PS Channel Belt Rugosity in Reservoir Characterization*

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Abstract

Fluvial systems are typically classified based on river channel morphology, with meandering and braided river patterns being the two most common end-member types. However, seismic data commonly cannot resolve channel morphologies, only the much larger channel belt. This creates challenges when applying channel classifications to subsurface reservoirs. Log and core data allow the interpretation of bar patterns within river channels that aid in the interpretation of larger channel belts. Typically, downstream accretion results in fewer sand/mud interbeds and is often associated with a braided channel morphology, whereas lateral accretion leads to abundant sand/mud interbeds and associations with a single thread sinuous channel. Still, core and log data do not allow for a direct and confident interpretation of braided or sinuous channel morphology. River channels and channel belts can easily be identified using satellite imagery. Channel-belt margins vary in smoothness depending on the dominant style of bar-form migration: lateral or downstream. We term this smoothness of the channel-belt margin, Rugosity. Rugosity is used in marine science to characterize seafloor habitats. Rugosity is herein used to describe how dissimilar the opposing sides of a fluvial channel belt are in planview. Rugosity (fr) is a measure of small-scale variations or amplitude in the height of a surface, fr = Ar/Ag, where Ar is the actual planform area and Ag is a geometric approximation of the channel-belt area. We found that increasing lateral accretion of barforms (caused by increased channel sinuosity) leads to an increase in channel-belt rugosity. Therefore, rugosity could be a proxy for interpreting the relative degree of lateral vs. downstream accretion within channel belts. This is a potentially powerful tool for resource estimation and extraction, as it may improve predictions of internal heterogeneity using seismic data.

Channel Belt Rugosity in Reservoir Characterization

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Abstract:

Fluvial systems are typically classified based on river channel morphology, with meandering and braided river patterns being the two most common end-member types. Seismic data commonly cannot resolve reservoir depth channels, but rather only image the larger-scale channel belts. Thus it is a challenge to apply modern river channel classifications to subsurface reservoirs.

Log and core through channel belts are commonly interpreted based on inferences that vertical grain size trends and the abundance of bed-scale heterogeneities reflect specific channel patterns: 1) braided rivers are assumed dominated by downstream accretion deposits with few mud interbeds and subdued upward-fining trend, whereas 2) Meandering river deposits are assumed to be dominated by lateral accretion deposits with abundant mud interbeds and more pronounced vertical fining trend. Despite these general rules of thumb, core and log data alone generally do not allow confident distinction of deposits formed by different types of rivers.

