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# Scour in large braided rivers and the recognition of sequence stratigraphic boundaries

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**Alluvial scour into shallow marine sediments may be caused by the incision of a river adjusting to a new base level[1–4] following a fall in sea level. The identification of such erosion surfaces[1–3] has therefore been pivotal in the reconstruction of past sea-level changes from ancient sedimentary sequences[1–14]. Here we report data from a study of the Jamuna river, Bangladesh, one of the world's largest modern braided rivers[15], which illustrate that bed scour associated with channel confluences and bends alone can be substantial—as much as five times greater than the mean channel depth. Indeed, the basal erosion surfaces produced by such deep scours have characteristics similar to those of boundaries in some ancient sedimentary sequences that have been assumed to result from sea-level fall[1–14], potentially leading to radically different interpretations of past variation in base level and climate. We suggest that, to discount unambiguously the influence of fluvial scour in ancient sediments, the erosive boundary should be greater than five times the mean channel depth and extend for distances greater than the floodplain width. Ideally, it should be traceable between different basins.**

Within ancient sedimentary successions, the interpretation of base-level fall, erosive 'sequence' boundaries and the accumulation of sediments in incised valley fills is commonly assessed using a number of diagnostic criteria[3,5]. These are diachronous juxtaposition across the erosive sequence boundary of sediments deposited in different environments (such as fluvial sediments lying stratigraphically above shallow marine or shoreface deposits)[1–3,5,7]; erosional relief on the sequence boundary that is significantly greater than the mean fluvial channel depth[5–9]; a regionally extensive basal erosional surface[3,7,9]; the presence of 'interfluve' sediments, such as palaeosols, that are laterally correlative with the sequence boundary and characterize the valley margins[3,6,7,10–12]; and an erosional boundary that can be correlated between basins[1–4], a criterion which is rarely applied[8–10].

Interpretation of some sequence boundaries, however, can be difficult where it is unclear what role is played by channel avulsion (the sudden switching of a river's course) and the prevailing alluvial sediment flux[13], or by contemporary coastal erosion[14]. Additionally, a key factor in recognition of sequence boundaries is the depth of 'autocyclic' scour within alluvial channels which owes its origin to intrinsic channel flow and sediment transport processes[16]. Although many studies of ancient sediments have inferred sea-level fall when the depth of incision along the sequence boundary is larger than the estimated mean channel depth[5,6,8], such guidelines have not been tested critically with scour and channel change data from large[15] modern rivers. Yet these data are essential both to verify the criteria used in the recognition of sequence boundaries and to provide margins of error for the interpretation of sea-level fall. Reliable scour data from braided rivers, such as those detailed here, may also have especial importance for the recognition of sequence boundaries, as the higher gradients of the alluvial plain generated following sea-level fall can favour formation of multichannel rivers[5,9].

One of the world's largest river channel confluences is between the sand-bedded Jamuna and Ganges rivers in Bangladesh. These rivers, which have braidplains up to 15 km wide, have a combined annual mean discharge of 40,000 $m^3 s^{-1}$ and a sediment transport rate of $1.2 \times 10^3$ million tons per year (ref. 17), one of the highest rates of any modern river. The basis for our analysis is five bathymetric surveys that were made within the framework of the River Survey Project[17], one of the projects conducted under the Bangladesh Flood Action Plan. The five bathymetric surveys, each covering an area of $10 \times 13$ km, were made at the confluence of the Jamuna and Ganges rivers during a 28-month period from October 1993 to January 1996. Survey transects were spaced 200 m apart, generating between 23,000 and 53,000 data points for each bathymetric map. All data were reduced to Standard Low Water level (SLW), an inclined plane that is derived from long-term river-stage records. SLW at Aricha is 2.6 m above present sea level. The discharge of both rivers is dominated by the monsoon hydrograph with non-coincident flood peaks in the Jamuna and Ganges usually occurring in July and late August respectively.

