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FLUME EXPERIMENTS ON THE HORIZONTAL STREAM OFFSET BY STRIKE-SLIP FAULTS

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ABSTRACT

Flume experiments, in which the middle section of an erosion channel is displaced horizontally, have been conducted to assess the response of streams to horizontal displacement by a strike-slip fault. The experimental erosion channel was developed in a mixture of sand and clay, which provided relatively stable banks with its cohesiveness. Horizontal displacement of a strike-slip fault perpendicular to the channel is expected to add a flat section to its longitudinal profile along the fault line. The experimental stream eliminated this flat section with downstream degradation, upstream aggradation, and lateral channel shift. As a result, a roughly continuous longitudinal profile was maintained. This maintenance of a continuous longitudinal profile along channel is considered to be the principle of stream response to horizontal displacement by a strike-slip fault. Downstream degradation was the dominant process of this stream response in the overall tendency of erosion without sand supply. When the rate of fault displacement was low (long recurrence interval), the experimental stream eroded the fault surface, jutting laterally into the channel like a scarp, and deflected the channel within the recurrence interval. This lateral channel shift gave some gradient to the reach created by fault displacement (offset reach), and the downstream degradation occurred as much as completing the remaining longitudinal profile adjustment. When the rate of fault displacement was high (short recurrence interval), the lateral erosion on the first fault surface was interrupted by the next fault displacement. The displacement was then added incrementally to the existing channel offset making channel shift by lateral erosion increasingly difficult. The channel offset with sharp bends persisted without much modification, and downstream degradation and upstream aggradation became evident with the effect of the offset channel course, which worked like a dam. In this case, a slight local convexity, which was incidentally formed by downstream degradation and upstream aggradation, tended to remain in the roughly continuous longitudinal profile, as long as the horizontal channel offset persisted. In either case, once the experimental stream obtained a roughly continuous gradient, further channel adjustment seemed to halt. Horizontal channel offset remained to a greater or lesser extent at the end of each run long after the last fault displacement.

KEY WORDS: flume experiment; erosion channel; strike-slip fault; offset stream; channel adjustment

INTRODUCTION

Horizontal displacement of a strike-slip fault is considered to make rivers offset, and therefore, the distribution of strike-slip faults has often been inferred from the existence of offset channels (e.g. Lensen, 1958; Allen, 1962; Kaneko, 1965; Matsuda, 1966; Wallace, 1968; Keller *et al*., 1982; Sieh and Jahns, 1984). However, how streams respond to displacement by strike-slip faults has not been examined seriously and is still a matter of speculation. The phenomenon seems to be more complicated than it looks. A variety of planimetric patterns of channels across strike-slip faults (e.g. Lensen, 1958; Allen, 1962; Wallace, 1968; Gaudemer *et al*., 1989; Huang, 1993) indicates that the effect of strike-slip faulting on rivers varies widely. Lack of independent seismic evidence, moreover, makes distinguishing channel offset exclusively by fault displacement very difficult. Offset rivers themselves are often the only evidence indicating fault activities. Under this condition, flume experiments, which are a useful tool for interpreting the complicated channel development processes (cf. Schumm *et al*., 1987), may provide some ideas of the channel response to strike-slip fault displacement. Few experiments on bedrock channels, which are the common nature of offset channels, however, have been performed in the past (e.g.

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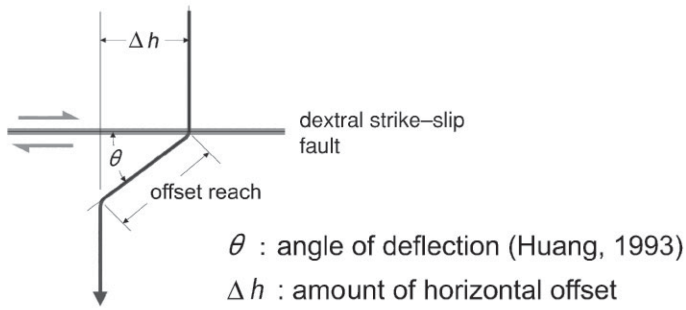

Figure 1. Terminology of an offset channel

Shepherd and Schumm, 1974; Gardner, 1983; Wohl and Ikeda, 1997). The large number of variables involved, many of which are difficult to measure, discourages scale-model experiments on bedrock channels. Adding another variable, namely tectonic movement, will make it more difficult. The flume experiment on horizontal stream offset conducted in this study, in which the middle section of an experimental channel is displaced horizontally, is not a scale-model attempt to reproduce real processes of channel development, but it is like the 'similarity of process' experiment described by Hooke (1968). The experimental streams are prototypes themselves in the experimental setting, and observing how these small streams respond to horizontal offset by fault-like displacement may provide some ideas to interpret the behaviour of real offset rivers. The conditions of experiments were mostly determined through trial and error within the limitation of experimental facilities. To assess the effects of strike-slip displacement, experimental fault displacement was limited to horizontal offset.

The reach connecting the original channel offset by fault displacement (or the reach created by fault displacement) is called 'offset reach' in this study (Figure 1). Offset reaches are usually modified by fluvial processes, and the angle of deflection (Huang, 1993), which is the angle between the fault slip direction and the offset reach (Figure 1), is considered to increase with lateral erosion.

FLUME EXPERIMENTS ON CHANNEL RESPONSE TO HORIZONTAL OFFSET

The experiments were performed in a flume at the Hydro-Geomorphology Laboratory, Tokyo Metropolitan University, Hachioji, Japan. The steel flume is 6·5 m long, 1·5 m wide and 0·5 m deep, with variable gradient (gradient was fixed at 0·043 for most of the runs). A mixture of sand ($D_{50} = 0{\cdot}57$ mm) and bentonite (2·4 per cent by weight) filled a wooden frame, 6 m long, 40 cm wide and 8 cm high, fixed on the flume floor (Figure 2a). Each run of the experiment started by cutting an incipient channel, 2·5 cm deep with a triangular cross-section, into this material. Water was supplied through a circulating pump with a discharge rate of 700 ml min^{-1}, and no sand was supplied. The side board of the wooden frame was cut about 60 cm in the middle and sealed with clay, so that the block of material in this section could be moved horizontally by pulling a piece of plastic net put beneath it (Figure 2a). The upstream and downstream ends of this section (about 314 cm and 254 cm from the downstream end of the flume) were cut beforehand with a thin stainless steel sheet to make fault lines. The fault block was then displaced producing sharp fault surfaces (as shown in Figure 2b). Water flow was first introduced into the channel after a piece of wood blocking the downstream end of the channel was removed, and an erosion channel with cohesive banks developed upstream into the mixture of sand and bentonite. Thalweg position and height were measured with a point gauge at certain time intervals, while stopping the water supply, for 500 cm of flume length excluding reaches at the downstream (30 cm) and upstream (120 cm) ends. The displacement of the fault block was started after the initial channel change mostly ceased. The fault block was pulled laterally by 2–4 cm at a time after the measurement of thalweg height and before the resumption of water flow. This fault block displacement was repeated at certain intervals of water flow. The conditions for each run are summarized in Table I, and results of measurement are partly shown in Figures 3–5. The point gauge records *x*- (horizontal distance parallel to the flume), *y*- (horizontal distance perpendicular to the flume), and *z*- (relative height from a datum plane) coordinates of every measured point, and the resultant data are shown in the figures as plan views, projected channel bed profiles and longitudinal channel bed profiles (Figures 3–5). The plan view

