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From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin

Edited by
A. W. Martinius, R. Ravnås,
J. A. Howell, R. J. Steel
and J. P. Wonham

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of Sedimentologists

**FROM DEPOSITIONAL SYSTEMS TO SEDIMENTARY SUCCESSIONS
ON THE NORWEGIAN CONTINENTAL MARGIN**

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Preface

The Norwegian Continental Shelf (NCS; Fig. 1) is a prolific hydrocarbon region and both exploration and production activity remains high to this day. Due to the wealth of data that have been collected and analyzed over the past half-a-century, with exploration starting in 1963, the region is relatively well understood. Exploration activity peaked during the first 20 years or so during which the bulk of the resources on the NCS were proven. However, the exploration revival of the last ten years has resulted in exciting results with significant new hydrocarbon discoveries. In addition, dedicated operators are pushing the recovery rates of producing fields to exceptionally high values, in some cases extending the originally estimated life time of a field by 10 to 20 years. Production outlook as presented by the Norwegian Petroleum Directorate (Petroleum Resources on the Norwegian Continental Shelf, NPD, 2013) is positive but critically depends, among other factors, on continued technological developments. Importantly, this includes improving the geological understanding of the genesis and nature of the sedimentary units in which the hydrocarbons were generated and accumulated.

A key element today and in the future is to couple technological developments to improving our understanding of specific geological situations. The theme of this volume, 'From Depositional Systems to Sedimentary Successions on the Norwegian Continental Margin' reflects the immense efforts made by all industry operators and their academic partners on the NCS to understand in detail the structural setting, sedimentology and stratigraphy of the hydrocarbon bearing units and their source and seal. It is a tribute to the fact that industry and academy are mutually dependent on each other to push both fields of human endeavour to a high level of performance.

The NCS stretches for c. 2500 km along the coastline of Norway from the North Sea in the south to the Barents Sea in the north (Fig. 1) and includes hydrocarbon plays ranging from Devonian to Pleistocene in age. Reservoir types vary from

alluvial fans to deepwater fans, in almost every climate type from arid through humid to glacial, in tectonic settings ranging from intra-montane through compressional/transpressional to extensional/transtensional basins and passive margins. This range of depositional systems and tectonic settings provides an exciting challenge for petroleum geologists trying to understand and predict stratigraphy and lithological properties. The initial focus of sequence stratigraphy on eustasy as the key control on depositional architecture has evolved to encompass tectonic, climatic and geomorphologic controls on sediment delivery and preserved stratal architecture.

The papers in this volume were presented at a three-day conference on the sequence stratigraphy of the NCS which was initiated, organised and hosted by the Norwegian Petroleum Society (NPF) in Stavanger in May 2010. The thematics outlined above and their impact on our understanding of the NCS was the focus of the conference. Special attention was given to the integration of both analogue studies and process-based models with the insights gained from the interpretation and visualisation of high quality subsurface well and seismic datasets and associated case studies. The conference followed on from previous successful NPF events on the subject, building further on advances in our understanding of the role of climate and tectonics in controlling sediment delivery from source to sink and its impact on stratigraphic architecture and petroleum exploration offshore Norway. The aim of the conference was to bring together sedimentologists and stratigraphers working on all aspects of sedimentary deposits on the NCS and present an up-to-date overview of current issues and a future outlook. More than seventy oral and poster presentations were accommodated and together they covered topics ranging from Triassic dryland river systems and reservoirs to Late Cretaceous deep marine systems. Moreover, core workshops as well as virtual geology workshops were organised with

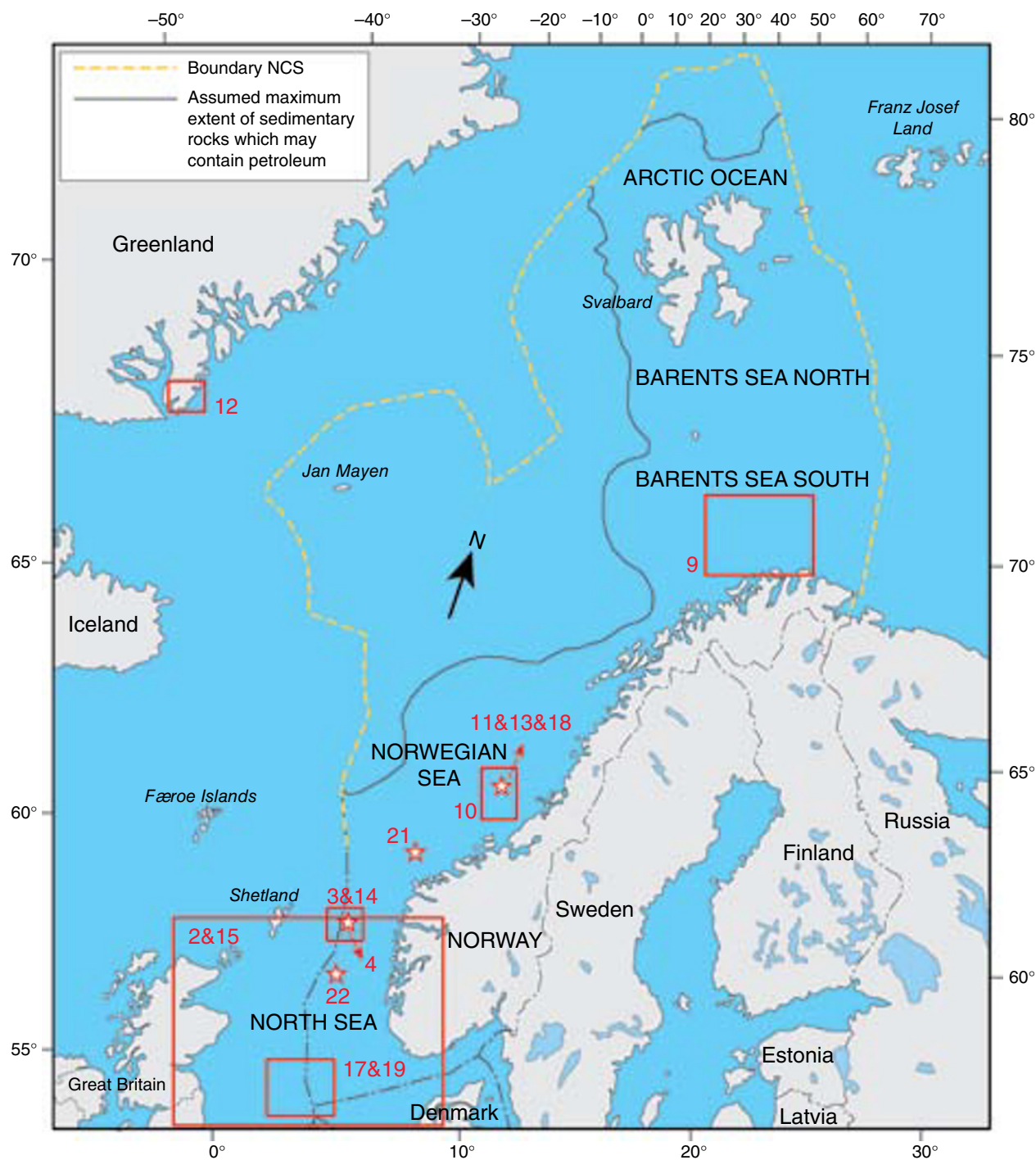


Fig. 1. The Norwegian Continental Shelf (NCS); the focus of this special publication (after Norwegian Petroleum Directorate report, 2013). The numbered boxes and stars refer to the location of the study area of the respective papers in this volume. Papers with a more generic topic are not included in this map.

special sessions on computer and flume tank modelling of stratigraphy and sedimentation.

The contributions to this volume are organised according to their approximate location on the hypothetical depositional profile from up-dip

fluvial environments through paralic to deep marine environments down dip. The contribution by Postma presents a perspective on generic auto-genic behaviour in fluvial systems as resulting from landscape-scale experimental research.

Steep-gradient, moderate-gradient and low-gradient systems display different autogenic behaviour and it is concluded that it is more logical to predict autogenic behaviour directly from aggradation rate and changes thereof than indirectly from sea-level, climate or tectonic forcing. This statement is supported by Martinius *et al.* in their sequence stratigraphic analysis of the fluvial Eiriksson Fm in the Statfjord Field in the Norwegian Sea (Fig. 1). They propose a practical definition of fluvial base level which is applied to identify changes in aggradation rate in the well data set leading to a reservoir zonation. McKie analyses the Triassic succession in the central North Sea (Fig. 1; Skagerrak Fm) deposited in structurally active basins identifying signals for alternating arid and pluvial depositional conditions related to warming and cooling periods in the Tethys region. Fluvial systems of the successive Lunde, Raude and Eiriksson fms at the Jurassic-Triassic boundary in the Norwegian Sea (Fig. 1) are examined by Nystuen *et al.* documenting systematic changes in fluvial style influenced by an overall low-frequency climatic change from more arid to more humid conditions. Allostratigraphic units are inferred to have formed in response to high-frequency climatic cycles (or base level changes).

Autogenic processes under controlled conditions at the delta top in flume tank experiments are investigated by Kim *et al.* to examine quantitatively sediment storage and release associated with river pattern changes as well as changes in fluvial autocyclic behaviour that are driven by external forces. The main concepts of autostratigraphy in river deltas are reviewed by Muto & Steel, who suggest that steady dynamic external forcing generally results in unsteady stratigraphic response; and that steady stratigraphic configuration can result from unsteady dynamic external forcing. Autogenic processes in deltas are also the topic of the paper by Olariu, who concludes that pervasive and rapid process changes were common in ancient deltas and particularly well-expressed on the delta front. It is suggested that the main intervals bounded by spatially extensive flooding surfaces are successive deltaic complexes, reflecting the allogenic response. The great internal variability reflects autogenic spreading of the lobes during the cross-shelf transits.

The contributions of wave forcing on the delta front to delta morphodynamics and time-varying stratigraphy are investigated by Hillen *et al.* using a high-resolution physics-based numerical model. The simulated stratigraphy is subsequently applied to a standard reservoir modelling workflow to

calculate rock properties. Fluvial-dominated delta plain deposition at the Jurassic-Triassic boundary in the Barents Sea (Fig. 1) is shown by Ryseth to be controlled dominantly by climate change, analogous to the conclusions of Nystuen *et al.* for the same time interval in the Norwegian Sea (Fig. 1).

