New challenges in erosion and sedimentation research: a Chinese perspective

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Abstract Erosion may be classified according to the erosion agent into: water erosion, gravitational erosion, glacial erosion, and wind erosion (aeolian erosion). Complex erosion caused by two or more agents can occur in watersheds and river corridors, producing unique features and causing new problems. Earthquake erosion represents the mass movements caused by earthquakes. The volume of sediment mobilised by earthquake erosion may be 10–100 times greater than that for other types of erosion. Nevertheless, only a very small fraction (<0.2%) of the sediment from earthquake erosion will be transported over long distances and it may therefore have little effect on fluvial processes in large rivers. Grain erosion is a phenomenon involving the disintegration or breakdown of bare rocks under the action of insolation and temperature change, the detachment of the constituent grains by wind, the downslope flow of grains under the influence of gravity and the accumulation of the grains at the toe of the mountain forming a depositional fan. Grain erosion can result in airborne particles and cause injury to humans, and has resulted in numerous slope debris flows. More effort needs to be directed to developing control strategies. Neo-tectonic activity can trigger landslides and avalanches, which dam rivers and initiate intensive fluvial erosion. A landslide dam may develop into a knickpoint, if it is stabilized by the long-term action of the flow. Large knickpoints can totally change the fluvial processes and river morphology. Bed load motion in mountain streams is complex and the available bed load formulae are in many cases not applicable. The measured and estimated rates of bed load transport can differ by several orders of magnitude. The measured bed load transport rate in the Diaoga River can vary by as much as 1000 times under steady flow conditions, as a result of the dramatic difference in the incoming sediment load and different degrees of development of bed structures. New theories and new formulae for bed load transport in mountain streams are needed. Eco-sedimentation is a new challenge in sedimentation studies. The biodiversity of benthic invertebrates greatly depends on the stability and diversity of bed sediment. Pollutants in water may be adsorbed by suspended sediment and accumulate in the bed sediment bed. Benthic invertebrates can develop high concentrations of heavy metals due to their proximity to contaminated sediment. These new challenges represent new growth points of research on erosion and sedimentation in China and worldwide.

Key words earthquake erosion; grain erosion; earthquake dams and lakes; knickpoints; bed load transport; eco-sedimentation

INTRODUCTION

According to the *Columbia Encyclopaedia*, erosion is generally defined as the processes by which the surface of the Earth is constantly being worn away. Averaged over the land surface of the planet, the average rate of erosion is about 0.02 mm year^{-1}. In some places the rate is much higher, and in others it is considerable lower (Columbia University, 2000). Erosion can be classified into water erosion, wind erosion (Aeolian erosion), gravity erosion and glacial erosion (Goldman *et al*, 1986; Korup & Schlunegger, 2009). Gravity plays an important role in all forms of erosion. Landslides and avalanches are the main forms of gravity erosion that transfer material from higher to lower elevations under the action of gravity.

Earthquakes in mountainous areas are known to trigger numerous avalanches and landslides. An avalanche is the collapse of a cliff or slope and a landslide is the mass movement of rock and soil down a slope along one or more sliding planes. The relationship between the magnitude of an earthquake and the intensity of the associated landslides has been investigated. It was found that the minimum earthquake magnitude to generate a landslide is M = 4.3 ± 0.4. Empirical relationships between landslide magnitude, landslide volume, and erosion rate and earthquake moment magnitude have also been established (see Malamud *et al.*, 2004). The 1999 Chi-chi earthquake in Taiwan, China, induced many landslides in the Tachia catchment. The subsequent rainfall events associated with the passage of typhoons have led to a significant increase in the land area affected by landslides, and as a result the sediment production rate was still increasing four years after the earthquake event (Lin *et al.*, 2005). Among the various factors that affect the erosion rate, the cumulative seismic moment has the highest correlation with the erosion rate (Dadson *et al.*, 2003). Since the Wenchuan earthquake, which occurred on 12 May 2008, numerous debris flow events have occurred in Sichuan, China, with the frequency 10 times greater than before the earthquake. The landslides and avalanches directly triggered by earthquakes and the high frequency of debris flows occurring after the earthquakes are together referred to as earthquake erosion.

The sediment volumes mobilised by earthquake erosion are generally much greater than the sum of other types of normal erosion. In the Tianshan Mountains, which are shared by China, Kazakhstan, Uzbekistan, Kyrgyzstan and Tajikistan, the Sarez earthquake triggered the Usoi landslide with a volume of 2.2 billion m^3. The landslide blocked the Murgab River with the highest landslide dam in the world (500–600 m high), forming the Sarez Lake, in 1911 (Gaziev, 1984). The Sarez Lake is still storing water and the water level is rising at a rate of 18.5 cm $year^{-1}$ (Schuster & Alford, 2004). Nevertheless, most of the sediment from earthquake erosion is rather coarse and cannot be transported by river flow. Moreover, landslide dams frequently create lakes, which trap sediment. Therefore, the sediment budgets of river basins affected by earthquakes can be complex.

If a landslide dam is preserved and stabilized it may develop into a knickpoint. The development of a landslide dam into a knickpoint may totally change the fluvial processes and river patterns. The stability and long-term persistence of landslide dams depends on many factors. Korup (2002) reviewed different methodological approaches, their relevance and their potential application for engineering and mitigation measures for landslide dams, and discussed the shortcomings of existing studies. Large landslides that cause channel blockages have the potential to inhibit channel incision. Safran *et al.* (2008) used a 1-D finite difference model of longitudinal profile evolution to explore the implications of such processes for long-term (106 years) incision patterns and morphological development, and concluded that the morphological signature of landslide dams is context-dependent. Ouimet *et al.* (2007) explored a probabilistic, numerical model to provide a quantitative framework for evaluating how landslides influence bedrock river incision and landscape evolution within the Dadu and Yalong river catchments. Wang *et al.* (2009a) indicated that preservation of landslide dams may reduce new landslide hazards for incised mountain streams. The preservation of landslide dams and the fluvial process induced by knickpoints are new challenges in the study of river dynamics and their management.

Grain erosion is defined as the phenomenon of breaking down or disintegration of bare rocks under the action of insolation and temperature change, the detachment of grains by wind, the downslope transport of grains under the action of gravity, and the accumulation of the grains at the toe of the mountain forming a depositional fan. Grain erosion is unique, involving the exposure of rock as a result of avalanches and landslides, weathering, wind erosion and mass movement. The grain particles are removed from the parent rock by wind or tremors, and they roll, slide, or saltate down the slope like a flow and then accumulate at the toe of the mountain and form a depositional fan. It is difficult to classify such a type of erosion into weathering, slope erosion, wind erosion, or gravity erosion. It differs from other erosion types because the particles are rather uniform in size and the detachment and movement generally involve single grains or multiple grains. Thus, this form of erosion is termed grain erosion and the flow of grains on slopes is named grain flow. Grain erosion itself is not new, but the study of grain erosion and the development of control strategies are in the early stages and more work is required.

Bed load motion in mountain streams is very complex and the numerous available bed load formulae are in many cases not applicable. Since the 1970s, researchers have tested, analysed and compared these formulae with measured data from mountain streams. The difference between the calculated and the measured rate of bed load transport could be as large as several orders of magnitude. The lack of agreement between predicted and measured bed load transport rates is one reason why work on bed load transport theories and prediction techniques has never stopped. Barry *et al.* (2006) used measurements of bed load transport from 24 gravel bed rivers in Idaho to compare the accuracy of eight different formulae and the results of that analysis showed substantial differences in the performance of the different formulae. Bathurst *et al.* (1987) tested the validity of bed load formulae for mountain rivers, and found that the Shields approach (based on constant dimensionless shear stress) failed for slopes $S \geq 0.01$ and where the ratio of water depth/median diameter was ≤ 10.

Bed load motion in mountain streams is influenced by many factors. Flow intensity (stream power), bed structures and the incoming bed load are all important. Bed structures, including step-pool systems and cluster and ribbing structures, consume flow energy and can inhibit the mobilisation of sediment particles from the bed. Because of changing bed structure and varying incoming bed load, the rate of bed load transport can vary over several orders of magnitude under the same flow conditions. Under these conditions, none of the bed load formulae can be used to provide reliable estimates of bed load transport, because most of these formulae were developed using data from laboratory experiments involving uniform sediment and simple boundary conditions. New theory and new types of formulae are needed to improve the prediction of bed load transport in mountain streams.

Eco-sedimentation is a new challenge in sediment studies. The biological diversity and species abundance in streams depend on the diversity of available habitats, of which sediment is the main element. Residents of the diverse habitats include benthic invertebrates, fish, reptiles and amphibians, which depend on aquatic habitats for reproduction and overwintering. Benthic macro-invertebrates, or macrobenthos, are important because they are in the middle of the food chain and most ecological assessments use benthic invertebrates as the indicator species.