Bathymetric plots from each survey (Fig. 1a–e) show two very deep scours, locally up to 30 m below SLW and five times the mean upstream channel depth (6 m), located at the Jamuna–Ganges confluence. Comparison of these surveys illustrates the remarkable mobility of these scours, which migrate up to 1.8 km during the April–October monsoon flood period (compare Fig. 1a, b with Fig. 1c; Fig. 1d with Fig. 1e). A 15-m-deep scour hole is also present on the outer bend of the western Jamuna anabranch upstream of the junction. Confluence, bend and protrusion scours up to 44 m deep have also been documented in other regions of the Bengali main rivers[18]. Maximum scour depths may also be greater during the flood hydrograph as some infilling of the major scours occurs during low flow (compare Fig. 1a with Fig. 1b and Fig. 1c with Fig. 1d). The area of the main confluence scour greater than 20 m below SLW extends for 2 km in length and 0.4 km in width. Changes in bed height between the first and last surveys (Fig. 1f) show

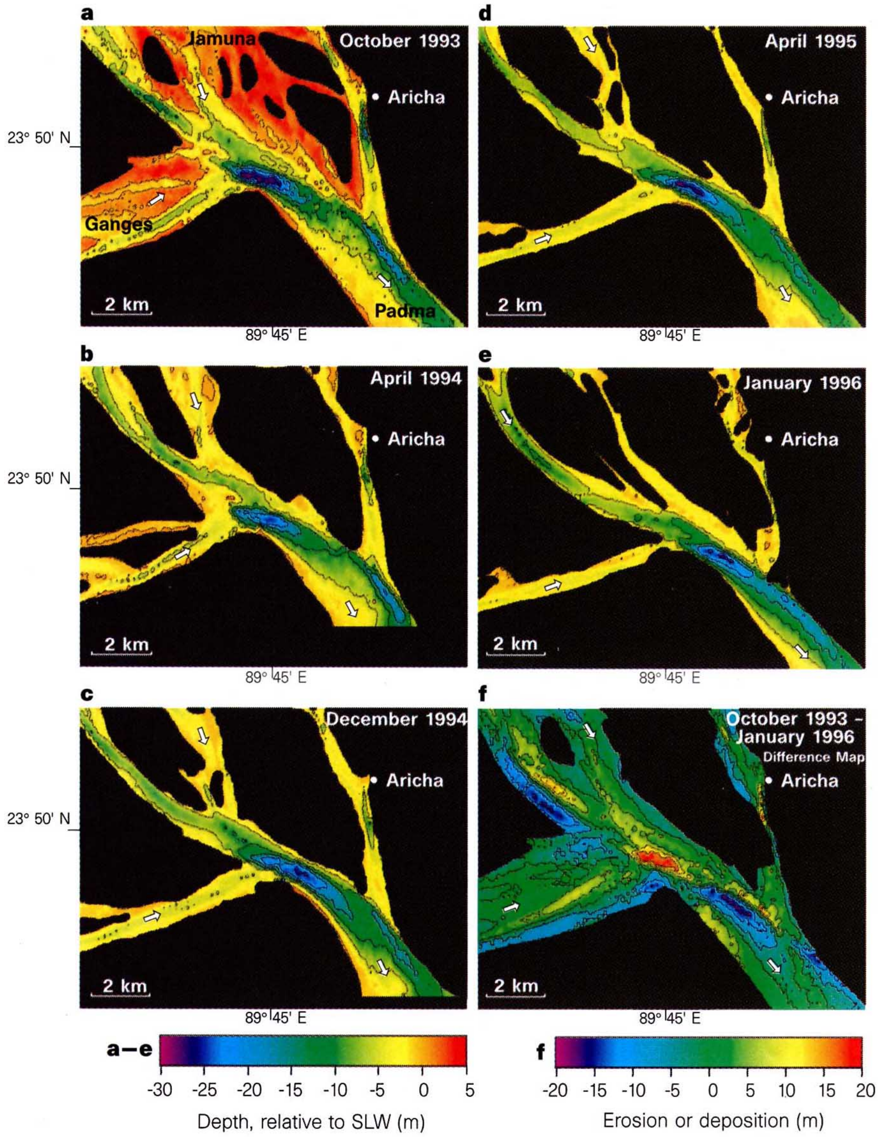


**Figure 1** Bathymetry of the Jamuna-Ganges confluence region, Bangladesh, over a 28-month period, for five surveys between October 1993 and January 1996. Bed heights are expressed relative to a Standard Low Water datum (SLW) at Aricha, obtained from long-term hydrological records, and the contour interval is 5 m. Surveys were made from boats using a differential Global Positioning system to fix location to within ±5 m and echo-sounders with a resolution of ±0.05 m to obtain bed height. Bar margins and bank edges were defined from the lateral extent of the shallow-draft boat surveys. Interpolation between survey lines is achieved by kriging (where interpolation uses a variogram model which minimizes the variance of any estimation errors) onto a 25 m grid using a spherical distribution. Parts **b** and **c** have a smaller survey coverage in the Padma River. Parts **a**–**e** show bed morphology for each survey period with superimposed position of the bar and bank margins. Part **f** shows the change in bed morphology between the October 1993 and January 1996 surveys, illustrating net erosion (<0 m) and net deposition (>0 m) between survey periods (again, contour interval is 5 m). Data provided by Delft Hydraulics/Danish Hydaulics Institute[17].