The Lower to Middle Jurassic succession of the Halten Terrace in the Norwegian Sea (Fig. 1) is the topic of three studies. Ravnås *et al.* recognise three megasequences, the Tilje, the Tofte-Ile and the Garn megasequences, with a common architectural motif and stratigraphic structure. These are interpreted to have formed in response to uplift of rift margins and hinterland and determine the distribution of high-quality sheet-like reservoir bodies. Thrana *et al.* present a revised depositional model for the fluviodeltaic overall transgressive Åre Fm (underlying the Tilje megasequence of Ravnås *et al.*) which forms the basis for a new stratigraphic framework and revised reservoir zonation in the Heidrun Field. The nature of the stratigraphic surfaces confirms the findings of Olariu in that these spatially extensive flooding surfaces bound successive deltaic complexes, each of which displays significant internal variability. A similar conclusion is reached by Ichaso & Dalrymple for the Tilje Fm in the Smørbukk Field based upon a detailed facies and stratigraphic analysis, identifying two major sequences (both within the Tilje megasequence of Ravnås *et al.*) resulting from two main tectonic pulses. Propagation of blind normal faults and the generation of isolated syndepositional shallow hanging-wall depocentres exerted a subtle control on facies distribution patterns within both Tilje sequences. Contemporaneously with the Lower to Middle Jurassic Halten Terrace succession, along the western side of the 400km wide proto-Norwegian-Greenland Sea, the Neill Klintor Group succession was deposited. Ahokas *et al.* suggest that it is an outcrop analogue for the Tilje and the Tofte-Ile megasequences, in particular for depositional environments, external and internal factors controlling depositional architecture and resulting three-dimensional heterogeneity of sandstone body architecture and rock properties.

The influence of developing structures on shallow marine sedimentation patterns and resulting stratal architectures was studied by a number of contributors to the volume. The Middle Jurassic succession in the northern North Sea (Fig. 1) was studied in the Gullfaks-Kvitebjørn area by Folkestad *et al.*, who showed that funnel-shaped hangingwall areas of rotated fault-blocks formed local depocentres typified by enhancement of

tidal currents. A wider perspective was taken by Jarsve *et al.* who reviewed the Mesozoic and Cenozoic basin configurations in the North Sea in order to understand changes in style of basin extension, geometry and infill dynamics in the context of source-to-sink relationships. Four main basin configurations were recognised associated with asymmetrical uplift and erosion of basin flanks. An alternative way to better understand and predict the effects of controlling factors on regional scale stratigraphic architecture is to employ three-dimensional stratigraphic forward modelling as shown by Granjeon. It is suggested that the numerical modelling technique can be applied as an industrial guide to reduce subsurface uncertainties. Wonham *et al.*, in a case study from the Upper Jurassic of the North Sea Central Graben, developed three tectono-sedimentary models to explain and predict sedimentation, erosion and redeposition in the basin. The nature of each of these models depends on the evolving geometry of the rift, the location in the rift and the timing of underlying salt displacement.

Repetitive cycles of tidal sand ridge deposition in a structurally confined and subsiding basin were analyzed by Messina *et al.* and related to quantified reservoir architecture and rock property distributions and anisotropy.

Patterns of chalk deposition in the Maastrichtian Tor Fm were studied in the Ekofisk Field and adjacent areas (North Sea; Gennaro & Wonham). An extensive channel, oriented along the bathymetric contours of major structural features, is identified and interpreted to have formed by bottom currents that originated from the deepest part of a nearby graben.

At the down-dip end of the depositional profile, Basani *et al.* constructed a three-dimensional model using deterministic process modelling

software for the simulation of turbidity currents with the aim to fill the gap between small-scale and large-scale modelling of turbidite architecture. The simulations show a close fit to experimental sandy turbidity current dynamics. Large-scale architecture in the Upper Maastrichtian to Danian Ormen Lange turbidite system were analysed by Ravnås *et al.* Multiple phases of repeated hinterland uplift, basin-margin tilting and sandy fan development occurred; and the turbidite systems evolved through fill-spill processes on the slope terraces or in minibasin(s) to backfilling and upslope onlapping. Similarly, the architecture of a mid to outer turbidite fan setting of the Late Palaeocene to Early Eocene Hermod Fan in the North Sea was analysed by Bryn & Ackers to understand its three-dimensional architecture. A network of fairways was mapped using advanced geophysical techniques. The combination of primary depositional patterns and extensive post-depositional sand remobilisation resulted in a complex three-dimensional architecture in which numerous thick units of clean sandstone occur.

We are sincerely indebted to the authors who have contributed to the volume and to the reviewers whose comments and insight have invariably and significantly improved the quality and presentation format of the papers. As always, without the expertise, dedication and efforts of the reviewers (acknowledged in each paper except where they prefer to remain anonymous) this volume would not have been published. Finally, we wholeheartedly thank Thomas Stevens, IAS Special Publications Editor, for his high standards of editing, quality assurance as well as his perseverance and patience. We are also grateful for all the prompt technical assistance from Adam Corres, Editorial Assistant for the IAS Special Publications.

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Dedication to John Gjelberg, Michael Talbot and Trevor Elliott

It is with considerable sadness that we dedicate this volume on Norwegian sedimentary geology to three of our colleagues who have recently passed away.

John Gjelberg received his doctorate from the University of Bergen in 1982. He began immediately to work for Norsk Hydro and worked there for the rest of his career, apart from a short period in Statoil/Hydro and a final few years in North Energy. John spent his entire working career researching and publishing papers on the sedimentology and petroleum geology of all parts of the Norwegian Continental Shelf, as well as on the tectono-stratigraphic development of the Congo Basin, offshore Angola, and on outcrop geology in France and Spain. Some of the highlights of John's work include study of the Carboniferous alluvial and marine strata of Bear Island and Svalbard, early exploration reservoir models on the Barents shelf, the tectono-stratigraphic development of the mid-Norwegian margin and seismic modelling of the Ainsa turbidite system. On the academic front, John is known for his 1994 paper (with W. Helland-Hansen) on the early sequence stratigraphy debate concerning the variability of systems tracts, with ideas that have gained new traction in the stratigraphic community in recent years. John also taught courses and supervised graduate students at the University of Bergen. John Gjelberg is greatly missed but remembered for his huge contribution to Norwegian Geology.

Mike Talbot received his Ph.D. in geology from the University of Bristol in 1968. He then worked on the coral reefs and associated sediments of the Seychelles as a NERC Post-Doctoral Research Assistant, University of Dundee, U.K. From 1972 to 1978 he was employed as a Lecturer in Geology at the University of Ghana's Department of Earth Sciences. He subsequently worked as a Lecturer at the Department of Earth Sciences, University of Leeds from 1978 to 1981 before accepting a post as Senior Lecturer at the Geological Institute in

Bergen, Norway. In 1984 he was appointed professor at the same institute (now Department of Earth Science). Mike had various research interests that were focused on limnogeology, modern and ancient rift sedimentation, carbonate sedimentology and diagenesis. His mid-career research effort was concentrated on the large lakes of East Africa. During the last 10 years, Mike returned to carbonates, focusing on sedimentological and diagenetic studies of collapse breccias associated with the Late Palaeozoic carbonates and evaporites in central Spitsbergen. Mike was an efficient and well-liked Editor-in-Chief of the journal *Sedimentology* from 1990 to 1994 and was European representative on the Lake Drilling Panel, Science Advisory Group of the International Continental Scientific Drilling Program. In 2007, Mike received the W.H. Bradley medal from The International Association of Limnogeology for "his stellar research career as well as his dedicated services to the Limnogeology community". Mike also supervised some 74 Masters and doctoral students and will be long remembered for the outstanding quality of his work and for his dedication to the University of Bergen.

Trevor Elliott, one of the most influential geoscientists of his generation, received his D.Phil. at the University of Oxford under the supervision of Prof. Harold Reading. After postdoctoral studies at Leiden and Reading, he became Lecturer in Sedimentology at the University College of Swansea (1976) and later the George Herdman Professor of Geology at the University of Liverpool, a position he held for more than 20 years. Trevor's long and productive teaching and advising career resulted in numerous undergraduate, postgraduate and postdoc theses and research projects. One of his substantial legacies is the impact that his students have made and are still making in their companies and geology departments around the world. Trevor authored the chapters on Deltas and Shorelines in the seminal book: *Sedimentary*

Environments and Facies that was first published in 1978 and subsequently updated and revised. Trevor's research interests were broad and ranged from fluvial to deepwater sedimentology, stratigraphy and basin analysis. He was awarded the Bigsby Medal from the Geological Society of London and was a Distinguished Lecturer of the AAPG. In the 1980s, Trevor researched shallow marine sandstone outcrops for application to the wave-influenced and tidally-influenced reservoirs of the Norwegian margin. This Norwegian industry collaboration led to further support for Trevor's PhD students on the sedimentological study of Norwegian sector cores. Trevor enjoyed much

collaboration with the petroleum industry. His long term study of the Clare Basin in Ireland and his dream of drilling boreholes behind the Clare cliff line to develop a three-dimensional model were eventually realised recently through Statoil and University College Dublin collaboration. From 2006, Trevor developed and taught industry classes in sedimentology and stratigraphy, engaging a large new community of geoscientists and engineers. Trevor's greatest strengths were his scientific method and teaching style. His keen insight, rigorous analytical mind and ability to engage at all levels were inspiring to students and earth science professionals alike.

