The thickness of BS indicates the lowest bank height. This means that one can reconstruct some channel dimensions from the thickness of each unit of ancient fluviatile deposits.

4) Sedimentation of BS takes place over gentle slopes at the inner accretionary bank, adjacent to the channel bed. Muddy sediments that originate mainly from continuous suspension are modified into cohesive materials by desiccation and compaction. Much organic debris are also contained.

5) FP and NL always have a distinctive inverse grading structure, which can be an effective tool to analyze sedimentological processes of floodplains.

6) NL are composed mostly of medium to fine sand, which are brought by intermittent suspension. The maximum thickness of a sedimentation unit is nearly 20 cm.

7) Natural levees, a conspicuous feature of the Sakura, develop well over the outer bank of the channel. Construction of a natural levee over the floodplain is initiated by only a few floods. Sedimentation on a natural levee accelerates toward the intermediate heights above the channel bed, and decelerates at greater heights.

4. Morphology and Stratigraphy of a River with Intermediate Sinuosity

4.1 The lower Teshio River

The lower Teshio River, northern Hokkaido, is one of the largest sand-bedded meandering rivers in Japan (Fig. 9). The meandering channel has incised through a deltaic plain of the post-glacial period. Silty cohesive sediments make up the plain, and peaty materials about 1.5-2 m deep overtop the plain surface. Mudstones and sandstones,
Miocene through Pliocene in age, make low mountains ranging from 100 to 250 m in relief.

Channel width and depth at bankfull stage are 100–150 m and 6–7 m. The gradient is gentle ($0.25 \times 10^{-3}$). The bed is mainly composed of medium sand (0.25–0.5 mm) to fine gravels (<10 mm); median diameter of the bed material is 0.6 to 1.5 mm. A total of 16.6 km of channel was artificially straightened to quickly discharge flood flows. The first and last canals were excavated in 1958 and 1975.

Figure 10 illustrates the middle reach of the lower Teshio River (22–28 km from the river mouth), where channel migration has been relatively active. The map was drawn from aerial photographs taken by the U. S. Army in 1947, before artificial straightening was started. The present floodplain occurs only in a narrow belt of confined meanders along the channel, because cohesive deltaic deposits and channel plug deposits exposed at the bank have prevented the channel from migrating freely. The floodplain surface is usually lower

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**Fig. 10.** Meander belt of the lower Teshio River. Aerial photos taken by the U.S. Army in 1947 were used to show floodplain and channel geometry before the channel was artificially straightened. The reach is in the 22–28 km distance of Fig. 9. The many lines on shaded area show floodplain ridges. Arrow indicates the floodplain shown in Figs. 12 and 13.
than the peaty land by 2–4 m. Neck cut-offs of meander loops can be recognized in many places. These possibly occurred naturally, because the land had little human influence before World War II. Short lines on the floodplain of Fig. 10 indicate a train of ridge-and-swale topography, which characterize the floodplain surface.

At the Maruyama gauging station (30 km from the river mouth), mean annual discharge equals 200 m$^3$/sec and mean annual maximum discharge equals about 1,500 m$^3$/sec. Figure 11 shows the hydrographs of two years. High flows always occur in the snow-melt season of April and May. Annual precipitation of the lower basin is about 1,100 mm, and a large flood is produced by heavy rain resulting from a depression, usually in August and September. The highest peak of August, 1981 was the largest flood for the last thirty years. Water discharge in the “August 1981 flood” reached approximately 3,500 m$^3$/sec. In a low-water season, a salt wedge extends upstream about 20 km from the river mouth.

![Graph showing hydrographs of two years at the Maruyama gauging station, 30 km upstream distance (Hokkaido Development Agency).](image)

Fig. 11. Hydrographs of two years at the Maruyama gauging station, 30 km upstream distance (Hokkaido Development Agency).

### 4.2 Field method

We investigated sedimentary structures of the floodplain from the river mouth to 50 km upstream. Good exposures of alluvium in the lower Teshio were provided by bank failures at almost all outer banks and artificially excavated channels. A boat enabled us to visit numerous sites with ease. We also observed the deposition of suspended sediment brought by the August 1981 flood, as well as some other high flows (IKEDA et al., 1984).

