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Unbalanced sediment budgets in the catchment–alluvial fan system of the Kuitun River (northern Tian Shan, China): Implications for mass-balance estimates, denudation and sedimentation rates in orogenic systems

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ABSTRACT

Mass balances are often used to calculate sediment fluxes in foreland basins and denudation rates in adjacent mountain ranges on intermediate to long timescales (from a few tens of thousand to a million years). Here, we study the simple Quaternary catchment–alluvial fan system of the Kuitun River, in northern Tian Shan, to discuss some ideas about sediment storage, release, and bypass in relatively short (100 km long) sediment routing systems. This study shows that the Kuitun catchment and piedmont areas clearly present evidence of a significant and temporary storage of sediments during the Pleistocene. These sediments were then excavated and delivered farther into the foreland basin during the Holocene. The difference between the volumes of materials released from the catchment and piedmont areas (5.5 ± 1.7 km^3) and the volume stored in a contemporaneous fan downstream (2.6 ± 0.6 km^3) indicates that the latter did not trap the whole sediment load transported by the river. The alluvial fan was bypassed by 27 to 78% of this load toward its distal alluvial plain. If this value is well estimated, it implies a major volumetric partitioning of the deposits between the fan and the alluvial plain, with a very high sedimentation rate in the fan (1.97 ± 0.52 mm·y^{-1}) and a much lower one downstream (0.11 ± 0.11 mm·y^{-1}). However, this volumetric partitioning might only occur during periods with a very specific hydrological regime such as the Holocene deglaciation. Eventually, the peculiar sediment storage and release pattern within the Kuitun catchment and piedmont areas during the Pleistocene and Holocene complicates the calculation of mean paleodenudation rates using either sediment budgets or in situ produced cosmogenic nuclides.

1. Introduction

Erosion in mountain ranges is a key parameter that partly controls the evolution of orogenic systems and their interactions with climate (e.g., Molnar and England, 1990; Raymo and Ruddiman, 1992; Ramstein et al., 1997; Willett, 1999; Whipple and Meade, 2006). However, denudation rates within mountain ranges are often difficult to estimate from the study of bedrock areas where the morphological markers of erosion are scarce and discontinuous. The alluvial terraces and sedimentary series that develop within neighboring basins usually constitute a more perennial record of the denudation. Several studies have successfully exploited this capacity of sedimentary basins to retain the eroded material to derive erosion fluxes from regional mass balance calculations (e.g., Métivier and Gaudemer, 1997; Métivier et al., 1999; Kuhlemann, 2002; Barnes and Heins, 2008; Hinderer, 2012, and references therein). Knowing the surface of a catchment, as well as the volumes and ages of the eroded sediments deposited at its outlet, deriving a mean denudation rate is possible. Variations in space and through time of this mean denudation rate can then be translated into variations in tectonic uplift or climatic forcing (e.g., Métivier and Gaudemer, 1997; Métivier et al., 1999; Kuhlemann, 2002; Barnes and Heins, 2008).

However, this calculation methodology relies on two strong hypotheses: (i) the sediments deposited in the basin correspond to the bedrock material eroded contemporaneously in the catchment area (i.e., no intermediate storage from source to sink), and (ii) this material is entirely trapped in the studied sedimentary series. Consequently, this mass balance approach is usually applied to large relief basin systems where sediment storage in catchment areas can be considered as minimal and sediment outputs from basins as null or negligible (e.g., Métivier and Gaudemer, 1997; Métivier et al., 1999; Kuhlemann, 2002; Barnes and Heins, 2008; Hinderer, 2012, and references therein). Indeed, when

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considering the denudation at the scale of a whole orogen (more than a few 10,000 km^2) and over long timescales (a few 100 ky to several Ma), the proportion of sediments delivered to the neighboring basins is usually very large compared to the total amount of stored sediments. Consequently, the sediment fluxes in these basins can be reliably converted into denudation rates and directly related to the topographic evolution of the catchment areas (e.g., Métivier and Gaudemer, 1997; Kuhlemann, 2007; Barnes and Heins, 2008).

