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# Differentiating Pleistocene tectonically driven and climate-related fluvial incision: the Sanggan River, Datong Basin, North China

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**Abstract –** The Sanggan River is an alluvial river flowing through a graben basin system of the northern Shanxi Rift Zone, North China. During Pleistocene times, the river reach in the Datong Basin was affected successively by various external variables, such as invasion by basaltic flow, along-valley faulting and climatic change. Therefore, it provides excellent constraints for differentiating tectonically driven and climate-related fluvial incision in the context of tectonic subsidence. Based on equilibrium profile analysis, K–Ar dating of basalts (0.74–0.41 Ma), studies of the river terrace and of stream action history, we present a conceptual model for differentiating fault-driven and climate-related fluvial incision by the river. The results show that fluvial incision induced by tectonic lowering of the base-level due to along-valley movement on the Sanggan River fault is equal to fault displacement. The amount of post-basalt fluvial incision of the reach upstream from the lava dam is 23 to 25 m, of which the fault-driven and climate-related incisions are 15 m and 8 to 10 m, respectively, the former predominating over the latter. The total amount of incision in the lava dam reach is 40 to 47 m, of which the fault-driven and climate-related incisions are 10 m and 30–37 m, respectively; here the latter is predominant over the former. Since $0.41 \pm 0.10$ Ma, the rate of fluvial incision of the lava dam reach of the river has reached 98–115 m/Ma, which is 1.5–2 times as great as those of the reaches upstream and downstream from the lava dam. The higher rate of fluvial incision can be attributed to high water levels supplied by the onset and maintenance of backwater conditions in the reach upstream from the lava dam, due to the long period of warm and humid climate in this region. Plucking, abrasion and knickpoint migration appear to be the primary erosional processes in the lava dam reach.

Keywords: Pleistocene, basalt, faulting, climate, fluvial incision, Sanggan River, China.

## 1. Introduction

The term 'fluvial incision' as discussed hereafter refers to vertical incision of stream channels into bedrock (Personius, 1995) and is controlled by external variables, such as tectonism, climate and base-level (Bull, 1990, 1991; Personius, 1995; Jones, Frostick, & Astin, 1999; Antoine, Lautridou, & Laurent, 2000; Maddy, Bridgland, & Green, 2000). Fluvial incision may result from crustal uplift (Bull & Knuepfer, 1987; Bull, 1991; Huisink, 1997; Maddy, Bridgland, & Green, 2000; Burbank & Anderson, 2001; Hartshorn *et al.* 2002). Base-level control on fluvial incision by both tectonism and sea-level change leads to knickpoint recession (Leopold & Bull, 1979; Schumm, 1993). However, climatic change cannot directly provide a mechanism for progressive incision, and it may control the Late Neogene fluvial incision through its influence on the sediment/discharge ratio. Incision would have been promoted when low sediment availability was concurrent with high discharge (Maddy, Bridgland & Green, 2000).

Many researchers (Harvey, 1996; Fuller *et al.* 1998; Jones, Frostick & Astin, 1999) have recognized that valley erosion takes place under wetter conditions and aggradation takes place under relatively arid conditions. Studies of fluvial incision are of great significance to the understanding of the history and dynamics of landscape evolution (Montgomery, 1994; Whipple & Tucker, 1999; Reneau, 2000; Wakabayashi & Sawyey, 2001), and to the evaluation of the relative contributions of tectonic and climatic controls on landscape evolution for different tectonic settings (basin subsidence and marginal upland uplift) (Pazzaglia, Gardner & Merritts, 1998). However, fluvial incision processes may collectively derive from both late Neogene tectonic and climatic variables, so that the differentiation of tectonic-driven from climate-related fluvial incision has become an important problem. In many cases, fluvial incision rates are calculated from study of fluvial terraces and have been taken as proxies for regional uplift rates in active deformation settings or in non-orogenic environments (e.g. Gardner *et al.* 1992; Merritts, Vincent, & Wohl, 1994; Burbank *et al.* 1996; Cheng *et al.* 2002).

Because the Sanggan River in the Datong Basin has been disturbed since the Pleistocene by various external processes, such as basaltic lava invasion, along-valley faulting and climatic change, it provides excellent constraints on differentiation of fault-driven and

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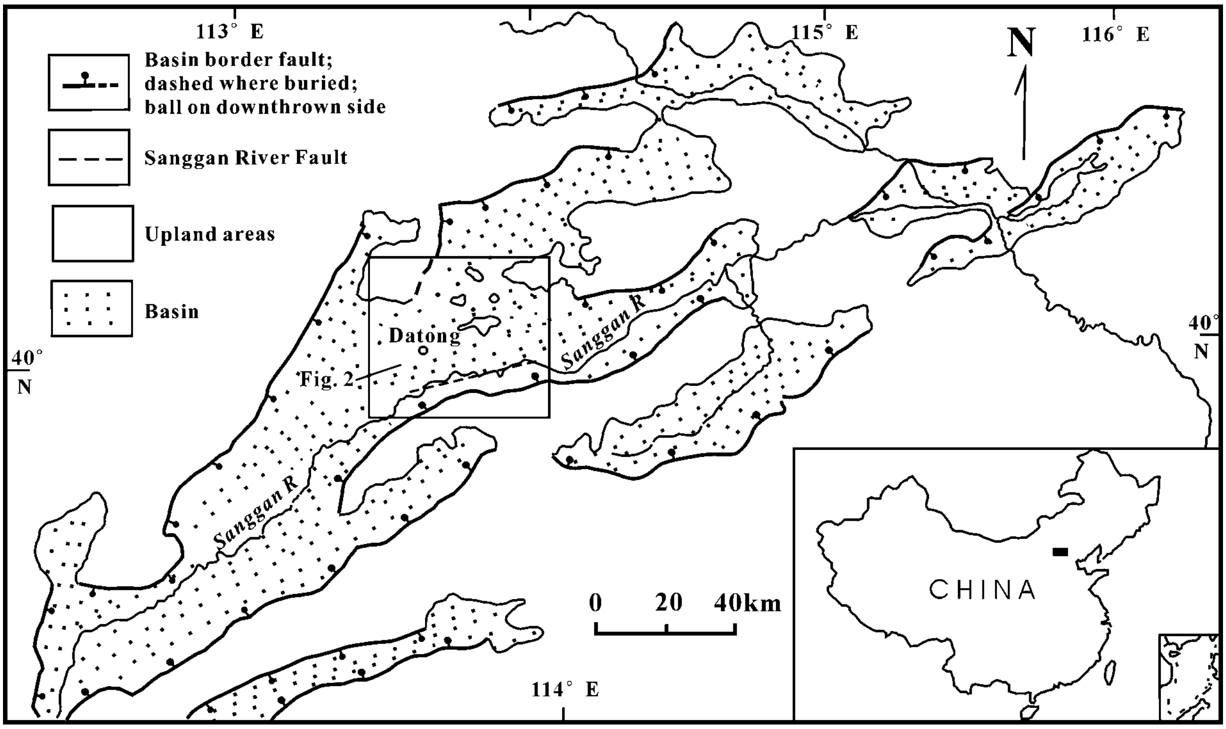


Figure 1. Simplified map of the northern Shanxi Rift Zone, showing the distribution of basins and upland areas as well as faults.

climate-related fluvial incision. The Sanggan River is an aggrading river as a whole, flowing through the basin system of the northern Shanxi Rift Zone, North China (Fig. 1). Due to basaltic lava invasion of the river channel in the Datong Basin, a basaltic bedrock reach had arisen on the aggrading channel, causing the change of stream-pattern, and this may provide an insight into the fluvial incision in the context of basin subsidence rather than mountain uplift of the region. Moreover, because the Sanggan River in the Datong Basin is controlled by the Sanggan River Fault, asymmetric valley geomorphology created by along-valley movement on the fault can provide information about fluvial incision rates.

## 2. Geological and geomorphological settings

The Datong Basin is a graben basin within the Shanxi Rift Zone (Fig. 1). The basin and its marginal upland areas comprise a series of rocks of various geological ages from Archaean to Holocene (Fig. 2). A number of exposures of Archaean metamorphic rocks and Lower Palaeozoic marine sedimentary rocks as well as a few exposures of Mesozoic continental volcanic rocks can be seen on the marginal upland areas (Bureau of Geology and Mineral Resources of Shanxi Province, 1989). Some of the rocks are also exposed within the basin, geomorphically appearing as relict mountains. Cenozoic sediments of great thickness were deposited within the basin, consisting of Palaeogene basalts, Pliocene laterites and Pleistocene deposits such as the fluviolacustrine deposits of the Nihewan Series, and loesses, as well as Pleistocene and Holocene colluvial deposits consisting mainly of loess soils, and alluvial deposits (Bureau of Geology and Mineral Resources of Shanxi Province, 1989).

The rifting of the Datong Basin began in the Miocene epoch (Bureau of Geology and Mineral Resources of Shanxi Province, 1989) and has continued to the present day. Evidence from sediment thickness indicates that up to 2000 m of basin subsidence has occurred since the Late Cenozoic and about several hundred metres during the Late Neogene (State Seismological Bureau, 1988; Bureau of Geology and Mineral Resources of Shanxi Province, 1989; Zhang, Yu & Jia, 1989; Zhang, Dou, & Yang, 1997; Xie *et al.* 2003). Studies on fault tectonic geomorphology and palaeoseismology (Deng *et al.* 1994; Duan & Fang, 1995; Xu *et al.* 1996; Cheng & Yang, 1999) suggest intense Holocene activity on the basin-bounding faults. Moreover, two recent strong earthquakes of magnitudes 6.5 and 5.8 occurred within the Datong Basin on October 18, 1989, and March 26, 1991, respectively.