Fluvial conditions that affect macrobenthos mainly include streambed geomorphology (Statzner *et al.*, 1988; Wallace & Webster, 1996), streambed stability (Verdonschot, 2001), and the streambed sediment or substrate (Reice, 1980). Benthic macroinvertebrate assemblages depend on the stability of the aquatic habitat (Brosse *et al.*, 2003), particularly the streambed stability at the reach scale (Verdonschot, 2001; Jowett, 2003). Any form of streambed instability is unfavourable for invertebrates (Beisel *et al.*, 1998). Rivers with intense bed load transport are unlikely to be suitable habitats for most benthic species, either because food sources are not present, where bed load movement occurs, or because the substrate does not provide a secure platform for benthic invertebrates (Jowett, 2003). Miyake & Nakano (2002) suggested that even subtle but constant movement of sediment particles could influence the diversity of stream invertebrates. Jowett (2000) also indicated that invertebrate habitat would be poor in the centre of the channel, where most sediment transport and disturbance occur. Disturbance is probably one of the main factors that determine macroinvertebrate community structure in running waters (Resh *et al.*, 1988).

Habitat disturbance associated with the large-scale movement of sediment particles by hydraulic stress has gained prominence as a likely determinant of the diversity of benthic communities, because such disturbance can cause mortality of residents and physical elimination (Lake, 1990). The severe physical disturbances have often been found to have a strong negative effect on the diversity of stream invertebrates (Death & Winterbourn, 1995). When the streambed is disturbed, most benthic residents, especially mayflies and stoneflies, will evacuate the stone substrate (Doeg & Lake, 1981) and drift to downstream reaches (Waters, 1972).

These new challenges for erosion and sedimentation studies have become growth points for the discipline. Erosion, sedimentation and stream ecology are closely and mutually related and integrated management strategies are needed (Wang *et al.*, 2007). This contribution summarizes the new challenges and the preliminary results from related studies in order to direct more attention to these problems.

EARTHQUAKE EROSION AND SEDIMENT BUDGETS

The Wenchuan earthquake (MS 8.0) occurred on the eastern margin of the Qinghai-Tibetan Plateau on 12 May 2008 (Beijing time). The earthquake occurred as a result of tectonic motion of the plateau along the Yingxiu–Beichuan-Qingchuan fault, which is the central fault of the Longmenshan fractural belt (Fig. 1). There are many deeply incised rivers in the mountain area hit by the earthquake. The landslides dammed the rivers and created many earthquake lakes. Figure 1 shows the rivers and the locations of landslide dams. The Minjiang, Tuojiang, Fujiang and Jialing Rivers are four large rivers in the area that flow into the Yangtze River. Other rivers are tributaries of the four rivers. The Longmenshan fracture belt consists of three faults: in the middle is the major Longmenshan fault, where the Wenchuan earthquake occurred, which extends from Yingxiu to Beichuan and Qingchuan; on the north side there are two broken faults called the back fault, and on the south side there are two broken faults called the front fault. The streams in the area are characterised by incised channels and the bank slopes are so steep that slope failures readily occur during rainstorm and earthquake events.

In general, the total volume of earthquake erosion increases with earthquake magnitude (Keefer *et al.*, 1994). After the Wenchuan earthquake, investigations were conducted using satellite images of Beijing no. 1 (identification scale 32 m, spectrum classes G, R, and NIR, scanning scale 600 km × 600 km, and scanning time 3 days) and IKONOS (Di, 2008). The earthquake caused in total 1 135 725 avalanches and landslides of different scales. The total area of avalanches and landslides was 2264 km^2, and the total volume of mobilized sediment was about 5.586 billion m^3 (Chen *et al.*, 2009). Similar estimates were also obtained by other researchers (Cao *et al.*, 2009; Wang *et al.*, 2009a).

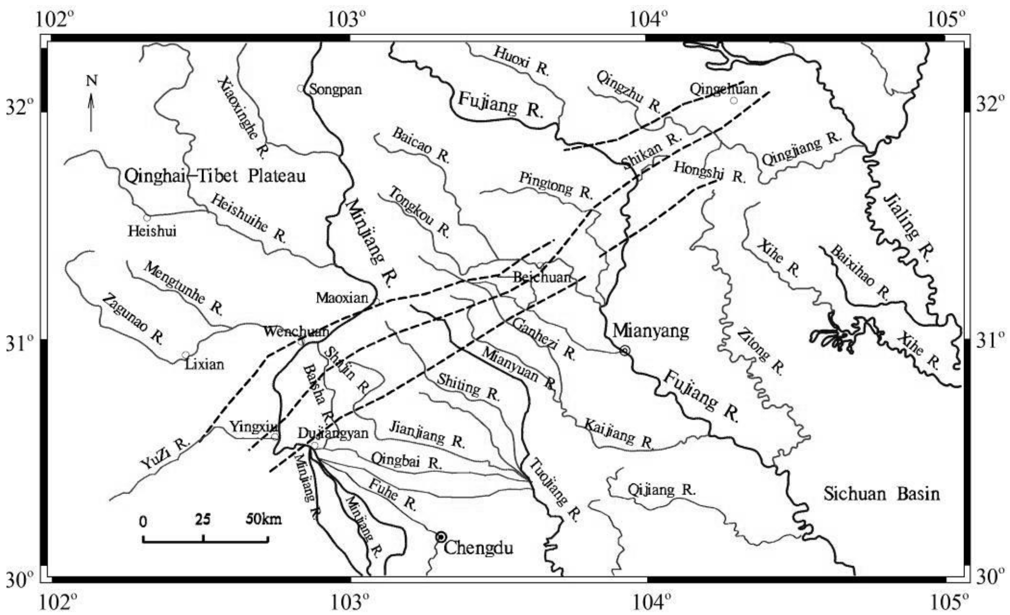

Fig. 1 The Wenchuan earthquake area, the Longmenshan faults and the rivers flowing from the Qinghai–Tibet Plateau to the Sichuan Basin.

Among the large-scale landslides triggered by the Wenchuan earthquake, the Daguangbao, Wenjiagou, Tangjiashan, Donghekou, and Huoshigou landslides are typical examples. The Daguangbao landslide, 4.2 km long, 1.2–3.2 km wide and 480 m thick was the largest landslide triggered by the Wenchuan earthquake. The total volume of the sliding body was estimated to be 742 million m^3 by Wu *et al.* (2010) and 750 million m^3 by Huang *et al.* (2009). The Wenjiagou landslide buried the Wenjiagou Ravine and its tributaries underneath landslide debris with a thickness of 20–180 m. The Wenjiagou landslide originated from a high elevation and slid very rapidly along the ravine to the confluence with the Mianyuan River. The total volume of landslide deposit was about 81.6 million m^3 (Sichuan Geological Engineering Corporation, 2009). Thirty-four houses were buried, and more than 80 people were killed by the landslide. The landslide deposit consists of loose solid materials with sizes ranging from boulders of several metres in diameter to clay and silt. The Tangjiashan landslide dammed the Jianjiang River and formed the largest earthquake lake in the earthquake area. The total volume of the sliding body was estimated to be 20.37 million m[3] (Ma *et al.*, 2008). The Donghekou landslide was 400 m long, 470 m wide and 100 m thick, with a total volume of about 15.5 million m^3. This landslide dammed the Qingzhu River and its tributary the Hongshi River, and created two landslide dams. Three villages were buried and 800 people were killed. The Huoshigou landslide was a high-speed and long-distance landslide, which created an extremely large air cushion and air waves that had a strong and destructive impact (Zhang *et al*, 2008). Hundreds of houses were buried and 39 people were killed by the landslide. Two days later, rainstorms caused three debris flows, which transported a very large amount of solid material to the downstream reaches and created a deposit 2–30 m deep along a reach of the river extending over about 7 km. The volume of the landslide deposit was 7.21 million m^3, and the volume of the debris flow deposit was 1.25 million m^3 (Xu *et al.*, 2010).

An assessment of the extent of the earthquake erosion was made in the Mianyuan River basin. The upstream reaches of this river are located around the Yinxiu-Beichuan fault and thousands of avalanches and landslides were triggered by the Wenchuan earthquake on 12 May 2008. Figure 2 shows the upstream reaches of the Mianyuan River and the locations of the landslides, avalanches and debris flows. The magnitudes of the mass movements are shown by different symbols. The largest mass movement was the Wenjiagou landslide. Figure 3 shows the number of events and the total volume of sediment deposited by mass movements of different magnitude. Along the 38 km-long Upper Mianyuan River, 196 landslides and avalanches occurred during the earthquake, and these created 25 landslide dams and earthquake lakes. In the following two years, eight debris flow events occurred in the tributaries of the river.