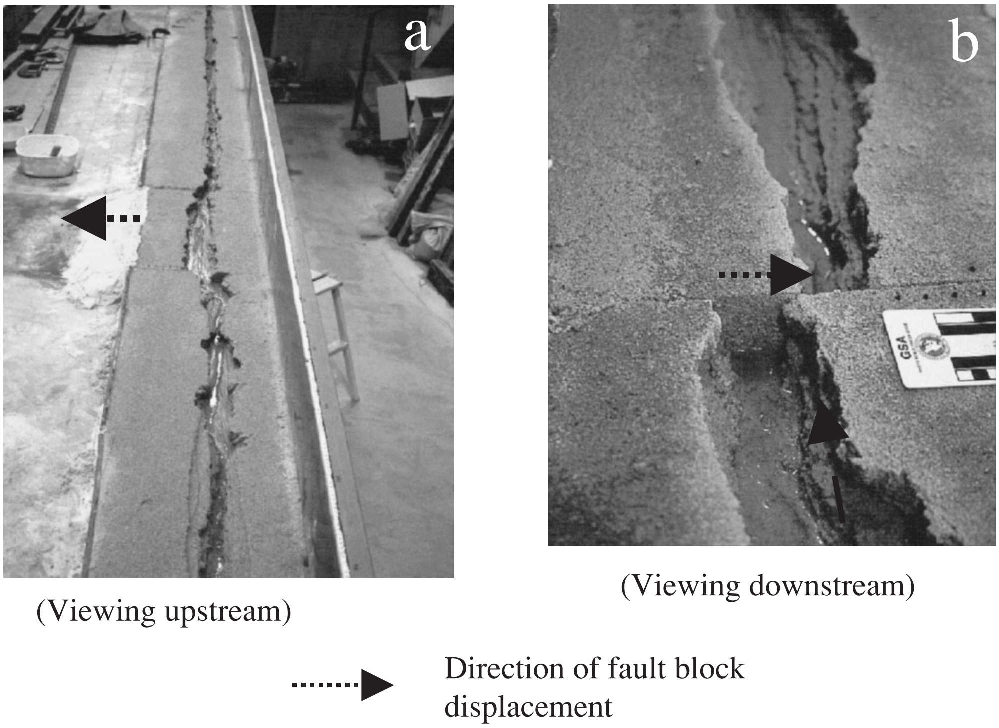

Figure 2. (a) Experimental channel and the fault block. The flume is at the Hydro-Geomorphology Lab, Tokyo Metropolitan University, Hachioji, Japan. (b) The sharp fault surface jetting laterally into the channel at the upper dextral fault during Run 2 (6 cm of displacement). (The surface of the material was mostly dry throughout the experiment. The water flow excavated banks beneath the dry surface during the development of an erosion channel, and the bank surface occasionally collapsed in places to form irregular fringes. Overhanging banks often developed, and sometimes part of these banks had to be destroyed for the measurement of thalweg height and position. This is another reason why banks have scalloping fringes.)

Table 1. Experimental conditions for Runs 1–3

Run number	Duration of water flow before the first fault displacement (h)	Amount of incremental displacement (cm)	Interval of displacement (h)	Total displacement (cm)	Total period of water flow (h)
1	48	2	2	14 (2 × 7)	76
2	125·5	2	0·5	14 (2 × 7)	152·5
3	30	4	1	32 (4 × 8)	100

Flume gradient: 0·043.
Material used: mixture of 97·6 per cent sand ($D_{50} = 0{\cdot}57$ mm) and 2·4 per cent bentonite by weight.
Water discharge: 700 ml min^{-1}.
Sediment supply: none.

shows thalweg positions projected to the *x–y* (horizontal) plane. Projected channel bed profiles, which are longitudinal channel bed profiles projected to the *x–z* (vertical) plane, express channel bed (thalweg) height in relation to the horizontal distance from a datum line (downstream end of the flume). This horizontal distance (cm) is exclusively used to express the location of a point in the flume. Longitudinal channel bed profiles are normal longitudinal profiles representing channel bed gradients along thalweg.

Run 1

The fault block displacement was started after 48 hours of water flow (after the measurement at 48 h) when the movement of sand on the channel floor mostly ceased. (The abbreviation of hours (h), is used for indicating a certain time of water flow in the run from the beginning.) The fault block was displaced horizontally 2 cm at a time, followed by 2 hours of water flow. This procedure was repeated seven times (48 h–60 h, a total 14 cm of fault displacement). The 2 cm of fault displacement was not enough to close the channel with the fault block, and at the upstream dextral fault the water flow (and therefore erosion) concentrated on the edge of the fault surface, jutting laterally into the channel from the left side like a scarp. In 2 hours of water flow following the fault displacement the stream eroded the fault surface and increased the angle of deflection. The stream was forced to flow towards the upstream side of the lower offset reach at the downstream sinistral fault. The lateral erosion on the fault surface to increase the angle of deflection did not occur here so much as at the upper dextral fault. The lower offset reach elongated with the lateral shift of the upstream reach on the fault block even after the faulting. The upper and lower offset reaches eventually combined to form a curved L-shaped channel course (Figure 3a). The final angle of deflection θ was about 70° at the upstream dextral fault and about 35° at the downstream sinistral fault. The curved L-shaped channel was actually formed by fluvial processes with the rather unusual arrangement of faults, two strike-slip faults of opposite displacing directions running perpendicular to the channel at a short interval. Multiple terraces formed at the upper right and lower left sides of the valley on the fault block with the lateral channel shift in the overall degradational trend.