This approach is sometimes also applied to catchment–fan systems (e.g., Kiefer et al., 1997; Oguchi, 1997; Allen and Hovius, 1998; Jayko, 2005; Hinderer, 2012, and references therein). Those are the smallest and simplest complete sediment routing systems that can be found in continental contexts (Densmore et al., 2007; Allen, 2008). They are composed of an upland catchment area, where sediments are produced, associated with an adjacent alluvial fan where some or all of those sediments are deposited. However, at the scale of those systems (extending typically from a few 10 km^2 to several 1000 km^2 and developing over a few 10 ky to a few 100 ky), the reliability of the negligible catchment storage and fan bypass hypotheses is still a key question in mass balance studies.

Before being delivered downstream, the material eroded within a catchment area can be partially stored for long periods compared to the development timescales of fans (Fig. 1) (e.g., Church and Ryder, 1972; Church and Slaymaker, 1989; Brooks, 1994; Hinderer, 2012, and references therein). This hillslope and valley storage, along with its release, can lead to apparent variations in sediment yield disconnected from the prevailing tectonic or climatic boundary conditions (e.g., Church and Ryder, 1972; Church and Slaymaker, 1989; Brooks, 1994; Coulthard et al., 2005) or to buffering the system response against their changes (e.g., Coulthard et al., 2002; Phillips, 2003). Thus, over intermediate timescales (a few 10 ky to a few 100 ky) that include large climatic changes during the Quaternary, varying or constant accumulation rates at the outlet of a catchment can be completely disconnected from the contemporaneous mean denudation rate. For example, during interglacial periods, a sudden release of sediments stored in a catchment area during glacial periods could artificially increase the sediment accumulation rate in a fan compared to the effective basement denudation upstream, which will then be overestimated. Conversely, trapping sediments in a catchment area could artificially decrease the sediment accumulation rate in the corresponding fan leading to underestimation of the catchment denudation rate. However, as far as we know, the proportion of sediments stored in catchment areas compared to the total amount of transported load is rarely assessed for periods longer than several millennia (Jordan and Slaymaker, 1991; Hinderer, 2012 and references therein).

Additionally, estimates of the sediment bypass through alluvial fans remain scarce (Kiefer et al., 1997; Oguchi, 1997; Allen and Densmore, 2000). In previous studies, catchment–fan systems were often considered as essentially closed in terms of sediment budget (e.g., Whipple and Trayler, 1996; Allen and Hovius, 1998; Jayko, 2005; Densmore et al., 2007; Giles, 2010), and for those that were not, quantifications are usually lacking (e.g., Denny, 1965; Allen and Hovius, 1998; Carretier and Lucazeau, 2005). Though variations in the amount of sediment bypass through time could also lead to apparent variations in accumulation rate disconnected from boundary condition changes or could buffer the system response against these changes. An important sediment bypass will artificially decrease the sediment accumulation in a fan compared to the effective sediment exportation from its catchment area. As a result, the apparent denudation rate calculated from this accumulation rate will be underestimated. In theory, sediment bypass can be assessed by comparing the amount of sediments accumulated in a fan and deposited in its downstream alluvial plain or exported from its upstream catchment area during a given period of time. Practically, this comparison requires a volumetric mapping of the sediments deposited in the fan and lying in the plain or coming from the source area. Unfortunately, the data (outcrops or wells) and markers (terraces), which are necessary to know the extension of these deposits in depth and the location of their source area, are often too scattered or even nonexistent in natural systems.

The catchment–fan system of the Kuitun River located on the northern side of the Tian Shan Range offers a natural case study for sediment storage, release, and bypass (Fig. 2). In that region, the rivers built several outstanding Quaternary alluvial fans and terraces, which have

Fig. 1. Evidence for sediment storage in a valley of the Ih Bogd massif (Gobi Altay, Mongolia). The white Mongolian guers at the meeting point of the two valleys give the scale. The dashed white line shows the boundary between the valley slopes and alluvial areas with sediment storage. To the west, the river started to incise the gravels stored in its valley and farther upstream, it incised a 25-m-deep canyon in the bedrock (Vassallo et al., 2007).
Picture by A. Chauvet (with permission).