PS Numerical Model for Prediction of Internal Stratigraphic Architecture and Heterogeneity in Fluvial and Tidally Influenced Point-Bar Deposits*

Na Yan[1], Nigel P. Mountney[1], Luca Colombera[1], and Robert M. Dorrell[1]

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Abstract

Stratigraphic successions of point-bar elements that accumulate in tidally influenced fluvial settings are typically characterized by vertical and lateral heterogeneity whereby sand-prone packages are draped and partitioned by mud-prone deposits of variable thickness and continuity in response to fluvial and tidal processes that vary spatio-temporally. Although the extent to which mud-prone deposits act to partition reservoirs is difficult to determine from subsurface data, quantification is important to predict reservoir behavior. This study has developed a numerical stratigraphic model that uses a mixed process- and geometric-based approach to predict the 3D distribution of sand- and mud-prone deposits. The model is able to reproduce changes in morphology and architecture of channels and associated point-bar elements (e.g., due to bar expansion, translation and rotation) based on real-world data. Episodes of sand movement occur during times of elevated current; episodes of mud deposition occur as currents wane to zero, thereby enabling suspension settling and mud-draping of inclined bar fronts. The model accounts for changes in current magnitude and direction arising from both short-term tidal effects (e.g., diurnal flood and ebb currents, spring-neap and annual cycles) and longer-term changes in fluvial discharge (e.g., seasonal and longer-term flood events). The distribution of facies around meander bends varies according to bend tightness and distance from bend apex; this allows for the effective modeling of features such as mud-prone counter point bars. The model also accounts for temporal changes in facies distribution in response to neck and chute cut-off, oxbow lake development, and nodal avulsion that induces abandonment of entire reaches. The model uses a series of look-up tables that reference real-world modern and ancient examples contained within an architectural database to determine the trajectories of different types of meanders and the distribution of different lithofacies. Additionally, the model uses stochastic approaches to depict inherent natural variability in architectural-element size, shape, orientation, distribution and migration trajectory. The model has been employed to demonstrate facies distributions and heterogeneity in both modern tidally influenced fluvial systems (e.g., Gironde) and reservoir successions, including the McMurray Formation, Alberta, Canada and the Mungaroo Formation, NW Shelf, Australia.

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Numerical model for prediction of internal stratigraphic architecture and heterogeneity in fluvial and tidally influenced point-bar deposits

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Abstract

Stratigraphic successions of point-bar elements that accumulate in tidally influenced fluvial settings are typically characterised by vertical and lateral heterogeneity whereby sand-prone packages are draped and partitioned by mud-prone deposits of variable thickness and continuity in response to fluvial and tidal processes that vary spatio-temporally. Although the extent to which mud-prone deposits act to partition reservoirs is difficult to determine from subsurface data, quantification is important to predict reservoir behaviour.

This study has developed a numerical stratigraphic model that uses a mixed process- and geometric-based approach to predict the 3D distribution of sand- and mud-prone deposits. The model is able to reproduce changes in morphology and architecture of channels and associated point-bar elements (e.g., due to bar expansion, translation and rotation) based on real-world data. Episodes of sand movement occur during times of elevated current; episodes of mud deposition occur as currents wane to zero, thereby enabling suspension-settling and mud-draping of inclined bar fronts. The model accounts for changes in current magnitude and direction arising from both short-term tidal effects (e.g., diurnal flood and ebb currents, spring-neap and annual cycles) and longer-term changes in fluvial discharge (e.g., seasonal and longer-term flood events). The distribution of facies around meander bends varies according to bend tightness and distance from bend apex; this allows for the effective modelling of features such as mud-prone counter point bars. The model also accounts for temporal changes in facies distribution in response to neck and chute cut-off, oxbow lake development, and nodal avulsion that induces abandonment of entire reaches.

The model uses a series of look-up tables that reference real-world modern and ancient examples contained within an architectural database - Fluvial Architecture Knowledge Transfer System (FAKTS) to determine the trajectories of different types of meanders and the distribution of different lithofacies. Additionally, the model uses stochastic approaches to depict inherent natural variability in architectural-element size, shape, orientation, distribution and migration trajectory.

The model has been employed to demonstrate facies distributions and heterogeneity in both ancient and modern tidally influenced fluvial systems and reservoir successions, including the Scalby Formation, England, and McMurray Formation, Alberta, Canada.

Introduction and Background

Basic meander-bend transformations have been well-recognised: expansion, translation, rotation, and combinations thereof (**Figure 1**). The relationship between point-bar geometry, migration, and facies distribution (in both plan views and vertical successions), however, remains inadequately understood, principally because of the limited availability of field data in the form of 2D outcrop sections in the rock record, and partially because of difficulty in reconstructing complex evolutionary history and internal architecture of meander bends. Stratigraphic successions of fluvial point-bar elements are typically characterised by vertical and lateral facies heterogeneity whereby sand-prone packages are draped and partitioned by mud-prone deposits of variable thickness and continuity in response to temporal and spatial variation in depositional processes. In contrast to sand-dominated point-bar elements, counter point-bar elements typically comprise mud-dominated lithofacies whereby distinctive concave scroll patterns are formed by downstream meander translation, notably in systems space constrained by incised valleys, local tectonics, or erosion-resistant mud-filled abandoned channel elements (Ghinassi et al., 2016; Smith et al., 2009).