Sedimentation of the Nihewan Series was an important geological event in the Datong Basin during Pleistocene times. The Nihewan Series is a series of fluviolacustrine deposits consisting from bottom to top of beds of sandy gravels, silty clays with sandy gravel lenses, marls, mudrocks, clayey siltstones and sandstones (Wu, Yuan & Sun, 1980). Observations show that ancient Nihewan lakes occupied almost all of the basin system of the northern Shanxi Rift Zone, in which the present-day Sanggan River flows (Hang, 1982; Liu & Xia, 1983). Some researchers (Wu, Yuan &

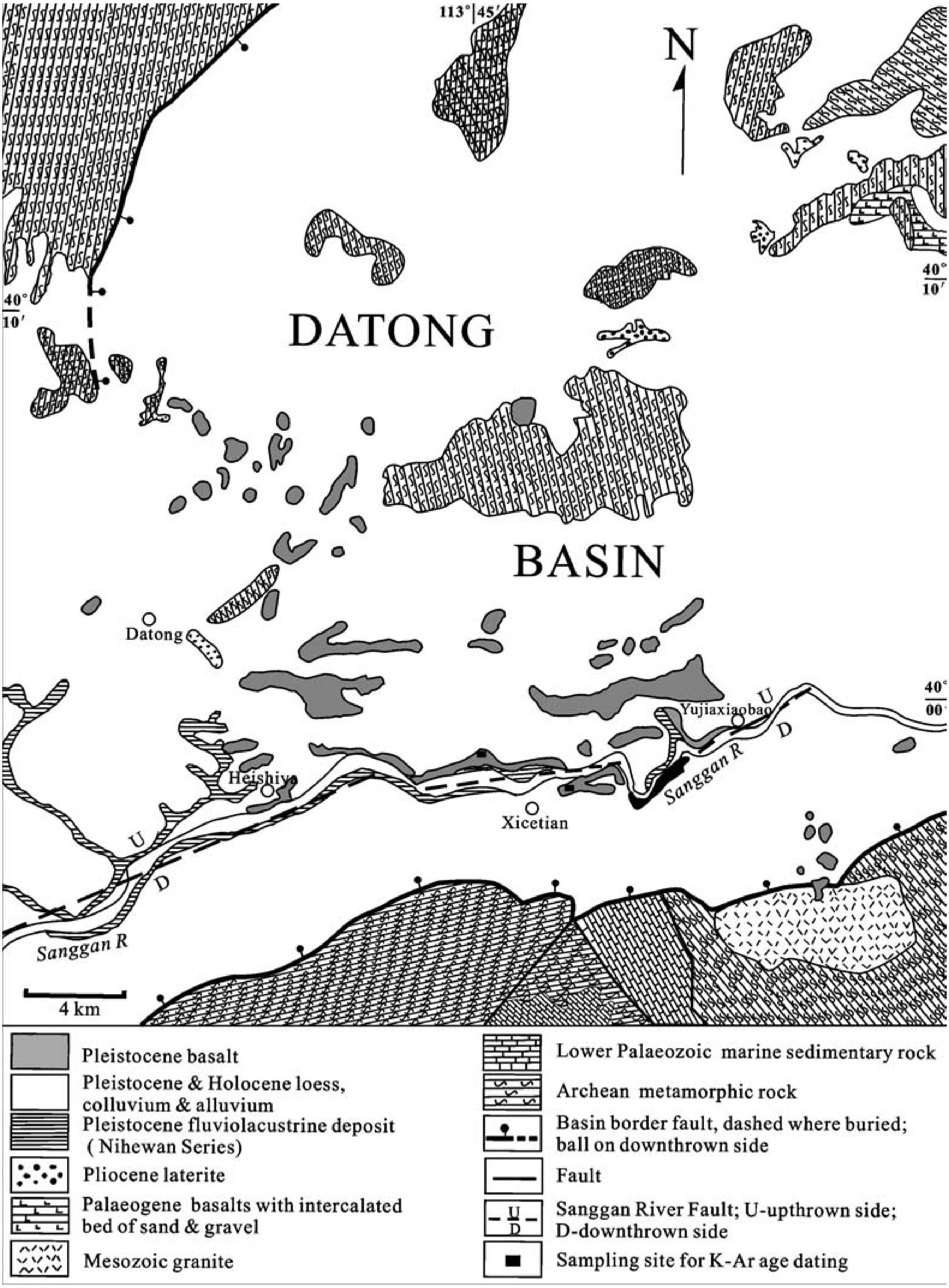


Figure 2. Geological map of the Datong Basin and its marginal upland areas (Simplified from Bureau of Geology and Mineral Resources of Shanxi Province, 1989).

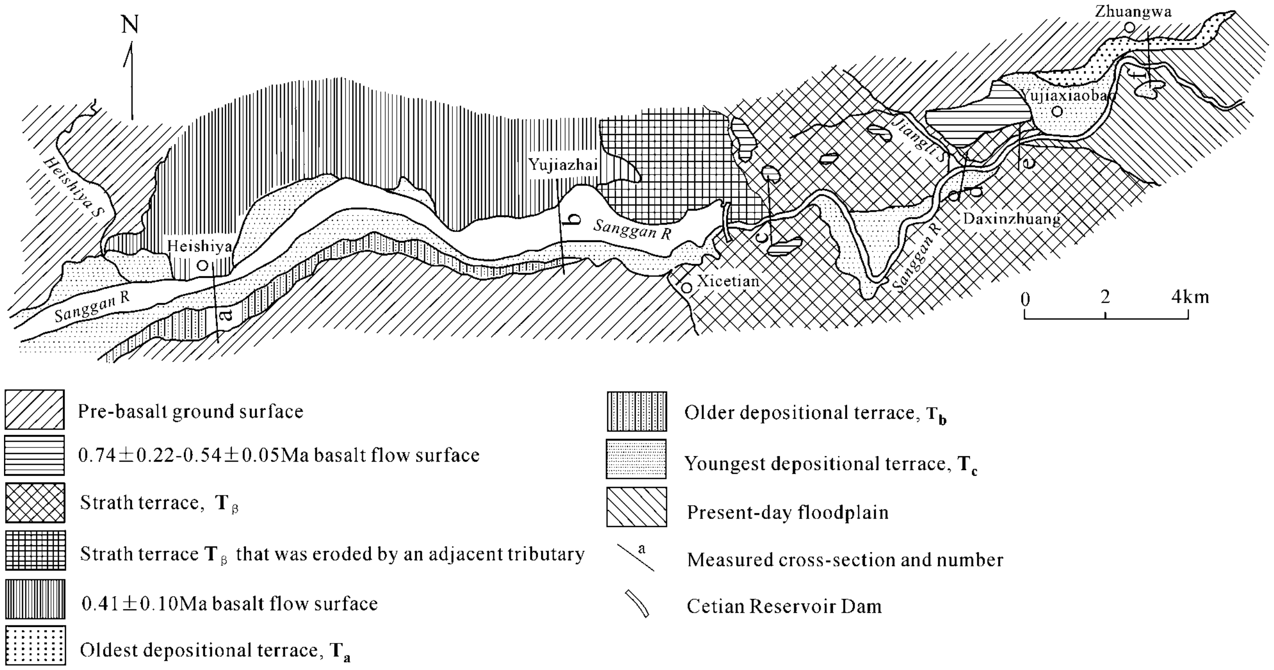


Figure 3. Distribution of terraces and geomorphic surfaces along the Sanggan River in the Datong Basin. The lava dam from Xicetian to Yujiaxiaobao, about 14 km long, was formed by the $0.74 \pm 0.22$ to $0.54 \pm 0.05$ Ma basaltic flow invasion into the valley. The basaltic strath terrace $T_b$ was developed in the lava dam reach. Note that because of erosion from an adjacent tributary, the basaltic strath terrace $T_b$ tread on the northern bank is lower than that on the southern bank as shown in Figure 4c. The $0.41 \pm 0.10$ Ma basalts are distributed only on the northern bank of the reach upstream from the lava dam. The oldest depositional terrace ($T_a$) is distributed only on the northern bank of the reach downstream from the lava dam.

Sun, 1980; Yuan & Wang, 1995) have suggested that the ancient Nihewan Lake had once coexisted with the Sanggan River, subjected alternatively to fluviation and lacustrine sedimentation. The Nihewan Series has a thickness of 60 to 223 m in the Datong Basin (Bureau of Geology and Mineral Resources of Shanxi Province, 1989).

## 3. Effect of Pleistocene external disturbances on the Sanggan River

### 3.a. Basaltic lava eruptions

Intense volcanic eruptions occurred in the Datong Basin during Pleistocene times. The lava, which occupies an area of about 50 km$^2$ within the basin, consists of two lithogenetic types: the alkaline basalts erupted from volcanic cones, and the tholeiites erupted along buried basement faults (Chen *et al.* 1992). The basaltic flows have affected the channel of the Sanggan River for about 26 km, from Heishiya to Yujiaxiaobao, of which about 14 km of the river channel from Xicetian to Yujiaxiaobao were totally filled with the lava, resulting in a lava dam on the channel (Figs 3, 4c, e). However, upstream from the lava dam, the lava reached only into the northern side of the ~12 km long channel from Heishiya to Xicetian (Fig. 4a, b). K–Ar dating of four basalt samples collected from the Sanggan River basin has been carried out by Chen *et al.* (1992) in the Laboratory for Isotope Geology, University of Bern, Switzerland. Of these samples, three were collected from the lava dam reach of the river, and were dated at $0.74 \pm 0.22$ Ma, $0.60 \pm 0.15$ Ma, and $0.54 \pm 0.05$ Ma, respectively. The fourth was collected from the reach upstream from the lava dam, and was dated at $0.41 \pm 0.10$ Ma.