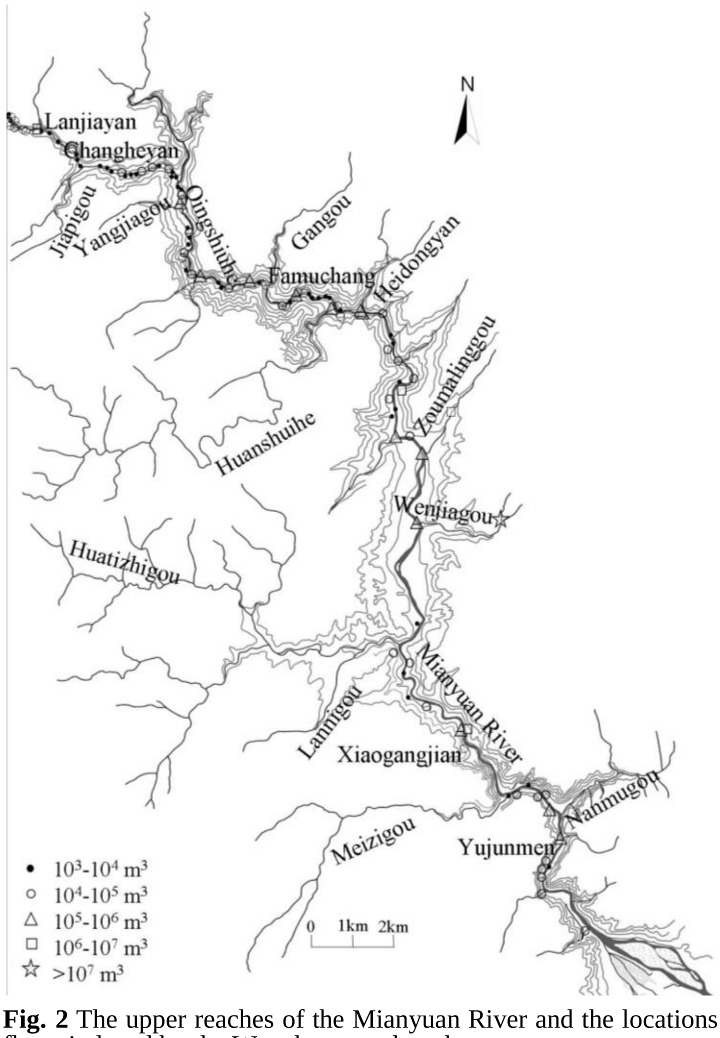

Fig. 2 The upper reaches of the Mianyuan River and the locations of landslides, avalanches and debris flows induced by the Wenchuan earthquake.

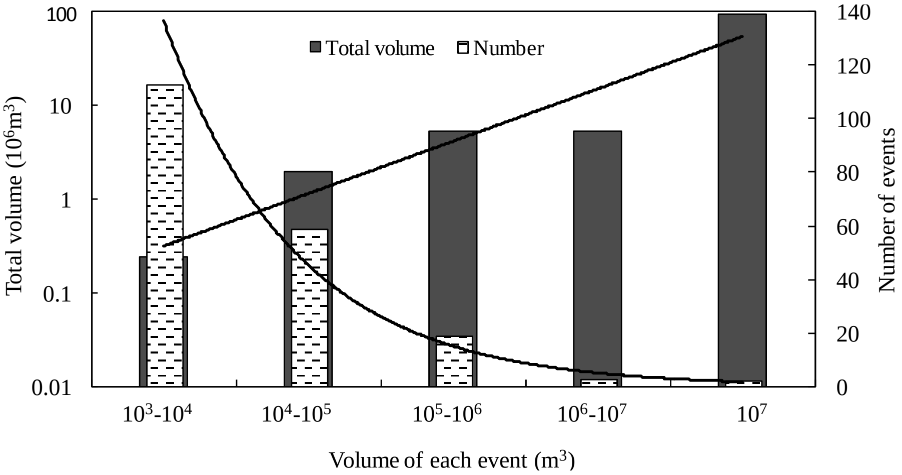

Fig. 3 The number of mass movement events and the total volume of sediment mobilised as a function of the scale of the mass movements.

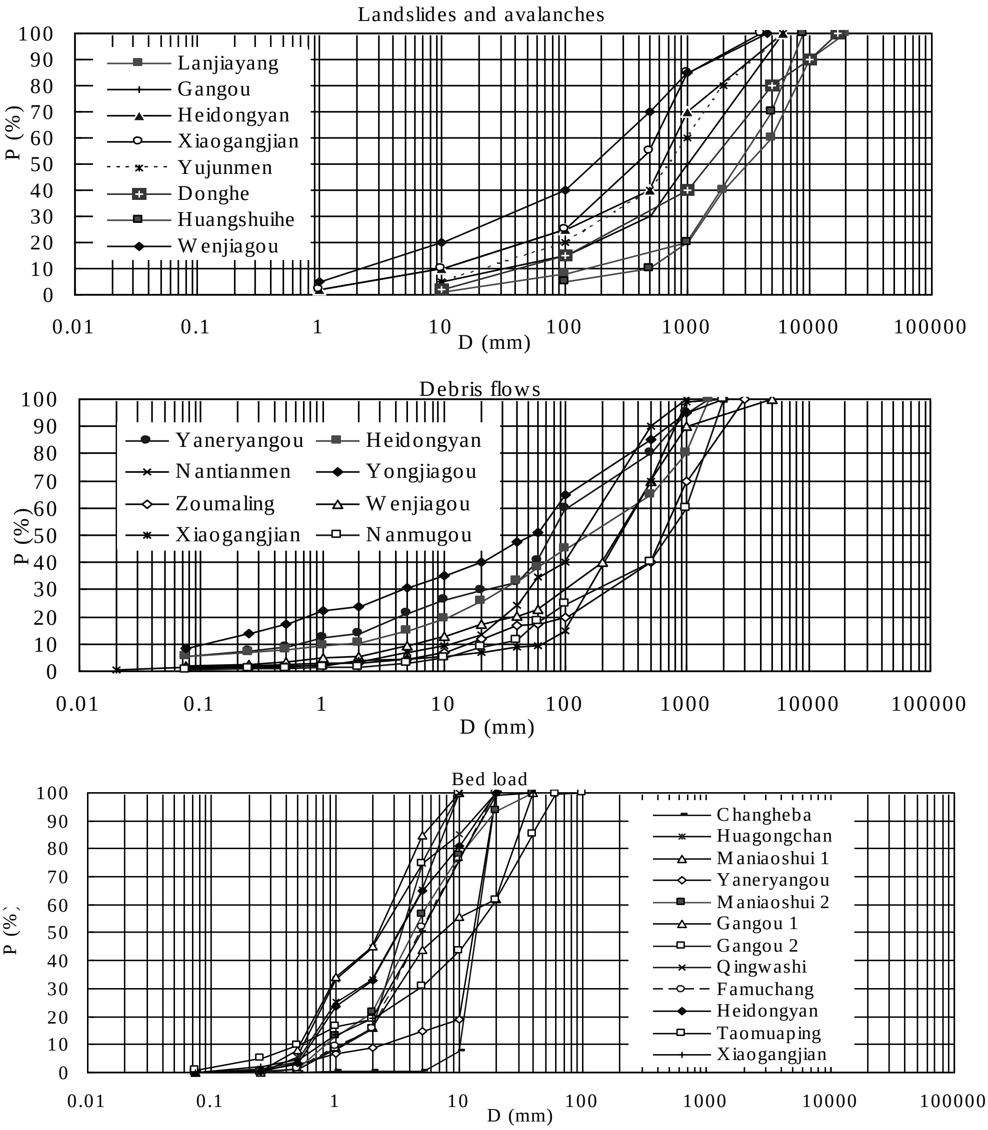

Fig. 4 Size distributions of sediment associated with landslides and avalanches, debris flows and bed load.

The total volume of sediment mobilised in the Upper Mianyuan River basin by the earthquake was caculated to be 10^6 million m^3, which is 75 times higher than that associated with soil erosion in a normal year. Debris flows transported gravel, cobbles and boulders into the tributaries and the main river, but only a part of this input could be transported by the river as suspended and bed load. The bed load was deposited in the upper ends of the earthquake lakes and formed deltas. The total volume of bed load deposited in the river and the 25 earthquake lakes was 1.43 million m^3. In addition, the earthquake lakes also trapped 0.123 million m^3 of the suspended load. Only 0.178 million m^3 of fine sediment (wash load) passed through the earthquake lakes and into the lower reaches of the Mianyuan River and the Tuojiang River, and then into the Yangtze River.

