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Braided Rivers: Process, Deposits, Ecology and Management

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Braided rivers: where have we come in 10 years? Progress and future needs

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INTRODUCTION

In 1992, the first conference on Braided Rivers was held at the Geological Society of London (Best & Bristow, 1993). It sought to bring together a wide range of practitioners, primarily sedimentologists, geomorphologists and engineers, to review the state-of-the-art in research, and discuss common problems and future research directions. At the time of the first conference, considerable effort had been devoted to the investigation of single-channel meandering channels, as well as more generic considerations of coarse-grained rivers, as championed by the benchmark series of gravel-bed rivers conferences that had begun in the 1980s. However, with the backdrop of the onset of management plans for one of the world's greatest braided rivers, the Brahmaputra–Jamuna (see Mosselman, this volume, pp. 277–288 and Sarker & Thorne, this volume, pp. 289–310, for updates), there was a consensus that research into braided rivers was not as advanced as for single channels, and several of the papers at the 1992 meeting outlined future avenues for research (e.g. Bridge, 1993; Bristow & Best, 1993; Ferguson, 1993). A decade on, after the second conference on braided rivers held at the University of Birmingham in 2003, it is thus appropriate to ask how much progress we have made during this period and what are the future research needs? The purpose of this brief introductory paper to the contributions in this book is to outline some key developments, place the chapters that follow into some kind of context and, perhaps most importantly, highlight areas where little progress has been made or where recent research has shown that more work is required. The topics identified are not, of course, exhaustive, but reflect the flavour of discussions at the second conference, and hopefully will serve as a backdrop to the contributions that follow.

DYNAMICS

It is fair to say that study of the dynamics of braided rivers has been revolutionized in the past decade, largely through the development of new techniques for measuring flow and bed morphology. Three broad techniques can be highlighted as having produced significant results and hold huge future promise:

1 flow quantification using acoustic Doppler current profiling (ADCP);
2 direct measurement of bed morphology using multibeam echo sounding (MBES);
3 remote sensing of braided river morphology using synoptic digital photogrammetric and airborne laser survey methods, from which digital elevation models (DEMs) can be developed (e.g. Lane, 2000, this volume, pp. 107–135; Westaway *et al*., 2000, 2001; Hicks *et al*., this volume, pp. 311–326).

Significant progress has been made in each of these areas and these now offer, for the first time, the possibility of quantifying flow process, bed morphology and channel change in a wide range of types and scale of braided rivers.

Richardson *et al*. (1996), Richardson & Thorne (1998, 2001) and McLelland *et al*. (1999) have applied ADCP to the study of flow around braid bars in the Brahmaputra–Jamuna, and examined the nature of secondary flows associated with braid bars. Acoustic Doppler current profiling technology, which has largely been transferred from oceanographic studies, has thus opened up the opportunity to study the fluid dynamics of large rivers (see Best *et al.*, in press) for examples in the Brahmaputra–Jamuna). Application of ADCP within large braided rivers can achieve quantification of the mean flow field in complex bed geometries such as that associated with large sand-dune fields (e.g. Parsons *et al.*, 2005), and at-a-point monitoring can offer the opportunity to examine turbulence characteristics (Barua & Rahman, 1998; Roden, 1998), although careful consideration must be given to sampling volume and time scales in relation to the scale of turbulence. Additionally, the recent development of shallow-water ADCP (see http://www.sontek.com/product/asw/aswov.htm) now opens up the opportunity of achieving flow-field quantification in smaller braided rivers. Recent work (Rennie *et al.*, 2002; Rennie & Villard, 2003; Kostaschuk *et al.*, 2004) has even begun to suggest that ADCP may be used to estimate bedload grain velocities over sand beds, and this may offer future potential for quantifying sediment transport rates.

Multibeam echo sounding technology has improved rapidly in the past few years, and systems are now available that can achieve accuracies of 5–10 mm in bed height and cover large swath widths relatively rapidly (e.g. see Bartholomä *et al.*, 2004; Wilbers, 2004; Parsons *et al.*, 2005). Multibeam echo sounding promises the ability to obtain high accuracy repeat surveys of the deepest and most turbid braided rivers, and achieve the long sought after aim of being able to accurately quantify channel change on a range of scales from the bedform to barform and whole channel. Again, these systems can be used with ADCP to examine sediment transport rates through quantification of bedform and bed morphological change (e.g. Abraham & Pratt, 2002; Bartholomä *et al.*, 2004).

Photogrammetric quantification of the surface morphology of braided rivers has also evolved rapidly in the past decade (see Lane, 2000, this volume, pp. 107–135; Westaway *et al.*, 2000, 2001; Lane *et al.*, 2003, this volume, pp. 107–135), and DEMs can be produced to quantify morphological change and estimate sediment transport rates, something that has always been problematic in braided rivers. Additionally, it has been demonstrated (Lane *et al.*, 2003) that the levels of error using these methods are similar to those of traditional ground surveying and are far superior where cross-section spacing exceeds 100 m. However, perhaps the real breakthrough is that these methods can be used over a much greater spatial scale than traditional ground surveys. For example, Lane *et al*. (2003) used DEMs that covered an area 1 km wide and 3.5 km long on the braided Waimakariri River (see Lane, this volume, pp. 107–135). Using traditional ground-based surveying, study reaches have been typically only of the order of hundreds of metres in length (e.g. Goff & Ashmore, 1994).

The improved quality of the morphological data now available will enable small-scale processes to be studied over much wider areas. This provides the opportunity for much greater collaboration with those undertaking numerical modelling, as data will become available at a much higher resolution, which is more appropriate for both gridding input and validation of some of the numerical modelling techniques outlined below. The challenges that lie ahead for the further development of DEM techniques are to try and apply them both at increased temporal scales and during high discharge events. This may restrict this type of study to rivers whose water may be relatively clear during flood. However, if DEMs could be constructed through flood events, this would greatly enhance our understanding of the dynamics of morphological change, as well as providing techniques for channel management. Additionally, all three of the methods outlined above hold significant promise for combining with improved techniques to study the subsurface (see 'Deposits' below) and provide a fuller understanding of the links between process, form and deposit.

When reviewing the research conducted over the past decade on both channel and bar dynamics, it is apparent that although braided rivers are composed of roughly equal numbers of confluences and diffluences, research has tended to be dominated by studies of the confluence zone. This is a clear gap in understanding, as diffluences also exert an important influence on the routing of sediment and water downstream, and hence the overall dynamics of the braidplain evolution. In recent years, some progress has begun to be made in this area (e.g. Richardson & Thorne, 2001; Bolla

Pittaluga *et al.*, 2003; Federici & Paola, 2003; Zolezzi *et al.*, this volume, pp. 233–256), but it is apparent that much further work is required to detail the dynamics of diffluences at a range of scales, and to elucidate how flow and sediment routing may be connected between confluence and diffluence nodes. In particular, there is an urgent need for comprehensive field studies of these diffluence zones utilizing the techniques outlined above to complement physical and numerical modelling work.

DEPOSITS

A decade ago, Bridge (1993, p. 13) concluded that 'existing braided-river facies models are virtually useless as interpretive and predictive tools'; it is thus pertinent to ask what has been achieved since the 1992 conference, and if we are any nearer to better predictive models of the subsurface character of braided rivers (see Bridge & Lunt, this volume, pp. 11–50)? One significant area of advance in this time has been the development and widespread adoption of ground penetrating radar (GPR) for use alongside the more traditional methods of trenching, outcrop description and coring. The application of GPR has enabled significant advances in the three-dimensional description of the architecture of braided river deposits and their facies. However, whilst being extensively utilized by those studying modern deposits (e.g. Bridge *et al.*, 1998; Best *et al.*, 2003; Skelly *et al.*, 2003; Lunt *et al.*, 2004) and Quaternary sediments (e.g. Huggenberger, 1993; Beres *et al.*, 1999), GPR has not been widely adopted by those studying ancient deposits, who often still rely on traditional techniques of outcrop observation. The more limited application of GPR to ancient braided river deposits is perhaps principally due to the problems generated by diagenesis and rock fracture that can overprint and obscure primary depositional fabrics (see Bristow & Jol, 2003, and references therein), although some studies have successfully employed GPR within ancient fluvial sediments (e.g. Corbeanu *et al.*, 2001; Truss, 2004).

Despite the significant progress made through the use of GPR, many issues remain unresolved. For instance, only a handful of modern braided rivers have received detailed study using GPR, and only one of these rivers has been gravel bed (Lunt & Bridge, 2004; Lunt *et al.*, 2004; Bridge & Lunt, this volume, pp. 11–50). Studies of ancient gravelly braided alluvium (e.g. Huggenberger, 1993; Beres *et al.*, 1999; Huggenberger & Regli, this volume, pp. 51–74) have thus been useful, although there is still a relatively poor characterization and understanding of both the similarities and differences in the depositional facies as a function of bed grain size. Additionally, most GPR data are still presented in a largely descriptive and qualitative way, and thus, although this has permitted a better understanding of facies relationships within and between different braided rivers (e.g. Sambrook Smith *et al.*, 2005), these data have rarely been collected, presented or used in a way that make them useful for modelling or undertaking statistical analyses to assess the differences/similarities between rivers.

Additionally, although progress has been made towards establishing explicit links between formative processes and depositional product (e.g. Ashworth *et al.*, 2000; Best *et al.*, 2003; Lunt *et al.*, 2004), it is clear that far more such studies, over a range of sizes and types of braided rivers, are required. Specifically, the new techniques outlined above (ADCP, MBES and photogrammetry) hold great promise for quantifying holistic braided river change, at a range of scales from the bedform to channel belt, and could be undertaken in conjunction with GPR surveys over longer time periods to link process and product more precisely than has hitherto been possible. Such an approach appears a priority. A final key problem is that the GPR studies mentioned above have generally concentrated on a few active bars within each river studied, and there is thus very little information on facies relationships across the entire braidplain (i.e. including channels). Such information is, however, critical when assessing preservation potential and applying such data to the ancient record, and there is thus a clear need for data to be collected from not just active bars but all areas of the braidplain. The study of abandoned sections of the braidplain may prove useful in this respect, and may require the use of other geophysical techniques such as electrical resistivity (Baines *et al.*, 2002) or time domain reflectometry (Truss, 2004), given that GPR does not perform well in clay-rich sediments such as may be found in older deposits of the braidplain. These techniques may also allow us to piece together more precisely the links between subsurface flow and alluvial architecture (e.g. Bridge & Tye, 2000; Truss, 2004; Huggenberger & Regli, this volume, pp. 51–74).

NUMERICAL MODELLING

A decade ago, little progress had been made in the numerical modelling of either flow dynamics or sediment transport within braided rivers. However, given the difficulty of obtaining reliable field-based datasets on flow and sediment transport in braided rivers, the derivation of robust numerical models was a clear priority that needed to be addressed, as identified by Ferguson (1993, p. 85) who stated that 'numerical modelling is potentially a much better way of investigating dynamic interactions in evolving braid units'. Since this statement, progress has been made in three broad areas:

1 the application of commercially available computational fluid dynamics (CFD) software;
2 the development of cellular models to investigate planform evolution and characteristics;
3 initial attempts to produce full physically-based numerical models of aspects of braided river evolution.

Computational fluid dynamics models involve the construction of a grid or mesh to represent the flow domain over bed topography, and the Navier–Stokes equations are then calculated for each cell in the grid in three dimensions, such that rules relating to the conservation of mass and momentum are not broken. Some success has been achieved with this approach where it has been applied to either channel confluences (e.g. Bradbrook *et al.*, 1998) or flow around an individual bar (e.g. Lane & Richards, 1998; Nicholas & Sambrook Smith, 1999). However, there are two outstanding issues that need to be resolved before such models can be applied further. First, since braided rivers are characterized by varying topography and multiple channels, the geometry at a range of scales from grain to channel is complex. Such topography requires schemes to account for complex flow both near the bed and within the bed (an important consideration in streambed ecology), such as those being advanced by Lane *et al*. (2002, 2004) and Hardy *et al*. (2005), which can better capture near-bed flow, including the numerous areas of separated flow. Second, modelling of braided river change requires linkage to sediment transport algorithms (see Marti & Bezzola, this volume, pp. 199–215; Meunier & Metivier, this volume, pp. 217–231) and simulation of new bed topography, thus demanding that a new mesh is constructed for each change in topography following erosion or deposition. This problem has also begun to be addressed by Lane *et al*. (2002) who have developed a method for using CFD that does not require structured grids with boundary-fitted coordinates. Although only tested on a small scale, this new methodology has great potential to begin to develop full physically based models of braided river flow and sediment transport dynamics. Some progress in this area has also begun with attempts to model the evolution of alternate bars (see Bernini *et al.*, this volume, pp. 153–175). Since alternate bars may represent one route in the first stages of bar growth (e.g. see model of Bridge, 1993), if these forms can be modelled, it could lead to the successful development of models for far more complex bed morphology. However, this remains some way off since the modelling conducted to date has been restricted to fairly simple channel geometries. The further development of these models also requires, as always, more computational power, although multinode parallel processing now offers greater potential than ever before.