Relatively large steps or holes in the reaches upstream and downstream of the fault block are prominent in longitudinal profiles (Figures 3b, c). However, these are potholes or pothole-like knickpoints developed during the upstream migration of erosion before the faulting. Knickpoints and potholes are common erosional bed forms in experimental channels formed in cohesive substrates (Wohl and Ikeda, 1997), and their formation is not related to the faulting. These potholes remained at nearly the same location throughout the run, except when sediments produced by occasional bank failure filled holes temporarily, as shown by the profile of 54 h. Longitudinal channel bed profiles along thalweg show a stairs-like feature with steps at potholes (Figure 3c). This type of stepped longitudinal bed profile may be a characteristic feature of predominantly degrading channels.

Projected channel bed profiles, which indicate degradation or aggradation at a point, show an overall trend of degradation (Figure 3b) apparently derived from the experimental setting. A short section between the upper fault and the large pothole upstream shows changes continuous to the reach on the fault block, and therefore, this short section is regarded as a part of the reach on the fault block (between the faults). In this reach on the fault block aggradation started after the first fault displacement probably due to the sediment derived from the lateral erosion in the upper offset reach. The slight aggradation turned to a rapid channel bed rise between 54 h and 56 h (the profile is not shown in the figure) due to the sudden increase in sediment supply from the large bank failure in the upstream reach. The channel bed perched at a similar height until 62 h. The increase in sediment supply from the lateral erosion and the smaller angle of deflection of the lower offset reach certainly contributed to the maintenance of the high profile in the reach on the fault block. After 62 h, relatively rapid degradation occurred, and the final channel bed in this reach became slightly lower than the channel bed before the faulting (48 h). In the reach upstream from the pothole above the upper fault, a slight trend of degradation, except for the sudden and temporal aggradation at 54 h, turned to rapid degradation after the last fault displacement (as shown by the profile of 62 h). The final channel bed became clearly lower (about 1 cm) than the channel bed before the faulting. In the downstream reach from the lower sinistral fault, a slight degradational trend after the first fault displacement was interrupted by aggradation from 56 h to 62 h. The sediment produced not only by the large bank failure in the upstream reach before 54 h but also by the lateral erosion in offset reaches during the faulting probably contributed to this downstream aggradation. The degradation then resumed after 62 h, and the projected channel bed profile at the end of the run (76 h) became about 1·5 cm lower than the bed before the faulting. The amount of lowering was the largest in this downstream reach.

Horizontal displacement by a fault perpendicular to the channel will produce a flat section in the longitudinal channel bed profile. Longitudinal channel bed profiles in Run 1, however, do not show such flat sections either at the upper dextral fault or at the lower sinistral fault (Figure 3c). A slight convexity appeared in the profiles of 52 h and 54 h around the lower offset reach, but it is difficult to consider this as the effect of fault displacement, because the longitudinal profile before the faulting (48 h) also has a similar feature. Offset reaches quickly