Generic autogenic behaviour in fluvial systems: lessons from experimental studies

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ABSTRACT

Substantial advancement in the recognition of generic autogenic behaviour in fluvial systems stems from recent landscape-scale experimental research, where features of stratigraphic architecture can be verified along known input and boundary conditions. Combining experimental work, numerical modelling and field data indicate different autogenic behaviour for 1) steep-gradient, stream-flow dominated alluvial fan-type systems, 2) moderate-gradient braided-river type systems and 3) low-gradient single-river meandering and anastomosing systems. Autogenic behaviour is by cyclic alternating sheet and channelised flow on alluvial fan surfaces, by avulsions of small bifurcating streams around migrating mid channel bars in the braided channel belt and by splitting of the flow from one into two channel belts in case of single thread rivers. Experimental studies indicate that aggradation rate is directly related to the frequency of autogenic behaviour and that absolute frequency values depend on the backfilling rate in the channel and the available accumulation space. Since aggradation rate is the direct result of the interplay of all allogenic controls, it is more logical to predict autogenic behaviour directly from aggradation rate than indirectly from sea-level, climate or tectonic forcing. It is shown that if the change in allogenic forcing is fast relative to the time that a river needs to come to grade (equilibrium time), then the change in aggradation rate and the frequency of autogenic behaviour is highest. If the change in allogenic forcing is slow relative to the river's equilibrium time, then there is also little change in the frequency of autogenic behaviour.

Keywords: Autogenic, avulsion, aggradation, alluvial fan, braided river, single thread river, backfilling.

INTRODUCTION

Generic autogenic behaviour of alluvial systems refers to the common intrinsic property of alluvial systems to shift their streams and rivers laterally by avulsion and bifurcation (Beerbower, 1964; Allen, 1965; Slingerland & Smith, 2004). In this way the river spreads its sediment load evenly over the available surface area to reach the lowest potential energy level and highest stability (Paola *et al.*, 2009). This intrinsic property can be observed everywhere in nature. The sediment spread is commonly more even for high-gradient and moderate-gradient river systems that carry little fine-grained suspension load and experience high

discharges (alluvial fans, outwash plains, braided river systems), than for low-gradient rivers that carry abundant suspension load. In the first case, bank stability is low and in the latter it is high, which keeps the river better in position. If all alluvial accumulation space is filled and the river has reached its grade (base level), no net erosion or deposition along the channel belt occurs and the spread of sediment and thus avulsion of streams is halted, while all supplied sediment bypasses the region.

In nature, boundary conditions that define base level fluctuate continuously by changes in discharge, sediment load, grain size etc., affecting the river's slope and its buttress (the point

where the river profile grades to, e.g. shoreline, see Holbrook *et al.* (2006) and further discussion below). Hence, fluvial systems are rarely at grade and usually alternate between spreading their sediment laterally, if still aggradational, and funnelling their sediment by incision down slope, if erosional. The degree of spreading is thus determined by upslope and downslope boundary conditions, which change continuously with changes in sea-level, climate and tectonics.

The aim of this contribution is to review the work that has been done over the last decades towards understanding autogenic behaviour in stream-flow dominated alluvial fan and fluvial systems. In particular, the results of new experimental, theoretical and numerical studies are used to arrive at a new working hypothesis to predict frequency of autogenic change from basic principles (thus by abductive inference, see Kleinhans *et al.*, 2010). The usefulness of the hypothesis is discussed along a few well-researched natural examples.

AUTOGENIC PROCESSES

A river shifts its course by lateral migration, avulsion and bifurcation (see review by Jones & Schumm, 1999). Kleinhans (2010) distinguishes avulsion from bifurcation simply by the shift of the course of a river over several meander bend wavelengths. At bifurcations, water and sediment are divided over two downstream branches. Avulsions can be instantaneous or gradual, whilst an avulsion site is at least temporarily a bifurcation, because the new channel develops while the old one is still active. For practical reasons in stratigraphic reconstructions and as a consequence of the limited resolving power of ^{14}C dating, Stouthamer & Berendsen (2000) defined instantaneous avulsion as an avulsion where two adjacent channel belts coexisted for less than 200 years. If two adjacent channel belts coexisted for more than 200 years, avulsion was defined as gradual (cf. Törnqvist, 1994).

Process-oriented studies discussed below reveal different autogenic processes for 1) steep-gradient alluvial fan (with slopes in the order of more than 2 degrees), 2) moderate-gradient braided river (slopes ~ 0.4 degrees) and 3) low-gradient, meandering or anastomosing river; so these will be dealt with separately.

Steep-gradient alluvial fan

Autogenic processes in a steep-gradient, stream-flow dominated, alluvial fan were studied from analogue experimental studies of small alluvial fan models. The slope of such a steep-gradient fluvial system builds up by alternations of sheet and channelised flow (Schumm *et al.*, 1987; Bryant *et al.*, 1995; Whipple *et al.*, 1998). In Eurotank, at Utrecht University, the autogenic behaviour was analysed in detail by Van Dijk *et al.* (2009, 2011). Alluvial fans and fan deltas (the latter defined by Nemeč & Steel, 1988, as alluvial fans prograding into a standing body of water) were formed by feeding water and sediment through a narrow (4.5 cm wide) duct. The water jet that issued from the duct could expand freely on a large sediment table 2.5 m wide and 2.7 m downslope. The observed morphodynamics are governed by cyclic alternating sheet flow and channelised flow. The sheet flow builds a convex-shaped fan apex cascading down onto the mid-fan region (Fig. 1). When the slope of the apex reaches its critical threshold value, the water flow incises creating progressively expanding channelised flow through fan incision and headward erosion. The trench so created in the fan apex funnels the sediment down the fan and forms telescoping fan lobes and bifurcating channels at the slope break in case of the alluvial fan and at the shoreline in case of the fan delta, while deposition is forced by reduction of the stream gradient. The backfilling of the trench starts with mid-channel bar formation, ultimately bringing the system back to the sheet flow stage and its critical slope; then the process of fan incision and channel formation will start again. In the experiments by Van Dijk *et al.* (2009, 2012) each channel incision was stacked on top of the previous one, a phenomenon which was ascribed to the upper boundary condition: a fixed 4.5 cm wide duct, through which the stream is debouching onto the fan apex (Van Dijk *et al.* 2009). When using wider ducts, bars can be seen developing both in and at the outlet avulsing the flow towards the right and left of the fan body producing compensation cycles and ‘fanning’ (e.g. Bryant *et al.* 1995; Whipple *et al.* 1998).

Moderate-gradient braided stream systems

The autogenic process in braided streams was studied in detail by Ashworth *et al.* (2004, 2007) through distorted Froude-scaled models (see

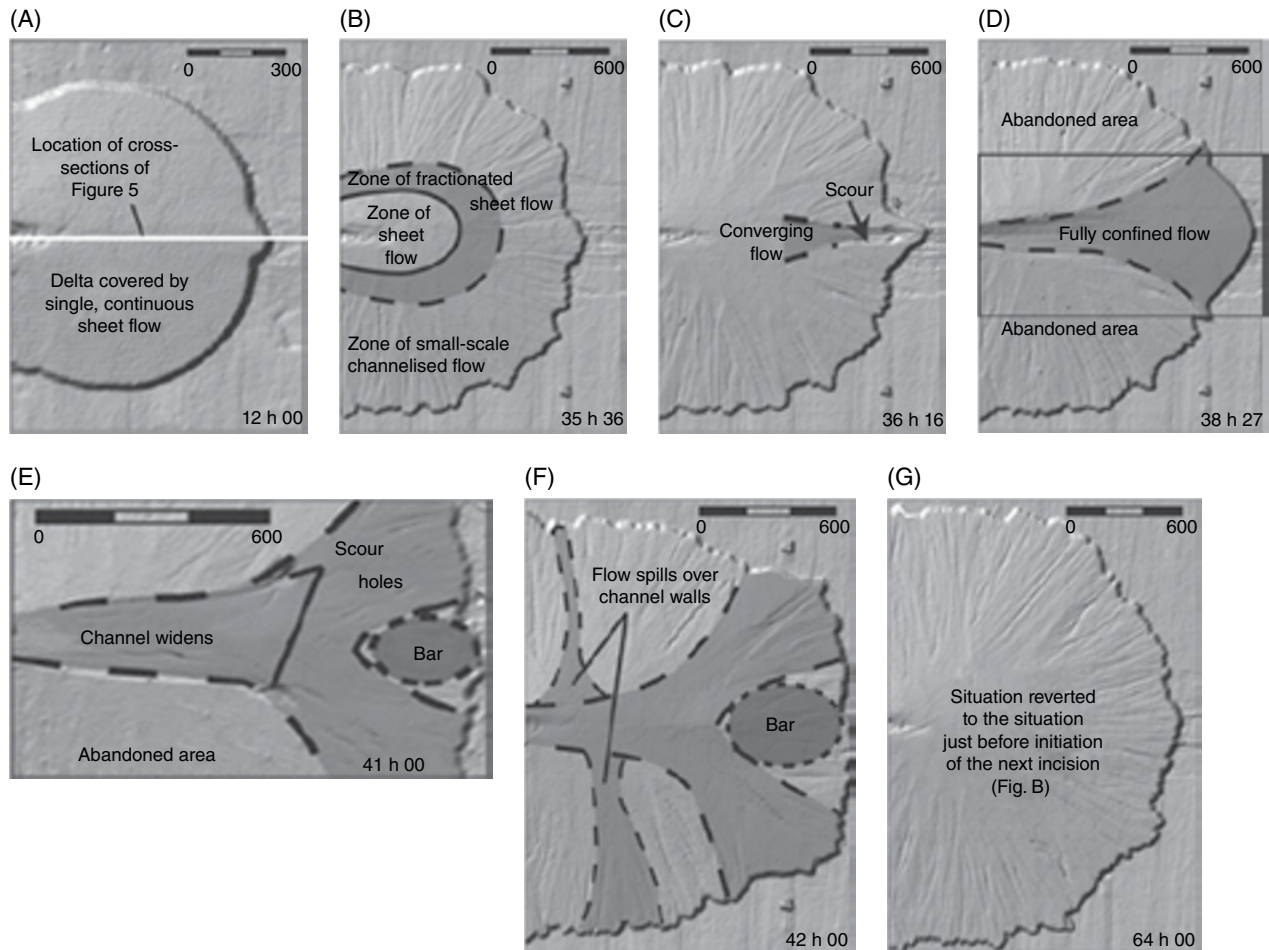


Fig. 1. Shaded relief maps of an autogenic cycle. Run time is shown in the lower right corner. The scale of the plots is indicated in the upper right corner; the position of panel (E) is given by the inset in panel (D). A. The initial jet transformed into an expanding sheet flow. Single sheet flow producing smooth delta plain topography; B. With growth of the delta plain sheet flow fractionates causing small-scale channelised flow near the shoreline; C. Progressive aggradation at the apex increased the gradient of the delta plain up to the point when a scour hole was initiated along the centre line of the fan delta; D. The scour hole developed quickly into a knickpoint that moved upstream connecting the scour with the feeder channel; E. Backfilling starts with the deposition of a mouth-channel or mid-channel bar; F. Progressive backfilling while the flow gradually started to exceed the confining channel walls and increasingly spilled over the margin in the course of the backfilling process; G. When the entire channel had been filled, fractionated sheet flow and aggradation of the apex were restored (from Van Dijk *et al.*, 2009).