The lava dam that resulted from the basaltic flow into the river channel gives a local base-level for the upstream reach, similar to the effect of base-level rise produced by uplift. The rise of the base-level causes the streambed elevation change of the upstream reach not far from the back edge of the lava dam, and this leads to the onset of backwater and backfilling on the valley floor (Leopold & Bull, 1979; Rice, 1980; Leopold, 1992; Hamblin, 1990, 1994). The backwater flow that is relatively sediment-free will soon spill over the lava dam and begin to incise the lava dam reach. On the other hand, the flow of basaltic lava onto the valley floor provides a constraint on the elevation of the river at the time of basaltic eruption and, in combination with the age of basalt samples, provides a basis for estimating rates of incision by the river.

### 3.b. Along-valley faulting

The Sanggan River Fault is an active fault developed along the Sanggan River valley (Fig. 2) (Wang & Ou,

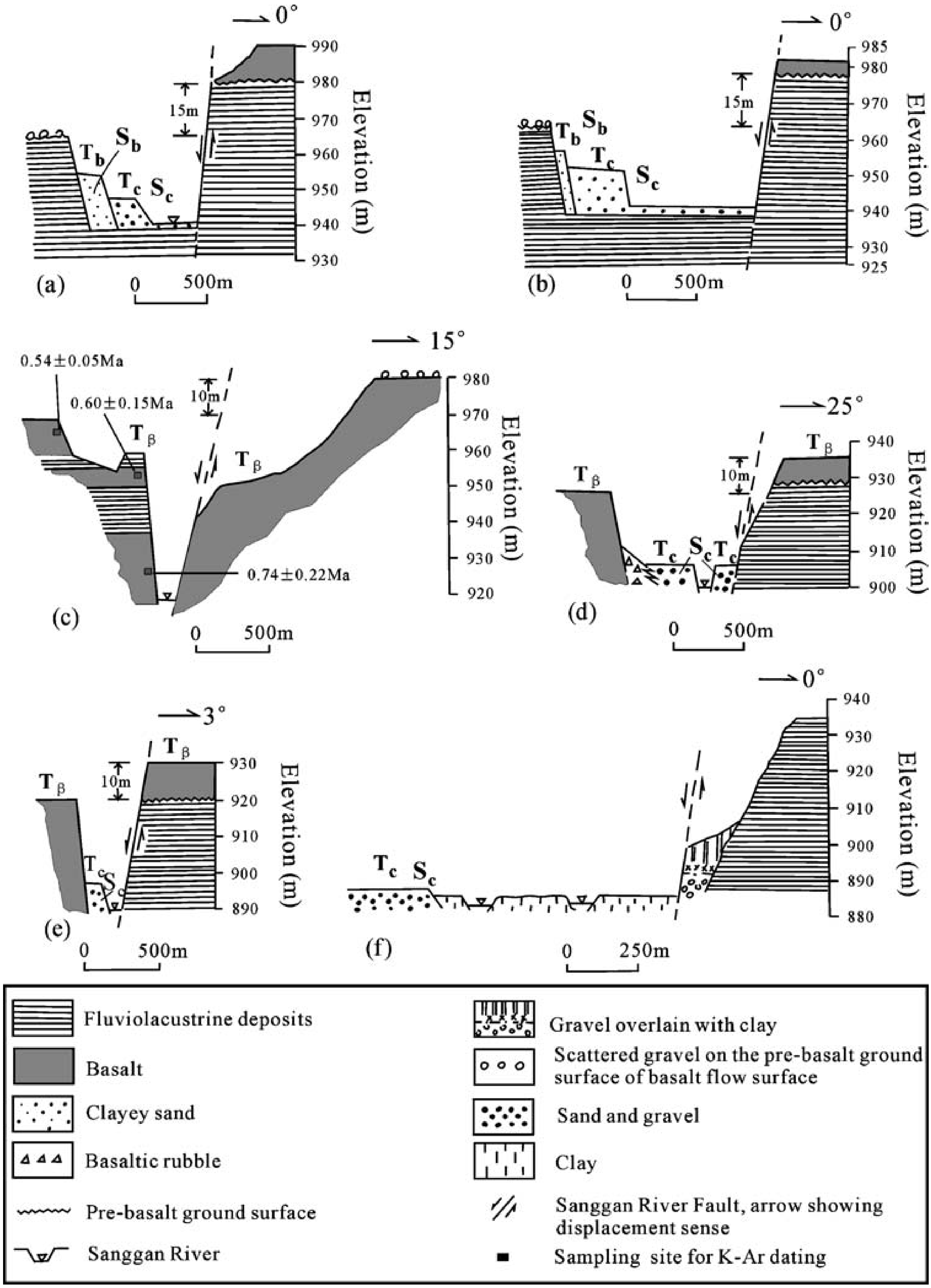


Figure 4. Measured cross-sections of the Sanggan River in the Datong Basin, showing the valley asymmetry caused by the movement on the Sanggan River Fault, and the fault displacements represented by asymmetric fluvial geomorphic surfaces. (a) Heishiya; (b) Yujiazhai; (c) Xicetian; (d) Daxinzhuang; (e) Yujiaxiaobao; (f) Zhuangwa. For cross-section locations see Figure 3.

1958; Cao, 1959; Yang, 1961). A number of nearly perpendicular but discontinuous fault planes can be observed in the basalts along the river valley. These fault planes strike ENE, consistent with the orientation of the Sanggan River. Many basalt fragments have accumulated at the foot of the valley-walls as a result of faulting. Local drill logs show that Cenozoic sediments on the hanging wall on the southern bank of the river are 450 to 950 m thick, much thicker than those on the footwall on the northern bank of the river (250–400 m) (Zhang, Dou & Yang, 1997).

Fault displacement and fluvial incision induced by faulting resulted in asymmetric valley geomorphology (Fig. 4). Field observations show that the pre-basalt original ground surface and the basaltic strath terrace, $T_b$, on the northern bank of the river, are generally higher than those on the southern bank of the river. An exception is observed in the cross-section near Xicetian, where $T_b$ on the northern bank is much lower than that on the southern bank (Fig. 4c), and probably can be attributed to erosion from an adjacent tributary (Fig. 3).

Fault displacement on the reach upstream from the lava dam is somewhat different from that on the lava dam reach. On the basis of the throw of the original ground surface of the Nihewan Series on both banks of the river, the fault displacement of the reach upstream from the lava dam has been measured at up to 15 m (Fig. 4a, b), whereas according to the throw of the basaltic strath terrace, $T_b$, on both banks of the river, the fault displacement of the lava dam reach has been estimated at 10 m (Fig. 4c–e). The precise time of occurrence of this faulting event is unclear but it is postulated to be synchronous with the emplacement of the basalts on the northern bank of the reach upstream from the lava dam at $0.41 \pm 0.10$ Ma BP.

Along-valley faulting may trigger or promote fluvial incision, which not only causes termination of basaltic-strath formation on the lava dam reach, but also controls the development of the lowest depositional terrace on the reach upstream from the lava dam. The upwarping caused by along-valley faulting may result in the increase of sediments supplied by the upthrown bank of the river, providing a source for the sedimentation of the depositional terrace. At the same time, tectonic displacement may cause relief favourable to sedimentation of depositional terraces, and hence provides the appropriate conditions for deposition to form a terrace.

### 3.c. Climatic change

During Late Pleistocene times an obvious climatic change, characterized by the transition from prevailing warm and humid climate to dry and cold climate, occurred in the studied area. Magnetostratigraphy (Li & Wang, 1985), pollen assemblages (Liu, 1980), the subaqueous ‘loess’–fluviolacustrine deposit sequence (Xia, 1992*a*) and palaeolimnology (Xia, 1992*b*; Wang *et al.* 1996) of the Nihewan Series, as well as comparison with the loess–palaeosol sequence in North China and with the oxygen isotope character of core samples from deep-sea deposits (Fig. 5) show that the warm and humid conditions of the studied area were initiated at the beginning of the Brunhes normal epoch at 0.78 Ma BP, resulting in the rise of water level and the increase of water volume and surface area for the ancient Nihewan lakes. The formation of the lava dam due to the invasion of basaltic lava into the river channel at $0.74 \pm 0.22$ Ma BP provided a sufficient water supply for the water to back up and its level to rise, causing the water to overflow and incise the lava dam. This humid phase continued until 0.13–0.09 Ma BP, as indicated by the appearance of stromatolites in the Nihewan Series (Xia *et al.* 1994). Thereafter, the climate shifted to dry and cold conditions until the occurrence of chemical sedimentation of hydro-magnesites at 0.027–0.023 Ma BP, which indicates that the ancient Nihewan lakes had become dry at that time (Yan & Xia, 1987). The change to dry and cold climate occurred by the end of Pleistocene times, resulting in the aggradation of the river valley and the formation of the lowest depositional terraces.

