Denudation intensity and control in the Chinese Tian Shan: new constraints from mass balance on catchment-alluvial fan systems
Laure Guerit, Laurie Barrier, Marc Jolivet, Bihong Fu, François Métivier

To cite this version:

HAL Id: insu-01249993
https://hal-insu.archives-ouvertes.fr/insu-01249993

Submitted on 6 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Denudation intensity and control in the Chinese Tian Shan: new constraints from mass balance on catchment-alluvial fan systems

Laure Guerit,1,2* Laurie Barrier,1 Marc Jolivet,3 Bihong Fu4 and François Métivier1

1 Institut de Physique du Globe de Paris, Sorbonne Paris Cité, Université Paris Diderot, UMR 7154 CNRS, F-75005 Paris, France
2 Department of Earth Science, University of Geneva, 1205 Geneva, Switzerland
3 Université Rennes 1, Laboratoire Géosciences Rennes, UMR6118 CNRS/INSU, Campus de Beaulieu, 35042 Rennes, France
4 State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, China

Received 12 May 2015; Revised 26 November 2015; Accepted 7 December 2015

*Correspondence to: Laure Guerit, Department of Earth Science, University of Geneva, 1205 Geneva, Switzerland. E-mail: laure.guerit@unige.ch

ABSTRACT: Tectonics and climate are usually seen as the main controlling factors of denudation rates, which seem to rise with the tectonic activity and to decrease when the climate becomes drier. However, the low denudation rates observed in semi-arid to arid contexts are generally measured on orogenic plateaus where the respective influence of the flat relief and the dry climate cannot really be unravelled. The Chinese Tian Shan was chosen as a case study. In the northern piedmont of this mountain range, a series of well-preserved Quaternary alluvial fans offer the opportunity to perform a mass balance study at the scale of several catchment areas and several hundreds of thousands of years. Based on a geometrical reconstruction of these fans, the volumes of sediments exported out of 10 drainage basins during the Middle–Late Pleistocene (from ~300 to ~12 kyr) and the Holocene (from ~12 kyr to present) have been estimated. From these volumes, an average denudation rate of ~135 m/Myr was determined in the Tian Shan Range for the last 300 kyr. In agreement with other mass balances performed in the same area, the typical denudation intensity of the northern Tian Shan is thus of a few hundred meters per million years at most, regardless of the space and time scales considered. From a comparison with denudation rates in other mountain ranges throughout the world, we suggest that a dry climate can dramatically limit the denudation intensity even in active orogenic systems with a high topographic gradient like the Tian Shan. As a result, the time required to reach equilibrium between denudation and rock uplift in these systems could be extremely long (i.e. of more than several million years). Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS: denudation; mass balance; alluvial fan; Tian Shan; climate

Introduction

Denudation is a key process for mountain range evolution and the quantification of denudation rates is crucial to better constrain topography dynamics and mass transfer in orogenic systems (e.g. Molnar and England, 1990; Métivier et al., 1999; Kirchner et al., 2001; Farias et al., 2008; Simoes et al., 2010), as well as interactions between erosion, tectonics and climate (e.g. Raymo and Ruddiman, 1992; Avouac and Burov, 1996; Whipple, 2009; Iafaldano et al., 2011).

These two forcings are usually seen as the main controlling factors of the denudation intensity (e.g. Riebe et al., 2001; Zhang et al., 2001; Vance et al., 2003; Binnie et al., 2010), but their respective influences depend strongly on the studied areas. Tectonics can be the dominant control (e.g. Riebe et al., 2001; Burbank et al., 2003; von Blanckenburg, 2005; Herman et al., 2010) or climate (e.g. Reiners et al., 2003; Grujic et al., 2006; Clift et al., 2008), and in some contexts it is not possible to determine the prevalence of one or the other (e.g. Dadson et al., 2003; Clift, 2006). Nonetheless, two trends seem to emerge from the existing data compilations (Wittmann et al., 2007; Matmon et al., 2009; Covault et al., 2013): denudation rate rises with the tectonic activity whereas it decreases when the climate becomes more arid. However, studies in semi-arid to arid contexts mostly focused on orogenic plateaus, such as the Tibet or Andes interiors (e.g. Lal et al., 2004; Chappell et al., 2006; Kober et al., 2007; Kong et al., 2007; Hippe et al., 2012). Yet low denudation rates could also be linked to flat relief (e.g. Summerfield and Hulton, 1994; Montgomery and Brandon, 2002; Carretier et al., 2013), hence the climatic control cannot really be asserted on plateaus. Very few studies have quantified denudation in orogenic systems where precipitations are less than 500 mm/yr but with strong topographic gradient (Ali et al., 2003; Pan et al., 2010) and there is still a clear need to document denudation in such ranges.

Denudation rates are often determined by thermochronology (e.g. Bullen et al., 2003; Dadson et al., 2003; Grujic et al., 2006; Jolivet et al., 2007, 2013a), cosmogenic isotopes (e.g. Brown et al., 1995; Granger et al., 1996, von Blanckenburg, 2005; Charreau et al., 2011), or mass balances (Hinderer, 2012, and references therein). The mass balance
studies usually consist of sediment budgets from sedimentary basins or of sediment load measurements in present-day rivers (e.g. Métivier and Gaudemer, 1997; Gabet et al., 2008; Barnes and Heins, 2009; Liu et al., 2011; Calvés et al., 2013). These approaches face several issues. On one hand, sediment budgets from sedimentary basins provide long-term values averaged over large areas. On the other hand, sediment load measurements give short-term values specific to the sampling location. Unless there is evidences that measurements can be extended over the whole drainage basin, huge field sampling efforts are then necessary to have a general view of the sediment budget within a complete river system.

Occasionally, mass balance is also performed on catchment–fan systems (Kiefer et al., 1997; Oguchi, 1997; Allen and Hovius, 1998; Jayko, 2005; Hornung et al., 2010; Jolivet et al., 2014). They cover intermediate scales that are complementary to those of other sediment budget approaches, both in space and time (Hinderer, 2012). In fact, catchment–fan mass balances offer a better spatial resolution than sediment budgets from sedimentary basins. They are also more integrative in space and time, and they are easier to implement than sediment load measurements. For these reasons, catchment–fan sediment budgets are of great interest in discussing the evolution of denudation in space and/or time in a given area. However, the characteristic denudation intensity in a region over different time scales can only be determined if all these methods are used together (e.g. Kirchner et al., 2001; Dadson et al., 2003; Matmon et al., 2003).

The Chinese Tian Shan Range is a high mountain belt located in Central Asia (Figure 1a) in a semi-arid to arid climate and it was chosen as a case study. On its northern side, which rises from 600 m a.s.l. up to more than 5000 m a.s.l., denudation rates have already been estimated by several methods, at different space and time scales (Métivier and Gaudemer, 1997; Charreau et al., 2011; Liu et al., 2011; Puchol, 2013; Jolivet et al., 2014). In this area, the piedmont is formed by a series of exceptionally well-preserved Quaternary alluvial fans (Avouac et al., 1993; Poisson, 2002; Lu et al., 2010). They are located at the transition between the catchment areas and the sedimentary foreland basin, which is a strategic position to record the denudation history of the range. Moreover, rivers have deeply incised the old fans, whose basal surfaces are presently visible in outcrop. These fans offer the opportunity to improve the existing denudation data of the mountain range by a mass balance at intermediate space and time scales (several drainage basins and several hundred of thousands years).

In this paper, the methodology and results of this mass balance are presented, before discussing the denudation intensity and controls in the northern Tian Shan. From a comparison with denudation rates in other ranges, we suggest that dry climatic conditions strongly limit the denudation magnitude even in ranges where the topographic gradient is high, notwithstanding the tectonics activity.

