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Reconstruction of the sediment transport conditions in the Urumqi alluvial fan (northeastern Tian Shan, China)

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ABSTRACT: Alluvial fans must contain information about the physical parameters of palaeo-rivers that built them. In particular, their grain-size evolution is partly related to water discharge and granulometry of the sediment supply. However, the temporal framework of deposits could also influence this grain size evolution. In order to discriminate the respective influence of the short- and long-term sedimentation dynamics on the grain-size organization of alluvial fans, we used a coupled experimental and field approach. The experiments show that aggradation is a local and short-term process, whereas progradation is a more long-term and regional one. Moreover, progradation is clearly related to time through a power law, which indicates a progradation rate lowering. Accordingly, the progradation rate seems to be a good proxy to reconstruct the overall evolution of fans. The field measurements performed on the Quaternary deposits of the Uumqi River shows that it is possible to observe a progradation rate lowering associated with a natural fan growth, and to document and quantify this lowering on a single vertical section using a granulometric approach. This example shows that granulometric studies could be a good manner to characterize the long-term and regional fan dynamics and, we hope soon, the associated transport conditions.

1 INTRODUCTION

Over the last twenty years, sediment transport by rivers and erosion dynamics have become the focus of a huge research effort. However, the morphological markers of erosion are scarce and discontinuous. At the outlet of drainage basins submitted to erosion, sedimentary series often constitute a more perennial archive of the relief evolution. In particular, the alluvial fan series, which are deposited by streams at the transition between reliefs and sedimentary basins, must contain information about physical parameters of palaeo-rivers. For example, the sediment mean size of ancient fans often rapidly evolves across space and through time (*e.g.*, Pivnik, 1990, Paola et al. 1992). As this size is partly related to flow discharge and granulometry of the sediment supply, a granulometric approach should be relevant to discuss river evolutions. However, beyond the sediment grain size, the temporal framework of deposits must also be investigated to reconstruct these evolutions. In fact, it is generally considered that, through a long period of time, the sedimentation dynamics can be averaged. This method is very useful because it smoothes natural variations and enables to compare parameters from different locations. Yet, alluvial fans are sedimentary structures built by the successive avulsions of the river. This fundamental mechanism implies that the whole surface of a fan is not active all the time and that fan areas must experience frequent and lasting dry periods of starvation. Consequently, once can question the relevance of long term averages and the possible loss of information. In other words, which is the respective part of the short- and long-term sedimentation dynamics in the grain-size organization of alluvial fans? It should be necessary to solve this question before to relate grain-size changes to fan evolutions and ancient sediment and water supplies.

For many reasons, laboratory experiments are the best and most simple way to address this problem (Paola *et al.*, 2009, Reitz et al. 2010). However, it is important to verify if experimental observations can be extended to natural systems. Therefore, we used a coupled experimental and field approach in order to tackle this issue of the reconstruction of past fan dynamics and transport conditions. As a natural example, we chose the northeastern piedmont of the Tian Shan range where the Urumqi gravel-bed braided river flows in a valley surrounded by terraces and inset in the deposits of a former Quaternary alluvial fan. As a consequence, it is possible to have access to the present and ancient sediments deposited by a same river. In this paper, we first present the experimental study we set up to clarify the relationships between the short- and long-term dynamics of alluvial fans. Then, we quantify the evolution of experimental fans through a topographic approach, which raises a series of questions related to the depositional record of such an evolution in the field. Finally, we describe the main geomorphologic features related to the Urumqi River and try to quantify these features through a granulometric approach designed to answer to these questions.