## 4. Conceptual model

A conceptual model for the Sanggan River is presented, to explain how the stream action of the river was changed because of disturbance by external factors. In this model, if the base-level of a river reach has risen because of a barrier caused by basaltic lava influx, so that the reach has sufficient power to incise vertically for a distance equal to the rise of base-level, then the height of this reach will be decreased and its gradient will decrease relative to that of the nearby upstream reach. Therefore, the homogeneous fluvial incision by the river depends merely on whether the river is able to overcome the gradient barrier. According to this model, sustaining the supply of water with sufficient energy to the reach with risen base-level plays a critical role in maintaining the vertical incision by the river. In order to maintain a sufficient water supply, it is required that the fluvial incision into the bedrocks by the nearby upstream reach due to along-valley faulting should be carried out uniformly along its length to maintain the graded profile for a long period of time, during which neither erosion nor sedimentation occurs so that sufficient water can be supplied. Obviously, this model emphasizes fluvial incision under prevailing warm and humid climatic conditions. Provided that the fault displacement is equal to the amount of fluvial incision caused by along-valley faulting, and that the stream action after the disturbance of external variables can be reconstructed, then the fluvial incision caused by faulting can be differentiated from that induced by climate.

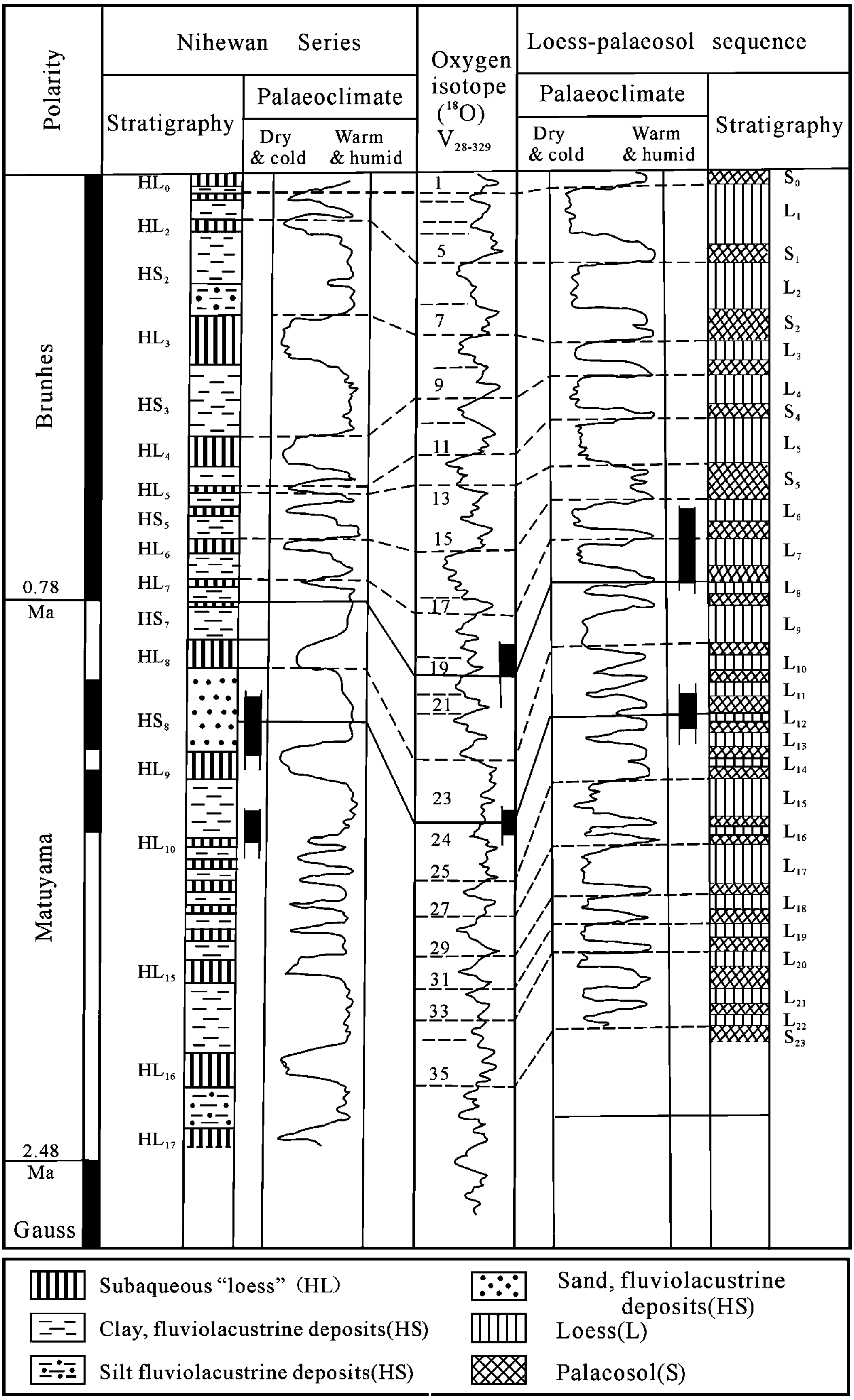


Figure 5. Correlation of the subaqueous 'loess'–fluviolacustrine deposits sequence of the Nihewan Series with loess–palaeosol sequences in North China and with deep-sea oxygen isotope ($^{18}O$) records (modified from Liu, 1985; Wang, 1989; Xia, 1992*a*). The subaqueous 'loess'–fluviolacustrine deposit sequence of the Nihewan Series reflects Late Neogene cyclic climatic changes of dry and cold to warm and humid. For most of time since the 0.74 ± 0.22 to 0.54 ± 0.05 Ma BP basalts entered into the Sanggan River valley, a warm and humid climate has generally prevailed over the study area. However, dry and cold climatic cycles also existed, although they were transient.

Table 1. Basic channel parameters, amounts of deviation of longitudinal profiles and corresponding fault displacements of the Heishiya Stream and the Jiangli Stream

| | Channel parameters | | | | | | |
|---|---|---|---|---|---|---|---|
| Stream | Catchment area (km$^2$) | Length (km) | Stream-mouth elevation (m) | Headwater elevation (m) | Regression of equilibrium longitudinal profile, and correlation coefficient r$^2$ | Amount of deviation* (m) | Corresponding fault displacement† (m) |
| Heishiya | 47.63 | 13.13 | 943 | 1160 | Elev = 907 + 61 ln (dist) $R^2 = 0.99$ | 14 | 15 |
| Jiangli | 13.50 | 5.35 | 912 | 970 | Elev = 927 + 17 ln (dist) $R^2 = 0.97$ | 11 | 10 |

*see Figure 6; †see Figure 4a–e.

## 5. Differentiating fault-driven and climate-related fluvial incision

### 5.a. Amounts of fault-driven fluvial incision

In the light of the longitudinal stream-profile analysis method of Goldrick & Bishop (1995), we have made an attempt to determine whether the amount of deviation of the equilibrium longitudinal stream-profile of a tributary at the junction between the tributary and the trunk is equal to the amount of fault displacement, in other words, whether it represents the amount of fluvial incision resulting from tectonic base-level lowering due to faulting along the trunk river. This method was based on the work of Hack (1973, 1975), who determined that the equilibrium longitudinal stream-profile on a single lithology is a straight line when plotted semi-logarithmically. The tributaries of the Sanggan River are concentrated mainly on the upthrown side of the Sanggan River fault on the northern bank of the river, and hence are suitable for the analysis of fluvial incision caused by the upwarping of the upthrown side of the fault. The Heishiya Stream and the Jiangli Stream on the northern bank of the Sanggan River were selected for analysis. The Heishiya Stream flows into the reach upstream from the lava dam, while the Jiangli Stream flows into the lava dam reach of the Sanggan River (Fig. 3). Both the tributaries run through the basalts underlain by the fluviolacustrine deposits of the Nihewan Series, meeting the requirement of a uniform lithology for the analysis method. The results of analysis indicate that the amount of deviation, *d*, at the point of departure from the semi-log straight line, is 14 m for the Heishiya Stream and 11 m for the Jiangli Stream (Table 1, Fig. 6). Fault displacement represented by the throw of the original ground surface of the fluviolacustrine deposits on both banks of the reach upstream from the lava dam is 15 m, while that represented by the throw of the basaltic strath terrace $T_b$ on both banks of the lava dam reach is 10 m (Fig. 4c–e). The fact that the deviation amount, *d*, is basically consistent with the fault displacement indicates that the fluvial incision may have kept pace with the upwarping on the fault. We have taken 15 m and 10 m fault displacements as the amount of fault-driven fluvial incision for the reach upstream from the lava dam and the lava dam reach, respectively.

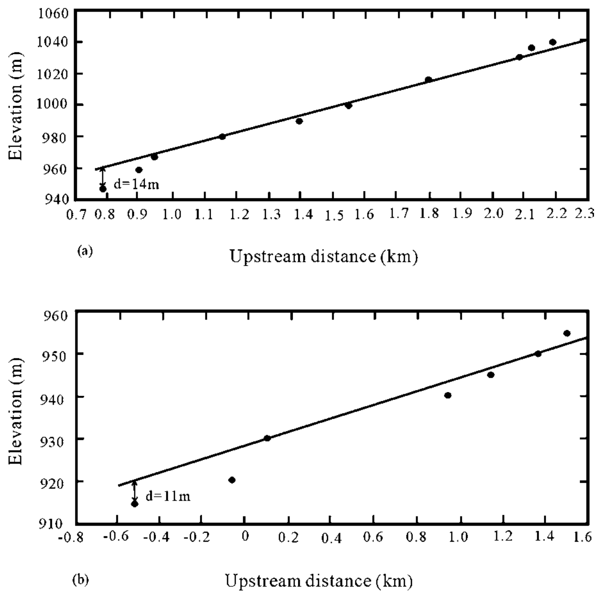


Figure 6. Equilibrium longitudinal profiles of two tributaries: (a) the Heishiya Stream and (b) the Jiangli Stream, on the northern bank of the trunk Sanggan River, showing the amounts of deviation, *d*, recorded at their junctions with the trunk. The amounts of deviation essentially are consistent with the fault displacements shown in Figure 4.