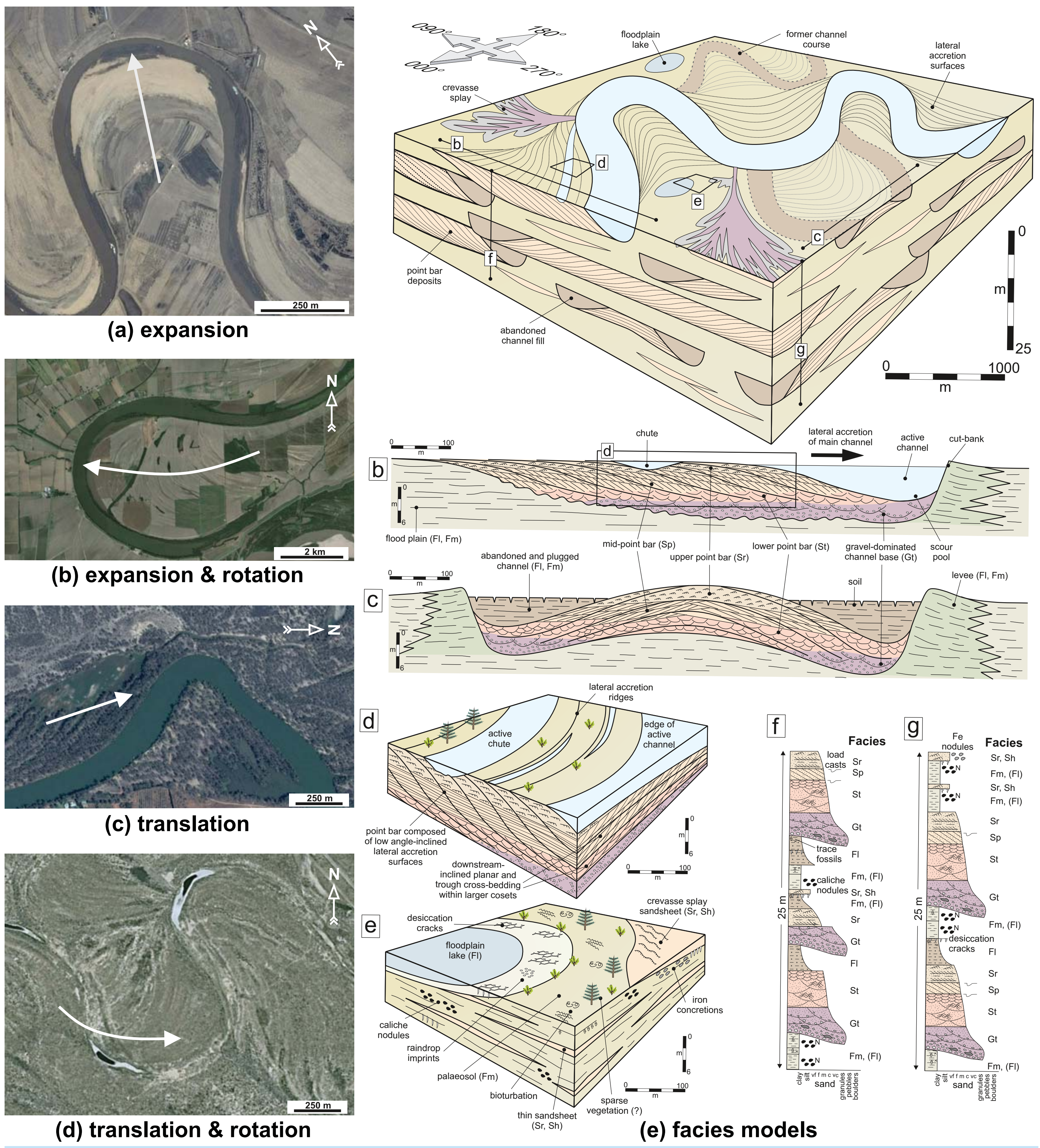

Figure 1. Basic forms of meander-bend transformations: (a) expansion, Songhua River, China; (b) expansion and rotation, Mississippi River, USA; (c) translation, Rio Negro, Argentina; (d) translation and rotation, Rio Negro, Argentina. Arrows show migration directions of scroll bars. (e) Traditional meandring river facies models built from observation of facies and their spatial distribution from limited number of case-studies (Ghazi & Mountney, 2009).

Forward Stratigraphic Modelling Algorithm

Combined geometric-based process, and stochastic approaches to reconstruct the complex spatio-temporal evolution of a variety of meandering river behaviours and to predict variations in 3D geometry and lithofacies distribution of sand- and mud-prone packages of point bars under different conditions of channel migration. The modelling algorithm is based on key parameter controls, such as the meander-bend transformation style, degree of sinuosity, distance from meander apex, and the locations of the inflection points of meanders and their change in position over time.

Morphological Evolution of Single Point Bar in Plan View

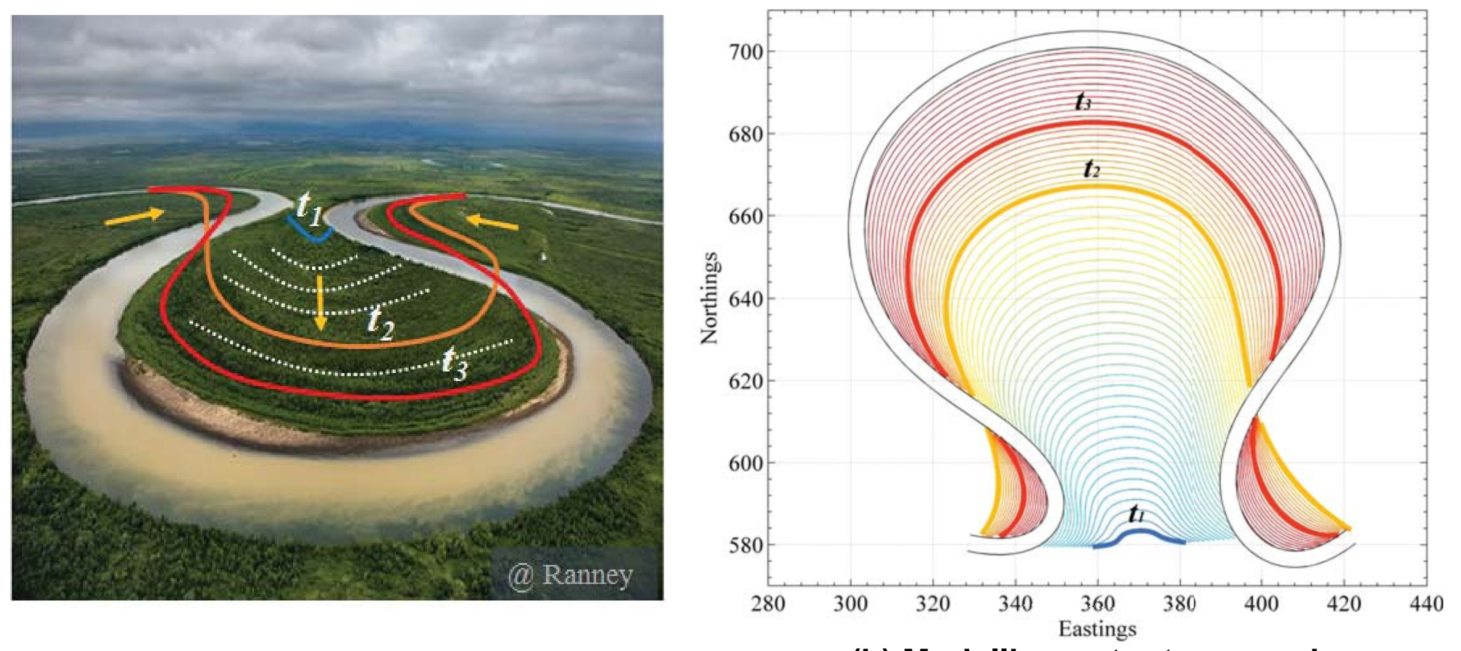

Figure 2. Modelling the evolution of point bars in plan view. The temporal locations at t_1, t_2, and t_3 are shown in bold lines. A jet colour (dark blue to dark red) scheme is used to differentiate meander positions at different times. The spatial dimensions here are arbitrary, but the modelling results can be readily scaled to physical units based on data from field measurements or remote sensing. The shape of the modelled point bar is comparable with that of point-bar elements commonly found preserved in the ancient rock record.

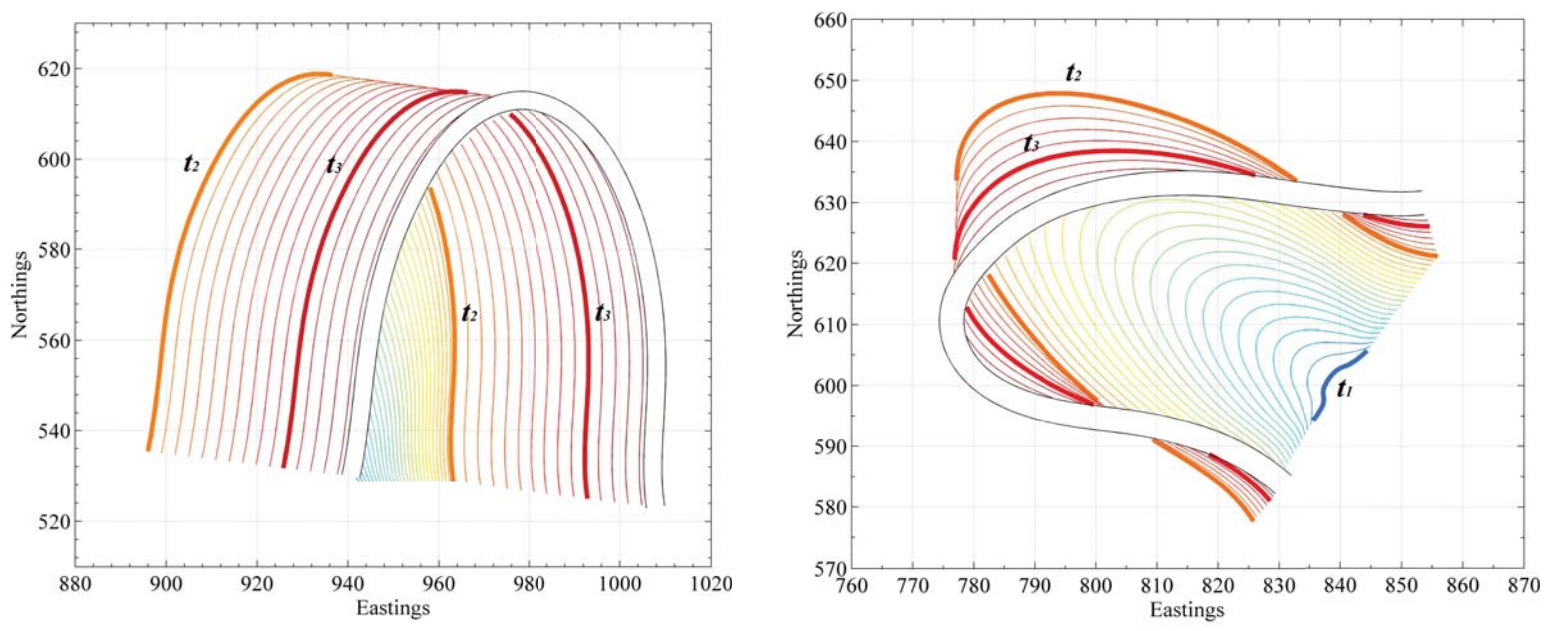

Figure 3. Modelling the evolution of point-bar elements developed by translation and rotation. Older point-bar trajectories have been partly overprinted by the later development of the point bar as it approached maturity.