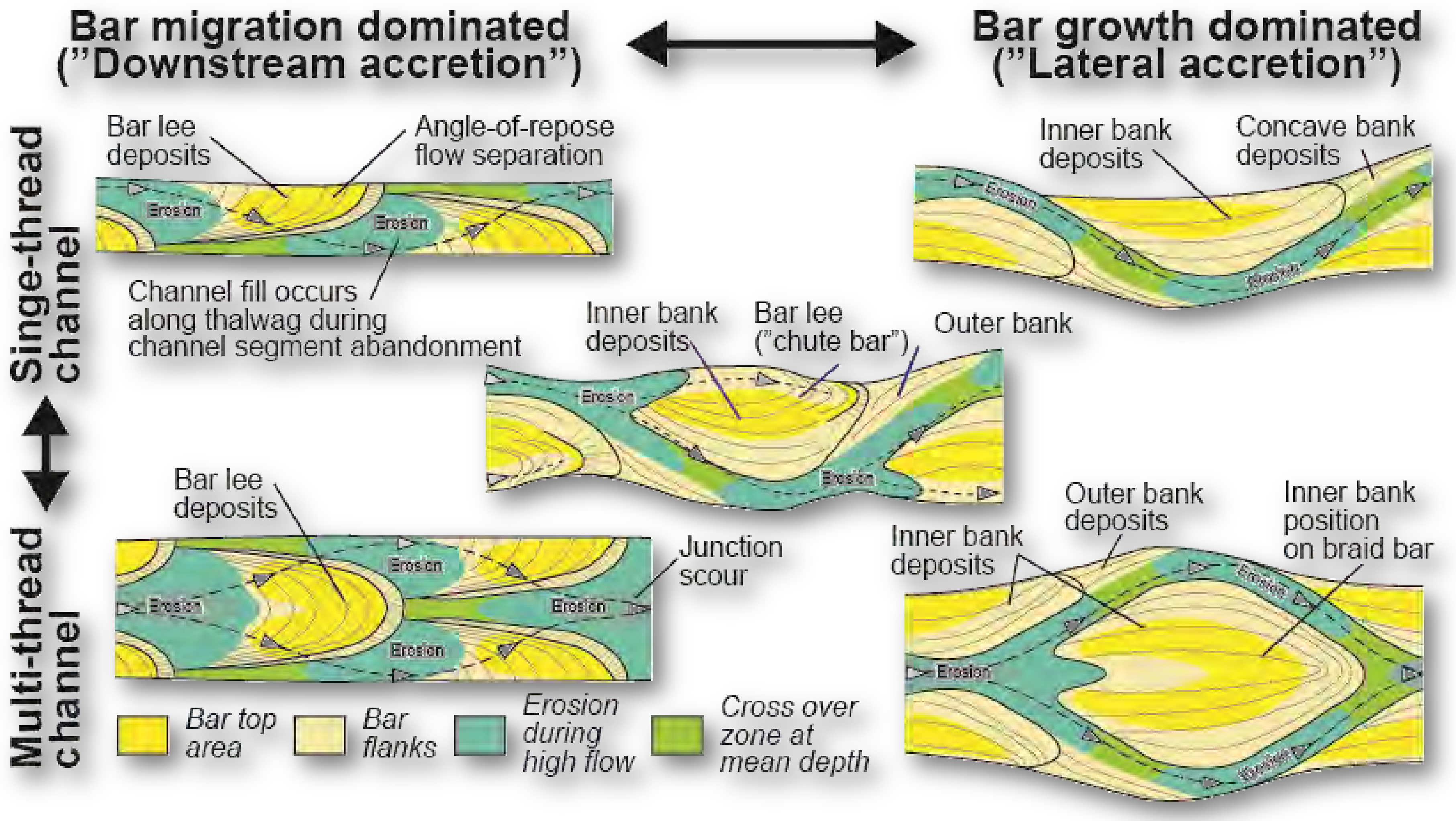
River channels and channel belts are easy to define using satellite imagery. Channel-belt margins vary in smoothness depending on the dominant style of bar-form migration: lateral vs. downstream. We quantify the relative channel-belt margin smoothness by defining a *Rugosity index*. Rugosity (fr) is a measure of small-scale variations or amplitude in the height of a surface, fr = Ar/Ag, where Ar is the actual planform area and Ag is a geometric approximation of the channel-belt area. We suggest that higher channel-belt rugosity is associated higher sinuosity river deposits that tend to be more dominated by lateral accretion bedsets. Therefore rugosity can provide a proxy for interpreting the formative channel morphology and predicting internal heterogeneity patterns. This is a potentially powerful tool for channel belt reservoir evaluation may improve recoverable resource estimates and extraction behaviour forecasts.