The project on the lower Teshio River has also included measurements of hydraulic processes in the channel. We did an echo-sounding survey of bedforms twice, at a low-water stage in summer and at a snow-melt flood in spring (IKEDA and ISEYA, 1980a, 1982). Both suspended load and bedload were sampled at a few sites (IKEDA and ISEYA, 1980b).
4.3 **Channel and floodplain morphology**

A typical example of deposition and stratigraphy of the lower Teshio was observed at the reach in Figs. 12 and 13. Although this meander has a smaller curvature than other, strongly curved bends, we chose this floodplain to study because meander scrolls have been well preserved.

**Channel bed:** A point bar platform was prominent at the downstream limb of the inner bank (Fig. 13(b)). It had a very flat surface and increased slightly in height downstream. The downstream extremity, which advanced about 40 m between 1972 and 1984 (Fig. 14(a)), appeared to have a pronounced lee surface facing the downstream pool. The maximum width of the platform at low flow was about 30 m, about two-fifths of the channel width. The greatest water depth, 3–4 m at low flows, occurred on the opposite side of the platform, parallel to the outer bank.

Although coarse (0.5–1 mm) to very coarse sand (1–2 mm) was the dominant grain size, aerial sediment sorting caused heterogeneity in grain size on the point bar platform. Small
Fig. 13. Channel changes (a), channel and floodplain morphology (b), and cross profiles (c) of the study site. Location is shown in Fig. 10. Data from Hokkaido Development Agency. The map and cross profiles of (b) and (c) were surveyed in 1976. Datum of the contours on the present floodplain is strand at mean sea level (unit: m).
Fig. 14. (a): Depth and grain size distribution of natural levee deposits left by the August 1981 flood; index map of cross profiles of Fig. 15 and sedimentary logs of Fig. 17. We did trigonometric surveys by using two theodolites in October 1982 (closed circles with dotted lines) and July 1984 (open circles with solid lines). The upstream part of the floodplain at the study site were artificially excavated to almost three meter depths before surveying. Materials excavated were used to build artificial levees. Other lines of the channel and floodplain morphology are the same as those of Fig. 13(b), which was surveyed in 1976 by the Hokkaido Development Agency. (b): Enlarged map at the downstream left portion of (a) and index map of cross profiles on Fig. 19. Dots with solid lines are surveying points of July 1984. Vegetation changed systematically.
pebble gravels, some of which were lag concentrates, commonly occurred on the upstream area. Over the downstream half, gravel was very occasional, and sand accumulations created a bar tail, whose surface was sometimes covered with small dunes. Such a segregation closely resembles that on the supra-bar platform of the River Endrich (Bluck, 1971).

A characteristic feature of the point bar platform was a longitudinal slough running along the toe of the inner bank slopes (Fig. 14(b)), which distinguished the point bar platform from the channel bank. In the middle length of the bar, coarse-grained bar deposits avalanched over a steep lee face into the slough. In 10 years of observation of this platform, this slough has always existed, and most of the slough surface has been covered with muddy deposits. The lower levels of the slough were submerged with water, even at low flow as deep as 20–50 cm. When a person stepped into sticky deposits, his feet were forced to sink until the underlying coarse-grained deposits were met. Actually this often happened. The slough also contained much driftwood.

Channel bank: The inner bank surface was commonly covered with willow trees of similar size or age. It had a very gentle slope which became less steep downstream (Fig. 15); the mean slope was about 8 degrees. However, the surface of the point bar platform did not always grade upward into the floodplain, but some bank profiles (F, G, and I) had a very sharp break in slope. This series of steps formed a bank bench about 1.5 m above the bar platform. This was the most characteristic micro-topography of the inner bank slope. It resulted from deep sedimentation of suspended load as described below.

In contrast, the outer bank had a very steep slope. The upper half was free of vegetation and the lower half was often covered with collapsed bank debris. Because the outer bank is retreating, it is not important from a depositional viewpoint. Floodplain characterized by ridge-and-swale topography: The floodplain surface along the outer bank was nearly 7 m above the low water level, but the height gradually decreased to about 3 m away from the channel and downstream (Fig. 13(b)). Ridges and swales are prominent on the floodplain. An aerial photograph taken on the falling limb of the August 1981 flood (Fig. 12) shows this most clearly. The irregular pattern of the water margin approximately conforms to the 5 m contour line.

The floodplain surface has been ploughed as a pasture during recent years. Accumulations of overbank deposits and human activity made it difficult to accurately illustrate original undulations. We distinguish, however, 8 sets of ridges and swales. The wave length varies between 20 m and 40 m, and has a mean value of about 28 m. The bearing of the ridge-and-swale topography nearly parallels that of the present inner bank.

