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Rapid grain size coarsening at sandstone/conglomerate transition: similar expression in Himalayan modern rivers and Pliocene molasse deposits

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ABSTRACT

Radical grain size changes between two main units of a sedimentary megacycle in a foreland basin are commonly interpreted to result from changes in tectonic activity or climate in the adjacent mountain range. In central Nepal, the Cenozoic Siwalik molasse deposits exposed in the frontal Himalayan folds are characterized by such a radical grain size transition. Locally gravel deposits completely replace sands in vertical succession over approximately a hundred metres, the median grain size (D_{50}) displaying a sharp increase by a factor of *ca.* 100. Such a rapid gravel–sand transition (GST) is also observed in present-day river channels about 8–20 km downstream from the outlet of the Siwalik Range. The passage from gravel-bed channel reaches (proximal alluvial fans) to sand-bed channel reaches (distal alluvial fans) occurs within a few kilometres on the Gangetic Plain in central Nepal, and the D_{50} ratio between the two types of channels equals *ca.* 100. We propose that the dramatic and remarkably similar increase in grain size observed in the Neogene Siwalik series and along modern rivers in the Gangetic foreland basin, results from a similar hydraulic process, i.e. a grain sorting process during the selective deposition of the sediment load. The sudden appearance of gravels in the upper Siwalik series would be related to the crossing of this sorting transition during progressive southward migration of the gravel front, in response to continuous Himalayan orogen construction. And as a consequence, the GST would be diachronous by nature. This study demonstrates that an abrupt change in grain size does not necessarily relate to a change in tectonic or climatic forcing, but can simply arise from internal adjustment of the piedmont rivers to the deposition and run out of coarse bedload. It illustrates, in addition, the genesis of quartz-rich conglomerates in the Himalayan foreland through gravel selective deposition associated with differential weathering, abrasion processes and sediment recycling during thrust wedge advance and shortening of the foreland basin.

INTRODUCTION

Foreland basins are important archives for recording climatic and tectonic history of adjacent mountain ranges. In such settings, changes in grain size are among the most readily observed features of sedimentary sequences. They have received repeated attention because they are traditionally interpreted as tracing tectonic and climate changes and supposed to embed substantial information on these changes. An abrupt change in facies is classically interpreted in terms of increased sediment flux and accelerated alluvial fan propagation, or alternatively, in terms of subsidence decrease due to the cessation or slowing of the tectonic activity and flexural loading, or also in terms of alluvial material coarsening in the sediment source (see review by Paola *et al.*, 1992; Fig. 1a). The most traditional mechanism invokes an increase in coarse sediment flux due to an increase in erosion of the source area. This erosion increase can arise from sudden or accelerated tectonic activity in the adjacent mountains (e.g. Burbank *et al.*, 1988; Newell *et al.*, 1999; Fang *et al.*, 2005), from a major climatic change (e.g. Zheng *et al.*, 2000; Peizhen *et al.*, 2001) or from a major change in the drainage area of the eroded catchment (Whittaker *et al.*, 2011). Numerical and analytic models have generally confirmed the role of these different mechanisms in controlling facies progradation (Paola *et al.*, 1992; Robinson & Slingerland, 1998; Armitage *et al.*, 2011). They have in particular stressed the first order controls on downstream fining of the ratio between subsidence and sediment supply rate, as well as of the dispersion of the grain size distribution in sediment supply (Paola & Martin, 2012). Recently, using an analytic self-similar solution to fining downstream profiles (Fedele & Paola, 2007), Duller *et al.* (2010) and

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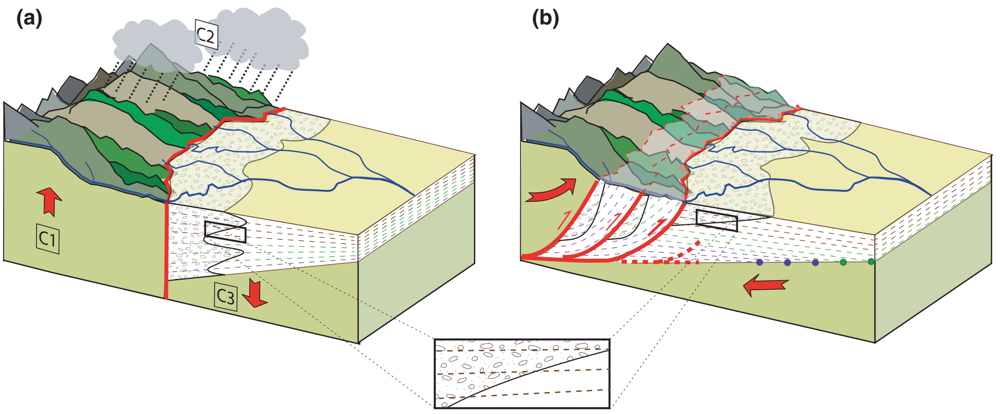

Fig. 1. Sketch of a foreland basin accumulating sediment exported from an adjacent mountain range and recording a facies transition, such as a gravel/sand transition (central inset), oblique relative to time lines (thin dashed lines in the depositional basin). (a) When the mountain range is fixed relative to the basin, oblique geometry of the facies limit can arise from transient response to variations in sediment input and/or gravel fraction due to tectonic uplift (C1), climatic (C2), or contributing drainage area variations, or from changes in subsidence rates (C3). (b) Alternatively, in a convergent orogen, the oblique geometry of the facies limit emerges, even at steady state, from concomitant subsidence and facies migration. During the convergence between the orogenic wedge and the foreland basin, the facies migration follows the onlap migration at depth (dark circles at the bottom of the foreland basin).

Whittaker *et al.* (2011) have proposed a more quantitative approach to interpret old continental foreland sedimentary series in the Spanish Pyrenees and to invert the values of subsidence and sediment supply rates from downstream grain size fining trends.

All above cited models and their quantitative applications consider a fixed reference frame, i.e. no relative displacement between the mountain range and the depositional area, and require a change in the external forcing to trigger gravel progradation. In convergent orogens, however, foreland basins associated with the flexure of the lithosphere under the load of an orogenic prism generally accompany the displacement of the orogenic prism. The resulting 'flexural wave' induces a horizontal facies migration (Flemings & Jordan, 1989; Sinclair *et al.*, 1991; DeCelles & DeCelles, 2001). This horizontal facies migration combined with continuous subsidence and aggradation also leads the limits of facies to be oblique relative to time lines (Fig. 1b). In a vertical fluvial succession, an upward coarsening can therefore reflect such horizontal facies migration even if the system, including the flexural wave, is in steady state.

The Himalayan or Gangetic foreland basin is characterized by thick Mio-Pleistocene molasse deposits issued from the erosion of the Himalayas. These deposits are presently exhumed by active thin-skin tectonics at the front of the Himalayas, along the Siwalik frontal belt. Within these Siwalik continental sedimentary series, gradual to abrupt grain size changes are commonly described. In central Nepal, like in many other sedimentary systems and terrestrial foreland basin sequences, an abrupt transition from sandstones to conglomerates in coarsening upwards fluvial successions is particularly noticeable. Modern fluvial deposits along the Himalayan rivers that drain the proximal part of the Gangetic foreland basin also present a sharp gravel-sand transition (GST), but this transition occurs longitudinally. Because molasse deposition is still an active process in the Gangetic foreland basin, the present alluvial deposits can be considered as a possible modern analogue of ancient molasse deposits. The comparison between ancient and modern fluvial deposits offers the opportunity to document in detail abrupt changes in grain size, and therefore to address the origin of the grain size transition both in the Siwalik series and in the modern channels. For this purpose, we have carried out grain size measurements along the Himalayan front. We surveyed sediments in the channels of five present-day rivers eroding the frontal Himalaya and draining the proximal Gangetic foreland basin, as well as along three sections across the frontal Himalayas, where Neogene molasse deposits outcrop (Fig. 2). For this study, we focused more particularly on the interfan areas, i.e. in between the megafans built by trans-Himalayan rivers (Fig. 2).

Geologic and geomorphic setting

The still ongoing collision between India and Eurasia initiated around 50 Ma ago (Patriat & Achache, 1984), and has shaped the Himalayan orogen into a broadly east–west structured range. The collision has been absorbed by crustal thickening of the northern margin of the Indian continent associated with the activation of several major thrust zones. The Himalayas are classically divided into several main E–W trending morpho-structural units. From north to south, we find: the Higher Himalaya, the Lesser Himalaya, the Mahabarat and the Sub-himalaya. The Higher Himalaya that supports the highest peaks on Earth is mostly composed of migmatitic gneisses, granite or metamorphosed sediments. The Lesser Himalaya (LH) presents more subdued, 500–3000 m high topographies, and is composed of low-grade metasediments

