PS Prediction of Fluvial Point-Bar Internal Architecture and Heterogeneity*

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Abstract

River bends are complicated and dynamic features of meandering fluvial systems; understanding point-bar deposits in seismic and at outcrop is challenging as successions represent partially preserved remnants. Predictive tools to capture geomorphological details of the internal architecture and heterogeneity of meander-fills, and to classify them in a meaningful way for comparison is important in understanding the geologic record. This research uses an integrated GIS and quantitative sedimentological approach to predict and classify the geometry and internal architecture of components of meandering fluvial systems from different settings to better understand scroll-bar development and modes of growth. A classification scheme identifies end-member models, which can be used to interpret the origin of ancient point-bar accumulations from their internal heterogeneity and architecture. To achieve this, a novel 'Intersection Shape Method' has been developed that allows quantitative comparison of meanders with markedly differing morphologies. Measurements of 35 morphometric parameters of 390 meander bends from 13 different rivers (13,650 in total) have been acquired using Google Earth Pro. Studied rivers were selected to isolate the effects independent variables (e.g., climatic zone, valley slope and discharge); systems strongly modified by anthropogenic activity have been avoided. Analyses of ancient point-bar successions (Pennsylvanian, Wales; Jurassic, England) serve as test data sets for the reconstruction of meander morphology from preserved stratal architectures; distributions of 19 lithofacies and 2500 palaeocurrent readings highlight subtle yet predictable variations in ripple, dune and bar growth histories. The approach has yielded the following novel findings: (i) climatic regime exerts a primary control on meander morphology through its role in determining mean annual discharge, sediment supply, and vegetation type and density; (ii) fluvial systems with different gradients, sediment calibers, channel sizes, accumulation rates and climate regime all exhibit different yet predictable trends in meander and scroll-bar development. This method can also be applied to high-resolution seismic slices (e.g., Cretaceous McMurray Formation, Alberta, Canada; Triassic Mungaroo Formation, NW Shelf, Australia) to help infer river characteristics and predict internal architectures and heterogeneity.

References Cited

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Miall, A.D., 1985, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits: Earth-Science Reviews, v. 22, p. 261–308.

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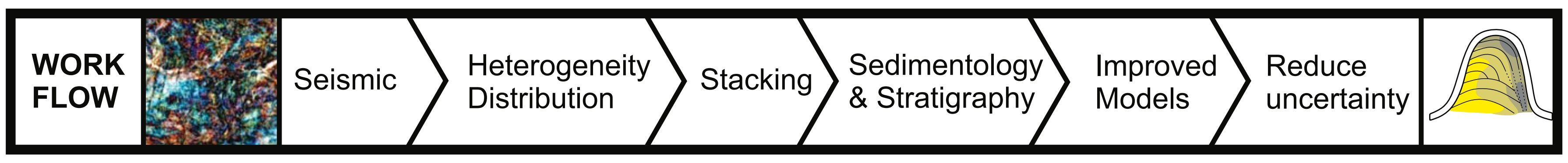
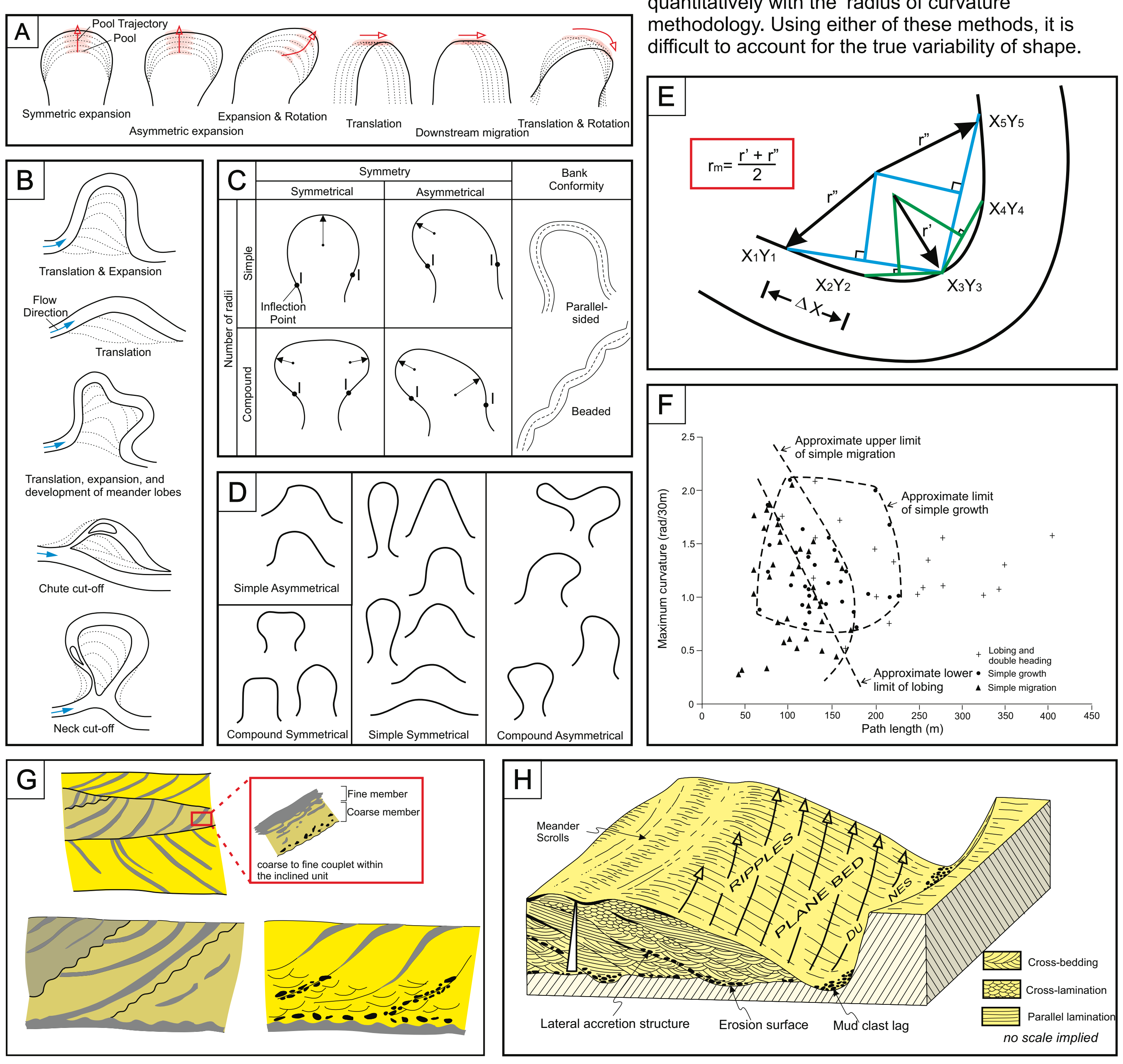
Point-bar elements representing preserved remnants of meandering fluvial channel systems are widely recognized in the rock record. They are internally heterogeneous at a variety of scales which results in variations in fluid flow properties and behaviors that are difficult to predict but which are important to understand to maximise hydrocarbon recovery in reservoir successions. This study brings us a step closer to understanding the specific controls of the variability in these deposits.

Application - The novel methodologies introduced herein have the potential to improve reservoir characterization via the development of a range of predictive facies models for meandering fluvial successions



Previous Work

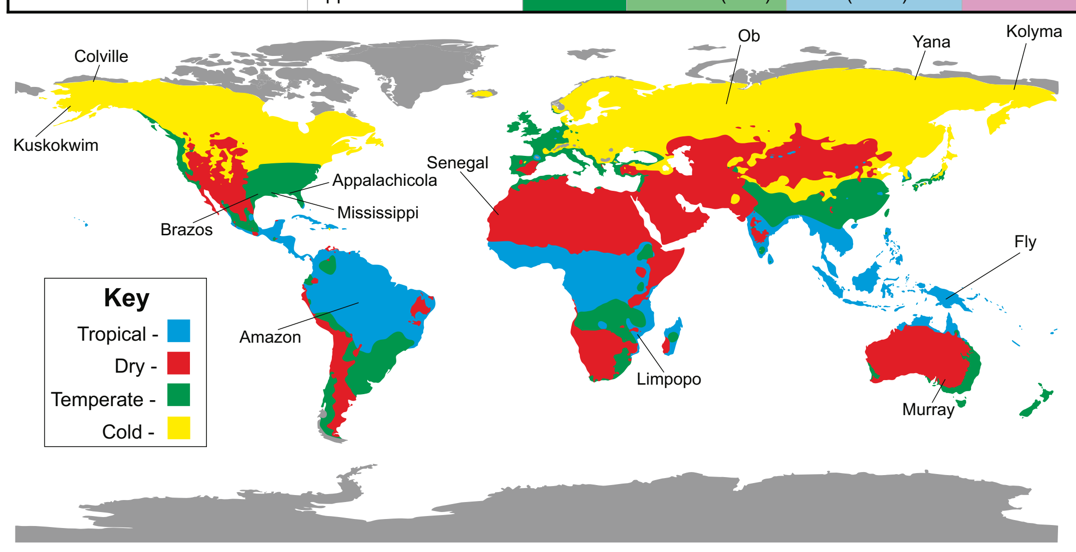
Meanders are differentiated in the literature through shape. This is either done through shape matching or quantitatively with the 'radius of curvature' methodology. Using either of these methods, it is difficult to account for the true variability of shape.