Figure 13(a) shows successive bankline changes for 52 years. This meander moved only downstream. The inner bank advanced about 50 m, leaving three ridges. The gently curved plan view of the terrace scarp extending behind the present floodplain indicates the continuum of positions of the maximum curvature of the concave bank. The bend apex moved about 140 m in 52 years, as indicated by the fact that the bend apex of 1924 was at the vicinity of the tree in Fig. 13(a) and that of 1976 was at the downstream end of the figure. Assuming that this rate has not changed, it took more than 200 years to generate the entire floodplain on the left bank. Thus, 8 sets of ridge and swale had been formed, on average, every 25 years.

4.4 Sedimentary sequences

Progressive downstream migration of a meander results in a vertical sedimentary sequence, as already explained in the Sakura. Major units in the Teshio are as follows (bottom to top): (1) channel bed deposits (CB), (2) bank slope deposits (BS), and (3)
Fig. 15. Successive cross profiles of the inner bank, and thickness of bank slope deposits left by the August 1981 flood. Datum is strand approximately at mean sea level. Location of each profile is in Fig. 14(a).
floodplain deposits (FP), including natural levee deposits (NL).

Figure 16 is the type of sedimentary structures which were seen at many cut-banks. In the river, our eyes were first caught by accumulations of gently dipping sand layers (BS), comprising the middle layers of exposures. A few thick mud layers were also distinctive at the bottom of such sand layers, where driftwood was often seen. Some mud layers were interbedded with lower coarse-grained deposits (CB). The upper one or two meters (FP) looked massive and white-colored because of desiccation. Finely laminated mud layers composed these strata.

Sedimentary logs of Fig. 17 were taken at the outer bank of the study reach. Log A was analyzed as precisely as possible, whereas Logs B, C and D were roughly sketched. Grain
size distribution of some samples are shown on Fig. 18. The following will describe each sedimentary unit and the deposits of the August 1981 flood.

**Channel bed deposits (CB):** Pebble-bearing, coarse-grained sand deposits comprised the uppermost strata, which usually had parallel laminations or small-scale, trough-cross stratifications. These structures were formed over the point bar platform. The entire vertical profile of the CB was never investigated in the Teschio because of deep water. We could expect to find, however, accumulations of cross-stratified units caused by migrating dunes with erosive contact between underlying cohesive deposits. This has been verified by echo-sounding surveys (Ikeda and Iseya, 1980a).

The greatest height of CB is more than 2 m (Fig. 17), which seems too high compared to the present surface of the point bar platform. This might be due partly to fluctuations of the bar surface height, and partly to lowering of the river bed as a result of artificial straightening of some meanders.

**Bank slope deposits (BS):** A few mud beds at the lowest strata and overlying thick sand beds composed the BS. Fine (0.125–0.25 mm) and very fine sand (0.063–0.125 mm) made up the entire overlying sand beds (Figs. 17 and 18). Grains larger than 0.5 mm (1 phi) were hardly seen among them, even though BS occurred immediately above the coarse-grained CB. Exceptionally, however, strong winds cause coarse sand patches, usually a few grains thick, on the mud surface. This is preserved in Log D of Fig. 17.

The lowest clayey beds, often 10 cm and sometimes nearly 20 cm thick, directly covered the coarse-grained CB (Fig. 19). These clayey beds were deposited at the foot of the inner gentle slope or over the slough described above. A thick mud bed concealed the coarse-grained surface of the point bar platform there. Once clayey materials were deposited, they were barely eroded again. Adjacent to the bankward margin of the point bar platform, a mud bed sometimes interfingered with cross-bedded coarse-grained deposits.

The main body of BS was composed by only three of four prominent sand beds (Fig. 19). The maximum depth of a single unit was nearly 50 cm. Small heterogeneities in grain size displayed climbing-ripple laminations. Some thin mud beds at the base of deep sand beds preserved an inverse grading structure. However, most original sedimentary structures have been obliterated by root growth and animal burrows.