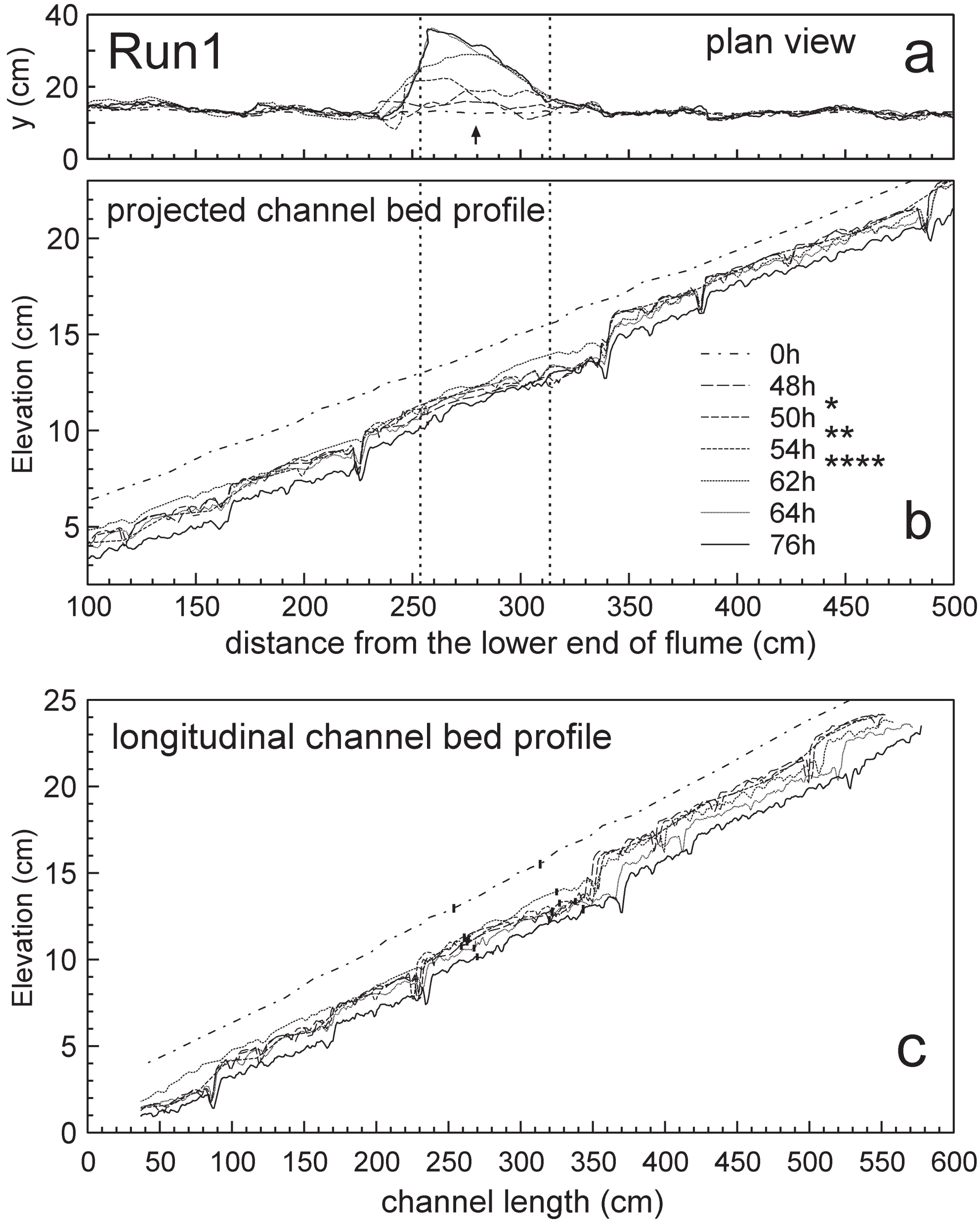

Figure 3. Changes in thalweg position and longitudinal bed profile with the displacement of faults in Run 1. Note that not all measurement results are shown in the figure in order to make the lines distinguishable. Also note that the ordinate of each graph is exaggerated for the same purpose. The legend in (b) applies to all the graphs. The dashed line labelled 0 h represents the bottom of the incipient channel excavated into the material at the beginning of the run. The longitudinal profile of 54 h looks smoother than other profiles due partly to the smaller number of measured points in the upstream and downstream reaches. (**a**) Thalweg position (plan view). An arrow shows the direction of fault block displacement. Two vertical dashed lines indicate fault lines. (**b**) Channel bed profiles projected to a plane parallel to the flume (projected channel bed profile). Each asterisk in the legend indicates 2 cm of fault displacement followed by 2 hours of running water. Two vertical dashed lines indicate the position of fault lines. (**c**) Channel bed profiles measured along thalweg (longitudinal channel bed profile). Short and thick vertical lines on each profile indicate the approximate position of faults, the upstream-most and the downstream-most points where the channel crossed the faults

obtained an average gradient similar to adjacent reaches. Channel incision accompanied by the larger downstream degradation mainly facilitated the gradient, while lateral erosion and channel shift played an important role in the upper offset reach.

Run 2

The fault displacement of 2 cm began after 125·5 hours of water flow (after the measurement at 125·5 h) when sediment movement on the channel bed had ceased. Because the stream had a long time to erode the channel before the faulting, an erosion channel was well developed and changes in channel bed height after the first fault displacement were smaller than other runs. The interval of fault displacement was shortened to 30 minutes to test how quickly the stream adjusts its longitudinal profile. The displacement was repeated seven times to the total displacement of 14 cm (125·5 h–128·5 h). The reach between upper and lower faults shifted almost exactly with the fault block displacement, and the channel offset with sharp bends developed and remained to the end of the run (Figure 4a). Water flow could not significantly erode the initial fault surface jutting laterally into the channel within the recurrence interval of 30 minutes. The next displacement added to the remaining offset and made lateral channel shift more difficult. In other words, the stream was unable to respond to this rate of fault displacement by lateral channel shift.

Projected channel bed profiles (Figure 4b) show a prominent and persistent pothole in the upstream reach at around 460 cm. The formation of the pothole, however, was unrelated to the faulting. Projected channel bed profiles indicate that degradation occurred continuously in the upper half of the reach between the pothole and the upper dextral fault (*c*. 400–460 cm). In the lower half of this reach (*c*. 314–400 cm), on the other hand, aggradation occurred after the first fault displacement (125·5 h) until 130·5 h (2 hours after the last fault displacement), apparently due to the faulting. After 134·5 h (the profile is not shown in the figure) degradation became dominant here, and the bed was lowered almost to the level prior to the fault displacement by the end of the run (152·5 h). In the reach downstream from the fault block, degradation was apparent after the first fault displacement, except for the short section just downstream of the lower fault, where aggradation occurred from 128 h to 129 h due to accidental bank failure on the left side of the lower offset reach near the lower bend. The degradation in the downstream reach continued, and the channel bed at the end of the run was clearly lower (up to about 1·5 cm) than the channel bed before the first fault displacement. On the fault block (excluding offset reaches), projected channel bed profiles show a similar change to the reach upstream of the upper fault, aggradation with the faulting. The amount of aggradation, however, was larger and erosion after the faulting was less, due probably to the horizontally offset channel course with sharp bends. The final channel bed became a little higher (about 0·5 cm) than the channel bed before the first fault displacement with a little gentler gradient of the projected lines. A pothole-like feature that formed before the faulting just below the upper dextral fault, together with the degradational trend downstream of the upper fault and the aggradational trend upstream of the lower fault, probably provided the gentler gradient. For the whole channel, the experimental stream quickly responded to the horizontal fault displacement by degradation in the reach downstream and aggradation in the reach upstream from the fault. Without sand supply the channel had an overall trend of erosion, and degradation eventually dominated in the whole length of the channel. Steps at the fault lines in the projected channel bed profiles (Figure 4b) mean that the offset reaches nearly perpendicular to the flume obtained some gradient with downstream degradation and upstream aggradation.

Longitudinal channel bed profiles (Figure 4c) indicate that offset reaches quickly obtained gradients roughly continuous to adjacent reaches with downstream degradation and upstream aggradation every time after the fault displacement. A slight local convexity with its centre in the reach between faults including offset reaches is the only feature possibly reflecting the effect of fault displacement. The local convexity grew with the fault displacement and persisted to the end of the run although it reduced in height after the faulting. Downstream degradation and upstream aggradation, which provide some gradient to the offset reach, will form a local convexity in its longitudinal channel bed profile at least temporarily. In the case of this experiment, two convexities were expected to appear in the longitudinal bed profile. The faults, however, were located close together (about 60 cm apart from each other), and the effects of two faults probably combined to form a local convexity in the longitudinal channel bed profile (Figure 4c). Although the local convexity may disappear if the stream completely adjusts its longitudinal profile, the slight local convexity is still seen in the profile of 152·5 h, 24 hours