Graphic representations depicting different methods for fluvial point bar classification. A) distinguishes between the types using the pool trajectory as a reference point (Modified from Ielpi et al. 2014). B) classifies the meander shape and mode of abandonment (Modified from Bridge 2003). C) classifies the overall shape from the inflection points (Modified from Allen 1982). D) shows a variety of meander shapes (Modified from Brice 1973). E) shows the methodology for measuring radius of curvature (Modified from Nanson & Hickin 1983). F) shows a plotted meander classification (modified from Hooke & Harvey 1983). G) shows heterolithic strata (after Thomas et al. 1987). H) shows an early, yet still widely used, point-bar facies model (Allen, 1982).

Rivers analyzed in this study

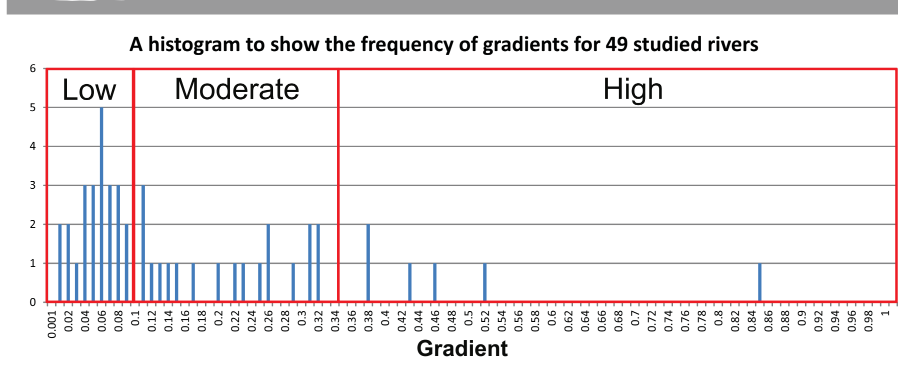
CATEGORY	River	Climate	Gradient (%)	River Size (km² per annum)	Accumulation Rate	Suspended Sediment (mg/l)
CLIMATE						
Humid	Fly (tributary)	A	Low (0.07)	Small (15.6)	Moderate	Moderate (815.6)
Dry	Senegal	B	Low (0.03)	Small (14.7)	Moderate	Low (77.9)
Temperate	Murray	C	Low (0.06)	Small (7.9)	Moderate	Moderate (1271.2)
Cold	Yana	D	Low (0.08)	Small (34.3)	Moderate	Low (114.4)
RIVER GRADIENT						
High	Colville (tributary)	D	High (0.5)	Small (0.63)	Moderate	Low (317.5)
Moderate	Kuskokwim (tributary)	D	Moderate (0.10)	Small (8.77)	Low	Low (116.9)
Low	Yana	D	Low (0.08)	Small (34.3)	Moderate	Low (114.4)
RIVER SIZE						
Large	Mississippi	A	Low (0.06)	Large (529.0)	Moderate	Moderate (862.1)
Moderate	Amazon (tributary)	A	Low (0.01)	Moderate (107.0)	Moderate	Low (182.1)
Small	Fly (tributary)	A	Low (0.07)	Small (15.6)	Moderate	Moderate (815.6)
ACCUMULATION RATE						
High	Ob (tributary)	D	Low (0.04)	Moderate (75.6)	High	Low (40.8)
Moderate	Yana	D	Low (0.08)	Small (34.3)	Moderate	Low (114.4)
Low	Kolyma (tributary)	D	Low (0.04)	Small (30.35)	Low	Low (125.8)
SUSPENDED SEDIMENT						
High	Brazos	C	Moderate (0.32)	Small (5.0)	Moderate	High (6349.2)
Moderate	Limpopo	C	Moderate (0.26)	Small (2.65)	Moderate	Moderate (1269.0)
Low	Appalachicola	C	Moderate (0.26)	Small (21.43)	Moderate	Low (7.2)



To classify the climate type for the studied rivers, a simplified Köppen-Geiger climate classification map has been used. The map is a simplified but updated version of that of Peel et al. (2007).

Climate zones have been classified into four categories (A-D) with river catchments being classified based on their location:

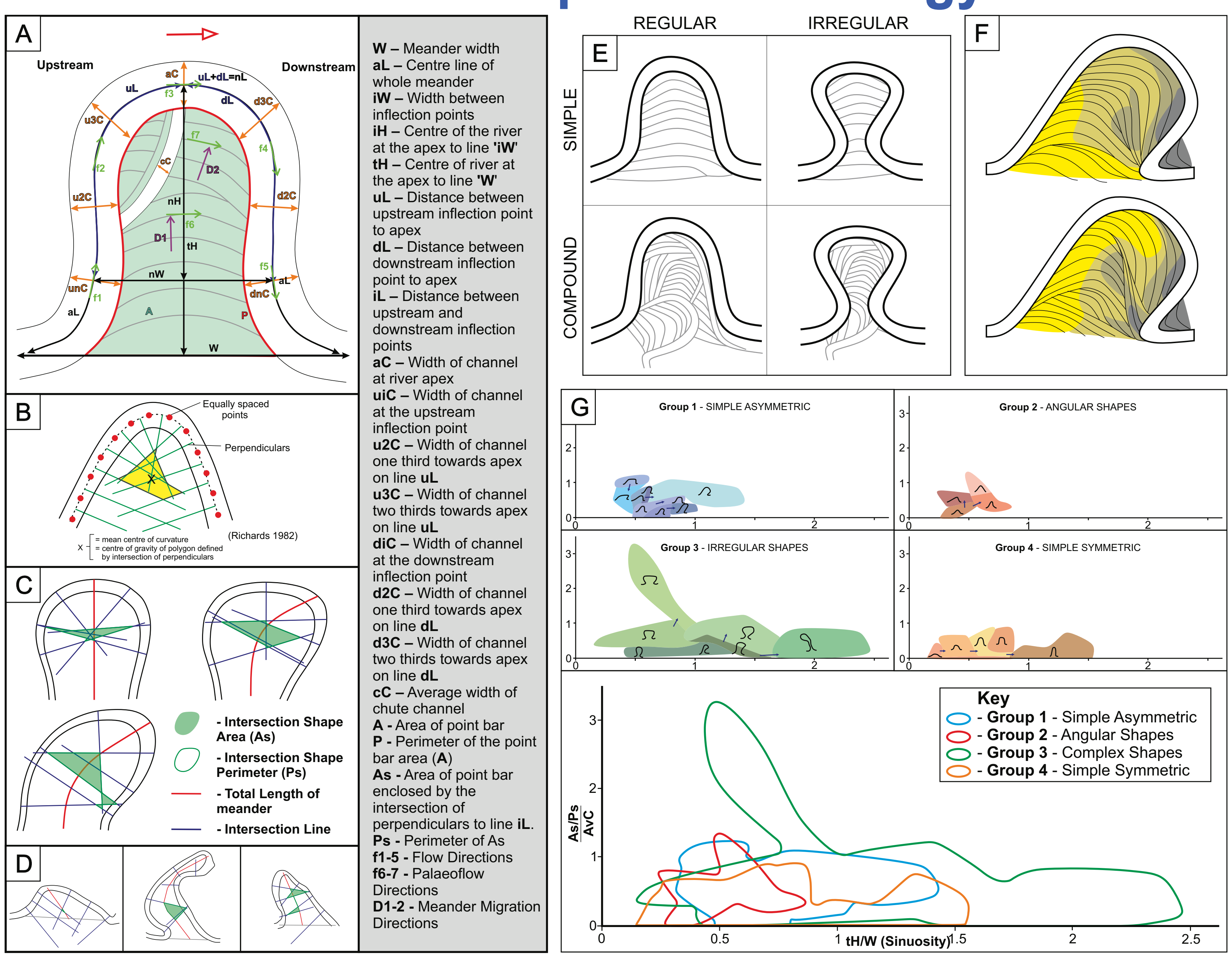
Peel, M.C., Finlayson, B.L. and McMahon, T.A., 2007 Updated world map of the Köppen-Geiger climate classification, *Hydrology and Earth System Sciences*, **11**, 1633–1644.



To determine gradients, 20 elevations were measured and averaged at either end of the studied river reaches. A histogram was then constructed to show rivers assigned to three classes of gradient: low, moderate and high.

