MECHANISM OF INVERSE GRADING OF SUSPENDED LOAD DEPOSITS

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Abstract. Temporal changes of the excess sediment supply during a flood cause the suspended load to form depositional units that have inverse grading, in which sand overlies silt-clay. The silt-clay is deposited at the beginning of a flood, when the concentration of silt-clay, the “wash load”, is high. Stagnation of the flow over densely vegetated floodplains promotes the sedimentation of silt-clay beds. Low floodplain surfaces are covered first with water and thus accumulate deep mud beds. The upper sand bed is formed by the deposition of “suspended-bed material load” after the wash load decreases. Medium and fine sand make up deep beds over natural levees. The lack of a discernible waning structure suggests that little deposition occurs on the falling limb of a storm event. This results mainly from a decrease in the suspended sediment concentration.

Inversely graded deposits of suspended load can be useful stratigraphic signatures for present- and paleo-basin hydrological analyses. Inverse grading would be most prevalent in rivers where hysteretic loops of both suspended-bed material load and wash load occur prominently, and where flood events are caused by intensive rainstorms, not by gradually increasing water discharges during snow melt.

1. Introduction

The basic sedimentation units on floodplains are produced by discrete overbank floods. Climbing ripple lamination, convolute bedding, or horizontal bedding are commonly observed in overbank deposits (McKee et al., 1967; Ray, 1976; also reviewed in Reineck and Singh, 1980). In contrast to the vast knowledge on sedimentary and hydraulic processes of point bars (e.g., Sundborg, 1956; Allen, 1965, 1970; Jackson, 1975, 1976), available literature on overbank deposits is relatively scarce, even though the overbank deposit is an important component of fluvial sedimentary sequences (Bridge, 1984; Farrell, 1987).

In a small sand-bed channel, Iseya (1979) found that an overbank deposit always has distinctive inverse grading. Investigations on several major sand-bed rivers in Japan have revealed that inverse grading is a common sedimentary structure which characterizes depositional units of suspended load (Iseya, 1982a; Iseya and Ikeda, this volume). Inversely graded bedding has also been found in sedimentary sequences of paleofluvial deposits (Katsura et al., 1980; Masuda and Iseya, 1985).

Iseya (1982a) used intensive hydraulic measurements to demonstrate the depositional process of inverse grading. High suspended load transport rates at the increasing limb of a
storm event were critical, and a low flow intensity over the floodplain was also favorable. This paper reviews the depositional process of inverse grading of overbank deposits, which provides a means of specifying sedimentary environments of ancient fluvial deposits, the hysteretic loop of suspended load transport, and the sediment yield of a paleo-basin.

2. Sakura River

Inverse grading of overbank deposits was first observed in the Sakura River (Iseya, 1979, 1982a), which flows into Kasumiga-Ura lake, central Japan. Most of the floodplain is rice fields (Fig. 1), but a narrow zone adjacent to the channel has been left in a natural state. Willows and densely rooted reeds protect bank slopes, and except in winter, the present floodplain surface is covered with grasses. The morphology and stratigraphy of the Sakura are described in detail by Iseya and Ikeda (this volume).

![Image](image-url)

Fig. 1. Floodplain of the Sakura River. Flow is from left to right. The measurement site was at bridge A. Bridges A and B were also used for calculating water surface slopes. Dot is the site where Figs. 2 and 3 were taken. Houses and forests at the lowest part stand on diluvial upland.

The upper course of the Sakura has a narrow channel with bank slopes which clearly distinguish the channel bed from the floodplain (cf., Fig. 4A). The bankfull width and depth of the channel are 15–20 m and 1.5–1.8 m; the bed slope is approximately 1/1000. Over 85% of the bed material consists of granule (2–4 mm) to coarse sand (0.5–1 mm) grains, originating from coarse-grained granite which compose the mountains on the uppermost drainage basin. Mts. Tsukuba and Kaba are two famous peaks of this range.

The mean annual precipitation for the last 20 years is about 1500 mm. Bankfull discharge occurs at least two or three times a year. Larger floods from typhoons between August and October often cause deep overbank deposition.

3. Inverse Grading of Overbank Deposits

We have observed inversely graded suspended load deposits in several major sand-bed rivers from northern to southern Japan, including the Tesho, Ishikari, Omono, Mabechi, Kinu, Tone, Edo, Yahagi, and Yasu Rivers. Both the grain size and the vertical sequence are very similar in these rivers, irrespective of the large variation in geometric and hydro-
dynamic parameters. So, inverse grading of overbank deposits of the Sakura is described in detail as the type, which is characterized as follows:

1) Deposits are usually parallel to the leaf litter of vegetated floodplains, and occasionally have an erosive base. 2) A sedimentation unit deposited in a single flood has two beds, a lower mud bed and an upper sand bed. 3) The two beds are separated by a distinct grain size change. 4) Upward coarsening in grain size is evident in both beds. 5) Deposition ceases without leaving a waning structure; grain size is the coarsest at the top of the sand bed. 6) The proportion of the two beds depends on floodplain morphology; deposits on natural levees show a slightly different facies than those on lower elevation floodplains.