These thick beds must have been built by concurrent deposition of suspended sediments over gentle slopes of the inner bank. In the August 1981 flood, a large sand mass with a lensoid shape deposited on the bank slope (Fig. 15), and made the bank bench more conspicuous. The thickest deposit, as deep as 30–50 cm, occurred at an intermediate height on the banks, not immediately above the channel bed. The lowermost part of the deposits had an inverse grading structure, and were overlain by deep fine sand accumulations. The thickness of underlying mud beds decreased with increasing height on the bank. Depositional-stoss climbing-ripple cross-lamination (Type B of Allen, 1973) was the main bedding type of deep sands. The orientation of ripples was almost perpendicular or aligned slightly inward to the direction of the inner bank. This type of lamination would be produced under conditions of rapid aggradation and low rates of ripple migration, as Ashley et al. (1982)’s flume experiment demonstrated. The uppermost 1–2 cm in depth showed a slight increase in the proportion of fine-grained deposits.

**Floodplain deposits (FP):** Finely laminated sand and mud layers made up the floodplain deposit. These overbank deposits were usually less than a few centimeters in thickness.

The uppermost sand layer of Log A (Fig. 17) was deposited by the August 1981 flood. At the flood peak, maximum flow depth was 1 m at the highest area of the floodplain next to the outer bank, and thus flow depth was 3–4 m over the lower surface of the floodplain. Figure 14(a) shows the aerial distribution of grain size and depth of new deposits. Deep
Fig. 17. Sedimentary logs of the study site. Logs B, C, and D were not recorded as precisely as Log A. Locations are shown on Fig. 14(a). Numbers of each log designate sediment samples of Fig. 18. Datum is strand approximately at mean sea level.

Fig. 18. Grain size distribution of sediments. A settling tube system was used for grain size analysis. Settling velocity was converted into settling grain diameter by an equation from Gibb et al. (1971).
Fig. 19. Cross profiles of bank slope deposits (BS). Trenching was done in July 1983. Although some inversely-graded mud beds clearly indicated a single unit of sedimentation, small heterogeneity in grain size of BS and bioturbation by root growth made it difficult to correlate beds between logs. Datum is strand approximately at mean sea level. Note that vertical exaggeration is $10 \times \cdot$.
overbank deposits were remarkably spread over a large area of floodplain. Deposits were nearly parallel to the undulations of the antecedent floodplain surface. Both grain size and depth were generally the greatest adjacent to the outer bank, and decreased away from the channel.

These deposits can be compared to the NL of the Sakura River. General sedimentary features such as grain size (the largest size in the range of medium sand, 0.25–0.5 mm) and inverse grading were similar to those of the Sakura. A few differences did exist, however. First, within a narrow width along the outer bank, deposits occurred on an erosive base, and some high areas were scoured without being deposited upon later. Erosion possibly occurred when the flood flow first overtopped the highest outer bank. Local steep energy gradients could be expected at the boundary between high velocity flows within the channel and the placid water surface on the adjacent floodplain. Second, a considerable amount of sediment was transported as traction load over the floodplain before deposition, indicated by small distorted dunes on the lee side of pasture vegetation. Third, an obscure sandy silt bed was seen at the bottom of a unit, instead of a distinctive mud bed which was deposited at the beginning of overflooding.

4.5 Depositional process of vertical sequence

Figure 20 summarizes a full cycle of deposition within a channel belt. Four phases for the depositional process of upper point bar deposits of the Teshio River would be expected. The four phases, of course, occur in order from bottom to top at a location, but they can be observed contemporaneously in the present channel and adjacent floodplain from the inner to outer bank regions.

Phase 1. Settlement of the bankward margin of a point bar platform: During the rising limb of a flood hydrograph, a point bar platform is first inundated by water with abundant wash load. Flow velocities are low, especially adjacent to the inner bank slope or over the slough, which promotes deposition of a mud bed. This process provides a footing for sedimentation of overlying BS.

Phase 2. Formation of a bank bench: Deep sand beds, only three or four, deposit onto the gentle inner bank slope, making a conspicuous bank bench (Fig. 15); this is preserved stratigraphically as gently inclined deep sand beds (Fig. 16). The sandiness of these deposits and climbing-ripple laminations indicate that a large amount of fine and very fine sand is continuously fed to these areas from overloaded waters. As a point bar platform migrates downstream, the zone of deepest deposition of the suspended load also migrates downstream, and the site becomes the floodplain.

Phase 3. Concurrent deposition over the floodplain: Flood waters with abundant suspended fines always invade the floodplain from its downstream end, where its height is lowest. Thus, low floodplain surfaces at the downstream end are flooded most frequently in the earliest stage of development. With increasing height of the floodplain surface, the sedimentation rate becomes less.