Parameter controls of single point-bar element:

- morphology of scroll bars at key times: t_1, t_2 & t_3
- migration rates between the times
- orientation
- longevity of evolution (e.g., time to cut-off)

Morphological Evolution of Amalgamated Point-bar Elements in Plan View

Parameter controls of multiple point-bar elements:

- domain size / modelling area
- density of point-bar elements
- proportions of different meander-bend transformations
- distribution of point-bar sizes (e.g., Gaussian distributon, **Figure 4**)
- distribution of point-bar orientations
- spatial distribution of point-bar elements (e.g., belt -like)
- distribution of point-bar longevities across model

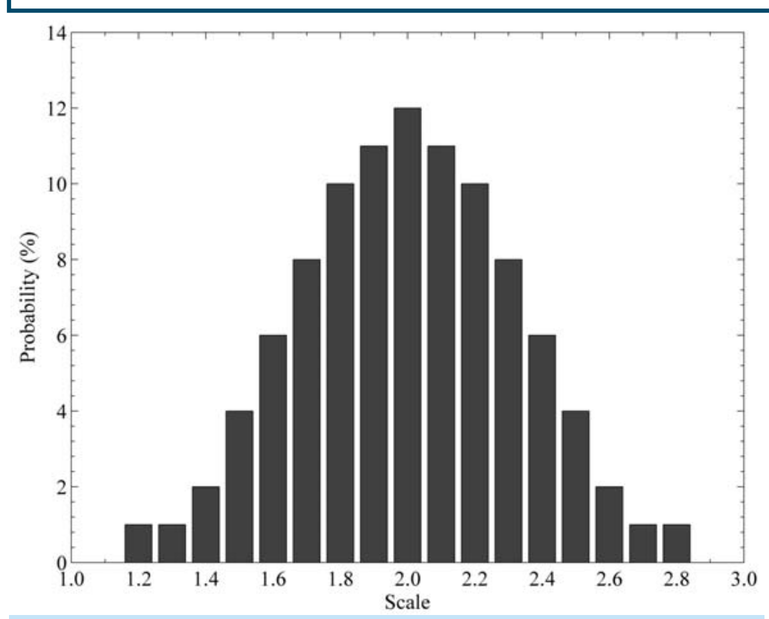

Figure 4. An example of the probability distribution of the scaling parameter for modelling a set of point-bar elements of variable size. Two end-members are specified, and then the probabilities of values between these two end-members are based on Gaussian distribution curves in this case.

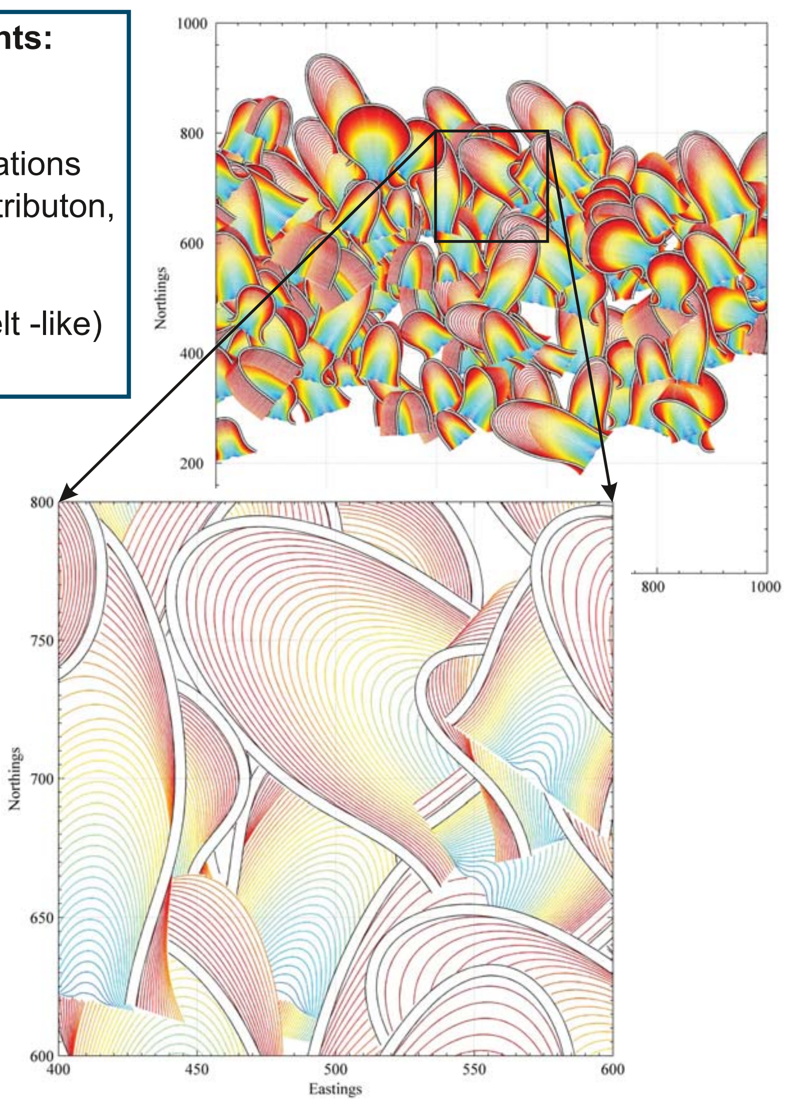

Figure 5. Modelling evolution of multiple point-bar elements.

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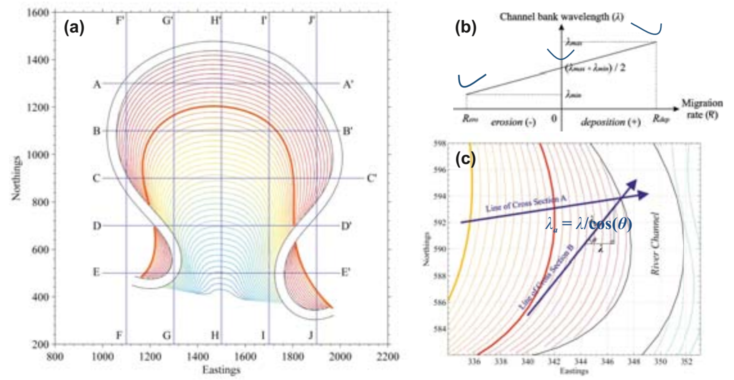
Forward Stratigraphic Modelling Algorithm

2D Cross Sections of Point-bar Elements

The cross-sectional complexity of point-bar architecture is modelled and depicted based on the plan-view model and the expected 2D architecture can be examined and rendered by selecting the start and end points of one or more transects. A transect can be defined by polyline segments - a simple straight line through a point bar or comprising multiple straight-line segments that are oriented in varying directions. The shape of inclined point-bar scroll surfaces is modelled as 'half-sine waves' to mimic the asymptotic nature of downlap of such surfaces onto channel bases and toplap in the region where the upper part of the bar merges into floodplain (**Figure 6**). For cross sections aligned perpendicular to the margin of the river channel, the shape of the inclined point-bar surfaces seen in cross section will be dependent on the shape of the river channel bank (angle of dip and rate of change of that dip from the channel base to its margin). The shape of the river channel around a meander bend is modelled using a process-based approach, as shown in **Figure 6b**. For cross sections aligned oblique to the margin of the river channel, the shape of the inclined point-bar surfaces seen in cross section will additionally be dependent on the angle of apparent dip that arises as a consequence of taking an oblique section relative to the channel margin (**Figure 6c**). The shape of inclined point-bar surfaces can effectively represent the shape the river bank at the time of sedimentation (**Figure 6d**).