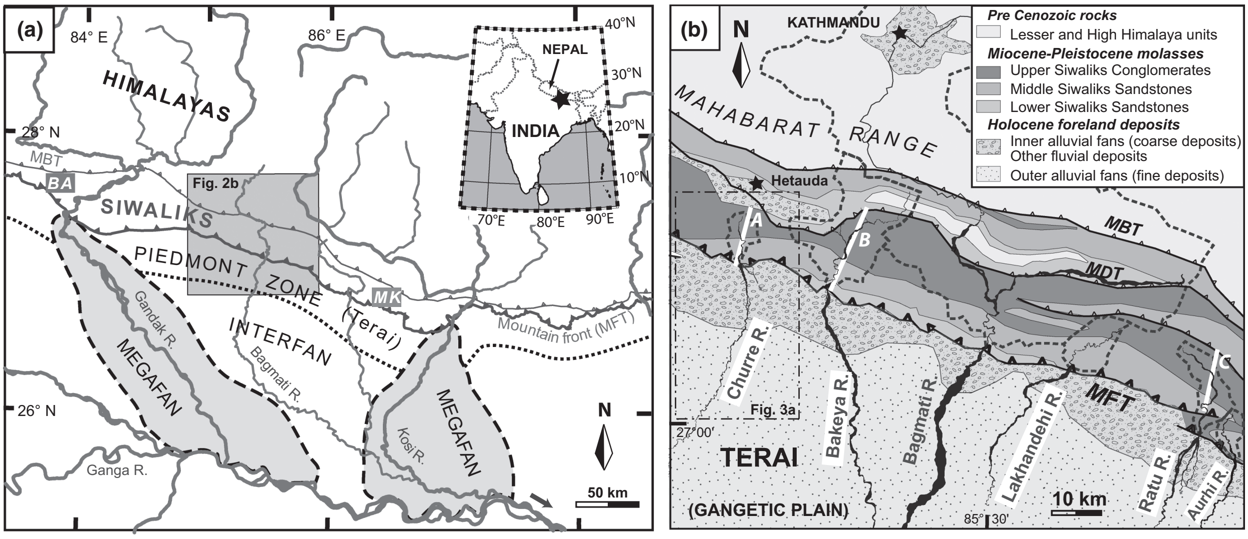

Fig. 2. (a) Hydrologic map of the Himalayas and Gangetic plain system in central Nepal. The study area is located in the Himalayan foothills of Central Nepal (Siwalik) and in the Eastern Gangetic Plain between the Kosi and the Gandak megafans. In the Terai piedmont zone, small transverse rivers form wide and flat coalescent alluvial fans. Pebbles and gravels are rarely transported south of this Piedmont Zone, which is largely isolated from the influence of large trans-Himalayan rivers (Kosi and Gandak rivers). The Main frontal Thrust (MFT) is the most active of the Himalayan thrusts, which progressively deform and incorporate the molasses of the Gangetic foreland basin into the narrow Siwalik Range. (b) Close up on the Himalayan front, the four studied rivers (white underlined names) and the three documented sections across the old Siwalik molasses (A = Churre section; B = Bakeya section; C = Ratu section). Note that all studied rivers, except the Bagmati, are foothills-fed and mainly drain Siwalik molasses. MDT = Main Dun Thrust; MBT = Main Boundary Thrust; BA and MK in (a) correspond to Binai-Arung (Tokuoka *et al.*, 1986) and Muksar (Ojha *et al.*, 2009) magnetostratigraphic sections.

ranging from quartzite to phyllite, schist and limestone. The Mahabarat is well expressed in central Nepal, south of Kathmandu and marks generally the topographical expression of the southern klippen that overthrust the Lesser Himalaya: it includes schist, quartzite, sandstones and unmetamorphosed limestone. Finally, the most frontal Himalayan unit, called Sub-himalaya or Siwalik Hills, is expressed by low elevation but rugged topographies. This small and narrow roughly east-west trending range, which hardly reaches 1000 m elevation and 20 km width, forms a continuous belt from Pakistan to Eastern India. It is associated with the most active thrust system across the Himalaya, the Main Frontal Thrust (MFT; Lavé & Avouac, 2000), which is thought to merge at depth on the major Himalayan Thrust (MHT) system (Schelling & Arita, 1991; Pandey *et al.*, 1995).

The Siwalik consist of Neogene fluvial sediments originated from Himalayan erosion, deposited in the Gangetic foreland basin and later exhumed by thin-skin tectonics and southward propagation of Himalayan deformation (Herail & Mascle, 1980). They record Himalayan erosion without any major hiatus and are therefore extensively used for characterising the evolution of climate and tectonic activity of the entire Himalayan region (e.g. Najman, 2006). Along the Himalayan arc, these foreland deposits generally present an upward evolution from siltstones and sandstones to coarse conglomerates, and are traditionally divided into three lithofacies units (Herail & Mascle, 1980; Delcaillau, 1992):

The Lower Siwalik (Miocene age in the outcrops) are made up of consolidated sandstones and siltstones. These facies are associated with a low energy floodplain environment, with meandering rivers.

The Middle Siwalik (Miocene to Pliocene) are dominated by poorly consolidated fine to coarse sandstone. Beds often reach thickness of several tens of metres with interbedded clay and silt deposits and with occasional thin lenses of pebbly sandstone (mainly at the top of the unit). These facies are characteristic of braided or meandering rivers, in the distal part of alluvial fans.

The Upper Siwalik at the top of the group (Pliocene to Pleistocene) mainly consists of unconsolidated ortho-conglomerates made of coarse gravels and pebbles. Sequences of massive conglomerates are commonly several-metres thick, and locally contain small sandy and muddy lenses or palaeosols. This facies represents unconfined braided rivers on alluvial fans.

In these three units, palaeocurrent studies (e.g. Tokuoka *et al.*, 1986; Delcaillau, 1992) indicate that the sediments were deposited by rivers draining constantly in a North-South direction, as is the case for present-day rivers south of the Himalayan front.

In central Nepal, the transition in grain size between sandstone units and conglomerate units is generally described as relatively abrupt. Despite the common interpretation of this coarsening upward trend as resulting from the continuous syntectonic long-term aggradation/progradation of alluvial fans at the front of the mountain range (Herail & Mascle, 1980; Tokuoka *et al.*, 1986; Delcaillau, 1992), the cause of the abruptness of the transition has not yet been explained. In addition, the age of this abrupt transition is poorly constrained in our study area: along the Bakeya Khola (Fig. 2b), a crude extrapolation from the top of a section dated by magnetostratigraphy (Harrison *et al.*, 1993) indicates an age of 2.5–3 Ma. Laterally, magnetostratigraphic studies document a grain size transition: at 2.5–3 Ma along the Surai Khola section in the central western Nepal (Appel *et al.*, 1991); at *ca.* 3.5 Ma and *ca.* 7 Ma in the Binai-Arung area across the Siwalik frontal southern fold and northern inactive fold respectively (central Nepal, see location on Fig. 2a; Tokuoka *et al.*, 1986); and at 3–3.5 Ma along the Muksar Khola in the central-Eastern Nepal (see location on Fig. 2a; Ojha *et al.*, 2009). The limited amount of data and the large uncertainties (*ca.* 0.5–1 Ma) preclude a definitive conclusion on the lateral synchronism or diachronism of the grain size transition along the southern most frontal fold (associated to the MFT) in central Nepal; however, the data in the Binai-Arung area suggest a strong diachronism of the transition across two successive fold belts, i.e. over a N-S distance of *ca.* 25 km (after section restoration).

Today, the Siwalik Hills, as well as the whole Himalayan range, are actively dissected by rivers during large and recurrent floods in summer monsoon time. The products of erosion go partly to the Gangetic foreland basin, although a significant part of the sediments is transported down to the Bengal fan (Lupker *et al.*, 2011), mostly by large trans-himalayan rivers that drain the Ganga foreland basin before merging with the main Ganga stream in the southeast of this plain. In between the megafans built by those trans-Himalayan rivers (Karnali, Narayani or Gandak and Kosi Rivers in Nepal), the interfan areas of the basin are filled with sediments issued from the erosion of the Siwalik and Mahabarat ranges and carried by small to medium size rivers (lengths of 10–80 km, and drainage areas of 20–2500 km²). The present study is more particularly focused on the interfan area and on those small to medium size rivers that drain the Himalayan front and the proximal part of the Ganga plain, called 'Terai'.

Grain size measurements: methods

Grain size measurements are inspired from previous studies (Kellerhals & Bray, 1971; Diplas & Sutherland, 1988; Milan *et al.*, 1999) and include sieving analysis (volumetric measurements) and photographic analysis (point measurements on a surface). Photographic analysis produces data biased by several factors, in particular by a sectional effect (the visible section is smaller than the real ellipsoid section) that we have to compensate before merging, sieving and photos data analysis. On subvertical outcrops (i.e. mainly on conglomerates), we estimated from joint analysis with both methods an empirical correction factor of *ca.* 1.7 that needs to be applied to photo-derived pebble median size (D_{50}) to estimate the equivalent median square sieve size (which underestimate by 10% the median b-axis of Himalayan pebbles according to Attal & Lavé (2006)). This correction roughly corresponds to the theoretical median ratio between the apparent and the true b-axis for a random distribution of ellipsoid-shaped pebbles as seen in a 2D section (Dubille, 2008). For pebbles presenting the same shape factors as those measured along the Marsyandi river (appendix in Attal & Lavé, 2006), this theoretical ratio ranges between 1.6, for isotropic distribution, and 1.8, for imbricated pebbles observed in a vertical section. In the following, we will therefore assume that the same correction factor can be used to calculate from photo analysis the D_{50} (median), as well as the D_{90} (90th percentile) of the grain size distribution.

For soft sediments in modern channels, bulk-samples (60–150 kg) were taken from the subsurface (i.e. at a depth larger than the largest pebble or boulder) to avoid potential surface coarsening or armouring. Sieving analysis was sometimes complemented by photographic analysis and line counting of the surface where the armour was not developed, or of cross sections of incised alluvial bars. The critical step is the choice of the place to sieve: we avoided local patches of sandy or silty upper bank deposits, and preferentially selected large river bars with relatively uniform bedload-type material. At each station (Fig. 3), we conducted between two and ten independent measurements on the same or different alluvial bars which generally provided comparable results.

For ancient Siwalik conglomerates, grain size was mainly estimated by photo analysis (*ca.* 90% of the dataset) because bulk-samples were difficult to extract and usually biased due to pebble breakage induced by tectonic fracturing and weathering. The sandstones were disaggregated in water (plus HCl for the most consolidated ones), and analysed in our laboratory with sieves and/or a laser granulometre (Malvern Mastersizer).