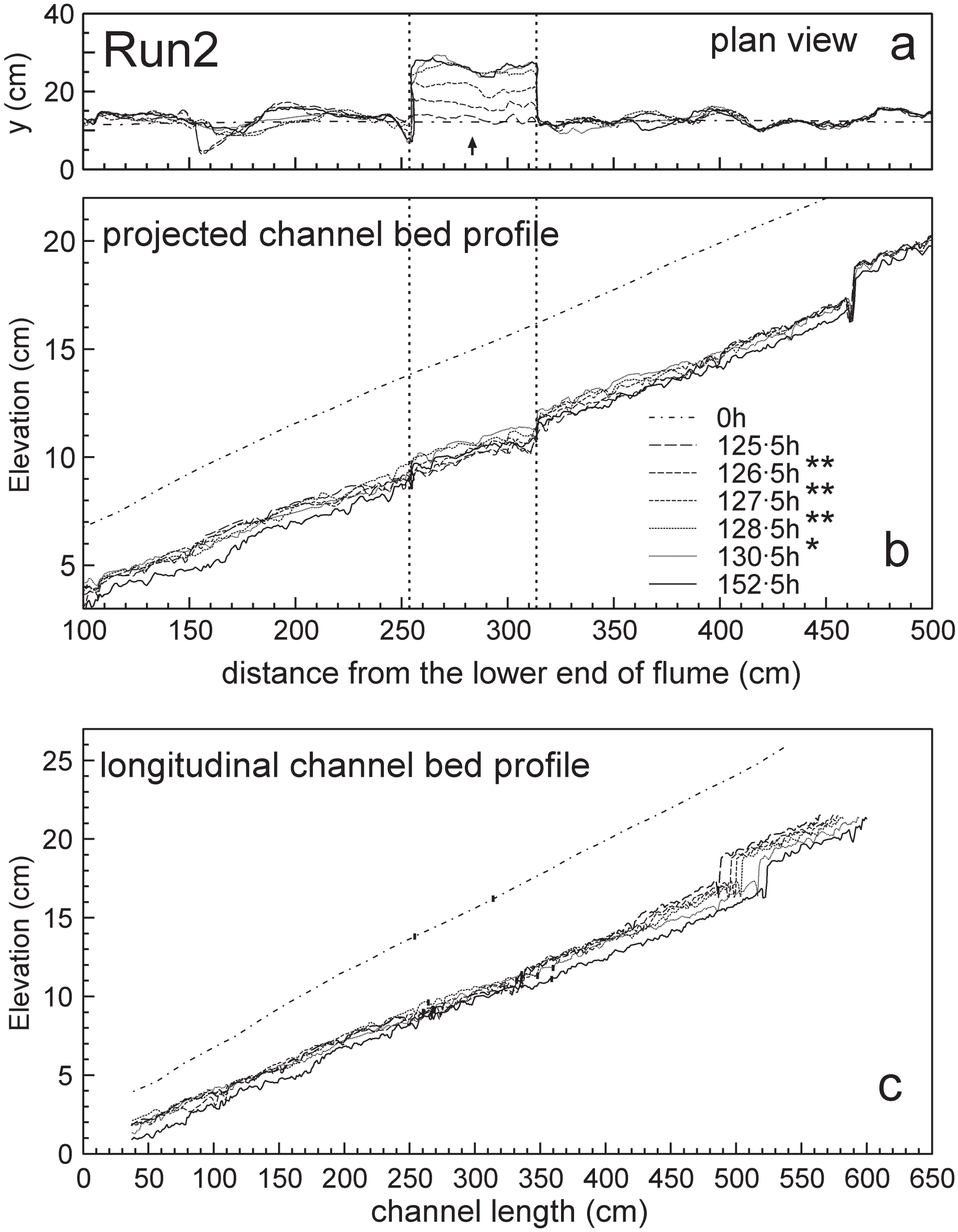

Figure 4. Changes in thalweg position and longitudinal bed profile with the displacement of faults in Run 2. Note that not all measurement results are shown in the figure in order to make the lines distinguishable. Also note that the ordinate of each graph is exaggerated for the same purpose. The legend in (b) applies to all the graphs. The dashed line labelled 0 h represents the bottom of the incipient channel excavated into the material at the beginning of the run. (**a**) Thalweg position (plan view). An arrow shows the direction of fault block displacement. Two vertical dashed lines indicate fault lines. (**b**) Channel bed profiles projected to a plane parallel to the flume (projected channel bed profile). Each asterisk in the legend indicates 2 cm of fault displacement followed by 0·5 hour of running water. Two vertical dashed lines indicate the position of fault lines. (**c**) Channel bed profiles measured along thalweg (longitudinal channel bed profile). Short and thick vertical lines on each profile indicate the approximate position of faults, the upstream-most and the downstream-most points where the channel crossed the faults

after the last fault displacement. This implies that the local convexity in the longitudinal bed profile persists as long as the horizontal channel offset with sharp bends remains.

Run 3

A larger displacement, 4 cm at a time and 32 cm in total, was generated in Run 3 to see whether the upper limit of stream response to the horizontal channel offset exists within the experimental setting. Fault block displacement started after 30 hours of running water (after the measurement at 30 h) and continued at 1 hour intervals, seven times (4 cm h^{-1}). After the last fault displacement at 37 h, water flow continued for 63 hours (total 100 hours). The channel was deformed almost as much as the fault block was displaced (Figure 5a). The experimental stream could neither shift laterally to increase the angle of deflection nor overflow to take a new straighter course. Even after the faulting the channel shifted in the direction to enhance the channel offset.

Projected channel bed profiles show larger aggradation and degradation of the channel than Run 2 (Figure 5b), reflecting the larger amount of fault displacement and the shorter time of erosion before the faulting. Prominent steps in projected channel bed profiles at the faults indicate that offset reaches obtained some gradient (similar to adjacent reaches) after the fault displacement. In the reach upstream from the fault block aggradation is apparent during the faulting. The projected channel bed profile in this reach rose up about 2 cm from 32 h to 38 h. The trend of aggradation reversed to degradation after 52 h (15 hours after the last fault displacement), and the channel bed of this reach at the end of the run (100 h) was somewhat lower (about 0·5 cm) than the channel bed before the faulting. In the reach downstream from the fault block, rapid and continuous incision after the first fault displacement is obvious. The final channel bed was about 3·5 cm lower than the channel bed before the faulting. In the reach between the faults (on the fault block excluding offset reaches), aggradation occurred during the fault displacement, but less than in the reach upstream from the fault block. The channel bed rose up to the highest level at 38 h and then lowered after 44 h (the profile is not shown in the figure). The final channel bed was about 2 cm lower than the channel bed before the faulting (Figure 5b). Degradation eventually dominated in the whole length of the channel, while the largest degradation occurred in the reach downstream from the fault block.

Downstream degradation and upstream aggradation as shown in the projected channel bed profiles apparently resulted in the maintenance of a roughly continuous longitudinal channel bed profile despite the horizontal channel offset by fault displacement (Figure 5c). Longitudinal channel bed profiles show some overall convexity, but this is not necessarily derived from the fault displacement because profiles before the faulting also show the same feature. The feature in the longitudinal channel bed profile possibly related to the fault displacement is the local convexity that developed with the fault displacement. A slight local convexity with its centre in the reach between faults appeared in the longitudinal channel bed profile of 32 h and grew larger to 36 h. The local convexity then spread and reduced the height after the faulting from 38 h, and became indistinguishable from the overall convexity at 100 h. The overall convexity in the profile of 100 h may include the convexity derived from the horizontal channel offset by fault displacement.