Figure 2, taken soon after a flood, shows a thick, inversely graded deposit on a low floodplain. The light-colored lowermost part of the deposit is fresh clay grading up into silt. The overlying sand bed is usually thin. Fine (0.125–0.25 mm) and very fine sand (0.063–0.125 mm) are interlayered finely with silt. The desiccation of water-saturated muddy sediments often produces polygonal mud cracks. Thicker mud beds produce larger polygons. The total thickness of a deposit is commonly 2–5 cm, and occasionally up to 10 cm.

![Image](image_url)

Fig. 2. Inverse graded deposits on a low floodplain. A deep mud bed is overtopped by an obscure sand bed. Light color at the lowermost edge indicates fresh clayey deposits. Desiccation produced a large polygon. Lens cap is 6 cm in diameter.

In contrast, muddy beds are obscure over natural levees (Fig. 3), which develop parallel to the outer bank of meanders (ISEYA and IKEDA, this volume). A silty thin bed, less than 5 mm in thickness, is seen at the base of a deep sand bed. The sand bed, commonly 15–18 cm in thickness, is composed of medium (0.25–0.5 mm) and fine sand (0.125–0.25 mm). At first glance, most deep sand beds look massive and without internal laminations, but small grain size heterogeneities sometimes create parallel or ripple lamination. Figure 3 also illustrates that deep sedimentation of well-sorted sand occurs repeatedly over the natural levee. Four large floods that caused deep sand beds are shown on Fig. 5. It is of great interest that grains larger than 0.5 mm in diameter never occur in deep beds.
4. Flood Hydrograph and Suspended Load Transport

Flood hydrographs of the Sakura show a rapid increase and decrease of water discharge. The floodplain is inundated for two days at most, even in an extreme flood. The May 1977 flood was due to heavy rain totaling more than 100 mm. Bankfull stage was reached within 6 hours of the initial rise (Figs. 4B and 5), and increased further until almost all of the floodplain was covered (Fig. 4C). The maximum flow depth in the channel was about 3 m.

ISEYA (1979, 1982a) measured suspended load transport, water stage, and a few hydraulic parameters during major high flows in 1977 when floodplain inundation happened more frequently than usual (Fig. 5). A straight measurement site (see Fig. 1) was
chosen to minimize the effect of secondary flows generated by a curved bend (Leeder and Bridges, 1975). The bridge labeled A in Fig. 1 was used for the measurement of flow velocities and suspended load concentrations. Simultaneous measurements of the water height at bridges A and B gave values of the water surface slope. Bedforms were surveyed by an echo sounder, which showed that the bed surface was always covered with dunes.

Overbank deposits are, of course, brought by flood waters that contain high concentrations of suspended materials. Water was commonly yellowish on the rising limb and turned dark during the flood peak and falling limb. The relation between suspended load transport and water stage, which is a critical factor in the inverse grading of overbank deposits, is summarized as follows:

1) Maximum suspended load concentration preceded the flood hydrograph (Fig. 5).
2) The silt-clay (<0.063 mm) component accounted for high values of suspended load transport at the beginning of flood hydrographs (Fig. 6). The sediment discharge of each size class was calculated from flow velocity and sediment concentration measured at several depths at the center of the channel (cf., Fig. 7). The transport rate of silt-clay was extremely high at the very beginning of the rising limb of the hydrograph, and decreased drastically near the flood peak (Fig. 6). The peak discharge of silt-clay was forty times as high as during the waning stages.
3) Silt-clay was distributed homogeneously in the flow, as observed by Straub (1932), Nordin and Dempster (1963) and Scott and Stephens (1966). The vertical
Fig. 4. Successive upstream views of a tremendous flood on the Sakura. Photos were taken at bridge A of Fig. 1 by H. Ikeda. A: Extraordinary low flow at 9:00 on May 15, 1977. The shoal changed alternately over obscure bars. Rainfall began about two hours before. B: Bankfull stage at 16:00 just before flooding. Floating debris flowed along a center line of the channel. Discharge was approximately 12 m³/sec. C: About one hour after the flood peak with very clear sky, taken at 10:00 on May 16. Flood waters were flowing into the channel. D: Last phase of a storm event at 10:00 on May 17. Flow depth was about 50–60 cm.
Fig. 5. Hydrodynamic measurements of several major storm events occurred in 1977. D: water depth above mean bed; Cs: concentration of suspended load at the water surface in the middle of the channel; Sw: water surface slope between bridges of A and B; Vs: surface flow velocity at the middle of the channel; Tw: water temperature; L and h: mean dune length and height measured by an echo sounder.
profile of silt-clay concentration had little gradient at different stages (Fig. 7). The gradient of very fine sand was also very small.