Grain size of Mio-Pliocene to Pleistocene Siwalik series (central Nepal)

Detailed grain size measurements have been conducted along the Churre, Bakeya and Ratu Rivers across the Siwalik Hills, south to southeast of Kathmandu (Figs 2 and 3). Except in the Bakeya (Fig. 2b) section, where Lower Siwalik units outcrop at the base of the monocline just north of the MFT, the other sections display only Middle to Upper Siwalik units. Along the three sections, the lithofacies successions and thicknesses are relatively similar. The Middle Siwalik facies are composed of alternating sandstone, siltstone and mudstone (see Tamrakar & Khakurel (2012) for detailed log along the Churre section). The siltstone and mudstone facies, which mostly correspond to overbank and inundation plain deposits, represent generally only a few per cent of the lithostratigraphic column in particular in the upper member of the Middle Siwalik unit (i.e. 1000–1500 m below the GST). For that reason, our sampling in the Middle Siwalik units was focused on the thick (up to 30 m) and homogeneous

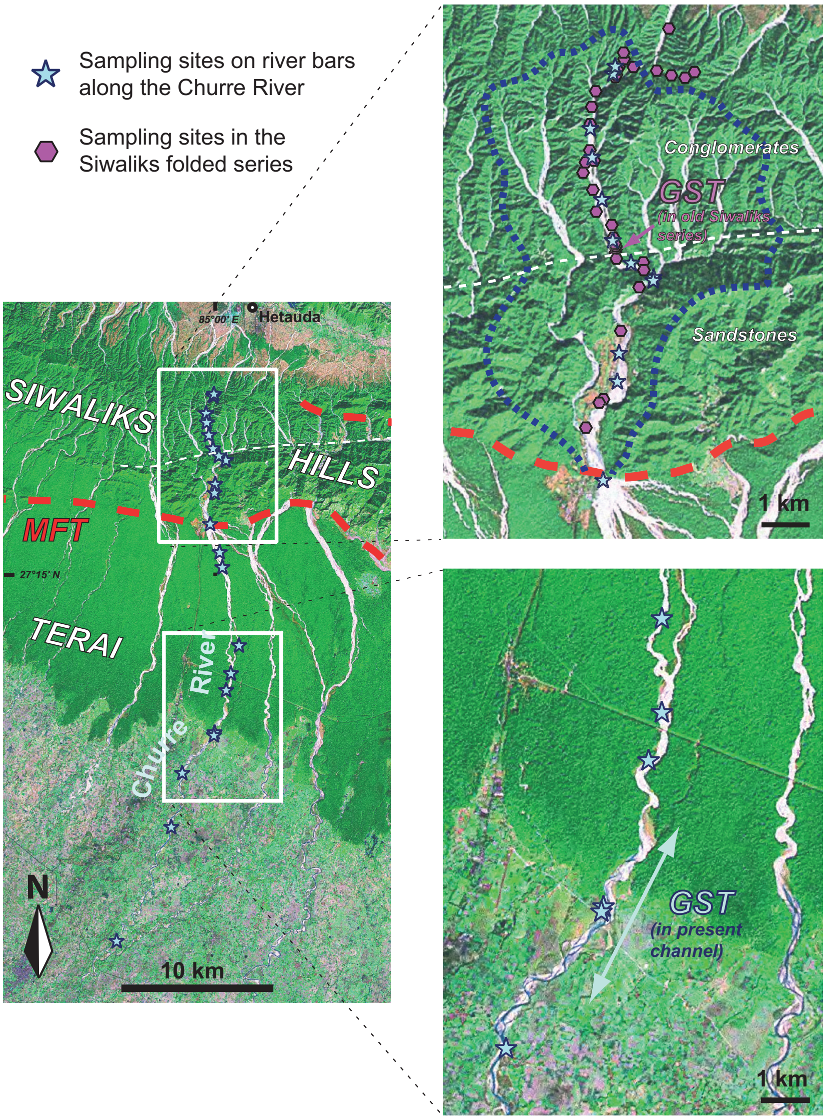

Fig. 3. Landsat image of the Churre river including all the sampling points for grain size measurements in gravel or sand bar deposits along the channel (blue stars), and within the folded Siwalik series (purple symbols).

sandstone layers, which comprise multistoried, planar to through cross-stratificated beds characteristic of large sandy braided or coarse-grained meandering rivers. They occasionally display at their base thin beds (<10 cm) of gravel (Ø < 3 cm) or pebbly sandstone layers. Volumetrically those gravels are negligible and were not sampled for grain size measurement. However, the number and thickness of the fine pebble layers intercalated with the sandstone or siltstone beds increases significantly at the GST (Figs 4 and 5), so we sampled both facies at this level. The Upper Siwalik facies in the studied area mostly comprise massive several-metres-thick beds of unconsolidated clast-supported conglomerates with sorting and planar cross-bedding in the lower part of the unit, becoming poorly sorted in the upper part with occasional metre-scale boulders. The lower sequences are interpreted as alluvial bars deposited by gravelly braided rivers whereas the upper sequences correspond to more proximal deposition in alluvial fan systems. The conglomeratic sequence contains small sandy and muddy lenses with planar stratification, and locally metre-thick red-weathered palaeosols. The proportion of sand and siltstone layers represents on average less than 5% of the volume of the conglomeratic member, except for the upper Churre section (upper 200 m). There, the fine-grained facies become important because sedimentation was affected by incipient activity of the MFT and took place in a nascent piggy back basin. For that reason, our size counting in the Upper Siwalik units was only focused on the thick and homogeneous gravel layers. These conglomerates mostly comprise clasts of the Lesser Himalaya, Mahabarat and Siwalik units: the clasts are dominantly quartzite or quartzitic sandstone, weathered metasediments (sandstone, marble, slate), weathered Siwalik sandstone (mostly in the upper part of the section) and Palung granite coming from the Mahabarat (southern part of the Kathmandu klippen).

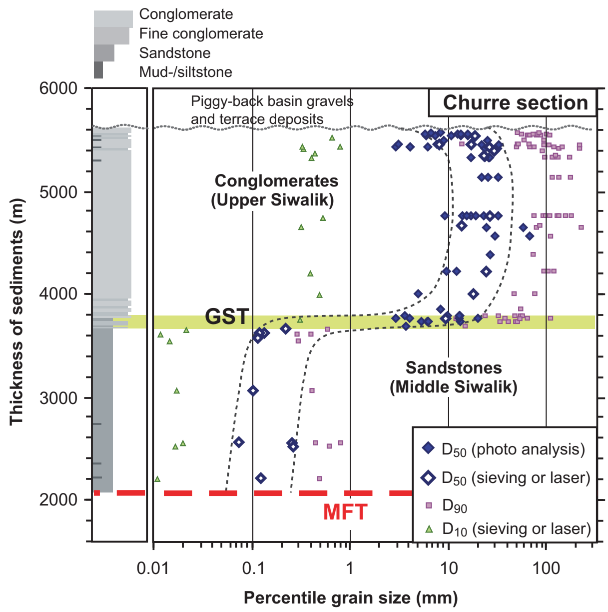

Fig. 4. Grain size evolution in old Siwalik molasses (Mio-Pliocene to Pleistocene) along the Churre section showing a very sharp transition, 80–100 m thick, between Middle Siwalik sandstones and Upper Siwalik conglomerates. On both sides of the transition, the grain size (the median size D_{50}, but also D_{10} and D_{90}) displays constant to gently decreasing values downsection. The median size and D_{90} measured from photo analysis in the Siwalik conglomerates includes correction of section effects.

Along the Churre valley (Fig. 3), the detailed grain size measurements show that, despite significant scattering between measurement stations, a clear trend with two distinct domains can be identified: the D_{50} of the Siwalik series present relatively constant values around 0.1 mm in the sandstones units and around 20 mm in most of the upper conglomeratic unit (Fig. 4). The facies transition is relatively abrupt, with a thickness of 70–100 m, and D_{50} changes by a ratio of *ca.* 150. At the level of this transition, first some small scattered pebbles and then thin layers of small gravels appear in sand deposits, then the gravel layers become thicker, the sand fraction coarser and finally sandstone layers are fully replaced by conglomeratic layers. Simultaneously, the D_{90} increases from *ca.* 0.4 mm to 100 mm, i.e. by a factor of about 250, although D_{10} increases only by a factor of 25 from 0.015 mm to 0.4 mm (Fig. 4). The transition is overlain by *ca.* 1800 m of unconsolidated conglomerates.

Despite small lateral variations in the transition architecture, the cross sections along the Bakeya and Ratu rivers further east display very similar patterns and complement observations in Churre section (Fig. 5). First, the Bakeya section, which is located only 20 km further east, presents the same median size above and below the transition. It also presents a comparable transition thickness of *ca.* 80–100 m. In addition, deeper units are outcropping in this section and indicate in fact a slight decrease in sand grain size between the transition and the