Peakall *et al.* 1996) of a braid plain with characteristic channel and mid-channel bar configurations. The set up differed from those of Bryant *et al.* (1995) and Van Dijk *et al.* (2009, 2011) in that the feeder channel was uplifted, herewith creating accumulation space (terminology *sensu* Blum & Törnqvist, 2000) in the braid plain basin. Ashworth and co-workers arbitrarily defined stream avulsion around the numerous mid channel bars by the sudden, lateral shift of minimal 30 cm of a channel, while the new channel position must be maintained for at least a 15 min period. Each

avulsion starts off from a bifurcation, where the mid-channel bar splits the active channel flow over two branches following similar processes as pictured in Fig. 1D and 1E. The experiments of Sheets *et al.* (2002) and Hickson *et al.* (2005) conducted at Saint Anthony Falls Laboratory had multiple entries, which produced a kind of braid plain showing autogenic processes probably more akin to those occurring on stream-dominated coalescing alluvial fans, each with characteristic alternating channelised and sheet flow processes. Sheet flow does occur in braided river systems, in

particular during floods, yet their possible contribution to the avulsion processes on the braid plain itself is not tackled by the experimental studies mentioned in this section.

Low-gradient rivers

The autogenic behaviour in the low-gradient river category includes the behaviour of all single thread leveed anastomosing and meandering channel systems. Experimental studies for this category focusing on effective aggradation rates and flow occupancy are almost non-existent, with the exception of the revolutionary cohesive-delta experiments by Hoyal & Sheets (2009). They find, on the basis of their experiments for cohesive delta plains, that avulsion of channels (and their lobes) happens in three steps: The first step involves bar aggradation above the point where the incipient topography affects the flow which leads to flow widening and flow bifurcation leaving a V-shaped, subaerial region on the bar surface and ending the bar cycle. The second step, of negative feedback, involves a morphodynamically mediated backwater effect that is created by the mid-channel bar. As the bar grows, a hydraulic backwater effect propagates slowly upstream in the delta distributaries and is followed immediately by a wave of channel bed aggradation. As the lobe continues to grow and channel bed aggradation increases, overbank flow drives accelerated subaerial levee growth. This drives the system to step 3, where the combined effect of bed aggradation and progressively upstream levee growth leads to super-elevation of the channel and ultimately to the ‘discovery’ of a more favourable path to the shoreline, i.e. avulsion.

Additional insight into the autogenic behaviour of low gradient rivers is mainly based on historical and sedimentological reconstructions and on numerical modelling. These reconstructions have led to the common belief that avulsion of single thread rivers is driven by 1) local super elevation of some part of a channel or channel complex above its surroundings by the ratio between cross-valley and down-valley gradient (gradient advantage) and 2) the occurrence of a trigger event, commonly a flood (see review by Jones & Schumm, 1999; Stouthamer & Berendsen, 2007) or storm surge, the latter being important in delta distributaries. The river flood may cause avulsion by blockage of the flow by

local reduction in channel capacity or by local obstruction. Flow blockage may also be caused by storm surge migrating up river (backwater effect).

For low-gradient, subcritical (Froude < 1), flowing rivers, the backwater effect is defined by the distance L at which the water level has adapted to 67% of its upstream normal flow depth and is estimated by

$$L = \frac{h}{3s} \quad [\text{m}] \quad (1)$$

with h =flow depth [m] and s =channel slope [-] (e.g. Van Rijn, 1994). Hoyal & Sheets (2009) found in their experiments that the real morphodynamic backwater effect may easily be twice as much of the calculated effect, which could bring the avulsion node that much farther upstream, theoretically. Several important examples of avulsions triggered by various means of channel blockages have been documented by King & Martini (1984), Schumann (1989), McCarthy *et al.* (1992) and Harwood & Brown (1993). The interaction of both drivers for autogenic change (i.e. gradient advantage and triggering events) was tested by numerical modelling of river behaviour (e.g. Mackey & Bridge, 1995; Törnqvist & Bridge, 2002; Karssenbergh & Bridge, 2008). Recent numerical modelling by Kleinhans *et al.* (2008) demonstrated that during the initial bifurcation of the river, when water and sediment are split over two branches, the choice of which bifurcate channel becomes more important than the other is determined by a number of factors of which local gradient advantage is just one. The other factors are the position of the avulsion node relative to the upstream meander bend (Kleinhans *et al.*, 2008), the channel width-depth ratio of the bifurcate channels or the breach (e.g. Slingerland & Smith, 1998), the grain size sorting and the presence of local obstructions (bars and bank irregularities, see Kleinhans *et al.*, 2008). The factors together offer an explanation of why some bifurcations were destabilised in decades and others in centuries in the Rhine Meuse system (Kleinhans, 2010).

Although avulsion drives the single thread rivers to distribute their sediment evenly over the coastal lowlands, bank stability and differential compaction rates between the fine grained and peaty floodplains and silty to sandy channel belts makes the surface area of such systems highly irregular, even at high avulsion rates (e.g.

Stouthamer & Berendsen, 2001). Peat formation potentially influences avulsion by inhibiting lateral migration and increasing aggradation in the channel belt. Peat compaction and oxidation in flood basins also leads to relief amplification and to super-elevation of channel belts (Van Asselen *et al.* 2009).

Cyclic avulsion processes in the Yellow River delta were forced by rapid delta progradation causing the river to adjust its channel belt profile by aggradation (Kriele *et al.*, 1998). At some point the aggradation led to an increase of transverse slopes causing the channel to avulse in another direction. It is noted here that this process is in contrast with the initiation of avulsion on stream-dominated alluvial fans as determined from our experimental studies, where sheet flow increases the gradient of the entire apex to levels of instability and new channel incision. In braid plains, gradient advantage in bifurcations does play a similar role, yet occurs on much smaller temporal and spatial scales.

In summary, autogenic behaviour in alluvial fans and braided river systems is different from that in moderate-gradient and low-gradient river systems and is most strikingly different by the effect that backwater has on the channel belt aggradation. The effect of backwater is virtually lacking in the moderate and steeply graded systems (see equation 1), while the water flow in the channels is often close to supercritical (Sheets *et al.* 2002; CGER, 1996; Hoyal & Sheets, 2009); so caution is needed when applying experimental studies of those systems to low gradient rivers. However, in all cases backfilling of the channels is a prerequisite for avulsion, since backfilling elevates the channel above its surroundings. In the case of alluvial fan systems, the avulsion trigger is clearly related to steepening of the apex by the sheet flow, which can only commence if backfilling is completed. In the case of braided river systems, the trigger is by a growing advantage of one bifurcate over the other. The avulsion process of the braided river is thus, in this respect, similar to that of the single river, where avulsion also starts with a bifurcation but where the change from bifurcation to avulsion is up to three orders of magnitude slower. Avulsion frequencies vary greatly among modern river systems, with a lowest rate of 28 years for the Kosi River in India and up to 1400 years for the Mississippi River (Slingerland & Smith, 2004).

FREQUENCY OF AUTOGENIC PROCESSES

The rate of backfilling (aggradation in the channel belt) defines the frequency of autogenic processes (cf. Van Dijk *et al.* 2009). Backfilling commences where there is sufficient reduction in channel slope to force deposition. If the lower boundary is the shoreline, then reduction of slope is obtained by progradation of the shoreline and the creation of a mouth bar (e.g. Kriele *et al.* 1998). If the fluvial system is prograding over a (flood) plain, it must also be the reduction in slope by progradation of the system that forces deposition and formation of a mid-channel bar, heralding the backfilling. The accumulation space and the rate at which the required sediment volume aggrades the channel both determine the avulsion frequency. Bryant *et al.* (1995), on the basis of their experimental results, were the first to link avulsion rate with aggradation rate, although they did not measure the aggradation but simply took sediment yield at the apex of the fan as a proxy for aggradation rate. Here, it is important to realise that it is not the total of the supplied sediment is important, but how much of the supply is used for aggradation of the bed. Supplied sediment that is not used for aggradation bypasses the channel and is used for progradation of the system at the channel mouth (telescoping fans). If the rate of backfilling is slow, observations from experiments (Van Dijk *et al.* 2009) indicate that the river valley has time to deepen and widen, which increases its accumulation space causing a negative feedback to avulsion frequency, thus reducing it. Incipient relief, channel length and fan-produced local surface irregularities (lobes, scours, channels and bars) are most probably causes for observed deviations in cycle duration and the timing of re-incisions.

Van Dijk *et al.* (2012) showed how frequency of autogenic processes in their steep gradient systems is related to channel backfill rate. The frequency in their experimental alluvial fans, which prograded over a near horizontal plain, appeared to be much higher than for fan deltas. Since the upper boundary conditions for the alluvial fans were the same in both experimental set ups, the change in frequency must have been caused by the only difference between the experimental fans, i.e. the presence of a shoreline. They demonstrated that the presence of the shoreline caused different aggradation rates on

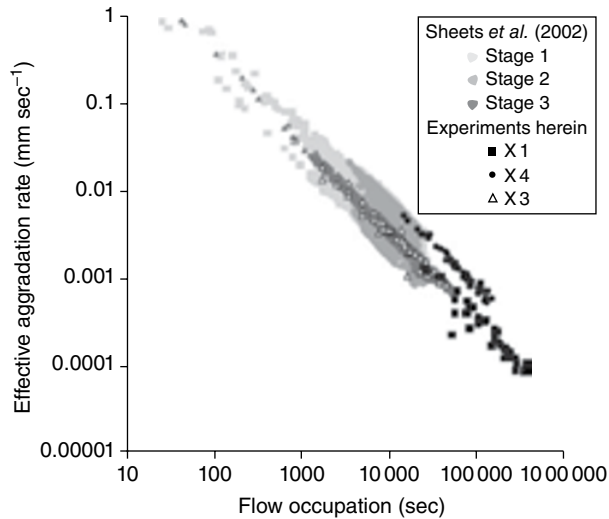


Fig. 2. Change in effective aggradation rate as a function of duration of flow occupancy for all sections in the three experiments. From Ashworth *et al.* 2007 with data from stages 1 to 3 from Sheets *et al.* (2002).

the alluvial fan surface. While in the first case all supplied sediment aggraded on the fan surface, in the second case part of the supplied sediment bypassed the fan surface and aggraded in the subaqueous delta.