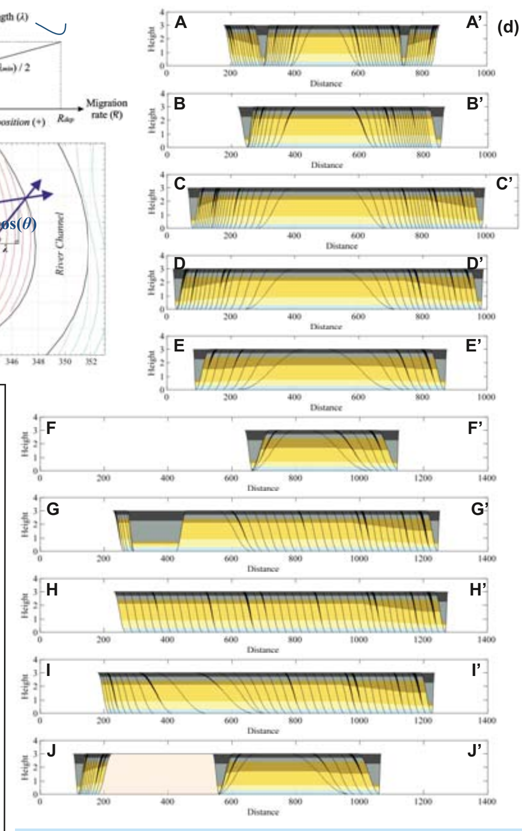


Figure 6. Modelling cross sections of point-bar elements. (a) Locations of sampled cross sections in plan view. (b) Channel bank wavelength change as a function of the local erosion or deposition rate. When neither erosion nor deposition occurs, the channel maintains symmetrical shape. (c) Apparent dipping direction shown in a cross section is adjusted based on the oblique of a cross section relative to the migration direction of the river channel. (d) Vertical geometry of different cross sections.

Lithological characteristics

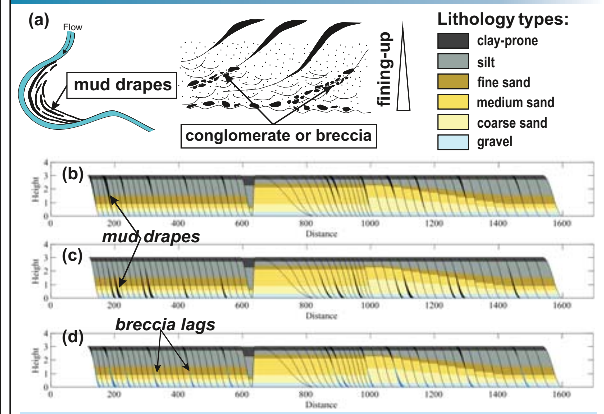


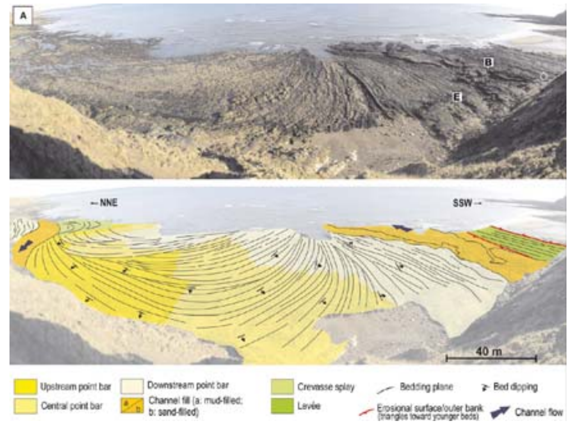
Figure 7. Modelling lithological characteristics of point bars. (a) Schematic drawing of facies distribution in plan view. Mud drapes and breccia at different thickness can be nested and combined with each other. The temporal distribution of each mud draping event within a hierarchy of events is controlled by a Gaussian distribution curve. (b) and (c) show examples of mud draping confined to the upper part and the basal part of a point-bar element respectively. (d) Mud drapes (black) and breccia lags (blue) that occur independently.

Application to Ancient Succession: Scalby Formation, England

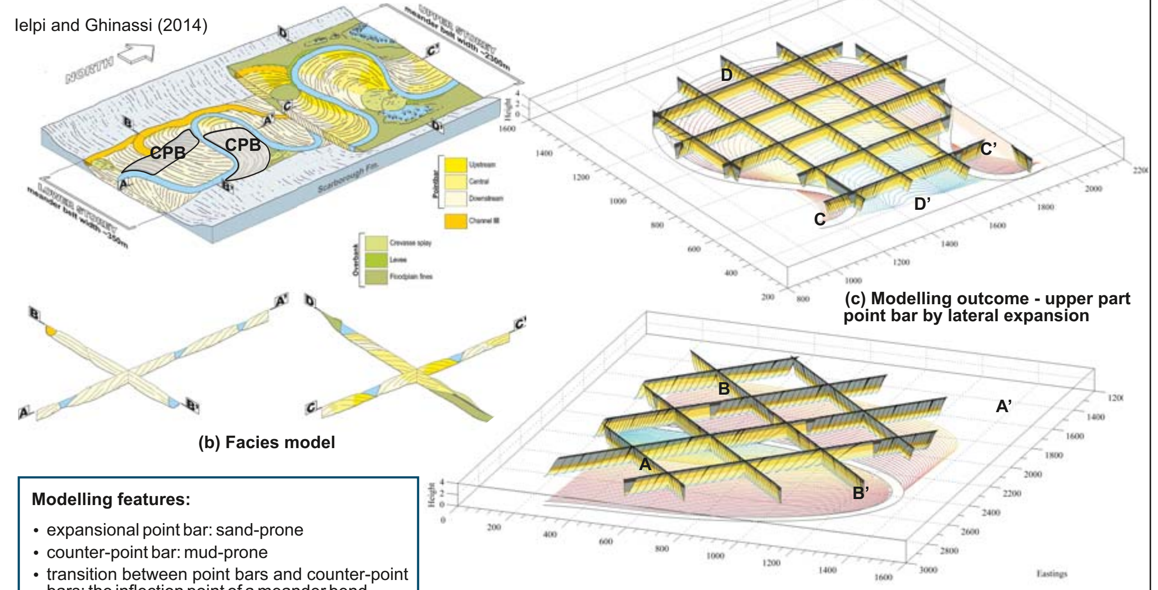
The Scalby Formation comprises two storeys of point-bar deposits. The upper part is dominated by non-confined expansional point-bar elements, whereas the lower part is dominated by laterally confined, downstream-migrating point-bar elements (Ielpi & Ghinassi, 2014).

Modelling upper part:
As a meander bend increases in sinuosity, the proportion of finer facies increases. In particular, for a meander bend developed by lateral expansion, the neck-tightening can also induce accumulation of finer facies deposited on adjacent smaller meander bends. The model implements the functionality by defining a threshold of sinuosity or maturity beyond which the set of facies association changes toward another predefined facies association.

Modelling lower part:
In contrast to point-bar deposits which exhibit convex-shaped scroll-bar morphologies and are usually dominated by sand-prone lithofacies, counter-point bar deposits display concave-shaped patterns and comprise low permeability silt-prone lithofacies, which could pose significant limits to reservoir connectivity. The transition between a sandy point bar and a muddy counter-point bar occurs at or close to the inflection or crossover point of a meander bend. This facies transition is modelled by defining two end-members of facies associations and specifying a transitional rate/width at the bend inflections between them.