Another area where progress has been made in modelling braided rivers in the past decade is the development of cellular models, as first outlined by Murray & Paola (1994, 1997) and more recently modified by others (e.g. Nicholas, 2000; Thomas & Nicholas, 2002; Lane, this volume, pp. 107–135; Nicholas *et al.*, this volume, pp. 137–150). The cellular modelling approach operates in a relatively simple way, starting with a network of cells with a random variation in their elevation. Water is then routed to adjacent cells on the basis of the bed gradient between cells, with more discharge flowing between cells with a greater bed slope. The movement of sediment can then also be routed such that the transport rate is related to the discharge moving between two cells, with lateral flows of water and sediment being accommodated in the model. Although this approach does not capture or simulate the process dynamics or real physics of braided river flow, Murray & Paola (1994, 1997) demonstrated that this relatively simple approach can replicate some of the gross planform features of braided rivers. The work highlights that the presence or absence of appreciable local redeposition of sediment appears to be a key control of braiding, as revealed in the early physical modelling studies of Leopold & Wolman (1957). This cellular automata approach was further developed by Nicholas (2000) to take account of more variable conditions of channel width and discharge, and generated improved estimates of bedload yield when compared with previous approaches. A significant result of the study of Nicholas (2000) was that, even at relatively low flows, the model predicted higher rates of sediment transport than other models, a reflection of how areas of deep water, and higher transport rates, still occur within the braidplain even when average depths are low. An increased braiding intensity may thus lead to higher rates of sediment transport. The further development of these approaches represents an area where progress should be possible over the next decade, as discussed by Nicholas (2005), Lane (this volume, pp. 107–135) and Nicholas *et al*. (this volume, pp. 137–150).

The development of numerical models to simulate the deposits of braided rivers has perhaps been more limited. Instead of the more physically based approaches adopted by geomorphologists and engineers in modelling using a CFD approach, focus has largely concentrated on geometrical models that 'attempt to produce spatial patterns similar to those observed in the field using empirically derived geometrical relationships' (Webb & Anderson, 1996, p. 534). This approach has the advantage that it requires less computational power and so can potentially be used to address issues on a broader temporal and spatial scale. However, some have questioned how closely such approaches represent the actual deposits of braided rivers (see Bridge & Lunt, this volume, pp. 11–50) and there is clearly more progress to be made in this respect. A more explicit linking of the physically based approaches used to study surface processes with likely depositional sequences forms one of the key frontiers in predicting the architecture of braided river alluvium and forms a key area for research between geomorphologists, applied mathematicians, engineers and Earth scientists.

SCALE

Issues relating to the scale of braided rivers are fundamental and were identified as a key research area by Bristow & Best (1993, p. 3) who wrote 'The issue of scaling depositional form and formative process across this range [laboratory flume to 20 km wide braidplains] of braided channel sizes is rarely addressed yet is central when applying results and models from one channel size to a system of a completely different magnitude'. There has been significant research into various aspects of scale over the past decade, perhaps most notably the papers by Sapozhnikov & Foufoula-Georgiou (1997; Foufoula-Georgiou & Sapozhnikov, 2001) on the scale invariant aspects of braided river surface morphology and evolution. This work concludes that braided rivers display statistical scale invariance in their morphology but dynamic scaling in their evolution. These conclusions were suggested to be valid for a wide range and type of braided rivers, and only break down where there are strong geological controls on the river channel pattern. The importance of this work is that it suggests that the results of morphological studies from a small section of a braided river can be applied to a larger one, or that the results obtained from physical modelling experiments can be applied to a field prototype. The application of these issues with respect to the modelling of braided rivers is discussed by Doeschl *et al*. (this volume, pp. 177–197). The challenge now remains to investigate whether hydrological variables also display the same type of scale invariance.

Progress has also been made in investigating the scale invariance of braided river deposits, a more complex problem since the three-dimensionality of the form must be considered, together with preservation potential, rather than solely the two-dimensional planform as discussed above. Relationships between the scale of bedforms and their preserved stratasets have been proposed (Bridge, 1997; Bridge & Best, 1997; Leclair *et al.*, 1997) and there is now a need to extend this approach to cover larger features such as unit and compound bars. From a broader perspective, Sambrook Smith *et al*. (2005) compared, in a qualitative sense, facies from three different sandy braided rivers spanning three orders of magnitude in scale. They concluded that these rivers did exhibit a degree of scale invariance although a range of other factors, such as discharge regime, local bar and channel topography, the channel width:depth ratio and abundance of vegetation, also needed to be taken into account. The discussions by Bridge & Lunt (this volume, pp. 11–50) and Kelly (this volume, pp. 75–106) develop the issue of scale further within the context of braided river deposits.

ECOLOGY

In 1999, Ward *et al*. (1999, p. 71) stated that 'The role of islands has been almost totally ignored by stream ecologists'. However, in recent years there has been a major re-evaluation of some of the paradigms of river ecology in the context of braided rivers (e.g. Ward *et al.*, 1999, 2001, 2002; Tockner *et al.*, 2000; Stanford & Ward, 2001; Tockner, this volume, pp. 339–359), together with a growing new understanding of how ecological and geomorphological processes interact in such areas as braid bar formation and evolution (e.g. Edwards *et al.*, 1999; Kollmann *et al.*, 1999; Gurnell *et al.*, 2000, 2001; Johnson, 2000; Petts *et al.*, 2000; Gurnell & Petts, 2002; Van der Nat *et al*., 2003; Francis *et al.*, this volume, pp. 361–380). This body of work represents substantive progress in new areas over the past decade, as evidenced by the fact that there were no contributions on ecological processes at the first Braided Rivers conference in 1992. Progress in this area has also been characterized by an interdisciplinary approach, primarily between ecologists and geomorphologists, and the results of this research have led to development of channel management based on sound ecological, as well as geomorphological, principles (see Piégay *et al.*, this volume, pp. 257–275; Surian, this volume, pp. 327–338); the need for, and utility of, such approaches are shown, for example, by the fact that they are a key component of new legislation such as the European Union Water Framework Directive.

The basic assumption underpinning many key concepts within river ecology, such as the River Continuum Concept (Vannote *et al.*, 1980), the Serial Discontinuity Concept (Ward & Stanford, 1983) and the Flood Pulse Concept (Junk *et al.*, 1989), is that rivers are essentially single-channel systems. Such an assumption makes these concepts difficult, if not impossible, to apply to braided rivers that characteristically have great spatial and temporal variability at a wide range of scales in properties such as flow depth, grain size, bar stability and the connectivity between channels. It is this variability in habitat that contributes towards the high biodiversity typical of braided rivers. For example, Tockner *et al*. (2000) modified the Flood Pulse Concept and coined the term 'flow pulse' to represent the importance of below-bankfull events in connecting different areas within a river system. This is especially important for braided rivers, where the multiple bars and channels can all be at slightly different elevations, and where modest changes in discharge can thus lead to significant differences in connectivity between the different parts of the river. The nature of this connectivity will determine the exchange of solids (e.g. organic material and siliciclastic sediment) and organisms across the braidplain; the complexity inherent within these relationships has only just begun to be identified and studied.

The problems associated with flow stage inherent within the idea of the 'flow pulse' are not unique within river ecology. Geomorphologists have long debated how flow stage can influence the processes of bar evolution, and whether it is valid to relate low-flow observations of exposed bars to high-flow conditions when bars may be submerged and thus often difficult to observe. Likewise, the calculation of the braiding index of a river or measurement of bar dimensions will all be influenced by flow stage. Bristow & Best (1993, p. 2) stated that 'little data exists for the comparison of bar and channel morphology at different flow stages', and it is still apparent that such data could prove a useful collaborative venture for both ecologists and geomorphologists alike. The new remote sensing techniques currently being used to quantify braided river topography (see Lane, this volume, pp. 107–135; Hicks *et al.*, this volume, pp. 311–326) promise greatly improved levels of accuracy in this respect and will find strong uses in ecological applications. For example, sequential images could be used to accurately quantify patterns of flow depth, bar area and bar edge length that can be related to ecological surveys conducted over the same time period; these can then be used to predict temporally varying connectivity and its ecological consequences across the braidplain. Use of this knowledge in a predictive sense requires closer collaboration between ecologists and Earth surface scientists seeking to model braided river systems. Again, although the numerical modelling of braided rivers is still in its infancy (see above), there is great potential to use such numerical models to predict patterns of change within a system of relevance to ecologists, as outlined by Richards *et al*. (2002).

SUMMARY

Perhaps the most influential positive trend in the past decade has been the increased level of communication and collaboration between the range of disciplines that have researched braided rivers. It is thus apparent that much progress has been made in meeting the challenge of Bristow & Best (1993) for a greater discourse between braided river scientists. This continued willingness to work in an interdisciplinary manner will be central when meeting the challenges of the next decade, and applying this knowledge in areas as diverse as channel management and sustainable river ecology to the characterization of ancient alluvium forming hydrocarbon reservoirs. Key areas of research that appear ripe for study, and some of which are begun in the contributions within this volume, include:

1 Quantification of the full range of feedbacks and links operating between the geomorphological and ecological components of the braidplain.
2 Increasing the temporal resolution at which geomorphological data are collected, with particular emphasis on flood events and long-term monitoring of channel evolution.
3 Providing a more explicit link between the processes of bedform, bar and channel evolution and their resultant deposits.
4 Using and applying sedimentological data in a more quantitative way to enable the development of statistical and numerical models of deposits.
5 Conducting the above studies in a range of braided river environments, scales and grain sizes to properly assess the degree to which current models (whether ecological, geomorphological or sedimentological) can be applied.

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REFERENCES

Abraham, D. and Pratt, T. (2002) *Quantification of Bed-load Transport using Multibeam Survey Data and Traditional Methods*. ERDC/CHL CHETN-VII-4, US Army Engineer Research and Development Center, Vicksburg, MS. http://chl.wes.army.mil/library/publications/chetn

Ashworth, P.J., Best, J.L., Roden, J.E., Bristow, C.S. and Klaassen, G.J. (2000) Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. *Sedimentology*, **47**, 533–555.

Baines, D., Smith, D.G., Froese, D.G., Bauman, P. and Nimeck, G. (2002) Electrical resistivity ground imaging (ERGI): a new tool for mapping the lithology and geometry of channel-belts and valley-fills. *Sedimentology*, **49**, 441–449.

Bartholomä, A., Ernstern, V.B., Flemming, B.W. and Bartholdy, J. (2004) Bedform dynamics and net sediment transport paths over a flood-ebb cycle in the Grådyb channel (Denmark), determined by high-resolution multibeam echosounding. *Geogr. Tidsskr. Dan. J. Geogr.*, **104**, 45–55.

Barua, D.K. and Rahman, K.H. (1998) Some aspects of turbulent flow structure in large alluvial rivers. *J. Hydraul. Res.*, **36**, 235–252.

Beres, M., Huggenberger, P., Green, A.G. and Horstmeyer, H. (1999) Using two- and three-dimensional georadar methods to characterize glaciofluvial architecture. *Sediment. Geol.*, **129**, 1–24.

Best, J.L. and Bristow, C.S. (Eds) (1993) *Braided Rivers*. Special Publication 75, Geological Society Publishing House, Bath, 419 pp.

Best, J.L., Ashworth, P.J., Bristow, C.S. and Roden, J.E. (2003) Three-dimensional sedimentary architecture of a large, mid-channel sand braid bar, Jamuna River, Bangladesh. *J. Sediment. Res.*, **73**, 516–530.

Best, J., Ashworth, P., Sarker, M.H. and Roden, J. (in press) The Brahmaputra–Jamuna River, Bangladesh. In: *Large Rivers* (Ed. A. Gupta). Wiley, Chichester.

Bolla Pittaluga, M., Repetto, R. and Tubino, M. (2003) Channel bifurcation in braided rivers: equilibrium configurations and stability. *Water Resour. Res.*, **39**, 1046–1059.

Bradbrook, K.F., Biron, P.M., Lane, S.N., Richards, K.S. and Roy, A.G. (1998) Investigation of controls on secondary circulation in a simple confluence geometry using a three-dimensional numerical model. *Hydrol. Process.*, **12**, 1371–1396.

Bridge, J.S. (1993) The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: *Braided Rivers* (Eds J.L. Best and C.S. Bristow), pp. 13–71. Special Publication 75, Geological Society Publishing House, Bath.

Bridge, J.S. (1997) Thickness of sets of cross strata and planar strata as a function of formative bedwave geometry and migration, and aggradation rate. *Geology*, **25**, 971–974.

Bridge, J.S. and Best, J.L. (1997) Preservation of planar laminae arising from low-relief bed waves migrating over aggrading plane beds: comparison of experimental data with theory. *Sedimentology*, **44**, 253–262.