Figure 4 shows the size distributions of the sediment mobilised by the landslides and avalanches and the debris flows as well as that of the bed load in the river. The median diameter of the landslides and avalanches ranged between 200 and 3000 mm; the median diameter of the debris flows was 70–700 mm and the median diameter of the bed load was only 2–15 mm. The wide range of the size distributions associated with the sediment mobilised by earthquake erosion resulted in major contrasts between the amounts of material mobilised and transported. In this context, earthquake erosion resulted in the mobilisation of a huge amount of sediment, which may be 10–100 times greater than that mobilised by the soil erosion caused by other agents. However, most of the sediment mobilised by earthquake erosion is only transported for a short distance by the landslides and debris flows. Less than 0.2% of the total volume of sediment mobilised by earthquake erosion may be transported into large rivers. Although the landscape may be totally changed in the upper Mianyuan River, the effects of sediment from earthquake erosion on fluvial process in the lower Mianyuan and Tuojiang rivers are limited.

GRAIN EROSION

Grain erosion is defined as the phenomenon involving the disintegration or breakdown of bare rocks under the action of insolation and temperature change, the detachment of the constituent grains by wind, the downslope flow of grains under the influence of gravity and the accumulation of the grains at the toe of the mountain forming a depositional fan. Grain erosion of bare rocks is much (100–1000 times) more intensive than rock surface erosion due to freeze thaw weathering. Rockfalls, slope failures, avalanches and landslides result in the exposure of bare rocks in mountainous areas, especially in mountainous areas affected by river incision. Human activities, such as highway construction and mining, also expose bare rocks. In Yunnan Province, south China, grain erosion occurs in dry valleys with a poor vegetation cover and cracked metamorphic rocks. Such dry valleys have two unique features, which may be used as diagnostic characteristics: (1) they are deeply incised into the plateau; and (2) they experience significantly higher temperatures and evaporation rates and lower precipitation than the surrounding area on the plateau. In general, grain erosion occurs within only a small fraction of dry valleys. In a few small desolate valleys grain erosion dominates the erosion and produces a lot of solid materials for debris flows, as shown in Fig. 5(a). The grain erosion has resulted in numerous depositional fans with an angle of about 35°, which is equal to the angle of repose of the granular material. The phenomenon has therefore attracted only limited attention to date. However, extensive grain erosion occurred in the Wenchuan earthquake area, mainly due to exposure of a huge area of bare rock. The erosion is extremely intense. A surface layer of 3–50 cm of the bare rock had been eroded one year after the earthquake. It is estimated that grain erosion occurred on about 10% of the bare rock surface in the Mianyuan River valley, and on about 30% of the bare rock surface in the Minjiang River valley.

A grain erosion site typically consists of three parts: an area of grain erosion on the bare rock surface at the top of the slope, a grain flow or transport section in the middle, and a depositional fan at the toe of the slope. Figure 5(b) shows the bare limestone rock on the Mianyuan River in Sichuan left by avalanches during the Wenchuan earthquake, which had experienced grain erosion continuously for two years. Rock surfaces subject to grain erosion commonly have a slope angle in the range of 45–60° (Wang *et al.*, 2009b). Figure 5(c) shows a grain flow section in the Xiaojiang dry valley in Yunnan. The particles detached by grain erosion roll or flow through the grain flow section, which has a slope angle of about 40°. The grain flow scoured the slope and over time forms a flume-like granular flow channel on the slope. Figure 5(d) shows a layer of grain erosion deposit covering an avalanche deposit fan on the Minjiang River near Wenchuan. The grains are uniform in size with a median diameter of about 1 cm, and are derived from exposures of granite rock. In general the median diameter of the material mobilised by grain erosion is about 1 cm for granite, but about 10 cm for limestone. Beneath the grain layer is the deposit associated with an avalanche, which occurred during the Wenchuan earthquake in 2008, and is much more heterogeneous. This includes boulders several metres in diameter, as well as fine particles less than 1 mm in diameter. Because the grains associated with grain erosion are uniform in size and regular in shape, the material has been used for building material at some grain erosion sites with access to transportation facilities.

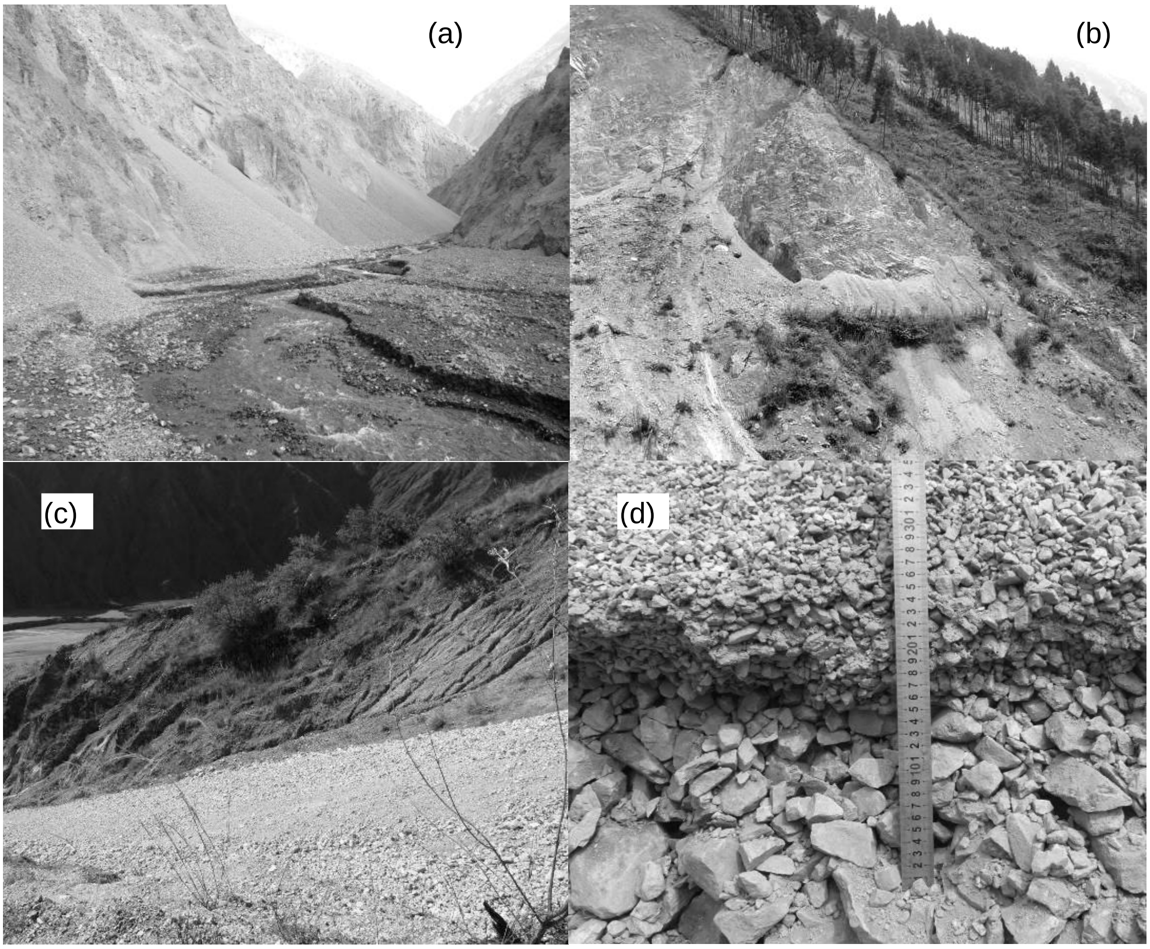

Fig. 5 (a) Grain erosion produces a lot of solid materials for debris flows in a small desolate valley (Menqian Gulley); (b) grain erosion developed on a bare rock surface on the Mianyuan River in Sichuan, which was caused by avalanches during the Wenchuan earthquake; (c) grain flow scoured the slope to form a 2 m-deep 42º channel in the Xiaojiang River basin; (d) a grain erosion deposit superimposed on an avalanche deposit fan on the Minjiang River near Wenchuan.

Grain erosion can cause particles to become airborne and and can trigger slope debris flows. Due to the grain erosion, particles with a diameter from 1 cm to 20 cm will roll and saltate down the slope potentially falling on cars and humans and has caused highways to become so-called "flying stone sections". The highway managers have had to hire many people to monitor the flying stones and issue warning signals. The highways are occasionally closed because of these flying stones. Because the depositional fans are composed of uniform loose solid materials and are characterized by high slope angles, rainfall with intensity greater than 20 mm day^{-1} can trigger mass movement of the grains. These mass movements behave like debris flows, but the run-out distance is much shorter than that associated with normal debris flows, and in general the transport distance is limited to several tens to 100 m. Because such a mass movement occurs on a slope rather than in a gully channel, it is referred to as a slope debris flow. Slope debris flows can transport large quantities of material into rivers or deposit the material on highways, causing blockage of highways or local sedimentation on the riverbed.