erosion and deposition up to 14 and 17 m respectively. During this time, the Jamuna–Ganges confluence scour shifted down channel by about 3.5 km, whilst the outer bend scour in the western anabranch of the Jamuna migrated laterally by 1 km (Fig. 1f). The deepest regions of these two sites show migration rates of 1.8 and 0.6 km $yr^{-1}$ for the junction and outer bend scour respectively. Downstream migration of the Jamuna–Ganges confluence scour is accompanied by 17 m of deposition at the upstream head of the October 1993 scour (Fig. 1f).

The large fluvial bed scours documented over this 28-month period erode up to 27 m below present sea level. Although subsidence will have allowed accumulation of fluvial sediments here during the period of delta progradation from this region to the present coast[19,20], these fluvial scours have incised substantially into the underlying sediments. This may result in the erosive juxtaposition of fluvial sediments on deltaic or shallow-marine deposits[20]. It is likely that scours of similar magnitude occur nearer the present-day delta mouth in the deltaic distributary channels, again generating superimposition of sediments from markedly different depositional environments. It is clear that substantial scour may thus arise from purely autocyclic processes, in the present case up to about five times the mean channel depth, in agreement with past studies of confluence scour[18,21,22]. The magnitude of such scours therefore suggests that use of mean channel depth as a criterion for inferring sea-level fall in ancient sediments[5–10] is inappropriate, and scour depths greater than five times the mean depth must be documented before autocyclic processes can be wholly neglected. This study also demonstrates that these deep river scours are extremely mobile and may migrate across the full width of the braidplain[23] (up to 15 km), thereby controlling the depth and morphology of the basal erosion surface. The erosion surface may also extend beyond the braidbelt width through the influence of channel switching and bed scour by other large rivers that drain the Bengali plain[24]. Some research[25] has suggested a progressive westward shift of the Jamuna over the past 200 years, possibly in response to tectonic tilting, and up to the 1770s the Jamuna drained into the Meghna river some 80 km northeast of the present Jamuna–Ganges junction[26]. This demonstrates that autocyclic scours, and their erosive bases, may have a far greater regional extent than the braidplain width, again highlighting the need for caution when interpreting such surfaces in the ancient rock record. It should also be noted that soils develop rapidly in abandoned parts of the floodplain and on stable, large (30 × 15 km) braid bar complexes[23,25], thus forming 'interfluve' regions, contemporaneous with the scour surfaces, but away from the true valley margins.

The morphology of the Jamuna–Ganges confluence has a strikingly similar geometry to junctions of smaller (<100 m wide) natural channels[18,21,22] and those simulated in laboratory experiments[21,22], although the bed slopes leading into the Jamuna scours are generally low angle (<5°) without a significant avalanche face. Predictions of scour depth from past studies[21,22] for the 75° junction angle of the Jamuna–Ganges confluence range between 2 and 4 times the mean channel depth[18]. The scale invariance of junction morphology increases the application of small-scale modelling experiments[21,22] and suggests similarity in the flow and sediment transport processes that control confluence geometry and stability. Because junctions form key nodes within the braided network, such scale invariance may aid our understanding of the fundamental processes that cause channel braiding[27].

Recognition of the extent and formative processes of fluvial scour is critical both in devising engineering strategies for large braided rivers[23,25,28] and in providing reliable and robust process-based criteria for aiding interpretation of ancient sediments and sea-level changes. These data from the Jamuna and Ganges rivers demonstrate that autocyclic scours may fulfil most of the diagnostic criteria used by many workers to infer sequence stratigraphic boundaries and sea-level fall in the ancient rock record. Although many case studies do convincingly document substantial sea-level fall and the subsequent alluvial response[3,4,19], our investigation of large alluvial channels suggests that to define base-level controlled incision unambiguously, several criteria must be examined and satisfied. First, the basal erosion surface must be greater than five times the mean channel depth. Second, an estimate of both channel and braidplain width should be obtained to provide limits for the local extent of basal scour. Third, mean avulsion step length should be estimated to indicate the regional extent of the autocyclic basal erosion surface. Fourth, erosive sequence boundaries should be traceable between basins. Finally, the occurrence of palaeosols, at the same chronostratigraphic level as the erosive surface, may not by itself be diagnostic of a true valley interfluve and must be examined in relation to the sedimentology of the underlying deposits. □

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