Bridge, J.S. and Tye, R.S. (2000) Interpreting the dimensions of ancient fluvial channel bars, channels, and channel belts from wireline logs and cores. *Am. Assoc. Petrol. Geol. Bull.*, **84**, 1205–1228.

Bridge, J.S., Collier, R. and Alexander, J. (1998) Large-scale structure of Calamus River deposits (Nebraska, USA) revealed using ground-penetrating radar. *Sedimentology*, **45**, 977–986.

Bristow, C.S. and Best, J.L. (1993) Braided rivers: perspectives and problems. In: *Braided Rivers* (Eds J.L. Best and C.S. Bristow), pp. 1–9. Special Publication 75, Geological Society Publishing House, Bath.

Bristow, C.S. and Jol, H.M. (Eds) (2003) *Ground Penetrating Radar in Sediments.* Special Publication 211, Geological Society Publishing House, Bath, 338 pp.

Corbeanu, R.M., Soegaard, K., Szerbiak, R.B., Thurmond, J.B., McMechan, G.A., Wang, D., Snelgrove, S., Forseter, C.B. and A. Menitove (2001) Detailed internal architecture of a fluvial channel sandstone determined from outcrop cores, and 3-D ground-penetrating radar: examples from the middle Cretaceous Ferron Sandstone, east-central Utah. *Am. Assoc. Petrol. Geol. Bull.*, **85**, 1583–1608.

Edwards, P.J., Kollmann, J., Gurnell, A.M., Petts, G.E., Tockner, K. and Ward, J.V. (1999) A conceptual model of vegetation dynamics on gravel bars of a large Alpine river. *Wetlands Ecol. Manage.*, **7**, 141–153.

Federici, B. and Paola, C. (2003) Dynamics of channel bifurcations in noncohesive sediments. *Water Resour. Res.*, **39**, 1162.

Ferguson, R.I. (1993) Understanding braiding processes in gravel-bed rivers: progress and unsolved problems. In: *Braided Rivers* (Eds J.L. Best and C.S. Bristow), pp. 73–87. Special Publication 75, Geological Society Publishing House, Bath.

Foufoula-Georgiou, E. and Sapozhnikov, V. (2001) Scale invariances in the morphology and evolution of braided rivers. *Math. Geol.*, **33**, 273–291.

Goff, J.R. and Ashmore, P.E. (1994) Gravel transport and morphological change in braided Sunwapta River, Alberta, Canada. *Earth Surf. Process. Landf.*, **19**, 195–212.

Gurnell, A.M. and Petts, G.E. (2002) Island-dominated landscapes of large floodplain rivers, a European perspective. *Freshwat. Biol.*, **47**, 581–600.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V. and Tockner, K. (2000) Wood storage within the active zone of a large European gravel-bed river. *Geomorphology*, **34**, 55–72.

Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollman, J., Ward, J.V. and Tockner, K. (2001) Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy. *Earth Surf. Process. Landf.*, **26**, 31–62.

Hardy, R.J., Lane, S.N., Lawless, M.R., Best, J.L., Elliot, L. and Ingham, D.B. (2005) Development and testing of a numerical code for treatment of complex river channel topography in three-dimensional CFD

models with structured grids. *J. Hydraul. Res*, **43**, 1–13.
Huggenberger, P. (1993) Radar facies: recognition of facies patterns and heterogeneities within Pleistocene Rhine gravels, NE Switzerland. In: *Braided Rivers* (Eds J.L. Best and C.S. Bristow), pp. 163–176. Special Publication 75, Geological Society Publishing House, Bath.
Johnson, W.C. (2000) Tree recruitment and survival in rivers: influence of hydrological processes. *Hydrol. Process.*, **14**, 3051–3074.
Junk, W.J., Bayley, P.B. and Spinks, R.E. (1989) The flood-pulse concept in river-floodplain systems. *Can. Spec. Publ. Fish. Aquat. Sci.*, **106**, 110–127.
Kollmann, J., Vieli, M., Edwards, P.J., Tockner, K. and Ward, J.V. (1999) Interactions between vegetation development and island formation in the Alpine river Tagliamento. *Appl. Vegetat. Sci.*, **2**, 25–36.
Kostaschuk, R.A., Best, J.L., Villard, P.V., Peakall, J. and Franklin, M. (2004) Measuring flow velocity and sediment transport with an acoustic Doppler current profiler. *Geomorphology*, doi: 10.1016/j.geomorph. 2004.07.012.
Lane, S.N. (2000) The measurement of river channel morphology using digital photogrammetry. *Photogram. Rec.*, **16**, 937–957
Lane, S.N. and Richards, K.S. (1998) Two-dimensional modelling of flow processes in a multi-thread channel. *Hydrol. Process.*, **12**, 1279–98.
Lane, S.N., Hardy, R.J., Elliott, L. and Ingham, D.B. (2002) High-resolution numerical modelling of three-dimensional flows over complex river bed topography. *Hydrol. Process.*, **16**, 2261–2272.
Lane, S.N., Westaway, R.M. and Hicks, D.M. (2003) Estimation of erosion and deposition volumes in a large gravel-bed, braided river using synoptic remote sensing. *Earth Surf. Process. Landf.*, **28**, 249–71.
Lane, S.N., Hardy, R.J., Elliot, L. and Ingham, D.B. (2004) Numerical modelling of flow processes over gravelly-surfaces using structured grids and a numerical porosity treatment. *Water Resour. Res.*, doi:10.1029/2002WR001934.
Leclair, S.F., Bridge, J.S. and Wang, F. (1997) Preservation of cross-strata due to migration of subaqueous dunes over aggrading and non-aggrading beds: comparison of experimental data with theory. *Geosci. Can.*, **24**, 55–66.
Leopold, L.B. and Wolman, M.G. (1957) River channel patterns—braided, meandering and straight. *US Geol. Surv. Prof. Pap.*, **282B**, 39–85.
Lunt, I.A. and Bridge, J.S. (2004) Evolution and deposits of a gravely braid bar Sagavanirktok River, Alaska. *Sedimentology*, **51**, 1–18.
Lunt, I.A., Bridge, J.S. and Tye, R.S. (2004) A quantitative, three-dimensional depositional model of gravely braided rivers. *Sedimentology*, **51**, 377–414.
McLelland, S.J., Ashworth, P.J., Best, J.L., Roden, J.E. and Klaassen, G.J. (1999) Flow structure and transport of sand-grade suspended sediment around an evolving braid-bar, Jamuna River, Bangladesh. In: *Fluvial Sedimentology VI* (Eds N.D. Smith and J. Rogers), pp. 43–57. Special Publication 28, International Association of Sedimentologists. Blackwell Science, Oxford.
Murray, A.B. and Paola, C. (1994) A cellular model of braided rivers. *Nature*, **371**, 54–57.
Murray, A.B. and Paola, C. (1997) Properties of a cellular braided stream model. *Earth Surf. Process. Landf.*, **22**, 1001–1025.
Nicholas, A.P. (2000) Modelling bedload yield in braided gravel bed rivers. *Geomorphology*, **36**, 89–106.
Nicholas, A.P. (2005) Cellular modelling in fluvial geomorphology. *Earth Surf. Process. Landf.*, **30**, 645–649.
Nicholas, A.P., and Sambrook Smith, G.H. (1999) Numerical simulation of three-dimensional flow hydraulics in a braided channel. *Hydrol. Process.*, **13**, 913–929.
Parsons, D.R., J.L. Best, R.J. Hardy, R. Kostaschuk, S.N. Lane and O. Orfeo (2005) The morphology and flow fields of three-dimensional dunes, Rio Paraná, Argentina: results from simultaneous multibeam echo sounding and acoustic Doppler current profiling. *J. Geophys. Res. Earth Surf*, **110**, FO4503, doi:10.1029/2004JF000231.
Petts, G.E., Gurnell., A.M., Gerrard, A.J., Hannah, D.M., Hansford, B., Morrissey, I., Edwards, P.J., Kollmann, J., Ward, J.V., Tockner, K., and Smith, B.P.G. (2000) Longitudinal variations in exposed riverine sediments: a context for the ecology of the Fiume Tagliamento, Italy. *Aquat. Conserv.*, **19**, 249–266.
Rennie, C.D., Millar, R.G. and Church, M.A. (2002) Measurement of bedload velocity using an acoustic Doppler current profiler. *J. Hydraul. Eng.*, **128**, 473–483.
Rennie, C.D. and Villard, P.V. (2003) Bedload measurement in both sand and gravel using an aDcp. *16th Canadian Hydrotechnical Conference October 22–24, 2003*. Canadian Society for Civil Engineers, Burlington, ON. 10 pp.
Richards, K., Brasington, J. and Hughes, F. (2002) Geomorphic dynamics of floodplains: ecological implications and a potential modelling strategy. *Freshwat. Biol.*, **47**, 559–579.
Richardson, W.R.R. and Thorne, C.R. (1998) Secondary currents around braid bar in Brahmaputra River, Bangladesh. *J. Hydraul. Eng.*, **124**, 325–328.
Richardson, W.R. and Thorne, C.R. (2001) Multiple thread flow and channel bifurcation in a braided river: Brahmaputra–Jamuna River, Bangladesh. *Geomorphology*, **38**, 185–196.
Richardson, W.R.R., Thorne, C.R. and Mahmood, S. (1996) Secondary flow and channel changes around a bar in the Brahmaputra River, Bangladesh. In:

Coherent Flow Structures in Open Channels (Eds P.J. Ashworth, S.J. Bennett, J.L. Best and S.J. McLelland), pp. 520–543. Wiley, Chichester.

Roden, J.E. (1998) *Sedimentology and dynamics of mega-sand dunes, Jamuna River, Bangladesh*. Unpublished PhD thesis, University of Leeds, 310 pp.

Sambrook Smith, G.H., Ashworth, P.J., Best, J.L., Woodward, J. & Simpson, C.J. (2005) The morphology and facies of sandy braided rivers: some considerations of spatial and temporal scale invariance. In: *Fluvial Sedimentology VII* (Eds M.D. Blum, S.B. Marriott and S.F. Leclair), pp. 145–158. Special Publication 35, International Association of Sedimentologists. Blackwell Publishing, Oxford.

Sapozhnikov, V.B. and Foufoula-Georgiou, E. (1997) Experimental evidence of dynamic scaling and indications of self-organized criticality in braided rivers. *Water Resour. Res.*, **32**, 1109–1112.

Skelly, R.L., Bristow, C.S. and Ethridge, F.G. (2003) Architecture of channel-belt deposits in an aggrading shallow sandbed braided river: the lower Niobrara River, northeast Nebraska. *Sediment. Geol.*, **158**, 249–270.

Stanford, J.A. and Ward, J.V. (2001) Revisiting the serial discontinuity concept. *Regul. River. Res. Manage.*, **17**, 303–310.

Thomas, R. and Nicholas, A.P. (2002) Simulation of braided river flow using a new cellular routing scheme. *Geomorphology*, **43**, 179–95.

Tockner, K., Malard, F. and Ward, J.V. (2000) An extension of the flood pulse concept. *Hydrol. Process.*, **14**, 2861–2883.

Truss, S. (2004) *Characterisation of sedimentary structure and hydraulic behaviour within the unsaturated zone of the Triassic Sherwood Sandstone aquifer in North East England*. Unpublished PhD thesis, University of Leeds, 252 pp.

Van der Nat, D., Tockner, K., Edwards, P.J., Ward, J.V. and Gurnell, A.M. (2003) Habitat change in braided flood plains (Tagliamento, NE-Italy). *Freshwat. Biol.*, **48**, 1799–1812.

Vanotte, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. and Cushing, C.E. (1980) The river continuum concept. *Can. J. Fish. Aquat. Sci.*, **37**, 130–137.

Ward, J.V. and Stanford, J.A. (1983) The serial discontinuity concept of lotic ecosystems. In: *Dynamics of Lotic Ecosystems* (Eds T.D. Fontaine and S.M. Bartell), Ann Arbor Science, Ann Arbor, MI, 347–356.

Ward, J.V., Tockner, K., Edwards, P.J., Kollmann, J., Bretschko, G., Gurnell, A.M., Petts, G.E. and Rossaro, B. (1999) A reference system for the Alps: the 'Fiume Tagliamento'. *Regul. River. Res. Manage.*, **15**, 63–75.

Ward, J.V., Tockner, K., Uehlinger, U. and Malard, F. (2001) Understanding natural patterns and processes in river corridors as the basis for effective river restoration. *Regul. River. Res. Manage.*, **17**, 311–323.

Ward, J.V., Tockner, K., Arscott, D.B. and Claret, C. (2002) Riverine landscape diversity. *Freshwat. Biol.*, **47**, 517–539.