(a) Exhumed point-bar deposits



Ielpi and Ghinassi (2014)

(b) Facies model

(c) Modelling outcome - upper part point bar by lateral expansion

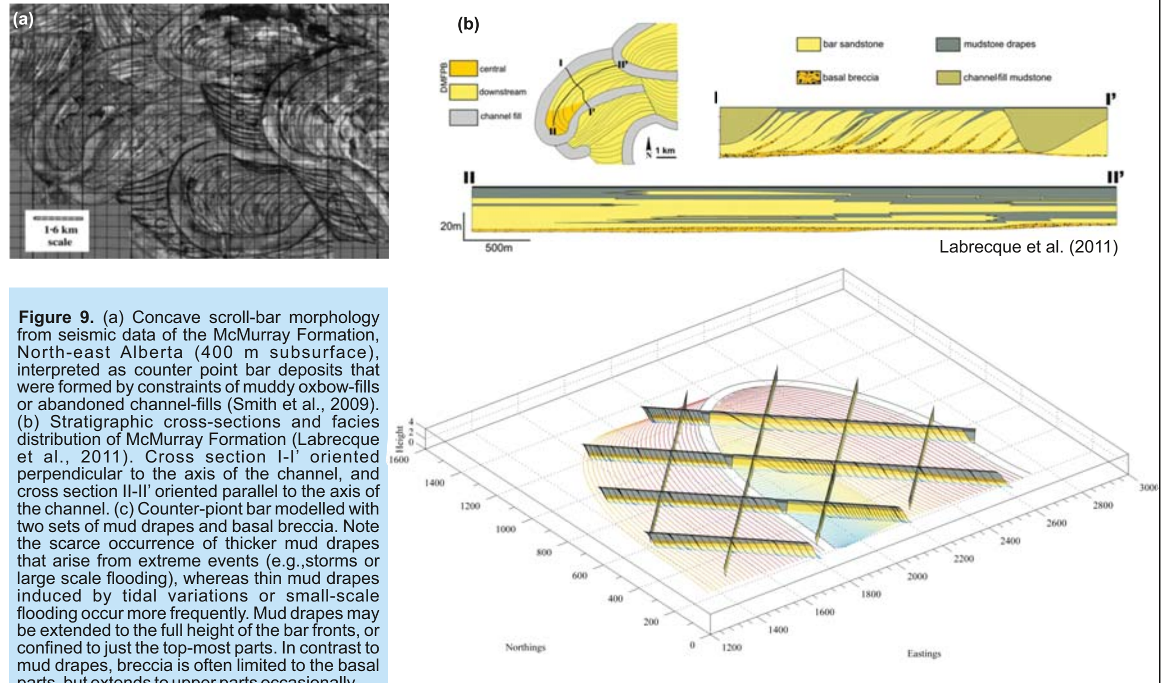
(d) Modelling outcome - lower part point bar by down-stream translation

Modelling features:

- expansional point bar: sand-prone
- counter-point bar: mud-prone
- transition between point bars and counter-point bars: the inflection point of a meander bend

Figure 8. Comparison of modelling outcome with a published facies model of the Scalby Formation, England. (a) Exhumed point bar elements preserved in plan view. (b) Facies model proposed by Ielpi and Ghinassi (2014) summarising the original plan-form morphology and relative stratigraphic signature of the exhumed meander plain of the Scalby Formation. (c) Modelling outcome akin to point bars formed by lateral expansion in the upper storey. The dip directions of bounding surfaces and channel shape are consistent with the published facies model. (d) Modelling outcome akin to point bars formed by downstream translation in the lower storey. Note the transition between point bar and counter-point bar elements.

Application to Ancient Succession: McMurray Formation, Canada

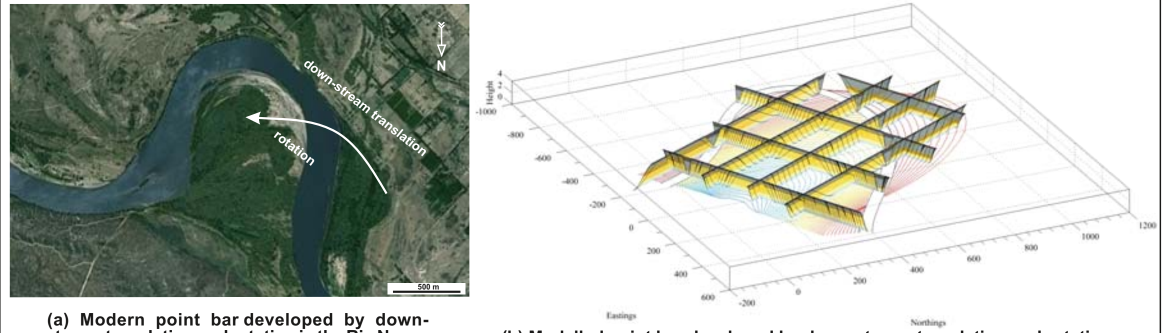


Labrecque et al. (2011)

(c) Modelled counter-point bar with mud drapes and basal breccia lags

Figure 9. (a) Concave scroll-bar morphology from seismic data of the McMurray Formation, North-east Alberta (400 m subsurface), interpreted as counter point bar deposits that were formed by constraints of muddy oxbow-fills or abandoned channel-fills (Smith et al., 2009). (b) Stratigraphic cross-sections and facies distribution of McMurray Formation (Labrecque et al., 2011). Cross section I-I' oriented perpendicular to the axis of the channel, and cross section II-II' oriented parallel to the axis of the channel. (c) Counter-piont bar modelled with two sets of mud drapes and basal breccia. Note the scarce occurrence of thicker mud drapes that arise from extreme events (e.g.,storms or large scale flooding), whereas thin mud drapes induced by tidal variations or small-scale flooding occur more frequently. Mud drapes may be extended to the full height of the bar fronts, or confined to just the top-most parts. In contrast to mud drapes, breccia is often limited to the basal parts, but extends to upper parts occasionally.

Application to Modern Rivers: Rio Negro, Argentina

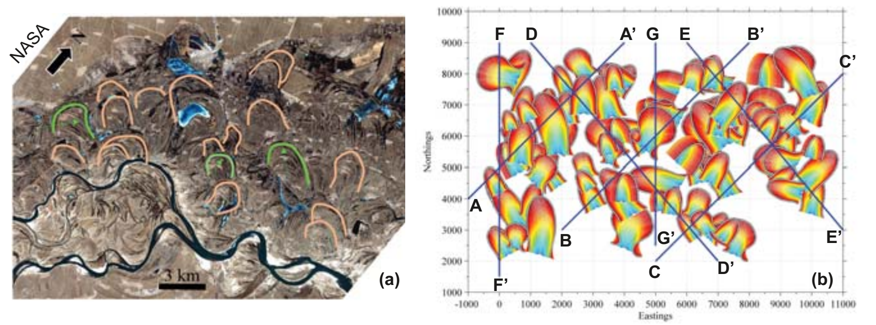


(a) Modern point bar developed by down-stream translation and rotation in the Rio Negro