**Geological Setting**

The Tian Shan is an east–west, 2500 km long, and up to 7400 m high, mountain belt that extends over western China, Kazakhstan and Kyrgyzstan (Figure 1a). After a complex Palaeozoic and Mesozoic orogenic history (e.g. Windley et al., 1990; Allen et al., 1992; Hendrix et al., 1992; Gao et al., 1998; Zhou et al., 2001; Jolivet et al., 2010, 2013b), the Tian Shan was reactivated during the Cenozoic in response to the India–Asia collision (e.g. Taponnier and Molnar, 1977; Avouac et al., 1993; Hendrix et al., 1994; Dumitru et al., 2001; Charreau et al., 2009a; Jolivet et al., 2010). Today, the range is still active, with a mean GPS shortening rate of up to ~2 cm/yr (Abrashkhatov et al., 1995; Reigber et al., 2001; Zolovovich et al., 2010). In its Chinese part, the northern side of the range is separated from the Junggar foreland basin by three series of east–west oriented fault propagation folds (Figure 1b). A major thrust zone generally separates this faulted and folded piedmont from the exhumed basement that forms the high range (Avouac et al., 1993; Burchfiel et al., 1999; Guan et al., 2009; Lu et al., 2010; Chen et al., 2014). In the piedmont, the slope rarely exceeds 25°, but it rises up to 40° in the range (Figure 1c).

Over the whole Cenozoic, the regional climate oscillated between semi-humid and semi-arid periods (Molnar et al., 1994; Rhodes et al., 1996; Yi et al., 2004; Poisson and Avouac, 2004; Gallaud, 2008; Sun and Zhang, 2008; Xu et al., 2010), and for the last 550 kyr several phases of glacial advances have been recorded in relation to the global glacial–interglacial cycles (Zhao et al., 2009). The last major deglaciation occurred about 12 kyr ago and was followed by a period of more abundant precipitations (Rhodes et al., 1996; Poisson and Avouac, 2004). However, since 6 kyr, the region has become increasingly arid. Nowadays, the regional climate is continental and semi-arid, influenced by the Westerlies and the Asian monsoon. Precipitation is typically less than 250 mm/yr in the northern piedmont (from 250 mm/yr around the city of Urumqi to less than 100 mm/yr in the West), and rises up to 300–400 mm/yr in the range (Métivier and Gaudemer, 1997; Poisson, 2002; Sobel et al., 2003).

In China, a dozen large rivers drain the northern side of the range (Figure 1b). They originate from glaciers in the hinterland mountains at an elevation of ~4000 m a.s.l. and flow northwards to the Junggar Basin, located about 3300 m below. In the piedmont, these rivers have built and incised several alluvial fans (Avouac et al., 1993; Poisson, 2002; Lu et al., 2010) (Figure 2). At least three sequences of fan growth, followed by abandonment and incision (Figure 2), occurred over the last 550 kyr (Zhou et al., 2002; Lu et al., 2010). The last abandonment–fan growth sequence initiated about 12 kyr ago during the last deglaciation (Avouac et al., 1993; Poisson, 2002; Poisson and Avouac, 2004; Lu et al., 2010; Gong et al., 2014). According to optically stimulated luminescence, electron spin resonance, ¹⁸Be and ¹⁴C dating, the alluvial fans abandoned at that time (called F3 in Lu et al. (2010) and F₃ in this study, see Table I for term definitions) are Middle–Late Pleistocene in age, as they were active between ~300 kyr and ~12 kyr for a total period of 277 ± 30 kyr (Molnar et al., 1994; Poisson, 2002; Poisson and Avouac, 2004; Lu et al., 2010; Yang et al., 2013; Gong et al., 2014). These fans are now deeply incised by up to 300 m deep canyons carved by the rivers (the KMZ coordinates of the river paths are given in Supplementary Data SA – supporting information) during the Holocene. As a consequence, the F₃ fan basal surface is sometimes visible along the cliffs surrounding active river channels (Figures 2b and 3). Contemporaneous with this incision, a new generation of fans formed downstream in the Junggar Basin. These fans (called F4 in (Lu et al., 2010) and F₄ in this study) are Holocene in age and have been active for a period of 11.3 ± 2.3 kyr (Poisson and Avouac, 2004; Lu et al., 2010). Remains of older fans exist in the region (F1 and F2 in Lu et al., 2010), but this study focuses on the two last generations only.

All the catchment–fan systems of the northern side of the Chinese Tian Shan exhibit similar and probably coeval fan systems and canyons, which developed during the last glacial and interglacial periods (Molnar et al., 1994; Poisson, 2002; Poisson and Avouac, 2004; Lu et al., 2010; Gong et al.,
Moreover, the locations of the river incisions generally do not correlate with active tectonic structures. For example, along the ~40 km long Kuitun River canyon, tectonic uplift affects a zone of ~5 km in length, which is known as the Dushanzi anticline. It has been shown by Poisson (2002) and Poisson and Avouac (2004) that this anticline cannot account for more than 10% of the local incision. Consequently, the fan aggradation–incision cycle is climate-driven and linked to changes in water and/or sediment discharges (Poisson, 2002; Poisson and Avouac, 2004).

Finally, the fans \( F_p \) and \( F_h \) are made up by conglomerates with grains from silts to metric boulders, with a porosity of 20 ± 10% (Clarke, 1979; Guerit, 2014). The Urumqi River is the only river where the sediment transport is quantitatively documented. Measurements in the upper part of its catchment show that 17.3 ± 0.3% of the material is transported as bedload, 35.2 ± 6.7% as suspended load and 47.5 ± 6.5% as dissolved load (Liu et al., 2011). Based on the morphological similarities between the catchment–fan systems in northern Chinese Tian Shan, we assumed that these ratios are identical along the whole river path and through time, for all the studied systems.

### Data and Methodology

The objective of this study was, first, to determine the volume of sediments that have been exported out of the drainage basins and deposited in the fans \( F_p \) and \( F_h \), and secondly, to convert these volumes into denudation rates for the Middle–Late Pleistocene (from ~300 kyr to ~12 kyr) and the Holocene (from ~12 kyr to present).

In order to reconstruct the sediment volumes, two morpho-sedimentary maps of the northern side of the Chinese Tian Shan were drawn to locate accurately the Middle–Late Pleistocene and Holocene alluvial fans and their catchment areas based on satellite images (Landsat and Digital Globe...
Figure 2. Morphology in cross-section of the northern Chinese Tian Shan piedmont (a) at the end of the Pleistocene and (b) nowadays, after the incision of the Middle–Late Pleistocene fans. The basal surface of these fans is now exposed along the cliffs surrounding active river channels. This figure is available in colour online at www.interscience.wiley.com/journal/espl.

Figure 3. Outcrops of Middle–Late Pleistocene fan basal surfaces along the (a) Guertu, (b) Anjihai, (c) Hutubi and (d) Urumqi rivers. These basal surfaces (white dash lines) are emphasized by a contrast in (a, b, c, d) colour, and (a, b) lithology between the dark-grey deposits of the Pleistocene fans and the older terrains. In the presented examples, these terrains correspond to (a) Paleozoic bedrock, (b) Tertiary orange silts, sandstones and conglomerates, and (c, d) Tertiary and Quaternary light-grey conglomerates. The cliffs are a few dozen (d) up to a few hundred (b) metres high. This figure is available in colour online at www.interscience.wiley.com/journal/espl.

Morpho-sedimentary maps of the catchment–fan systems

Several morpho-sedimentary maps of the region are available, but the different data used and the variety of purposes have led to inconsistencies between these published documents (Avouac et al., 1993; Poisson, 2002; Graveleau, 2008; Charreau et al., 2009b; Lu et al., 2010). In particular, the extension of fans and drainage basins differ from one map.
to another, and the distinction between the Pleistocene and Holocene features (fans, canyons) is not always considered. In addition, these documents mostly focus on the central part of the piedmont only. Therefore, to perform a study on the whole piedmont and to accurately locate the outlines of the fans $F_p$ and $F_h$ and their respective catchment areas, two new morpho-sedimentary maps based on satellite images, digital elevation model and field observations were drawn. One concerns the Late Pleistocene landscape (Figure 4) and the other one the present-day landscape (Figure 5). The map construction and uncertainties are detailed in Appendix A. These maps enabled the extraction of the drainage basins and fan outlines for the two periods (KMZ coordinates given in Supplementary Data S2, S3, S4 and S5) and their areas (Tables II and III). Note that in this study only the 10 catchment–fan systems for which the position of the basal surface of the fans $F_p$ could be identified in the field were considered.