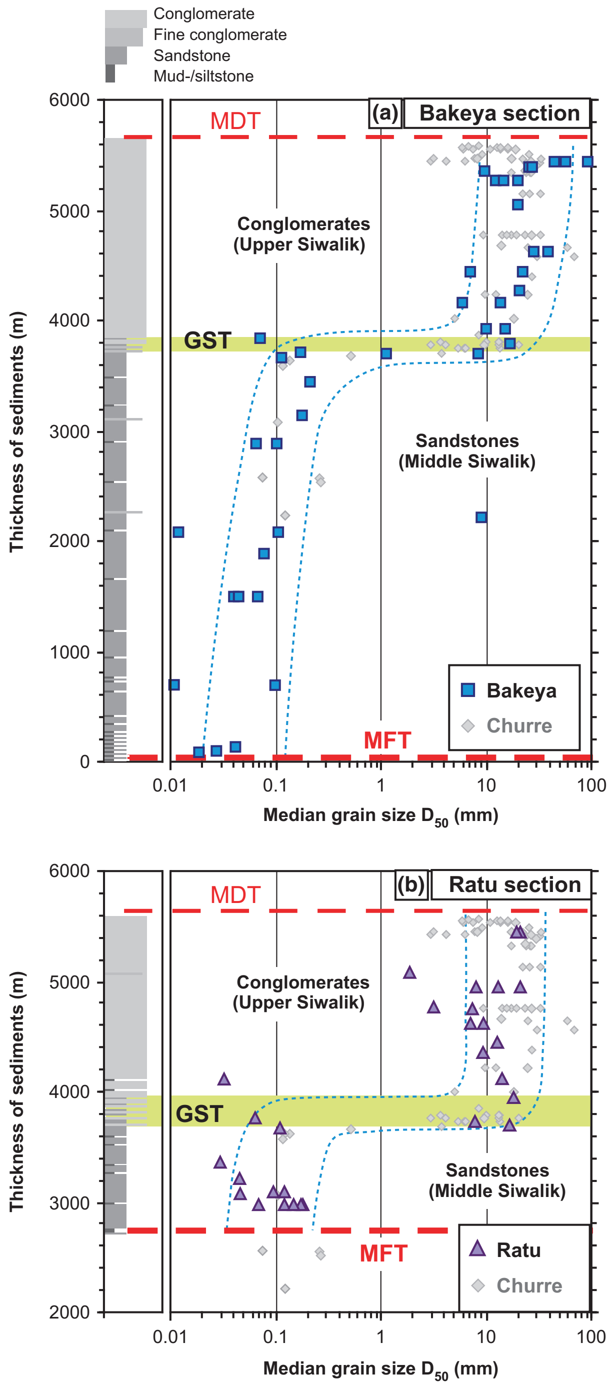

Fig. 5. Evolution of the median grain size, D_{50}, in the old Siwalik molasses (Pliocene to Holocene) along the Bakeya section (a) and Ratu section (b) showing, as along the Churre section, a very sharp transition between Middle Siwalik sandstones and Upper Siwalik conglomerates. The transition is 80–100 m thick in Bakeya, and a little more diffuse along the Ratu section. On both sides of the transition, the median grain size displays constant to gently decreasing values downsection. In order to provide comparison with the Churre section, the median grain size along the Churre (Fig. 4) is represented with light grey symbols. Because of the uncertainties in reconstructing the total sediment thickness from structural data at the surface (uncertainties are lower or equal to 400 m), we have chosen, for a commodity of representation, to adjust the relative position of the GST in the Churre section with the one in the Bakeya or Ratu stratigraphic section.

Lower Siwalik from 0.10.2 mm to *ca*. 0.04 mm. The Ratu section displays also a similar grain size evolution with two major domains of roughly constant grain size; however, the median pebble size in the conglomerate is there slightly lower, around 10 mm, and the transition is clearly thicker, around 150 m. Despite these differences, all the sections display a relatively sharp sand-gravel transition and a two orders of magnitude upward increase in the median grain size.

Grain size of present rivers bars

The Siwalik series of the sub-Himalaya are actively eroded and incised by a dense fluvial network. South of Kathmandu, across the frontal fold, incision rate can reach up to 15 mm yr^{-1} (Lavé & Avouac, 2000). In between the large trans-Himalayan rivers, i.e. upstream of the interfan areas (Fig. 2), the Siwalik Hills are generally drained by many small transverse rivers (Fig. 2b), with drainage areas of a few tens to hundreds of km^2, except for the Bagmati River (drainage area of 2800 km^2), which also drains the Mahabarat Range (metasediments and Palung granite of the Kathmandu klippe). At the outlet of the range, all these rivers abruptly form a very wide system of braided pebble-covered channels which spread on extensive coalescent low-gradient alluvial fans. Channels progressively become meandering on the outer fans, which stretch 50–100 km towards the south before being absorbed by mega fans of the old Gandak River (or Burhi Gandak River) or the Kosi River (Sinha *et al*., 2005; Fig. 2a).

The evolution of grain size was measured in a ten rivers that drain the Siwalik Hills towards the Terai in the interfan area between the Narayani and Kosi rivers, but emphasis is given to five rivers (Churre, Bakeya, Lakhendei, Ratu and Aurhi Khola), where denser measurements were made (Fig. 6). The selection of these rivers was in addition based on their different watershed size, between 25 and 350 km^2, and also on the variable proportions in conglomeratic and sandstone drained by those rivers. The Ratu Khola drains mainly coarse upper Siwalik units (*ca*. 80%). On the contrary, the Lakhandei River essentially drains sandstone middle Siwalik units (only *ca*. 30% of conglomeratic units), whereas the Bakeya and Churre Rivers drain roughly similar proportion of the two grain size facies.

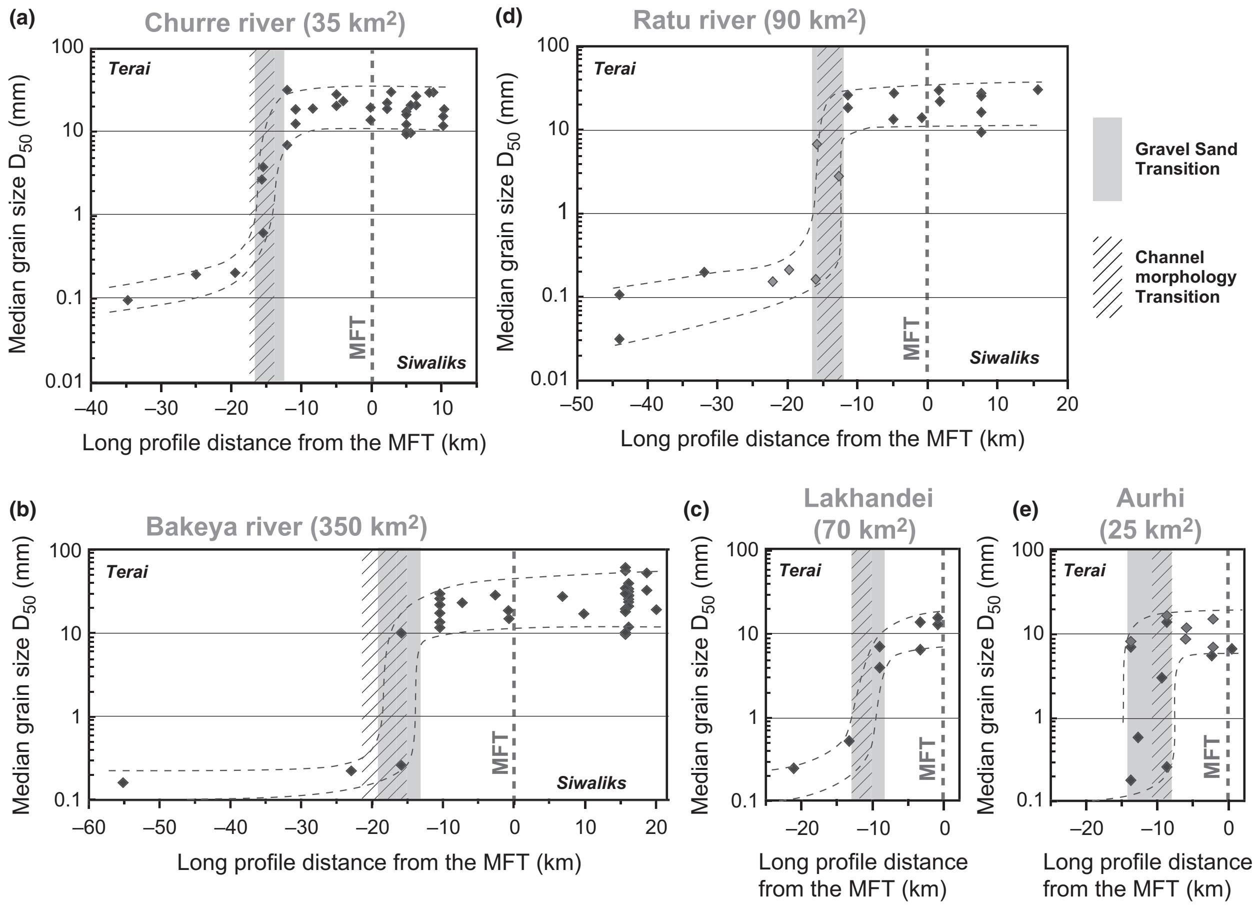

Fig. 6. Grain size measurements in gravel or sand bar deposits along five rivers draining the Terai south of Kathmandu. Although sampling density does not permit to document the precise length of the sand-gravel transition along the Lakhandei and Aurhi Khola, a drop of two orders of magnitude in grain size is observed as along the Churre, Bakeya or Ratu rivers. Along the Aurhi Khola, where sampling stations are absent along the most downstream-most part, the lower end of the gravel-sand transition is not constrained but only by morphologic arguments (change in channel sinuosity and resurgence of the water table).