(b) Modelled point bar developed by down-stream translation and rotation

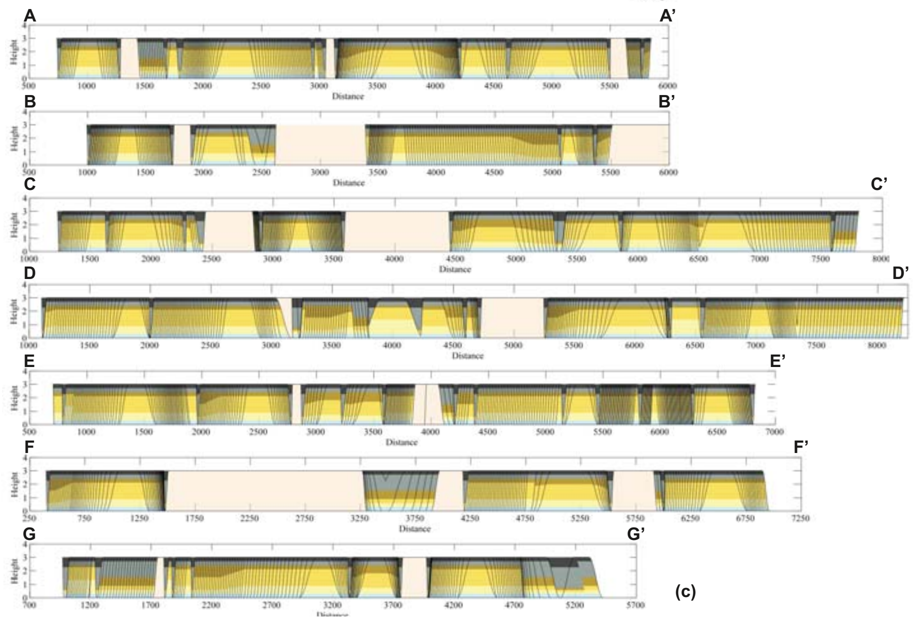
Figure 10. Modelling a point bar developed by downstream translation and rotation. (a) Satellite image from Google Earth showing a point bar developed by translation and rotation in the Rio Negro, Argentina. (b) Modelling outcome that can qualitatively predict 3D architecture of the point bar. Note that validation of the quantitative modelling would require more detailed field study.

Application to Modern Rivers: Songhua River, China



Parameter Setting:

- Preferred orientation
- Size variations
- Different transformations
- Down-stream axis: even distribution
- Cross-stream axis: Gaussian distribution



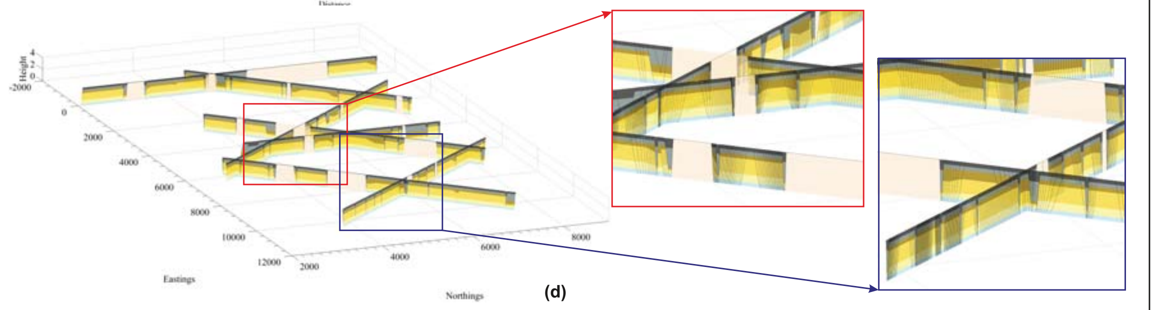


Figure 11. Modelling architecture of large-scale multiple point-bar elements. (a) Satellite image of Songhua River, China (from NASA). (b) Modelling output showing morphology of point bars in plan view. Blue lines show locations of cross sections. (c) Architecture shown in cross sections. (d) Cross sections in 3D view. The model is able to simulate complex stratigraphy arising from overprinting of multiple point-bar elements. The model is vector-based and enables examination of 3D architecture and facies distribution in great detail. This example demostrates how the model serves as a useful tool to improve our understanding of the origin of stratigraphic complexity and heterogeneity in fluvial depositional systems at a variety of different spatial scales.

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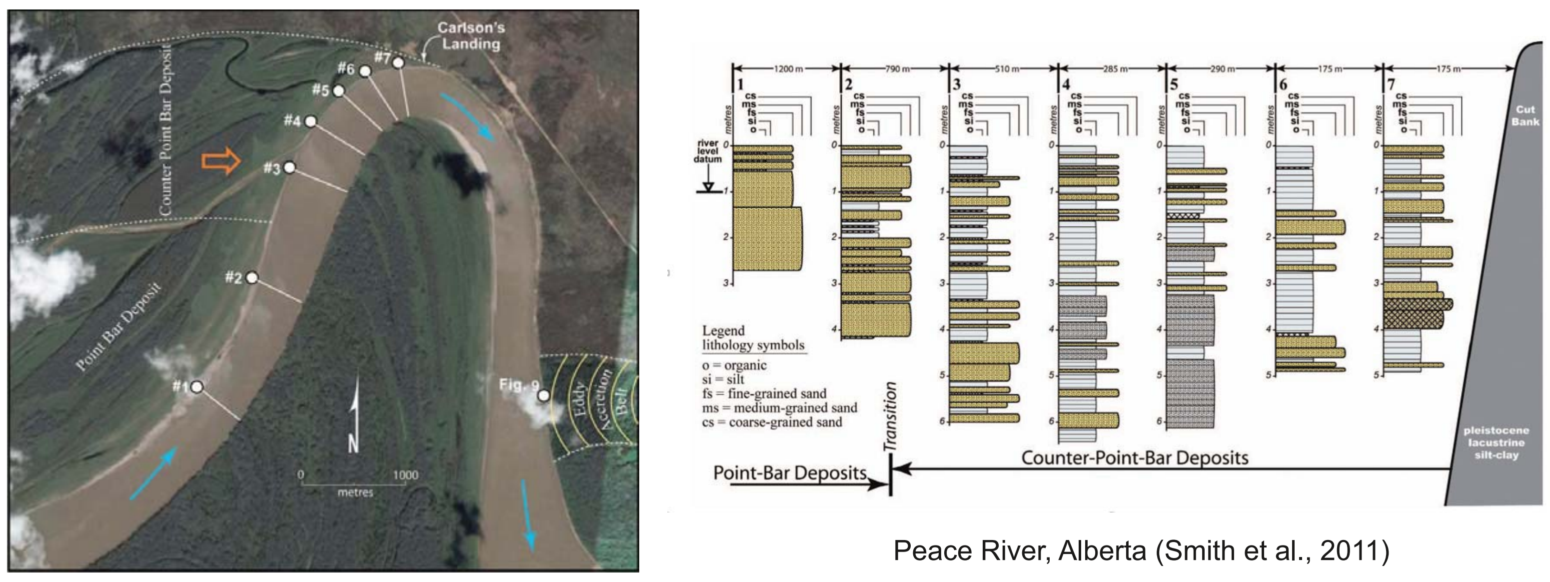
Integration of Numerical Modelling Approach

Literature

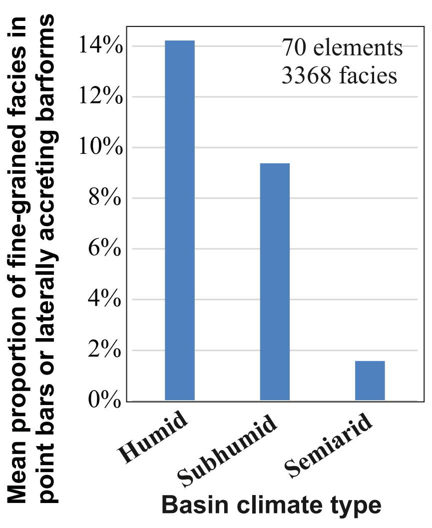
Field Studies

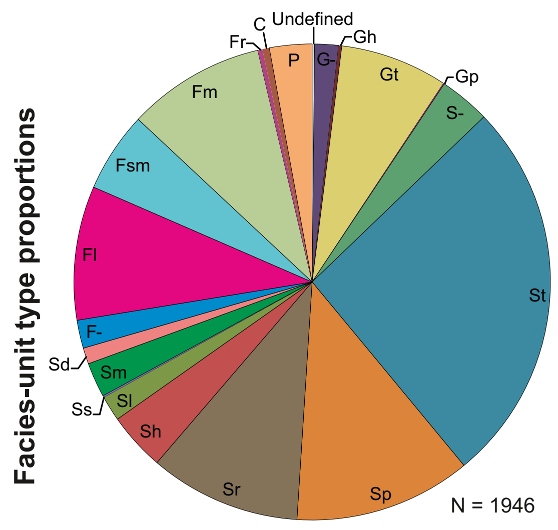


Peace River, Alberta (Smith et al., 2011)

Figure 12. Examples of data from literature and field studies.