### Volumes of sediments

**Fan outlines**

Given their growth dynamics, the outlines of the fans $F_p$ and $F_h$ can be used to map the extent of both their top and basal surfaces. Outline elevations were extracted from the ASTER DEM (~10 m vertical resolution) with a point every meter, and interpolated when required (e.g. where fan outlines have been eroded or covered by other deposits). Finally, a sliding window over 10 m was applied to the dataset in order to filter the DEM noise.

**Fan top surfaces**

For the two fan generations, the top surface elevations were extracted from the ASTER DEM with a grid resolution of 250 m. Here again, data were interpolated to recover the original fan surface over the areas of the fan surface ‘damaged’ by posterior erosion and deposition, or by human land uses. Two different interpolation schemes (linear or cubic) were used in order to quantify the error associated with the interpolation method. The final fan top surface was then obtained on a 250 × 250 m model grid (Figure 6a, b).

Fan basal surfaces

The basal surfaces of the Middle–Late Pleistocene fans were reconstructed from field surveys along the river canyons. As explained above, the rivers of the northern Chinese Tian Shan have incised the fans $F_p$ during the Holocene. In the cliffs surrounding the streams, the $F_p$ basal surfaces are often identifiable, due to contrasts in sediment colour, lithology or dip between the fan deposits and older series (Figure 3). However, the further from the relief, the more difficult this identification as the contrasts become less and less marked (see Appendix B.1 for details on outcrop identification and data acquisition). Consequently, the $F_p$ basal surface outcrops were mostly identified close to the fan apexes or to the anticlines in the piedmont (Figure 7a, b; Data S6). The $F_p$ basal surfaces were modelled from this dataset on the basis of two hypothesis. First, in agreement with field observations (Figure 3b), we considered that the basal surfaces are parabolic in transverse cross-section (Figure 7c). Then, we assumed that the basal surfaces are regular between two points and that there is no major tectonic or topographic structure hidden underneath the fans (Figure 7d). Finally, the interpolation methods presented for the top surface reconstruction were used to model the fan basal surfaces over 250 × 250 m model grids (Figure 6d).

Fan and sediment volumes

Fan thickness maps were built as the difference in elevation between the reconstructed top and basal surfaces of the fans. The thickness on each cell, $h$, was defined as the mean value

### Table 1. Terms and definitions used in this study

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_p$</td>
<td>Middle–Late Pleistocene fans</td>
</tr>
<tr>
<td>$F_h$</td>
<td>Holocene fan.</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Areas of the fans $F_p$</td>
</tr>
<tr>
<td>$A_h$</td>
<td>Areas of the fans $F_h$</td>
</tr>
<tr>
<td>$A_{PL}$</td>
<td>Areas of the Middle–Late Pleistocene drainage basins</td>
</tr>
<tr>
<td>$A_h$</td>
<td>Areas of the Holocene drainage basins</td>
</tr>
<tr>
<td>$A_{H+PL}$</td>
<td>Areas of the Holocene extension of the drainage basins</td>
</tr>
<tr>
<td>$V_{f_p}$</td>
<td>Volumes of the fans $F_p$</td>
</tr>
<tr>
<td>$V_{f_h}$</td>
<td>Volumes of the fans $F_h$</td>
</tr>
<tr>
<td>$V_{CAN}$</td>
<td>Volumes of the Holocene canyons dug into the piedmont</td>
</tr>
<tr>
<td>$V_{SP}$</td>
<td>Volumes of sediments in the fans $F_p$</td>
</tr>
<tr>
<td>$V_{S_h}$</td>
<td>Volumes of sediments in the fans $F_h$</td>
</tr>
<tr>
<td>$V_{ST}$</td>
<td>Volumes of sediments removed from the Holocene canyons</td>
</tr>
<tr>
<td>$V_{ST_{H+PL}}$</td>
<td>Differences between the volumes of sediments trapped in the fans $F_h$ and removed from the Holocene canyons</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Sediment porosity (20 ± 10%)</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Fraction of the total river load trapped in fans (17.3 ± 0.3%)</td>
</tr>
<tr>
<td>$p_p$</td>
<td>Period of $F_p$ fan construction (277 ± 30 kyr)</td>
</tr>
<tr>
<td>$p_h$</td>
<td>Period of $F_h$ fan construction (11.3 ± 2.3 kyr)</td>
</tr>
<tr>
<td>$\epsilon_p$</td>
<td>Middle–Late Pleistocene denudation rates</td>
</tr>
<tr>
<td>$\epsilon_h$</td>
<td>Holocene total denudation rates</td>
</tr>
<tr>
<td>$\epsilon_{sp}$</td>
<td>Holocene denudation rates in the piedmont</td>
</tr>
<tr>
<td>$\epsilon_{sr}$</td>
<td>Holocene denudation rates in the range</td>
</tr>
</tbody>
</table>
obtained by the two interpolation methods. The total volume of a fan, \( V_F \), was calculated by the addition of the individual volumes of each cell (Tables II and III; Figure 6e, f). The volume of sediments trapped in fans, \( V_{\lambda F} \), is then the volume \( V_F \) corrected for the porosity of the deposits \( \lambda \) (Tables II and III; see Appendix B.2 for details on the volume reconstruction and uncertainties). As the simplest geometry was used to reconstruct the \( F_p \) basal surfaces (i.e. a sharp transition between the \( F_p \) fan and plain slopes), Holocene volumes correspond to maximum estimates.

From sediment volumes to denudation rates

The denudation rate, \( \epsilon \), of a given area was calculated from the volume of sediments trapped in the associated fan \( V_{\lambda F} \) through a simple mass conservation law:

\[
\epsilon = \frac{V_{\lambda F}}{\alpha \times A_d \times P}
\]

where \( \alpha \) is the proportion of river sediment load trapped in the fan, \( A_d \) is the drainage basin area of interest, and \( P \) is the
implies that the reconstructed volumes of the canyons are rectangular and did not include the uppermost terraces. This consequence, the denudation rates assessed in this study for the Late Pleistocene ones), and the incision duration, $P$, in years. The same process of incision and reworking could have happened when the fans older than the Middle–Late Pleistocene were also subtracted from the volumes of sediments trapped in the fans $V_{f_l}$, in order to estimate the remaining volumes of sediments, $V_{f_l}-V_{f_l-c}$, coming from upstream. Once corrected for the sediment partitioning, these volumes were used to calculate the denudation rates of the long-standing parts of the catchment areas.

The same process of incision and reworking could have happened when the fans older than the Middle–Late Pleistocene ones were abandoned, but no information exists on that point. Accordingly, the volumes of sediments trapped in the fans $F_p$ should be considered as maximum estimates. Similarly, the volumes of sediments trapped in the fans $F_p$ and the volumes exported from the Holocene canyons are respectively maximized and minimized due to the geometric simplifications. In consequence, the denudation rates assessed in this study for both periods correspond to maximum values.

**Table II.** Morpho-sedimentary parameters of the Middle–Late Pleistocene catchment–fan systems. $A_p$ is the catchment area, $A_f$ the fan area, $V_f$ the fan volume, and $V_{f_l}$ the volume of sediments trapped in the fan. $\Delta$ are the uncertainties associated with each parameter.