Meandering River: Single thread channel

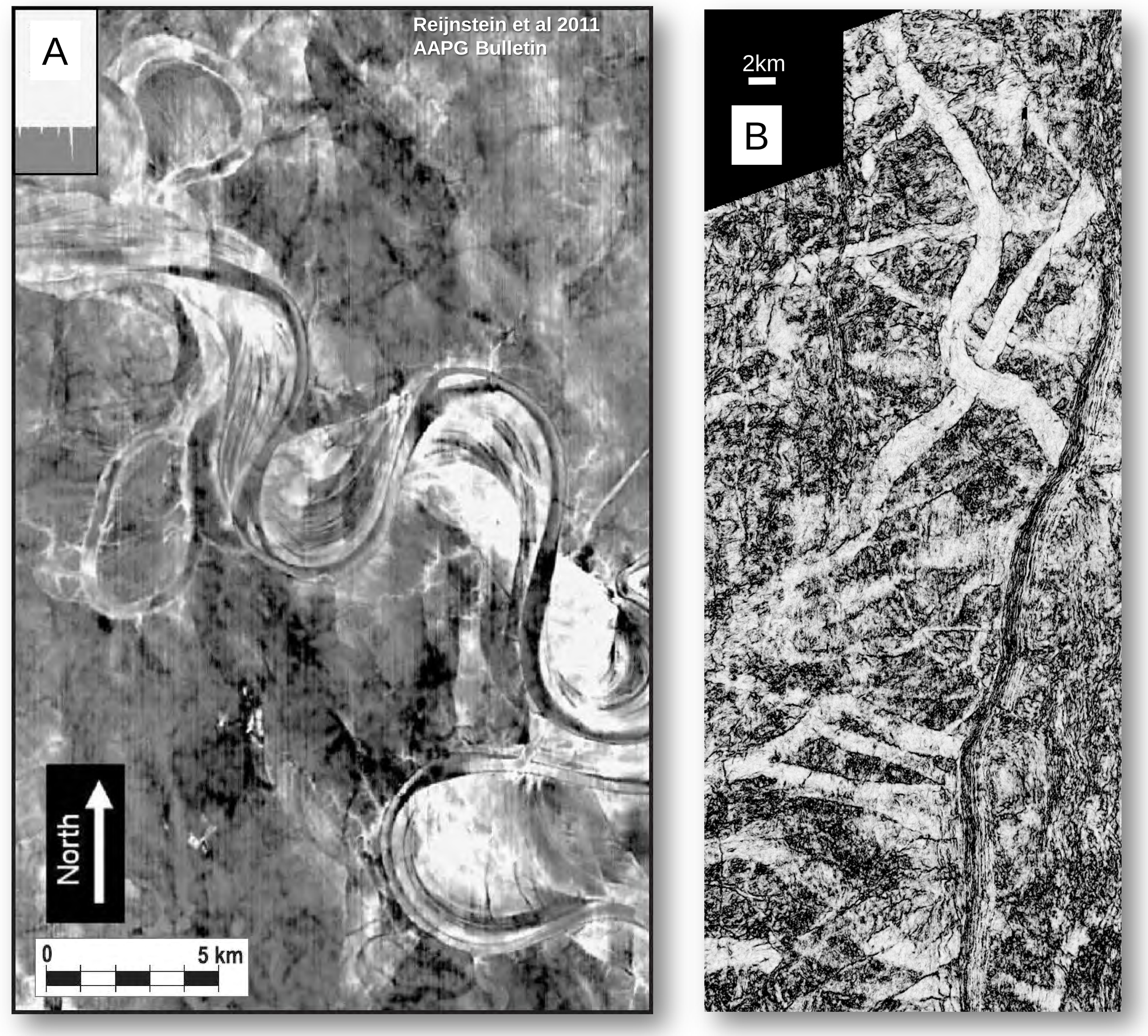
Braided River: Multi-thread channel

Rationale:

Heterogeneity inside fluvial channel belts is typically controlled by the amount of downstream vs. lateral accretion, and the amount of channel migration and abandonment.



