# PS Three-Dimensional Modeling of Facies Architecture and Connectivity Variations of Meandering River Successions in Evolving Rift Basins*

**Na Yan[1], Luca Colombera[1], and Nigel P. Mountney[1]**

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[1]School of Earth and Environment, University of Leeds, Leeds, United Kingdom. (N.Yan@leeds.ac.uk)

## Abstract

The spatial organization of meandering river deposits varies greatly within rift-basin fills, depending on how differential rates of subsidence and sediment supply interplay to drive changes in channel-belt position and rate of migration, avulsion frequency, and mechanisms of meander-bend cut off. This process fundamentally influences stacking patterns of the accumulated successions. Quantitative predictions of the spatio-temporal evolution and internal architecture of meandering fluvial deposits in such active settings remain limited.

A numerical forward stratigraphic model – the *Point-Bar Sedimentary Architecture Numerical Deduction (PB-SAND)* – is used to explore the relationships between differential rates of subsidence and resultant fluvial channel-belt migration, reach avulsion and stacking in active, fault-bounded half grabens. The model is used to reconstruct and predict the complex morphodynamics of fluvial meanders, their generated bar forms, and the associated lithofacies distributions that accumulate as heterogeneous fluvial successions in rift settings. Point-bar connectivity and stacking patterns are predicted in response to variations in rates of fault-driven subsidence, resulting accommodation generation, rates of river migration and avulsion frequency. Results show how the connectivity of point-bar sandbodies can be quantified as a function of subsidence rate, which itself decreases both along and away from the locus of fault displacement. Model outputs are analyzed quantitatively in terms of horizontal and vertical changes in static-connectivity metrics at multiple scales, to document the modeled connectivity of channel belts, point bars within them, and intra-bar sand-prone packages. Spatial variations in the connectivity of point-bar sandbodies are controlled by the relative significance assigned to input parameters that mimic allogenic and autogenic processes.

PB-SAND facilitates understanding of facies heterogeneity and connectivity variations of fluvial successions in rift basins, allowing examination of the influence of geologic boundary conditions on sedimentary architecture at different scales. Model outputs incorporate sedimentary architecture and stratigraphic heterogeneities of fluvial system elements realistically, and in a format that can be integrated into conventional reservoir-modeling practice, particularly to aid in the assessment of sandbody connectivity.

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Na Yan, Nigel P. Mountney, Luca Colombera

Fluvial & Eolian Research Group, University of Leeds, UK

## Abstract

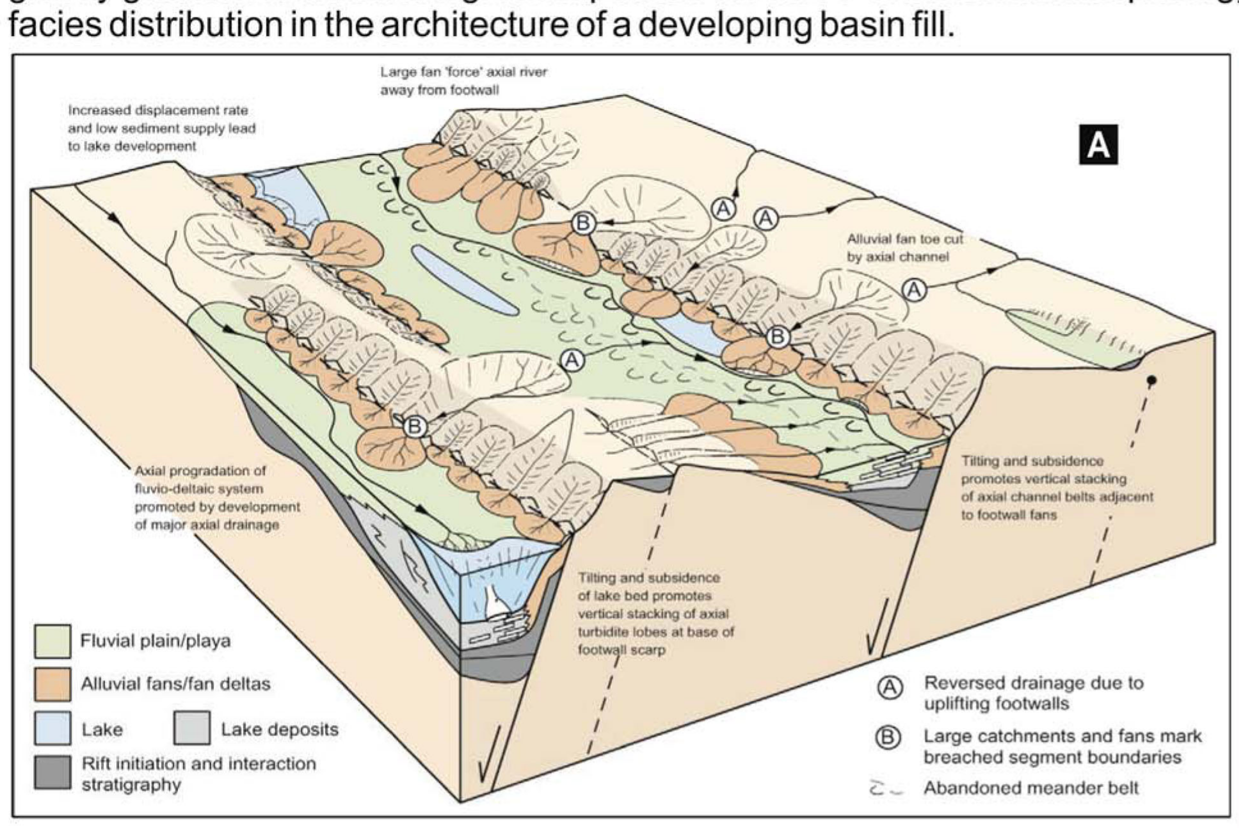
The spatial organization of meandering river deposits varies greatly within rift-basin fills, depending on how differential rates of subsidence and sediment supply interplay to drive changes in channel-belt position and rate of migration, avulsion frequency, and mechanisms of meander-bend cut off. This process fundamentally influences stacking patterns of the accumulated successions. Quantitative predictions of the spatio-temporal evolution and internal architecture of meandering fluvial deposits in such active settings remain limited.