### 5.b. Reconstruction of post-basalt fluvial incision and aggradation events

*5.b.1. Reach upstream from the lava dam*

Since the influx of basaltic flows into the Sanggan River channel during the period $0.74 \pm 0.22$ to $0.54 \pm 0.05$ Ma, the reach upstream from the lava dam has experienced a history of stream flow with two aggradation and two fluvial incision events as recorded by the sequence of two fill-cut terraces (Fig. 4a, b). The lava dam that was formed on the original graded channel of the fluviolacustrine deposits (Fig. 7a) has created an effect similar to that caused by a base-level rise, which leads to rising water-levels and backfilling on the valley floor, and therefore to raising the streambed of the reach upstream from the lava dam

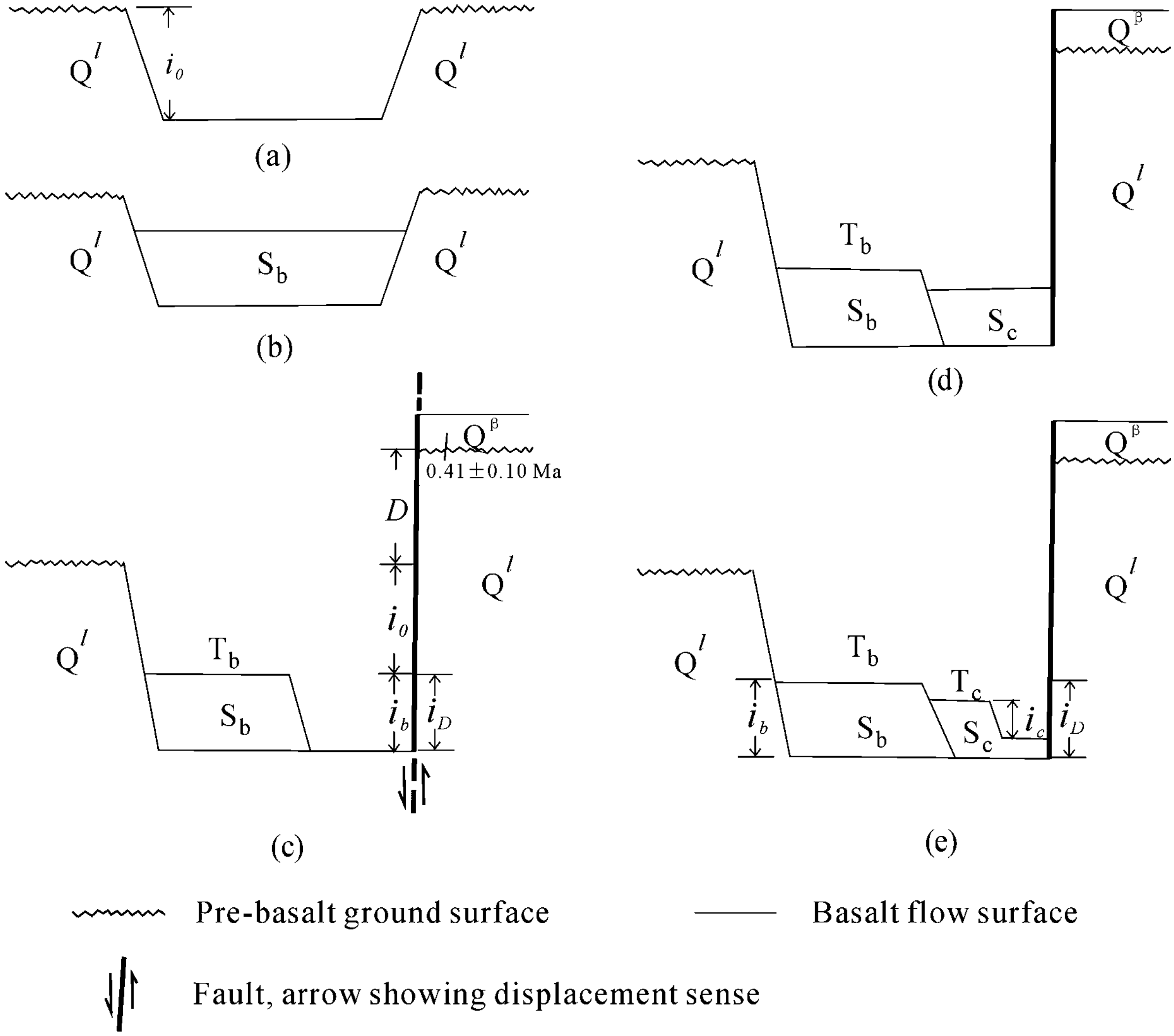


Figure 7. Diagrammatic cross-sections of the reach upstream from the lava dam, showing the reconstruction of the evolutionary valley history and the analysis of the fluvial incision and aggradation events during the Pleistocene. (a) The original Sanggan River channel with incision $i_0$. (b) $0.74 \pm 0.22$ to $0.54 \pm 0.05$ Ma basaltic flow invasion into the channel, resulting in $S_b$ aggradation. (c) The occurrence of along-valley faulting, with fault displacement $D$ and fault-driven fluvial incision $i_D = D$. The fault-driven fluvial incision cut through $S_b$, forming a strath surface on the valley floor. The first post-basalt fluvial incision event that was driven by along-valley faulting is $i_b = i_D = D$. (d) $S_c$ aggradation related to the climatic change. (e) Incision of $S_c$. The second post-basalt fluvial incision event that was related to the climatic change is $i_c$. Lithologies of $Q^l$, $Q^b$, $S_b$ and $S_c$ are described in the text and shown in Figure 4.

(Fig. 7b). The onset of backwater conditions with high water level has resulted in the aggradation of fine-grained sediments, mainly clayey silts ($S_b$). According to local water-well data, the aggradation of fine-grained sediments ($S_b$) has caused the original river channel bed to rise by 15 m.

Later, a sudden movement probably occurred at $0.41 \pm 0.10$ Ma on the Sanggan River Fault, and the along-valley faulting has driven the incision, which is regarded as the first post-basalt fluvial incision event, $i_b$, in the reach. This event cut through the entire 15 m thickness of the $S_b$ deposits and left the higher aggradational surface $T_b$ (Fig. 7c). Thereafter the channel maintained the graded profile for a long period of time, until the initiation of the aggradation associated with the climatic change that occurred during latest Pleistocene times. As mentioned above, the fluvial incision driven by faulting, $i_d$, is equal to fault displacement, $D$, which is 15 m.

The lowest depositional terrace, $T_c$, indicates the latest fluctuation of climate from cold and arid to warm and humid conditions, which caused the onset of aggradation of the river valley and the subsequent erosion process. Under cold and arid climatic conditions, aggradation has resulted in the deposition of coarse-grained gravels ($S_c$) of 10 to 13 m thickness (Fig. 7d). Under the subsequent warm and humid climate conditions, the $S_c$ deposits have been incised, and this incision event is considered to be the second fluvial incision event in this stream reach, $i_c$, which terminated the sedimentation of aggraded terrace tread $T_c$ (Fig. 7e). However, the $i_c$ event incised only into the 8–10 m thickness of $S_c$ deposits, and did not reach the original streambed level.

Table 2. Amounts and rates of fluvial incision since 0.41 ± 0.10 Ma

| Location | Faulting-driven fluvial incision (m) | Climate-related fluvial incision (m) | Total: Amount (m) | Total: Rate (m/Ma) |
|---|---|---|---|---|
| Reach upstream from the lava dam | | | | |
| Heishiya | 15 | 8 | 23 | 56.10 |
| Yujiazhai | 15 | 10 | 25 | 60.98 |
| Lava dam reach | | | | |
| Xicetian | 10 | 30 | 40 | 97.56 |
| Daxinzhuang | 10 | 30 | 40 | 97.56 |
| Yujiaxiaobao | 10 | 37 | 47 | 104.63 |
| Reach downstream from the lava dam | | | | |
| Zhuangwa | 10(?) | ? | 32 | 78.05 |

In summary, the net incision resulting from two fluvial incision events in the reach upstream from the lava dam in the post-basalt period after $0.41 \pm 0.10$ Ma is 23 to 25 m, of which incision driven by faulting is 15 m, while that related to climatic change is 8 to 10 m (Table 2). Obviously, in this stream reach the incision driven by faulting is dominant over incision related to climatic change. On the one hand, after the formation of the lava dam, the river channel was subject to a backfilling environment, and on the other hand, the incision driven by faulting had caused the channel to return to its original height with no further incision.