Phase 4. Occasional modification by natural levee deposits: This is the final phase of floodplain development before it undergoes bank erosion. NL occur only when an extremely large flood overtops the highest outer bank. In contrast to the Sakura River, the NL were observed very occasionally in vertical sedimentary sequences. However, once deep flooding occurs, the sedimentation rate is high and flood waters cover a wide area of the floodplain, so that a prominent deep sand sheet is deposited on the uppermost part of a vertical profile.
Fig. 20. (a): Fully developed sedimentary sequence of the lower Teshio River. Log A of Fig. 17 is used to represent stratigraphy. (b): Schematic depositional model of confined meanders. Vertical exaggeration is about 4x.
4.6 Concluding remarks

Sedimentological and geomorphological characteristics of a moderately sinuous river are shown in Fig. 20. Concluding remarks are summarized as follows.

1) Ridges and swales are prominent over the floodplain of the lower Teshio River. A point bar platform is apparent at the downstream limb of the inner accretionary bank. A slough which runs longitudinally along the toe of the inner gentle bank slopes is a characteristic micro-topography of the point bar platform.

2) The sedimentation units (CB, BS, FP and NL) basically resemble those of the Sakura. Four phases—settlement of the bankward margin of a point bar platform, formation of bank bench, concurrent deposition over the floodplain, and occasional modification by NL—comprise a full cycle of the sequence.

3) The most distinctive difference from the Sakura is in the BS. A few mud beds at the lowermost part and overlying deep sand beds compose the BS. Much driftwood is also contained.

4) A mud bed, often with a depth of 10 cm and sometimes as thick as 20 cm, overlies the toe of gentle inner bank slopes, and also lies over the slough.

5) Three or four deep sand beds, 40–50 cm in thickness, are discretely deposited over the inner accretionary bank slope, forming a prominent bank bench at the middle height of the bank. Fine to very fine sand that has depositional-stoss, climbing-ripple, cross-lamination structure accumulates. An inversely graded mud bed occurs at the bottom of each deep sand bed.

6) Finely laminated sand and mud layers make up FP. NL are occasionally deposited over a large area of the floodplain, and create a prominent deep sand sheet on the uppermost part of FP.

7) Medium and fine sand make up NL, which also display inverse grading structure. Some NL overlie erosive bases.

8) Grains larger than 0.5 mm in diameter are rarely observed in BS, FP and NL, except those grains introduced by strong winds.

5. Discussion

5.1 Formation of natural levees

Natural levee deposits (NL) and crevasse splay deposits are two distinctive overbank deposits which occur adjacent to channels (COLEMAN, 1969; BRIDGE, 1984; FARRELL, 1987). In Japanese sand-bed rivers, crevasse splay deposits are rarely observed because of the rapid increase of flood hydrographs. The flood water overtops the outer bank of a channel without funneling through distinct channels cut across levees.

We see two similarities in NL along both rivers. One is the spatial distribution of NL deposited by a single flood. In the Sakura, both the sedimentation rate and grain size of NL are greatest within a narrow width over the outer bank (Fig. 7), and thus prominent natural levees occur on the upstream half of a meander (Fig. 4). This is somewhat similar to the Teshio (Fig. 13(a)), where very occasional large floods deposit prominent deep sand sheets over a wide area of the floodplain and form NL. Another similarity is grain size: medium and fine sand compose NL, and grains coarser than 0.5 mm in settling diameter are absent. The grain size of NL is coarser than that of underlying BS, even though BS overlie CB which contain a large quantity of much larger grains.

We introduce another river here to illustrate the relationship between the spatial distribution of NL over the floodplain and the flow patterns of flood waters. The upper reach of the Edo River was surveyed (Fig. 21(a)), where the Ministry of Construction took
aerial photos of flood flows. The Edo River is a distributary that was artificially excavated to control the flood discharge of the Tone River. Since the floodplain surface has been fully planed off and the bank slope has also been executed as protection work, the Edo provides a special opportunity to examine the effect of channel plan form on sedimentation over a floodplain. Bankfull width, depth, and bed slope are about 80–90 m, 4 m, and 0.29×10⁻¹. Coarse sand (0.5–1 mm) makes up 50–60% of the channel bed deposits.

As shown in Fig. 21(b), sandy overbank deposits were restricted, and NL occurred at extremely limited areas adjacent to the bank and face upstream. Except for those places, a mud bed covered the floodplain surface, even very near the channel.