2 EXPERIMENTAL STUDY

2.1 *Experimental setup and procedure*

The experiments presented below were designed to simulate the growth of an alluvial fan within a sedimentary basin supplied in water and sediments by an adjacent catchment area. They were conducted in a plexiglass tank with a side neck sloping toward its central plane. Water and sediments were introduced at the top of the neck before to flow into it and reach the tank floor. There, the sediments were deposited, whereas water drained away by the front side of the tank. The sediments were glass beads with a mean diameter of 477 mm, a standard deviation of 65 mm, and a density of 2485 kg/m^3. They were heavy enough to be transported as bed load (see Meunier and Métivier, 2006). During all the experiments, sediments and water were supplied at constant fluxes controlled by an electronically controlled pump connected to a flow-meter .

As a consequence, a fan built in the tank at the neck outlet where water flow diverged and sediments piled up (Figure 1). This fan formed by the short-term deposition of successive lobes (Figure 2), which leads to long-term aggradation and progradation. The experiments were then stopped either because the fan has reached the tank edge, or because it has aggraded so much that water could no longer flow on it and leaked into its deposits. Typically, this occurred between 30 to 60 minutes after the beginning of a run. Finally, to record the topographic evolution of each growing fan, we used the optical Moiré method described in detail by Limare *et al.* (2011).

