LETTERS

Reorganization of the western Himalayan river system after five million years ago

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Uplift of mountains driven by tectonic forces can influence regional climate[1,2] as well as regional drainage patterns, which in turn control the discharge of eroded sediment to the ocean[3,4]. But the nature of the interactions between tectonic forces, climate and drainage evolution remains contested[5–7]. Here we reconstruct the erosional discharge from the Indus river over the past 30 million years using seismic reflection data obtained from drill core samples from the Arabian Sea and neodymium isotope data. We find that the source of the Indus sediments was dominated by erosion within and north of the Indus suture zone until five million years ago; after that, the river began to receive more erosional products from Himalayan sources. We propose that this change in the erosional pattern is caused by a rerouting of the major rivers of the Punjab into the Indus, which flowed east into the Ganges river before that time. Seismic reflection profiles from the Indus fan suggest high mass accumulation rates during the Pleistocene epoch partly driven by increased drainage to the Indus river after five million years ago and partly by faster erosion linked to a stronger monsoon over the past four million years[1]. Our isotope stratigraphy for the Indus fan provides strong evidence for a significant change in the geometry of western Himalayan river systems in the recent geologic past.

Tectonic forces in continental collision zones are widely recognized to drive rock and surface uplift that in turn affects climate locally, and even globally[1,8]. Changing topography and climate also affects regional drainage patterns, which in turn control the discharge of eroded sediment to the ocean. Thus, mountain uplift and associated orographic rainfall might be expected to accelerate continental erosion and increase mass accumulation rates on continental margins. However, in practice the sediment discharge to the ocean may also be controlled by the loss or gain of drainage to the main river course. South and East Asia are the global type areas for studies of how tectonic forces have influenced climate and drainage evolution. In East Asia, Clark *et al.*[3] analysed drainage patterns in eastern Tibet and suggested that the Red River had originally been the ancestral river of East Asia, suffering progressive loss of drainage to neighbouring systems, caused by the long-term change in regional topography. Unfortunately, the timing of capture events cannot be reconstructed from the terrestrial evidence alone.

Marine sediments can provide temporal control to drainage development models through the biostratigraphy that defines their depositional age. Capture events must affect the composition and rate of delivery of sediment to the ocean. In this study, we chose to study drainage evolution in the Indus river because the exhumation history of the source mountains is relatively well constrained[9] and the palaeoceanography and palaeoclimatology of the Arabian Sea itself has been documented back to ~14 Myr ago, allowing ready comparison with the sediment record of erosion[10,11].

We reconstructed the long-term erosional discharge from the Indus river using new and previously published seismic reflection data (Supplementary Fig. 1) to estimate accumulation rates of clastic material as a proxy for continental erosion rates. Although some sediment is preserved onshore, around two-thirds of the total volume is preserved offshore[12]. Although the profiles used to generate this budget only extend ~400 km from the coast they provide representative coverage of the sub-seafloor structure over the thickest parts of the fan. They are dated by ties to industrial well Indus Marine A-1 (ref. 13). The budget calculation process is described in the Supplementary Methods. In addition, we studied sediment samples from a series of scientific and industrial boreholes across the Arabian Sea to characterize the changing composition of Indus discharge during mountain uplift (Fig. 1). Because no single borehole penetrates the entire sequence we used a series of wells to construct a composite section (Supplementary Table 1). The provenance of the sediment was constrained through Nd isotope analysis of bulk samples. This method is based on the age and compositional differences between rocks across the India–Asia collision zone[14–17].

The Nd isotope data show a coherent temporal development, with ε_{Nd} values[18] rising gradually from around −11 at 30 Myr ago to −9.5 at 5 Myr ago (Fig. 2), implying a relatively stable provenance. This is surprising given the major tectonic events that occurred in the Himalayas during that interval, not least the exhumation of the Greater Himalayas, probably during the Early Miocene[19]. ε_{Nd} values of −10 to −11 are consistent with a relatively stable sediment provenance dominated by erosion from the Karakoram[12,14], and contrasting with the more negative (that is, Himalayan) values of the Bengal fan[20]. Erosion from the Greater Himalayas is calculated to comprise ~25% of the total Indus discharge for ε_{Nd} values of −10. However, these values are less negative than those measured from sands in the modern delta (ε_{Nd} around −15)[14]. Our new results show that the low modern ε_{Nd} values represent a trend to more negative values that started after 5 Myr ago, reaching very low values no later than the Late Pleistocene (~300 kyr ago). This shift can only be achieved by greatly increasing the input from Himalayan sources at the relative expense of the Karakoram or arc rocks of the Indus suture zone. Although the difference between the modern river and the Pleistocene may partially reflect damming of the Indus river in the past 30 years, this first-order shift from the Oligo-Miocene values must be a response to natural processes.