Such a highly organized distribution of the NL coincides exactly with the flow pattern observed at the water surface (Fig. 21(c)). Deep sand beds occurred where the in-channel flows overtopped the bank and invaded the floodplain. Those flows were easily distinguished from others by a conspicuous dark brown color, which indicated high turbulence of the overtopping flows. In contrast, low velocity flows among grasses had a milky white color.

In short, the excess sand supply enters the floodplain only over the outer bank, where the in-channel water first exits the channel. These flows should have a high concentration of coarser sand grains. The flood flow loses its coarse load once it leaves the channel. This results in no distinctive sand deposits on the floodplain further downstream on a meander.

As stated earlier, BS, FP and NL are deposited from suspended load. Suspended load contains two different types of sediments: finer particles that are almost continuously in suspension, and coarser particles from the channel bed that are suspended intermittently by high flow turbulence (e.g., LEWIN, 1981). These two kinds of suspended load, however, have no sharp distinction by grain size.

The NL certainly originate as intermittent suspended load (MIDDLETON and SOUTHARD, 1978), or suspended-bed material load (SHEN, 1971; RICHARDS, 1982). The grain size of NL on the Sakura, the lower Teshio, and also the Edo is always smaller than 0.5 mm, irrespective of river geometry or hydraulic characteristics. Although there is a large stochastic element in suspension, the 0.5 mm size of NL suggests that it is very unusual to suspend larger grains, even by a strong eddy or a kolk (JACKSON, 1976b) associated with active growth of dune dimensions (ISEYA, 1984). Such a large vertical velocity fluctuation can be readily recognized by many boils at the water surface (Fig. 21(c)).

Luna B. LEOPOLD has also been aware of the limiting size of suspended load. He has written, on the basis of his vast experience, “Grains that appear in the suspended load are nearly always less than 0.5 mm in diameter.” (DUNNE and LEOPOLD, 1978, p. 677, 118). Unfortunately, he indicated no evidence to support this.

5.2 Origin of ridge-and-swale topography

Scroll-patterned floodplains are the most arresting features in meandering rivers (e.g., MELTON, 1936; FISK, 1947; RUSSELL, 1954; SUNDborg, 1956; CAREY, 1969;ナンソン, 1980). As the channel migrates laterally toward the concave bank, successive ridges and low-lying swales or meander scrolls are created on the convex side of bends, roughly conformable with the curve of the channel (LEOPOLD et al., 1964; ALLEN, 1965). Thus contemporary ridge and swale systems faithfully record meander-growth patterns (HICKIN, 1974; LAPOINTE and CARSON, 1986).

In conventional descriptive models, scroll bars are always accompanied by the retreat of the opposite concave bank and a flood or a series of floods (ALLEN, 1970b, p. 128–136; HICKIN, 1974). In spite of numerous descriptions of their morphology, there have been few field studies which illustrate the formative process of meander scrolls.

During his intensive research in the lower Wabash River, JACKSON (1976a) distinguish-
Fig. 21.
ed planar cross beds due to migrating scroll bars (his subfacies 3). He observed that scroll bars occurred down-channel from locally emergent topographic highs, and scroll bars marched toward the inner bank of the bend. Once accelerated by colonizing vegetation, they come to constitute the positive relief of the characteristic ridge-and-swale topography (Jackson, 1976c). His measurements of depth and velocity over the crest of a scroll bar indicated that scroll bars migrate only during an extremely narrow range of river stage, because they become submerged during higher stages and exposed at lower ones.

On the other hand, Nanson (1980) drew a completely different model in the Beatton River, British Columbia, Canada. Grain size and vertical sedimentary structure indicate that a scroll bar is initiated on a point bar platform by deposition of suspended load during only a single flood.

Floodplain scrolls may result from complex operations of different mechanisms in different environments. However, there must be two different origins of meander scrolls. Which plays an decisive role in their formation, bedload or suspended load transport? Scrolls of the Teshio appear to originate from deposition of suspended load on the inner accretionary bank slope. The Teshio River is much like the Beatton River except for less channel curvature, and thus they offer a useful comparison to discuss the mechanism of ridge-and-swale topography.