Database (FAKTS)





(Colombera et al., 2013)

1D QUANTITATIVE FACIES MODEL FOR SANDY MEANDERING SYSTEMS

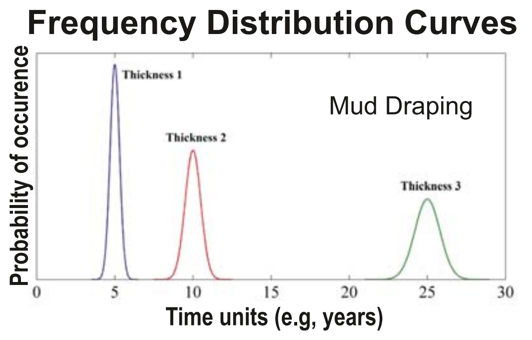
- G: gravel; S: sand; F: fines;
- P: pedogenic carbonate;
- C: coal or organic mud;
- h: horizontally bedded sand (Sh) or crudely bedded gravel (Gh);
- t: trough cross-bedded;
- p: planar cross-bedded;
- l: low-angle cross-bedded sand (Sl) or laminated mud (Fl);
- r: ripple cross-laminated sand (Sr) or root-bed fines (Fr);
- s: scour fill;
- m: massive sand (Sm) or massive mud (Fm);
- d: soft-sediment deformation;
- sm: silt and mud.

Numerical Modelling

Parameters of Scalby Formation

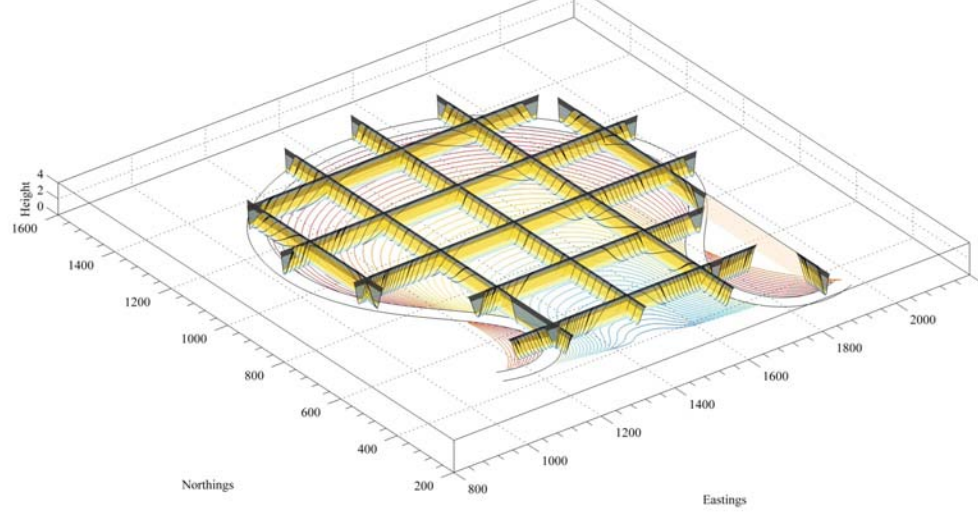
		Mean	Min	Max	Std.
	bar thickness (m)	6			
	channel width (m)	74			
mud drape	thickness (m)	0.20	0.06	0.66	0.18
	length along accretion surfaces (m)	7.80	1.60	19.00	4.56
	spacing (m)	5.74	1.90	10.20	2.56
	position (to the top) (m)	1.35	0.28	3.30	0.79
	position (to the top)	23 %	5 %	55 %	13 %
facies	mud-prone	11 %			
	very fine sand	7 %			
	fine sand	37 %			
	medium sand	45 %			

Frequency Distribution Curves



Model Components:
- Morphological evolution
- Vertical cross sections
- Stacking patterns

3D Architecture



Model Outupts:
- High resolution morphology
- Facies distribution
- Bounding surfaces
- Probability of possible scenarios
- Sensitivity of major environmental controls
- Prediction of 3D architecture
- 2D and 3D figures