#### 5.b.2. *The lava dam reach*

The history of the post-basalt stream activity of the lava dam reach is characterized by the development of one higher basaltic terrace and one lower fill-cut terrace, with continuous channel incision between the terraces (Fig. 4c–e), recording four fluvial incision events and one aggradation event. Soon after the lava dam was formed (Fig. 8a), because of the backfilling of fine-grained sediments into the reach upstream from the lava dam, the backwater flow with a relatively smaller amount of sediments spilled over the lava dam, excavating the inner channel of the lava dam reach in a normal erosion process. High water-level conditions ensured sufficient water supply for uniform flow erosion either vertically or laterally, resulting in a basaltic strath surface $T_b$ on the floor of the inner channel (Fig. 8b). This is the first post-basalt fluvial incision event, $i_1$, in this reach. This event has cut into the inner channel down to a depth of 10 m.

The subsequent sudden movement that probably occurred at $0.41 \pm 0.10$ Ma on the Sanggan River Fault gave rise to the incision of the basaltic strath floor and the formation of the strath tread ($T_b$). Thereafter, under the prevailing warm and humid climate conditions, the reach upstream from the lava dam maintained a high enough water level to supply sufficient water, so that the channel of the lava dam reach experienced a prolonged period of down-cutting until the onset of cold and arid climate conditions and the aggradation of the river valley. This down-cutting process consisted of a fault-driven fluvial incision event and a post-faulting fluvial incision event. As mentioned above, the fluvial incision driven by along-valley faulting in this reach, that is, the second post-basalt fluvial incision event, $i_D$, is 10 m (Fig. 8c). Post-faulting fluvial incision, the third fluvial incision event, $i_2$ (Fig. 8d), in this reach is 23 to 30 m (Fig. 4c–e).

In this reach, the lower fill-and-cut terrace resulting from the latest phase of cold and arid climate recorded the same aggradation and erosion history as in the reach upstream from the lava dam. The aggradation caused by climate fluctuation gave rise to the deposition of 15 m thick coarse-grained gravelly alluvium ($S_c$), as estimated from local water-well data (Fig. 8e). Subsequent incision of $S_c$ deposits has been designated the fourth post-basalt fluvial incision event, $i_c$ (Fig. 8f), which incised into the $S_c$ by 7 m (Fig. 4c–e).

The above analysis shows that since $0.41 \pm 0.10$ Ma, the total amount of four fluvial incision events in the lava dam reach is 40–47 m, among which the incision driven by faulting is 10 m, and that related to climate is ~30–37 m. In contrast to the situation in the reach upstream from the lava dam, here the incision related to climate is dominant over the fault-driven incision.

## 6. Discussion

### 6.a. Event correlation and longitudinal stream-profile evolution

The synchronous landforms produced by the long-period effects of the adjustment of stream action in response to various external variables may provide excellent constraints for comparing fluvial incision and aggradation, as well as for reconstructing the evolution history of the longitudinal profile of a river. Bull (1990, 1991) has noted that the main strath formed during the evolution of the longitudinal profile of a river can be considered as a synchronous landform. The main strath studied in this paper was formed after the faulting event. Although the formation time of the strath cannot be determined precisely, it can be deduced from whether fluvial incision occurred after the faulting event. The strath was the first to form in fluviolacustrine deposits of Nihewan Series, and it then maintained the graded profile for a long period of time, so that it was able to provide the downstream reach with high energy water flow for maintaining fluvial incision until the lava dam reach has surmounted the gradient barrier produced by the invasion of basaltic lava; finally, the new strath was also formed on the basaltic valley floor in this reach. Although the straths in the reach upstream from the lava dam and in the lava dam reach are heterochronous, based on the final effect of the adjustment of the river in response to external variables, as well as on the fact

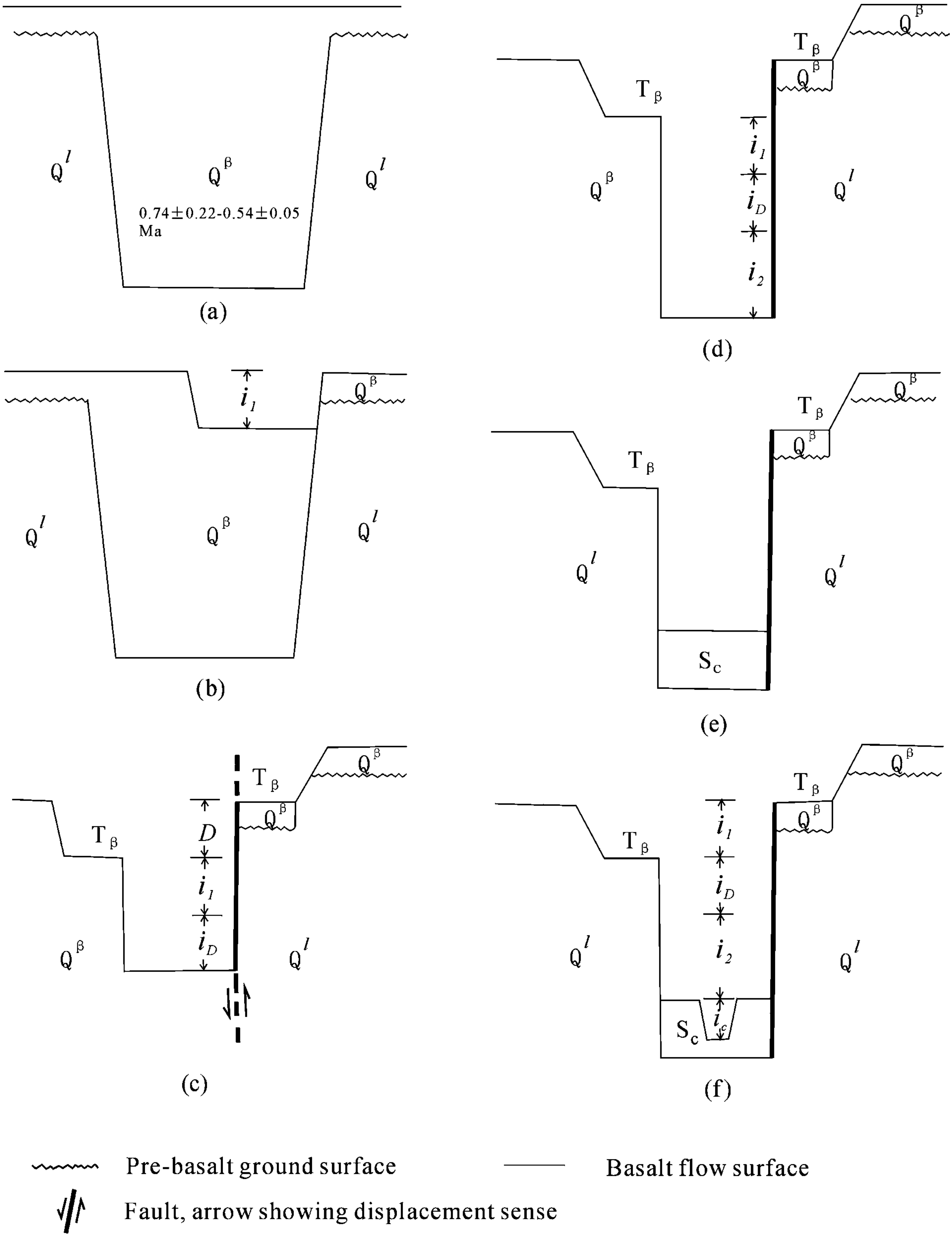


Figure 8. Diagrammatic cross-sections of the lava dam reach, showing the reconstuction of the evolutionary valley history and the analysis of the fluvial incision and aggradation events during the Pleistocene. (a) $0.74 \pm 0.22$ to $0.54 \pm 0.05$ Ma basaltic flow invasion into the Sanggan River valley, forming the lava dam on the channel. (b) Because of the upstream effect of the lava dam, backwater in the reach upstream from the lava dam spilled over the lava dam and the flow excavated the basaltic inner channel. The first post-basalt fluvial incision event related to climate is $i_1$. (c) The occurrence of along-valley faulting. The second post-basalt fluvial incision event driven by the along-valley faulting equals the fault displacement of the reach. (d) Post-faulting fluvial incision. The third post-basalt fluvial incision event related to climate is $i_2$.(e) $S_c$ aggradation resulting from the climatic change. (f) Incision of $S_c$. The fourth post-basalt fluvial incision event related to the climatic change is $i_c$. Lithologies of $Q^l$, $Q^b$, $S_b$ and $S_c$ are described in the text and shown in Figure 4.

that the main straths were covered synchronously with the alluvium ($S_c$) produced by aggradation related to the cold and arid climate in the latest Pleistocene, it can be deduced that the main strath composed of both of the above-mentioned straths can be considered as a typical synchronous landform, which may provide constraints for comparing fluvial incision with aggradation events.

The climatic fluctuation in the latest Pleistocene had caused the roughly synchronous aggradation of the alluvial deposits $S_c$, while the regional fluvial incision event occurred pervasively all over the drainage area of the Sanggan River within the Datong Basin at that time. During the Late Neogene, a cold and arid climate induced aggradation processes, while a warm and humid climate caused incision processes (Harvey, 1996; Jones, Frostick, & Astin, 1999; Fuller *et al.* 1998). Post-basalt fluvial incision recorded by the river terraces in the Datong basin confirms the fluctuation of regional prevailing climate from cold and arid conditions to warm and humid conditions in the latest Pleistocene (Liu, 1980; Li & Wang, 1985; Yan & Xia, 1987; Xia, 1992*a*,*b*; Xia *et al.* 1994; Wang *et al.* 1996). In addition, incision of the aggradation surface in a given reach occurs over a very short time span at the transition of climatic and environmental conditions (Vandenberghe, 1995; Antoine, Lautridou & Laurent, 2000), representing a momentary transition of stream activity modes from aggradation to incision (Bull, 1990, 1991). Therefore, the incision of aggradation surfaces can be taken as evidence for correlating incision and aggradation events. The correlation of the post-basalt fluvial incision and aggradation events for the Datong Basin reach of the Sanggan River is shown in Figure 9.