The erosion rate for grain erosion is defined as the thickness of the surface layer of bare rock eroded per year. Several tens of grain erosion sites, both in the dry valleys and the Wenchuan earthquake area, were investigated and measured. The rate of grain erosion in the Wenchuan earthquake area (the Minjiang and Mianyuan rivers) was in the range of 3–50 cm year^{-1}, but in the Xiaojiang River basin, which was not affected by the Wenchuan earthquake in 2008, the rate was only 1–5 cm year^{-1}. The rate of grain erosion in the earthquake area was much higher than in the Xiaojiang River basin because the bare rocks in the earthquake area were freshly exposed and the surface of the bare rocks was very vulnerable. The rate of grain erosion will gradually reduce, even if no control strategies are introduced. Compared with the normal weathering by freezing and thawing, the rate of grain erosion was more than 100 times higher (Wang *et al.*, 2010a).

The process of grain erosion has yet to be fully investigated. It seems that insolation and temperature change, wind and tremors, and gravity are the main agents involved. Field observations demonstrated that if a thin layer of lichen and moss grows on the rock surface, the insolation and temperature change, and the action of wind are mitigated, since they cannot act directly on the rock, and no grain erosion occurs. A preliminary experiment to examine this further was undertaken at a grain erosion site in the Mianyuan River valley. A clay suspension containing the spores of five moss species was applied to the bare rock surface. Two species of moss successfully germinated on the rock surface two months later and the grain erosion on the experimental plots was controlled (Wang *et al.*, 2010a)

KNICKPOINTS AND FLUVIAL PROCESSES

A knickpoint represents a section of the channel bed of a river, where the gradient is locally increased. As such, a knickpoint is therefore a section of river having a significantly higher bed slope than the upstream and downstream reaches. Knickpoints can result from the non-uniform incision of a bedrock channel into layered or jointed rocks or from the stabilization of landslide dams and the fill of earthquake lakes. In southwestern China, almost all knickpoints are developed from landslide dams. Landslide dams represent the natural dams formed as a result of large-scale avalanches, landslides and debris flows transporting huge amounts of sediment and depositing this in the river. In the rivers of the Qinghai-Tibet Plateau and the Yunnan-Guizhou Plateau thousands and tens of thousands of landslides, avalanches and debris flows have occurred. In many cases these have dammed the rivers and caused the development of knickpoints.

The stability of landslide dams is a key issue for the development of knickpoints. In general, as the water level in the lake reaches the lowest point in the top of the landslide dam, the ponded water flows over the dam and the flow scours the loose material and forms a spillway channel. The top part of the landslide dam is therefore scoured by the flow, but the exposure of erosion-resistant boulders can result in the formation of a step-pool system along the spillway. The step-pool system consumes flow energy and therefore protects the landslide dam from further erosion. If there are no large boulders within the deposits forming the landslide dam and the stream power of the flow is high, the flow will continue to scour and downcut and the dam will eventually fail. The stability of landslide dams therefore depends on the size distribution of the loose material forming the dam, the stream power of the flow, and any management strategies introduced by humans.

Under natural conditions, many landslide dams will survive and will become knickpoints. Korup *et al.* (2006) found that the dams associated with many large landslides and avalanches that had blocked rivers in the late Pleistocene and Holocene had survived and had developed into knickpoints in the Himalayas, the Tianshan, and the New Zealand Southern Alps. If a landslide dam that persists for more than 10 years is designated as "stable", an analysis of the status of an inventory of 232 landslide dams and earthquake lakes showed that only 37% of all landslide dams appear to have failed (Korup, 2004a,b). Wang *et al.* (2010b) studied the stability of landslide dams and found that a landslide dam is likely to survive if more than 10% of the loose solid materials comprising the dam have a diameter larger than 1 m.

The stability of landslide dams and the formation of knickpoints are important for controlling channel incision and for maintaining river ecosystems. River bed incision is a key cause of landslides through increasing the potential energy for landslide occurrences. At the eastern margin of the Qinghai-Tibetan Plateau river-bed incision dominates the fluvial processes. If the river cuts down below the sliding surface, the sliding body loses the support of the sediment and rock at its toe. The sliding body will eventually slide along the slip plane into the river. The development of landslide dams into knickpoints initiates extensive and prolonged aggradation upstream. Sedimentation will occur in the lake behind the dam as soon as it is formed. Over time the lake will be filled with sediment and the height and slope of banks will be reduced. The river banks will stabilise and can remain stable, even during earthquakes. Figure 6 shows the bed profile of the Shenxi Ravine. Three landslide dams (N1, N2 and N3) formed lakes more than 1000 years ago (estimated from the sedimentation rate) and the three lakes have filled up. This stream is located at the epicentre of the Wenchuan Earthquake. No landslides or avalanches occurred on the stream during the earthquake. The extraordinary stability is mainly due to the three preserved landslide dams.

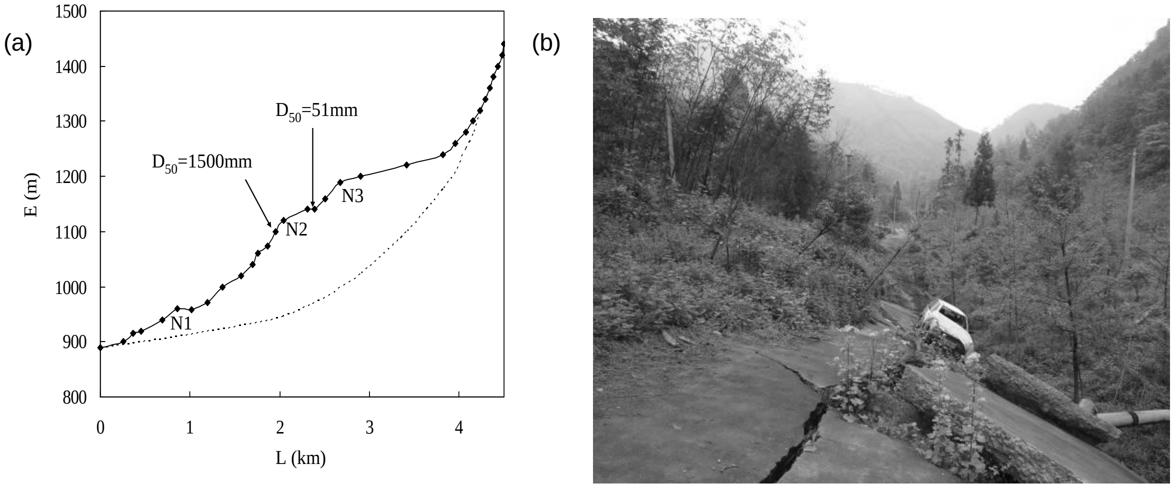

Fig. 6 (a) The bed profile of the Shenxi Ravine, showing three landslide dams and the infilled lakes; (b) a tilted and broken highway along the Shenxi Ravine resulting from the Wenchuan earthquake.

A landslide dam develops into a knickpoint in two stages: (1) a bed structure, in general a step-pool system, consisting of boulders and cobbles develops on the new channel bed from the lowest point on the crest of the dam to the downstream end of the dam. This commonly takes about 10 years during which a large flood should occur. The structure is strong enough to resist flood flows and remains stable at high bed gradients. (2) Sediment from the upstream reaches is trapped by the barrier lake, which will eventually be filled up and the bed gradient in the upstream reach becomes very gentle. The second stage takes 10–1000 years, depending on the capacity of the barrier lake and sediment load of the river. However, the landslide dam can be regarded as a knickpoint, once the first stage has been completed.

In the first few years after the formation of a landslide dam the fluvial processes will operate very quickly, e.g. filling of the upstream reaches of the earthquake lake and incision into the landslide debris forming the landslide dam (Ouimet *et al.*, 2007). Figure 7 shows the Yujunmen landslide dam on the Mianyuan River and the sedimentation in the earthquake lake. The original bed profile was reconstructed using the 1:50 000 topographical map. The height of the landslide dam was measured with laser range meters and GPS receivers. The depth of sedimentation in the earthquake lake was measured by excavating and measuring the depth of the lake bed sediment deposits. The measurements were performed when the landslide dam was formed in May 2008 and one year later in June 2009. The initial dam height was 47 m, but about 7 m of the upper part of the dam was removed by highway restoration. A step-pool system was initiated during the first flood and became well-developed after two flood seasons. Suspended sediment consisting mainly of clay and silt was deposited in the earthquake lake and formed a mud layer. Bed load was deposited at the upper end of the lake forming a delta.