Ashworth *et al.* (2007) plotted flow occupancy against effective aggradation rates including the data from Sheets *et al.* (2002). The plot shows a near-inverse relationship and demonstrates that with the highest aggradation rates the channels still have time to distribute sediment sufficiently over the braid plain. With the lowest aggradation rates, the channel can be seen to migrate predominantly laterally with, rare, sudden shifts. Ultimately, a perfect inverse relationship between effective aggradation rates and flow occupancy must exist if the braidplain aggrades evenly over its entire surface. Ashworth *et al.* (2007) compiled their data and that of Sheets *et al.* (2002) in a diagram (Fig. 2) to demonstrate that aggradation rate is an important driver of flow occupancy and thus frequency of autogenic processes. In spite of the fact that the avulsion process is of a different kind than in the alluvial fan studies of Sheets *et al.* (2002), the correlation is excellent.

For low-gradient rivers, Karssenbergh & Bridge (2008) modelled bifurcation and avulsion frequency three dimensionally by simulating sediment transport by the diffusion equation. The

timing and location of channel bifurcation is controlled stochastically as a function of the cross-valley slope of the floodplain adjacent to the channel belt relative to the down-valley slope and of annual flood discharge. To examine how the model responds to extrinsic controls, the model was run under conditions of changing base level and increasing sediment supply. Rises and falls in base level and increases in sediment supply occurred over 10,000 years. Rising base level caused a wave of aggradation to move up-valley, until aggradation occurred over the entire valley. Frequency of bifurcations and avulsions increased with rate of base-level rise and aggradation rate. Kleinhans *et al.* (2008) modelled numerically duration of the avulsion time, which is assumed to be determined by the width to depth ratio of the channel, the upstream bend radius determining the gradient advantage for one bifurcate over the other and the length of the bifurcates. According to Kleinhans *et al.* (2008) the model explains how combination of variables may result in the observed large variation of avulsion duration in historical and geological data.

In summary, experimental and numerical studies show that aggradation rate is an important driver for the frequency at which autogenic processes occur. Furthermore, these process studies show that absolute values of frequencies depend on the backfilling rate of the channel, which depends strongly on the accumulation space that needs to be filled, but also depends on local factors that determine the hydrology. It is important to note at this point that all experimental modelling discussed here showed that avulsion frequency is certainly not constant with aggradation rate or varies around a mean value, as assumed in the modelling of Leeder (1978).

ALLOGENIC CONTROLS ON GENERIC AUTOGENIC BEHAVIOUR

The experiments on three-dimensional alluvial stratigraphy by Hickson *et al.* (2005) were designed to investigate the influence of allogenic controls on architecture in alluvial successions. They concluded that the alluvial architecture of their models is controlled, very strongly, by externally forced facies migrations, hence by changes in sediment supply, base level or subsidence. Sea-level, climate and tectonics change the accumulation

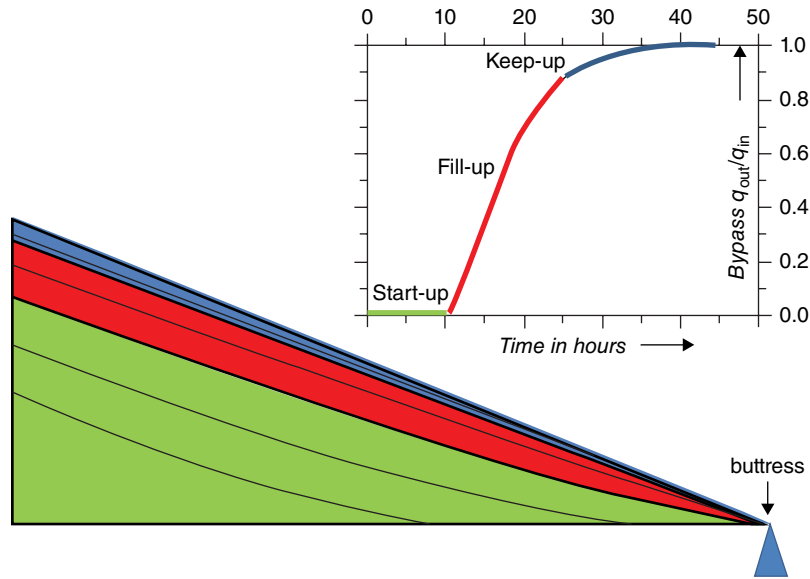


Fig. 3. Schematic illustration of the stratigraphic development of a two-dimensional, fluvial sediment wedge in a duct of 0.11 m width and 4.5 m length. The changes from start-up, to fill-up and from fill-up to keep-up stages have been marked by colours. The black lines are time lines at about 5 hour intervals. During the start-up stage the system progrades to base level. Once its toe has reached base level the system will come in its fill-up stage and finally in its keep-up stage. The graph in the inset shows the percentage of sediment bypass relative to what enters the system (based on Postma *et al.*, 2008).

space in the fluvial realm continuously and together control the ultimate gradient of the fluvial system. Detailed studies of fluvial architecture in the Rhine Meuse delta system in combination with good age control have led Stouthamer & Berendsen (2000, 2001, 2004 and 2007) and Van Asselen *et al.* (2009) to relate avulsion frequency to these allocyclic controls. However, since the interplay of sea-level, climate, local tectonics and regional tectonics together defines the aggradation rate, it will always remain challenging to unravel the relative contributions of each from that which drives autogenic behaviour directly: aggradation rate. For the geologist who wishes to predict fluvial architecture and sandstone body connectivity, the direct relationship between aggradation rate and frequency of autogenic behaviour is thus an interesting one (cf. Leeder, 1978), because it simplifies questions about cause and effect. Aggradation rate can reasonably be measured and bounding surfaces can be dated, so prediction of autogenic behaviour can be done on the basis of quantitative criteria.

Aggradation rate

Aggradation or deposition rate is not to be confused with sediment supply rate, since aggra-

gradation rates do not vary linearly with sediment supply, as was demonstrated by simple 2-dimensional experiments performed in a duct of 0.11 m width and 6 m length (Postma *et al.*, 2008). The purpose of these experiments was to produce fluvial stratigraphy by adding water and sediment to the duct. It was found that channel aggradation is predicted best by non-linear diffusion (Fig. 3). For the two dimensional channel belt case, there is increasingly more bypass with steepening of the channel gradient, when the channel system is building up to grade. Depending on the amount of bypass, each channel system can be seen to pass through three development stages: 1) a start-up stage, in which the system aggrades towards base level and during which no sediment can bypass base level, 2) a fill-up stage, where the system both aggrades and progrades beyond base level, hence with sediment bypass up to the arbitrarily chosen 90% level and 3) a keep-up stage, in which less than 10% of the sediment input is used for aggradation, whilst the rest bypasses the system. Allogenic controls will force the system back and forth between the start-up and keep-up stages resulting in variation in aggradation rate and related avulsion frequency. In the section below, an estimate is made of this variation.