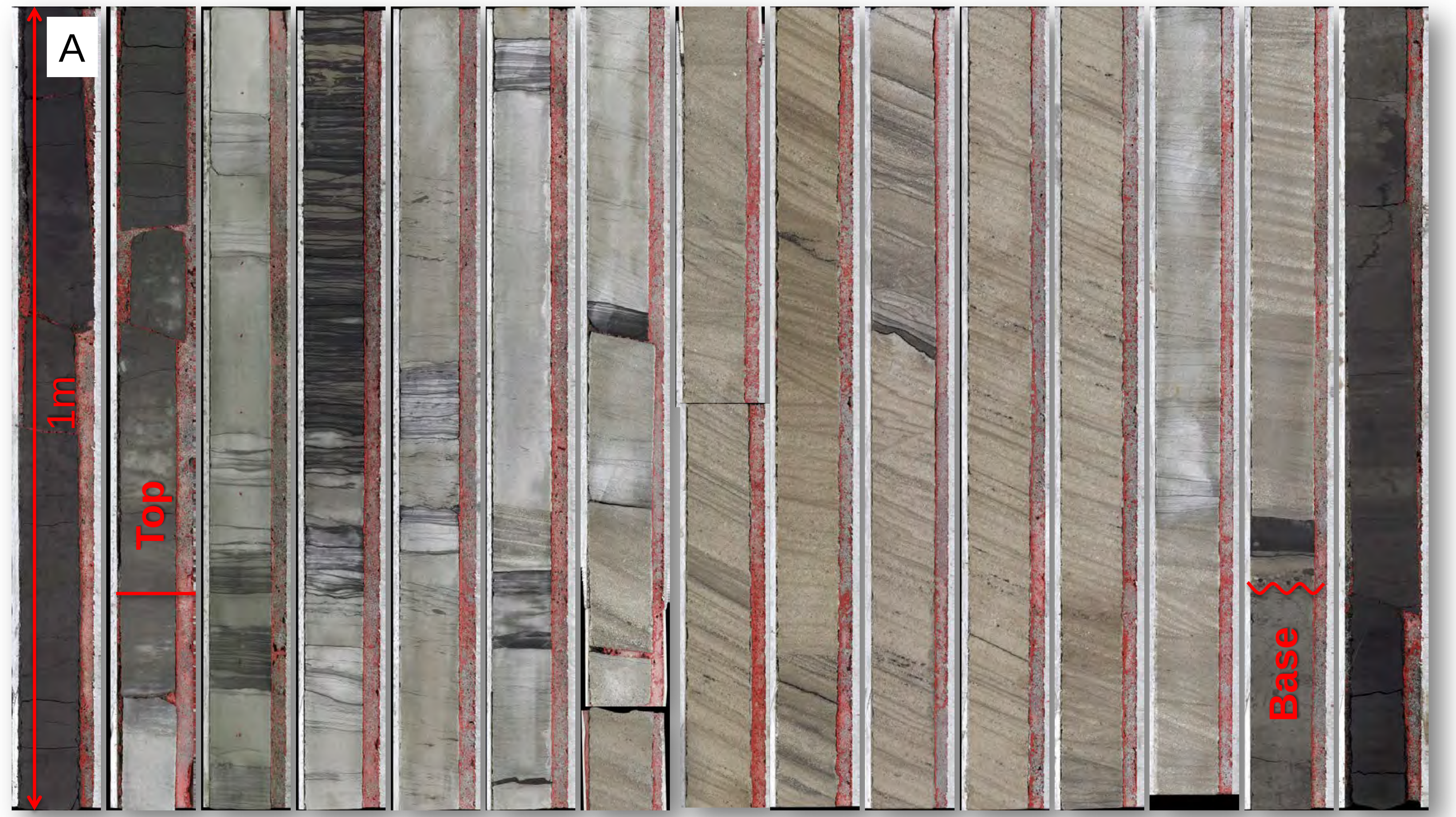
Diagrams illustrating the internal heterogeneity of fluvial channel belts dominated by downstream accretion (left) and lateral accretion (right). Note the bulging of the channel belt margin with an increase in lateral accretion.