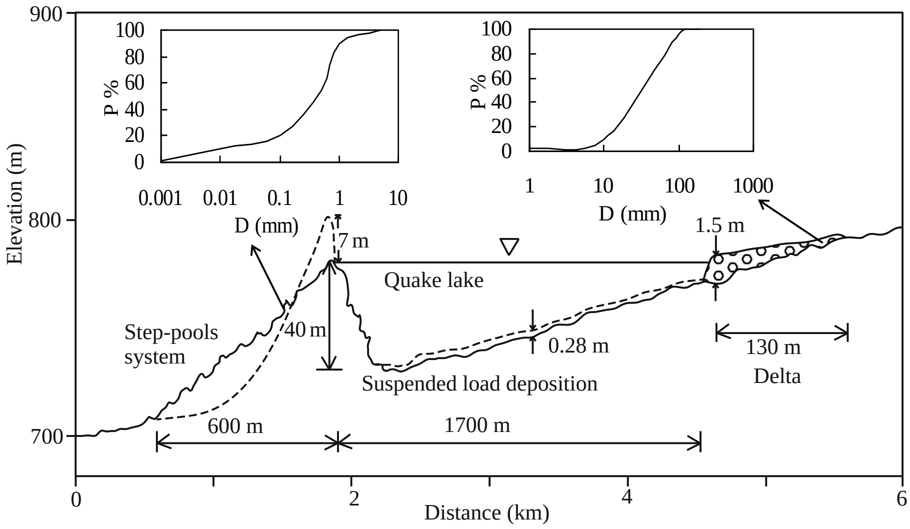

Fig. 7 The bed profile of the Yujunmen landslide dam and the associated earthquake lake measured one year after the formation of the dam.

The uplift of the Qinghai–Tibetan Plateau is the ultimate driving force for topographic changes in southwestern China. An end-scenario can be formulated in which the rate of bedrock uplift is matched by the rate of stream incision (Hovius & Stark, 2006). Nevertheless, this scenario has never occurred because many landslide dams have formed knickpoints, which have controlled the river bed incision. Large knickpoints may totally change the fluvial process and river morphology. Figure 8(a) shows the bed profile of a reach of the Yigong Tsangpo River on the Qinghai-Tibet Plateau. The Yigong Landslide Dam that was formed in April 2000 has partly failed and the rest of the dam has developed into a knickpoint. The longitudinal bed profile is unusual, exhibiting a convex upward curve caused by the large knickpoints. The upstream reaches have adjusted to the new stable base level provided by the knickpoint. The downstream reaches are steep, but incision is controlled by step-pool systems. Figure 8(b) shows a plan view of the river. The upstream section of the knickpoint has become wide and shallow, whereas the knickpoint section itself is narrow and deep. Localized aggradation upstream of the knickpoint has resulted in a transition from vertical bed evolution to horizontal fluvial process. The reduction in slope and accumulation of fine-grained sediment has facilitated the development of braided channels.

Debris flows may also dam rivers and change the landscape and fluvial processes. The Parlungtsangpo was a deeply incised river with a typical V-shape channel in Tibet. A very large debris flow occurred in the Guxiang Gully, which is a tributary of the Parlungtsangpo, and dammed the Parlungtsangpo in 1953. A huge quantity of boulders with diameters ranging from 200 mm to 2000 mm was transported into the Parlungtsangpo and raised the river bed by more than 200 m. Figure 9 shows the present bed profile of the Parlungtsangpo (a) and the river patterns upstream and downstream of the confluence with the Guxiang Gully. A reach downstream of the confluence has developed into a knickpoint and changed the fluvial process and river patterns. The reach has a straight single-thread V-shaped channel. Step-pool systems developed and stabilized the bed. The average bed slope is about 1.2%. The upstream reach has changed into a braided river with numerous bars and channels. Fine sand and silt deposited in this reach of the river. From the confluence of the Guxiang Gully to Bomi the average slope is only 0.2%. Retrogressive siltation also occurred in the Bodui Tsangpo tributary, which has become a braided river.

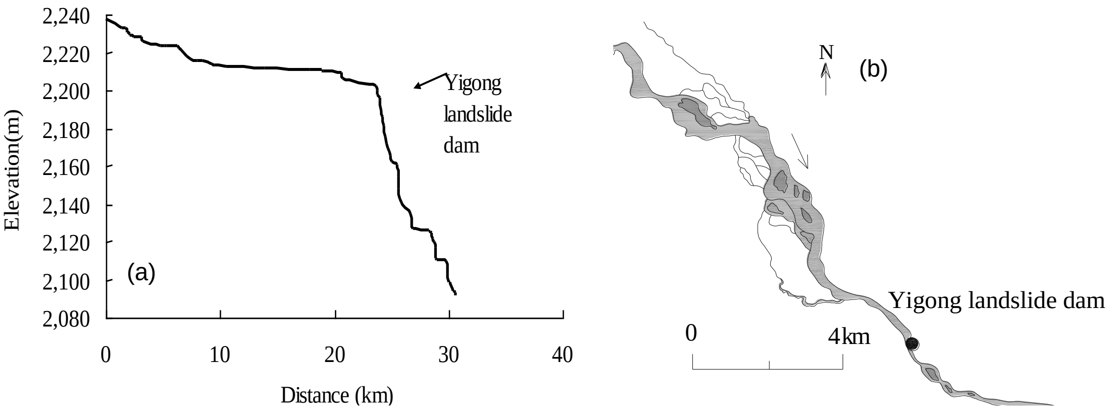

Fig. 8 (a) The bed profile of a reach of the Yigong Tsangpo River on the Qinghai-Tibet Plateau; (b) a plan view of the river reach and the location of the Yigong Landslide Dam.

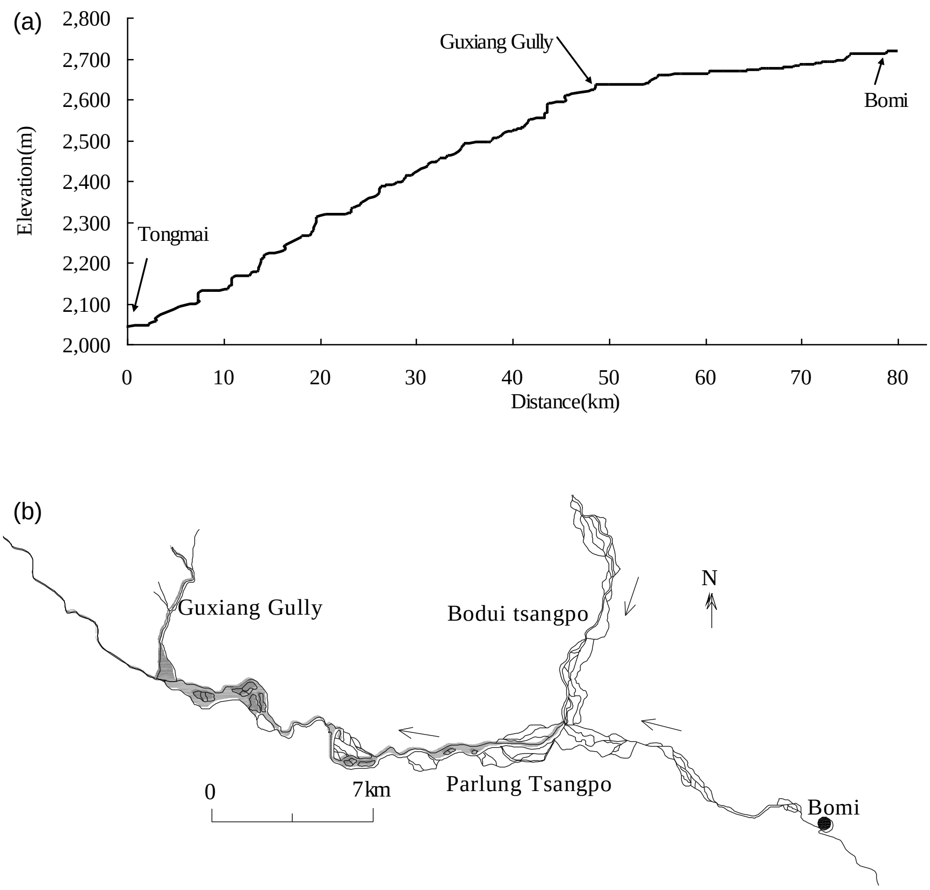

Fig. 9 (a) The bed profile of the Parlungtsangpo, (b) a plan view of the channel patterns of the

Parlungtsangpo upstream and downstream of its confluence with the Guxiang Gully.