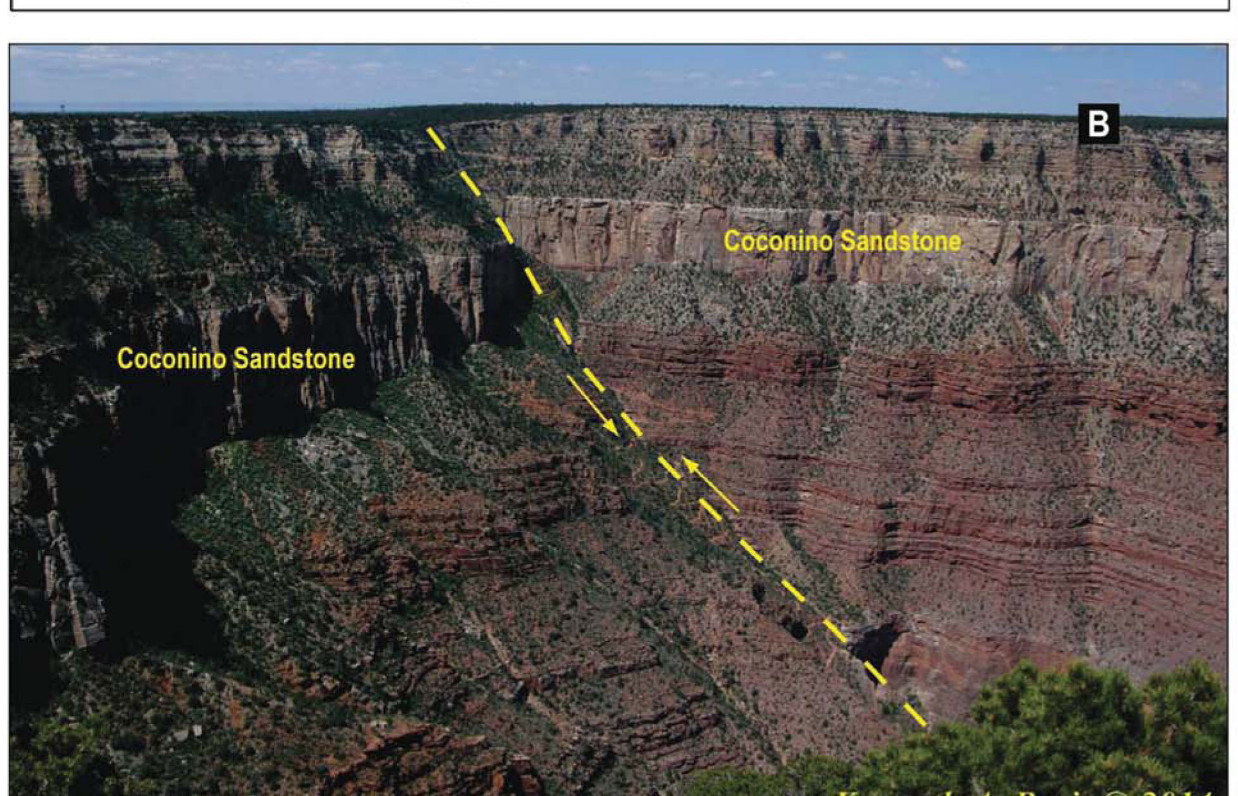
A numerical forward stratigraphic model – the Point-Bar Sedimentary Architecture Numerical Deduction (PB-SAND) – is used to explore the relationships between differential rates of subsidence and resultant fluvial channel-belt migration, reach avulsion and stacking in active, fault-bounded half grabens. The model is used to reconstruct and predict the complex morphodynamics of fluvial meanders, their generated bar forms, and the associated lithofacies distributions that accumulate as heterogeneous fluvial successions in rift settings. Point-bar connectivity and stacking patterns are predicted in response to variations in rates of fault-driven subsidence, resulting accommodation generation, rates of river migration and avulsion frequency. Results show how the connectivity of point-bar sandbodies can be quantified as a function of subsidence rate, which itself decreases both along and away from the locus of fault displacement. Model outputs are analyzed quantitatively in terms of horizontal and vertical changes in static-connectivity metrics at multiple scales, to document the modeled connectivity of channel belts, point bars within them, and intra-bar sand-prone packages. Spatial variations in the connectivity of point-bar sandbodies are controlled by the relative significance assigned to input parameters that mimic allogenic and autogenic processes.

PB-SAND facilitates understanding of facies heterogeneity and connectivity variations of fluvial successions in rift basins, allowing examination of the influence of geologic boundary conditions on sedimentary architecture at different scales. Model outputs incorporate sedimentary architecture and stratigraphic heterogeneities of fluvial system elements realistically, and in a format that can be integrated into conventional reservoir-modeling practice, particularly to aid in the assessment of sandbody connectivity.

## Introduction and Background

Half-grabens are the fundamental basin elements formed by a combination of footwall uplift and hanging wall subsidence, and comprise a narrow, steep footwall scarp slope along the fault zone and a gentler, broader hangingwall dip slope, as a schematic diagram shown in Fig. 1. The asymmetric tilting of depositional surfaces causes differential subsidence within the basin with a decrease of displacement from the fault centre to fault tips and basin margins. The displacement of a half-graben accumulates as the hangingwall pivots away from the footwall. Differential subsidence caused by tectonic tilting in an extensional half-graben system creates a gravity gradient and exerts a great impact on the three-dimensional morphology, internal stratal geometry, and facies distribution in the architecture of a developing basin fill.