<table>
<thead>
<tr>
<th>River</th>
<th>$A_p$ (km²)</th>
<th>$\Delta A_p$ (km²)</th>
<th>$A_f$ (km²)</th>
<th>$\Delta A_f$ (km²)</th>
<th>$V_f$ (km³)</th>
<th>$\Delta V_f$ (km³)</th>
<th>$V_{f_l}$ (km³)</th>
<th>$\Delta V_{f_l}$ (km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guertu</td>
<td>1056</td>
<td>8</td>
<td>419</td>
<td>4</td>
<td>13</td>
<td>0.7</td>
<td>10.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Kuitun</td>
<td>1926</td>
<td>14</td>
<td>597</td>
<td>7</td>
<td>29.2</td>
<td>0.6</td>
<td>23.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Anjihai</td>
<td>1340</td>
<td>10</td>
<td>471</td>
<td>4</td>
<td>14.4</td>
<td>0.6</td>
<td>11.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Jingou</td>
<td>1321</td>
<td>10</td>
<td>336</td>
<td>4</td>
<td>6.4</td>
<td>0.4</td>
<td>5.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Manas</td>
<td>5356</td>
<td>40</td>
<td>381</td>
<td>4</td>
<td>9.1</td>
<td>0.2</td>
<td>7.3</td>
<td>0.9</td>
</tr>
<tr>
<td>Taxi</td>
<td>632</td>
<td>5</td>
<td>141</td>
<td>2</td>
<td>3.2</td>
<td>0.0</td>
<td>2.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Hutubi</td>
<td>2150</td>
<td>16</td>
<td>480</td>
<td>5</td>
<td>15.7</td>
<td>0.6</td>
<td>12.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Santun</td>
<td>1996</td>
<td>15</td>
<td>416</td>
<td>5</td>
<td>8.3</td>
<td>0.3</td>
<td>6.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Toutun</td>
<td>1597</td>
<td>12</td>
<td>264</td>
<td>2</td>
<td>7.7</td>
<td>0.1</td>
<td>6.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Urumqi</td>
<td>1115</td>
<td>8</td>
<td>323</td>
<td>2</td>
<td>5.2</td>
<td>0.1</td>
<td>4.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Average</td>
<td>1850</td>
<td>14</td>
<td>383</td>
<td>4</td>
<td>11.2</td>
<td>0.4</td>
<td>9.0</td>
<td>1.2</td>
</tr>
</tbody>
</table>

**Table III.** Morpho-sedimentary parameters of the Holocene catchment–fan systems. $Q_w$ is the present-day river average annual discharge, $A_p$ the catchment area, $A_f$ the fan area, $V_f$ the fan volume and $V_{f_l}$ the volume of sediments trapped in the fan. $\Delta$ are the uncertainties associated with each parameter.

<table>
<thead>
<tr>
<th>River</th>
<th>$Q_w$ (m³/s)</th>
<th>$A_p$ (km²)</th>
<th>$\Delta A_p$ (km²)</th>
<th>$A_f$ (km²)</th>
<th>$\Delta A_f$ (km²)</th>
<th>$V_f$ (km³)</th>
<th>$\Delta V_f$ (km³)</th>
<th>$V_{f_l}$ (km³)</th>
<th>$\Delta V_{f_l}$ (km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guertu</td>
<td>/</td>
<td>1111</td>
<td>8</td>
<td>45</td>
<td>1</td>
<td>0.4</td>
<td>0.1</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Kuitun</td>
<td>20</td>
<td>2049</td>
<td>15</td>
<td>98</td>
<td>1</td>
<td>2.4</td>
<td>0.3</td>
<td>1.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Anjihai</td>
<td>9.8</td>
<td>1512</td>
<td>11</td>
<td>189</td>
<td>2</td>
<td>3.6</td>
<td>0.5</td>
<td>2.9</td>
<td>0.7</td>
</tr>
<tr>
<td>Jingou</td>
<td>10.2</td>
<td>1906</td>
<td>14</td>
<td>133</td>
<td>1</td>
<td>2</td>
<td>0.3</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Manas</td>
<td>40.5</td>
<td>5594</td>
<td>42</td>
<td>182</td>
<td>1</td>
<td>1.8</td>
<td>0.2</td>
<td>1.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Taxi</td>
<td>7.2</td>
<td>782</td>
<td>6</td>
<td>46</td>
<td>1</td>
<td>0.7</td>
<td>0.1</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Hutubi</td>
<td>15.1</td>
<td>2275</td>
<td>17</td>
<td>102</td>
<td>1</td>
<td>1.1</td>
<td>0.1</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Santun</td>
<td>9.9</td>
<td>2250</td>
<td>17</td>
<td>57</td>
<td>1</td>
<td>0.6</td>
<td>0.0</td>
<td>0.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Toutun</td>
<td>7.4</td>
<td>1701</td>
<td>13</td>
<td>43</td>
<td>1</td>
<td>1</td>
<td>0.0</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>Urumqi</td>
<td>7.5</td>
<td>1318</td>
<td>10</td>
<td>102</td>
<td>1</td>
<td>1.2</td>
<td>0.1</td>
<td>1.0</td>
<td>0.2</td>
</tr>
<tr>
<td>Average</td>
<td>14.2</td>
<td>2050</td>
<td>15</td>
<td>100</td>
<td>1</td>
<td>1.5</td>
<td>0.2</td>
<td>1.2</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Results

Morpho-sedimentary characteristics of the catchment–fan systems

The two morpho-sedimentary maps (Figures 4 and 5) focus on the 10 catchment–fan systems for which the basal surface of the Middle–Late Pleistocene fans $F_p$ could be identified in the field, namely from west to east: the Guertu, Kuitun, Anjihai, Jingou, Manas, Taxi, Hutubi, Santun, Toutun and Urumqi systems (called after the main stream names given in Zhou et al., 1999). These maps display features of the Late Pleistocene and present-day landscapes in the studied area, namely the fans $F_p$ and $F_h$, and the associated catchment areas with their long-standing part and their recent extension (Figures 4 and 5). In addition to the catchment–fan system outlines, the
sequently, the Holocene drainage basins are larger than the Middle–Late Pleistocene ones, ranging from 782 ± 6 km² for the Taxi system to 5594 ± 42 km² for the Manas one, with an average of 2050 ± 42 km² (Table III). The Holocene extensions of these drainage basins correspond to an increase in size of 4% for the Manas system and up to 44% for the Jingou one, with an average of 11% (Table IV).

Owing to the propagation of the erosion–sedimentation boundary down the river systems, the alluvial fans Fₜ are mostly located in the foreland basin at the toe of the fans Fₚ. Contrary to the catchment areas, the fans Fₜ are smaller than the fans Fₚ. Their areas range from 43 ± 1 km² for the Toutsun fan to 189 ± 2 km² for the Anjihai one, with an average of 100 ± 1 km² (Table III). In terms of volume, they contain between 0.3 ± 0.1 and 2.9 ± 0.7 km³ of sediments (for the Guertu and Anjihai fans, respectively) with an average volume of 1.2 ± 0.3 km³ (Table III). In these fans, the sediment thickness is maximal at the slope break between the fans Fₚ and the downstream alluvial plain, with up to 90 m thick deposits (Figure S1).

During the Middle–Late Pleistocene, the drainage basins are mostly located in the hinterland mountains. Their areas range from 632 ± 5 km² for the Taxi catchment–fan system to 5356 ± 40 km² for the Manas one, with an average of 1850 ± 14 km² (Table II). The associated alluvial fans Fₚ are located both in the piedmont and the foreland basin, and their areas range from 141 ± 2 km² for the Taxi system to 597 ± 7 km² for the Kuitun one, with an average of 382 ± 4 km² (Table II). In terms of volume, these fans store between 2.6 ± 0.3 and 23.4 ± 2.8 km³ of sediments (for the Taxi and Kuitun fans, respectively), with an average volume of 9.0 ± 1.2 km³ (Table II). In most cases, their thickness is maximal at their apex, with up to 120 m thick deposits (Figure S1).

During the Holocene, the catchment areas expanded in the piedmont due to the downstream propagation of an erosion wave triggered by changes in water and/or sediment discharges (Poisson, 2002; Poisson and Avouac, 2004). Consequently, the Holocene drainage basins are larger than the topographic and deformation fronts as well as the main folds are indicated.