Webb, E.K. and Anderson, M.P. (1996) Simulation of preferential flow in three-dimensional, heterogeneous conductivity fields with realistic internal architecture. *Water Resour. Res.*, **32**, 533–545.

Westaway, R.M., Lane, S.N. and Hicks, D.M. (2000) The development of an automated correction procedure for digital photogrammetry for the study of wide, shallow, gravel-bed rivers. *Earth Surf. Process. Landf.*, **25**, 209–226.

Westaway, R.M., Lane, S.N. and Hicks, D.M. (2001) Airborne remote sensing of clear water, shallow, gravel-bed rivers using digital photogrammetry and image analysis. *Photogram. Eng. Remote Sens.*, **67**, 1271–1281.

Wilbers, A. (2004) *The development and hydraulic roughness of subaqueous dunes*. PhD thesis, Faculty of Geosciences, Utrecht University, Netherlands Geographical Studies 323, 224 pp.

Depositional models of braided rivers

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ABSTRACT

Depositional models of braided rivers are necessary for rational interpretation of ancient deposits, and to aid in the characterization of subsurface deposits (e.g. aquifers, hydrocarbon reservoirs). A comprehensive depositional model should represent bed geometry, flow and sedimentary processes, and deposits accurately, quantitatively, and in detail. Existing depositional models of braided rivers do not meet these requirements, and there are still many misconceptions about braided rivers and their deposits that need to be expunged. Over the past decade, there have been major advances in our understanding of braided rivers, making it possible to develop new and improved depositional models. First, the use of groundpenetrating radar in combination with cores and trenches has allowed detailed description of the different scales of deposit in braided rivers that vary widely in channel size and sediment size. Second, the study of braided channel geometry and kinematics has been facilitated by the use of aerial photographs taken at short time intervals. In some cases, these photographs have been analysed using digital photogrammetry to produce digital elevation models. Third, water flow and sediment transport at the all-important flood stages have been studied using new equipment and methods (e.g. acoustic Doppler current profilers, positioning using differential global positioning systems). However, such high-flow studies are rare, which is one reason why there has not been much progress in development of realistic theoretical models for the interaction between bed topography, water flow, sediment transport, erosion and deposition. Laboratory experimental studies of braided rivers have continued to be useful for examining the controls on channel geometry and dynamics, but have not been able to generate all of the different types and scales of strata observed in natural braided river deposits.

New depositional models for sand-bed and gravel-bed braided rivers are presented here based mainly on studies of natural rivers. They comprise:

1 maps showing idealized active and abandoned channels, compound bars and lobate unit bars;
2 cross-sections showing large-scale inclined strata and their internal structures, associated with migration of compound bars, unit bars and their superimposed bedforms;
3 vertical logs of typical sedimentary sequences through different parts of compound bar deposits and channel fills.

Compound bars migrate laterally and downstream, associated mainly with accretion of lobate unit bars. Abandoned channels are mainly filled with unit-bar deposits. The geometry of the different scales of strataset is related to the geometry and migration of the bedform associated with deposition of the strataset. In particular, the length-to-thickness ratio of stratasets is similar to the wavelength-to-height ratio of associated bedforms. Furthermore, the wavelength and height of bedforms such as dunes and bars are related to channel depth and width. Therefore, the thickness of a particular scale of strataset (e.g. medium-scale cross sets, large-scale sets of inclined strata)

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will vary with river dimensions. These relationships between the dimensions of stratasets, bedforms and channels mean that the depositional models can be applied to channels of all scales. However, realistic models of the spatial distribution and degree of preservation of channel bars and fills within channel belts need to be developed.

Keywords Braided rivers, depositional model, fluvial deposits, sedimentary structures.

INTRODUCTION

Braided rivers and their deposits are important components of the Earth's surface, now and in the past. The deposits of ancient braided rivers are indicators of past Earth surface environments, and may contain significant reserves of water and hydrocarbons (Martin, 1993; Bal, 1996; Anderson *et al.*, 1999). Depositional models based on knowledge of modern braided rivers are necessary to allow rational interpretation of ancient deposits. Depositional models can also aid in the prediction of the nature of subsurface deposits where data (cores, well logs, seismic) are sparse. Ideally, a depositional model must represent landforms and sedimentary processes accurately, must contain detailed, three-dimensional sedimentary information (including the various superimposed scales of deposits), must be quantitative, and should have some predictive value. A depositional model should also provide parameters (e.g. permeability, porosity) relevant to modelling fluid flow through aquifers and hydrocarbon reservoirs. Existing depositional models for braided rivers (e.g. Miall, 1977, 1992, 1996; Bluck, 1979; Ramos *et al.*, 1986; Bridge, 1993, 2003; Collinson, 1996) do not meet these ideals, because the nature and origin of modern river deposits are generally not known in detail. This is due partly to difficulties in:

1 describing deposits in three-dimensions below the water table;
2 studying depositional processes during the all-important high-flow stages, and over large time and space scales (see reviews by Bridge, 1985, 1993, 2003).

Over the past decade or so, some of these difficulties have been overcome by:

1 use of ground-penetrating radar (GPR) in combination with coring and trenching to describe all of the different scales of deposits in detail and in three dimensions (Jol & Smith, 1991; Gawthorpe *et al.*, 1993; Huggenberger, 1993; Siegenthaler & Huggenberger, 1993; Alexander *et al.*, 1994; Huggenberger *et al.*, 1994; Jol, 1995; Bridge *et al.*, 1995, 1998; Beres *et al.*, 1995, 1999; Leclerc & Hickin, 1997; Asprion & Aigner, 1997, 1999; Van Overmeeren, 1998; Vandenberghe & Van Overmeeren, 1999; Bristow *et al.*, 1999; Ekes & Hickin, 2001; Wooldridge, 2002; Regli *et al.*, 2002; Best *et al.*, 2003; Bristow & Jol, 2003; Skelly *et al.*, 2003; Woodward *et al.*, 2003; Lunt & Bridge, 2004; Lunt *et al.*, 2004a,b; Sambrook Smith *et al.*, 2005);
2 study of channel deposits in frozen rivers, allowing easy access to the whole channel belt, and the procurement of undisturbed cores of unconsolidated gravel (Lunt *et al.*, 2004a,b; Lunt & Bridge, 2004);
3 study of the evolution of channel geometry using sequences of aerial photographs taken at short time intervals (Lane *et al.*, 1998, 2001; Stoijic *et al.*, 1998; Wooldridge, 2002; Lunt & Bridge, 2004).

These studies have allowed the construction of a new generation of depositional models for braided rivers (Lunt *et al.*, 2004a,b; this paper).

However, studies of processes of fluid flow, sediment transport, erosion and deposition in braided rivers during flood stages are rare (Bridge & Gabel, 1992; Richardson *et al.*, 1996; Richardson & Thorne, 1998; McLelland *et al.*, 1999). Therefore, there has been little progress in the generation of realistic empirical models that link bed topography, fluid flow, sediment transport, erosion and deposition in braided rivers. The same goes for theoretical models. Braided-river processes and deposits have also been studied in laboratory flumes (Ashmore, 1982, 1991, 1993; Ashworth *et al.*, 1999, 2004; Moreton *et al.*, 2002; Sheets *et al.*, 2002; Ashworth *et al.*, 2004). Advantages of experimental studies are that the environment is manageable and channel-forming flow conditions can be studied. However, scaling problems must be overcome. Although experimental studies have been useful for elucidating the controls on braided channel geometry and dynamics, they have not been able to generate all of the superimposed scales of bedforms and associated strata observed in natural rivers. For example, in the experiments described by Ashworth *et al*. (1999), only relatively large-scale strata associated with bar accretion and channel filling were discernible.

The purpose of this paper is to discuss this new information on the geometry, flow and sedimentary processes, and deposits of braided rivers, and to show how this information has led to the development of new depositional models for braided rivers. The organization of this paper is as follows:

1 discussion of recent studies of braided river processes and deposits;
2 discussion of the usefulness of experimental and theoretical studies to development of depositional models;
3 presentation of new depositional models and their implications for interpreting and predicting the nature of ancient deposits.

STUDIES OF MODERN BRAIDED RIVER PROCESSES AND DEPOSITS

Methods

The most significant advance in studies of the deposits of modern braided rivers is the use of ground-penetrating radar (GPR) in combination with coring and trenching. Ground-penetrating radar reflection data are acquired in real time by moving transmitting and receiving antennae together along lines in a grid. The GPR reflections are due to changes in dielectric permittivity (and less commonly due to magnetic permeability), related to the amount and type of pore-filling material, sediment texture and composition (Van Dam & Schlager, 2000; Kowalsky *et al*., 2001, 2004; Van Dam *et al*., 2002; Lunt *et al*., 2004a,b). As reflections are primarily caused by changes in pore-water saturation or volume, which are closely related to sediment texture and composition, reflections give a record of sedimentary strata. The amplitude of radar reflections depends on contrasts in radar velocity between adjacent strata and on stratal thickness compared with the wavelength of the transmitted pulse (Kowalsky *et al*., 2001). A particular reflection amplitude can be caused by different combinations of sediment texture (sands adjacent to sandy gravel, open-framework gravel adjacent to sandy gravel). Above the water table, reflections are primarily related to variations in water saturation. Below the water table, reflections are related mainly to variations in porosity and sediment composition. In permafrost, reflections are related to porosity and relative proportions of water and ice in the pores.

Central frequencies of antennae commonly used in sedimentological studies are 50 to 1000 MHz. For a given subsurface sediment type, the depth of penetration decreases, and the resolution of sedimentary strata increases, with increasing antenna frequency (Jol, 1995; Woodward *et al*., 2003). For example, 100 MHz antennae may have a penetration depth of the order of 10 m, and be able to resolve strata 0.3 m thick, whereas 450 MHz antennae may have a depth of penetration of several metres and be able to resolve strata 0.1 m thick. In order to distinguish all scales of stratification, it is desirable to use a range of antenna frequencies (50–1000 MHz). As an example, cross strata that are centimetres to decimetres thick, within cross sets of the order of many decimetres thick, can be discerned using high-frequency antennae. With low frequency antennae, only the set boundaries would be represented, giving the appearance of planar strata. If the set thickness of cross strata is of the order of only a few decimetres, even the high frequency antennae will only pick up the set boundaries. As a result, GPR has been most useful for imaging the larger scales of strata in channel belts. Furthermore, radar facies cannot be clearly related to sedimentary facies unless their three-dimensional geometry is investigated using a range of antenna frequencies, the antenna frequency is stated, and reasons for variation in reflection amplitude are understood. For example, concave-upward reflections in radar profiles may be associated with confluence scours, main channel fills, small cross-bar channels adjacent to unit bars, scours upstream of obstacles such as logs or ice blocks, or bases of trough cross strata. Interpretation of the origin of such reflections will depend on their three-dimensional geometry and an understanding of adjacent strata. The central antenna frequency and vertical exaggeration of GPR profiles need to be considered when making sedimentological interpretations. In addition, vertical variation in radar wave velocity must be considered when converting two-way travel time to depth in order to obtain the correct geometry of reflections.

Interpretation of the origin of the observed deposits has been accomplished from knowledge of, or inferences about, the nature of bed topography, flow and sedimentary processes during the flood stages when most erosion and deposition occurs. However, such high-flow data are very sparse. In the case of the Calamus River, data collection was facilitated by the operation of measuring equipment from bridges built across the channel (Bridge & Gabel, 1992; Gabel, 1993). In the case of the Brahmaputra River, high-stage flow data (and suspended sediment concentration) were collected using an acoustic Doppler current profiler operated from a boat, positioned using differential global positioning systems (GPS) (Richardson *et al.*, 1996; Richardson & Thorne, 1998; McLelland *et al.*, 1999).

Knowledge of the nature of channel and bedform migration is also essential for interpreting the origin of river deposits. This has been accomplished by repeat surveys using depth sounders, differential GPS, and using aerial photographs taken at frequent intervals. Recently, it has been possible to survey the bed topography of rivers and assess sediment transport rates using digital photogrammetry in combination with geographical information system (GIS) based digital elevation models (Lane *et al.*, 1994, 1995, 1998, 2001; Martin & Church, 1996; Ashmore & Church, 1998; Stojic *et al.*, 1998; Chandler, 1999; Westaway *et al.*, 2000; Lane *et al.*, 2003). These techniques have a vertical accuracy of the order of 0.1 m in clear, shallow water, but cannot be used in turbid opaque rivers.

Results

Only river studies where there are extensive new data on the channel geometry, flow and sedimentary processes, and deposits are discussed here. These studies were conducted on the Calamus River in Nebraska, USA (Bridge *et al.*, 1998), the Brahmaputra/Jamuna River in Bangladesh (Best *et al.*, 2003), the Sagavanirktok River on the North Slope of Alaska (Lunt *et al.*, 2004a,b; Lunt & Bridge, 2004), and the Niobrara River in Nebraska, USA (Skelly *et al.*, 2003). These studies are from sand-bed and gravel-bed rivers, and cover channel-belt widths from 200 m to 10 km. Note, for future reference, that sand-bed rivers commonly contain some gravel, and gravel-bed rivers always contain appreciable quantities of sand. These field studies, and some theoretical and experimental studies, form the main basis for the depositional models presented.