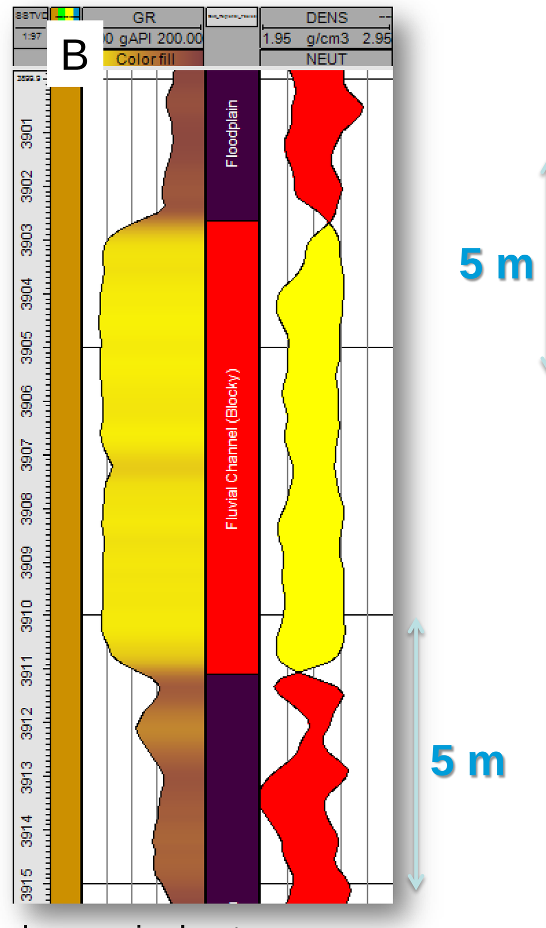


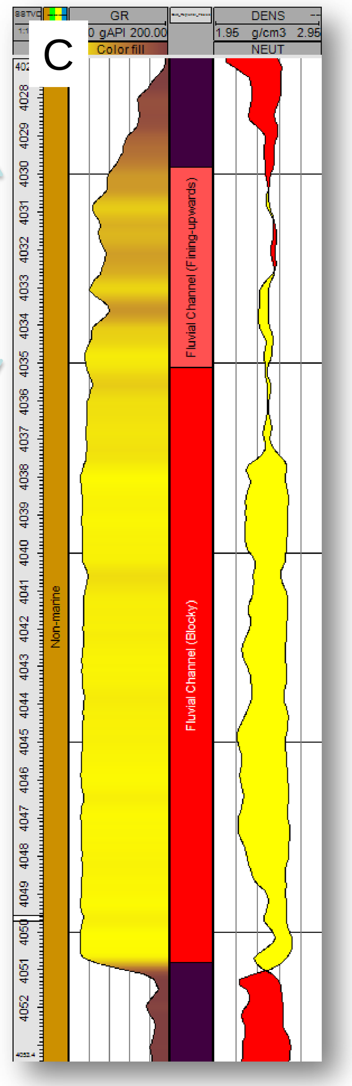
On seismic data it is rare to see detailed channel and bar morphologies inside channel belts (example A, near-seafloor data). More typically, only the entire channel belt is imaged on deep, reservoir-depth seismic data (example B).

Challenge:

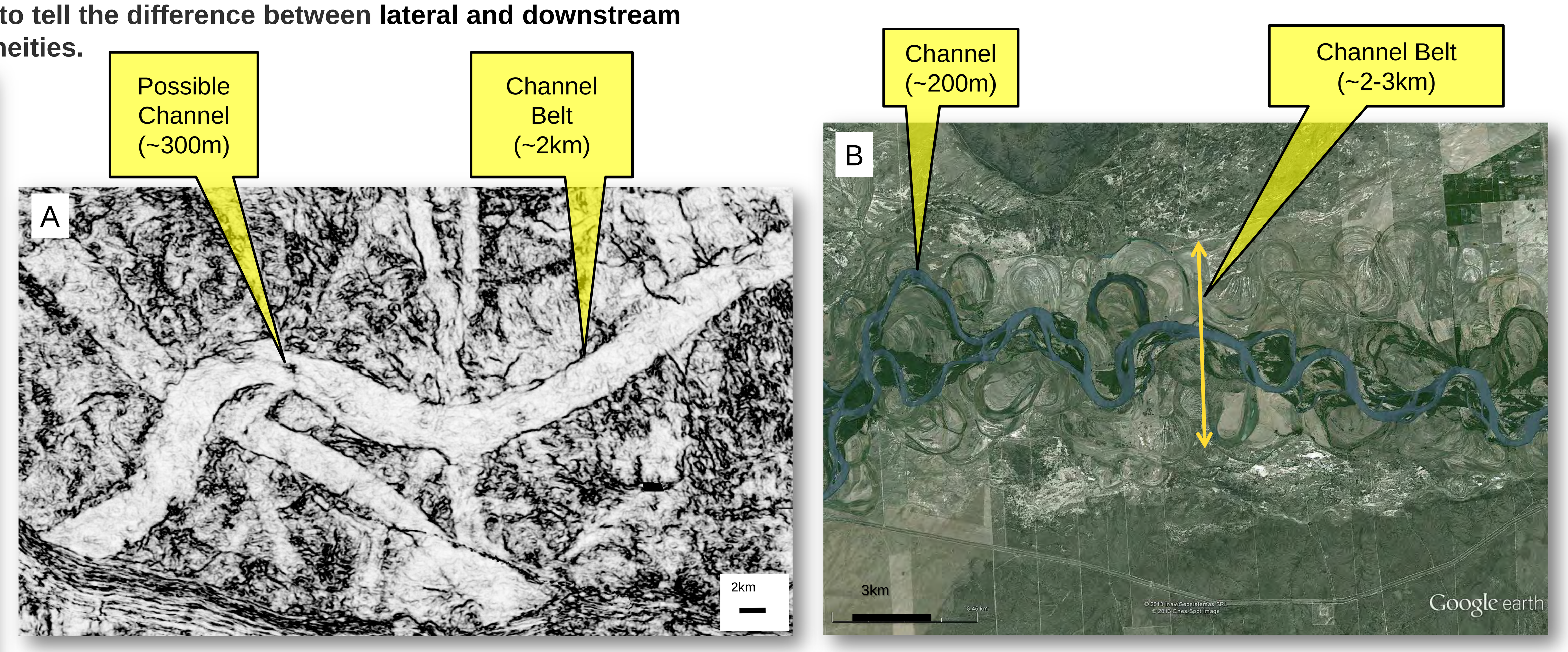
How can one predict channel belt internal heterogeneity? Wireline log and core data make it often difficult to tell the difference between lateral and downstream accretion. Seismic data at reservoir depth typically only images the channel belt, and no internal heterogeneities.







Borehole subsurface data of fluvial deposits showing A) 12m of blocky to fining-upwards sandstone interpreted as a single-storey channel belt deposit. B) Wireline log expression of a 10m thick, blocky channel belt deposit . C) Wireline log expression of a 20m thick, blocky to fining-upwards channel belt deposit. In all cases it is challenging to ascribe a dominant bar migration type.