Low - 0.0 - 0.09 m/m
Moderate - 0.1 - 0.35 m/m
High - 0.36 + m/m

The 'Intersection Shape' Methodology

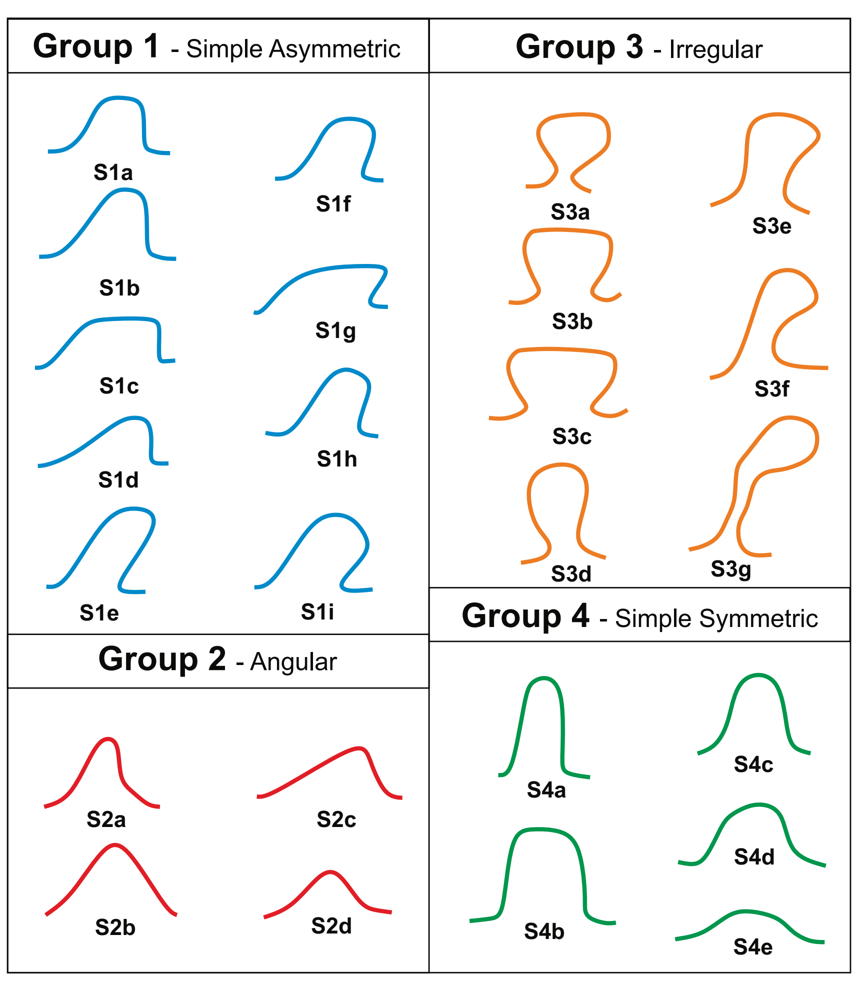


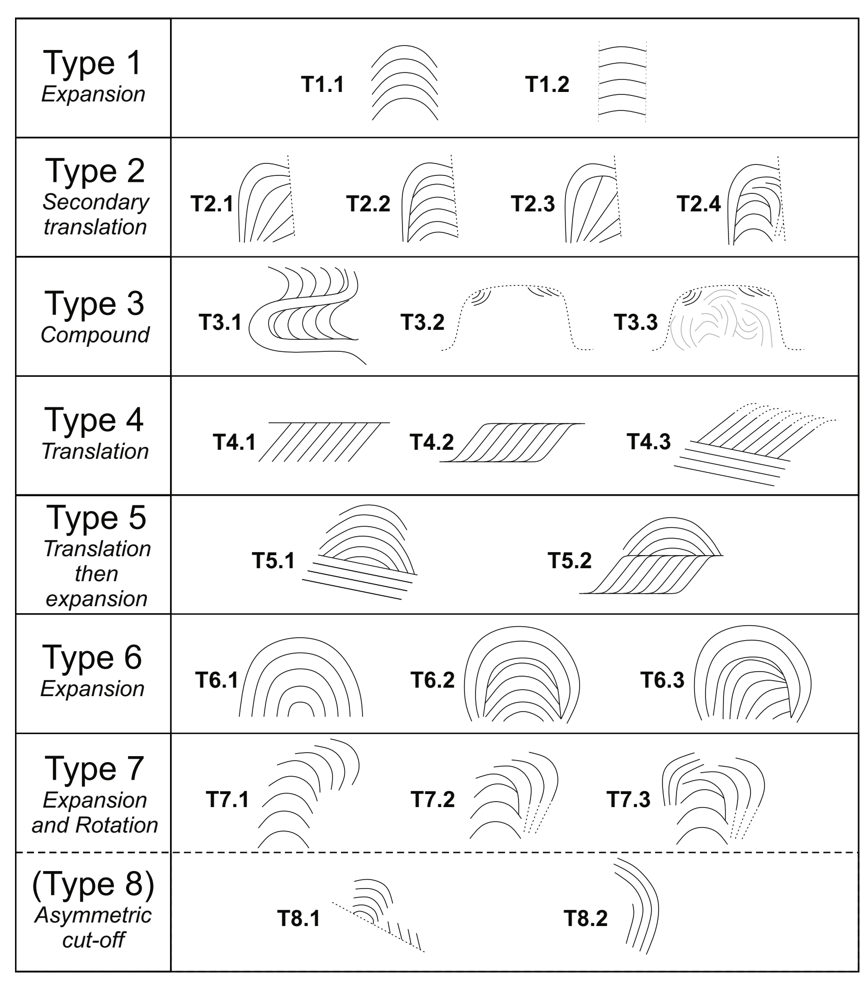
A) Describes the measurements taken from each studied meander. B) Shows Richards (1982) method for finding centre of curvature. C) Demonstrates the 'Intersection Shape' methodology. D) Shows this method as applied to real examples. E) shows that it is important to separate the shape from the scroll bar style because each can be very variable. F) shows that even when the shape is the same, the internal scroll-bar architectures and facies distributions might be different, so the classifications need to be identified separately. G) Shows the results from the analysis of shape distribution using the novel 'Intersection Shape' Methodology developed here. Each style of shape fits into one of Groups 1-4 and as a result, the shape can be quantitatively assessed. This enables more detailed and complex shape comparison to be undertaken.

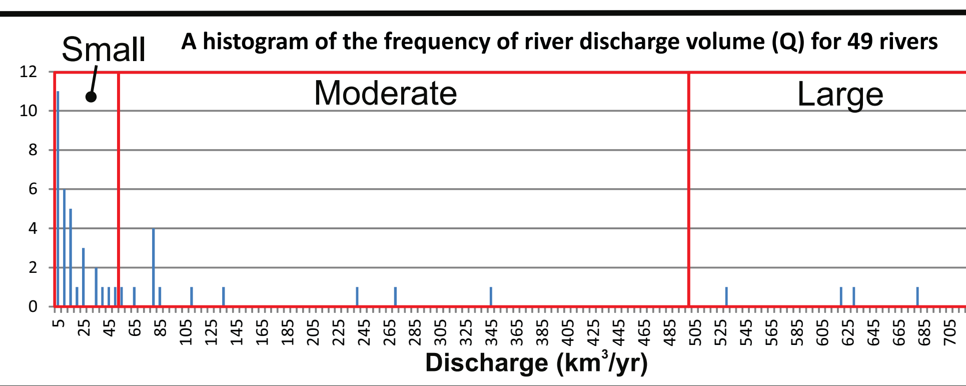
Shape and Scroll Bar Classifications

Shape classification has been assigned through implementation of the quantitative 'Intersection Shape' Methodology. The morphology of the shapes justifies the category which it sits in.

Scroll bar classification has been assigned based on analysis of typical combinations of meander migration in 200 meanders from 13 modern systems. Variability within Types is based on style and location of truncation.







River discharge data were gathered from the "world river discharge database" (Meybeck et al. 2012). A histogram was then constructed to show rivers assigned to three classes of discharge: small, moderate and large

Small - 0 - 50 kg^3/yr
Moderate - 50 - 500 kg^3/yr
Large - 500 + kg^3/yr

Meybeck, M. and Ragu, A., 2012. *GEMS-GLORI world river discharge database*. Laboratoire de Géologie Appliquée, Université Pierre et Marie Curie, Paris, France, doi:10.1594/PANGAEA.804574

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Prediction of Fluvial Point-Bar Internal Architecture and Heterogeneity From Outcrop and System-Independent Morphometric Analysis of Meander Bends

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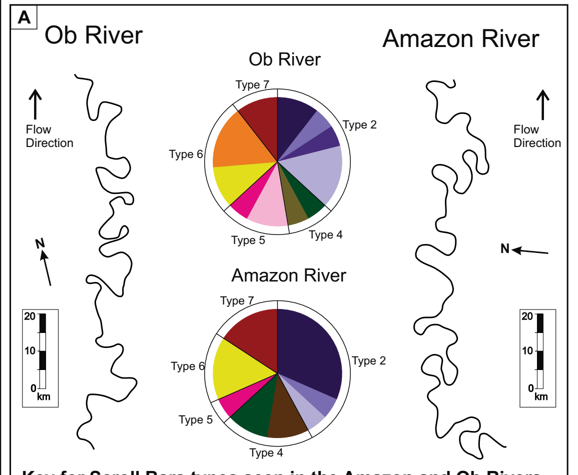
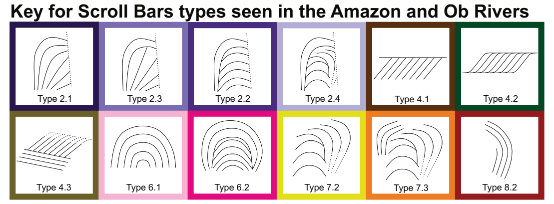
Typically a style of scroll bar is closely associated with the shape of a meander but it is found here that one shape will not exclusively give rise to a specific scroll bar style. In this study, a diverse database of different meander characteristics has been collated from morphometric analysis of 13 rivers (200 individual meanders), that encompass a variety of physiographic and geographic regions across the globe. Detailed planform morphology maps have revealed a variety of features and behaviors.