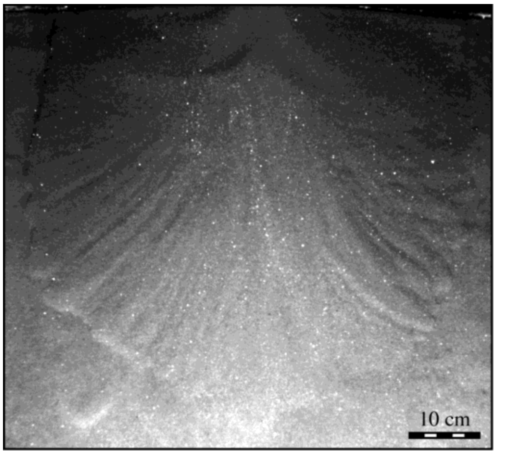

Figure 1 Map view of a fan built during an experiment

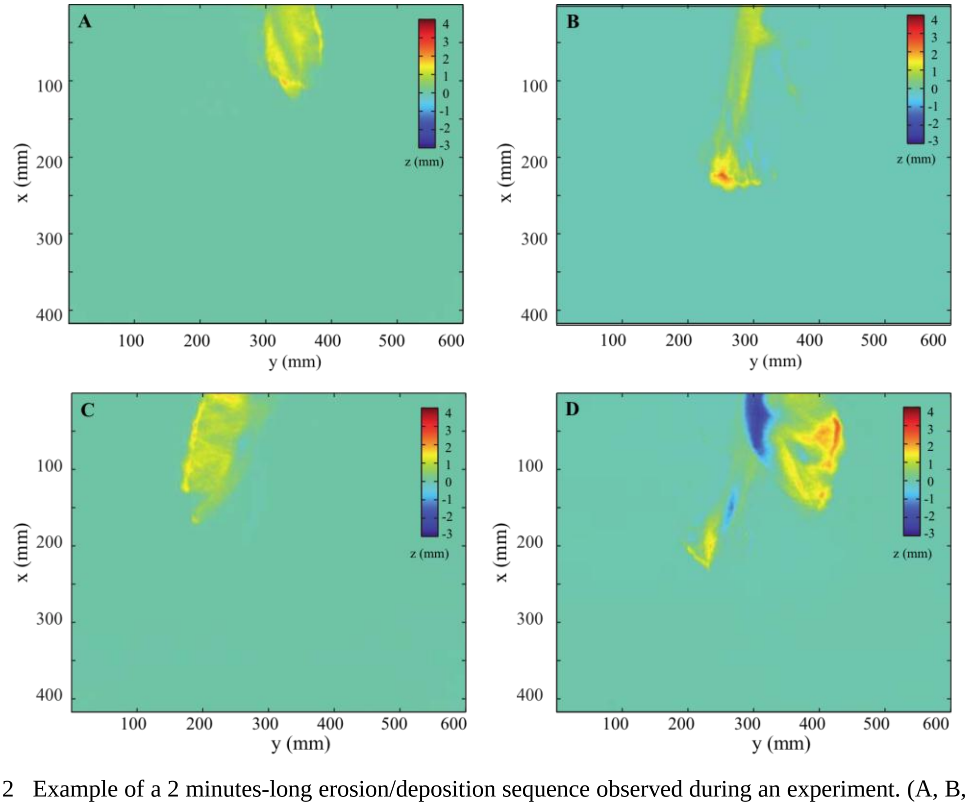

Figure 2 Example of a 2 minutes-long erosion/deposition sequence observed during an experiment. (A, B, C and D) Successive mass balances across the fan. These mass balances are calculated every 30 seconds from the fan topographic evolution. In green, yellow and red: locations with sediment deposition. In blue: locations with sediment erosion. Note the lobate shape of the successive deposits

In this paper, we use the results from eight different runs. In these runs, the sediment flux was fixed at approximately 0.035 g/s, whereas the water flux changed from 0.25 to 0.90 +/- 0.02 L/min (Table 1).

Table 1 Values of the input water and sediment fluxes during the eight experiments presented here. The water flux (Qw) varies from 0.25 to 0.90 L/min, whereas the sediment flux (Qs) was the same for the eight runs.

Run	Qw (L/min)	Qw *min*	Qw *max*	Qs (g/s)
1	0.4525	0.4200	0.5100	0.035
2	0.4500	0.4000	0.5000	0.036
3	0.9018	0.8800	0.9200	0.035
4	0.3013	0.2800	0.3100	0.033
5	0.3009	0.2900	0.3200	0.034
6	0.6015	0.5900	0.6100	0.034
7	0.6021	0.5900	0.6200	0.034
8	0.2508	0.2400	0.2600	0.034

2.2 *Fan aggradation*

Unsurprisingly, we first observed that the experimental fan growth is not homogeneous across space. This is demonstrated by the elevation changes of the sediment surface at different locations along three profiles: one in the centre and two at the edges of the fans (Figure 3). Aggradation is twice faster in the centre than at the edges. Moreover, the further is an area from the water and sediment inputs, the lower is the aggradation rate. However, the fans are not perfectly symmetrical and at the same distance from the inputs, the aggradation rate can take different values.