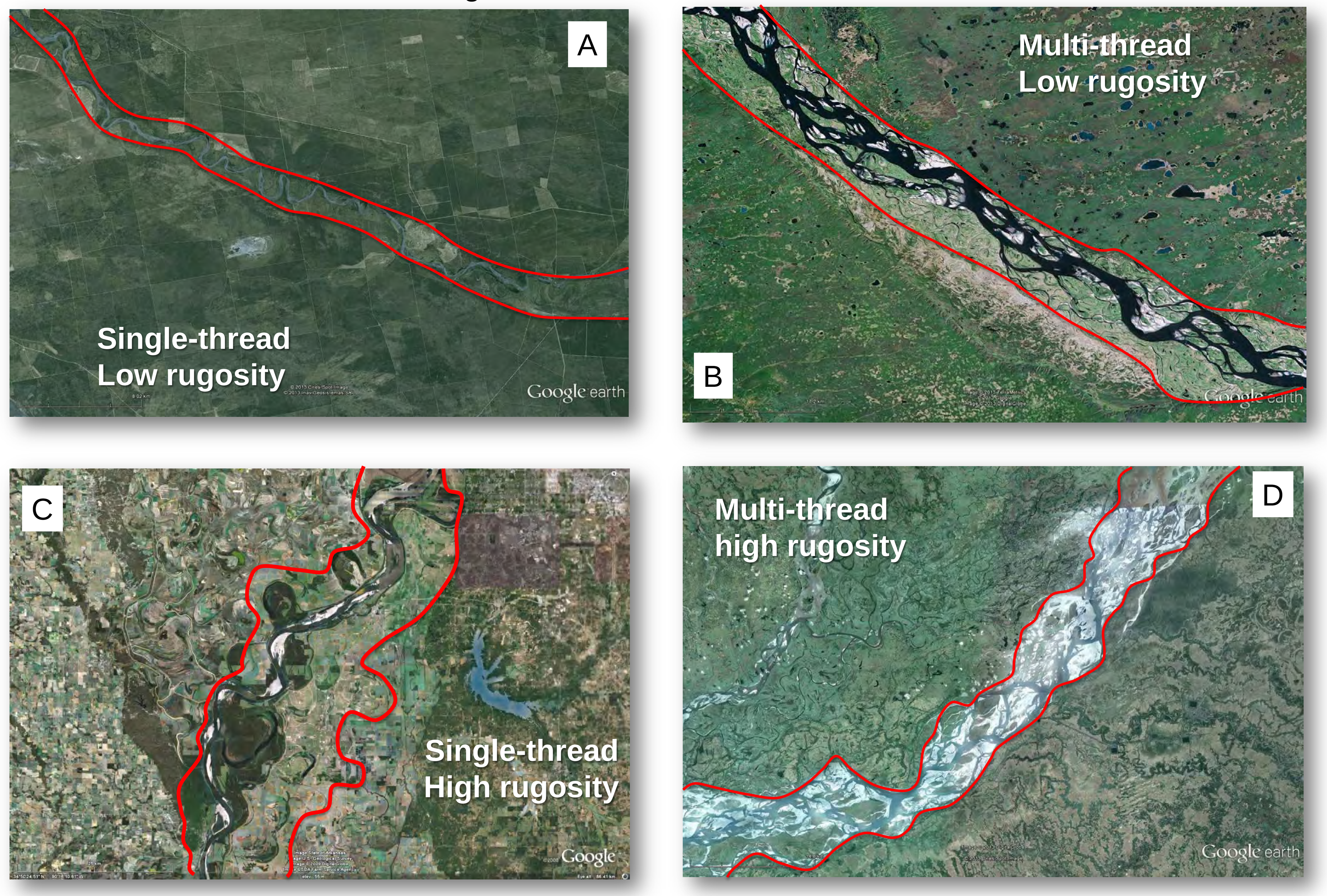


Examples of fluvial channel-belt variations: A) Very good quality optical stack seismic image of a channel belt with parallel walls that locally show a hint of a channel inside it. Typically seismic data can only image the channel belt, and not the internal complexities, as often seen on satellite images. (B)

Channel Belt Rugosity in Reservoir Characterization

Opportunity:

An opportunity exists to predict reservoir heterogeneity using standard petroleum industry subsurface data; more specifically, using 3D seismic data.