Relationship Between Meander Shape and Scroll-Bar Style

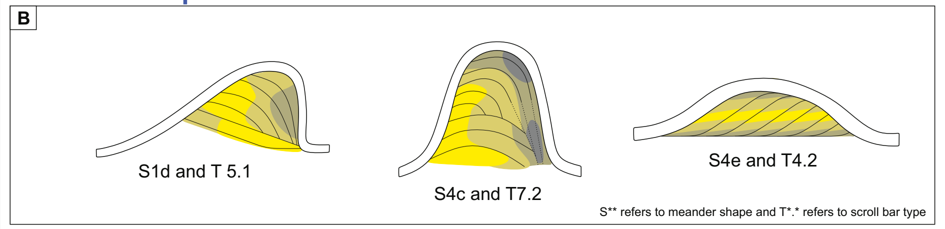
The Amazon and Ob rivers, are similar in terms of the distribution of their meander shapes as determined by the 'Intersection Shape' Methodology. A) Shows how reaches of both the Amazon and the Ob rivers are characterized by meanders of a similar type. Both have a similar proportion of scroll bar Type 2. Within Type 2, meanders of the studied reaches of the Amazon are dominated by translation and rotation. There is a tendency towards translating and expansion behavior in the Ob River. Where the style of cut-off in the Amazon seems to be dominantly asymmetric and erosive, the style in the Ob additionally involves the development of asymmetric forms. Considering the database in its entirety, specific meander shapes yield consistent scroll bar styles in ~50 % of cases as seen in B) below. In some circumstances, two scroll bar types are equally abundant in a given meander shape as seen in C) below. However within a given fluvial system, scroll bar and shape characteristics are more strongly related.

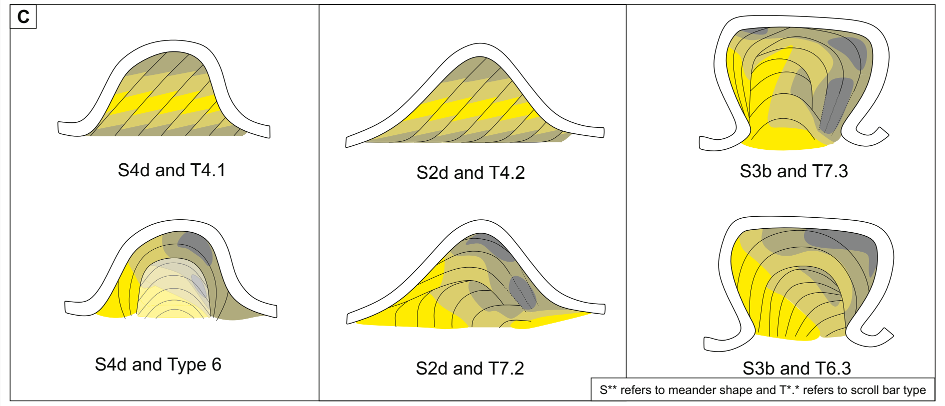


Key for Scroll Bars types seen in the Amazon and Ob Rivers



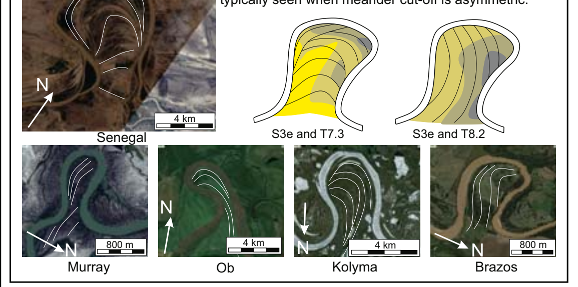
Common shape and scroll bar associations





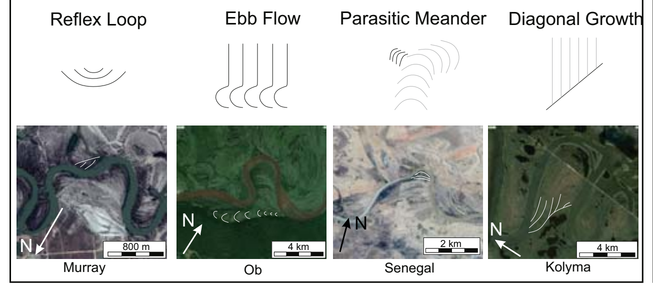
Symmetry

In simple models, scroll bars are depicted as being perpendicular to the channel during cut-off, but in the studied examples this trend is not common as scroll bars tend to be approximately parallel to the channel. This is typically seen when meander cut-off is asymmetric.

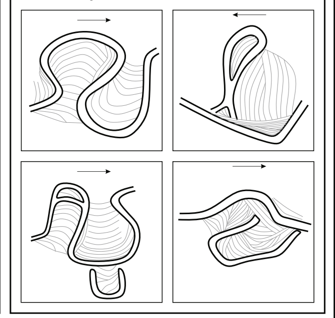


Features

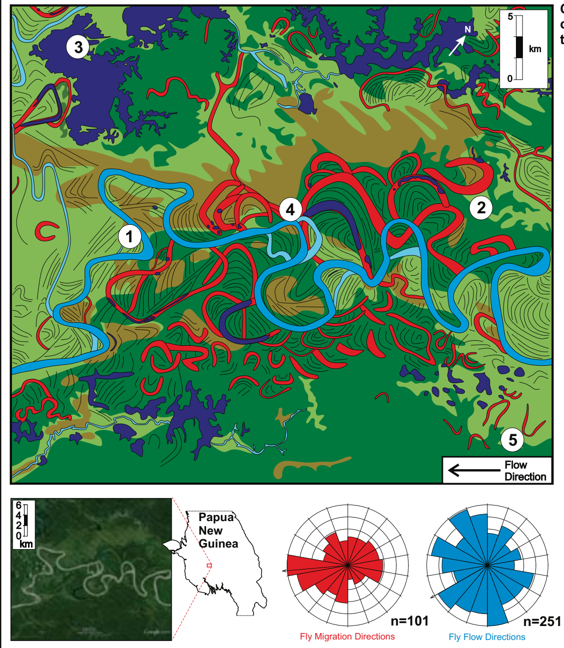
Other features may be used to aid prediction:



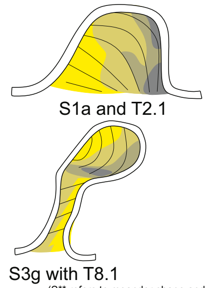
Some meanders shapes commonly occur adjacent to others



Fly River, Papua New Guinea



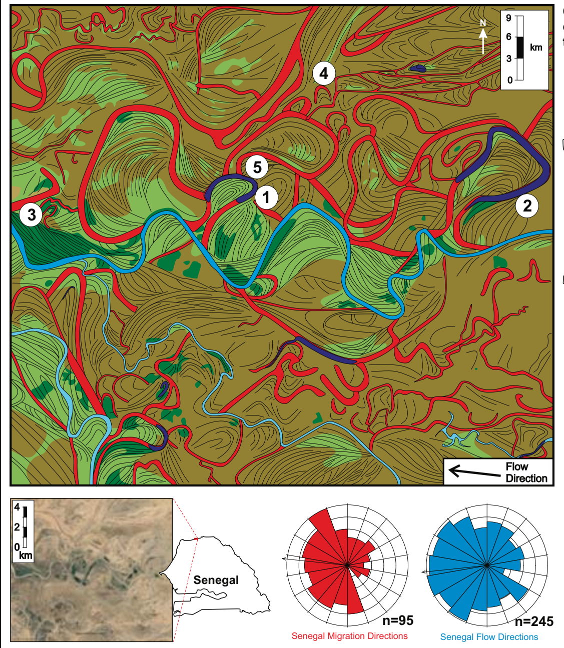
Common shape and scroll bar combinations in this reach of the Fly River



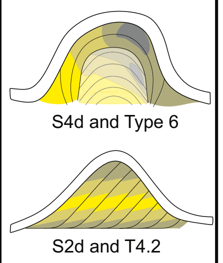
(S** refers to meander shape and T*.* refers to scroll bar type)

1. Dominant meander shapes are mostly symmetrical and compound, though some irregular meanders have notable asymmetry.
2. Abandoned channels are overlapping and overprinting.
3. Large floodplain lakes. Some lakes also occur in abandoned channels as oxbows.
4. Rare chute channels on elongated meanders along the active channel.
5. Vegetation is variable across the floodplain; it is characterized as vegetated with areas of sparse vegetation.

Senegal River, Senegal



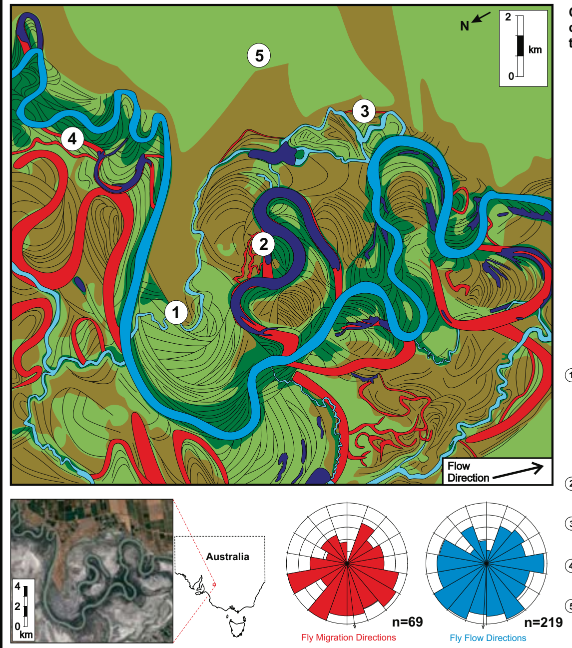
Common shape and scroll bar combinations in this reach of the Senegal River



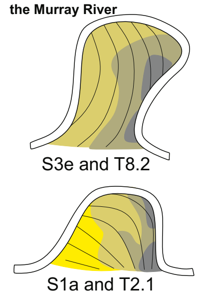
(S** refers to meander shape and T*.* refers to scroll bar type)

1. Dominant meander growth pattern is via expansion with some translation and gradual directional changes.
2. In relation to the size of the river, meander migration occurs in small increments.
3. Vegetation is affected by human activity in places: area of floodplain colonized by dense vegetation (not naturally occurring). Much of the floodplain is non-vegetated.
4. Abandoned channels, clearly preserved and undisturbed.
5. Rare lakes in abandoned channels.