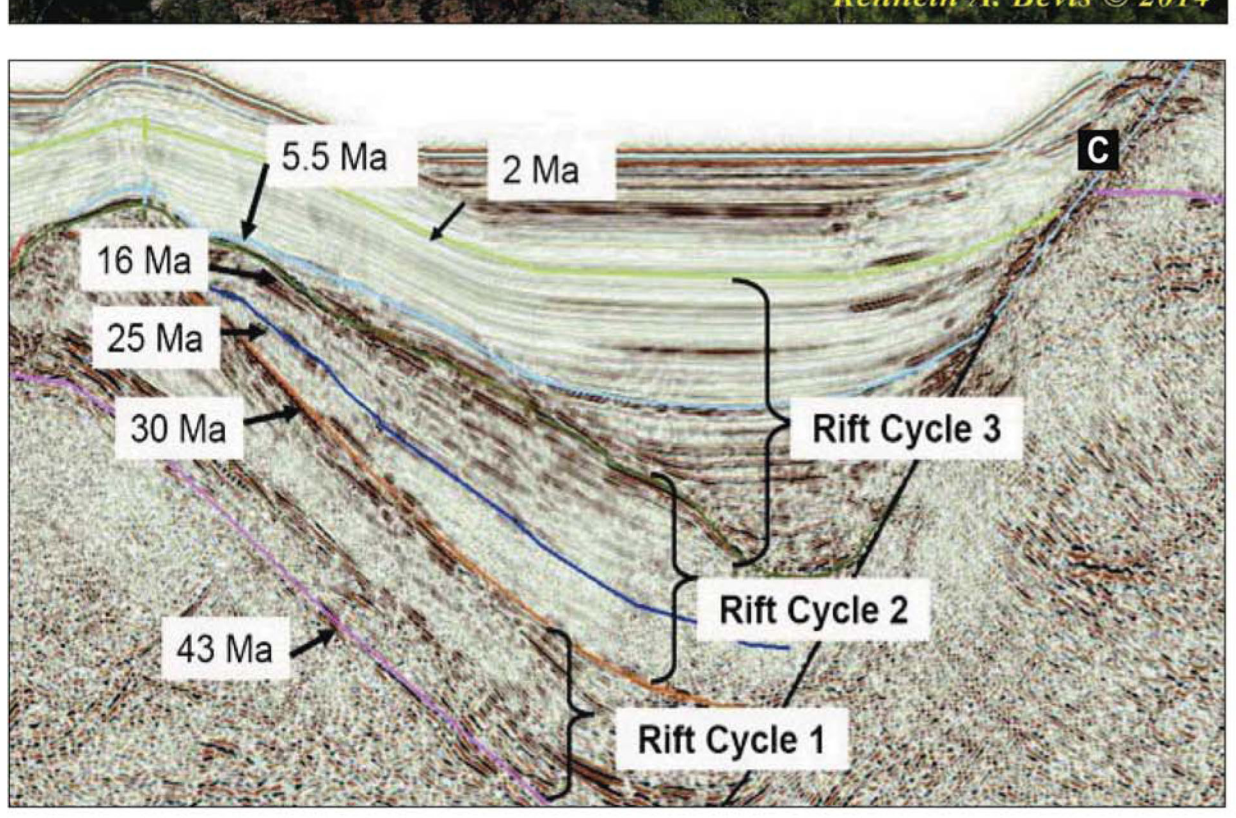




**Fig. 1.** (A) Schematic diagram illustrating evolution of continental half-graben systems (Gawthorpe and Leeder, 2000). The evolution of fluvial meandering rivers and the distribution of channel-belt deposits are controlled by spatial and temporal variations of accommodation development and basin physiography arising from differences in fault slip rates and local subsidence that are superimposed on the pre-existing channel gradient. A transverse slope, which is normal to the fault strike, increases the lateral migration of rivers and encourages channel belts to shift toward the position of topographic minimum, i.e., the site of maximum subsidence adjacent to the main fault, through meander cut-offs or channel avulsions. The progressive migration of channels can produce an asymmetric channel belt and wide channel deposits, whilst leaving abandoned meander loops facing up the paleo-slope. The repeated tectonic movement especially seismic events with varying frequency and magnitude strongly controls the spatial heterogeneity of facies within a rift basin and the facies stacking patterns over time. (B) Bright Angel fault of Grand Canyon. The displacement of Paleozoic sedimentary rocks can be easily identified. (C) Seismic lines showing three rift cycles in half graben in Luconia Basin, offshore Sarawak, Malaysia (Thies et al., 2005).

## Forward Stratigraphic Modelling Algorithm

The model uses combined geometric-based and stochastic approaches and can be applied to reconstruct the complex spatio-temporal evolution of a variety of meandering river behaviours and to examine the effect of repeated tilting events of a half graben on the three dimensional distribution and stacking patterns of meandering channel-belt deposits.

### Half-graben Geometry

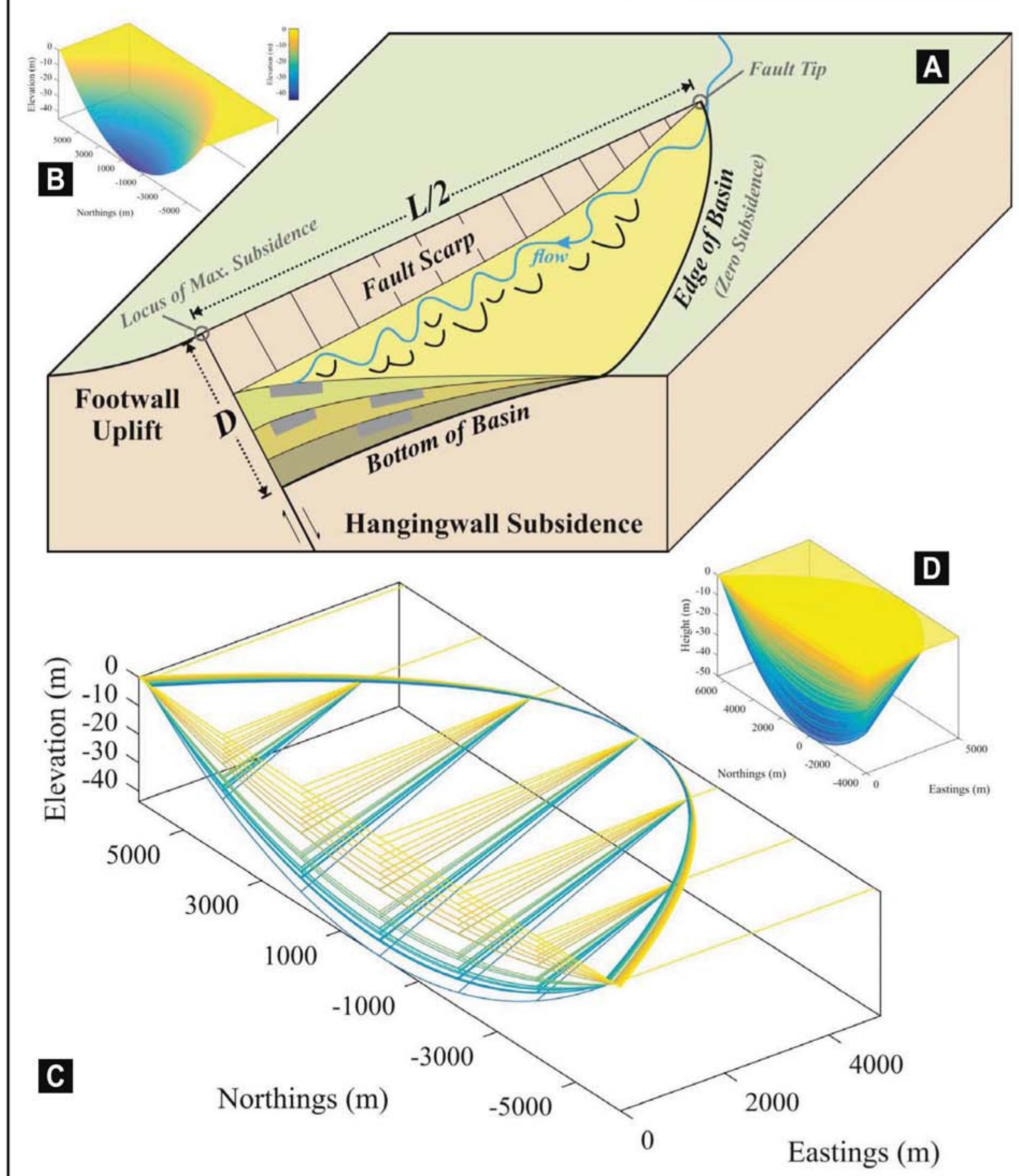



**Fig. 2.** (A) Schematic diagram of half of a half-graben system. Subsidence is maximum at the centre of fault zone and decreases from the locus to the edge of a basin. Axial rivers tend to migrate towards the fault zone within an evolving rift basin. (B) A typical scoop-shaped geometry of half-graben basin, generated from PB-SAND using a combination of parabolic-shaped displacement change along the strike parallel to the fault and linear decrease of displacement perpendicular to and away from the fault. (C) A modelling example of an evolving rift basin showing different sedimentary units emplaced by tectonic activity (earthquakes). (D) Sedimentary units of an evolving rift basin in 3D with a cross section shown in side view.