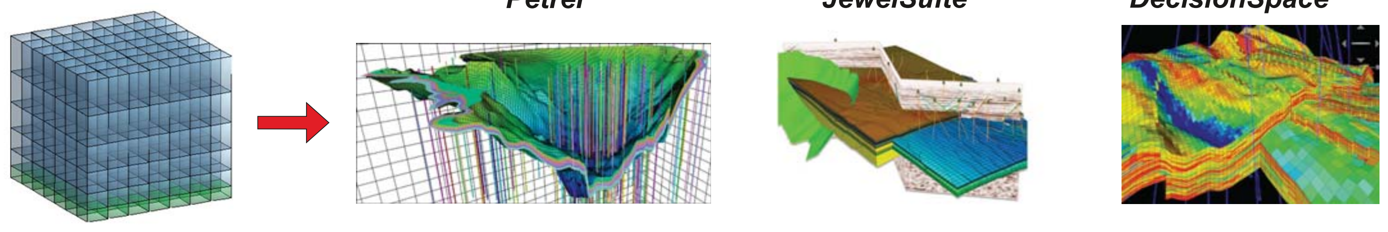
Reservoir Software

Grid-based models

Schlumberger Petrel™

Baker Hughes JewelSuite™

Landmark DecisionSpace™



Future Work

Application to Predict Subsurface Heterogeneity

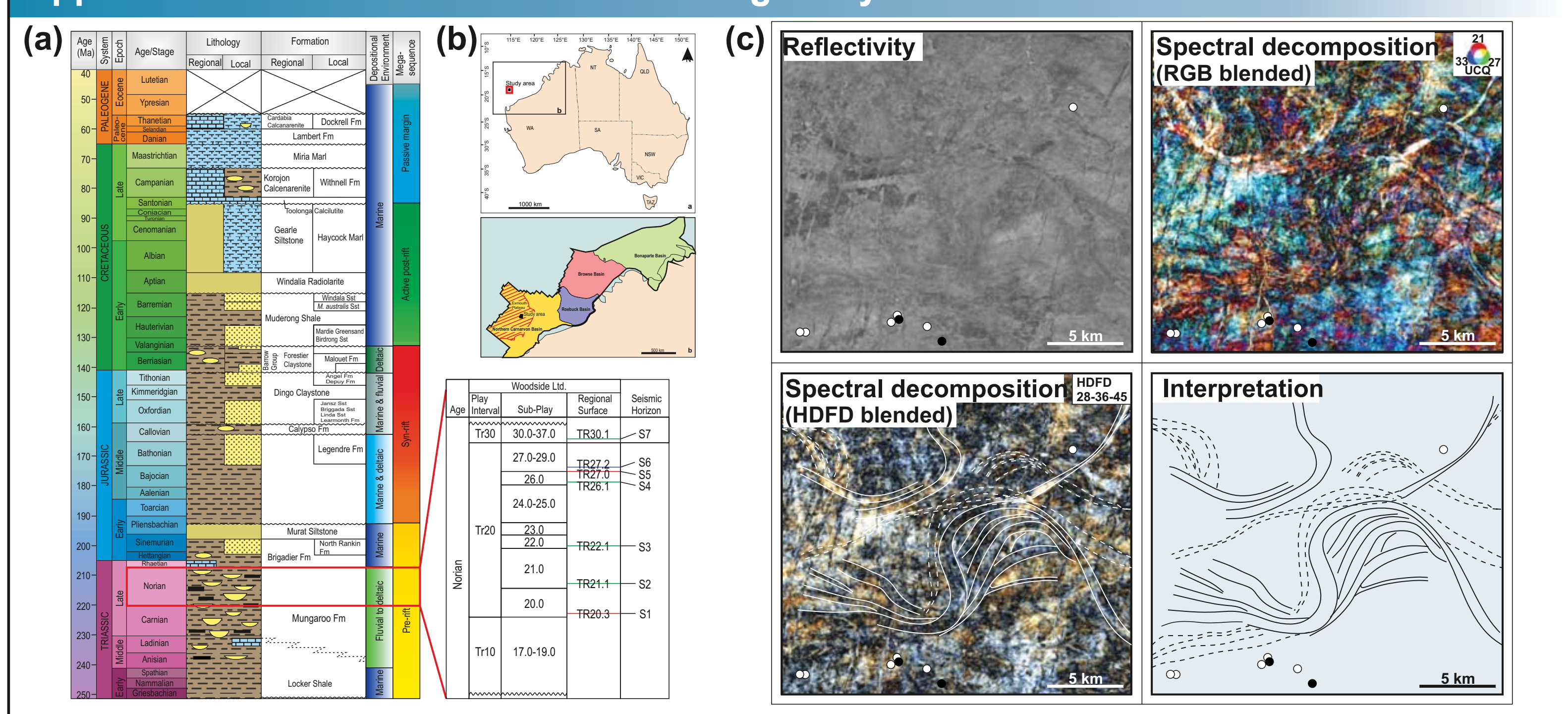


Figure 13. (a) Stratigraphy of the Northern Carnarvon Basin, offshore NW Australia. (b) Locations of the point bars studied using seismic images, Late Triassic Mungaroo Formation. (c) Point bars identified using seismic attribute analysis and spectral decomposition. (Stuart, 2015)

Application to Predict Architecture under Variable Accommodations

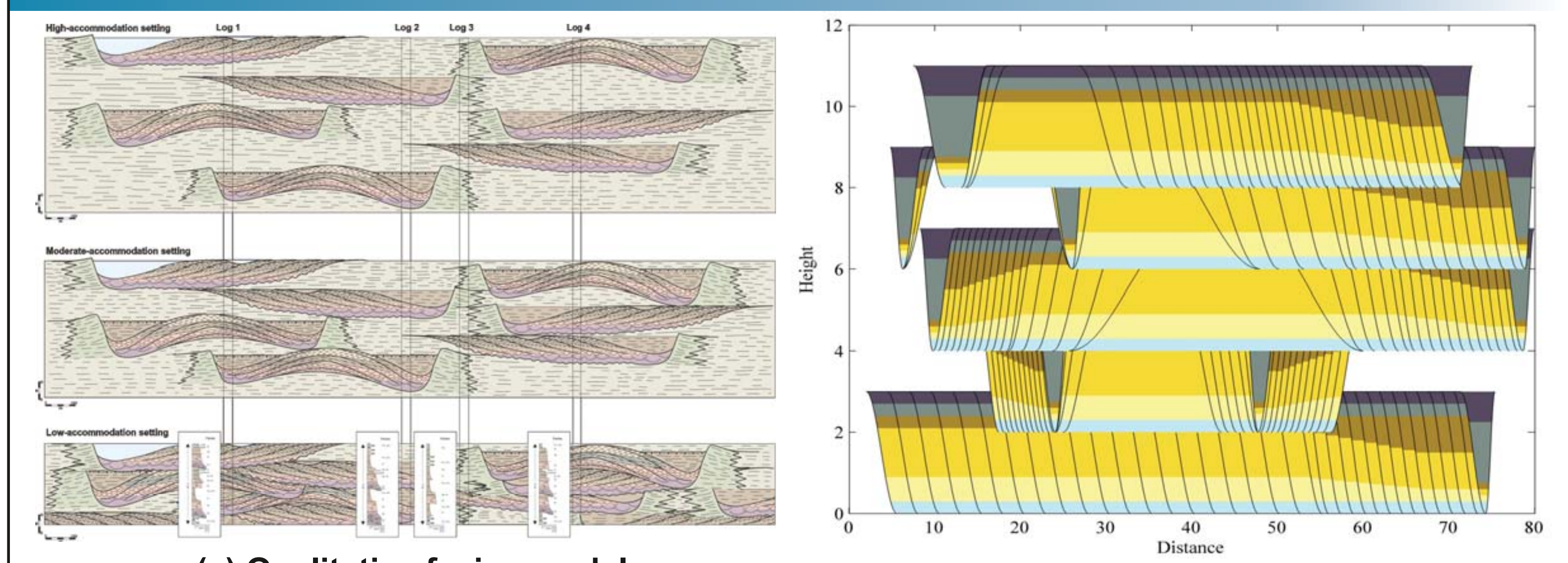


Figure 14. (a) Point-bar facies models at different accommodation settings (Mountney, 2012). (b) Preliminary modelling example with moderate accommodation setting.

Application to Predict Fluvial Point-bar Architectures in Rift Basin Settings

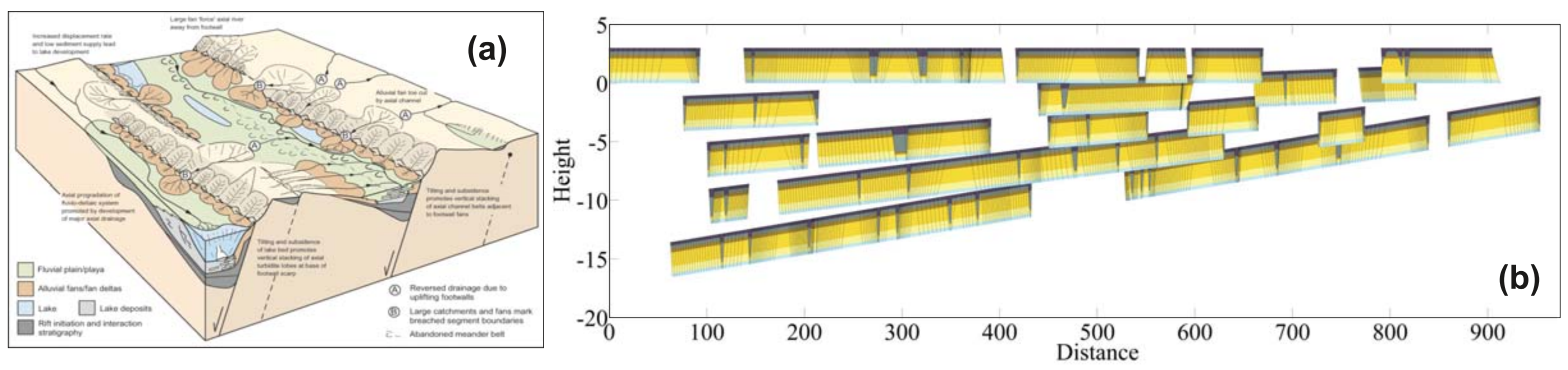


Figure 15. (a) Schematic diagram showing point-bar development in rift basins (Gawthorpe and Leeder, 2000). (b) Preliminary modelling example showing variable connectivity of point bars caused by tectonic tilting. Units are not defined in this case.

Application to Predict Architecture by Interaction between Fluvial and Tidal Currents

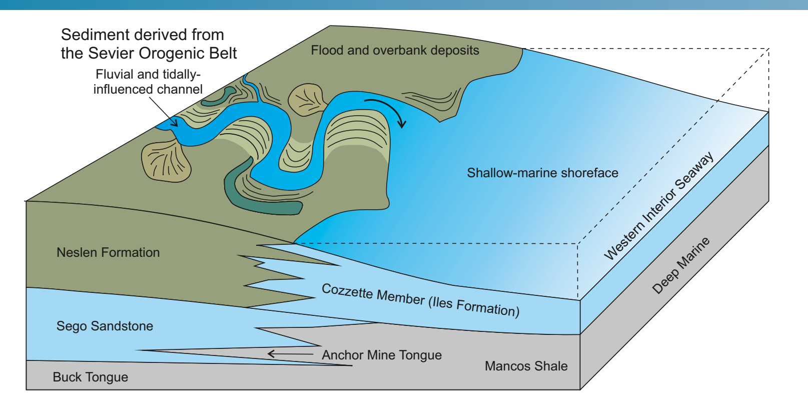


Figure 16. Schematic diagram showing relationship of upper Campanian strata and their depositional environments. The Neslen Formation comprises fluvial, tidally influenced fluvial and estuarine channel and barform elements interbedded with coal-prone flood-basin and mire elements (after Shiers et al., 2014).

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