Run 4 (supplemental run)

In response to the horizontal channel displacement by faults, degradation occurred downstream and aggradation upstream from the fault, especially in Runs 2 and 3. As a result a nearly continuous longitudinal profile along thalweg was maintained, while the horizontal channel offset by fault displacement mostly remained. What drove this response, however, could not be established from the results of these runs. Run 4 was then conducted to observe the change in flow conditions responding to the horizontal channel offset.

After some trial and error, the flume gradient was lowered to 0·031 in order to restrain the pothole formation, and the amount of bentonite in the sand and clay mixture was increased to 5·7 per cent to make banks more stable and reduce the rate of channel change for the observation and measurement of water flow. The fault block was displaced horizontally once by 8 cm after 92 hours of running water, and the longitudinal profiles of the water surface and the channel bed were measured before and an hour (of water flow) after the fault displacement. The experimental setting is slightly different from previous runs, but the purpose of this supplemental run is to see the effect of horizontal channel offset on water flow in the channel. For this purpose, these differences are considered to be within the tolerance level necessary to make changes in water flow observable.

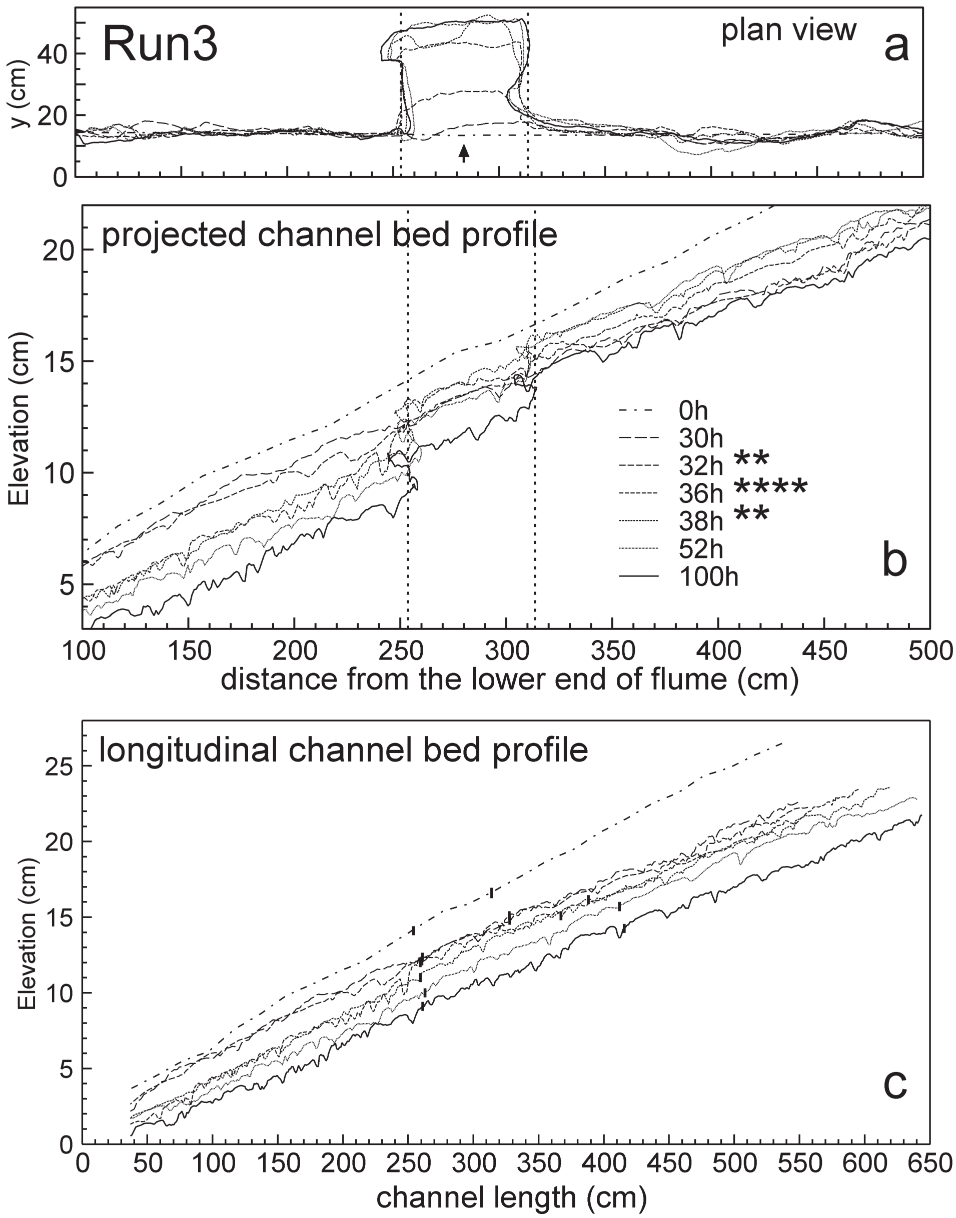

Figure 5. Changes in thalweg position and longitudinal bed profile with the displacement of faults in Run 3. Note that not all measurement results are shown in the figure in order to make the lines distinguishable. Also note that the ordinate of each graph is exaggerated for the same purpose. The legend in (b) applies to all the graphs. The dashed line labelled 0 h represents the bottom of the incipient channel excavated into the material at the beginning of the run. (**a**) Thalweg position (plan view). An arrow shows the direction of fault block displacement. Two vertical dashed lines indicate fault lines. (**b**) Channel bed profiles projected to a plane parallel to the flume (projected channel bed profile). Each asterisk in the legend indicates 4 cm of fault displacement followed by 1 hour of running water. Two vertical dashed lines indicate the position of fault lines. (**c**) Channel bed profiles along thalweg (longitudinal channel bed profile). Short and thick vertical lines on each profile indicate the approximate position of faults, the upstream-most and the downstream-most points where the channel crossed the faults

The water surface profile shows clear impoundment of water by the fault (Figure 6b). The fault block nearly dammed the stream at the upper fault, and water flowed through a slit between the fault surface jutting laterally into the channel and the channel wall on the right side. Surface flow velocity was measured in three 40 cm sections with floating polystyrene powder (upstream of the upper fault, 357–317 cm, between the faults,