The Holocene fans, their thickness is maximal at their apex, with up to 120 m thick deposits (Figure S1).
Denudation rates

During the Middle–Late Pleistocene

The Middle–Late Pleistocene denudation rates, $\epsilon_p$, were calculated as

$$\epsilon_p = \frac{V_{\lambda p}}{\alpha \times A_{\lambda p} \times P_p}$$

$p$ referring to the Middle–Late Pleistocene values estimated from the morpho-sedimentary maps and from the literature (see ‘Data and Methodology’, above). These denudation rates range from $30 \pm 10$ m/Myr for the Manas system to $250 \pm 60$ m/Myr for the Kuitun one, with an average value of $100 \pm 30$ m/Myr for the Kuitun one, with an average value (yellow line) of $170 \pm 110$ m/Myr (Table V and Figure 9). One may notice that $\epsilon_p$ varies within almost a factor of 10 between the different drainage basins.

During the Holocene

The total denudation rates for the Holocene, $\epsilon_h$, were calculated as follows:

$$\epsilon_h = \frac{V_{\lambda h}}{\alpha \times A_{\lambda h} \times P_h}$$

$h$ referring to the Holocene values. These total rates range from $110 \pm 40$ m/Myr for the Santun system to $970 \pm 460$ m/Myr for the Anjihai one, with an average value of $300 \pm 130$ m/Myr (Table V and Figure 9). Here again, a factor of 10 is observed between the different rates. However, to discuss the evolution of the denudation rates from the Middle–Late Pleistocene to the Holocene, the denudation in the piedmont must be differentiated from the denudation in the mountain range.

The denudation rates in the piedmont, $\epsilon_c$, were calculated as the volumes of sediments removed from the canyons artificially spread over the Holocene extensions of the drainage basins:

$$\epsilon_c = \frac{V_{\lambda c}}{A_{\lambda c} \times P_h}$$

As these rates are calculated from eroded volumes and not from deposited ones, $\alpha$ is not required in this equation. Values range from $60 \pm 20$ m/Myr for the Taxi system to $1550 \pm 780$ m/Myr for the Kuitun one with, on average, $260 \pm 130$ m/Myr (Table V). On the other hand, considering the remaining volumes of sediments in the fans $F_p$ and the long-standing part of the drainage basins, the denudation rates in the range, $\epsilon_r$, were calculated as follows:

$$\epsilon_r = \frac{V_{\lambda F} - c}{\alpha \times A_{\lambda p} \times P_p}$$

These denudation rates range from $0$ m/Myr for the Guertu and Kuitun systems to $610 \pm 400$ m/Myr for the Anjihai one, with an average value of $170 \pm 110$ m/Myr (Table V and Figure 9).

The Holocene denudation in the piedmont results from sediment reworking linked to the river incision at the onset of the last deglaciation, which is a local and probable short-term contribution. The denudation in the range should be more representative of the regional and long-term rate and is therefore the relevant value to compare the Middle–Late Pleistocene and Holocene periods. It did not noticeably evolve through time, with average values weighted by the drainage areas of $100 \pm 30$ m/Myr and $170 \pm 100$ m/Myr respectively (Figure 9).

Finally, these calculations lead to an average denudation rate of $\sim 135$ m/Myr for the northern Tian Shan for the last 300 kyr. Since the sediment volumes have systematically been maximized, this rate is a maximum estimate.

Discussion

Catchment–fan mass balance

Denudation rates issued from catchment–fan mass balances are subject to several sources of uncertainty. In addition to the volumes of sediments and areas of the drainage basins, the duration of fan construction $P$ and the fraction of the river sediment load trapped in the fans $\alpha$ must be determined. In most cases, the volumes and areas, as well as their uncertainties, can be accurately quantified. In this study, these uncertainties related to the geometry of the system are very small (less than 2%) and could have been neglected. In contrast, the values of $P$ and $\alpha$ are not so well constrained because they require strong field efforts and access to the whole drainage system to be characterized.

The published time constraints for the northern side of the Chinese Tian Shan are scarce compared to the number and size of the fans (Molnar et al., 1994; Poisson, 2002; Poisson and Avouac, 2004; Lu et al., 2010; Yang et al., 2013; Gong et al., 2014). Yet the fan onset and abandonment seem to vary across space from a few thousand years and it would be important to quantify better this variability because of its potential impact on denudation rate assessment. For the Holocene, a variation of a few thousand years over $P_h$ ($\sim 11.3$ kyr) would imply a drop or rise of the denudation rates by a factor of up to 2. On the contrary, for the Middle–Late Pleistocene, this variability has no major impact on the determination of the denudation rates as it is an order of magnitude smaller than $P_p$ ($\sim 277$ kyr).

The sediment partitioning, which is quite difficult to estimate, is the other main critical parameter in such mass balance studies. In this work, we considered that the alluvial fans are built by the deposition of the entire bedload. The only data available in the region were used to define the fraction of sediments transported as bedload ($\sim 17\%)$ compared to the total river load (Liu et al., 2011). As the potential variation from
one basin to another could not be quantified, uncertainty on this ratio relates to measurements only. However, other studies on gravel-bed rivers indicate that the bedload can represent 10–50% of their total load (Lane and Boland, 1951; Meunier et al., 2006; Schieler et al., 2010). With such ratios, the average denudation rate of the northern Tian Shan since 300 kyr could be between 50 and 230 m/Myr. It is also possible that fans are built by a fraction of the total load that does not correspond exactly to the entire bedload. Studies on sediment partitioning in alluvial systems suggest that 25–80% of the solid load of a river can be deposited in alluvial fans (Kiefer et al., 1997; Oguchi, 1997; Jolivet et al., 2014). In the Urumqi River, the solid load represents ~53% of the total load (Liu et al., 2011). Extrapolating this ratio to the other rivers of the piedmont implies that the fans could have trapped ~12–38% of the total load. With such ratios, the average denudation rate could be between 60 and 200 m/Myr.

Further work is thus strongly required to determine better the sediment transport and partitioning in alluvial systems. Yet, in the northern Tian Shan, the values discussed previously show that the average denudation rate cannot exceed a few hundreds of metres per million years for the last 300 kyr.

Denudation in the northern Chinese Tian Shan

At a local scale, the catchment–fan mass balances show that the denudation rate varies from one drainage basin to another (Figure 9) but it is difficult to understand what controls this variability. It could result from changes in space of the forcing factors, but the potential variations of tectonic and climatic conditions over the studied area are not known. Therefore, their influence on the denudation variability cannot be discussed. Instead, the relationship between denudation rates and some geomorphologic characteristics of the drainage basins can be studied, such as the drainage area, mean elevation, mean slope and channel steepness index. These parameters are generally considered as proxies in a broad way for sediment production and transport (e.g. Ahnert, 1970; Summerfield and Hulton, 1994; Hovius, 1998; von Blanckenburg, 2005). However, the correlation between denudation rates and basin morphometrics in the northern Tian Shan is poor (Figure S3). Such a scattering could be due to differences in bedrock properties (e.g. in lithology, fracturing, dip, foliation) and erodibility, vegetation cover, glacial processes and/or sediment transport efficiency (e.g. de Vente et al., 2007; Insel et al., 2010; Norton et al., 2011; Torres Acosta et al., 2015). In the studied area, these factors are likely to vary from one drainage basin to another with, for example, different proportions of Palaeozoic igneous rocks, Palaeozoic carbonates and Meso-Cenozoic clastic sediments affected by a more or less complex tectonic history. Vegetation could also vary a lot with different proportions of bare rock/soils, herbaceous plants and trees that could influence the sediment production and transport. In addition, denudation rates could be influenced by glacial erosion or morphological heritage, as well as sediment storage that has been evidenced in the drainage basins (Li et al., 2001; Jolivet et al., 2014). Unfortunately, these basins are poorly accessible and all those factors are very difficult to quantify in this region. Finally, changes in sediment production, transport and deposition should also influence the sediment partitioning, and therefore, α might vary from one catchment area to another. The determination of this parameter for all the basins over the considered periods could be a way to assess whether or not differences in the parameters mentioned previously (e.g. lithology, vegetation) are the sources of the denudation variability. However, to date, there is no method to perform such measurement. Further work would be of interest to understand better what influence catchment–fan mass balance and the denudation rates at the local scale.