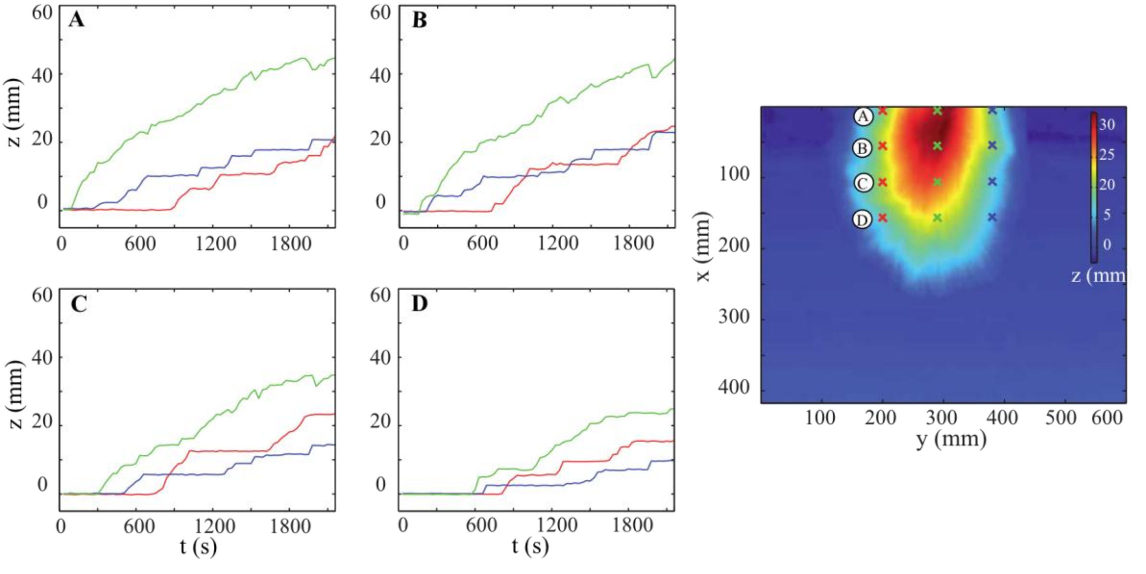

Figure 3 (A, B, C and D) Examples of the aggradation evolution through time at different locations within an experimental fan. The topographic map to the left represents the fan topography at the end the experiment. Along the profiles marked by the red, green or blue crosses, the distance from the fan apex increases from A to D

Secondly, we also observed that, depending on the location, the aggradation is more or less constant through time. Near the fan apex, aggradation is quite continuous. Further downstream, it becomes more discontinuous. In fact, the further is an area from the water and sediment inputs, the less frequent are the deposition periods (Figure 3 and 4). These results demonstrate that it is therefore essential to have reasonable volumetric estimates (Metivier, 2002) in order for example to reconstruct past fluxes of sediments from the record of aggradation. Both aggradation and progradation must be known.

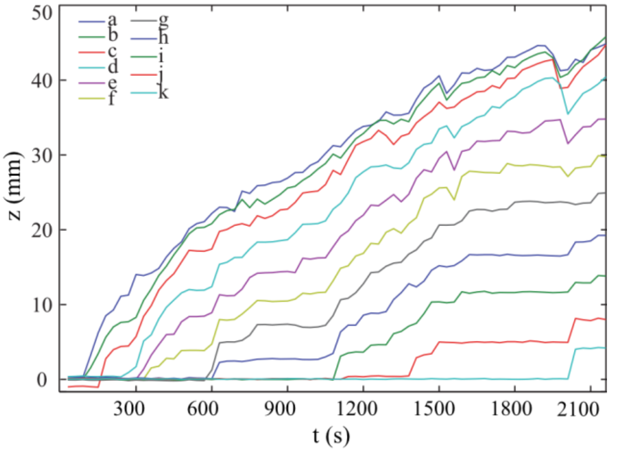

Figure 4 (a to k) Examples of the aggradation evolution through time at different locations along the green central profile of figure 3. The distance from the fan apex increases from a to k

2.3 *Fan progradation*

We then focused on the progradation rate of the fan central part. After a coalescence stage of the first fan lobes, the fan toe progradation starts (Figure 5). This progradation is discontinuous but clearly related to time through a power law. One can also notice that the exponent of this relation seems, to the first order, to be independent on the water input. This relation is more probably a direct consequence of the fan development at a given sediment supply. When a fan grows, its area increases and the sediment must be spread out on a wider surface, leading to a deacreasing progradation through time if the sediment flux stays constant.

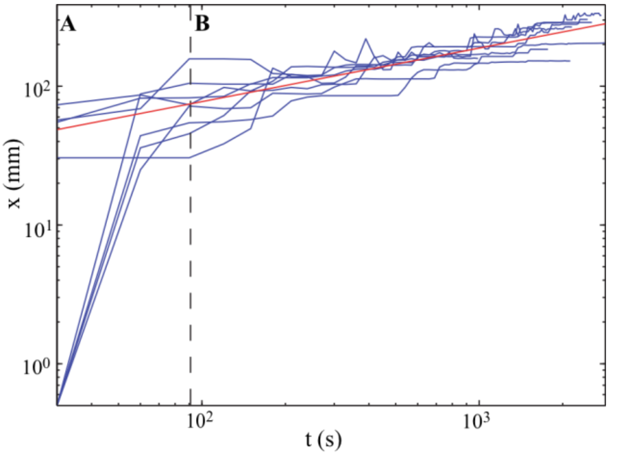

Figure 5 Progradation evolution through time of the toe of eight experimental fans. After a stage of lobe coalescence (A), progradation is related to time though a power law (B)