### Fault Growth

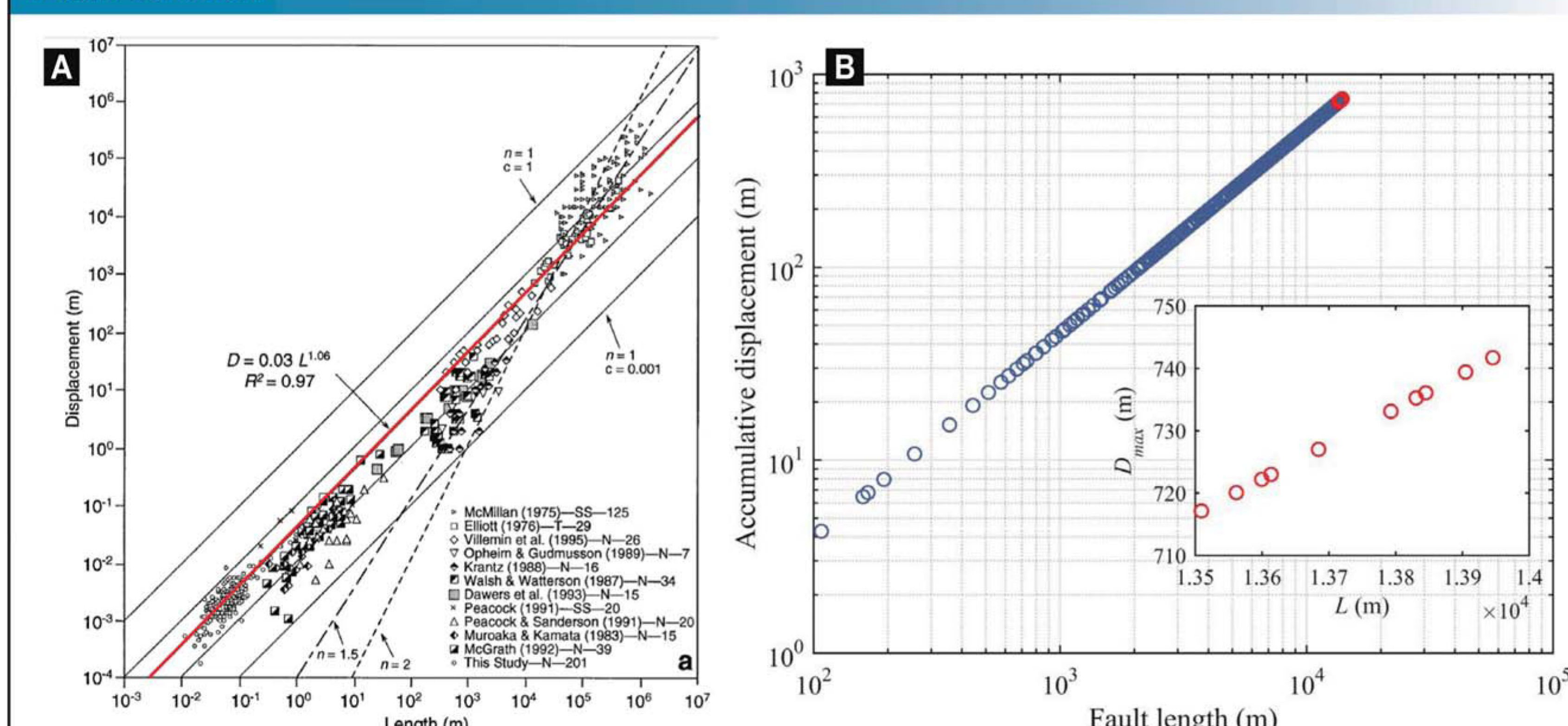



**Fig. 3.** (A) Relationship between basin length and fault displacement reported from field measurements (Schlische et al., 1996). (B) A modelling example generated to show the growth of an isolated basin. The slip rate is sampled from a normal distribution with a mean of 0.003 m $yr^{-1}$ and 3 of ±0.002 m $yr^{-1}$, within the range of rates reported from normal faults in the continental settings. Red circles and the inserted graph denote the most recent 10 slip events.