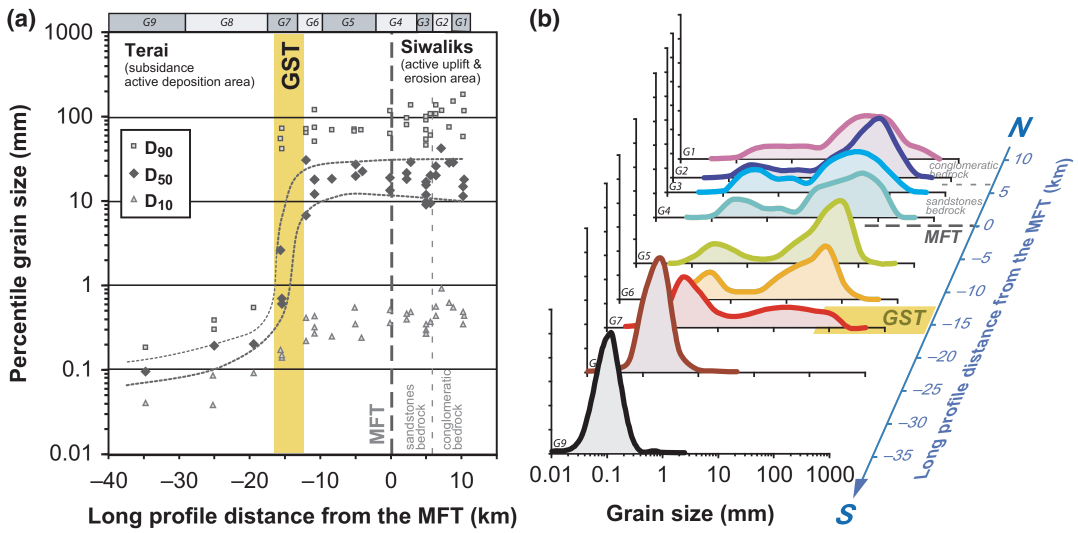

Fig. 7. (a) Grain size measurements in gravel or sand bar deposits along the Churre River show a sharp transition between gravel-covered channel reaches and sand-covered channel reaches, which impacts all the granulometric indices D_{10}, D_{50} and D_{90}. The D_{50} remains constant from the source in hilly areas to 12 km downstream from the topographical front, in the Teraï plain, and then drops by two orders of magnitude in a 4 km-long transitional reach. D_{10} and D_{90} display similar features as D_{50} but with a size drop by a factor 10 and 200 respectively. (b) In addition, the downstream evolution of the average sediment size distributions highlights the bimodal nature of the transported sediment, and the drop of the gravel mode close to the gravel-sand transition (The nine river segments along which size distributions have been grouped and averaged are displayed at the top of Fig. 7a).

In the upper part of the Churre, Bakeya and Ratu Rivers watersheds, where the rivers drain through the upper Siwalik conglomerates, the D_{50} of the gravel bar material in braided channels is similar to the D_{50} of the sedimentary source rock (Figs 4, 5 and 6). Although some pebbles have been fractured by tectonic loading, and other deeply weathered, most quartzitic pebbles of the loose conglomerates are transferred unchanged to the fluvial network from the hillslope, so that no major change in D_{50} is expected. Where draining middle Siwalik sandstones, the D_{50} in the gravel bars of the river channel does not change because the sandstone contribution to the gravel and pebble fraction is minor, except for a few large and easily erodible boulders. The majority of the fine particles supplied by these units does not contribute to the gravel bar material, but probably travels mostly as suspended load. At the outlet of the range the Churre and Ratu Rivers spill onto a wide alluvial fan and divide into several branches, whereas the Bakeya, Lakhendei and Aurhi Rivers build similar fans but develop a single tread channel.

Further downstream along the Churre, the D_{50} and D_{10} of the gravel bars material remain almost constant for 12 km (D_{50} between 10 and 30 mm), while D_{90} decreases progressively by a factor two in the Terai plain (Fig. 7a). Between 12 km and 16 km downstream of the topographical front, D_{50} rapidly drops from 20 to 0.2 mm (fining ratio *ca*. 100), whereas D_{90} decreases from 80 to 0.4 mm (fining ratio *ca*. 200), and D_{10} from 0.7 to 0.07 mm (fining ratio *ca*. 10). Across the GST, however, the D_{50} values are scattered and may vary over a wide range. Downstream of the GST, the fining of particle size is much less pronounced than at the GST, since D_{50} decreases only from 0.2 to 0.1 mm over a distance of 20 km.

The description of the whole grain size distribution curve along the Churre provides additional information on the transition. After having grouped and averaged the granulometric distribution of several adjacent stations to reduce scattering between measurements stations (Fig. 7b), we observe that the distribution above the GST is basically bimodal, that the sand mode in the gravel bars appears clearly after draining the Middle Siwalik sandstones units, and that the GST occurs by the rapid suppression of the gravel mode. Those observations are coherent with a much higher fining ratio for the coarse fraction (D_{90}) than for the fine one (D_{10}; Fig. 7a). They also show that at the GST, the calculated D_{50} in the pea-gravel or granule size does not mean that this size fraction dominates the distribution but rather that the two modes (gravels and medium to fine sand) are present in almost similar proportions and that the median size takes an intermediate value between these two modes. In those conditions, large scattering of D_{50} in the GST mostly arises from slight variations in the relative sand/gravel contents in the fluvial bars.

The evolution of grain size along the four other rivers similarly shows a sharp GST and seems insensitive to the watershed size (Fig. 6). In the Churre, Bakeya and Ratu watersheds, where the source of sediment is slightly to strongly dominated by conglomerates, the D_{50} of the alluvium drops by a factor of 100–150 over a distance of nearly 4 km. This drop occurs at a distance of 12–15 km downstream of the MFT. Along the Lakhandei River, which drains mainly sandstone, as well as along the Aurhi Khola, the gravel front is closer to the mountain front, i.e. *ca*. 8 km downstream of the MFT. Along those two rivers, despite being of similar abruptness, the GST display a lower D_{50} fining ratio of *ca.* 50, partly because the mean D_{50} in river bars is clearly lower, i.e. around 10 mm, in the upper reaches (Fig. 6).

Along all the interfan rivers, including the five measured in more detail, the gravel-sand transition appears closely related to the plan-view morphology of the channel: the GST is located within a few kilometres of a change from wide to straight braided channel to a generally narrower and more sinuous single tread channel (Fig. 3 and Fig. S1). In addition, this change is associated during winter time (i.e. during low stage) to the resurgence of the water table above the channel bottom (Fig. 3). We infer that such phenomenon mostly arises from a permeability change in the channel alluvium between the coarse alluvium upstream of the GST and the finer sandy to silty alluvium further downstream. Based on this correlation with channel morphology and water table surface expression, and also based on sparse direct measurements of grain size in other rivers, we determined that all the rivers in the Gandak/Kosi interfan area, even the larger Bagmati River, appear to display a GST located at a distance of 8–25 km downstream of the MFT.

In contrast, the relation between channel slope and downstream fining or gravel front location is more ambiguous (Fig. 8 see also channel elevation profiles of Fig. S1). On one side, the Ratu and Churre Rivers both display a significant slope decrease (by a factor 2–3) between the MFT and the GST, and might present a slight break in slope close to the GST in association with a decrease in the slope derivative on both sides of this break. On the other hand, the Bakeya River and more particularly the Lakhendei River present a more continuous slope evolution without obvious break in slope or/and slope derivative change.

DISCUSSION

Origin of sharp gravel-sand transition in present-day Himalayan rivers

Sharp GSTs have been documented in many modern and ancient fluvial systems worldwide and have been generally related to a break in slope, a local base level control, an excess in sand supply or abrasion/breakdown of fine gravel (e.g. Sambrook Smith & Ferguson, 1995; Knighton, 1999; Yatsu, 1955). If the physics of the process is still debated, selective sorting is, however, most commonly invoked as the dominant cause of an abrupt GST in aggrading

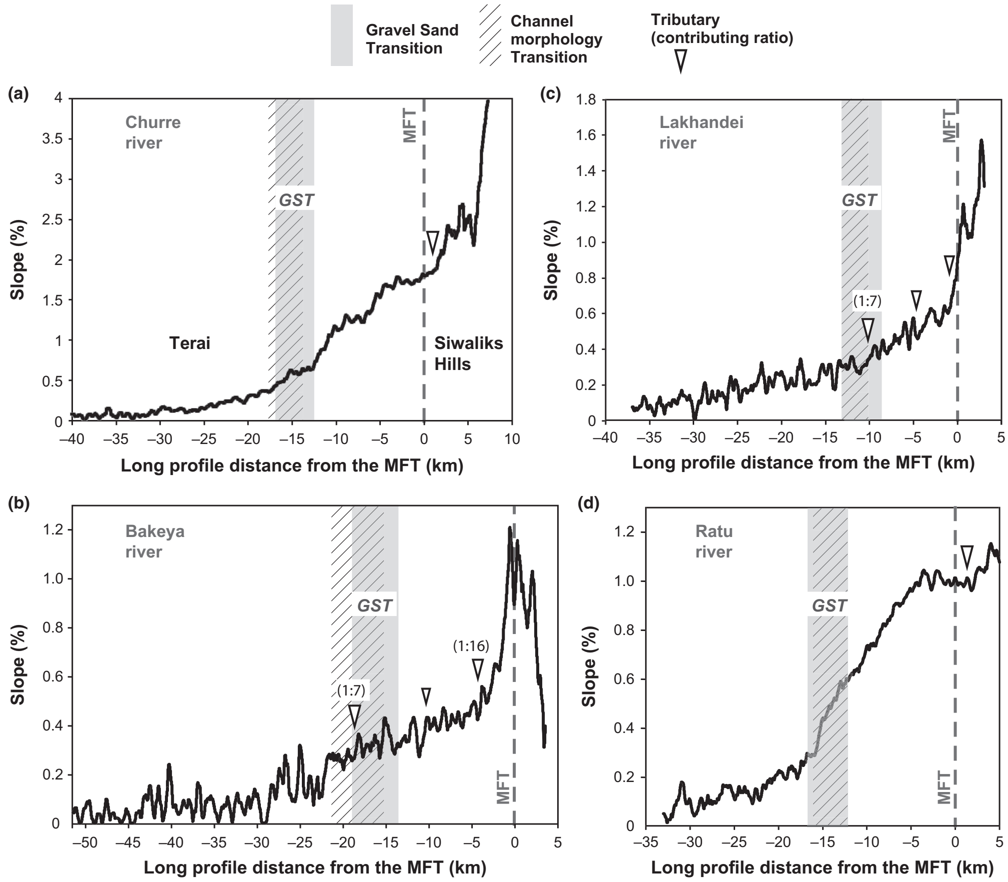

Fig. 8. Profiles of the channel gradients of the four studied Himalayan rivers. The location of the gravel-sand transition (GST) along these rivers seems independent of any significant change in channel slope along the Lakhandei and Bakeya channels, but seems to correspond to a 2-fold decrease in channel slope along the Ratu Khola and possibly along the Churre Khola. In contrast, the GST initiation does not correspond to any confluence with a major tributary that could potentially bring large sandy sediment input into the main channel.

systems (Cui & Parker, 1998; Ferguson, 2003) because downstream fining by selective sorting is greatly enhanced by active bedload sedimentation, and several attempts have been made to propose models of sediment motion that explain rapid grain sorting along river profiles (Wilcock, 1998).