BED LOAD TRANSPORT IN MOUNTAIN STREAMS

The measured rate of bed load transport in mountain streams is sometimes much lower or much higher than the value calculated using bed load formulae. Carson & Griffiths (1987) evaluated the validity of a range of bed load formulae using time-averaged transport measurements available for the Waimakariri River and other gravel-bed rivers in New Zealand. In particular, they focused on the ability of bed load equations, including the Bagnold formula, to estimate transport in braided rivers. They concluded that bed load formulae often under-predict transport rates by several orders of magnitude. Martin (2003) evaluated the original and revised versions of the Bagnold formula, the Meyer-Peter-Mullër formula and a stream power correlation formula based on the data from the Vedder River, a mountain stream in British Columbia, and concluded that the formulae under-predicted gravel transport rates by orders of magnitude .

Yu *et al.* (2009) measured the rate of bed load transport in the Diaoga River in Yunnan Province in southwestern China with a double-box sampler. The outer box was buried under the stream bed with the top edges of the box level with the local bed surface. Bed load particles were trapped, removed, weighed and sized using sieves. Figure 10 shows the measured rate of bed load transport per unit width as a function of flow discharge per unit width q and the Shields dimensionless shear stress, Θ. For the same q or Θ, the measured rate of bed load transport varied over a range of three orders of magnitude.

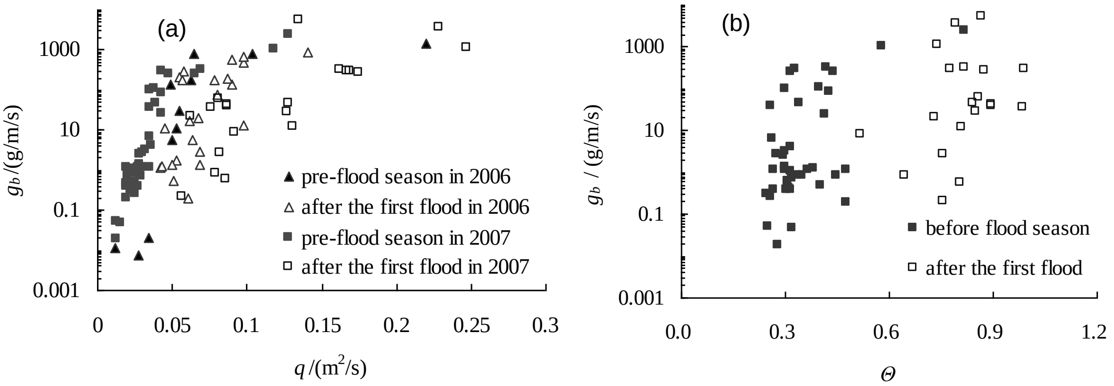

Fig. 10 The measured rate of bed load transport per unit width in the Diaoga River as (a) a function of water discharge per unit width and (b) the Shields dimensionless shear stress Θ.

Bed load motion in mountain streams is a complex process, which is influenced by many factors. Among these factors, the incoming sediment load and bed structures are the most important. If bed structures develop, especially a step-pool system, most of the flow energy is consumed by the form drag due to the structure. The rate of bed load transport is very low or even zero. Moreover, the structures may be buried and the bed may be flattened if the incoming bed load is high. Because of changing bed structure and varying incoming bed load, the rate of bed load transport can vary over several orders of magnitude for the same flow conditions. Therefore, none of the bed load formulae can be used to calculate bed load transport, because these formulae were developed using data from laboratory experiments with uniform sediment and simple boundary conditions.

The flow energy can be represented by the stream power:

$$p = \gamma q J \tag{1}$$

where p is the unit stream power or stream power per unit width, q is the unit flow discharge, and J the energy slope, which is equal to the bed slope S for steady and uniform flow. Figure 11 provides images of Shengou Creek and Hunshui Gully in Yunnan Province, southern China. The two rivers are located in close proximity and both are tributaries of the Xiaojiang River. The measured stream power per unit width for the two streams was almost equal (p = 10.34 kg m^{-1} s^{-1} for Shengou Creek and p = 10.16 kg m^{-1} s^{-1} for Hunshui Gully) and the sediment in the two rivers originated from debris flow deposits and had very similar size distributions. Nevertheless, the rate of bed load transport in the two streams was very different. A step-pool system had developed in Shengou Creek. The energy consumed by the step-pool system was quite high and the flow had no energy to carry bed load. Therefore, the rate of bed load transport was nearly zero (g_b = 0.002 kg m^{-1} s^{-1}). In contrast, there was no step-pool system present in the Hunshui Gully. The flow energy was consumed mainly for bed load motion and the measured rate of bed load transport was g_b = 18.9 kg m^{-1} s^{-1}, which was about 10 000 times higher than that in Shengou Creek.

Fig. 11 Comparison of Shengou Creek (left) and Hunshui Gully (right) (Shengou: p = 10.34 kg m^{-1} s^{-1}, gb = 0.002 kg m^{-1} s^{-1}, Hunshui: p = 10.16 kg m^{-1} s^{-1}, gb = 18.9 kg m^{-1} s^{-1}).

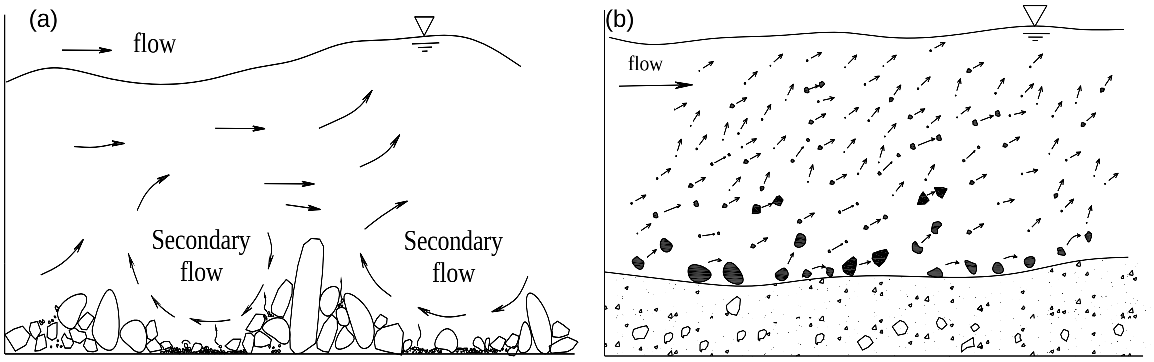

Fig. 12 (a) Almost no bed load motion occurs under natural conditions with a well-developed bed structure; (b) incoming bed load buried the bed structure and intensive bed load motion occurred.

To study the influence of bed structure and incoming bed load, an experiment was carried out in the Diaoga River during the non-flood season. Sediment was fed into the river at a cross section 22 m upstream from the measurement section. The bed slope of the experimental reach was 0.05. The flow discharge was 0.126 m^3 s^{-1}. There was very low sediment transport under the natural conditions due to bed structures. The measured maximum rate of bed load transport was 0.008 kg min^{-1}. The median diameter of the bed sediment was about 60 mm and the median diameter of the bed load was only 3 mm. The flow energy was dissipated by bed structures, as shown in Fig. 12(a).

Sediment taken from the flood plain was fed into the stream. The sediment was transported through the experimental reach and the bed structure was buried, as shown in Fig. 12(b). A lot of bed load particles were transported by the flow to balance the extra stream power. The maximum rate of bed load transport was measured at 18 kg min^{-1}, which is 2250 times higher than that found with the bed structures.

If the stream power, the bed structure and the rate of incoming bed load are considered to be the most important factors controlling bed load motion in mountain streams, a bed load formula may be expressed in the following form:

$$g_b = f(p, S_p, g_{bi}) \tag{2}$$

in which g_b is the rate of bed load transport per unit width; S_p is a parameter to represent the degree of bed structure development; and g_{bi} is the incoming rate of bed load transport. The formula cannot be parameterized using standard laboratory experiments because the bed structure development cannot be simulated in normal flumes. The formula may, however, be parameterized empirically using experiments and measurements in mountain streams.

ECOLOGICAL AND ENVIRONMENTAL SEDIMENTATION

Variation of substrate is an essential consequence of fluvial processes. Substrate (sediment in most cases) is the primary refuge of benthic organisms and represents the principal habitat of benthic invertebrates (Beisel *et al.*, 1998). Many benthic taxa exhibit preferences for different substrates (Verdonschot, 2001). An extensive literature exists on substrate choice by macroinvertebrates. Inorganic substrate characteristics primarily influence macroinvertebrate composition at the sample scale or smaller scales (Reice, 1980; Downes *et al.*, 1995). Distribution patterns of individual benthic organisms and species occurrence are highly dependent on sediment size (Erman & Erman, 1984; Evans *et al.*, 1997; Beisel *et al.*, 1998; Buss *et al.*, 2004). Generally, as median diameter increases, physical complexity (heterogeneity) increases, and thus benthic biodiversity increases (Beisel, 2000; Jowett, 2003). Buss *et al.* (2004) in a previous study stressed that each substrate supports a particular macroinvertebrate assemblage, corroborating that macroinvertebrate assemblages are not random assemblages of species. Excessive sediment loads degrade benthic habitats and thus alter macroinvertebrate assemblages. Zweig & Rabeni (2001) found many good relationships (r = 0.53~0.91) between macroinvertebrate metrics and the characteristics of deposited sediment. Substrate stability and deposition of fine sediment provided hydraulic constraints on habitat suitability. Deposition of suspended sediment may reduce the abundance of invertebrates by: (1) smothering and abrasion; (2) reducing their periphyton food supply or quality; and (3) reducing available interstitial habitat (Jowett, 2003).