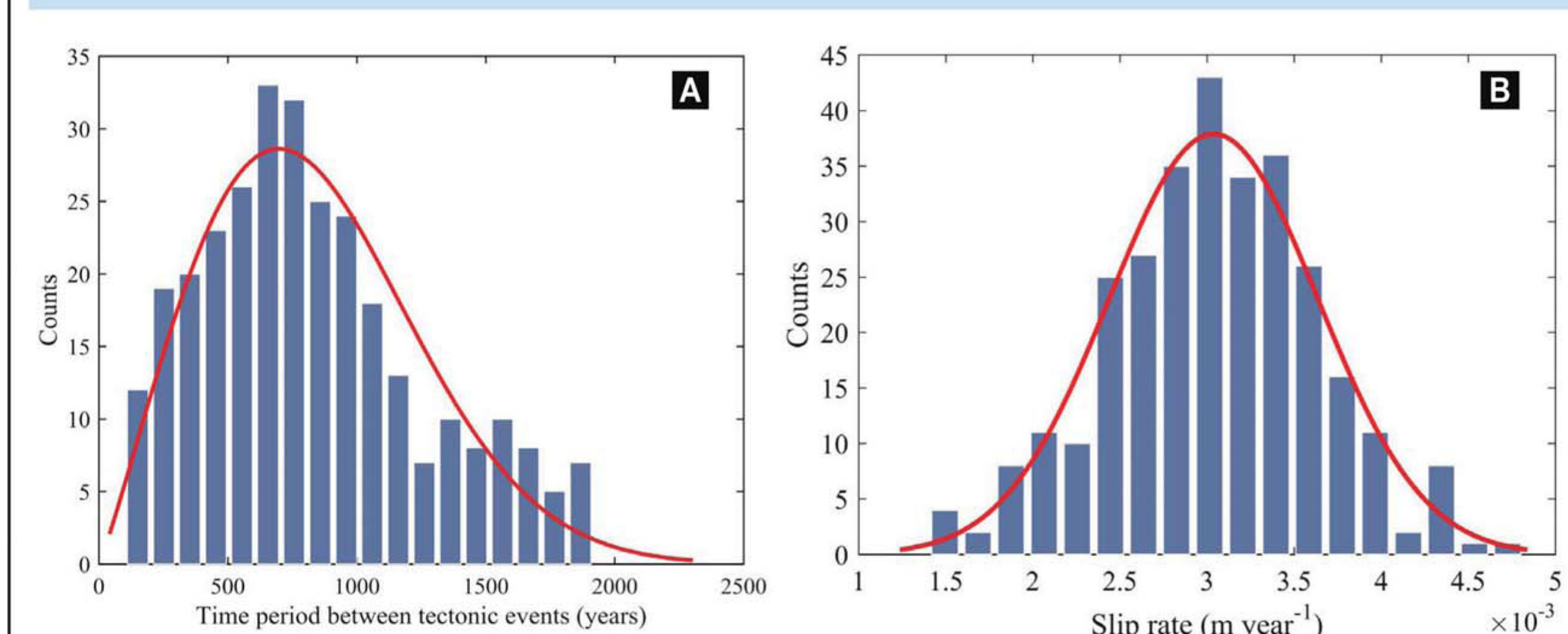



**Fig. 4.** (A) Histogram example of time period between tectonic events with Weibull distribution fit. The period of seismic events is modelled using the 2-parameter Weibull probability density function based on observations that the likelihood of an earthquake increases progressively with time as crustal strain accumulates since the release of strain by the previous earthquake. (B) Histogram example of slip rate between tectonic events with normal distribution fit.

## Forward Stratigraphic Modelling Algorithm

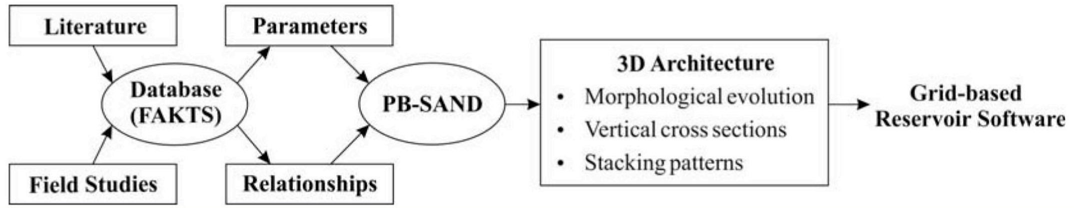



**Fig. 5.** Flow diagram of the modelling strategy (Yan et al., 2017). The modelling approach, including the ability to incorporate and use FAKTS-hosted data (Colombera et al., 2012) from multiple real-world examples as inputs to PB-SAND, brings several advantages: (1) flexibility to determine meander bend migration rates and morphology without the need to account for complicated hydraulic processes; (2) capability to incorporate independent geomorphic controls (e.g., valley confinement); (3) ability to constrain the model output using parameters derived directly from empirical field measurements and remote sensing; (4) ability to directly compare modelling outcome with real-world datasets derived from outcrops, aerial imagery or subsurface data; and (5) high computational efficiency.

## Growth Modes of Isolated Half Graben

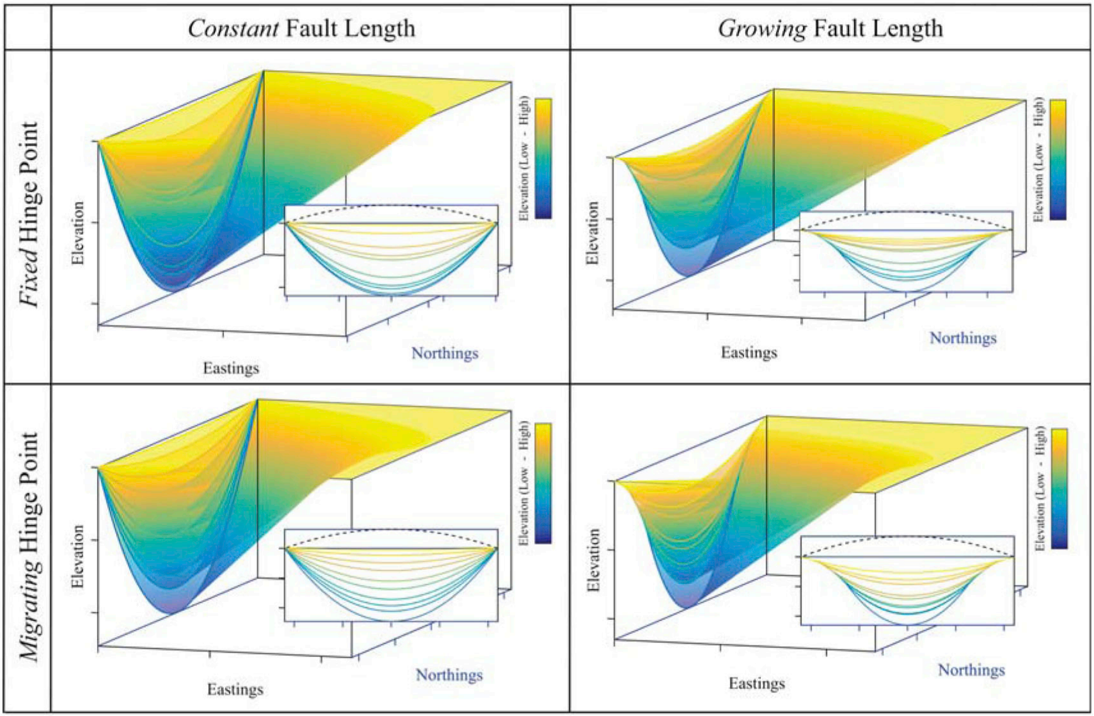



**Fig. 6.** Development of individual faults induced by episodic slip events. Ten most recent sedimentary units emplaced by tectonic events are shown in 3D. The slip frequency associated with tectonic events is modelled using a Weibull distribution. Inserted panels also show subsidence change along the fault zone. Blue axes denote the direction of northings. As subsidence increases, a basin changes in shape depending on whether the fault zone extends laterally and whether the hinge point of the hangingwall migrates away from the fault. The vertical axes (elevation) are highly exaggerated.