Sagavanirktok

The deposits of the gravelly Sagavanirktok River on the North Slope of Alaska were described using cores, wireline logs, trenches and GPR profiles (Lunt *et al.*, 2004a,b; Lunt & Bridge, 2004). Study of the Sagavanirktok River when it was frozen allowed access to the whole channel belt and procurement of undisturbed cores of unconsolidated gravel. Porosity and permeability were determined from core samples, and the age of the deposits was determined using optically stimulated luminescence (OSL) dating. The origin of the deposits was inferred from:

1 interpretation of channel and bar formation and migration, and channel filling, using annual aerial photographs;
2 observations of water flow and sediment transport during floods;
3 observations of bed topography and sediment texture at low-flow stage.

The Sagavanirktok River contains compound braid bars and point (side) bars. Compound braid bars originate by growth of lobate unit bars and by chute cutoff of point bars (Fig. 1). Compound bars migrate downstream and laterally, associated with accretion of successive unit bars. The upstream ends of compound bars may be sites of erosion or accretion. During floods, most of the active riverbed is covered with sinuous-crested dunes, with minor proportions of bedload sheets (Fig. 2). Transverse ribs and ripples occur rarely in very shallow water. A channel segment may become abandoned if its upstream end becomes blocked by a channel bar. Channels that are becoming abandoned and filled contain lobate unit bars.

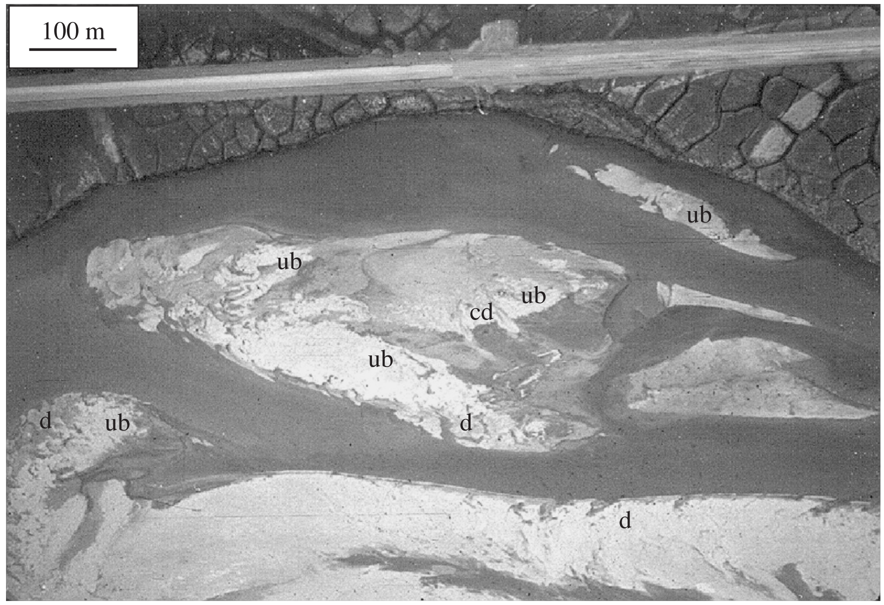


Fig. 1 Aerial photograph of the gravel-bed Sagavanirktok River, Alaska, with different scales of bed form indicated: ub, lobate unit bar; d, dunes superimposed on bar surfaces; cd, small channels and depositional lobes associated with the edges of unit bars. The photograph shows a single compound braid bar with flow from left to right. The bar tail is a relatively low area (dark colour) and contains a relatively large cross-bar channel. The compound braid bar grew by accretion of unit bars on its upstream end, sides and downstream end.

Recognition of different scales of bedform (e.g. bars, dunes), their migration patterns, and associated stratification was essential for building a model of gravelly braided rivers (Lunt *et al.*, 2004a,b: Figs 1 to 3). Channel-belt deposits are composed of deposits of compound braid bars and point bars and large channel fills (Fig. 3A–C). Channel belt deposits are up to 7 m thick and 2.4 km wide, and are composed mainly of gravels, with minor sands and sandy silts (Fig. 3A). A channel belt may be capped by a decimetre thick, sandy–silty soil horizon, unless eroded by later channel belts. Migration of compound bars within channel belts forms compound sets of large-scale inclined strata composed of simple sets of large-scale inclined strata (formed by unit bars) and small channel fills (formed by cross-bar channels). Compound sets are hundreds of metres long and wide, metres thick, have basal erosion surfaces, and terminate laterally in large channel fills (Fig. 3B & C). Set thickness and vertical trends in grain size depend on the bed geometry and surface grain size of compound bars and the nature of bar migration.

Relatively thick, fining-upward sequences form as bar-tail regions migrate downstream into a curved channel or confluence scour. Grain size may increase towards the top of a thick fining-upward sequence where bar-head lobes migrate over the bar-tail. Relatively thin compound sets of large-scale strata with no vertical grain-size trend are found in riffle regions. Compound sets are composed mainly of sandy gravel, but open-framework gravel is common near set-bases (Fig. 3A). Reconstructing the origin and evolution of compound-bar deposits from only recent aerial photographs or cores is impossible. It is also impossible and unnecessary to determine from core whether a compound bar was a point bar or a braid bar (see Lunt & Bridge, 2004). A complete understanding of the evolution of a compound-bar deposit is only possible with a combination of frequent aerial photography, orthogonal GPR profiles and cores. Large channel fills are also composed mainly of simple sets of large-scale inclined strata (Fig. 3C), but are capped with sandy strata containing small- and medium-scale cross sets, and planar strata. These deposits are also generally sandier in the downstream parts of a channel fill. Between two and five compound bar deposits or large channel fills occur within the thickness of a channel-belt deposit (Fig. 3A).

Migration of unit bars forms simple sets of large-scale inclined strata (Fig. 3D). These sets are decimetres to metres thick, tens of metres long and wide, and generally fine upwards, although they may show no grain-size trend. Between three and seven simple sets of large-scale strata make

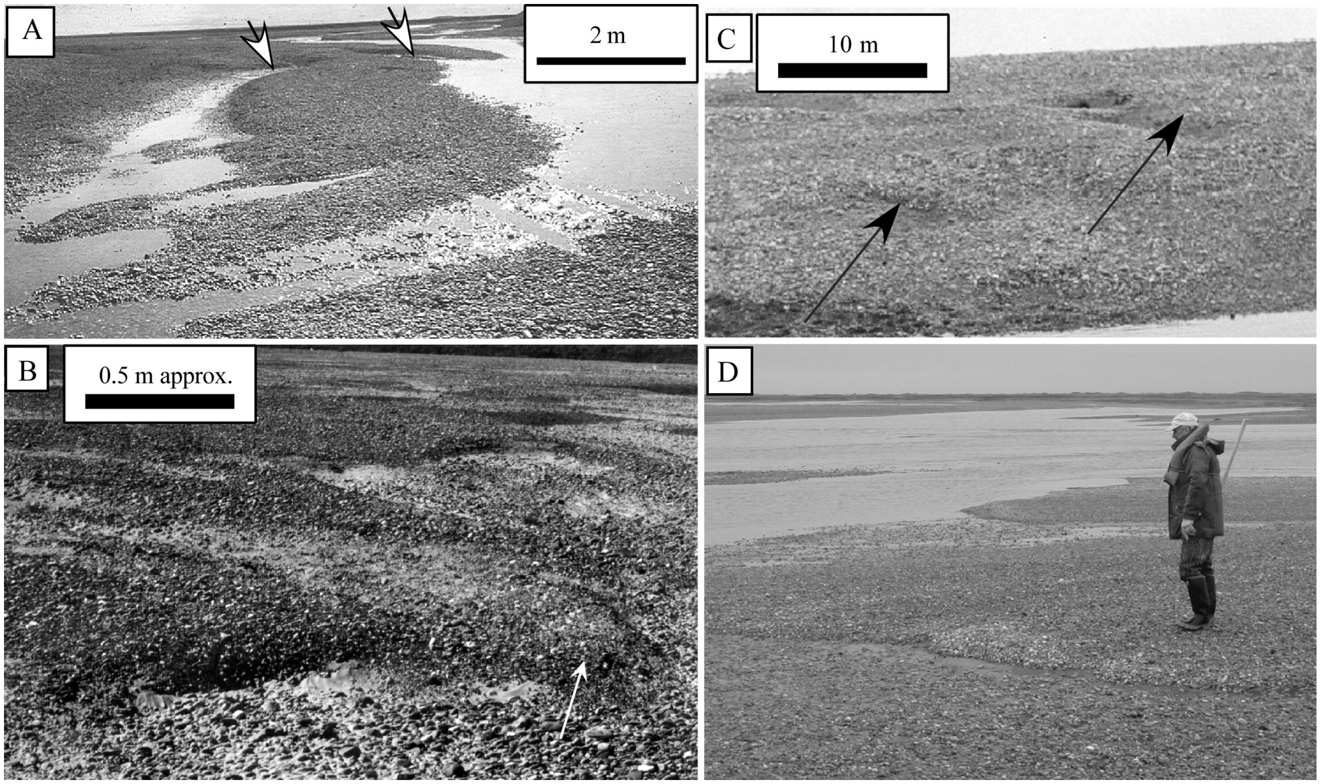


Fig. 2 Photographs of different scales of typical bedforms in the Sagavanirktok River. (A) Lobate unit bar with its side cut by small cross-bar channels and depositional lobes in the adjacent swale. Tyre tracks occur in cross-bar channel nearest to observer. This unit bar is in the tail region of a compound bar. The fronts of two other unit bars (arrows) occur in the (upstream) head region of the compound bar. (B) Dunes on surface of compound bar. Dunes are 0.5 m high and have crestline lengths of around 10 m. Modification by falling-stage flow indicated by arrow. (C) Dunes on the exposed side of a unit bar. Flow is from right to left. (D) Bedload sheets.

up the thickness of a compound large-scale set. Open-framework gravels are common at the base of a simple large-scale set. The large-scale strata are generally inclined at <10°, but may reach the angle of repose at the margin of the unit bar.

Small channel fills (cross-bar channels) are made up of small- and medium-scale cross sets, and planar strata. They are tens of metres long, metres wide, and decimetres thick, and occur at the tops of simple sets of large-scale strata, especially where simple large-scale sets occur at the top of compound large-scale sets.

Dune migration forms medium-scale sets of cross strata. Medium-scale cross sets are decimetres thick and wide, up to 3 m long, and contain isolated open-framework gravel cross-strata and sandy trough drapes. The thickness of medium-scale cross sets decreases upwards in compound bar deposits. Planar strata are formed by bedload sheets and may be made up of sandy gravel, open-framework gravel or sand. Individual strata are centimetres thick and decimetres to metres long and wide. Imbricated pebbles and pebble clusters are commonly found at the base of planar strata. Small-scale sets of cross strata, formed by ripples, generally occur in channel fills, as trough drapes, and as overbank deposits. Small-scale cross sets are centimetres thick and long, are always composed of sand, and may contain organic remains, root traces or burrows where they occur in channel fills or overbank deposits.