Along the studied Himalayan rivers, abrasion/breakdown can easily be ruled out. As described earlier, most of the gravel load of these rivers comes from the direct input of the conglomeratic Siwalik units as confirmed by similar median size in Neogene units and present channels that drain them. To complement this first observation, we carried out some statistical analyses of pebble lithology and mechanical resistance on pebbles larger than 3 cm in the Upper Siwalik conglomerate, using a crude resistance test with the hammer. All along the conglomeratic series, the quartzitic pebbles (quartzites, quartz veins, quartzitic sandstones) represent > 75% of the pebbles (Fig. 9). Most of those pebbles are unweathered and mechanically intact, and are delivered unchanged to the fluvial network after the erosion of the conglomeratic hillslope ('recycling' of the pebbles). Experimental tests on Himalayan quartzite with bedload transport conditions close to the ones prevailing in the Himalayan rivers (Attal & Lavé, 2006) indicate abrasion rates between 0.1 and 0.2% km^{-1}, i.e. a size decrease of only *ca.* 1% after 15 km of fluvial transport. A few of the quartzitic pebbles will not survive, however, a long transport and are suspected to be rapidly fragmented either because of the weathering when micas are present or because they were fractured during tectonic loading. The other lithologies, in particular the schist or the granites, are systematically deeply weathered: even a 30-cm-large granitic boulder fully disaggregates in sand and silt fractions in a few tens of metres once delivered to the channel network. To summarize, a small proportion of weathered pebbles break down very early during transport across the frontal range and the majority of the quartzitic pebbles will survive several tens of kilometres of fluvial transport with minor size reduction. In those conditions, the observed gravel front in the Terai plain could hardly emerge from pebble breakdown/abrasion.

An excess of sand supply can also be *a priori* ruled out at least as a systematic origin of GST in Terai. For most studied rivers, the GST does not indeed coincide with a major confluence, except for the Lakhendei (Fig. 8). There, GST occurs downstream of the confluence with a tributary that drains mostly sandstone and represents 1:7 of the Lakhendei source basin. For this river, the sudden sand supply could have helped to stabilize the gravel front. Along the Bakeya, a confluence with a tributary (the Dhansar Khola) draining mostly sandstone in its headwaters occurs just downstream of the GST. Even if this local sand supply may have influenced the total length of the grain size transition, it is clearly not at the upstream origin of this transition. In other words, this process seems marginal during GST formation along most of the studied rivers.

As discussed in a previous section, the link between the GST and a break in slope along the channel profile is not systematic. In any case, deposition in the Gangetic foredeep basin has been active since several Ma in response to a long-term subsidence rate close to 0.5 mm yr^{-1} at the front of the Himalayas (Lyon-Caen & Molnar, 1985; note that this subsidence rate can be considered as almost uniform in the studied region, since it decreases progressively southward to *ca.* 0.2 mm yr^{-1} over a distance of 250 km). In such a setting, the channel long profile, as shown in 2D modelling (Paola *et al.*, 1992; Cui & Parker, 1998; Robinson & Slingerland, 1998; Ferguson, 2003; Armitage *et al.*, 2011) is not an external condition to which the river has to respond, but rather a variable that adjusts to river transport capacity and sediment size distribution and supply rate. Although we do not observe in Terai rivers a break in slope as important as in Cui & Parker's (1998) models, we qualitatively note a similar tendency as the one described in their preliminary exploration of the different variables controlling the GST geometry: in their model an increasing proportion of the sand fraction in the

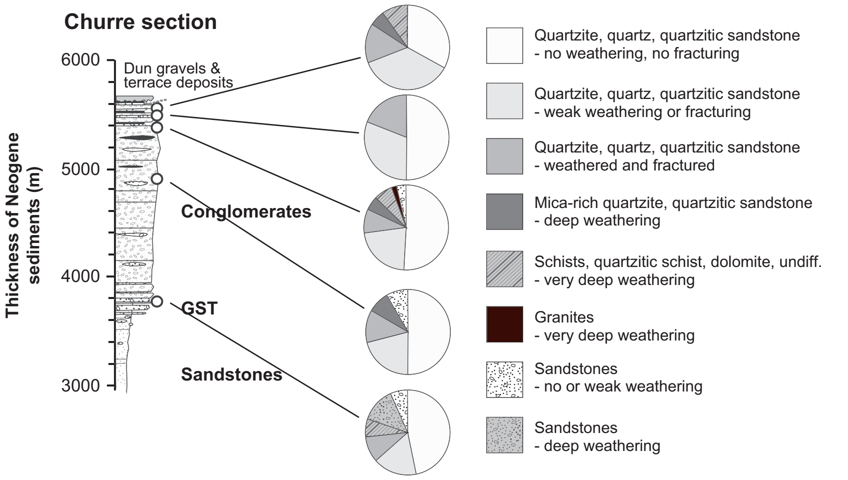

Fig. 9. Lithologic counting, including the degree of weathering or fracturing, in the conglomeratic units of the Churre section.

upstream sediment supply tends to lower the amplitude of the break in slope, because the required channel gradient to transport the sand load is higher. In central Nepal, the relative proportion of eroded Siwalik sandstone and conglomerate, i.e. the relative proportion of sand and gravel transported by the river at the mountain outlet, seems to directly impact the amplitude of the break in slope. Along the Ratu Khola, which transports the largest proportion of coarse material issued from conglomerates, the amplitude of the break in slope could be as high as a factor three, meanwhile the Lakhendei Khola that has the lowest conglomerate proportion (*ca.* 30%) does not display any break in slope at the GST.

In addition to the above discussion on the geometry of the river long profile, our observations indicate that the channel width and morphology may display a close relation with grain size. The change from braided morphology to meandering at the GST could be systematic observation as suggested by Parker & Cui (1998). Similarly, the apparent channel narrowing (Fig. S1) would have to be accounted for in 2D modelling of downstream grain size evolution as already pinpointed by Robinson & Slingerland (1998).

To summarize, our present observations along the five studied rivers rule out explanations like pebble breakdown or sand supply. We therefore propose that the distance up to which gravels are dominant in bedload is internally controlled as shown in various models (e.g. Paola *et al.*, 1992) by the available flux of gravels at the outlet of the Himalayan belt, by the subsidence rate in the Gangetic plain that permits gravel to run out by selective transport and grain sorting, and possibly by the nonlinear selective transport of two-fractions sediment load (Wilcock, 1998; Ferguson, 2003). For this latter process, as suspected by Sambrook Smith & Ferguson (1995) or Parker & Cui (1998), the bimodal nature of the sediment load (Fig. 7b), which arises for present rivers from the grain size contrast between conglomerate and sandstone units in the source rocks, could play a determinant role in the GST abruptness.

Finally, present-day rivers constitute a direct analogue to sediment transport and deposition in the proximal Gangetic plain, and bring invaluable insights on the origin of the abrupt upward coarsening in the Siwalik series. The comparison is in particular justified by the fact that present frontal Himalayan rivers erode and drain mostly molassic series: similar selective transport and sorting behaviours are thus expected to emerge from similar sediment grain size distribution with the presence of two characteristics modes (a gravel mode around 20 mm and a sand mode around 0.1 mm).

Origin of the upward sand-gravel transition in present-day Siwalik series and effect of horizontal facies migration

In central Nepal, as typically in other setting, external causes such as a climatic or a tectonic change could be invoked to explain the sharp upward coarsening. Although, the Late Pliocene age of the transition documented along the southern most frontal fold might suggests a link with the presumed global increase in erosion driven by the major Plio-Quaternary climatic change (Peizhen *et al.*, 2001), more detailed time constraints on the GST would be needed to discriminate the climatic origin of this transition. Between the Churre and Ratu sections, there are no sufficient well dated sections to determine precisely, if the age of the GST varies laterally and is clearly diachronous. However, in the Binai-Arung area, 100 km west of the Churre section (Fig. 2a), the *ca.* 4 Myr difference in GST age over a N-S restored distance of *ca.* 25 km (Tokuoka *et al.*, 1986) testifies to a strong obliquity between time lines and the facies limits transverse to the Himalayan range. In the Himachal Pradesh, foreland (northwestern India), Brozović & Burbank (2000) have similarly shown that local gravel-sand facies transition, dated around 8–10 Ma, is diachronous and vary by 2–3 Myr across distances of 20–30 km perpendicular to the Himalayan chain. The *ca.* 4 Myr age difference of identical lithofacies boundaries across the Siwalik over a distance of 25 km is much larger than the time required for a lithofacies boundary (gravel front or coarser sediments) to propagate over a similar distance following a sudden climatic or tectonic perturbation (typically less than a few 100 kyr, see Paola *et al.*, 1992; Armitage *et al.*, 2011). This suggests that a single sedimentary event driven by a regional climatic change cannot explain the sharp grain size transitions observed in the Siwalik.

External tectonic forcing can be probably ruled out for similar reasons. In addition, no major tectonic change has been documented at the end of the Pliocene: the shortening rate across the Himalayas seems roughly constant since at least 15 Ma (Mugnier *et al.*, 2004) and the onset of the major Himalayan thrust is early Miocene for the Main Central Thrust (e.g. Hubbard & Harrison, 1989), or around 11–18 Ma for the emplacement of the Ramargh thrust sheet onto the sedimentary units of the LH (e.g. DeCelles *et al.*, 1998). Similarly, magnetostratigraphic sections in central Nepal (Appel *et al.*, 1991; Ojha *et al.*, 2009) do not document any major decrease in subsidence rate during the Plio-Pleistocene that could trigger a sudden drop in coarse sediment extraction (Paola & Martin, 2012) and the concomitant and rapid progradation of a gravel front.