At a regional scale, the average denudation rate in the mountain range seems to be around 135 m/Myr for the last 300 kyr. This value is in good agreement with previous mass balance estimates performed at different scales (Figure 10). Using the same approach applied to one Holocene catchment–fan system and on the solid sediment load only, Jolivet et al. (2014) suggest a rate lower than 100 m/Myr for the last 12 kyr. From a sediment budget over the whole Junggar basin, Métivier and Gaudemer (1997) propose a long-term regional denudation of ~40 m/Myr since 6 Myr. From sediment load measurements in one river during 2 years, Liu et al. (2011) determine a short-term and local denudation of ~20 m/Myr. Studies in the same area based on cosmogenic analysis point toward higher average values of 200 to 600 m/Myr for the last 8 Myr (Charreau et al., 2011; Puchol, 2013). However, cosmogenic concentrations are influenced by the distribution of the sources or of the samples in the drainage basin (nearby an active fault or a glacier), by the story of the sediment transport and also by a possible unsteady erosion that could lead to maximize denudation rates (Jolivet et al., 2014; Carretier et al., 2015). Finally, basement-derived fission track ages indicate

<table>
<thead>
<tr>
<th>River</th>
<th>εp (m/Myr)</th>
<th>Δεp (m/Myr)</th>
<th>εb (m/Myr)</th>
<th>Δεb (m/Myr)</th>
<th>εr (m/Myr)</th>
<th>Δεr (m/Myr)</th>
<th>εh (m/Myr)</th>
<th>Δεh (m/Myr)</th>
<th>εr (m/Myr)</th>
<th>Δεr (m/Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guertu</td>
<td>210</td>
<td>60</td>
<td>150</td>
<td>90</td>
<td>510</td>
<td>290</td>
<td>0</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kuitun</td>
<td>250</td>
<td>60</td>
<td>480</td>
<td>220</td>
<td>1550</td>
<td>780</td>
<td>0</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anjihai</td>
<td>180</td>
<td>50</td>
<td>970</td>
<td>460</td>
<td>660</td>
<td>330</td>
<td>610</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jingou</td>
<td>80</td>
<td>20</td>
<td>430</td>
<td>210</td>
<td>70</td>
<td>40</td>
<td>430</td>
<td>280</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manas</td>
<td>30</td>
<td>10</td>
<td>130</td>
<td>60</td>
<td>180</td>
<td>90</td>
<td>90</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taxi</td>
<td>80</td>
<td>20</td>
<td>370</td>
<td>170</td>
<td>50</td>
<td>20</td>
<td>390</td>
<td>180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hutubi</td>
<td>120</td>
<td>30</td>
<td>200</td>
<td>80</td>
<td>220</td>
<td>190</td>
<td>130</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Santun</td>
<td>70</td>
<td>20</td>
<td>110</td>
<td>40</td>
<td>60</td>
<td>20</td>
<td>80</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toutun</td>
<td>80</td>
<td>20</td>
<td>240</td>
<td>80</td>
<td>70</td>
<td>20</td>
<td>230</td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urumqi</td>
<td>80</td>
<td>20</td>
<td>370</td>
<td>150</td>
<td>210</td>
<td>100</td>
<td>220</td>
<td>130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>100</td>
<td>30</td>
<td>300</td>
<td>130</td>
<td>260</td>
<td>130</td>
<td>170</td>
<td>110</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
that the northern Tian Shan (Borohoro range) rose between 15 and 10 Ma ago (Dumitru et al., 2001; Jolivet et al., 2010). Considering a maximum geothermal gradient of 30° C/km, these ages correspond to 4 km of rock exhumation, leading to an average erosion of 260–400 m/Myr for this period (Figure 10). However, erosion rates derived from apatite fission track data rely largely on the understanding of the geothermal gradient and the behaviour of the isotherms (i.e. their capacity to re-equilibrate) during tectonic deformation (e.g. Ehlers and Farley, 2003). In other words, the rates determined by cosmogenic and thermochronological methods in the Tian Shan might correspond to maximum possible values. Consequently, only the values determined by mass balances are considered in this study to determine the average denudation rate for this range. They all converge toward a few hundreds of metres per million years at maximum regardless of the space or time scale.

Influence of tectonics and climate

For the whole northern side of the Tian Shan (range and piedmont), the average denudation rate rises from ~100 m/Myr during the Middle–Late Pleistocene to ~300 m/Myr during the Holocene (Table V and Figure 9). This increase is a direct consequence of the downstream extension of the catchment areas associated with sediment reworking due to the last glacial-interglacial transition (Molnar et al., 1994; Poisson, 2002; Poisson and Avouac, 2004; Lu et al., 2010; Gong et al., 2014). Over the last 300 kyr, the evolution of the sediment fluxes from the Tian Shan to the Junggar Basin is thus clearly climate-driven, as observed in other places at the same period (Church and Ryder, 1972; Church and Slaymaker, 1989; Delmas et al., 2015). However, once corrected for this sediment recycling, the average denudation rates in the long-standing part of the drainage basins are quite similar for the two periods (~100 and ~170 m/Myr). The consistency between these rates and those previously published (Métivier and Gaudemer, 1997; Charreau et al., 2011; Liu et al., 2011; Puchol, 2013; Jolivet et al., 2014) suggests that the pulse observed at the onset of the Holocene is a local and transient feature associated with a major morphological evolution that did not affect the denudation of the hinterland mountains (see also; Jolivet et al., 2014).

As mentioned previously, an average rate of a few hundred metres per million years seems to be more representative of the denudation intensity in the mountain range whatever the considered space and time scales. This rate is quite low for a high and active mountain belt like the northern Tian Shan, as it is closer to the rates observed in the flat Middle Europe (Schaller et al., 2001; Hoffmann et al., 2007) than to those observed in the Himalayas (Bhutiyani, 2000; Galy and France-Lanord, 2001; Grujic et al., 2006; Vance et al., 2003) (Table VI). To discuss whether this low rate is controlled by tectonics or climate, recent shortening rate and precipitations can be used as respective proxies for the two forcings in different mountain ranges throughout the world. Recent shortening rate in the Chinese Tian Shan is around ~1 cm/yr (Reigher et al., 2001; Champagnac et al., 2012) and seems to have been stable for the last million years (Avouac et al., 1993; Burtman et al., 1996; Burchfiel et al., 1999; Charreau et al., 2009b). Present-day precipitation is around 300 mm/yr (Métivier and Gaudemer, 1997; Poisson, 2002; Sobel et al., 2003). Their amount might have varied over the last million years since alternations of drier and wetter periods are documented in the region at different time scales (Molnar et al., 1994; Rhodes et al., 1996; Poisson and Avouac, 2004; Yi et al., 2004; Gallaud, 2008; Xu et al., 2010). However, in spite of these variations, the average denudation rate is always low (i.e. less than a few hundred metres per million years) whatever the time scale over which it is integrated: 2 years (Liu et al., 2011), the Holocene (Jolivet et al., 2014, and this study), the last 300 kyr (this study) or a few million years (Métivier and Gaudemer, 1999; Charreau et al., 2011).

First, the denudation rates according to the shortening rates are compared in ranges where the precipitation rates are equivalent (~300 mm/yr; Table VI and Figure 11a). Denudation rates increase slightly with the shortening rate (from ~30 to ~135 m/Myr), but stay within the same order of magnitude. In these semi-arid areas, the denudation rate is systematically low. Next, the denudation rates according to the annual precipitation rates are compared in ranges where the shortening rates are equivalent (~1 cm/yr; Table VI and Figure 11b), excluding orogenic plateaus to avoid a topographic bias. Two groups clearly appear: (i) ranges with limited rainfall (<1000 mm/yr), where the denudation rates are low (~100 m/Myr); versus (ii) ranges with higher precipitations (>1000 mm/yr), where the denudation rates are one order of magnitude higher (>1000 m/ Myr). In other words, an increase of one order of magnitude in the shortening rate in a semi-arid climate induces a limited change of the denudation rate. On the contrary, a rise of one order of magnitude in the precipitation rate in equivalent shortening velocity areas induces a similar increase of the denudation rate. Therefore, we propose that the low denudation rate observed in the Tian Shan is due to the aridity of the region.