The geometry of the different scales of strataset in the Sagavanirktok River is related to the geometry and migration of their formative bedforms. In particular, the wavelength:height ratio of bedforms is similar to the length:thickness ratio of their associated deposits (Fig. 4). These relationships seem to apply to other sandy and gravelly

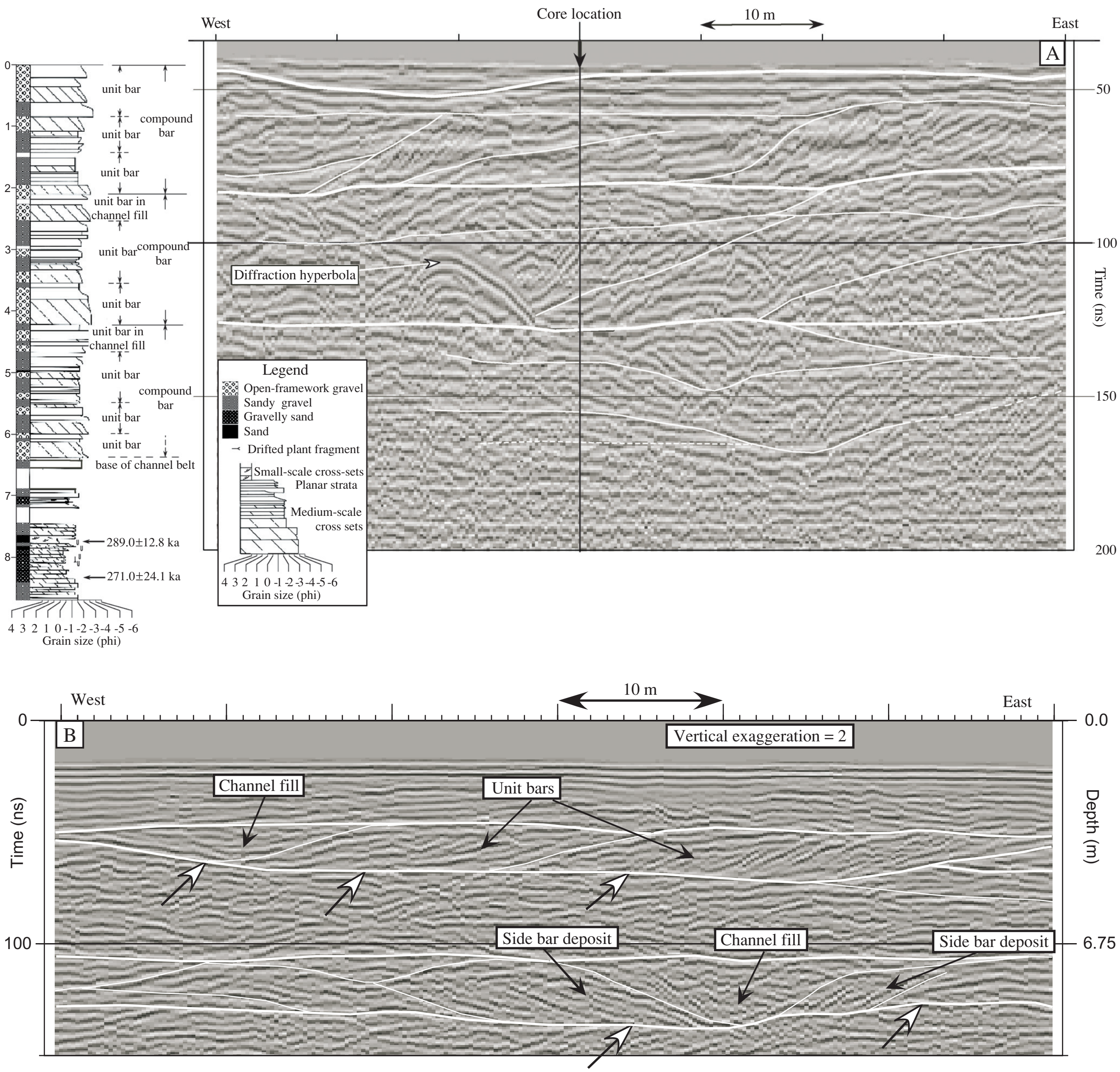
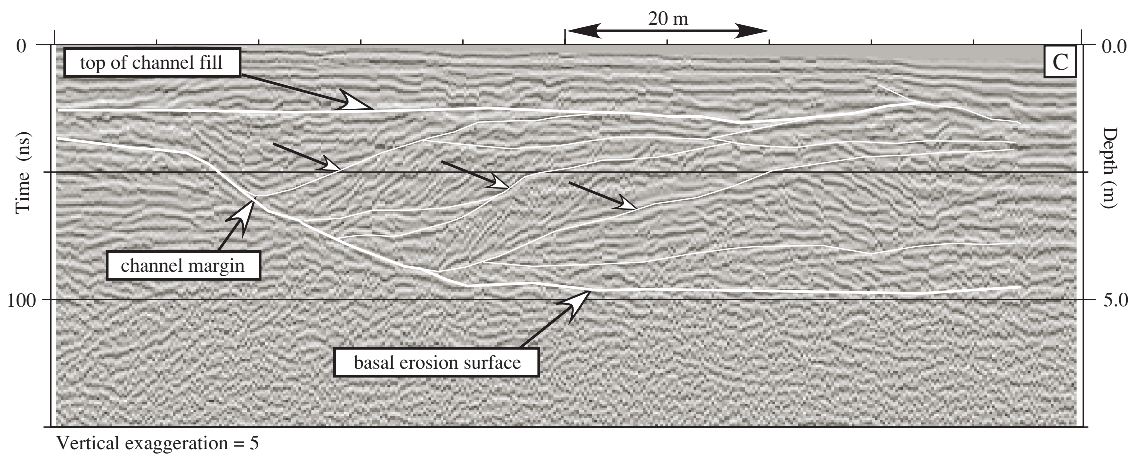


Fig. 3 Sagavanirktok channel deposits. (A) Example of 110 MHz GPR profile (across stream view) and core log through the channel belt. Core log and GPR profile are shown at the same vertical scale. Core log shows three compound-bar deposits each comprising three or four unit-bar deposits. Internal structure of unit-bar deposits is medium-scale cross strata (from dunes) and planar strata (from bedload sheets). The base of the active channel-belt (not visible on the GPR profile) is 6.4 m below the surface and overlies burrowed and rooted sands containing small-scale and medium-scale cross sets. The GPR profile has a vertical exaggeration of 5:1 and shows the two-dimensional geometry of simple sets of large-scale inclined strata due to unit bars (set bases marked by thin white lines) and compound sets of large-scale inclined strata due to compound bars (set bases marked with thick white lines). From Lunt *et al*. (2004b). (B) Example of 110 MHz GPR profile (across stream view) showing compound large-scale inclined strata associated with lateral accretion of a braid bar (upper part). The basal erosion surface is marked by arrows, and unit-bar deposits and a channel fill are bordered by white lines. The lower part of the profile shows accretion of side bars (bordered by white lines) towards a central fill of a confluence scour zone. From Bridge (2003).



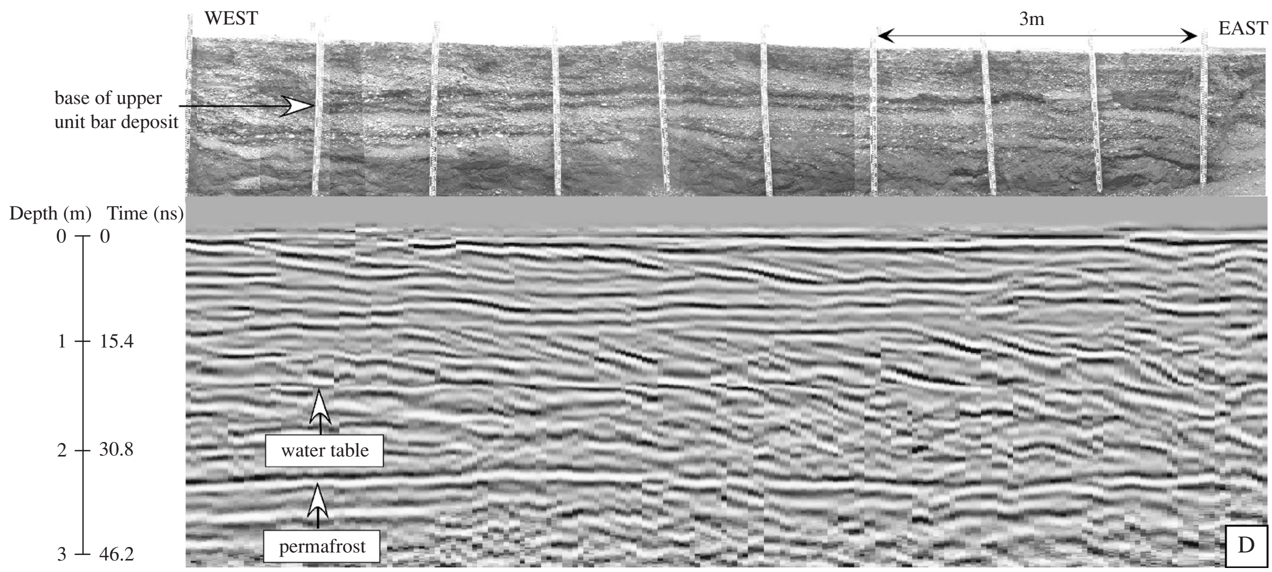


Fig. 3 (*cont'd*) (C) Example of 110 MHz GPR profile (across stream view) showing channel filling with unit bar deposits (bases arrowed) that accreted onto the western margin of a compound bar. Large-scale set boundaries are represented by white lines. From Bridge (2003). (D) Trench photomosaic and 450 MHz GPR profile through two superimposed unit bar deposits, cut oblique to flow direction. Large-scale inclined strata dipping to the east are formed by migration of unit bars. These strata vary in inclination laterally and reach the angle of repose in places. The large-scale inclined strata are composed internally of sets of medium-scale cross strata (formed by dunes) or planar strata (formed by bedload sheets). From Bridge (2003). Depth scale for GPR profile converted from TWTT using a radar velocity of 0.13 m ns^{-1}.

braided river deposits (Fig. 4). Furthermore, the wavelength and height of bedforms such as dunes and bars are related to channel depth and width (Bridge, 2003). Therefore, the thickness of a particular scale of strata set (i.e. medium-scale cross sets and large-scale sets of inclined strata) will vary with the scale of the palaeoriver. These relationships between the dimensions of stratasets, bedforms and channels mean that the depositional model developed from the Sagavanirktok River can be applied to other fluvial deposits.

Calamus

The sandy Calamus River was studied in a reach that is transitional between meandering and

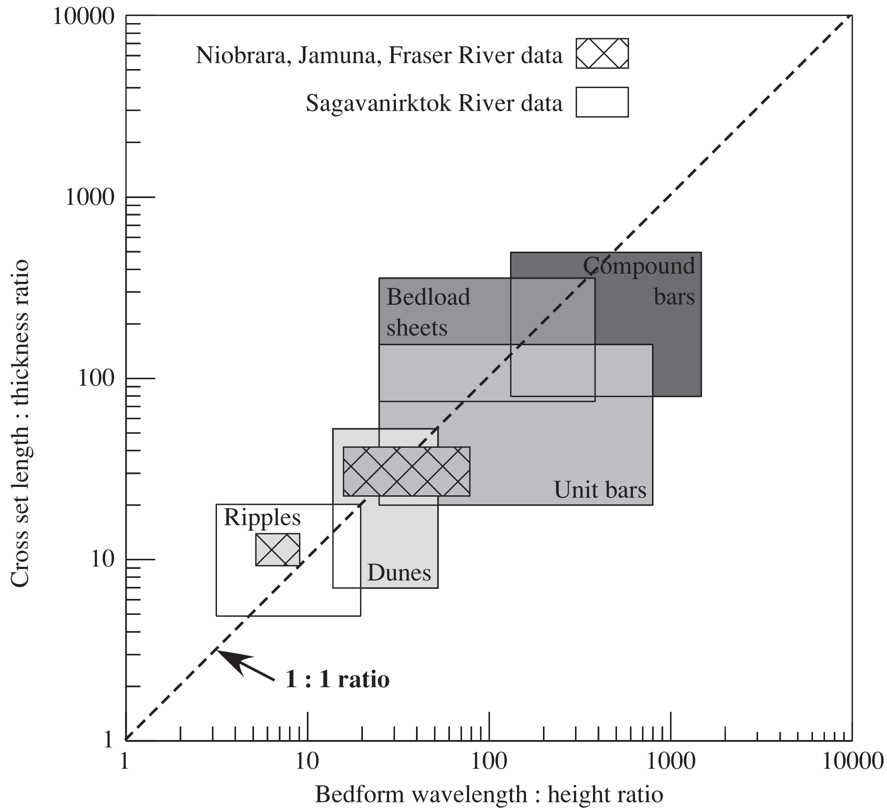


Fig. 4 Bedform length-to-height ratio plotted against corresponding strataset length-to-thickness ratio. The bedform dimensions were taken from reinterpreted aerial photograph measurements or descriptions, and preserved cross-set dimensions from reinterpreted GPR profiles or descriptions. Bedform measurements for the Sagavanirktok River were taken at low flow stage, and may not represent formative bedform dimensions. Measurements from other rivers were made from aerial photographs, trenches, river bed profiles and GPR profiles. Data sources are: Best *et al*. (2003), Lunt *et al*. (2004b), Skelly *et al*. (2003) and Wooldridge (2002).

braided, such that the average number of channels per cross-valley transect (a braiding index) is between 1 and 2 (Bridge *et al*., 1986, 1998; Bridge & Gabel, 1992; Gabel, 1993). The interaction between channel geometry, water flow, sediment transport and deposition around a braid bar on the Calamus River was studied using measurements made over a large discharge range from catwalk bridges (Bridge & Gabel, 1992; Gabel, 1993). In the curved channels on either side of the braid bar, the patterns of flow velocity, depth, water surface topography, bed shear stress, and the rate and mean grain size of bedload transport rate are similar to those in single-channel bends. Because of the low sinuosity of these channels, topographically induced across-stream water flow was stronger than curvature-induced secondary circulation (as also found by McLelland *et al*. (1999) in the much larger Brahmaputra/Jamuna River). A theoretical model of bed topography, flow and bedload transport in bends (Bridge, 1992) agreed well with Calamus River data, and was subsequently used as the basis for simple numerical models for deposition in braided channels (Bridge, 1993). In the diffluence zone upstream of the Calamus braid bar, the depth-averaged flow velocity converges over the deeper areas (talweg) and diverges over topographic highs (bars).