Moreover, it has to be noted that most bedrock and detrital thermochronologic studies (e.g. Bernet *et al.*, 2006; Herman *et al.*, 2010) do not indicate any obvious Plio-Pleistocene denudation event in the central Himalayas that could sign a major regional tectonic or climatic change.

Finally, the effect of a potential increase in the upper catchment size (Whittaker *et al.*, 2011) of the rivers draining the Terai region during the Plio-Pleistocene can also probably be ruled out: first because of the N-S diachronism observed in Binai-Arung area; second because of the megafan and interfan architecture is believed to persist without major fluvial network reorganization since the Main Boundary Thrust inception during the mid-Miocene (Gupta, 1997); and third, and perhaps more importantly, because the study of present Terai rivers shows that the GST location (Fig. 6) is apparently not very sensitive to the upper catchment area, ranging in this study between 35 km^2 (Churre) and 350 km^2 (Bakeya).

As mentioned in the introduction, classical models relating gravel progradation to an external cause have been defined in a fixed tectonic framework (Fig. 1a). In the Himalaya, like in other convergent orogens, underthrusting of the India plate below the South Tibet leads to the relative motion between the Gangetic plain and the Himalayan tectonic wedge, for example, the topographical load that flexes the Indian plate. Such relative motion, present at steady state and also called 'flexural wave', is expressed in the Gangetic plain by the southward migration of the sedimentary facies relative to the Himalayan wedge (Lyon-Caen & Molnar, 1985). In such a framework, the steady horizontal migration of a gravel front (Fig. 1b) would produce the sudden upward coarsening from sand facies to gravel facies in a vertical Siwalik section.

Even if in an old sedimentary series, geomorphic conditions such as break in channel slope or lateral sand input can hardly be reconstructed, the observation that the GST is similar in modern channels and in the Pliocene Siwalik upward sections, with a very consistent D_{50} fining ratio of *ca.* 100–150 across the transition (Fig. 10a), strongly suggests that Siwalik sediments have been deposited by palaeo-rivers whose dynamics were similar to those of the present Teraï plain rivers. The sudden appearance of pebbles in the basal part of the upper Siwalik in our sections would reflect the crossing of the sharp GST observed in present rivers. If so, the progressive southward progradation of sedimentary facies in the Himalayan foreland basin (Fig. 10b,c), is expected to induce the southward migration of the GST through time and a low obliquity of the GST relative to the stratification, in agreement with north-south progradation of the GST, with younger age towards the south, as identified further west along the Binai-Arung cross sections (Tokuoka *et al.*, 1986).

In detail, if we consider a given point of the foreland basin, during a time increment Δt, the basin subsidence, at a rate V_s, induces a sedimentation of $\Delta T = V_s\ \Delta t$. In the meantime, the sedimentary facies that characterizes that given point will prograde southward by a length $\Delta L = V_{fm}\ \Delta t$, where V_{fm} is the mean horizontal facies migration rate induced by the orogenic wedge southward motion. Removing Δt between the two equations, and applying them to the average horizontal length of the GST in piedmont rivers, L_t, and the vertical thickness, T_t, of the upward coarsening in foreland deposits (Fig. 10c), leads to the following relation:

$$V_s/V_{fm} = T_t/L_t \tag{1}$$

At the front of the Siwalik in central Nepal, V_s and V_{fm} have been estimated for the last 10 Ma, as roughly constant, with V_s = 0.4–0.5 mm yr^{-1} (Harrison *et al.*, 1993; Gautam & Rosler, 1999) from magnetostratigraphy, and $V_{fm} \approx 18 \pm 5$ mm yr^{-1} (Lyon-Caen & Molnar, 1985) from onlap migration, assuming that it equates to facies migration rate over Late Cenozoic timescale. Consequently, if the thickness of the GST in the Siwalik series is around 80–100 m, which corresponds to a vertical accumulation over *ca.* 0.16–0.25 Myr, the equivalent horizontal facies migration for the same duration, i.e. in steady conditions the length of the GST, would reach *ca.* 4 ± 2 km. This rough value (second-order compaction effects are not taken into account) is consistent with the mean length of the GST measured along present Terai plain rivers. This suggests that the GSTs observed in the Pliocene series and modern rivers have a common origin.

However, the above calculation has to be considered as mostly indicative because it is based on long-term average tectonic or sedimentary considerations.

First, facies migration is controlled by the relative displacement of the main topographical load, here the High Himalayan range, and possibly by some bending moment and force on the subducting plate (Lyon-Caen & Molnar, 1985), but also by the wedge widening (DeCelles & DeCelles, 2001). If the first process is expected to vary slowly through time, the second one can be more discontinuous (e.g. Simpson, 2006; Naylor & Sinclair, 2007). The location of the gravel front is in particular constrained by its distance to the MFT, i.e. the limit between the eroding part and the depositional part. In thin-skin tectonic scenarios, wedge widening operates through activation of new folds in front of the system. In the case of the Himalaya, new folds emerge at a distance of 15–20 km from the previous mountain front with generally the temporary existence of a piggy back basin. Such discrete events with their complexities and evolution in terms of erosion, deposition and outcropping facies, may probably blur the steady gravel front progradation related to the 'flexural wave' and induce local variations around the mean GST thickness, as potentially recorded along the Ratu section.

Secondly, we have implicitly hypothesized in the above calculation that the grain size distribution observed along the channels of the rivers draining the Terai will be directly transcribed and recorded as such into the stratigraphic record through long-term sedimentation. But the 'locking in' of the gravel-sand transition into the long-term stratigraphic record is expected to be perturbed by temporal and lateral facies variability. In the rivers studied, channel depths reach a few metres, so that, given a sedimentation rate of 0.5 mm yr^{-1}, the sediments could be reworked for several thousand years before being locked into the stratigraphic record. During this time, discharge as well sediment flux variations might induce longitudinal variations in the GST location. Channels also

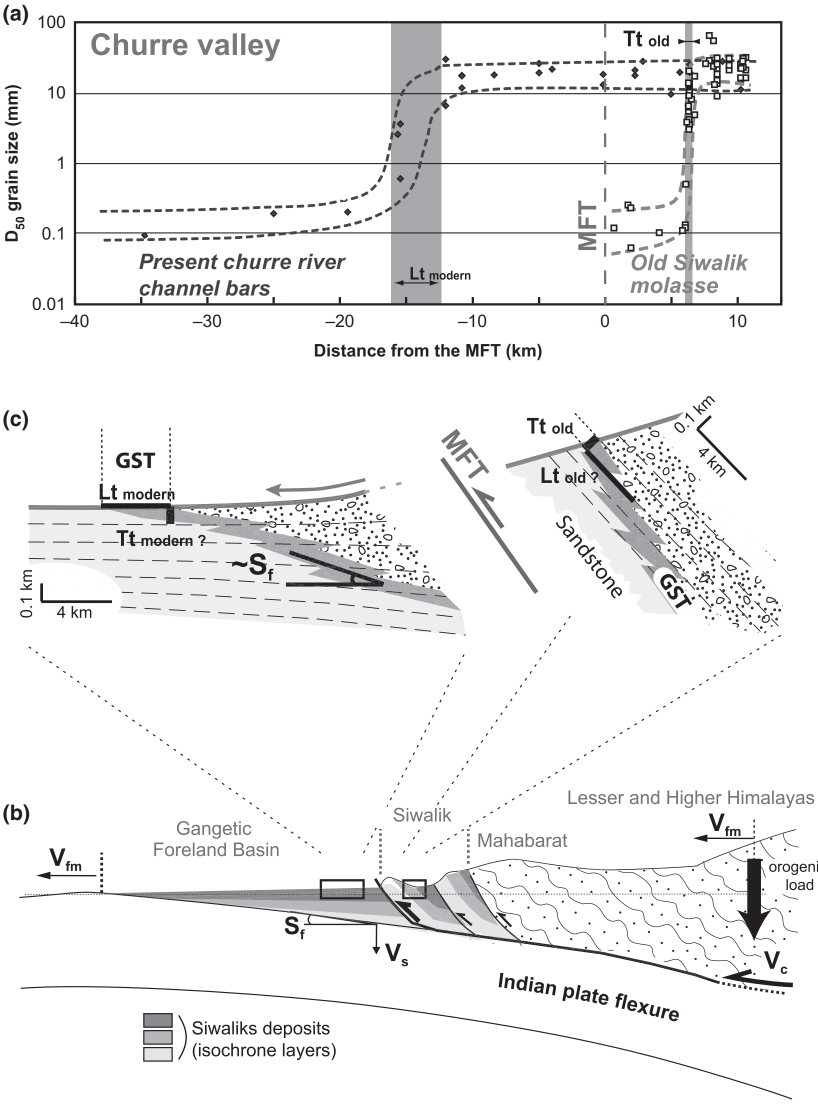

Fig. 10. (a) Along the present channel of the Churre River, the D_{50} of rivers bars display a similar evolution to the D_{50} in old Siwalik series. The horizontal length of the gravel-sand transition $L_{t\ modern}$ in the river measures about 4 km, whereas the vertical thickness of the equivalent transition $T_{t\ old}$ in molasse deposits only reaches 100 m. (b) In a context of orogenic building and convergence (at a rate V_c), the southward migration of the mountainous wedge that flexed the Indian plate induces subsidence (at a rate V_s) and facies migration (at a rate V_{fm}) in the foredeep basin. (c) The interplay between subsidence and facies migration reflects into the relation between length and thickness of the gravel/sand transition (respectively L_t and T_t), and is expressed through the relation $T_t/L_t = V_s/V_{fm}$. If we hypothesize that grain size transitions in old (right) and modern (left) Siwalik deposits have the same geomorphic origin, and that the geodynamic setting has not changed, we therefore expect $L_{t\ old} = (V_{fm}/V_s).T_{t\ old}$ to be similar to modern value of the transition length $L_{t\ modern}$. On both panels, the dashed lines represent isochrones. The '?' symbols behind Tt_{modern} and Lt_{old} indicate that these two variables are generally hardly observed or measured in many settings, in contrast to the variables Lt_{modern} and Tt_{old} measured for this study in the Gangetic plain, and in the Siwalik fold and thrust belt respectively.

migrate laterally and can thus induce at any given point facies variability such as overbank deposits within a sequence of gravel bars deposits. Although we have tried to overcome these limitations by stripping off the surface layer to the depth of the largest clasts on present-day rivers, and by not taking into account layers of overbank deposits (in the minority) in the conglomeratic Siwalik series, we recognize that these effects might both blur the abruptness of GST and its apparent thickness in the stratigraphy.