Murray River, Australia



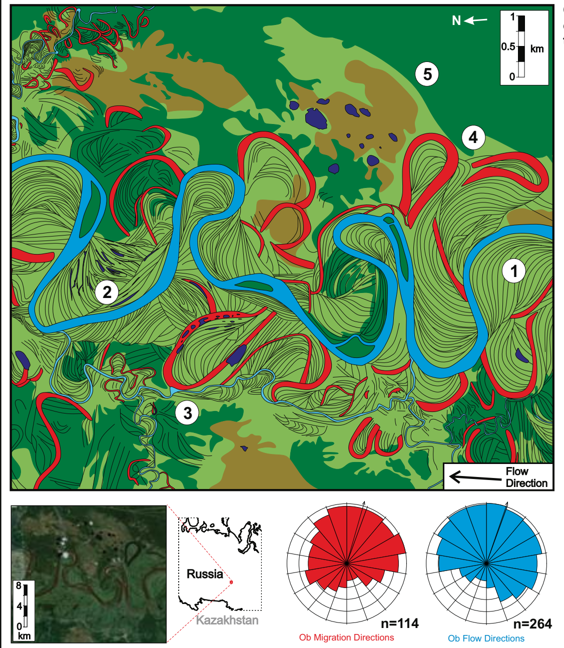
Common shape and scroll bar combinations in this reach of the Murray River



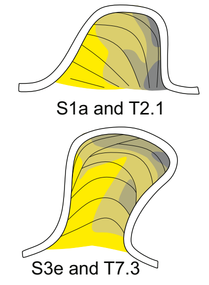
(S** refers to meander shape and T*.* refers to scroll bar type)

1. Dominant meander growth pattern by translation and expansion with directional changes leading to further expansion. The overall shapes are mostly symmetrical with some asymmetrical tendencies.
2. Lakes form in abandoned channels.
3. Smaller secondary channels connect meander loops.
4. Dense vegetation only occurs along the primary channel.
5. Human activity has affected the vegetation distribution in some areas of the floodplain.

Ob River, Russia



Common shape and scroll bar combinations in this reach of the Ob River



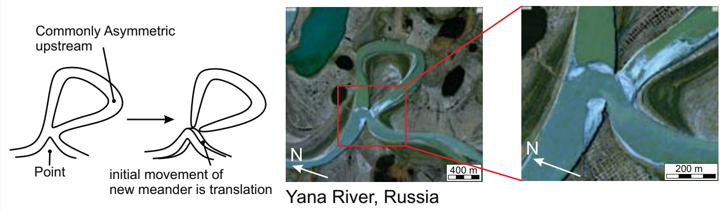
(S** refers to meander shape and T*.* refers to scroll bar type)

1. Meander growth is dominated by translation and rotation. These migrations are noticeably large and sweeping.
2. There are narrow lakes on the point bar deposits.
3. Only two scales of river are seen. There is a wide main channel and several narrow rivers which also meander on the flood plain.
4. Repeated asymmetric cut-off is present.
5. Directly around the river, sparse vegetation is seen. Away from the channel, denser vegetation is present.

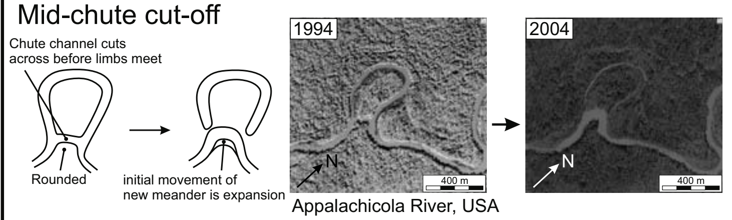
Types of Cut-off

Three styles of meander abandonment are commonly identified; chute cut-off, neck cut-off, and avulsion (Erskine 1992). By studying the variability of abandonment in detail, more can be determined about the characteristics of the system because the style of cut-off has been found to influence the style of initial growth in the new meander.

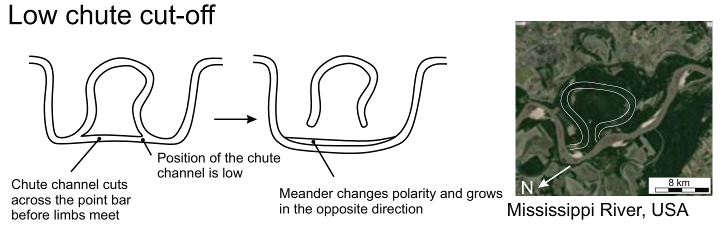
Pointed cut-off



Mid-chute cut-off

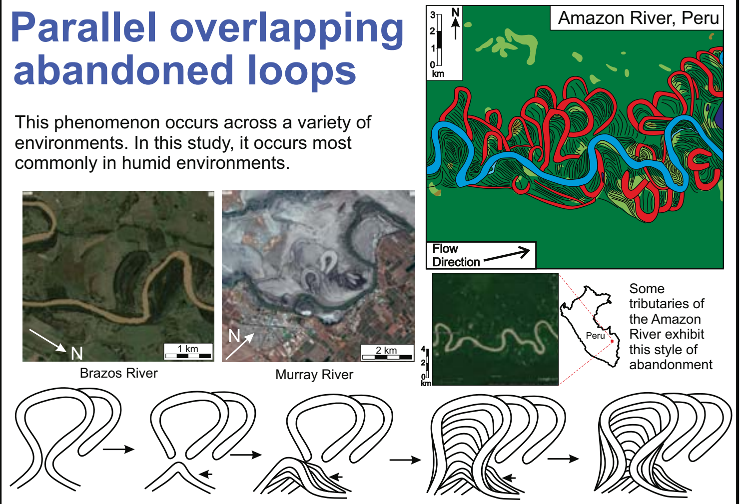


Low chute cut-off



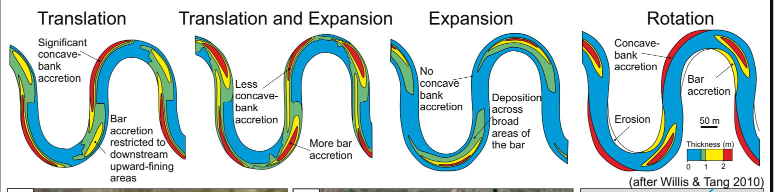
Parallel overlapping abandoned loops

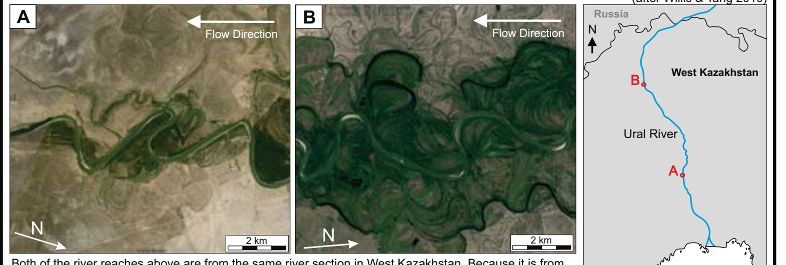
This phenomenon occurs across a variety of environments. In this study, it occurs most commonly in humid environments.



Bank Erosion and Rotation

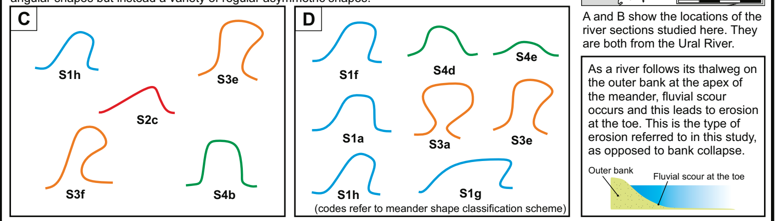
Through studying a wide variety of meander bends, a potential correlation has been found between bank strength and the frequency of rotation of meanders within a reach. Bank strength is a factor in determining the rate of bank retreat and this in turn influences the growth of the point bar. Willis and Tang (2010), modelled bank erosion and deposition (see below). Rotation gives rise to more localised erosion and deposition on the downstream side of the meander, which indicates that this would be the most likely mechanism to erode a strong bank.





Both of the river reaches above are from the same river section in West Kazakhstan. Because it is from the same river, the effects of other variables have been minimised and this study attempts to isolate the effects of differing rates of bank erosion. A) shows more angular shapes (see C), whereas B) shows no angular shapes but instead a variety of regular asymmetric shapes.