2.4 *Transition from the experiments to the field*

These experiments point out that aggradation is a local and short-term process, whereas progradation is a more long-term and regional one. These space and time behaviours should be taken into account to interpret any data set on alluvial fan deposits. Anyway, the progradation rate seems to be a good proxy to reconstruct the overall dynamics of a fan. Though, the direct observation in the field of a fan toe progradation requires very long outcrop panels or many vertical sections. Therefore, we wondered whether it is possible to (1) observe in the field a progradation rate lowering related to a fan growth, and (2) to document and quantify this lowering on a single vertical section, using a granulometric approach for example.

3 FIELD STUDY

3.1 *The Urumqi River*

We chose the alluvial system of the Urumqi River as a natural case study. This river is a shallow braided gravel-bed river that flows through the northeastern piedmont of the Tian Shan Mountains in Central Asia, near the Chinese town of Urumqi (Figure 6A). In this area, the Urumqi River and the nearby streams incise into folds and display well-developped alluvial fans and fluvial terraces. Based on a geomorphologic, stratigraphic and chronologic study, Lu *et al.* (2010) showed that over the past 550 kyr, at least three sequences of fan growth and abandonment/incision occurred within the piedmont. These alluvial sequences are synchronous across the area and controlled by climate changes related to the last Quaternary glacial-interglacial cycles.

More specifically, the Urumqi River flows from a glacier at an elevation of ~3600 m in the high range into the Junggar to the north, where it dies out in the desert at an elevation of ~1100 m. Its catchment area is approximately 1000 km^2 and is mainly fed by summer rains and snow or ice melting. Hence, the Urumqi River mostly flows from May to September (Figures 6B and 6C), with a mean annual discharge of 7.47 m^3/s and a total sedimentary load on order of 1-2 10^8 kg/year (Métivier *et al.*, 2004; Liu *et al.*, 2008, 2010). Downstream of the topographic front, the river braids within a valley surrounded by well-preserved terraces and inset in the deposits of a former alluvial fan (Zhou *et al.*, 2002) (Figure 6).