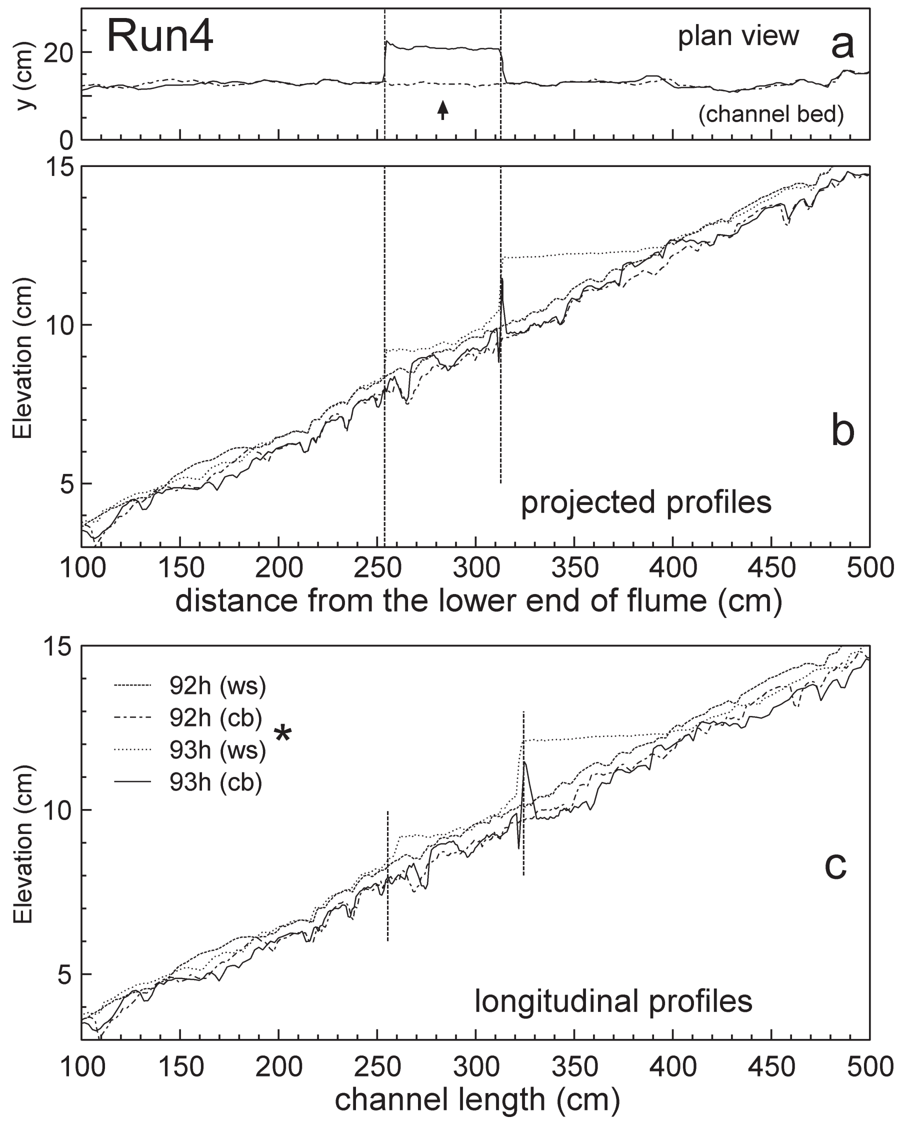

Figure 6. Thalweg position, water surface profile (ws) and channel bed profile (cb) before (92 h) and 1 hour of water flow after the displacement of faults (93 h) in Run 4. Note that the whole length of the channel is not shown in the figure in order to make the lines distinguishable. Also note the vertical exaggeration. The legend in (c) applies to all the graphs. (**a**) Thalweg position (plan view). An arrow shows the direction of fault block displacement. Two vertical dashed lines indicate fault lines. (**b**) Profiles projected to a plane parallel to the flume wall before and 1 hour after the fault displacement. Two vertical dashed lines indicate the position of fault lines. (**c**) Longitudinal profiles measured along thalweg. Two vertical dashed lines crossing the profiles indicate the approximate position of faults. An asterisk in the legend indicates 8 cm of fault displacement after 92 hours of water flow

307–267 cm, and downstream of the lower fault, 237–197 cm) before and after the fault displacement. Surface velocity decreased significantly from 25·5 to 2·9 cm s^{-1} in the upstream reach, but little change occurred in the reaches downstream of the lower fault (slightly decreased from 24·8 to 23·0 cm s^{-1}) and between the faults (slightly increased from 24·8 to 28·8 cm s^{-1}). The flow downstream of the fault was in the range of turbulent (Reynolds number, *Re*, can be estimated at somewhere between 5000 and 6000, assuming flow depth of about 2 cm) and sub-critical ($Fr < 1$) both before and after the faulting, but a thread of dye (Brilliant Blue FCF) put in the flow indicated that turbulence increased substantially through the offset reach after the fault displacement.

DISCUSSION

Huang (1993) assumed that the angle of deflection of an offset river (Figure 1) increased linearly with time by fluvial processes. Results of the experiment, however, indicate that the horizontal adjustment of an offset stream is a more complicated process even within the experimental setting. While bank erodibility and eroding ability of water flow are considered to determine the occurrence of lateral channel shift, the recurrence interval and the amount of fault displacement seemed to control the lateral shift of offset reaches in the experiment. In Run 1 when the rate of offset was low (2 cm of displacement followed by 2 hours of water flow, or 1 cm h^{-1}), the stream eroded the fault surface, jutting laterally into the channel, and shifted the offset reach to have a larger angle of deflection during the recurrence interval, at the upper dextral fault. This channel shift deflected the water flow to the upstream direction at the lower sinistral fault, and the lateral shift of the offset reach did not occur here so much as at the upper fault. In Runs 2 and 3, in which the rate of fault displacement was higher (2 cm of displacement followed by 30 minutes of water flow in Run 2 and 4 cm displacement with 1 hour of water flow in Run 3, or 4 cm h^{-1}), the lateral erosion on the fault surface was interrupted by the next fault displacement. The fault displacements were then added one after another to the existing channel offset, making channel shift by lateral erosion increasingly difficult. Erosion of the first fault surface within the recurrence interval, therefore, is considered to be critical for the occurrence of channel adjustment by lateral shift. The experimental stream could erode the first fault surface, jetting 2 cm into the channel, within the recurrence interval of 1 hour in Run 1, but it could not erode the same fault surface enough within 30 minutes in Run 2, nor the fault surface of 4 cm long within an hour in Run 3. Once established, the offset channel course tended to persist even long after the faulting ceased. The channel offset with sharp bends (no angle of deflection) persisted without much modification through Runs 2 and 3, and even in Run 1 the channel offset with the curved *L*-shaped channel course remained to the end of the run. The angle of deflection did not increase linearly with time in the experiment.