The Sanggan River within the Datong Basin may have experienced six stages of longitudinal stream-profile evolution since the Late Neogene, as shown in Figure 10. The fluvial incision and aggradation events which occurred in each stage are as follows:

(1) The pre-basalt stage (Fig. 10a). In this stage, the Sanggan River was developed in the fluviolacustrine deposits of the Nihewan Series, and attained an original graded profile (Fig. 10a). It should be noted, however, that the $T_a$ terrace in the Zhuangwa profile in the reach downstream from the lava dam is the oldest aggraded terrace within the Datong Basin. The lower part of the terrace consists of gravel bed, in which the gravels are mainly limestone without any basaltic composition; the middle part consists of lacustrine clay sediments and the upper part of middle Pleistocene red soils. These results of field investigations indicate that the aggradation of $S_a$ sediments might have occurred before the invasion of basaltic lava into the river channel.

(2) The basaltic flow invasion stage (Fig. 10b). This stage was initiated at $0.74 \pm 0.22$ to $0.54 \pm 0.05$ Ma BP, and continued until $0.41 \pm 0.10$ Ma BP, as indicated by the invasion of basaltic flow into the northern bank of the upper reach of the Sanggan River (Fig. 10b). The movement on the Sanggan River Fault might have occurred synchronously with the emplacement of basalts in this stage. The adjustment of the river in response to the invasion of the basaltic flow caused the aggradation of $S_c$ sediments in the reach upstream from the lava dam, while in the lava dam reach the fluvial incision event, $i_1$, occurred.

(3) The along-valley faulting stage (Fig. 10c). In this stage, the fault-driven fluvial incision event, $i_D$, occurred along the entire reach of the river.

(4) Post-faulting stage (Fig. 10d). In this stage, the reach upstream from the lava dam maintained the graded profile condition for a long period of time, but an important fluvial incision event, $i_2$, occurred in the lava dam reach.

(5) Climate-induced aggradation stage (Fig. 10e) and (6) subsequent erosion stage (Fig. 10f). During these two stages, the aggradation event $S_c$ and the fluvial incision event $i_c$ occurred in the Datong Basin reach of the Sanggan River.

### 6.b. Rates and controls of fluvial incision

The emplacement of basalts on the northern bank of the reach upstream from the lava dam at $0.41 \pm 0.10$ Ma might be synchronous with the occurrence of the movement on the Sanggan River Fault. Therefore, the occurrence time of basalt emplacement, $0.41 \pm 0.10$ Ma, may provide a constraint for estimating the average rate of post-basalt fluvial incision for the Datong Basin reach of the Sanggan River. As shown in Table 2 and Figure 11, the average rate of fluvial incision is estimated to be 56–61 m/Ma for the reach upstream from the lava dam and 78 m/Ma for the reach downstream from the lava dam. However, an exceptionally high incision rate of up to 98–110 m/Ma occurred in the lava dam reach.

Although regional tectonic uplift is generally considered to be the primary cause of fluvial incision by Late Neogene rivers (Merritts & Vincent, 1989; Veldkamp & Vermeulen, 1989; Marple & Talwani, 1993; Veldkamp & Van Den Berg, 1993; Hamblin, 1994; Kuzucuoglu, 1995; Maddy, 1997; Pazzaglia, Gardner & Merritts, 1998; Maddy, Bridgland & Green, 2000; Cheng *et al.* 2002), and rates of incision by streams in mountainous regions affected by rapid uplift are several orders of magnitude faster than that by streams in sediment basins (Jones, Frostick & Astin, 1999; Ward & Carter, 1999; Humphrey & Konrad, 2000), the exceptionally high incision rate in the lava dam reach of the Sanggan River cannot be attributed to tectonic movement, for the following reasons. Firstly, fluvial incision in the Sanggan River proceeded under a

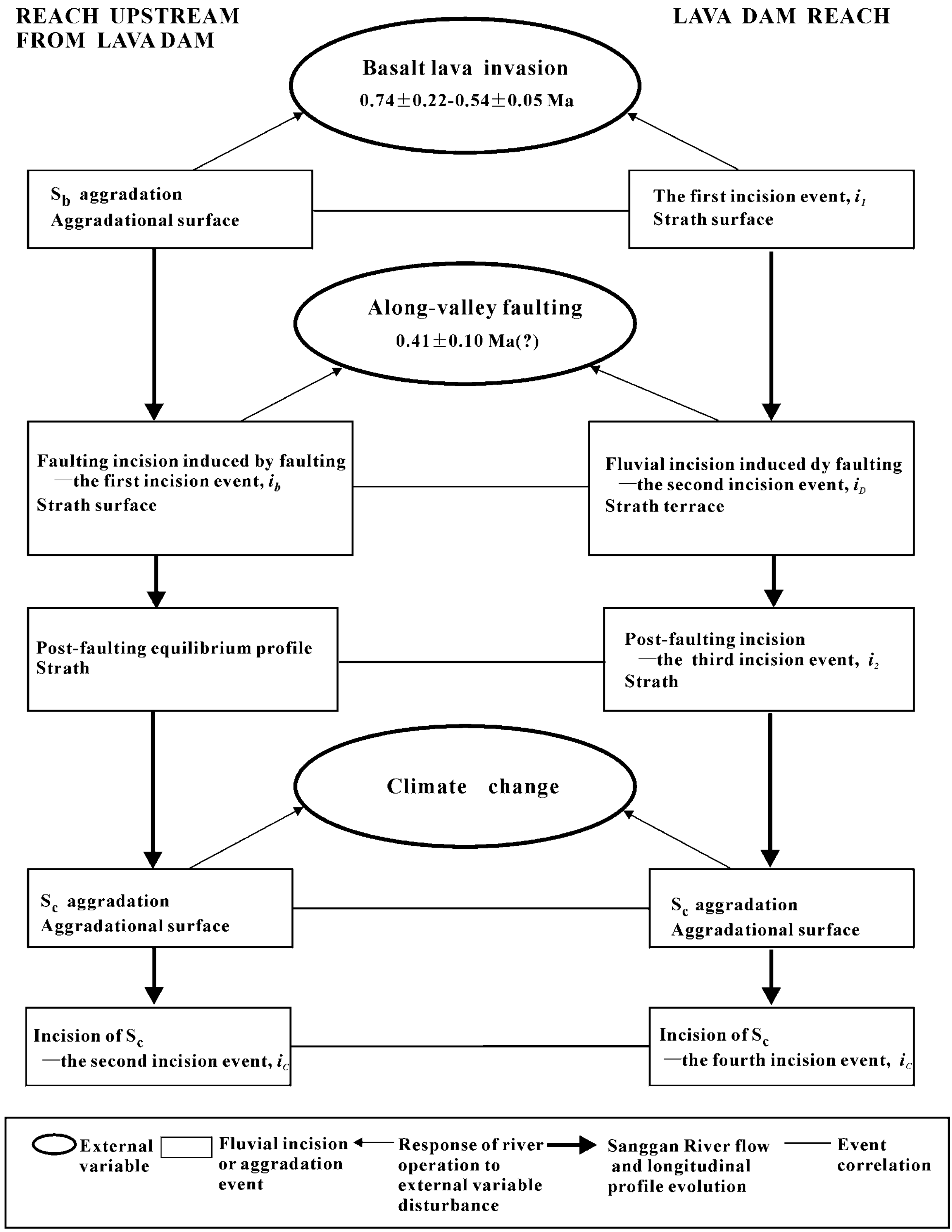


Figure 9. Correlation of the post-basalt fluvial incision and aggradation events. Note that the post-faulting united major strath and the $S_c$ aggradational surface in both the reach upstream from the lava dam and the lava dam reach are synchronous landforms, becoming the frameworks for correlation of events.

long-term tectonic subsidence rather than uplift setting of the northern Shanxi rifted-basin system during the Late Cenozoic era (Fig. 1). Although local upwarping of 10–15 m had been produced by the movement on the Sanggan River Fault in the Datong Basin since $0.41 \pm 0.10$ Ma, this amount of upwarping is negligible