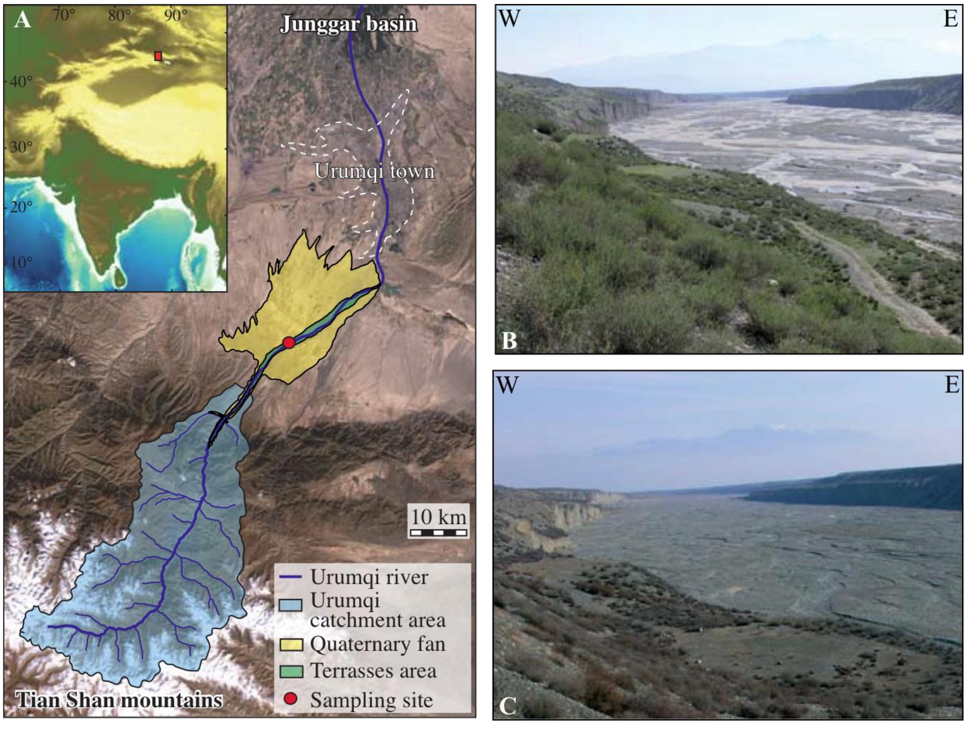

Figure 6 (A) Location of the sampling site along the Urumqi River. Photographs of the Urumqi River at the sampling site in (B) summer and (C) winter

The Urumqi River probably built this fan during the last glacial period (Figure 7A and 7B). Then, at the glacial-interglacial transition, the river incised this fan to form a valley flanked by terraces and to build a new fan further downstream (Figures 7C and 7D). As a consequence, it is now possible to observe the past and present alluvial deposits from the Urumqi River along its incised valley. Moreover, we observed no deformation of the main geomorphologic features of this system, which was most likely mainly controlled by the last Quaternary climate changes and the coeval evolution of water and sediment supplies. Therefore, the Urumqi system is a good example to study the granulometric evolution associated with the growth and incision of fans, as well as to elaborate methods for the quantitative reconstruction of fan dynamics and transport conditions.

In order to quantify the Quaternary evolution of the Urumqi River, we chose a sampling site located approximately 10 km from the topographic front (Figures 6A). In that place, deposits of four terraces and three layers of the fan can be observed (Figure 8). As their grain size must be related to the river palaeo-flows, we performed a granulometric characterization of these sediments.

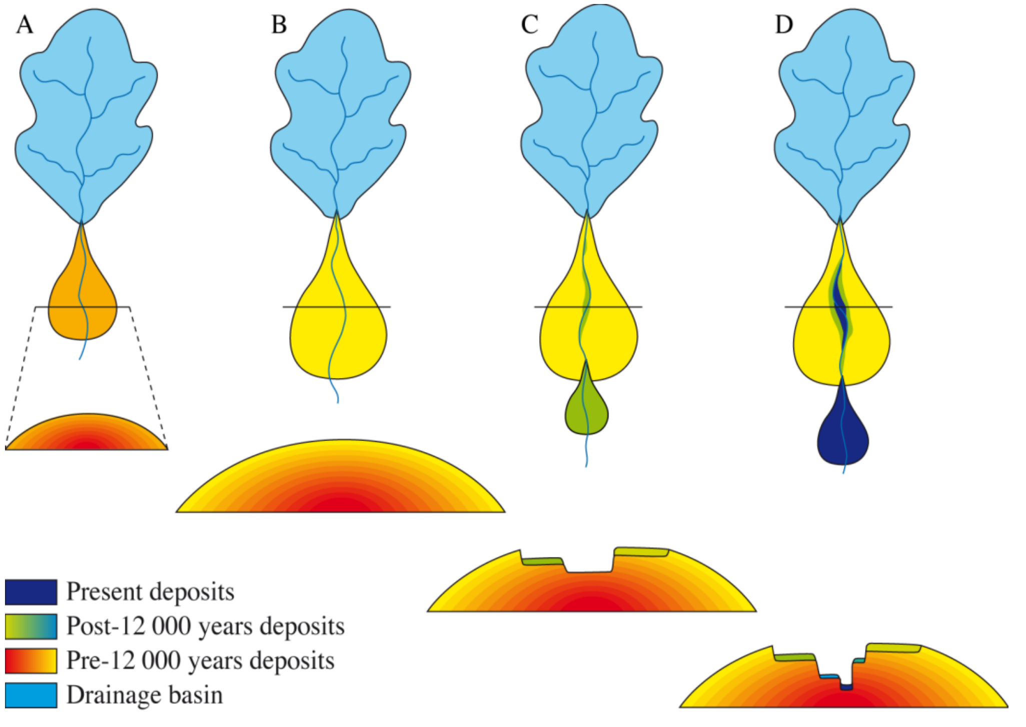

Figure 7 Quaternary evolution of the Urumqi River. (A and B) Pre-Holocene aggradation and progradation stage. (C and D) Post-Holocene incision and forced progradation stage. Ages are only indicative as they are estimated from ages of the geomorphic features associated with nearby rivers (Poisson and Avouac, 2004; Lu *et al.*, 2010)