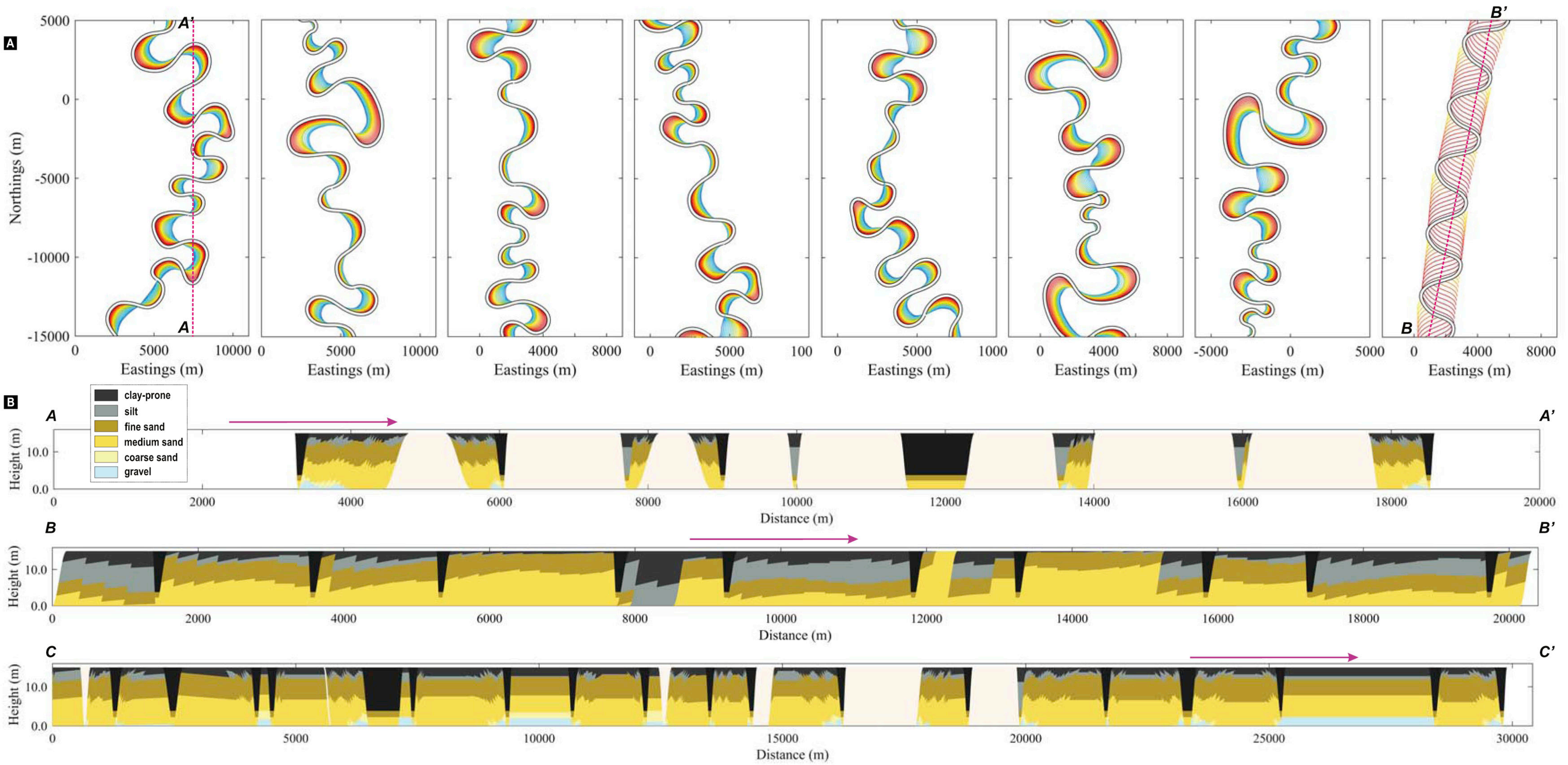



**Fig. 7.** (A) Modelling examples of meandering rivers. The algorithm has been designed to be able to include point bars with different sinuosity, variability, upstream-downstream trends, cut-off controls, and avulsion frequency. (B) Cross-sectional examples showing the geometries and facies changes within point-bar elements. PB-SAND is vector-based model and cross sections can be generated in any orientations. A classic fining-upward facies association is used in these cases. The model allows of generating sedimentary architectures of different styles of meandering rivers realistically without compromising small-scale geometries of intra-bar deposits. Line of cross section C-C' is shown in Fig. 8 (next page).

## Avulsion and Cut-off

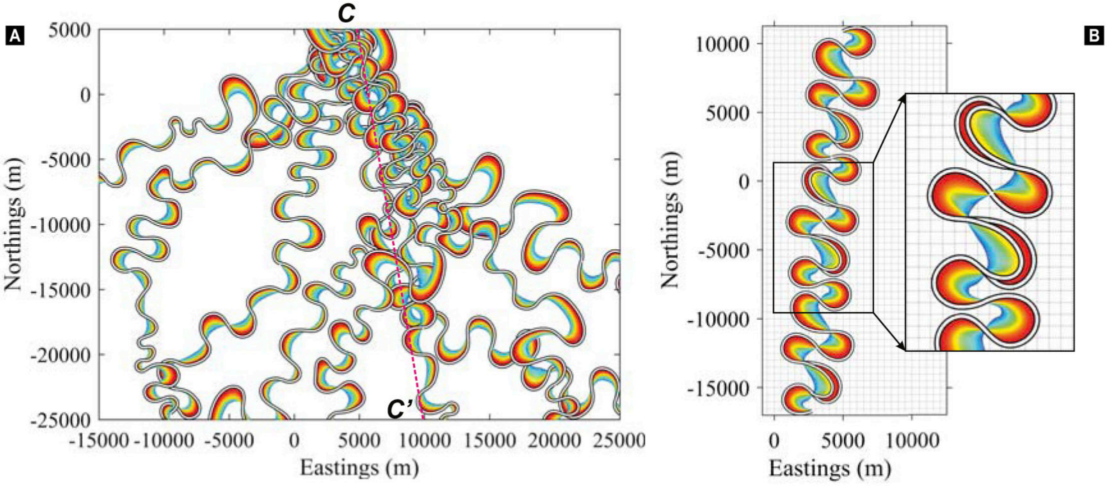



**Fig. 8.** (A) A modelling example of meandering rivers showing nodal avulsions. The cross section *C-C'* is shown in Fig.7. (B) A model example showing chute cut-offs.

## Preferable Channel Migration

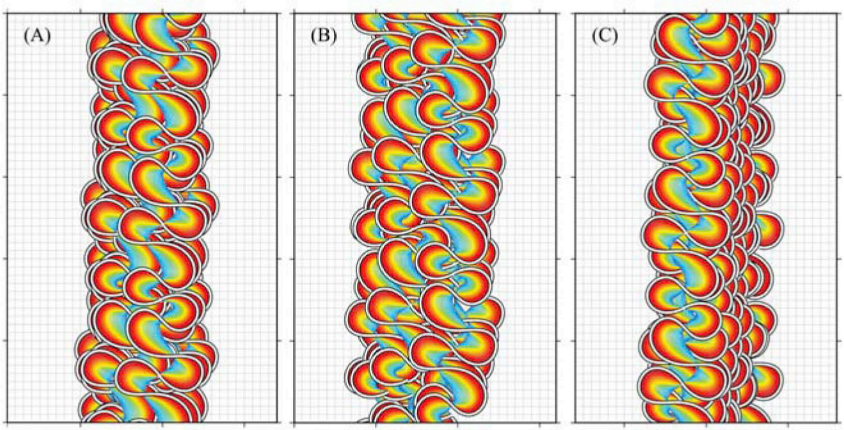



**Fig. 9.** Modelling examples of meander-belts caused by different styles and rates of channel migrations associated with different degree of displacement by tectonic activities. Channel migrates randomly at low displacement (A) and migrates preferably towards the direction of higher subsidence (B: to the right; and C: to the left). The lateral migration rate is controlled by local gradients; the channel in (B) migrates faster in comparison with (C). A slope threshold is defined below which a channel migrates or avulses randomly (either towards or away from the fault zone) and no preferable migration occurs.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# Half-graben Modelling Example