A and B show the locations of the river sections studied here. They are both from the Ural River.



As a river follows its thalweg on the outer bank at the apex of the meander, fluvial scour occurs and this leads to erosion at the toe. This is the type of erosion referred to in this study, as opposed to bank collapse.

The river Ural analysed above shows a gradation from one meandering style to another. A) is the more angular downstream reach in which downstream migration is dominated by translation. B) is further upstream and exhibits a more asymmetric style caused by rotation of the meanders. The shapes identified in each are shown in C) and D). Vegetation varies between A) and B) considerably and this could be a factor in the increased bank strength, though isolating this control is not straightforward. Additionally, the system is also likely to be influenced by a variety of autogenic and allogenic factors.

Further development and refinement of the techniques discussed herein for the characterization of meander shape are being applied to abandoned channel segments and to ancient preserved meander successions.

Key

Relative Decreasing Sand Proportion	
Primary Channel	Vector mean
Secondary Channel	n= 7 Number of measurements in rose diagram
Floodplain Lake	Percentage number of migration directions in bin
Non-Vegetated Floodplain	Percentage number of flow directions in bin
Sparsely Vegetated Floodplain	
Fully Vegetated Floodplain	
Abandoned Channel	

Erskine, W., McFadden, C., & Bishop, P. (1992). Alluvial cutoffs as indicators of former channel conditions. Earth Surface Processes and Landforms, 17(1), 23-37;
Willis, B. J., & Tang, H. (2010). Three-dimensional connectivity of point-bar deposits. Journal of Sedimentary Research, 80(5), 440-454

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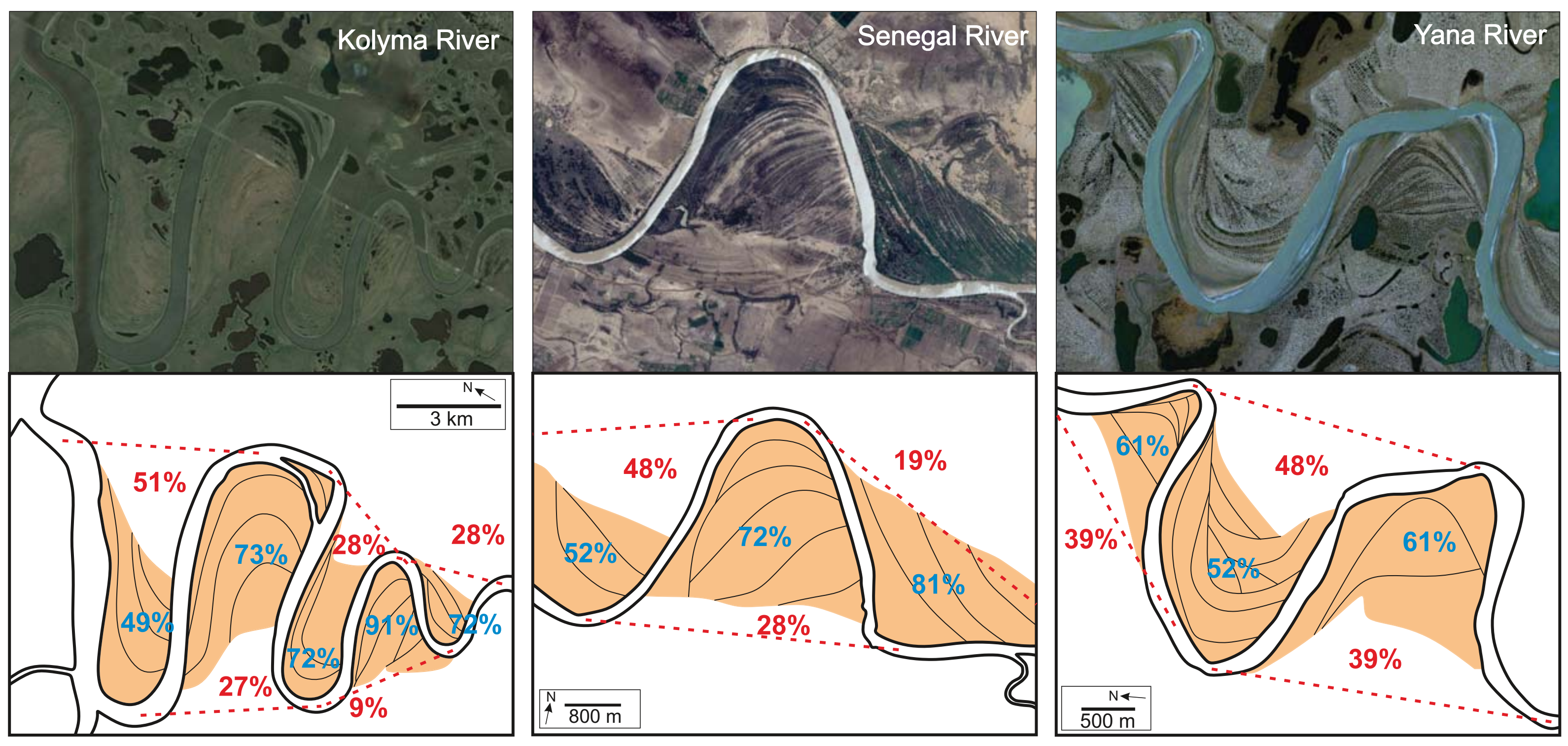
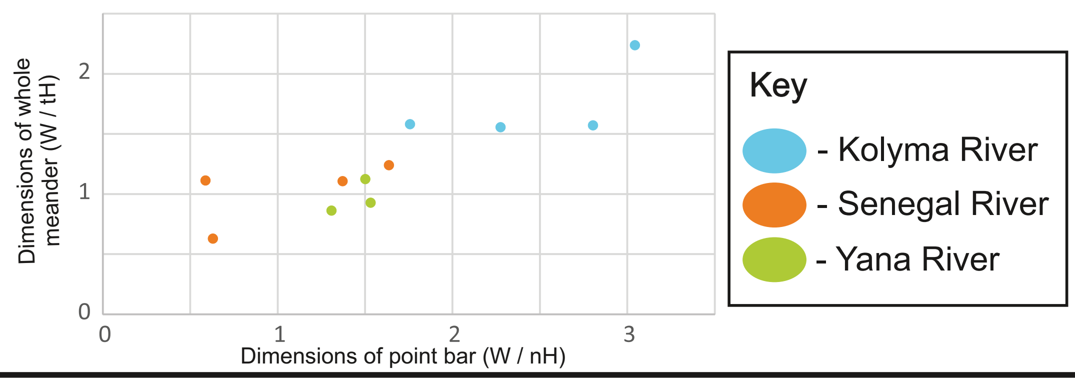
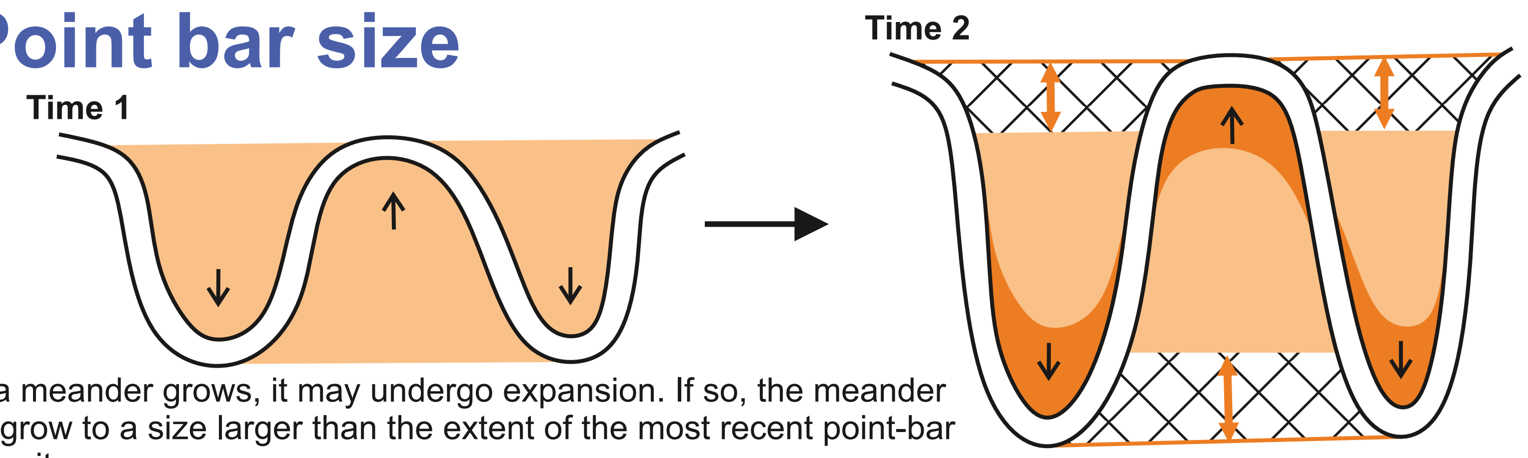
Typically when studying point-bar elements, an incomplete data set is available at either outcrop or as part of a seismic study. Because of this, predictive modelling is required to more effectively describe the expected distribution of lithological heterogeneity within such successions, including in subsurface hydrocarbon reservoirs. The "Intersection Shape" Methodology combined with the scroll-bar classification scheme and other observations can reveal trends and characteristics of modern systems. These methods can be readily integrated into the analysis of seismic slices that image ancient preserved scroll bars to predict characteristic shapes and facies distributions, and therefore potential processes and controls which in turn will lead to a better understanding of heterogeneity distribution.