As ridges and swales of the Teshio run parallel to the direction of the present inner bank, they apparently originate from the morphology developed at the lee side of a meander. The bank bench, which results from deep sedimentation of suspended load over the antecedent gentle bank slope (Phase 2), can form the foundation of a ridge. Concurrent deposition would be concordant with the original undulations of the ridge and swale behind it. This results only in accelerating the floodplain vertically (Phase 3). An outcrop perpendicular to the direction of lateral accretion could appear as in Fig. 20(b).

If ridges and swales originate in BS, then three questions arise: 1) Why does an excessive supply of suspended load, which has been recorded on depositional-stoss, climbing-ripple, cross-laminations, occur over the inner bank slope? 2) What controls the periodicity of a ridge? 3) Why does a point bar platform occur along the upstream limb of the concave bend? For the inner bank accretion is, of course, accompanied by the movement of a point bar platform.

Flow separation in a meander bend (Bagnold, 1960; Leeder and Bridges, 1975) would be an instrument for the first question. Nanson (1980) assumes that much suspended load deposits along the outer edge of the shear zone on a point bar platform and produces an initial scroll bar. Deep deposition on the bank bench on the Teshio River, however,
suggests strong inward flow circulation within a separation zone. Bank vegetation could reduce flow velocities (Sundborg, 1956; Jackson, 1976c; Nanson, 1980) and promote sedimentation from waters laden with fine and very fine sand. In the Teshio, willows would become a ti-tree screen (Taylor and Woodyer, 1978). Another possibility is that flood waters returning to the channel would pass mainly over the inner bank and would interfere with flow in the channel. The resulting deceleration of the upward component of the flow over the inner bank would cause deep sedimentation of suspended load there.

Flow separation in a bend might be insignificant in coarser-grained meanders (McGowen and Garner, 1970; Bluck, 1971; Jackson, 1976a), but would play an important role in the stratigraphy and morphology of floodplains in finer-grained meanders. Concave bank benches are conspicuous features of the latter (Taylor and Woodyer, 1978; Woodyer et al., 1978; Page and Nanson, 1982). Although formation of concave bank benches is not fully understood, many are constructed in flow separation zones. In spite of having a pebble-bearing, coarse-grained sand bed, the Teshio River can be categorized as a "muddy, fine grained meandering river (Model 6)" as the Beaton is, employing the architectural style of Miall (1985).

Concerning Question 2, the average recurrence interval of a ridge in the Teshio is estimated to be 25 years. This rate closely resembles that of the Beaton, where an average periodicity determined from tree-ring dates is 27 years (Hickin and Nanson, 1975). Hickin (1974) and Hickin and Nanson (1975) identified the importance of channel curvature on the rate of channel migration, and showed that the periodicity of ridges is inversely related to the channel migration rate. Nanson (1980) supposed that a critical channel width within a bend would foster deposition of a scroll bar by providing a balance between point bar accretion and excess erosion of the opposite outer bank. This may be or may not be so in the case of the Teshio. As deep sedimentation of suspended load occurs over both the inner bank and a stable point bar platform, the periodicity of a ridge must be closely related to the settlement of the point bar platform for a considerable time. We have had no data, however, to show the relation between downstream movement of a point bar platform and erosion of the opposite bank.

Question 3 is discussed in the other paper (Ikeda, 1989). One might expect that differences in curvature radius cause the difference between the two types of bars shown in Fig. 1. Common point bars are often seen in channels which continually expand outward. A point bar platform on the Teshio appears to be the emerging downstream end of a forced bar; that is, one whose occurrence depends on a river bend.

6. Prospect

During flood stages, the excess sand supply enters the floodplain only over the outer bank, where the in-channel water with abundant intermittent suspended load first exits the channel. The flood flow loses its coarse load once it leaves the channel. This results in no distinctive sand deposits on the floodplain further downstream on a meander. Thus conspicuous natural levees develop over the outer bank of the channel. On the other hand, the foundation of floodplain scrolls is the bank bench which occurs on the gentle slopes of the inner accretionary bank. Flow separation in a meander bend is possibly an instrument for the excessive supply of suspended sediment there, which is preserved as climbing-ripple laminations among deep bank slope deposits.

In this paper, mechanisms of formation of natural levees and ridge-and-swale topography are discussed only qualitatively. Natural levees develop well in the Sakura River. Floodplain scrolls are prominent in the Teshio River. What causes the difference
between the two rivers? This paper stresses conclusively the importance of hydrodynamical flow analyses adjacent to bank slopes within a meander having various bend curvatures and also different flood stages.

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