The faulting in the experiment was horizontal displacement of a fault block perpendicular to the channel, which is expected to create two flat sections in the longitudinal channel bed profile. The experimental stream eliminated these flat sections quickly and obtained a roughly continuous longitudinal channel bed profile in all runs (Runs 1–3). This channel adjustment was achieved with downstream degradation, upstream aggradation, and lateral shift of the offset reach. Downstream degradation was especially important in the overall trend of degradation due to the experimental setting (no sand supply). Degradation became dominant all over the channel to the end of each run, but the amount of degradation was the largest in the reach downstream from the fault block. Adjustment of longitudinal profiles by horizontal channel shift to increase the angle of deflection occurred in Run 1. Upstream aggradation was not clear in this run and downstream degradation was obscured by sediments derived from lateral erosion in offset reaches during the faulting. In Runs 2 and 3, in which significant lateral shift of offset reaches did not occur, roughly continuous longitudinal channel bed profiles were obtained with downstream degradation and upstream aggradation. The horizontal adjustment by fluvial processes seemed to halt, and the channel offset with sharp bends persisted through the runs even long after the faulting. Downstream degradation and upstream aggradation incidentally cause a local convexity in the longitudinal profile during the faulting. A slight local convexity around the fault block can be observed in the roughly continuous longitudinal profile in Runs 2 and 3. This convexity spread and reduced the height after the faulting, but persisted through the runs. The slight local convexity in the longitudinal profile derived from the channel adjustment with downstream degradation and upstream aggradation possibly remains as long as the lateral channel offset persists.

The result of experiments suggests that maintaining a continuous longitudinal channel bed profile is the principle of stream response to the deformation by strike-slip faults. In the case that the stream obtains a roughly continuous longitudinal profile exclusively by lateral channel shift, downstream degradation and upstream aggradation do not necessarily occur. In other words, lateral shift of the offset reach will be inevitable, if either degradation or aggradation hardly occurs. When the experimental stream shifts the offset reach laterally in the way to increase the angle of deflection (and therefore give some gradient to the offset reach) to a certain degree, downstream degradation and/or upstream aggradation occur as much as completing the remaining longitudinal profile adjustment. On the other hand, if lateral shift of the offset reach is restrained by any cause, such as the high rate of fault displacement and/or resistant channel banks, downstream degradation and upstream aggradation will occur prior to the lateral shift. In any case, once the stream obtains a roughly continuous longitudinal profile, possibly with a slight local convexity around the fault line, further channel adjustments will halt, and the horizontal channel offset can remain for a long time even after the fault displacement ceases.

The evident decrease in flow velocity in the upstream reach of the fault block observed in Run 4 explains the aggradation upstream of the fault, but the velocity change in the downstream reach does not explain the degradation downstream from the fault, which was the prominent response of the experimental stream in the overall tendency of degradation. Channel incision or degradation is usually explained by the increase in tractive force (or shear stress), $\tau = \gamma RS$ (where γ is specific weight of water, R is hydraulic radius, and S is slope), or stream power, $\Omega = \gamma QS$ (where Q is water discharge, and stream power per unit width, ω, can be written as $\omega = \tau v$, where v is flow velocity). In the experiment, however, water discharge was kept nearly constant, and channel bed slope did not increase in reaches downstream from the fault. Moreover, no significant increase in flow velocity was observed in the reaches downstream from the fault in Run 4. An offset reach created by fault displacement is considered to have a narrow channel at first, and this can cause the increase in flow depth and stream power per unit width. The impounding effect of channel offset, caused by the channel bend and the narrow offset reach, also increases tractive force or stream power in the offset reach by increasing water surface (energy) gradient. The increase in stream power in the offset reach can explain the erosion in the offset reach; however, it does not explain the degradation in the whole reach downstream from the fault block. Degradation downstream of channel obstructions, such as a dam, is a well-known phenomenon, and it is usually explained by the deficiency of bed material discharge downstream of the structure that traps sediments (e.g. Galay, 1983). Galay (1983) indicated that the downstream progression of degradation from a dam can advance a long distance in a short time. The horizontal channel offset by strike-slip faults worked like a dam as shown in Run 4. Downstream degradation and/or upstream aggradation shown in longitudinal profiles seem to reflect this damming effect. However, the decrease in sediment load downstream from the fault during the faulting was not clear. Horizontal channel displacement more or less induced erosion in offset reaches, and this erosion supplied sediment downstream. Another possible cause of downstream degradation is increase in flow turbulence through the offset channel course as indicated by a thread of dye in Run 4. Holland and Pickup (1976) pointed out that the turbulence evident at all the incising segments of their experimental channel was important for profile incision. They also stated that turbulence helped to dislodge large particles by sudden pulsations of stream energy. A dam apparently increases flow turbulence downstream. Although what actually caused the degradation in reaches downstream from the fault is still unclear, the horizontally offset channel course certainly can work like a dam, at least until the channel obtains a roughly continuous longitudinal profile. The lateral shift of the offset reach to increase the angle of deflection, of course, reduces the damming effect as shown in Run 1.

SUMMARY AND CONCLUSIONS

The experimental stream responded to horizontal displacement by a strike-slip fault, which is expected to create a flat section in the longitudinal channel bed profile, with downstream degradation, upstream aggradation, and lateral shift of the offset reach to increase the angle of deflection. Downstream degradation was prominent in the overall tendency of degradation due to the experimental setting.

These responses seemed to continue until the channel gained a roughly continuous longitudinal profile. The maintenance of a continuous longitudinal profile along channel is considered to be the principle of stream response to horizontal displacement by a strike-slip fault.

If the stream shifts the offset reach to increase the angle of deflection giving some gradient to the reach, downstream degradation and upstream aggradation will occur only to complete the rest of the longitudinal profile adjustment. If degradation and aggradation do not occur easily, lateral shift of the offset reach will be the main response. On the other hand, if lateral shift of the offset reach is restrained by any cause, downstream degradation and upstream aggradation will occur prior to the lateral channel shift. Once the stream obtains a roughly continuous longitudinal profile, further adjustments would halt. The horizontally offset channel can remain for a long time after the faulting.

Downstream degradation and upstream aggradation as a response to horizontal displacement by a strike-slip fault cause local convexity in the longitudinal profile. The trace of this convexity remained in the roughly continuous longitudinal profile for a long time, probably as long as the horizontal channel offset persists.

The horizontally offset channel course worked like a dam in the experiment. Aggradation upstream and degradation downstream from the fault may be explained by the analogy with the effects of a dam, namely, trapping sediments upstream (reducing sediment downstream) and increasing flow turbulence downstream. If lateral shift of the offset reach occurs, the damming effect will be reduced as much.

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