4) It is a surprising but important fact that the peak of medium and fine sand transport also occurred during the increasing limb at stage II (Fig. 6), and not at stages III and IV when water depth was maximum. This contradicts theoretical predictions (e.g., LANE and KALINSKE, 1939; EINSTEIN, 1950) that suspension of sandy bed material is strongly governed by flow regimes. In other words, there should be a simple correlation between suspended-bed material transport (not including “wash load”) and water discharge.

5) Grains larger than 0.5 mm in diameter were rarely suspended, except immediately above the channel bed (Fig. 8).

5. Flow Characteristics

If the flow velocity were high enough to prevent deposition of any grain size within the suspended load, inverse grading would not occur. Some flow characteristics are briefly described as follows:

Water discharge and mean flow velocity at the bankfull stage were about 12 m³/sec and 0.5–0.6 m/sec. Maximum flow velocity occurred just below the water surface, and reached about 1.2–1.3 m/sec before flooding (Fig. 5). However, surface velocities during two large floods (May 16, and September 19, 1977) decreased at the flood peak, due to three-dimensional distribution of the flow velocity. Flow velocity near the peak stage did not
always increase with increasing flow depth, but reached a maximum value at the bankfull height (Fig. 9). Maximum velocity was about 1.35 m/sec.

Strong secondary flow circulation during large floods may account for the decrease in flow velocity at the water surface. This was expected by large boils over the bank slopes at

Fig. 9. An example of three-dimensional distribution of flow velocity (m/sec). Measurement was made at bridge A at 10:30 May 16, 1977, just after the picture of Fig. 4C was taken. Datum is strand at mean bed.
flood stages (Fig. 10). Before flooding, frequent small boils were observed within the channel. These boils were caused by increasing dune dimensions (ISEYA, 1984). During initial flooding, however, large periodical boils became conspicuous over the outer bank of a meander, and expanded toward the center of the channel. These boils, in turn, suggest that local high upward turbulence was generated along bank slopes.

The flow intensity over the floodplain directly affects the sedimentation of overbank deposits. Although they are difficult to measure, velocities immediately above the floodplain surface must have been very low due to the presence of thick grasses.

6. Depositional Process of Inverse Grading

Inverse grading has often been observed in thick sequences of sediments deposited by turbidity currents or subaqueous debris flows (e.g., KUENEN and MIGLIORINI, 1950; KUENEN and MENARD, 1952; SANDERS, 1965; FISHER, 1971). Inversely graded bedding has been observed in volcanioclastic sediments (FISK, 1974), and channel deposits left by a tremendous flood (COSTA, 1974). In the majority of cases cited, inversely graded deposits are most obvious in conglomerates and breccias, in which gravity processes are the basic mechanism. However, inverse grading is found also in fine sediments; CLIFTON (1969) described reverse grading in thin fine-grained layers created by grain segregation during wave backwash over beaches.

The critical factor in producing the inverse grading of suspended load deposits treated in this paper is the temporarily high availability of sediment supply. Little depends on hydraulic regimes. Suspended load could be deposited in three phases (Fig. 10):

1) Deposition of a silt-clay bed at the beginning of a flood: Bottom layers accumulate at the very beginning of a flood, when flood waters contain high concentrations of fine-grained suspended load, mainly silt-clay. Stagnation of the flow over dense vegetation promotes sedimentation of fine materials. Low floodplain surfaces are covered first with water and thus accumulate deep mud beds. In contrast, natural levees are still above water at this stage and thus contain indistinct mud beds.

2) Deposition of a sand bed during rising water stages: The overlying sand bed is deposited after the finer suspended load decreases. A gradual increase of flow intensity over the floodplain might eventually result in upward coarsening. The maximum grain size of natural levee deposits (Fig. 3A) was slightly larger than sand grains that were sampled just above bankfull flow at the center of the channel (Fig. 8). This suggests that larger sand grains would be temporarily suspended in the localized high upward flows, which are visually apparent as large violent boils at the water surface adjacent to banks. The limiting size of natural levee deposits, 0.5 mm in diameter, is very similar to the sizes of grains suspended just above the channel bed (Fig. 8).