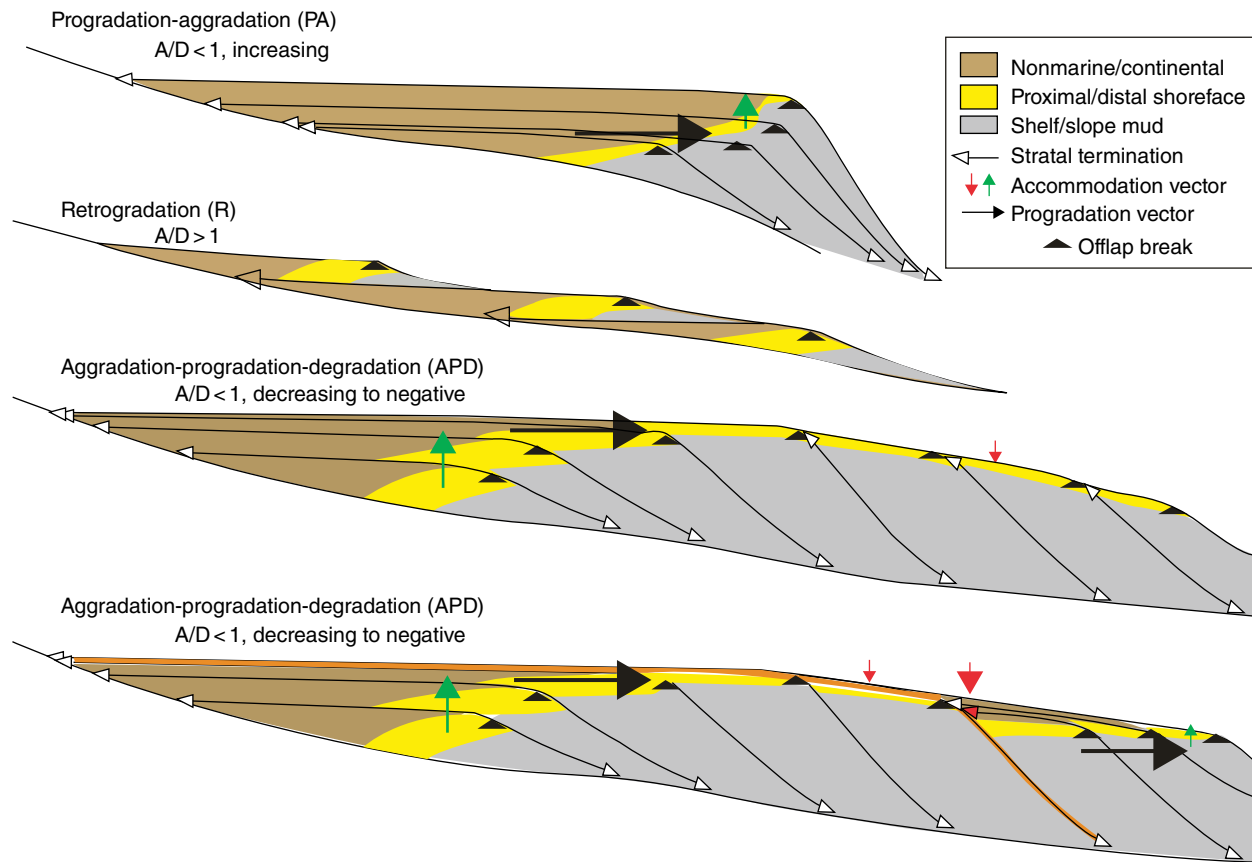


Fig. 4. Stratigraphic stacking patterns associated with changing rates of coastal accommodation creation (A) and sediment fill (S), referred to as accommodation succession. Following a sequence boundary, the stratigraphic motif observed in the geologic record is progradation to aggradation (PA), retrogradation (R) and aggradation to progradation to degradation (APD), representing stratal geometries of lowstand, transgressive and highstand systems tracts, respectively. APD systems tract indicates a decrease in accommodation on the shelf through time. Toward the end of the APD systems tract, accommodation on the shelf may become negative, generating degradational stacking, not showing downward shift in coastal onlap. When downward shift in coastal onlap is observed, onlapping of proximal facies over distal ones would indicate formation of sequence boundary and initiation of another PA, R and APD succession (from Neal & Abreu, 2010).

Sea-level

Large-scale, sea-level forced architectural styles of river-delta systems comprise progradation-aggradation, progradation-degradation and retrogradation-aggradation stacking styles (Curry, 1964). These styles are recognised widely in seismic sections (e.g. Neal & Abreu, 2010) and related to normal regression, forced regression and transgression, respectively (Catuneanu *et al.*, 2009) (Fig. 4). Curry (1964) and Jervey (1988) related the three stacking styles to the rate of change of accommodation space (at the shoreline) [A] and the rate of sediment supply [S], thus A/S . The filling of accommodation, however, is not directly controlled by S , but by the aggradation (deposition) rate (D) (as was also argued by Muto & Steel (1997;

2001), so that the ratio A/D defines the fluvial deltaic architecture.

During normal regression there is accumulation space to fill in the alluvial system (PA, see Fig. 4). During the fill, there is significant bypass of sediment causing the progradation of the clinof orm. Hence, the alluvial system will start somewhere in the fill-up stage and, depending on the progradation rate, reaches the keep-up stage. Under these conditions slow back filling in the channels occurs (significant bypass of sediment), so avulsion rate can be expected to be low.

During forced regression there is deposition, erosion and down stepping of the alluvial system (APD, see Fig. 4). Above the knickpoint, fluvial systems can still aggrade, as has been observed in landscape evolution experimental studies

(Van Heijst & Postma, 2001). Muto & Swenson (2005) quantified the maintenance of the fluvial grade by the specific square-root-of-time dependent rate of relative sea-level fall. The specific coefficient depends on sediment-water supply and system geometry. Hence, upslope of the knick-point the alluvial river system can remain aggradational for a wide range of relative sea-level fall rates and channels can still back fill and avulse. Downslope of the knickpoint the river profile steepens, which hinders the back-fill process.

During transgression the shoreline steps back (PA, see Fig. 4). During the retrogradation brief stages of progradation occur (delta lobe building), during which the fluvial system can aggrade (see the experimental results of Muto & Steel (2001) and Hoyal & Sheets (2009)). The development of a coastal barrier system forces the shoreline seaward bringing out the base-level point towards which the fluvial system is going to adjust itself. In this period of time the system is brought back close to the start-up stage leading to maximal aggradation in the alluvial realm and hardly any sediment bypass. During these periods, backfilling in channels is maximal and avulsion rates must be at their highest. The regular avulsions cause regular delta lobe progradation and shifting that is recognised as parasequences: shallowing upward sequences developed on top of flooding surfaces. The precise development of these coastal sequences can depend strongly on rate of sea-level rise (e.g. Cattaneo & Steel, 2003).

Climate

Holbrook *et al.* (2006) described the river profile as being highly variable due to changes in discharge and supply, i.e. by climate change. All potential river profiles are bounded above by a profile of highest possible aggradation and below by the profile of maximum possible incision. These upper and lower profiles are called 'buffers' and they envelop the available fluvial preservation space (Fig. 5). Thickness of the buffer zone is determined by variability in upstream controls and should increase up dip to the limit of downstream profile dominance.

The buffer model considers fluvial preservation to be limited to some space between upper and lower maximum possible profiles: 'buffers' that move and/or alter shape with downstream base-level shifts. Downstream, base level is considered to be controlled by movement of some physical

'buttress' (e.g. sea-level) below which streams cannot incise and above which streams cannot aggrade substantially. Upper and lower buffers are both anchored to this buttress and may diverge for some distance up-dip as profile variability is introduced by increasing influence of upstream base level controls. Upstream controls like climate and tectonics primarily determine spacing trends between these upper and lower buffers.

The change in river profile as a consequence of climate change is relatively fast in the case of a change in average discharge and much slower in the case of averaged change in sediment yield, as shown by experimental studies by Van den Berg van Saparoea & Postma (2008). These experiments demonstrate a fundamental difference between the response of the sediment flux at the river mouth due to changes in discharge and due to changes in sediment flux and differences between the total mass accumulation history in response to changes in discharge and sediment flux. The first fundamental difference between a response to either discharge or sediment input change is the total sediment budget at the valley outlet, which is much larger in case of a discharge change. The second fundamental difference is that the gradient of the valley floor is correlated positively with sediment influx and negatively with discharge (cf. also Mackin, 1948). The third difference is that the response to changes of discharge is very rapid, whilst the response to sediment flux changes is much slower (Van den Berg van Saparoea & Postma, 2008).

Hence, aggradation rates of the channel belt (and thus avulsion frequencies) would decrease at high discharges, as a consequence of reduction of accumulation space by lowering of the river profile; yet, backwater effects and channel blocking may temporarily increase the avulsion rate, silting up adjacent floodplains. If the river system would be near its grade, deviations in accumulation space forced by climate change are not likely to be very large, so the system will remain in the fill-up stage.

Tectonics

As also hypothesised by Holbrook *et al.* (2006), regional tectonics result in tilting of the river profile, while more local tectonics cause sagging, all with direct consequences for aggradation rate (Fig. 5). Channel belts appear not to be attracted to the subsidence maximum, unless subsidence