Despite these potential complexities, the similarity of the gross features of the GST in modern rivers and in the old Siwalik series, i.e. the two orders of magnitude decrease in grain size and the length/thickness of the GST, suggest that the GST in the Siwalik series of Nepal might simply emerge from the continuous and steady southward progradation of a gravel front. By analogy with the gravel front observed along present rivers, we propose that this gravel front was likely resulting from the initial grain size distribution and selective transport of the bedload, independently of an internal cause like the response to an initial break in channel slope or lateral sand input or of an external cause like a major climatic or tectonic change.

The comparison between present and past GST brings additional information: it has been proposed by Cui & Parker (1998) that a sharp gravel-sand transition could arise from two mechanisms: the gravel runs out or/and the sand transport reaches capacity and overwhelms the gravel transport capacity. Volumetric observations in Neogene Siwalik series, characterized by the relative scarcity of isolated gravel or thin gravel beds at the base of massive sand bodies below the GST, suggest that the first mechanism, i.e. gravel running out, could be the primary cause of abrupt GST in present-day Terai rivers. Such inference can be tested on present-day rivers: if gravel front forms by gravel running out, then mass conservation between gravels eroded and deposited must be verified. From incision rate profiles along the Bagmati and Bakeya rivers (Lavé & Avouac, 2000), we can roughly estimate that the mean flux of eroded conglomerate along a 15-km-long section perpendicular to the folds ranges between 7 and 25 m^2 yr^{-1} since the late and early Holocene respectively. Accounting for an *ca.* 75% survival of resistant unweathered gravels (Fig. 9), an average distance of 15 km between the MFT and the gravel front would correspond in the case of gravel running out to a sedimentation rate of coarse material between 0.35 and 1.25 mm yr^{-1} in the proximal Terai plain during the late and early Holocene respectively. Although error bars are too large for drawing any firm conclusion, those values are consistent with the mean late Neogene sedimentation rate of 0.4–0.5 mm yr^{-1} deduced from magnetostratigraphy (Tokuoka *et al.*, 1986; Appel *et al.*, 1991; Harrison *et al.*, 1993). If those conclusions could be confirmed by tighter estimates of gravel load flux leaving the Siwalik fold and thrust belt, this observation could be used in other setting either to determine either the flux of coarse bedload leaving a mountain range if the sedimentation rate is independently known or, conversely, the sedimentation rate in the proximal foreland basin if the flux of coarse bedload is known. Such development would be consistent with what has been recently proposed by Duller *et al.* (2010) or Whittaker *et al.* (2011) to unravel past sediment flux from basin subsidence rate and longitudinal fining rate in old continental series. The main difference is, however, that a method based on the gravel front location would not require as many longitudinal observations nor hypothesis on the self-similarity of the gravel or sand downstream fining (Fedele & Paola, 2007).

Gravel recycling during thin-skinned tectonic regime in the interfan areas

If the study of grain size evolution, and more particularly of the GST, can potentially bring important constrains on past flux of gravel loads leaving an orogen, and/or subsidence in the adjacent foreland basin, the evolution of the lithologic content of gravel layers could presumably bring additional information on the eroded landscape upstream. Our study of the Himalayan foreland system illustrates, however, how the original lithologic signal of the sediment source can be strongly altered in the stratigraphic record, in particular through sediments recycling in front of the orogen.

It has been shown previously across the Himalayan range that abrasion processes during fluvial transport and very contrasted mechanical resistance of the lithologies outcropping in the Himalaya lead to an over-representation of quartzitic pebbles compared to other Himalayan lithologies (dominantly gneiss, schist, limestone and sandstone) when trans-himalayan rivers reach the mountain outlet (Mezaki & Yabiku, 1984; Attal & Lavé, 2006). From this original Himalayan material already concentrated in quartz, the recycling of gravels in the interfan areas and Siwalik fold will enhance further this preconcentration. The efficiency of the quartz ‘purification’ process depends on several factors: (i) the short distance (10–20 km) of deposition of the gravels compared to the whole width of the Gangetic plain, that favours the gravel staying in the interfan area during several cycles in absence of major trans-Himalayan river outlets reorganization; (ii) the low physical erodibility of pure quartzite that permits a gravel being recycled several time without major mass and size decrease (the diametre of a quartzite pebble is expected to decrease by *ca.* 1% during a cycle), even if fracturing during tectonic loading induce some systematic per cent loss of pebbles; (iii) perhaps more importantly, the much higher resistance of quartz to weathering (see also Dal Cin, 1968; Jones & Humphrey, 1997) that rapidly removes any other lithology including impure quartzites containing micas. Regarding this later point, it is not clear if dominant weathering occurs during deposition in the Gangetic plain, a process that has been shown to be quite efficient on the sand/silt fraction (Lupker *et al.*, 2012), or/and during denudation of the Siwalik folds.

In fact, the whole erosional and sedimentation engine in convergent orogens is very efficient in concentrating quartz in coarse sediments and in suppressing other lithologies. This operates through: weathering on hillslopes that first weakens the less quartzitic lithologies; the differential pebble abrasion during fluvial transport; and through the physical pebble abrasion and mostly weathering during one to several cycles of deposition/exhumation in front of the range.

These observations on quartz survival and over-concentration in the Himalayan/Ganges system illustrates how this process can rapidly obliterate or erase the lithologic signal of the initial sediment source, i.e. of the lithologic proportions outcropping in the eroded orogen. Given that quartzite have been described as dominating gravel content in many other present or past depositional settings (e.g. Cox *et al.*, 2002), we suspect that this process might be a relatively common phenomenon in the conglomeratic stratigraphic record.

CONCLUSION

Although many terrestrial foreland basins are punctuated by sudden grain size change and despite the fact it is a widely recognized phenomenon of modern and ancient river systems, sudden and lasting transitions between fine-grained and conglomeratic facies at the scale of a sedimentary megacycle have received different and contrasting explanations, mostly based on external forcing in a context of a fixed depocentre relative to the sediment source (e.g. Burbank *et al.*, 1988; Peizhen *et al.*, 2001). Here, from a direct comparison of the grain size evolution in old Neogene Gangetic deposits and along modern rivers that drain the proximal part of the Gangetic plain, we show that an abrupt size coarsening can also arise from the steady migration of a gravel front in the foredeep basin of a converging orogen and that no change in the external forcing is required. In front of the Himalayas, as in many foredeep basins in front of convergent areas, an upward coarsening can simply emerge from steady facies migration over millions years associated to a flexural wave (Flemings & Jordan, 1989; DeCelles & DeCelles, 2001). In those situations, the abruptness of the facies transition reflects the progradation of a gravel front due mostly to internal river dynamics processes, i.e. selective sorting processes possibly in close association with the bimodal nature of the transported sediments. In actively convergent zones, like all around the Tibetan plateau and the Tien Shan, it seems for example difficult to interpret the sandstone to conglomerate transition simply as an increase in the erosion flux related to a global climatic event (Peizhen *et al.*, 2001) as confirmed, for example in Tien Shan, by important lateral diachronism of this transition (Charreau *et al.*, 2009).

Our study did not exclude the role of allocyclic mechanisms (change in external forcing and source material) as those investigated by Paola *et al.* (1992) to explain time transgression in any facies migration, including those of gravel front, in particular in setting where the depocentre is not moving relative to the sediment source. It illustrates, however, that explanations based on external forcing need to be generally backed up by independent evidence, i.e. palaeobotanical, geochemical or thermochronological data, or for large scale studies by dating of the lateral variations of GST (e.g. Burbank *et al.*, 1988). It also suggests that in convergent setting it is necessary to first remove the component due to the gravel front displacement that goes with continuous flexural wave effect before any quantitative interpretation related to an external forcing.

The Himalayan case-study illustrates also that, in contrast to a narrower range, we can define a double and partly separate tectonic control on the gravel front migration: a regional tectonic control of the High Himalayas on the location of the main load, and therefore on the flexural wave propagation and on the subsidence in the proximal part, and a local tectonic control on the mountain outlet, i.e. on the transition between the area in erosion and the area in deposition. In the setting of the Himalayan intermegafan area, both processes control the distance between the mountain front and the gravel front: the first one through the subsidence rate, the second one through the detailed geometry of the mountain front and relative proportion of eroded conglomeratic units. In any case, our study confirms (see also Fedele & Paola, 2007; Duller *et al.*, 2010; Whittaker *et al.*, 2011; Allen *et al.*, 2013) that grain size evolution in foreland series can bring important constraints on the mountain front palaeo-location, the relative balance between the flux of coarse material delivered by an orogenic source and the subsidence rates in the foreland basin.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Figure S1. Channel width and elevation profiles of the four studied Himalayan rivers.

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