## Development of Evolving Rift Basin

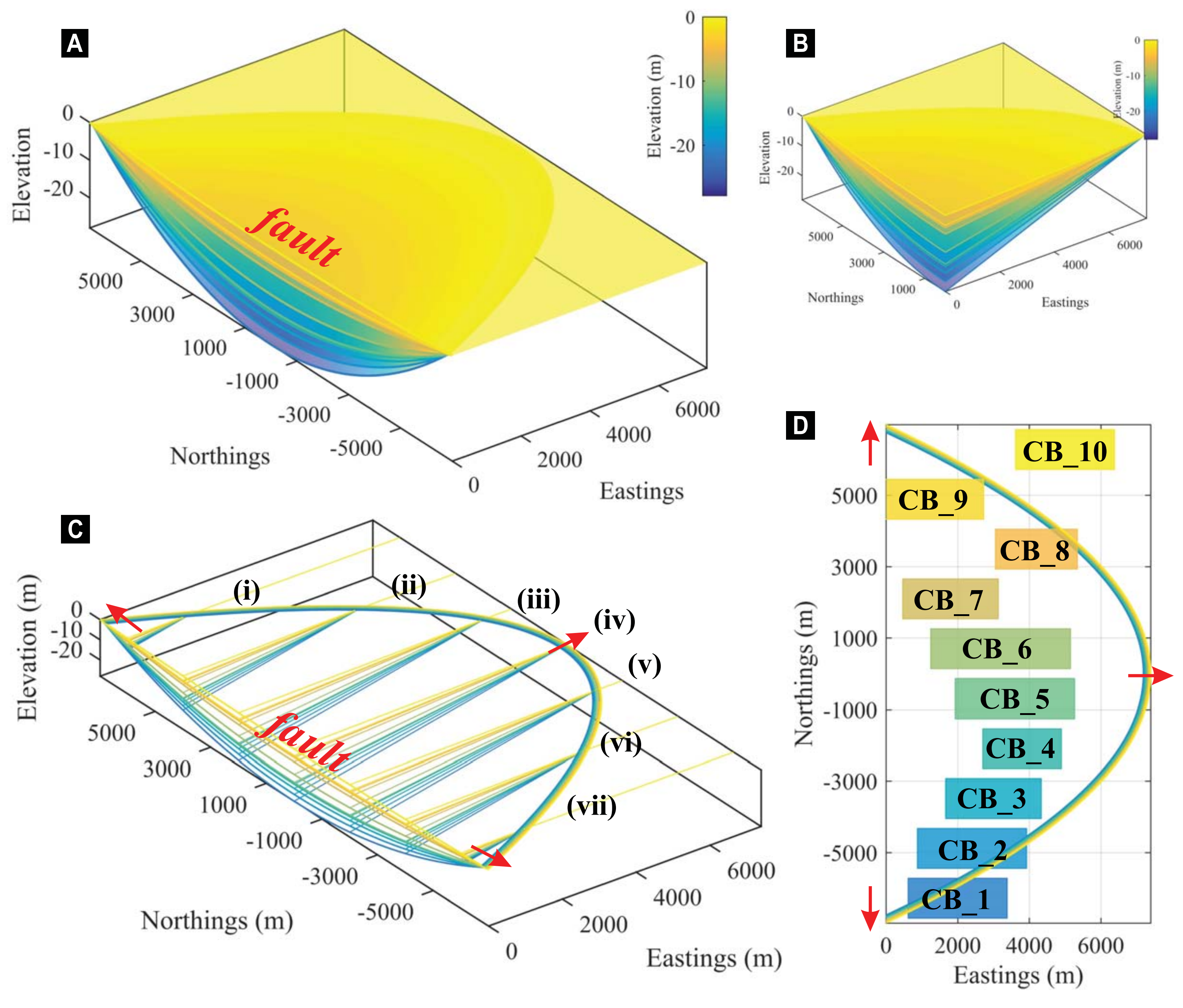


**Fig. 10.** (A) Most recently formed ten sedimentary units modelled in an evolving rift basin system shown in 3D view. (B) Half of a half-graben modelled. (C) Frame diagram showing sedimentary units emplaced by ten episodic seismic events. As can be seen, the fault is propagating laterally and the hinge of the basin is moving away from the fault zone (shown in red arrows). Representative cross sections of the fault are shown in Fig. 11. (D) Locations of modelled meander-belts in plan-view. CB-10 is the most recent meander belt developed on the top of the basin. A relatively longer slip period enables development of a wider meander belt. A larger tilting angle of the basin also encourages enhanced rates of lateral migration of rivers towards the fault.