The evolution of the channel geometry in the Calamus River reach was studied by Bridge *et al*. (1986), and further analysed by Bridge *et al*. (1998). Braid bars form either from chute cut-off of point bars or from growth of lobate unit bars in mid-channel, as is the case in most braided rivers (e.g. Brahmaputra, Sagavanirktok, discussed here). Growth of braid bars is mainly by an increase in width and downstream length (i.e. lateral and downstream accretion). Lateral accretion is not necessarily symmetrically distributed on each side of the braid bar. The upstream ends of braid bars may experience erosion or deposition. A curved channel may become abandoned as a side bar or point bar grows into its entrance. During the early stages of filling, the channel contains relatively small unit bars, especially at the upstream end.

Vibracores and GPR profiles show that channel bar deposits reflect:

1 the distribution of grain size and bedforms on the streambed during high flow stages;
2 the mode of bar growth and migration.

The geometry and orientation of large-scale inclined strata reflect mainly lateral and downstream migration of the bar, and accretion in the form of lobate unit bars and scroll bars (Bridge *et al.*, 1998). Within the large-scale strata are mainly medium-scale cross strata associated with the migration of dunes, which cover most of the bed at high flow stages. Small-scale cross strata from ripple migration occur in shallow water near banks. Bar sequences have an erosional base and generally fine upwards except for those near the bar head, which show little vertical variation in mean grain size. Channel-fill deposits are similar to channel-bar deposits, except that the large-scale inclined strata are concave upward in cross-channel view, and the deposits are generally finer grained in the downstream part of the channel fill (Bridge *et al.*, 1998). Figure 5 shows a model of the channel geometry, mode of channel migration, and deposits of the Calamus River reach studied.

Brahmaputra/Jamuna

There have been many studies of the geometry, flow and sedimentary processes, and patterns of erosion and deposition of the sandy Brahmaputra/Jamuna River (Coleman, 1969; Bristow, 1987, 1993; Bristow *et al.*, 1993; Thorne *et al.*, 1993; Mosselman *et al.*, 1995; Richardson *et al.*, 1996; Best & Ashworth, 1997; Richardson & Thorne, 1998; McLelland *et al.*, 1999; Ashworth *et al.*, 2000; Best *et al.*, 2003).

Detailed studies of water flow in the Brahmaputra/Jamuna include those by Richardson *et al.* (1996), Richardson & Thorne (1998) and McLelland *et al.* (1999). McLelland *et al.* (1999) measured near-bed and near-surface velocity vectors, and suspended sediment concentrations, in the channels around a compound braid bar at high and low flow stages. However, as the time interval between measurements was several months, and bedload transport rate was not measured, the sediment continuity equation could not be used to quantitatively relate the velocity and sediment transport fields to the nature of channel and bar erosion and deposition. Richardson *et al.* (1996) and Richardson & Thorne (1998) measured flow patterns in the diffluence zone upstream of a braid bar. Complicated patterns of convergence and divergence of the depth-averaged flow velocity were associated with bars. The primary flow tends to diverge away from bar troughs and converge towards bar crests, giving rise to associated secondary circulation cells. The pattern of flow in curved channel segments is similar to that in single-river bends. These flow patterns measured by Richardson *et al.* (1996) and Richardson & Thorne (1998) differed from those measured by McLelland *et al.* (1999), particularly in the nature of the secondary circulation.

Braid bars in the Brahmaputra/Jamuna originate from mid-channel unit bars and by chute cut-off of point bars, as seen in other braided rivers. Once formed, braid bars grow episodically by lateral and downstream accretion. The upstream parts of braid bars may be sites of accretion or erosion, depending on flow stage and geometry. Braid bars in the Brahmaputra/Jamuna are typically up to 15 m high, 1.5 to 3 km long, and 0.5 to 1 km wide (Coleman, 1969; Bristow, 1987; Ashworth *et al.*, 2000). The amount of lateral and downstream accretion on bars during a monsoonal flood can be of the order of kilometres. The accretion on braid bars is normally associated with migration of unit bars. Unit bars (called sand waves by Coleman, 1969) are commonly several metres high, but can exceed 10 m. Although lobate unit bars within channels and on compound braid bars are figured prominently by Coleman (1969), Ashworth *et al.* (2000) and Best *et al.* (2003), Ashworth *et al.* (2000) and Best *et al.* (2003) argued that unit bars occur less commonly in the main channels of the Brahmaputra/Jamuna than in other sand-bed rivers. This may be a reflection of the fact that unit bars may not be prominent at low flow stage (as shown by Coleman, 1969), and would be difficult to observe in aerial photographs taken at high flow stage when the water is extremely turbid. During high flow stages, the channels and bars are covered with dunes, although there may be restricted areas of upper-stage plane beds and ripples near bar tops. In the deeper parts of the channels, dunes are typically 3 to 4 m high, but are 0.5 to 1 m high near bar tops. The 'accretionary dune front' described by Ashworth *et al.* (2000) and Best *et al.* (2003) is probably the front of a lobate bar-head unit bar (Fig. 6).

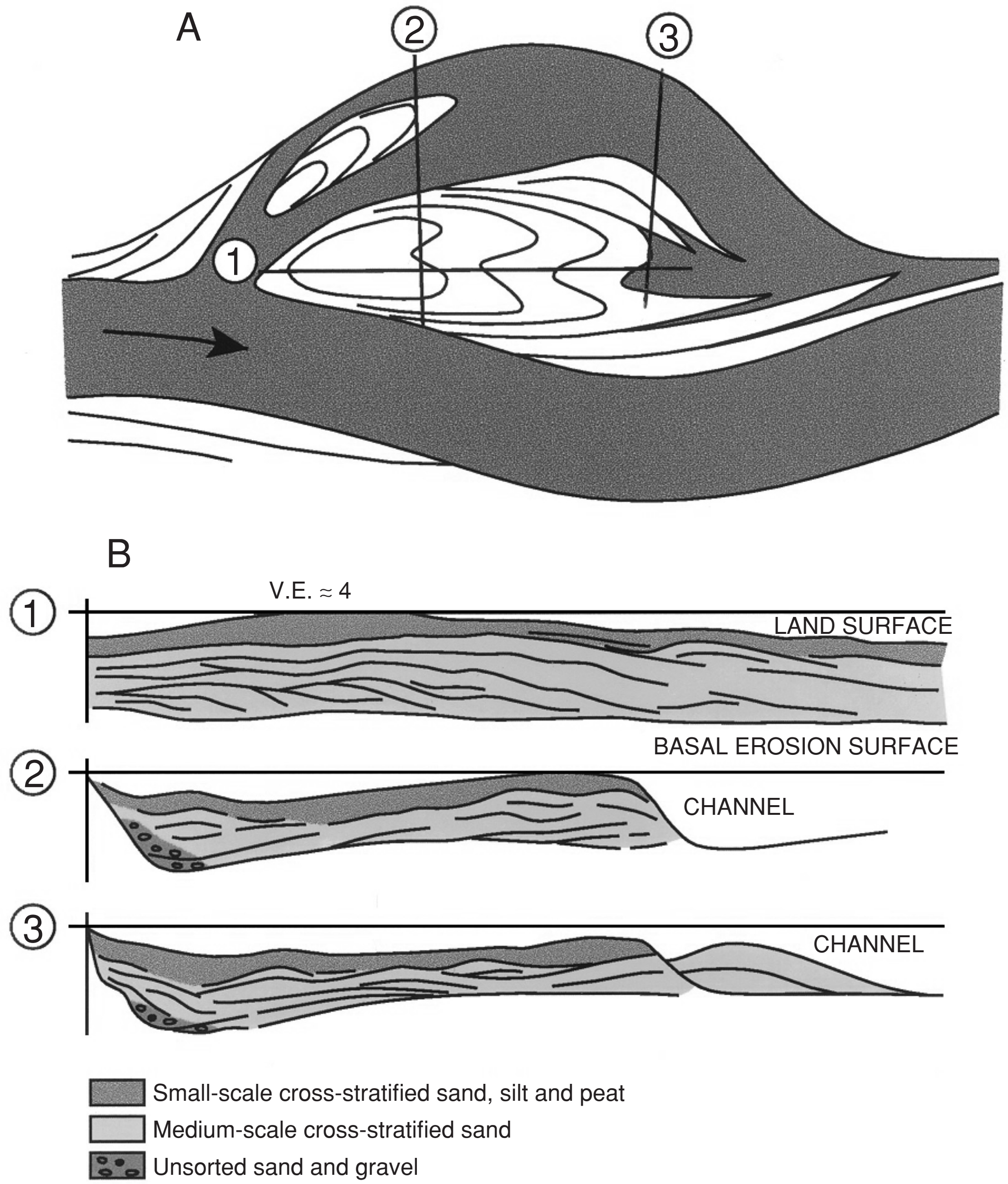


Fig. 5 Model of channel geometry, mode of channel migration, and deposits of the Calamus River. The map shows accretion topography on a compound braid bar, suggesting bar growth mainly by incremental lateral and downstream accretion. Relatively small unit bars occur within the filling channel. The cross sections show large-scale inclined strata associated with the accretion of unit bars (convex upward patterns), the lateral and downstream accretion of the compound braid bar, and channel filling. Lower bar deposits are composed mainly of medium-scale cross strata due to dune migration. Upper bar deposits and channel fills are composed mainly of small-scale cross strata (due to ripples), plus bioturbated silt and peat. The overall sedimentary sequence generally fines upward from very coarse or coarse sand to fine or very fine sand. Modified from Bridge *et al*. (1998).

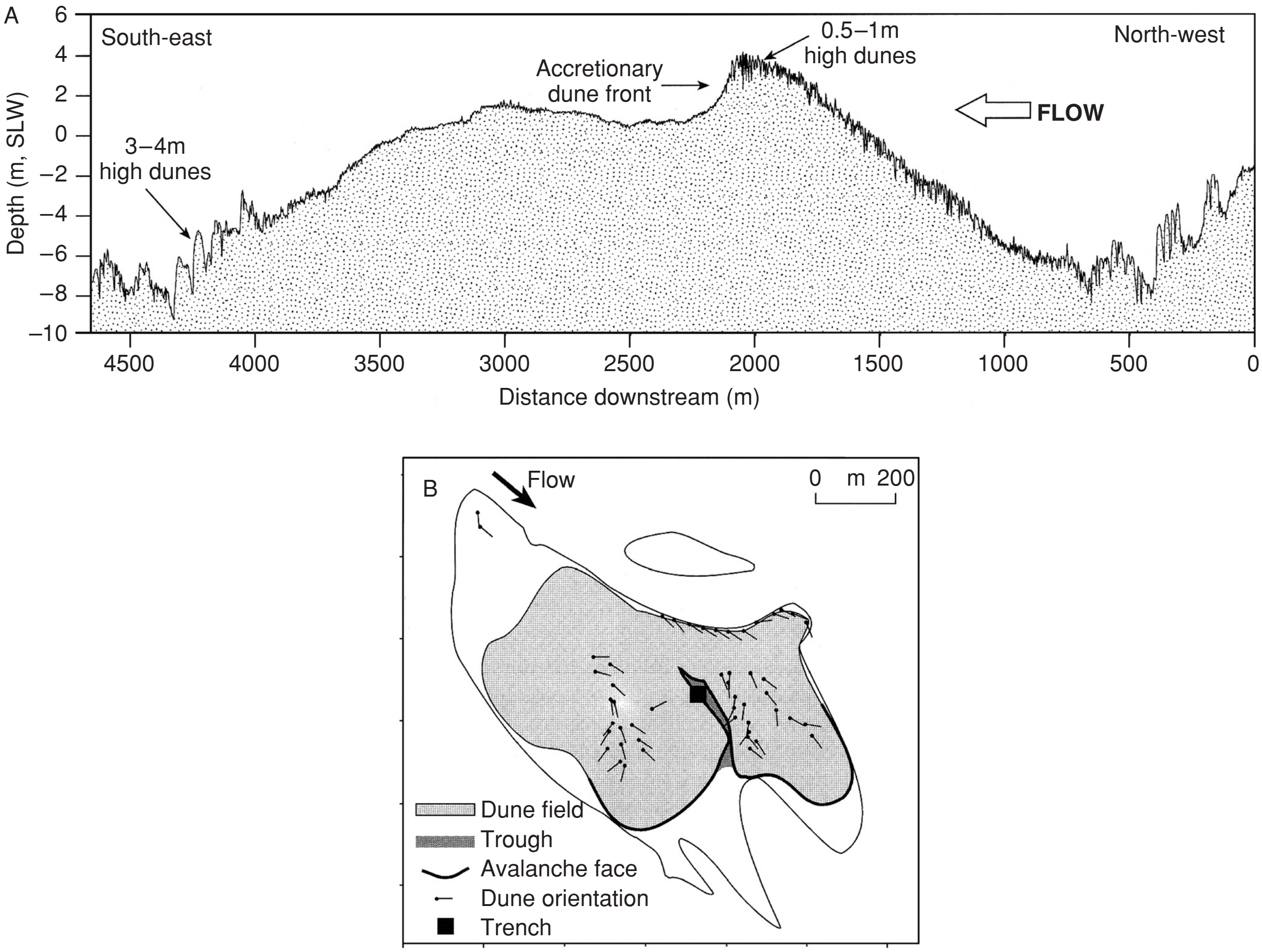


Fig. 6 (A) Along-stream topographic profile of a Brahmaputra/Jamuna compound braid bar at high flow stage on 12 August 1994 (from Ashworth *et al.*, 2000). Note decrease in dune height with water depth. The 'accretionary dune front' marked is probably the front of a unit bar. As the vertical exaggeration of profile is about 75, this bar front is not at the angle of repose. (B) Map of the compound bar in A at low flow stage on 13 March 1995 (from Ashworth *et al.*, 2000). The compound bar is covered with dunes, and the 'avalanche faces' of two lobate unit bars are separated by a trough. The bar-tail region contains three scroll (unit) bars.