Dry climatic conditions are attested in this area for longer than the period documented for the denudation. The Cenozoic
The tectonic uplift rate in the Tian Shan remains to be fully quantified. In a dry climate, the range has not reached equilibrium. The response time of this orogenic system is thus possible that the range has not reached equilibrium. The average denudation rate in the range did not evolve much between the Middle–Late Pleistocene and Holocene as it varies from 100 m/Myr to 170 m/Myr. Accordingly, we propose an average denudation rate in the range of ~100 m/Myr to ~300 m/Myr for the Middle–Late Pleistocene and Holocene, respectively. The denudation increase between the two periods is climate-driven. It is a direct consequence of the extension of the catchment areas in the piedmont associated with sediment reworking following the last glacial–interglacial transition. However, this evolution did not affect the denudation intensity of the hinterland mountains.

In fact, the average denudation rate in the range did not evolve much between the Middle–Late Pleistocene and Holocene as it varies from ~100 m/Myr to ~170 m/Myr. Accordingly, we propose an average denudation rate in the range of ~135 m/Myr for the last 300 kyr. In agreement with the other studies performed in the same area, the typical denudation rate of the northern Tian Shan is thus of a few hundred metres per million years at maximum, regardless of the space and time scales.

### Table VI. Precipitation, shortening and denudation rates of some mountain ranges over the world

<table>
<thead>
<tr>
<th>Setting</th>
<th>Precipitations (mm/yr)</th>
<th>Shortening (mm/yr)</th>
<th>Denudation (mm/yr)</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Alps (NZ)</td>
<td>7000 ± 1000</td>
<td>7.5 ± 0.5</td>
<td>7500 ± 1500</td>
<td>Henderson and Thompson (1999); Herman et al. (2010); Norris and Toy (2014)</td>
</tr>
<tr>
<td>East Andes</td>
<td>1750 ± 250</td>
<td>6 ± 2</td>
<td>430 ± 290</td>
<td>Sahrai et al. (2005); Champagnac et al., 2012, and references therein</td>
</tr>
<tr>
<td>East Cascades</td>
<td>300 ± 100</td>
<td>~0</td>
<td>30 ± 10</td>
<td>Reiners et al. (2003)</td>
</tr>
<tr>
<td>Middle Europe</td>
<td>1000 ± 500</td>
<td>~0</td>
<td>40 ± 20</td>
<td>Schaller et al. (2001); Hoffmann et al. (2007)</td>
</tr>
<tr>
<td>East Himalayas</td>
<td>3500 ± 2500</td>
<td>17 ± 3</td>
<td>1400 ± 400</td>
<td>Grujic et al. (2006); Champagnac et al., 2012, and references therein</td>
</tr>
<tr>
<td>East Himalayas</td>
<td>2500 ± 1500</td>
<td>17 ± 3</td>
<td>700 ± 150</td>
<td>Grujic et al. (2006); Champagnac et al., 2012 and references therein</td>
</tr>
<tr>
<td>West Himalayas</td>
<td>1650 ± 150</td>
<td>15 ± 5</td>
<td>~1800</td>
<td>Bhutiyani (2000); Winiger et al. (2005), Champagnac et al., 2012, and references therein</td>
</tr>
<tr>
<td>Qilian Shan</td>
<td>275 ± 120</td>
<td>5.5 ± 1.8</td>
<td>200 ± 100</td>
<td>Bhutiyani (2000); Winiger et al. (2005), Champagnac et al., 2012, and references therein</td>
</tr>
<tr>
<td>Longshou Shan</td>
<td>~200</td>
<td>5.5 ± 1.8</td>
<td>155 ± 12</td>
<td>Pan et al. (2010); Palumbo et al. (2011), Champagnac et al., 2012, and references therein</td>
</tr>
<tr>
<td>Tian Shan</td>
<td>300 ± 100</td>
<td>10 ± 3</td>
<td>135 ± 140</td>
<td>This study, Mélivier and Gaudemer, 1997; Reigber et al., 2001; Sobel et al., 2003, Champagnac et al., 2012, and references therein</td>
</tr>
<tr>
<td>Zagros</td>
<td>400 ± 100</td>
<td>8 ± 2</td>
<td>85 ± 75</td>
<td>Ali et al. (2003); Javamard et al. (2010), Champagnac et al., 2012, and references therein</td>
</tr>
</tbody>
</table>

**Figure 11.** (a) Denudation rates according to shortening rates in mountain ranges where precipitations are close to 300 mm/yr. (b) Denudation rates according to mean annual precipitation in mountain ranges where shortening rate is close to 1 cm/yr (see Table VI for references). This figure is available in colour online at www.interscience.wiley.com/journal/espl.
This is low for such a high and active mountain belt. From a comparison of the denudation rates observed in the Tian Shan and in other ranges, we suggest that, notwithstanding the tectonic activity, a dry climate can dramatically limit the denudation intensity even in orogenic systems with a strong topographic gradient. As a result, the time required to reach equilibrium between denudation and rock uplift could be extremely long in these systems (more than several million years). Therefore, in such climatic contexts, further work on range uplift and topographic evolution should be carried out to constrain better the state of the system in terms of topographic and flux equilibrium.

Appendix A: Construction of the Morpho-sedimentary Maps

The two morpho-sedimentary maps are based on the interpretation of Landsat and DigitalGlobe (in Google Earth) satellite images (28 m and 2.5 m resolution respectively) coupled with the study of the Aster GDEM2 digital elevation model (30 m resolution).
horizontal resolution, 7–14 m vertical resolution). The same protocol was used to map the 10 catchment–fan systems for which the position of the \( F_p \) fan basal surface can be identified in the field:

1. The path of the main river and its tributaries were identified from the DEM and the satellite images.
2. The positions of the \( F_p \) and \( F_h \) fan apexes along the main stream were identified (Figure 12a).
3. The Holocene drainage basin was extracted from the DEM, considering the \( F_h \) apex as the catchment outlet (Figure 12b).
4. The \( F_p \) and \( F_h \) fan outlines were drawn from the satellite images and from the contour lines extracted from the DEM. The fan toes were considered as the slope break between the fan aprons and the surrounding alluvial plain downstream. The alluvial valley upstream of the fan \( F_p \) was also mapped when it contained an important amount of contemporaneous deposits (see also (Jolivet et al., 2014)). At this point, the morpho-sedimentary map of the present-day landscape in the studied area was obtained (Figure 12c; Data S2 and S3).
5. The morpho-sedimentary map of the Late Pleistocene landscape was inferred from the previous one by the suppression of the fan \( F_h \) and the Holocene extension of the drainage basin (i.e. the part of the drainage basin located between the \( F_p \) and \( F_h \) apexes). The \( F_p \) fan outlines were interpolated where missing (e.g. where they were covered by Holocene deposits) and the upstream part of the drainage basin was assumed to be the same during the two periods as there is no evidence for a major catchment evolution in the range from the Middle–Late Pleistocene to the Holocene (Figure 12d; Data S4 and S5).

From the two maps, the drainage basin and fan areas, \( A_d \) and \( A_f \) respectively, were extracted (Tables II and III). The uncertainties \( \Delta A_d / A_d \) associated with the drainage basin areas were defined as the overlaps between adjacent catchments and correspond on average to \( A_d \pm 0.75\% \) (Tables II and III). Considering that the fan outlines are positioned at the pixel precision, the uncertainties \( \Delta A_f / A_f \) on the fan areas were calculated from the Landsat imagery resolution and are, on average, close to \( A_f \pm 0.5\% \) (Tables II and III).