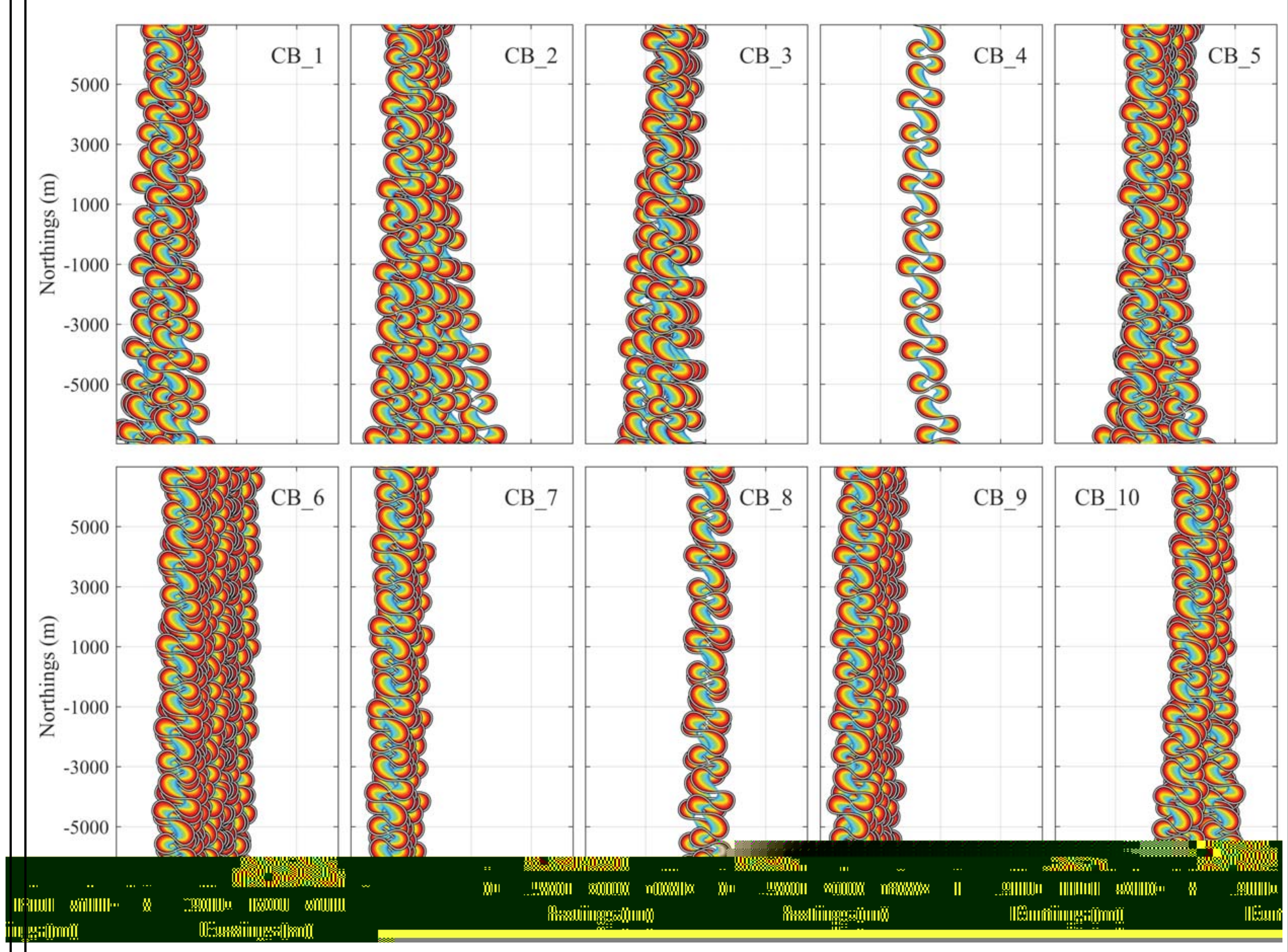


**Fig. 11.** Meander belts developed between episodic seismic events. The width of channel belt including active and abandoned channels and channel-fills depend on the residence time of the channel belt controlled by the time period between two successive tectonic events and the transverse slope caused by titling of half grabens, because a higher channel migration rate toward the fault zone increases the channel-belt width and the abandonment of meander-loops upslope via cut-offs and avulsions. The thickness of channel belts is equal to the depth of river channels, both of which are kept constant in our simulations for simplicity. We assume that subsidence can be accommodated by river aggradation, and river characteristics maintain the same on the modelled temporal scale of tens to thousands of years. Avulsion is assumed to occur episodically following each seismic event and the channel can shift to any favourable position on the floodplain surface obtained by Monte Carlo sampling from a presumed distribution, e.g., an increased probability toward the fault zone.

## Stacking Patterns of Meander-belt deposits

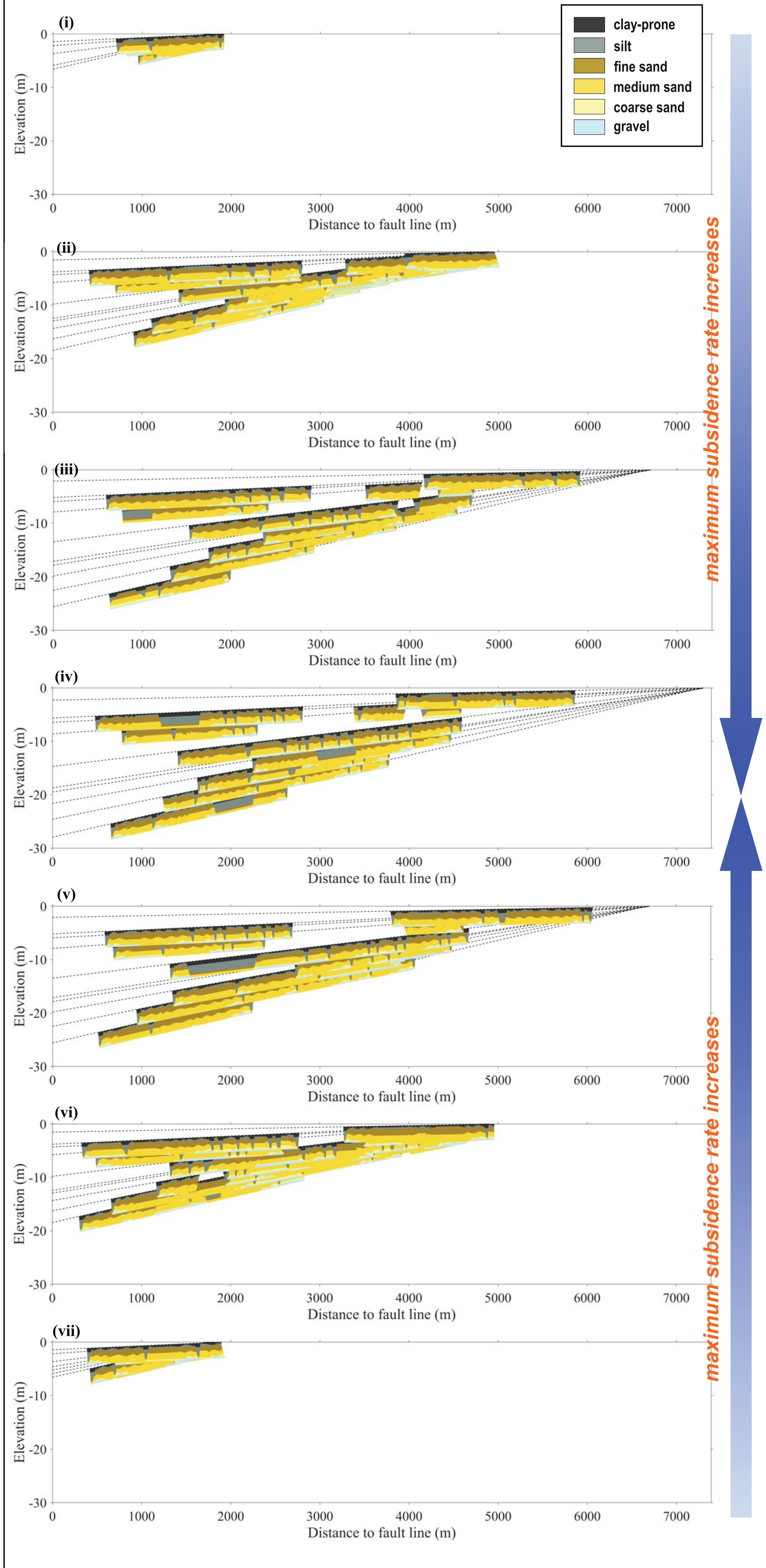


**Fig. 12.** Examples of modelled cross sections (Fig. 9C) after 10 episodes of channel avulsions by a spatially complex pattern of subsidence (in terms of rate) induced by tectonic tilting in this evolving half-graben basin. The black dotted lines denote the top of the geological bodies accumulated between successive tectonic events. Model results show how the connectivity of point-bar elements changes through the basin and with varying proximity to the bounding fault by different subsidence rates induced by tectonic tilting (*cf.* Alexander and Leeder, 1987).