The correlation between the dimensions for the entire meander and for the point bar show a correlation: this can be used as a predictive tool to show where the most recent point bar deposit lies in an ancient meander shape.

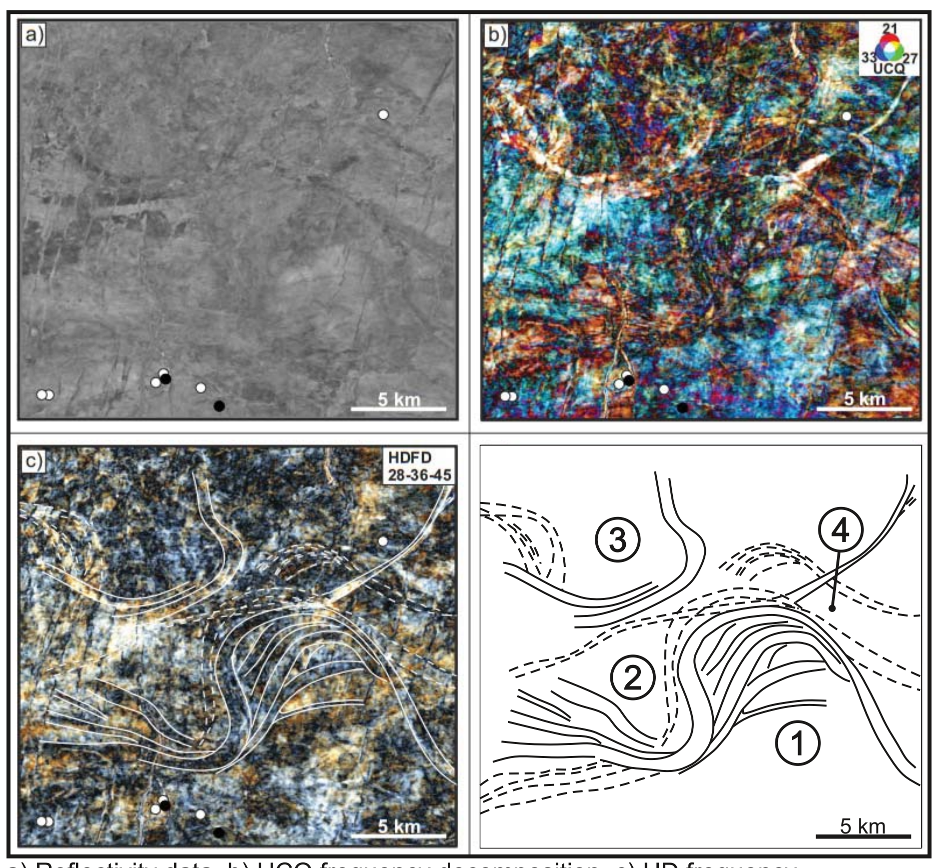
Point bar size



As a meander grows, it may undergo expansion. If so, the meander will grow to a size larger than the extent of the most recent point-bar deposit.

Application to the Subsurface

Triassic Mungaroo Formation, Australia

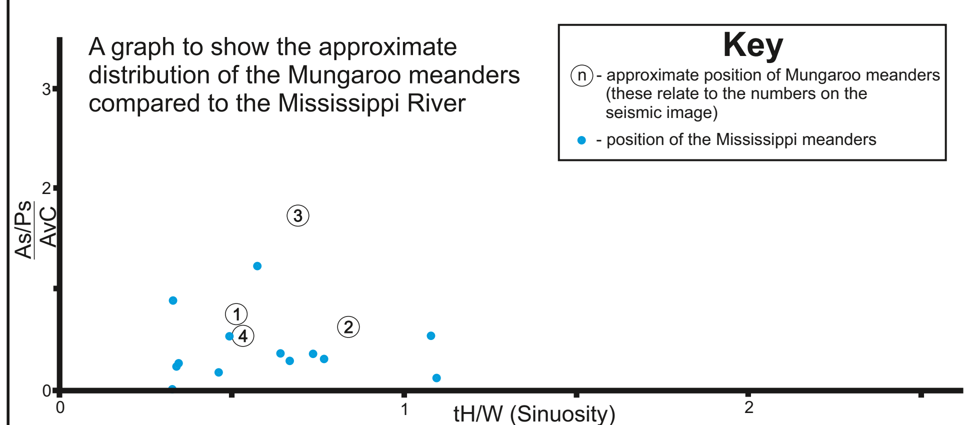


a) Reflectivity data, b) UCQ frequency decomposition, c) HD frequency decomposition reduces vertical smearing and so better shape isolation occurs, d) Final interpretation of fluvial point-bar and channel architecture (Stuart J. 2014).

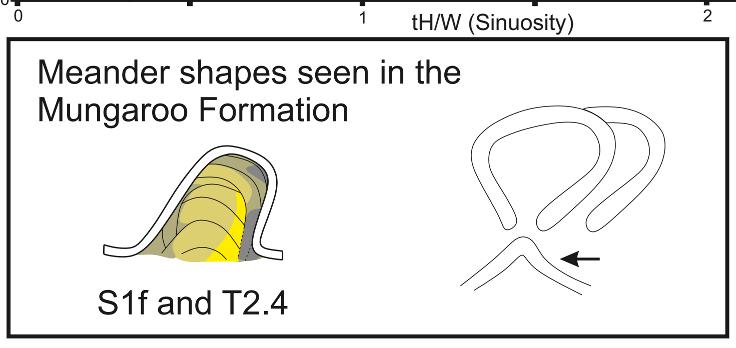
This meandering reach has been abandoned through avulsion as it still maintains the shape of an active channel. Aside from this it looks like the dominant mode of cut-off is low chute cut-off. There are also 'Fish Scales' created by meanders 1) and 4). The overall style of scroll bar growth is rotation and translation.

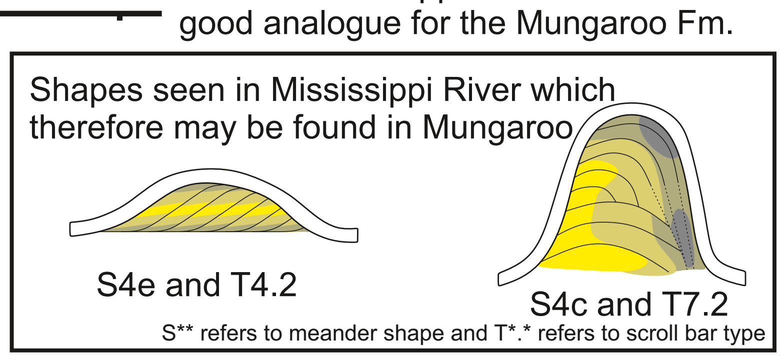
1) exhibits rotation and translation and there is a clear truncation of the rotating scroll bars by the translating ones. It also overlays 4) in a 'Fish Scales' manner. 2) had a low chute-channel and migrated through translation. 3) the scroll bar is poorly imaged but appears to record an irregular shape and therefore likely to have involved some translation or rotation or both.

The Mississippi River has been selected for comparison because the style of meandering is similar to that of the meanders imaged in the seismic data from the Mungaroo Formation.



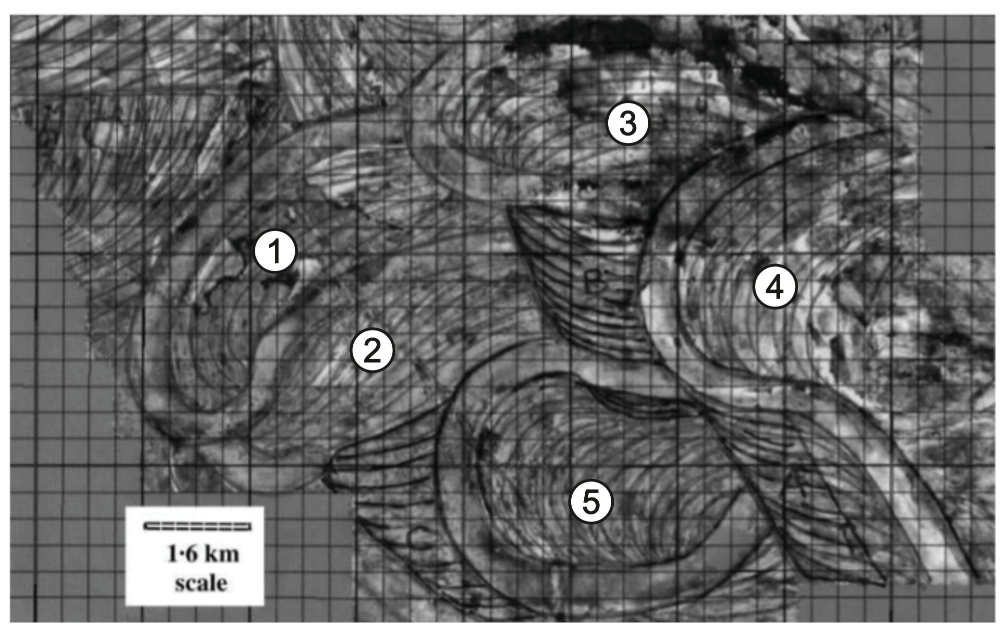
In the graph to the left, the numbers cluster around the same area as the Mississippi river meanders. This tells us that the Mississippi meanders are a good analogue for the Mungaroo Fm.