The bulk of the Himalayan material now contributing to the Indus river is delivered by the four large rivers of the Punjab (the Sutlej, Ravi, Chennab and Jellum rivers; Fig. 1). Although erosion of the Nanga Parbat massif contributes material of very negative ε_{Nd} values (−22 to −30)[21], the Indus river immediately downstream of Nanga Parbat has an ε_{Nd} value of around −11, which is far short of the −15 seen at the delta, or even in the Pleistocene fan sediments[12,14]. The only way to shift the net Indus sediment budget from the pre-5-Myr levels to those seen today is by an increase in the relative discharge

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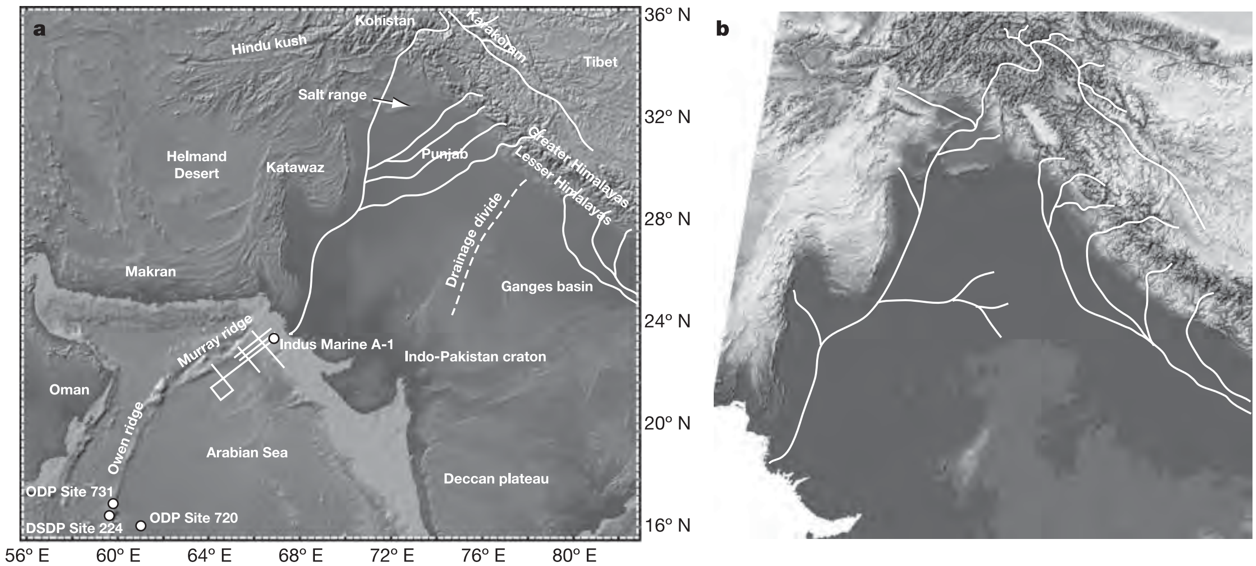

Figure 1 | Topographic maps showing post- and pre-capture Indus drainage, together with locations of drill and seismic data. a, Shaded relief map of the Arabian Sea and surrounding land masses, showing the location of the drill sites and seismic profiles considered in this study. Major tributaries of the Indus river are shown. **b**, Proposed drainage geometry in the Indus river drainage before ~5 Myr ago.

from the Himalayas. This implies that input from the Punjabi rivers before 5 Myr must have been largely non-existent.

This seems odd, because reconstruction of the exhumation histories for the western Greater Himalayas shows that these mountains were in existence before 20 Myr ago[9,21] and foreland sediments demonstrate that these ranges were being rapidly eroded during the Early to Mid-Miocene[22,23]. Nonetheless, this erosion does not seem to be communicated to the Arabian Sea until after 5 Myr ago. We suggest that the simplest explanation for this pattern is that the ancestral Punjabi rivers were connected to the Ganges and not the Indus drainage. Support for this model comes from the palaeocurrent measurements of Burbank *et al.*[23], who showed eastward flow in the foreland basin of northeast Pakistan, in the region now occupied by the Punjabi tributaries, during much of the Miocene.

The dramatic switch in isotopic character after 5 Myr ago must be driven by capture of these Punjabi tributaries to the Indus river. Why this capture occurred is not certain. This period was one of tectonic rejuvenation of the Main Central Thrust[24,25], which would be predicted to have increased the erosional contribution into the basin. In addition, early Pliocene uplift of the Salt range[26] may have been crucial in diverting rivers from their original southeastward flow into the Indus system. Alternatively, drainage capture may have occurred by a simple northeastward advance of tributaries of the Indus that short-circuited the older drainage pattern into the Ganges to provide a more direct route to the ocean.