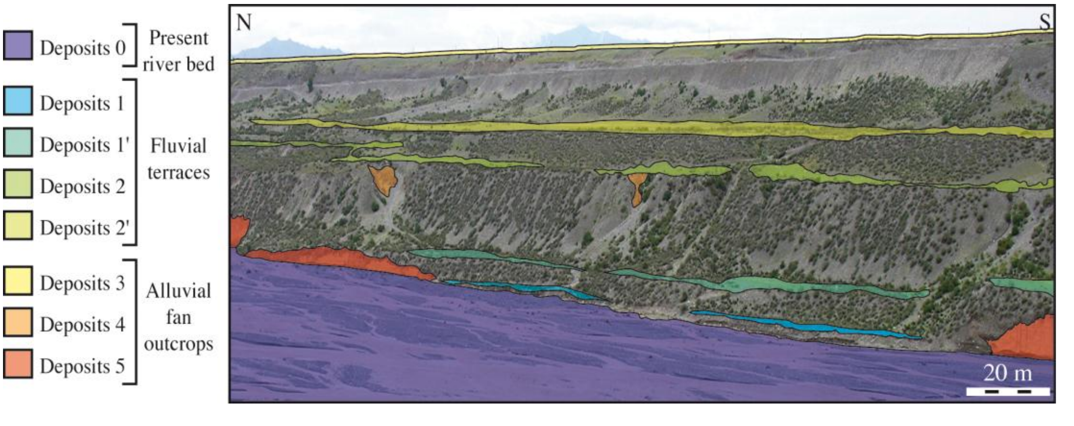

Figure 8 Location of the river-bed, terraces and alluvial fan deposits cropping out at the sampling site. The deposits 0, 1, 2, 3, 4 and 5 were sampled for this granulometric study

3.2 *The data acquisition and analysis*

We characterized the grain-size distribution of the different deposits using the Wolman surface count sampling method (Wolman, 1954). For each surfacial sampling, a grid with knots every 0.2 m was layered over a vertical outcrop of sediments. The intermediate diameter of the grains located under the grid knots was then measured. However, grains with an intermediate diameter smaller than four millimeters were not considered, as it is not possible to measure them correctly. For each sediment levels, we measured approximately 300 grains. Our purpose was not to determine the exact granulometry of the Urumqi deposits, but its relative evolution. If a bias exists in our data acquisition (*e.g.*, toward the small or big grains), it is probably the same at each sampling location. Consequently, our results must be valid at least for relative values.

Grain-size distributions can be fitted by different laws (Otto, 1939; Krumbein and Tisdel, 1940; Bagnold and Barndor-Nielsen, 1980). However, in most cases, the lognormal law is used as it analyses distributions through only two parameters: their mean (m) and standard deviation (s). To verify the validity of this fit for the Urumqi data, we could not use classic statistical tests as all of them are sensitive to the sample size. Indeed, small samples can be fitted by any law whereas big samples cannot. Consequently, the simplest way to assess the accuracy of the lognormal fit was to use quantile-quantile plots. The latter compare the quantiles of two distributions to determine whether they are equivalent or significantly different. For instance, to compare the grain-size distribution of a sample to its lognormal fit, the discrete Cumulative Density Function (CDF) is first calculated for both of them. Each quantile, Q5, Q10, …, Q95, Q100 is then compared individually in a plot. If the distributions are equal, the plotted points are aligned on a y=x line. In the case of the Urumqi data, this test was satisfied and the lognormal fit model was validated. Then, we used Monte Carlo simulations to calculate error bars for the distribution parameters.