3) Preservation of inversely graded units: Waxing-and-waning sequences, which are recorded stratigraphically in grain size and laminations, are common in deposits caused by a single flood (MCKEE, 1966; MCKEE et al., 1967; COLEMAN, 1969; SINGH, 1972; RAY, 1976; NANSON, 1980). Such flood cyclothems result mainly from increasing and decreasing flow velocities.

In contrast, the inversely graded deposits described in this paper have no discernible waning structure. This is evidence that no deposition occurs at the falling limb of a flood. As the water level falls, flood water flows back from the floodplain to the channel (ISEYA, 1982a) and hence more suspended materials do not invade the floodplain. This appears to be true for small rivers such as the Sakura. However, the largest sand-bed rivers flowing through the Kanto Plain, the Tone, Edo and Kinu, show no distinct difference in flow
direction between increasing and decreasing stages.

The major reason for the lack of sediment supply over floodplains during falling stages is the hysteretic loop of suspended load transport. Flood waters contain relatively little sediment during falling stages. For both the Sakura, described above, and the Tone Rivers (Kinoshita, 1984, his Fig. 1), transport rates of fine and medium sand became small before the flood peak. Such a hysteresis might be caused by disequilibrium in sand-dune bedforms. Flume experiments by Isey (1984) suggest that strong eddies that scour the bed surface and carry sediment into the main flow increase suspended sediment concentration. Strong eddies are prominent during rising stages, when dunes grow.

Inverse grading caused by depositions of suspended load has been described only in the Barwon River (Taylor and Woodyer, 1978), where deposition occurs mainly on three bank benches within the channel. Laminated reverse-graded bedding is the most prevalent structure on the highest two benches. Page and Nanson (1982) did not detail sedimentary sequences on concave bank benches of the Murrumbidgee River. However, their Fig. 3A, which shows fine suspended-sediment deposits, might indicate inverse grading structure. A mud bed appears to have a sharp contact with the underlying bed and a gradational contact with the upper bed. Both rivers, which drain New South Wales, Australia, have gentle flood flows and relatively high concentrations of suspended load, and thus a similar mechanism of inverse grading would be expected.
7. Source of Suspended Load

Suspended load can be divided into two components: the "wash load", and the "suspended-bed material load" (Shen, 1971a; Richards, 1982; Lewin, 1983), or "intermittent suspension load" (Middleton and Southard, 1978). The former is the finest sediments, which are almost continuously in suspension. Because they are derived mainly from sources outside the channel, the amount of wash load does not depend on hydraulic conditions, but on the supply rate (Einstein et al., 1940; Shen, 1971a). The suspended-bed material load is coarser sediment that originates from bed material suspended intermittently by the turbulence of flow.

There has been no way to distinguish these two components because both are sampled simultaneously in field measurements (Leopold and Maddock, 1953; Kikkawa, 1954; Nordin, 1964; Nordin and Beverage, 1965; Guy, 1964; Walling and Teed, 1971; Wood, 1977). As a rule of thumb, the grain size of wash load has been assumed to be smaller than 0.063 mm (e.g., Shen, 1971b; Richards, 1982, p. 99).

The main cause of the mud bed in inversely graded deposits is that silt-clay, assumed to be the wash load, precedes the flood hydrograph. What is the origin of such a high sediment supply? Fine-grained materials transported as wash load are stored in the channel bed, banks, and the floodplain. The floodplain and banks introduce little sediment into the flow, except where banks are eroded. In the large flume at ERC, high concentrations of silt-clay appear just after water is introduced into the flume, because fine sediments in the interstices of small gravels are discharged out. However, the channel bed contains a very small amount of fine material, too small to cause deep sedimentation over a floodplain.

Accordingly, it is natural to consider that most fine sediment stored at source areas are transported by way of tributaries to main channels. The concept of Horton overland flow (Horton, 1933) assumes that all parts of a small drainage area contribute to surface runoff at times of intense rainfall. If this were so, fine materials produced within an entire basin could reach the channel with ease in high concentrations. However, Horton overland flows has never been observed in humid forested areas, even during the most intense rainfall. Instead, surface runoff occurs only in small areas, very near the heads of streams. This is an aspect of the variable-source concept which was measured definitively by Dunne and Black (1970) and Dunne et al. (1975). Tanaka et al. (1986) also confirmed the concept in a small forested basin in Hachioji, Japan.

The variable-source concept suggests that the small areas adjacent to channels, such as side slopes and heads of rills and gullies, are the primary source of fine sediments transported by a storm surface runoff. At headwater catchments, therefore, the timing of surface runoff contribution to a flood hydrograph would control the hysteresis of the wash load yield.