The effect of the proposed capture on sediment accumulation rates can be seen in Fig. 2. Unfortunately the low resolution of the provenance and erosion histories makes a convincing link between the two impossible to establish at present. However, there is a clear increase in sedimentation rates from Pliocene to Pleistocene as the provenance was changing, consistent with drainage capture into the Indus system. Nd isotope character starts to change by 3.6 Myr ago when sedimentation rates were still low. However, the shift in isotope value is small, suggesting limited capture. The greatest change in provenance correlates at the first-order level with the increase in accumulation rates during the Pleistocene. However, increases in marine sedimentation rate are known from throughout Asia during the Pleistocene[27]. Average sedimentation rates approximately doubled between the Pliocene and the Pleistocene in the Indus Fan, but how much of this increase reflects drainage capture is unclear.

The Nd isotope data allow us to generate a rough estimate of how much extra Himalayan discharge would be required to produce a shift in average $\varepsilon_{\mathrm{Nd}}$ values from −10 to −13, assuming the discharge from the upper reaches of the Indus remained constant over the past 5 Myr. If the pre-capture Indus comprised ~25% Himalayan material (with an average $\varepsilon_{\mathrm{Nd}}$ value of −17 compared to −11 for the Karakoram and +8 for Kohistan[14]) to produce an average $\varepsilon_{\mathrm{Nd}}$ value of −10, then the post-5-Myr-ago shift to values of −13 would require the proportion of Himalayan material to rise to ~70% of the total, approximately a threefold increase. Total sediment discharge would thus increase by around 45%. However, because mean

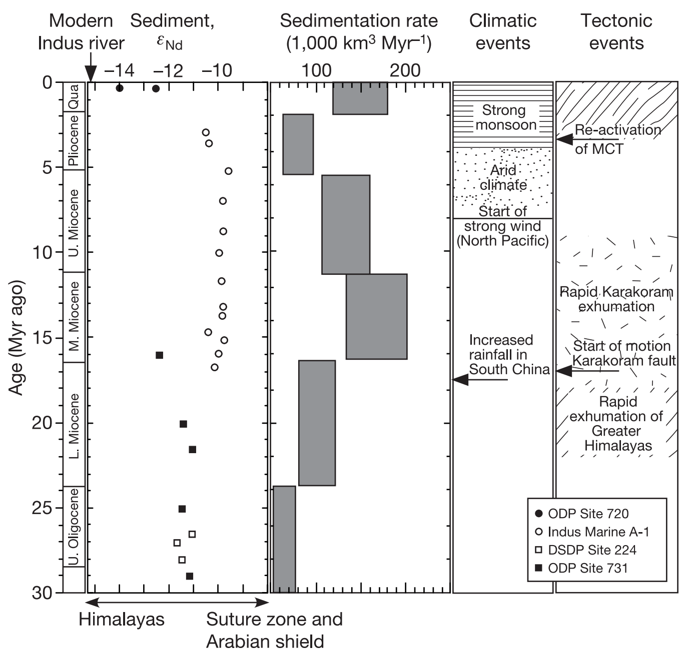

Figure 2 | The evolving Nd isotope composition and sedimentation rates on the Indus fan in relation to climatic and tectonic events known from onshore in Asia. MCT, Main Central Thrust. U., Upper; L., Lower; M., Middle; Qua, Quaternary.

accumulation rates approximately doubled after 5 Myr ago it follows that an additional volume of sediment, similar in size to that contributed from the Punjabi tributaries, must have been supplied to the Indus as a result of enhanced erosion throughout the catchment.

This study presents evidence for the nature and timing of a major drainage capture event in the western Himalayas. Faster sediment accumulation in the Pleistocene after a low in the Pliocene is estimated partly to reflect capture to the Indus after 5 Myr ago, but also seems to require faster erosion, probably driven by a stronger, wetter summer monsoon after 4 Myr ago[1]. We note that fast erosion is not unique to the cyclical glacial–interglacial climate of the Plio-Pleistocene[7], but must be controlled by other factors, at least during in the middle Miocene. Although the exact timing of drainage capture has yet to be established, the new isotope stratigraphy for the Indus fan provides strong evidence for a major change in the geometry of western Himalayan river systems in the relatively recent geologic past, probably caused by compressional deformation in the mountains. This study highlights the need to account for such capture events when trying to interpret marine erosional records, where changes in sediment composition and accumulation rates need not be directly linked to either source uplift or climate change, but simply to drainage reorganization.

Received 11 March; accepted 18 October 2005.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements P.D.C. thanks the Government of Pakistan and ConocoPhillips for access to the PAK77 survey data. We thank BGR (Hanover, Germany) for access to SO122 cruise data. N. Kusznir and A. Roberts are thanked for allowing us to use the Flex-Decomp backstripping software.

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