Bristow (1993) described the deposits in the upper 4 m of channel bars exposed in long cut banks during low flow stage. He described the deposits of sinuous-crested dunes (trough cross strata), ripples (small-scale cross strata) and upper stage plane beds (planar strata). These stratasets were arranged into larger scale sets of strata indicative of seasonal deposition on bars (Fig. 7). The orientation of these flood-generated stratasets (large-scale inclined strata) indicated bar migration by upstream, downstream and lateral accretion. Bristow (1993) cited evidence for migration of small dunes over larger dunes at various stages of a monsoonal flood; however, it is likely that some of the larger, metres-high bedforms are actually unit bars (Fig. 7). The fills of cross-bar channels are common in these upper bar deposits (Fig. 7). These data are incorporated in the depositional model below.

Best *et al.* (2003) recognized the following types of cross (inclined) strata in their GPR profiles, trenches and cores through a compound braid bar (Fig. 8):

1 large-scale (sets up to 8 m thick, cross strata dipping at the angle of repose or less), associated with deposition on bar margins;

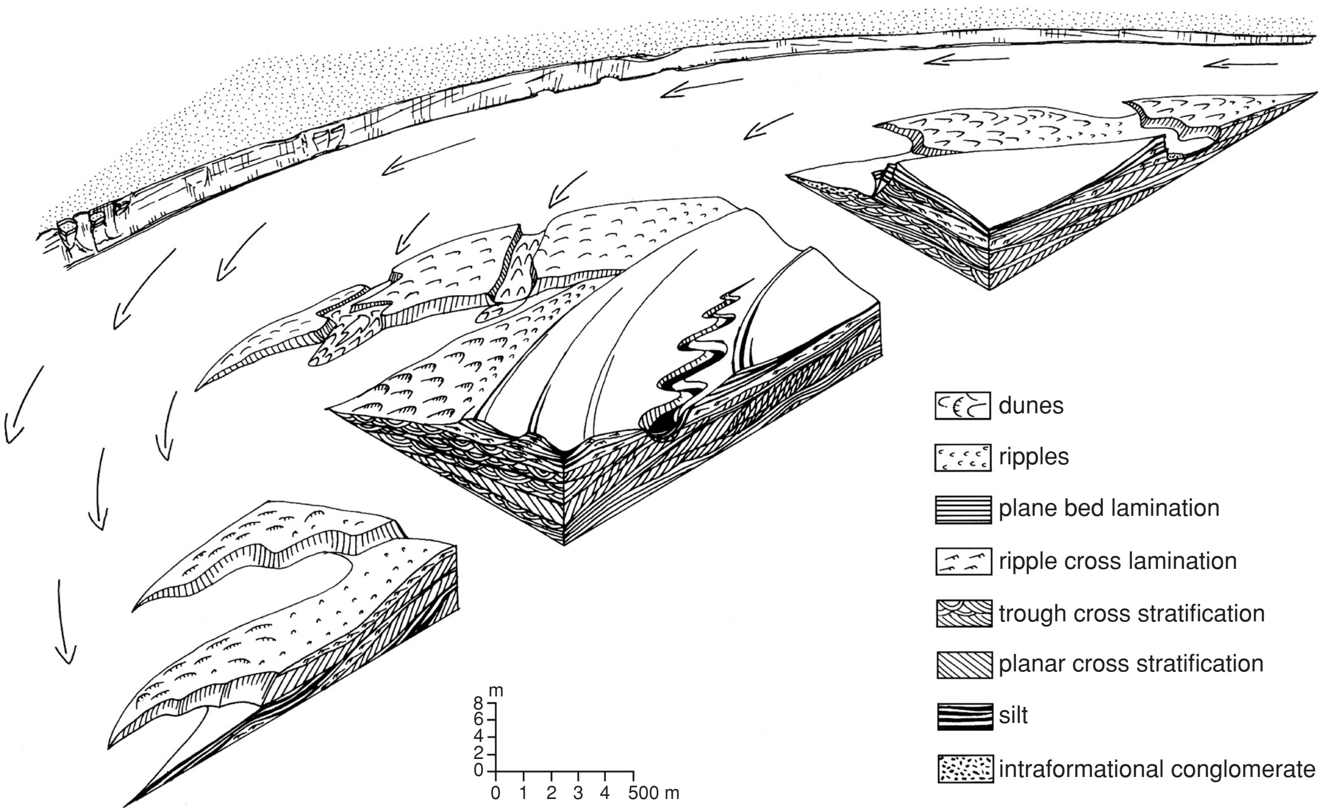


Fig. 7 The model of Bristow (1993) for compound bar-top deposits of the Brahmaputra River. The upstream part of the bar may be erosional or accretionary. The central part shows vertical and lateral accretion. Unit bars (including scroll bars) can be seen accreting onto the compound braid bar, giving rise to ridge-and-swale topography. These bars are covered with sinuous-crested dunes and in places are cut by small channels. Internal structures include trough cross strata from sinuous-crested dunes, small-scale cross strata from ripples, and planar strata from deposition on upper-stage plane beds. 'Planar cross strata' are associated with accretion of unit bars according to Bristow.

2 medium-scale (1 to 4 m thick, cross strata dipping at the angle of repose or less), associated with migration of large dunes;
3 small-scale (sets 0.5 to 2 m thick) due to dunes migrating over bar flanks.

Set thickness of small-scale cross strata decreases upwards. Cross strata associated with ripples (called ripple cross stratification) occur locally at the top of the bar. The terminology of large, medium and small scales of cross strata is different from that used in this paper. Furthermore, the ranges of set thickness in these categories overlap, so that it is difficult to know how to classify any specific cross set. Best *et al*. (2003) did not explicitly recognize the distinction between unit bars and compound bars, and the different scales of deposits associated with them. Cross sets associated with dunes that have a mean height of 3 m are likely to have a mean set thickness of the order of 1 m (Leclair & Bridge, 2001). Therefore, most of the medium-scale cross sets (with thickness of 1–4 m) are unlikely to be formed by dunes, but rather by unit bars (as recognized by Best *et al*. (2003, p. 521), and implied in fig. 11B of their paper).

Figure 9 indicates that vertical accretion deposits on the bar top pass laterally into both upstream and lateral accretion deposits, and that both bar margin slipface deposits and vertical accretion deposits in the channel pass laterally into downstream/oblique accretion deposits. There are clearly terminology problems here. In fact, if vertical deposition occurs on any mound-like form (i.e. a braid bar), it would appear that there are components of accretion in the upstream, lateral and downstream directions. If such vertical accretion on

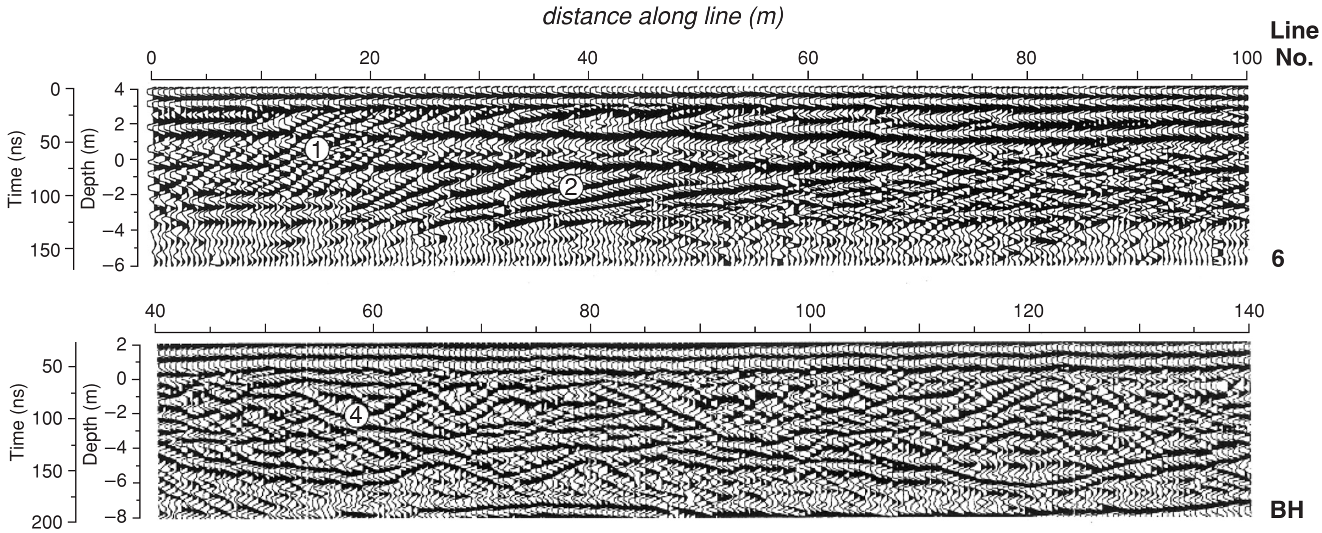


Fig. 8 Examples of 100 MHz GPR profiles through Brahmaputra compound braid bar deposits (from Best *et al*., 2003). Vertical exaggeration is 1.58. Profile 6, across stream through the downstream part of the braid bar (location on Fig. 9), shows large-scale inclined strata associated with unit bar migration. The spatially variable dip angles (up to angle of repose) are typical of unit bar deposits. Profile BH, alongstream through the upstream part of the bar, shows concave upward reflections that were interpreted by Best *et al*. (2003) as trough cross sets up to 2 m high associated with migration of large sinuous-crested dunes. However, Fig. 6A shows that dunes in this region are only 0.5 to 1 m high. Lower in this profile, 3 m thick inclined strata are ascribed to downstream accretion of a bar head.

a braid bar is followed by local erosion on the bar top, the original vertical deposition may not even be discernible. As the braid bar studied by Best *et al*. (2003) experienced both lateral and downstream growth simultaneously, a lateral accretion deposit will also be a downstream accretion deposit. Therefore, terminology based on two-dimensional vertical profiles can be very misleading. The data of Best *et al*. (2003) are reinterpreted below and incorporated in the new depositional model.

Niobrara

Skelly *et al*. (2003) interpreted the following sedimentary facies from radar facies using 100 and 200 MHz GPR antennae: trough cross beds associated with small three-dimensional dunes; planar cross beds associated with small two-dimensional dunes; horizontal to low-angle planar strata or cross-set boundaries associated with large three-dimensional dunes (or linguoid bars); channel-shaped erosion surfaces associated with secondary channels (and filled with deposits of two-dimensional and three-dimensional dunes); sigmoidal strata associated with accretion on braid bar margins. Skelly *et al*. (2003) also interpreted superimposed sequences, 1 to 1.5 m thick, as due to stacking of braid bars, and most bar sequences fined upward. These depositional patterns were associated with high-stage bar construction and upstream, lateral and downstream bar accretion, and low-stage dissection of the bars by small channels. Unfortunately, the uppermost parts of the radar profiles were not linked to the geometry and migration of specific extant channels and bars. The distinction between unit bars and compound bars was not made. However, Fig. 10A (Skelly *et al*., 2003, fig. 10) shows an example of a lateral transition from low-angle strata to angle of repose strata to low-angle strata, as observed in unit-bar deposits elsewhere. These deposits were interpreted by Skelly *et al*. (2003) as due to small two-dimensional dunes. These unit-bar deposits accreted onto the western margin of a compound bar deposit (Fig. 10B: Skelly *et al*., 2003; fig. 11) and the dimensions of these unit bar deposits are consistent with those in other rivers (Fig. 4).

Discussion of recent studies of braided river deposits

The new data reviewed above have resulted in greatly improved understanding of braided rivers