S** refers to meander shape and T*.* refers to scroll bar type

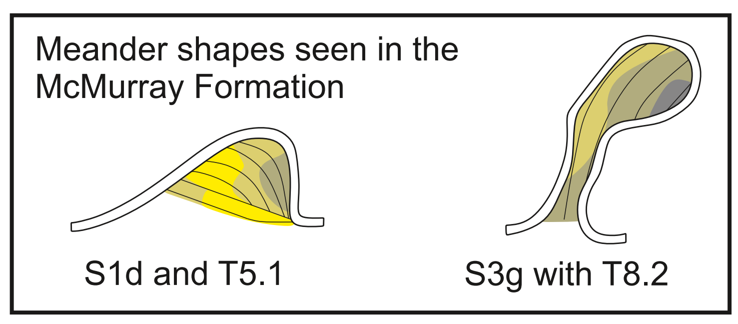
Cretaceous McMurray Formation, Alberta

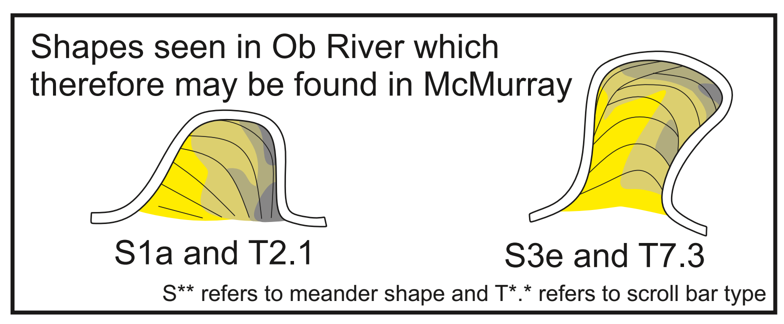


A Seismic image of Nexen's property lease of the Lower Cretaceous McMurray Formation near Fort McMurray, North-east Alberta. (Smith et al. 2009)

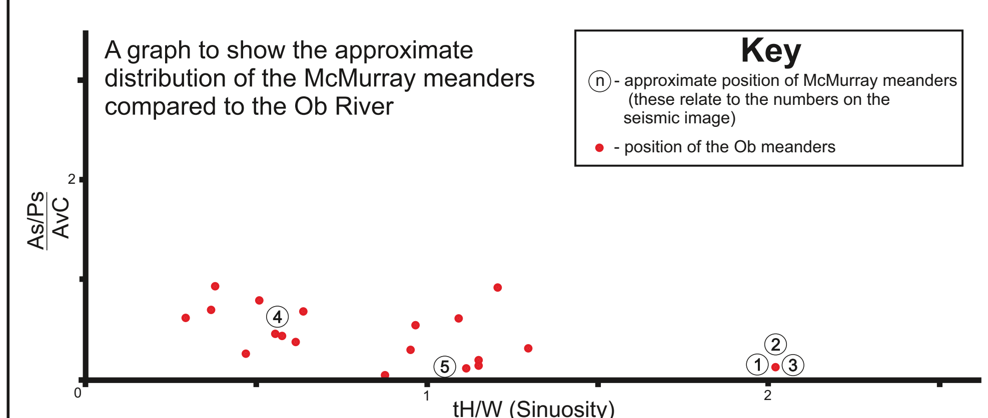
These meander loops are highly sinuous and the scroll bars in many are Type 8 of the scroll-bar classification. There is a dominant mode of translation and expansion that culminated in asymmetric cut-off in many cases.

1), 2) and 3) all show the style of scroll bar as in T8.2, and therefore this indicates that there was an asymmetrical cut-off potentially repeating from the same section of river, 4) exhibits translation and rotation such as in T2.1. The shape is likely to have been S1d and the correlation in this relationship supports this theory.

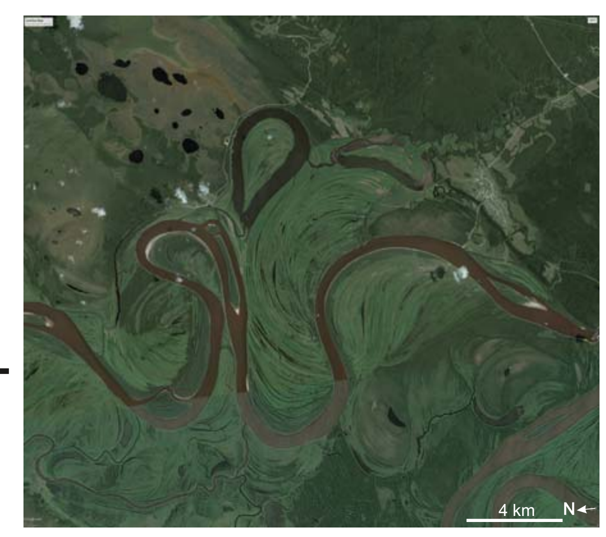




S** refers to meander shape and T*.* refers to scroll bar type



In the above graph, there are more points plotting at a high sinuosity of 2 because the shapes in the McMurray Fm have been cut-off and abandoned whereas an active channel of the Ob River has been studied. This research is integrating a data set of 153 abandoned meander loops from 13 rivers globally.



The River Ob has been selected for comparison with preserved meander deposits imaged seismic slices from the McMurray Formation because the style of meandering and cut-off is similar.

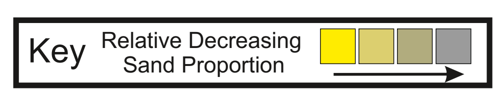
Application to Reservoir Modeling

- Numbers and statistics for element modeling and size prediction
- Informed prediction of 3D distribution of lithological heterogeneity in preserved point-bar elements.
- Development of enhanced predictive models such that reservoir uncertainty and associated risk is reduced.

Conclusions

- A limited data set can can serve as a valuable predictive tool when applying the 'Intersection Shape' methodology and the scroll bar classification scheme
- Observation of the cut-off style helps to understand the processes that governed evolution of the fluvial system.
- Studying a variety of modern systems in detail reveals characteristics which can be referenced across systems.

Smith, D. G., Hubbard, S. M., Leckie, D. A., & Fustic, M. (2009). Counter point bar deposits: lithofacies and reservoir significance in the meandering modern Peace River and ancient McMurray Formation, Alberta, Canada. Sedimentology, 56(6), 1655-1669.;
Stuart J. 2014 unpublished thesis; Subsurface architecture of fluvial-deltaic deposits in high- and low-accommodation settings



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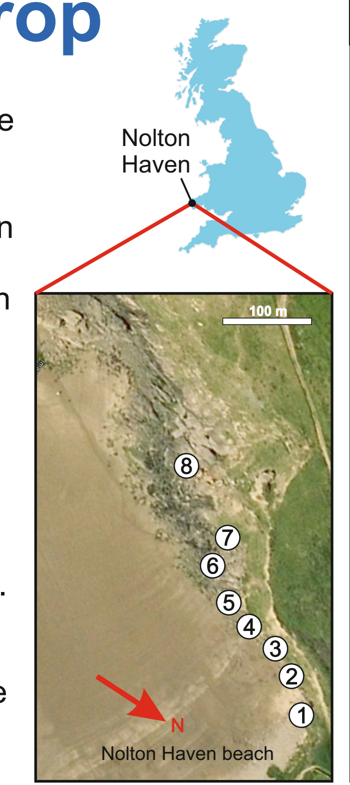
Ancient outcrop

A high-resolution study has been undertaken to characterize the internal sedimentary succession of an ancient point-bar deposits from a Westphalian (Carboniferous) "Coal Measures" succession at Nolton Haven, Pembrokeshire, UK. Over 2505 paleocurrents have been measured and related to lithofacies distributions via detailed graphic logging and architectural depictions of the distribution of internal bounding surfaces within the bar element. Over 1121 mud drapes were measured, 37 detailed logs drawn and over 503 clasts have been measured, counted and classified.



Legend

- St – Trough-cross bedding
- Spm – Planar X-Stratification (medium grain size)
- Spc – Planar X-Stratification (course grain size)
- Spvc – Planar X-Stratification (v.course grain size)
- Srs – Sand Ripples
- Sh3 – Horizontal Lamination (packages of 3 laminations)
- Sh4 – Horizontal Lamination (packages of 4 laminations)
- Sh5 – Horizontal Lamination (packages of 5+ laminations)
- Slm – Low-Angle X-beds (medium grain size)
- Slc – Low-Angle X-beds (course grain size)
- Sec – Erosional Scour Deposits (Clast supported)
- Sem – Erosional Scour Deposits (Matrix supported)
- Ss – Scour Fill
- Fl – Fine Laminations & Small Ripples
- Fm – Mud / Silt
- Fsc – Laminated to Massive silt / mud
- C – Coal / Carbonaceous Material
- (1) Section Number
- Major Erosional Surface
- Minor Erosional Surface

Rose diagrams

- Vector mean
- Percentage number in bin
- n= 7 – Number of measurements in rose diagram

References

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McGowen, J.H. and Garner, L.E., 1970. Physiographic features and stratification types of coarse-grained pointbars: modern and ancient examples. *Sedimentology*, **14**, 77–111.

Miall, A.D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Science Reviews*, **22**, 261–308.