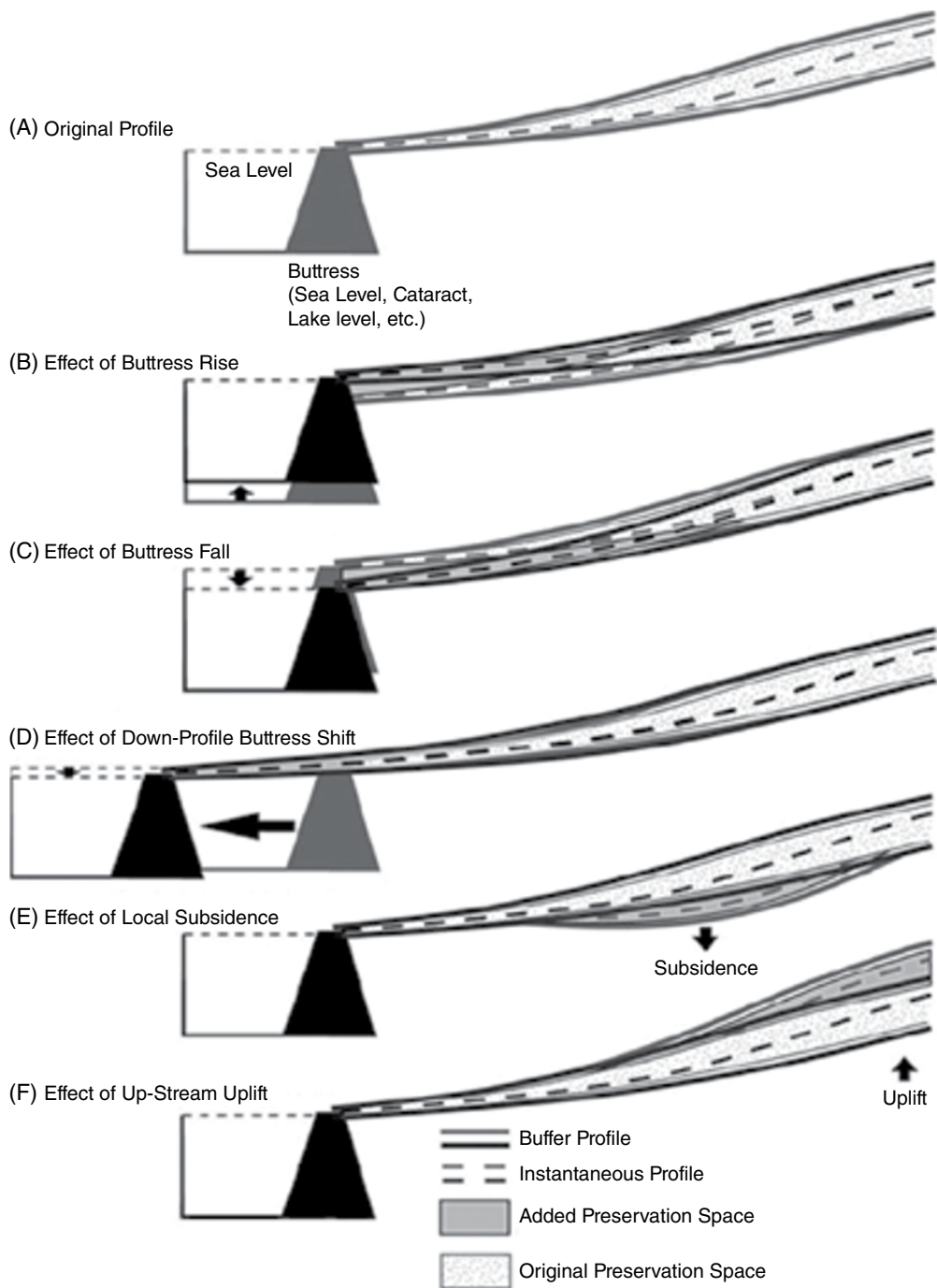


Fig. 5. Preservation space added as a result of shifts in initial buffer profiles (A) because of either buttress movement or tectonic adjustment. Fluvial preservation space may be added as a result of a simple buttress rise (B) or fall (C). Sediments deposited in added preservation space resulting from a buttress fall (C) are generally sequestered as easily eroded terraces hanging from the valley wall. They thus tend to have less long-term preservation potential than deposits buried by aggradation during a buttress rise (B). Movement of the buttress along the trajectory of the original longitudinal profile (D) tends to lengthen preservation space but otherwise adds minimal room for sediment accumulation. Subsidence beneath reaches of the lower buffer profile (E) tends to lower sediments deposited within the prior preservation space beneath active erosion. Long-term preservation potential of these sediments is high. Uplift beneath buffer profiles (F) tends to leave deposits from previous preservation spaces stranded as terraces where they could potentially be preserved long term but have high probability of erosion before eventual burial. In each of the above cases B through to F, the total space for potential accumulation of a fluvial unit is the integral of all preservation spaces produced over the period through which the depositing fluvial system was actively preserving sediment (from Holbrook *et al.*, 2006).

proceeds faster than aggradation of the river so that the latter can adjust to the formation of a topographic low by the deposition of overbank material in the form of splays and sheet sands (see experiments of Hickson *et al.* 2005).

Kim & Paola's (2007) experimental studies of sedimentation in an experimental relay ramp showed that autogenic cycles developed stratal packages of subaerial prograding lacustrine delta deposits bounded by fluvial aggradation units under constant discharge and sediment yield. These cycles were formed by strong variations in sediment delivery associated with tectonically-driven routing of river flow across and around the footwall uplift. Flow patterns of sheet flow and channelised flow ('avulsion cycles') became five times longer during the active subsidence (delayed the backfilling process). The period of the tectonic-driven autogenic processes was inferred to be of the order of 10 kyr to 100 kyr, which would be much lower than the normal autogenic behaviour.

Hence, the response in aggradation rate to tectonic change varies strongly with the kind of kinematics. Active fault scarps could make a fluvial stretch to subside instantly, bringing the system from fill-up to start-up stage, herewith increasing aggradation rates instantly. Basinward tilting of the fluvial profile as occurs, for instance, in passive margin settings would decrease aggradation rates, because the profile is tilted towards its grade.

DISCUSSION

In a discussion about how well fluvial architecture can be predicted in surface and subsurface analyses, Miall (2006) concluded that little can be expected beyond the provision of a general starting point. He argued that the variety of fluvial forms in modern rivers and the ancient record is vast, making the choice of an appropriate analogue very difficult. Fluvial style varies laterally or vertically through most real stratigraphic units because of the constant interplay of several allogenic controls acting on different time scales. Given the complex-response character of fluvial systems to allogenic forcing and including the tendency for systems to lag behind changes in forcing functions at varying rates, the predictability of fluvial architecture aerially and stratigraphically must be considered quite limited.

However, the experimental research mentioned here give reasons toward a more positive attitude. In spite of the fact that the experiments are not scaled hydraulically, the experimentalist has the great advantage of looking at a natural 'forward' model with similarity of process where the product can be studied in relation to input conditions (Paola, 2000; Paola *et al.* 2009).

The existence of scale-invariable morphological features like channels, bars and lobes hints to the similarity of process that is obtained in laboratory models. Sediment transport averaged over sufficiently long time periods can be predicted by diffusion (Paola *et al.* 1992). The crude fluvial architecture stemming from aggradation as well as from variations in depositional slope characteristic for the various river types can be simulated easily by using different exponents in a non-linear diffusion equation (Postma *et al.* 2008). Fig. 6 shows a dimensionless plot of aggradation rate by normalised sediment yield q_{in}/q_{out} against time (T) relative to the timescale that the fluvial system requires to reach grade (T_{eq}). The equilibrium timescale is the ratio of L^2/k , with L being a length scale which is given by the river's active depositional trajectory and k the diffusivity coefficient, which is related to the discharge (Paola *et al.*, 1992). The active depositional trajectory relevant for autogenic behaviour (avulsion) would be the backfill trajectory. With mean diffusivities of the order of $0.01 \text{ km}^2/\text{yr}$ (Paola *et al.*, 1992), channel depth of 7 m to 10 m and slopes of the order of 0.0001 (from Kleinhans *et al.*, 2008), most low gradient rivers in the delta plain have a backwater length of approximately 25 km, so that T_{eq} for the reach is about 60 kyr. For low gradient rivers a linear diffusion equation for simulation of sediment transport over long time intervals is justified (e.g. Paola *et al.*, 1992), so that the start-up stage is almost non-existent (Fig. 6). However, it should be noted that both the length scale and the diffusivity coefficient vary dynamically and with that the calculated equilibrium time. Hence, its value should be treated with caution and only in a first order of approach.

Allogenic forcing brings the system continuously out of balance and changes its accumulation space and herewith the aggradation rate, as was discussed above. In asking 'is it possible to predict the change in aggradation rate?' the author believes it is possible to predict the change in a first order of approach. If the time period for the change in accumulation space is much faster than T_{eq} ,

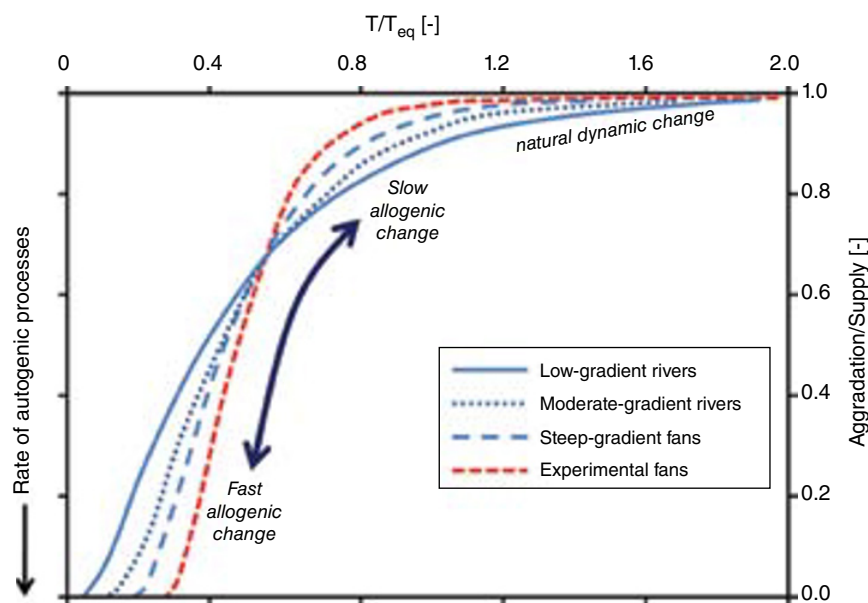


Fig. 6. Dimensionless plot of aggradation rate by normalised sediment yield q_{in}/q_{out} against time (T) relative to the time that the fluvial system requires to reach grade (T_{eq}). Sediment transport is calculated with a non-linear diffusion equation using different exponents. The low-gradient rivers are simulated with the linear diffusion equation (exponent $m = 1$, based on Paola *et al.* 1992). The steepest curve is calibrated against experimental results, for which the equilibrium slope is much steeper than for the deeper natural streams. The dotted curves intermediate of experimental fans and low-gradient rivers are estimations based on numerical interpolation between the steep experimental slopes and those of low gradient rivers (see Postma *et al.*, 2008). If the time period of allogenic forcing is much faster than equilibrium time of the river system then the frequency of avulsion will change with it. If it is slow then there will be no significant change (see text for further explanation).

aggradation rates are enhanced and if the period of change is much slower than T_{eq} , there will be little change in aggradation rate (see also Paola *et al.* 1992; Van Heijst & Postma, 2001). Hence, slow changes, as imposed for instance by regional tectonics, will hardly affect the aggradation rate so that the system remains in, or close to, the keep-up stage. Yet, rapid progradation of a delta lobe and subsidence near a fault scarp can have a significant effect on the accumulation space of the fluvial system and may bring it back into the start-up stage (Fig. 6). The experiments by Hickson *et al.* (2005) illustrate this point beautifully: fast subsidence is counterbalanced by high aggradation rates and slow subsidence rates by low aggradation rates. This causes fluvial systems not to migrate towards places with highest subsidence rates unless aggradation rates cannot keep up with the subsidence.

The analysis above leads us to a new working hypothesis that predicts the change in autogenic frequency: the rate of change (i.e. fast or slow change) in allogenic forcing relative to the equilibrium time related to the morpho-dynamically

active part of the river system is the dominant driver of the rate of change in aggradation and herewith the change in frequency of autogenic behaviour. Slow changes in aggradation rate do not change autogenic behaviour significantly, whereas fast change does. However, it is not to say that other parameters, like peat growth in adjacent floodplains, flood frequency, storm surge frequencies and others cannot be important in causes for a change in avulsion rate. Yet, it would be interesting to test the launched hypothesis and measure aggradation rates in delta plains and plot them against reconstructions of avulsion frequency.