The first author and his students have studied the effects of sediment on benthic invertebrates. Figure 13 shows the relationships between the taxa richness (number of species per site) and abundance (number of individual organisms per unit area) and the status of the fluvial processes at

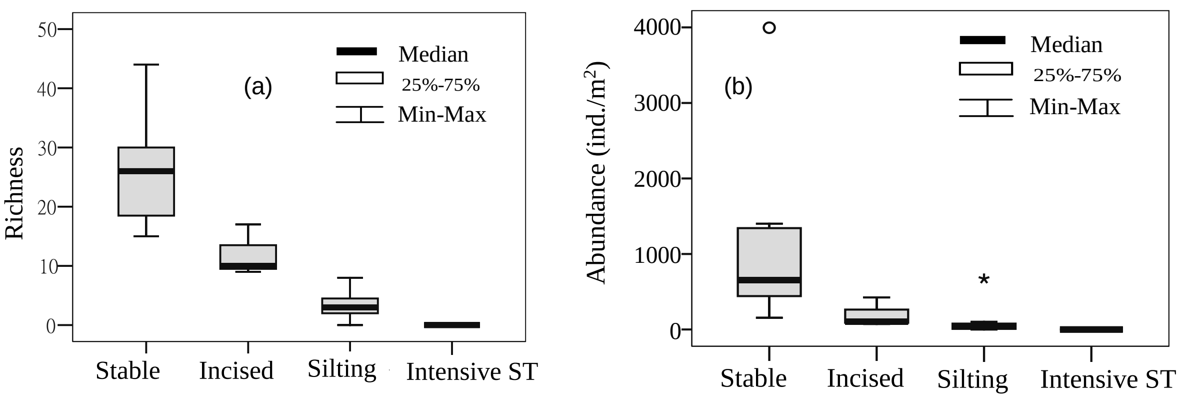

Fig. 13 (a) The relationship between species richness of macroinvertebrates and the status of the fluvial

processes in a river; and (b) the relationship between the abundance of macroinvertebrates per unit area and the status of the fluvial processes.

the sampling sites, in which “Stable” represents stable streams, “Incised” represents incised streams, “Silting” represents streams with continuous sediment deposition, and “Intensive BT” represents the streams with intensive bed load transport. The biodiversity and density are high in stable streams and lower in degraded and aggraded rivers, but lowest in streams with intensive sediment transport. Compared with fluvial processes, pollution is of only secondary importance in controlling river ecology. Bed stability is a precondition for stream ecology and is the most important factor for biodiversity. Field experiments demonstrated that cobbles are the most favourable substrate for benthic invertebrates, followed by gravel and then clay. Sand is the most unfavourable substrate for any species of benthic invertebrate.

River water often contains chemical constituents including: heavy metals (e.g. Cd, Cr, Cu, Fe, Pb, As, and Zn), organometallic species, polycyclic aromatic hydrocarbons (PAHs), fossil fuels (petrol and diesel), lubricating and transmission oils, grease, and anti-corrosion and anti-freeze agents (Ward, 1995). These chemical pollutants may be adsorbed by sediment and deposited on the riverbed, and are deleterious to biological or aquatic ecosystems (Baekken, 1994; Hares, 2000). In recent years, the rapid development of industry and agriculture has resulted in increased pollution of river water by heavy metals and sublethal effects or death in local fish populations (Liang, 1999; Zauke, 1999; Megeer *et al.*, 2000; Jones *et al.*, 2001; Almeida, 2002; Xu, 2004). Suspended sediment adsorbs pollutants from the water, thus lowering the concentration of pollutants in the water column. However, pollutants may also be released when deposited sediment is disturbed (Mohapatra, 1988; Douben & Koeman, 1989). Benthic sediments also provide habitat and a food source for benthic fauna. Pollutants may be directly or indirectly toxic to the aquatic flora and fauna. The effect of pollutants may also be detected on land due to the effects of bioaccumulation and bioconcentration in the food web (Zhang, 2004; Wu, 2005). Given the detrimental effects of pollutants, many researchers have studied their effects on aquatic flora and fauna (Morrisse & Edds, 1994; Chen, 2002; de Mora *et al.* 2004).

Yi *et al.* (2008) studied the concentration of heavy metals (Cr, Cd, Hg, Cu, Fe, Zn, Pb and As) in water, sediment, and fish/invertebrates sampled from the middle and lower reaches of the Yangtze River during 2006–2007. Because the pollutants in water were adsorbed by sediment and accumulated in the bed sediment, the concentrations of heavy metals in the sediment were 100–10 000 times higher than those in water. A number of studies have reported a similar phenomenon (Anderson, 1978; Enk & Mathis, 1977; Anderson *et al.*, 1978; Burrows & Whitton, 1983; Barak & Mason, 1989; Morrissery & Edds, 1994). Heavy metals do not degrade in water, but are generally not found in high concentrations, primarily due to adsorption in sediment, but also because of uptake by plants and animals.

The highest concentrations of Cu, Cd, Zn, and Cr were found in *Eriocheir*. Conversely, *Leptobotia* Bleeker had the highest concentrations of Pb, *Hemiramphus kurumeus* had the highest concentrations of Hg, and *Rhinogobio* Bleeker had the highest concentrations of As. The species of fish living in the vicinity of the bed (e.g. *Eriocheir* and *Leptobotia* Bleeker) and other fish that inhabit the lower zone of the water column (e.g. *Rhinogobio*) are likely to have more contact with polluted sediments than fauna that inhabit the upper water column. Accordingly, the highest heavy metal concentrations were found in zoobenthic predators.

Benthic invertebrates had relatively high concentrations of heavy metals in their tissues due to their proximity to contaminated sediment. The pollutants were accumulated in the food chain. Benthic fish feeding on invertebrates had moderately high concentrations of heavy metals, whereas the fish species feeding on phytoplankton, such as the silver carp, accumulated the lowest concentration of heavy metals. The concentrations of Cu, Zn, and Fe were higher than Hg, Pb, Cd, Cr, and As in the tissue samples.

CONCLUSIONS

Several new problems are challenging scientists and river managers and have become new growth areas for research on erosion and sedimentation: (1) Earthquakes cause extremely high rates of sediment mobilisation. The volume of material mobilised by the Wenchuan earthquake was 10–100 times greater than that mobilised by other forms of erosion. Nevertheless, only a very small fraction (<0.2%) of the sediment mobilised by earthquake erosion was transported over a long distance and reached the large rivers. Therefore, earthquake erosion has little effect on sediment transport and fluvial processes in large rivers. (2) Grain erosion is a phenomenon involving the continuous breakdown of bare rocks under the action of insolation and wind, occurring as a consequence of the exposure of rocks due to avalanches, landslides and human activities. Grain erosion causes flying stones and injuries to humans and can result in slope debris flows. Grain erosion represents an important type of erosion in the deeply incised valleys and dry valleys in Yunnan and Sichuan. Research on strategies for controlling grain erosion is required. (3) Most of the knickpoints in China were developed from landslide dams. Large knickpoints can totally change the fluvial processes and river patterns. Step-pool systems develop in the channel on the landslide dam and the upstream reach changes from an incised stream into braided or anabranching rivers with multiple channels. The valley becomes very wide after filling of the earthquake lake with sediment. (4) The rate of bed load transportation in mountain streams depends not only on the flow, but also, or even more importantly, on the bed structure and incoming bed load. If the flow energy is consumed due to the resistance of the bed structure, the flow is not able to initiate and carry bed load. New theories and new formulae for predicting bed load motion in mountain streams are needed. (5) The biodiversity of benthic invertebrates depends heavily on the stability and diversity of bed sediment. Cobbles, gravel and fluid mud are favourable habitats, but sand and silt beds are hostile habitats for benthic invertebrates. Pollutants, especially heavy metals accumulate in the bed sediment. Benthic invertebrates can contain high concentrations of heavy metals due to their proximity to contaminated sediment. The pollutants can transmit along a food chain from benthic invertebrates to fish and finally to humans.

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