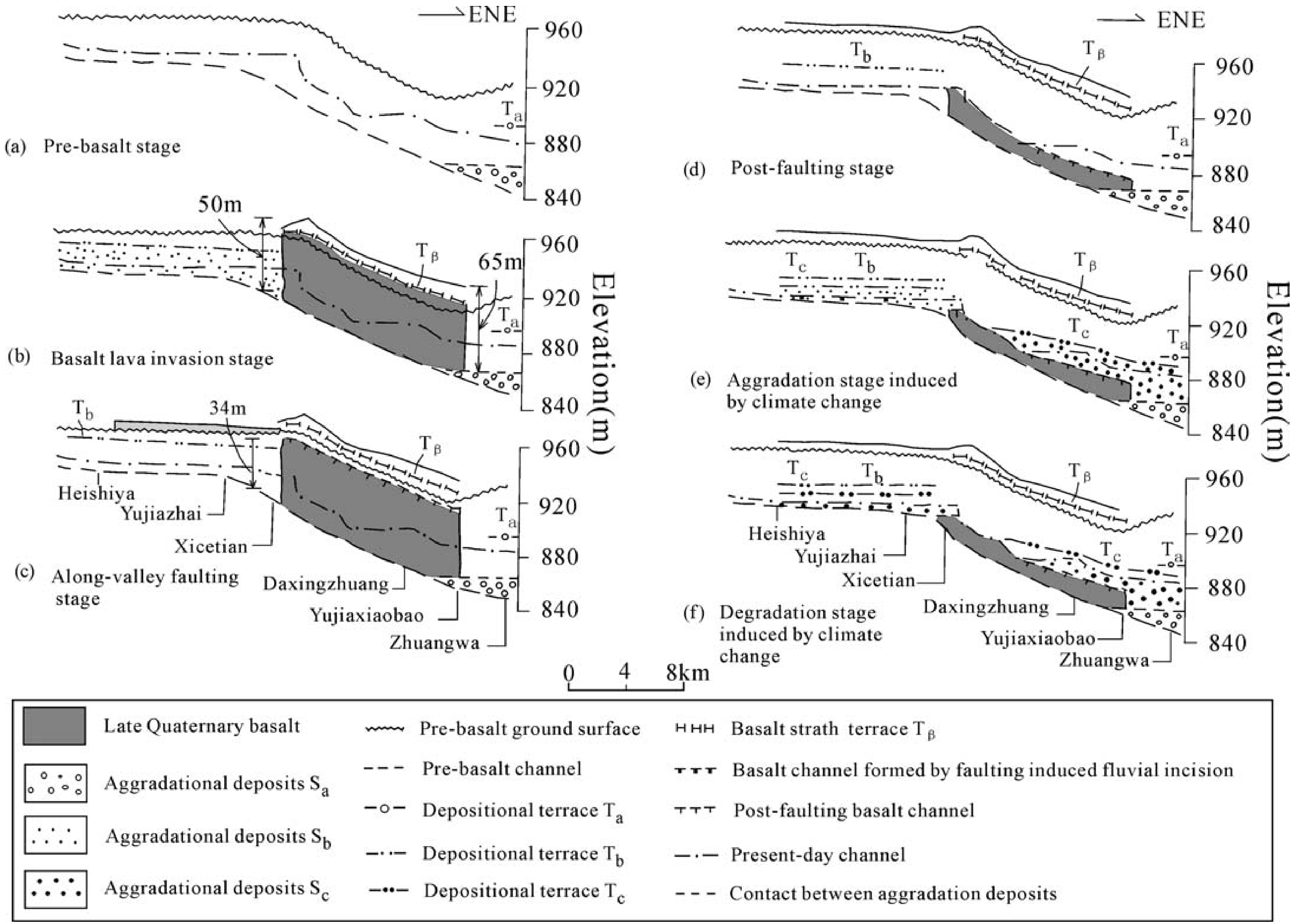


Figure 10. The six stages of the longitudinal stream-profile evolution of the Sanggan River in the Datong Basin during the Pleistocene (a) pre-basalt stage, (b) basaltic flow invasion stage, (c) along-valley faulting stage, (d) post-faulting stage, (e) climatic change-induced aggradation stage and (f) climatic change-induced degradation stage.

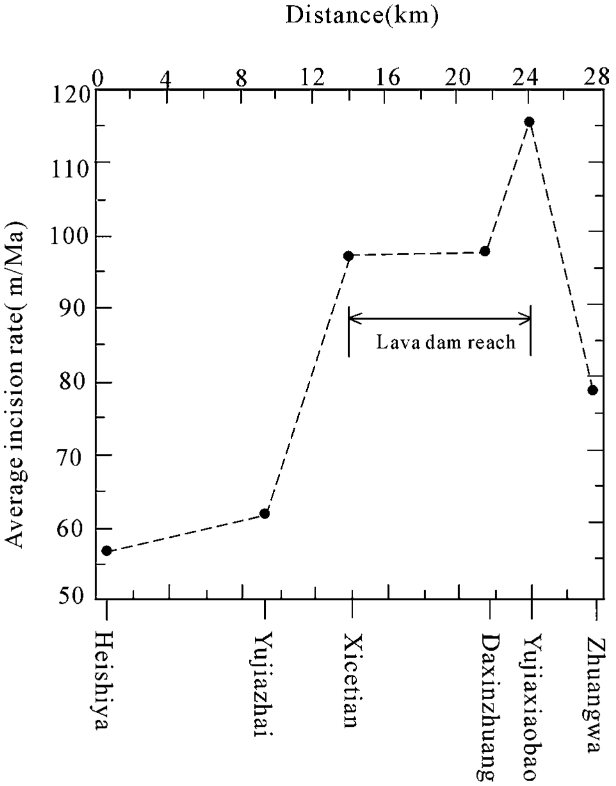


Figure 11. Distribution of average rates of fluvial incision along the river since $0.41 \pm 0.10$ Ma, showing that the exceptionally high rate occurs in the lava dam reach.

as compared with the amount of regional subsidence of the basin, which was several hundred metres during the Late Neogene and about 2000 m during the Late Cenozoic era. Secondly, there is no evidence to indicate that the exceptionally high rate of incision in the lava dam reach was related to tectonic base-level fall caused by active faulting, tilting or folding in the reaches further downstream.

The onset of backwater conditions and the maintenance of long-term high water-level conditions in the reach upstream from the lava dam caused rapid incision in the lava dam reach. According to the height of the basalt surface above the original streambed of the Sanggan River, it can be calculated that the water-level was raised by 50 m soon after the invasion of basaltic flow into the channel (Fig. 10b). Under backwater conditions, fine-grained alluvium of 15 m thickness was deposited in the reach upstream from the lava dam. High water-level might have prevented incision of aggraded sediments (Waters, 1988). The subsequent along-valley faulting triggered fluvial incision into the channel of this stream reach, cutting down to the level of the original streambed and maintaining a graded profile condition. At that time, the height of the backwater was still up to 34 m (Fig. 10c). However, no net erosion or deposition had occurred in the reach with a graded profile (Bull, 1990, 1991), so that the reach upstream from the lava dam provided efficient discharges of water with relatively less sediment for the lava dam reach to incise effectively.

The strata attitude, joint frequency and orientation, and bed thickness of the basalts have indicated that the main erosional processes in the lava dam reach were plucking and abrasion. Field observations show that the basalts in the study area are characterized by well-developed vertical joints and thicker beds, having 1–2 m horizontal spacing between joints and 0.5–1 m bed thickness. Plucking may effectively erode the well-jointed thick basalt bed, resulting in boulders the size of which depends on the bedding and joints of the basalts. The boulders entrained and transported by the stream become effective 'tools' (Bull, 1990, 1991; Sklar, Dietrich & Howard, 1996) for abrading the channel floor, leading to down-cutting.

Another important process of erosion in a lava dam reach is migration of knickpoints initially formed on the downstream end of the lava dam (Hamblin, 1990, 1994). The relatively erosion-resistant basaltic flows were directly on top of the relatively less erosion-resistant marly limestone bed of the fluviolacustrine Nihewan Series, forming caprock. The marly limestone is eroded easily by undercutting beneath the knickpoint on the footslope. On the other hand, the basalt columns that resulted from vertical jointing could readily topple into the plunge pool beneath the knickpoint. The combined effects of less erosion-resistant marly limestone and the columnar jointing of basalts caused the rapid migration of the knickpoint toward the upstream reach. The original knickpoint height on the downstream end of the lava dam at $0.41 \pm 0.10$ Ma was 65 m (Fig. 9b), while depth of backwater at that time was 28 m, as estimated from the height of the $T_a$ terrace at Zhuangwa (Figs 4f, 10b). The ratio between the knickpoint height and water depth is 2.32. According to Leopold, Wolman & Miller (1964), knickpoint migration may occur when the knickpoint height/water depth ratio is in excess of 1.0. Thus, the ratio of 2.32 indicates that knickpoint migration did occur from the downstream end of the lava dam.

## 7. Conclusions

The Sanggan River reach in the Datong Basin provides a useful example for differentiating between fault-driven and climate-related fluvial incision.

(1) The amount of fluvial incision driven by the lowering of tectonic base-level caused by along-valley faulting on the Sanggan River Fault is equal to the amount of fault displacement, which is 10 m in the lava dam reach and 15 m in the reach upstream from the lava dam.
(2) Since the invasion of basaltic flows into the channel of the Sanggan River during the period $0.74 \pm 0.22$ to $0.54 \pm 0.05$ Ma, the reach

upstream from the lava dam and the lava dam reach experienced different stream action histories. The former experienced two aggradation and two fluvial incision events, while the latter experienced one aggradation and four fluvial incision events. The net incision produced by two fluvial incision events in the reach upstream from the lava dam is 23–25 m, of which the amount of incision driven by faulting is 15 m, and that induced by climatic change is 8–10 m. In contrast, the net incision produced by four fluvial incision events in the lava dam reach is 40–47 m, of which the incision driven by faulting is 10 m, while that induced by climatic change is 30–37 m.

(3) Since $0.41 \pm 0.10$ Ma, the rate of fluvial incision for the lava dam reach is 98–115 m/Ma, which is 1.5 to 2 times as great as that for the upstream and downstream reaches from the lava dam. The rapid incision can be attributed to the adequacy of discharge under the prevailing warm and humid climate conditions after basalt extrusion.

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