IMPLICATIONS

At the scale of the channel belt, Leeder (1978) attempted to establish fundamental connections amongst subsidence, avulsions and channel belt sandstone bodies stacking density. He suggested that channel-belt stacking density and hence connectivity is *inversely* correlated to temporal (vertical) changes in sedimentation rate and that

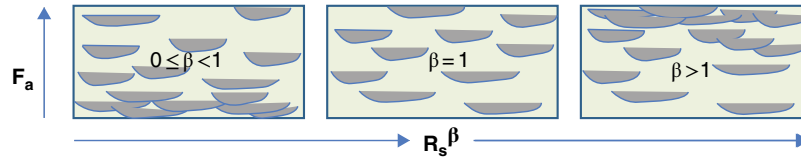


Fig. 7. Relation between channel-belt stacking density and sedimentation rate for three possible regimes defined by the exponent β in a power law relation between avulsion frequency and sedimentation rate. Dark grey indicates channel belt sand bodies and yellow indicates flood plain fines (redrawn from Bryant *et al.* 1995). Experiments suggest that the relationship pictured in the right hand side panel is most likely to occur in nature, which is an increase of avulsion rate with aggradation rate causing channels to stack more densely resulting in higher connectivity. F_a is the frequency of avulsions and R_s is the aggradation rate.

channel-belt stacking density and hence connectivity is directly correlated to lateral (horizontal) changes in sedimentation rate. Leeder (1978) suggested that reduction in subsidence rate with time increases the stacking density by allowing channel belts more time to remove floodplain fines.

Bryant *et al.* (1995) examined various forms of coupling between avulsion frequency and aggradation rate by examining their exponential relationship. If F_a is the frequency of avulsions and R_s is the aggradation rate then $F_a \approx R_s^\beta$, where β is a positive, real valued exponent. This leads to three qualitatively different regimes (Fig. 7) with $\beta=0$ resulting in a constant avulsion frequency, as assumed in Leeder's (1978) model. For $\beta=1$ the stacking pattern is independent of aggradation rate and for $\beta > 1$ the autogenic behaviour would increase with aggradation rate; this case is evident for all laboratory models presently known. This means that maximal removal of floodplain fines and greatest connectivity of channel bodies would occur if aggradation rates are highest.

Hickson *et al.* (2005) conclude, on the basis of their findings, that the two-dimensional variation in alluvial architecture is controlled very strongly by externally forced sedimentary facies migrations such as changes in sediment supply, base level or subsidence. However, the three variables together control the aggradation rate, the basic control on facies change. If the imposed variations are slow then facies migrations are kept at a minimum but if they are relatively fast (as in some of Hickson *et al.*, 2005 runs), then they become a dominant control on alluvial architecture. Leeder's (1978) point about the effect of the lateral changes in sedimentation rate (stating that avulsion rates must be highest at subsidence maxima and lowest at subsidence minima, while the overall lateral stacking density of channel belts may remain unchanged) agrees well with the experimental

findings of Hickson *et al.* (2005), who state that only if subsidence is faster than aggradation rate, will the river adjust and migrate to the topographic low that is formed.

Reconstructions of generic avulsion behaviour

For reconstructions of generic avulsion behaviour, detailed surface and subsurface mapping in combination with good age control is needed. Much of the hypothesis launched here still needs to be tested by thorough fieldwork, which at present gives ambiguous results. The cases dealt with below are nothing more than examples that help to demonstrate the frequency of avulsion and its relation to aggradation rates and are not meant as an exhaustive review.

Steep-gradient and moderately-gradient systems

Scott and Erskine (1994) studied twelve similarly sized Australian alluvial fans all subjected to the same catastrophic, rain-triggered, floods. The fans and catchment areas involved have similar sizes and gradients and were all located in a zone which received very similar rainfall intensities. Hence, the fans were subject to similar but significant flood discharges. Of the 12 fans, seven were entrenched and five were not before the storm event. The fans reacted in a different way to the storm event. Effects ranged from no change at all to trench incision or backfilling. Scott & Erskine (1994) propose that each fan showed a different stage of a similar autogenic cycle. The cycle consists of: (i) aggradation of the fan; (ii) the initiation of a fan-head trench due to exceeding the threshold slope; (iii) coalescence of scour pools to a continuous trench; and (iv) backfilling of the trench due to its widening and slope reduction.

Careful mapping of fan architecture and reconstruction of the hinterland degradation may permit a complete evaluation of fan history. Yet, age control in these coarse clastic environments is often not sufficient to determine details about the periods of autogenic processes in these coarse clastic systems (e.g. Nemeč & Postma, 1993; Mack *et al.* 2008) and much more field work in combination with improved age control of the rock record is needed to confirm the findings of experimental studies.

Low-gradient river systems

No doubt the most detailed avulsion reconstructions come from the Rhine-Meuse delta complex. Although a complete review of these works is beyond the scope of this paper, it is worthwhile to point out how much fast and slow changes relative to equilibrium time affect the avulsion frequency.

From a detailed reconstruction of the Holocene avulsion history of the whole Rhine-Meuse delta Stouthamer & Berendsen (2000, 2001, 2007) determined quantitative values for the avulsion parameters, avulsion frequency, avulsion duration and inter-avulsion period. In the Rhine-Meuse delta the number of coeval channels is related to avulsion frequency supported by high resolution age control that helps to analyse beginning and ending of river activity. The data show that instantaneous and gradual avulsions were almost equally important in the Rhine-Meuse delta, with two dominant avulsion styles: (1) regional avulsion: the new channel followed an entirely new course and (2) avulsion leading to reoccupation of existing channels. In the case of reoccupation, they found two possibilities: the new channel reoccupied (a) its previous channel (local avulsion) or (b) a pre-existing channel. Stouthamer *et al.* (2010) found that, over the Holocene time scale, avulsion style was related to aggradation rate and coastal evolution. Initial high avulsion frequencies decreased with dropping rates of sea-level rise (dropping rates of accumulation space) from 9000 years ago until ~3000 years ago. Thereafter avulsion frequency increased again (1.89 avulsions/100 yrs) during an inferred period of increased delivery of fine sediment and slightly altered discharge regimes (Stouthamer *et al.*, 2011), which increased back barrier aggradation rates significantly.

For the Mississippi delta, a database on avulsion frequency like that available for the Rhine-Meuse

delta does not exist. Over the past 5 kyr, the Mississippi River avulsed only four times and the Red River avulsed twice in the southern Lower Mississippi Valley, as found by Aslan *et al.* (2006). Relocation of the Mississippi River eastward shifted local base level and led to the Red River avulsion. Mississippi and Red River avulsion occurred primarily through channel reoccupation. Aslan *et al.* (2006) argue that gradient advantages did not necessarily lead to the avulsions, although gradient advantages along the Mississippi River floodplain are widespread.

Fielding *et al.* (2006) found climate change to be a primary control on the Holocene Burdekin delta architecture, inhibiting a shorter avulsion period by facilitating extreme variability of discharge. They suggested further that more frequent avulsion may also have been facilitated by the lengthening of the delta-plain channels as the system progrades seaward, which would increase the accumulation space rapidly. The Mfolozi River Floodplain (South Africa) is characterised by avulsions in the floodplain head that occur primarily during extremely infrequent large flood events, where the stream flow capacity of the channel is insufficient (Grenfell *et al.* 2009).

Other factors that control avulsion more indirectly have been forwarded from the study of natural examples, including neotectonics, subsidence, substrate composition, sinuosity changes and human activities (Fisk, 1952; Schumann, 1989; Schumm *et al.*, 1996; Jones & Harper, 1998; Smith *et al.*, 1998; Stouthamer & Berendsen, 2000) and meander bend properties (Kleinhans, 2010). Schumm *et al.* (1996) describe how reductions in channel gradient caused by increased channel sinuosity lead to decreased sediment transport capacity and avulsion (e.g. Makaske, 2001). It is challenging to relate the control of all these factors back to the control they have on aggradation rate and to relate that to frequency in autogenic behaviour. Yet, future stratigraphic studies in ancient fluvial and delta settings should be conducted to evaluate the significance of the change in aggradation rate on channel stacking density and connectedness further. That evaluation of change in aggradation rates is more practical than applying sequence stratigraphical principles in surface and subsurface stratigraphic analysis is shown by Moscariello (2003) and Martinius *et al.* (this volume) in correlating stratigraphic sequences in the Triassic-Jurassic Statfjord Formation (Norwegian Sea).

CONCLUSIONS

Autogenic behaviour is discussed for steep, moderate and low gradient fluvial systems and is found to be different for each fluvial type. In the first two types sediment is spread evenly over wide areas, in contrast with the low-gradient rivers. Other differences are that:

- 1 Steep-gradient systems show alternations of sheet flow and relief steepening, incision and progradation followed by backfilling. Cycle duration depends on the total volume of the fan incision and the backfilling rate, ranging from years to decades, depending on fan activity;
- 2 Moderate-gradient systems show bifurcations of short duration during high aggradation rates and bifurcations with slowly lateral migrating channels during low aggradation rates. Cycle duration is relative short ranging from days to years;
- 3 Low-gradient rivers build their channel belts up to grade while their floodplains lag significantly behind. It is inferred on the basis of numerical modelling that the origin of avulsion lies in gradient advantage, channel plugging and local hydrology in river bends. Details of the avulsion process are least understood in this type because experiments that allow study of their autogenic behaviour are absent. Cycle durations are relatively long and of the order of decades to centuries and strongly dependant on the backwater adaptation length.
- 4 Aggradation rate in the channel belts is the most important driver for the frequency of autogenic behaviour. Aggradation rate decreases non-linearly when the fluvial system builds up to grade, so that a full spectrum from high to low frequency autogenic behaviour is to be expected in natural systems that build up to grade.
- 5 Fast and slow changes in allogenic forcing relative to the equilibrium time (here related to the backwater length) of delta plain river systems is suggested here as the dominant driver of changes in the rate of aggradation and herewith the frequency of autogenic behaviour (Fig. 6). Fast change will increase the frequency of autogenic processes and will force rapid vertical changes in fluvial architecture, whilst a slow change will result in little or very gradual change of architecture.

Significant advancement in recognition and quantification of generic autogenic behaviour stems from experimental research on a landscape scale, where drivers for stratigraphic architecture can be verified along known input and boundary conditions. Scaling is by similarity of process, which is justified by scale invariant architecture and morphology as channels, sheet flow deposits, bars and lobes. Such landscape experiments are, as yet, non-existent for low gradient river systems, although stretches of low gradient river systems are presently studied by groups experimenting in more detail. In addition, field studies with high resolution age control are required to learn about the forcing mechanisms of avulsion in fluvial systems.

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