As the Quaternary river evolution seems to be relatively synchroneous in the northeastern Tian Shan piedmont, deposit ages were estimated from ages of the geomorphic and stratigraphic features associated with nearby rivers (Poisson and Avouac, 2004; Charreau *et al.*, 2009; Lu *et al.*, 2010).

3.3 *The granulometric evolution of the river deposits*

At the sampling site, the studied fan, terrace and river-bed deposits display a clear granulometric evolution associated with the growth and incision of the Urumqi fan (Figure 9). The fan growth is recorded by a slight grain-size coarsening, which slows down through time. Then, the fan abandonment and early incision are contemporaneous with a strong and sharp grain-size coarsening. Finally, the subsequent incision is associated with a rapid grain-size fining, which seems to accelerate through time.

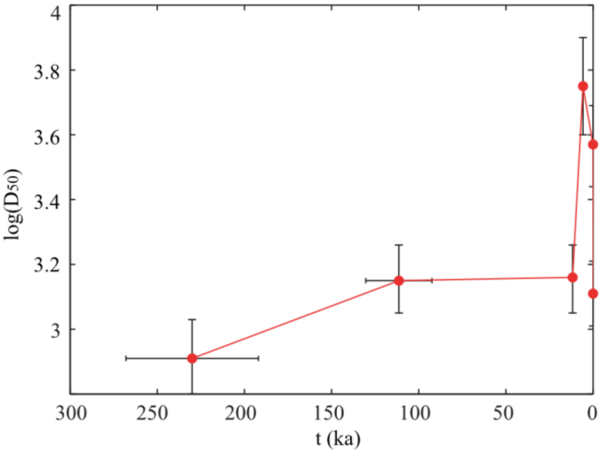

Figure 9 Mean grain-size evolution of the Urumqi deposits through time. The grain sizes are determined by Wolman surface count samplings. Ages are indicative only as they are estimated from ages of the geomorphic and sedimentologic features associated with nearby rivers (Poisson and Avouac, 2004; Charreau *et al.*, 2009)

Thus, the fan progradation during the last glacial period and forced progradation at the glacial-interglacial transition produce a clear granulometric signal. Furthermore, one can notice that this granulometric evolution is in good agreement with the progradation dynamics observed in experiments. Indeed, the grain-size coarsening contemporaneous of the fan growth is not linear in time as it progressively slows down. This example therefore shows that granulometric studies could be a good manner to approach fan dynamics and, we hope, transport conditions.

4 CONCLUSIONS

Based on a set of preliminary experiments, we show that fan aggradation is a local and short-term process, whereas fan progradation is a more long-term and regional one. These space and time behaviours should be taken into account to interpret any data set on alluvial fan deposits. Nevertheless, the progradation rate seems to be a good proxy to reconstruct the overall fan dynamics as progradation is clearly related to time through a power law. In fact, this relation is probably a direct consequence of the fan development at a given sediment supply. When a fan grows, its area increases and the sediment must be spread out on a wider surface, leading to a deacreasing progradation through time if the sediment flux is constant. Based on this experimental result, it should be possible to set up a conceptual framework to differentiate fan progradation related to fan expansion or not (*e.g.*, when fans with a steady size move forelandward at the front of a growing mountain chain).

The field measurements performed on the Quaternary deposits of the Urumqi River shows that it is possible to observe a progradation rate lowering associated with a natural fan growth, and to document and quantify this lowering on a single vertical section using a granulometric approach. This example shows that granulometric studies could be a good manner to characterize the long-term and regional fan dynamics and, we hope soon, the associated transport conditions. Moreover, on the basis of a more detailed analysis, local and short-term variations could also be observed and related to aggradation and avulsion. Finally, a series of experiments with different sedimentation rates should be planed to reinforced this preliminary work.

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