Appendix B: Reconstruction of the Volume of Sediments

B.1: Middle–Late Pleistocene fan basal surface

The \( F_p \) fan basal surfaces were reconstructed from the fan outlines plotted on the morpho-sedimentary maps and from outcrop observations in the field. During two field campaigns, the main Holocene canyons crossing the piedmont were explored and several places where the basal surface of the fans \( F_p \) crops out (Figure 3) were identified. The coordinates and elevation of these basal surface outcrops were then defined.

From a position \((x, y, z)\) known thanks to a GPS, three parameters were measured to determine the coordinates of each basal surface outcrop: \( A_z \), the azimuth of the outcrop line-of-sight obtained with a compass; \( \beta \), the angle between the horizontal and the outcrop line-of-sight given by an inclinometer; and \( L_z \), the distance to the outcrop measured with a distance meter along the line-of-sight. Alternatively, \( \beta \) can be replaced by the measurement of \( L_y \), the horizontal distance to the cliff where the fan base is observed in the \( A_z \) direction. Coordinates of the basal surface outcrop were then determined by trigonometry (the outcrop KMZ coordinates are given in Supplementary Data S6).

\( A_z, L_y \) and \( L_z \) along three rivers (the Kuitun, Jingou and Urumqi rivers), and \( A_z, \beta \) and \( L_z \) along the seven others were measured with 18–95 points for each fan basal surface. The two methods lead to similar accuracy and are sensitive to several parameters: the GPS accuracy (7–10 m); the compass and inclinometer accuracy (1°); and the distance meter maximum capacity (800 m), which is strongly influenced by the atmospheric conditions, in particular by the presence of dust in the air. Therefore, the coordinates of the basal surfaces were determined within 50 m, which is quite satisfying for the longitude and latitude compared to the length of the fans \( F_p \) (about 30 km). However, this uncertainty is too high for the outcrop elevations. Consequently, the outcrop elevations were not determined directly from field measurements but extracted from the DEM in coherence with estimations made on outcrops and field pictures.

B.2: Fan and sediment volumes

To obtain the volume of the fans, \( V_f \), the individual volume of the 250 x 250 m\(^2\) cells used to model the fan geometry were added up. Consequently, uncertainties on \( V_f \) result from the addition of uncertainties on the cell thickness \( h \) and the fan area \( A_f \). Uncertainties on \( h \) correspond to the difference between the two geometric models (produced with linear or cubic interpolations) and are around 1%. Uncertainties on \( A_f \) come from the Landsat resolution and are also around 1%. Another source of uncertainties must be added to consider the reconstruction inconsistencies. In fact, in areas where the fan thickness is small, a coherent geometry could not be modelled from the DEM and the field constraints. Each cell with a thickness of less than 5 m was thus removed from the volume calculation but included in the uncertainties. These cells represent from 1% to 25% of the fan areas (Figure 6e, f). Therefore, the uncertainties \( \Delta V_f / V_f \) range from \( \pm 3\% \) to 27% (Tables II and III).

To convert \( V_f \) into real sediment volumes, \( V_{AF} \), the porosity of the deposits was required. As mentioned in the geological setting, all these deposits correspond to conglomerates with grains from silts to metric boulders. From trenches dug in the sediments of the fan \( F_p \) and of the present-day river bed of the Urumqi River, a porosity \( \lambda \) of 20 ± 10% was measured for these conglomerates (Guerit, 2014), in good agreement with published values for such a lithology (Clarks, 1979). The uncertainties on the volumes of sediments, \( \Delta V_{AF} / V_{AF} \), result from the addition of the uncertainties on \( V_f \) and \( \lambda \). Therefore, they correspond to:

\[
\frac{\Delta V_{AF}}{V_{AF}} = \frac{\Delta V_f}{V_f} + \frac{\Delta \lambda}{\lambda}
\]

and range from \( \pm 13\% \) to 37% (Tables II and III).

Appendix C: Estimate of the Denudation Rates

The uncertainties associated with the Middle–Late Pleistocene and the total Holocene denudation rates, \( e_{\beta} \) and \( e_{\omega} \) can be calculated as the sum of the uncertainties on the values used to estimate these rates: the volumes of sediments \( V_{AF} \), the proportion of the total sediment load trapped in the fans \( \omega \), the drainage basin areas \( A_d \) and the duration of the fan construction \( P \). Accordingly, the uncertainties associated with
the Middle–Late Pleistocene denudation rates, $\Delta \varepsilon_p / \varepsilon_p$, were calculated as follows:

$$\frac{\Delta \varepsilon_p}{\varepsilon_p} = \frac{\Delta V_{a,b-p}}{V_{a,b-p}} + \frac{\Delta A_{d,b-p}}{A_{d,b-p}} + \frac{\Delta P_h}{P_h}$$

and range between 24% and 30% (Table V). Similarly, the uncertainties associated with the total Holocene denudation rates, $\Delta \varepsilon_h / \varepsilon_h$, were calculated as follows:

$$\frac{\Delta \varepsilon_h}{\varepsilon_h} = \frac{\Delta V_{a,c}}{V_{a,c}} + \frac{\Delta A_{d,b-p}}{A_{d,b-p}} + \frac{\Delta P_h}{P_h}$$

and are between 33% and 58% (Table V).

The uncertainties associated with the Holocene denudation rates in the piedmont $\varepsilon_c$, can be calculated as the sum of the uncertainties on the values used to estimate these rates: the volume of sediments reworked from the canyons $V_{a,c}$, the areas of the Holocene drainage extensions $A_{d,b-p}$, and the duration of the fan construction $P_h$. Accordingly, the uncertainties associated with the Holocene denudation rates in the piedmont, $\Delta \varepsilon_c / \varepsilon_c$, were calculated as follows:

$$\frac{\Delta \varepsilon_c}{\varepsilon_c} = \frac{\Delta V_{a,c}}{V_{a,c}} + \frac{\Delta A_{d,b-p}}{A_{d,b-p}} + \frac{\Delta P_h}{P_h}$$

$\Delta A_{d,b-p} / A_{d,b-p}$ being $\Delta A_0 / A_0 + \Delta A_1 / A_0$, and $\Delta V_{a,c} / V_{a,c}$ being $\Delta V_c / V_c + \Delta \beta / \beta$. Consequently, the Holocene denudation rates in the piedmont are associated with uncertainties of 32–82% (Table V).

Finally, the uncertainties associated with the Holocene denudation rates in the range $\varepsilon_r$, can be calculated as the sum of the uncertainties on the values used to estimate these rates: the difference between the volumes of the sediments trapped in the $F_h$ fans and those reworked from the canyons $V_{a,0}$; the proportion of the total sediment load trapped in the fans $\alpha$; the areas of the Middle–Late Pleistocene drainage basins $A_{d,0}$; and the duration of the fan construction $P_h$. Accordingly, the uncertainties associated with the Holocene denudation rates in the range, $\Delta \varepsilon_r / \varepsilon_r$, were calculated as follows:

$$\frac{\Delta \varepsilon_r}{\varepsilon_r} = \frac{\Delta V_{a,0}}{V_{a,0}} + \frac{\Delta A_0}{A_0} + \frac{\Delta P_h}{P_h}$$

$\Delta V_{a,0} / V_{a,0}$ being $\Delta V_{a,0} / V_{a,0} + \Delta V_{a,1} / V_{a,1}$. The Holocene denudation rates in the range are thus associated with uncertainties of 33–92% (Table V).

Acknowledgements— This work was supported by the French CNRS-INSU and the French–Chinese SALADYN International Associated Laboratory. We thank the ESPL Associate Editors and two anonymous reviewers for their very interesting comments that improved the overall quality of the paper. Acknowledgements are also due to N. Shawwa for his editorial assistance. This paper is the IGP Geosciences contribution #3615.

References


**Supporting Information**

Supporting information may be found in the online version of this article at the publisher’s web site.