My observations during rain storms have shown that banks and channel beds in headwater streams are heavily eroded and become the major sources of wash load. Erosion of land surfaces disturbed by human activities is another important source of fine sediment. Horton overland flow is generated where the infiltration capacity of the soil is lowered by packing or denudation, such as that on roads, skid trails in forests, ploughed fields or gardens. In the basin of the Futagami, a tributary of the Sakura (Fig. 1), a large quantity of fine material originates from surface runoff over unpaved roads densely developed for gravel mining.

However, available literature cannot fully explain the occurrence of peak wash load concentration at the beginning rises in discharge, which is fundamental for producing
inversely graded deposits. The sediment load of a stream responds in a highly sensitive,
nonlinear fashion to changes in stream flow and sediment availability. The larger the basin
is, the more complicated would be the relationship between water discharge and wash load.
The sequential processes of erosion from sources, storage and transport in channel systems
have remained elusive so far (WOLMAN, 1977; WALLING, 1983). Understanding would be
enhanced by performing both detailed empirical investigations (e.g., HENDRIKS and
IMeson, 1984; IMeson and VIS, 1984) and calibrated modeling (VANSICKLE and BESHTA,
1983).

Sedimentological evidence from mud beds gives some insights into the dynamics of
wash load and the production of fine materials in a basin: 1) Larger floods produce deeper
mud beds. 2) A flood closely following another of similar size deposits a thinner mud bed
than the first, because of the smaller wash load concentration of the later flood. The two
consecutive floods of August, 1977 (Fig. 5) serve as an example. This suggests that it takes a
period of time for more fine sediment to become available in a basin. 3) Floods during
spring deposit more clay at the base of units than during any other season. This
demonstrates the seasonal variation of suspended load concentration (GUY, 1964; WALLING
and TEED, 1971). In the dry winter season, mechanical weathering, such as that by frost
action which is often observed on bare ground, would cause a high fine sediment yield. 4)
Mud beds just downstream of sediment sources are deep and light-colored. With increasing
distance downstream, mud beds become shallower and darker and contain much organic
debris. The sediment source is commonly a tributary that discharges high suspended load
concentrations. For example, the Futagami River, transported suspended sediment concentra-
trations measured as high as 15,300 ppm (ISEYA, 1982b). The difference in the color of mud
beds upstream and downstream of the mouth of the Futagami was very distinct, reflecting
the proportions of organic and fresh clay minerals.

8. Summary and Conclusions

Inverse grading is common in deposits of suspended sediment from single floods in
several major sand-bed rivers of Japan. The deposition of inverse graded beds depends on
hysteretic loops of suspended-bed material load as well as wash load.

The inverse grading of suspended load deposits is characterized as follows: a) The
sedimentation unit deposited in a single flood consists of a lower mud bed and an upper
sand bed, b) Upward coarsening is evident in both beds, and c) Deposition ceases with no
discernible waning structure. The proportion of the two beds depends on floodplain
morphology. Deep mud beds are deposited over low floodplain surfaces; obscure mud beds
and deep sand beds are deposited over natural levees.

The critical cause of inverse grading is the change in sediment supply during floods.
The lower mud bed is deposited at the beginning of a flood, when the concentration of
silt-clay, the so-called “wash load”, is extremely high. Stagnation of the flow over dense
vegetation promotes sedimentation. Progress through variable-source concepts of storm
hydrographs in humid regions suggests that only confined locations adjacent to headwater
streams contribute wash load, by erosion from surface runoff during intense rain. Thus,
erosion of headwater channel margins and beds can be the major source of fine sediments.
Surface erosion of disturbed land that has a reduced infiltration capacity can also be an
important sediment source.

The upper sand bed is deposited from suspended-bed material load, after wash load
drastically decreases. An increase in flow depth over the floodplain might eventually result
in upward coarsening. Deposition would not occur on the recession limb of a flood, because
of limited sediment supply. This limitation might be due mostly to the decrease in concentration of intermittently suspended sediment.

Thus, inversely graded suspended load deposits are clearly caused by storm hydrographs that produce hysteresis in suspended sediment transport. Inversely graded deposits might be overtopped by waning grading in those rivers and floods in which the flood hydrograph has a long tail of retreating flows, which is typical in snow-melt seasons.

Mud beds are strong evidence for high wash load concentration at the rising limb of flood hydrographs. Sedimentological sequences of mud beds give some insights into the dynamics of wash load and differences in sediment yield between storms, catchments, and seasons. Inverse grading of suspended load deposits must provide important information for present- and paleo-basin analyses.

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