Individual river channel(s) within channel belts can be defined in modern satellite images. The margins of different channel belts vary in smoothness depending on the dominant barform migration pattern: lateral vs. downstream. We define a measure of channel belt edge smoothness "*Rugosity*". Rugosity calculations are commonly used in marine science to characterize sea floor habitats. In that application, Rugosity (f_r) is a measure of small-scale variations (amplitude) in the height of a surface, $f_r = A_r/A_g$ where A_r is the actual surface area and A_g is the area of the vertical projection of the surface to the water surface.

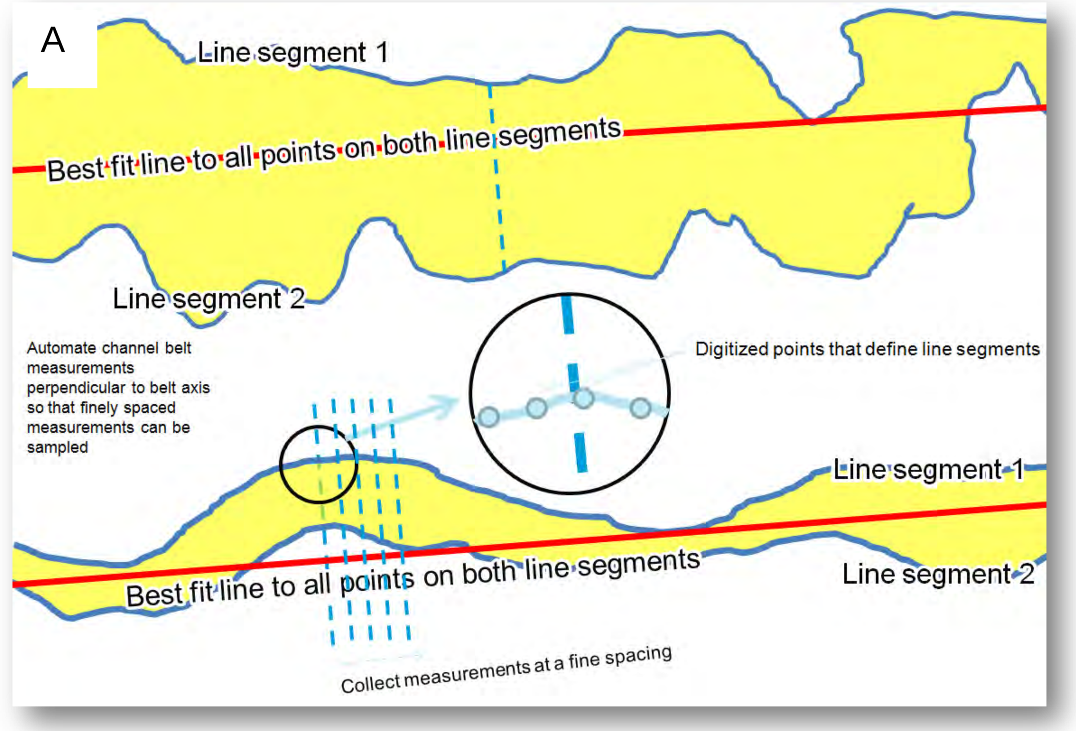
Rugosity here is used to describe the un-parallel nature of the opposing channel belt margins. High river channel sinuosity is associated with more barform lateral accretion and increased rugosity. Therefore the rugosity of a channel belt could be used as a proxy for interpreting the degree of lateral vs. downstream accretion within channel belts in the subsurface using seismic data. This is a potentially powerful tool for resource estimation and extraction, as it may better predict internal heterogeneity.

Rugosity is different from river sinuosity, in that rugosity is applied to the entire channel belt (the deposit) while river sinuosity applies to a modern river channel (which is sometimes preserved as a distinct abandonment fill deposit). Because river channel abandonment fills typically cannot be imaged on seismic, using channel sinuosity classify river deposit types directly in the subsurface is impractical. To the extent that channel belt rugosity and river channel sinuosity are related, comparisons between ancient and modern deposits may be better supported. To characterise the curving of the entire channel belt across the floodplain, the term "wandering" is introduced.

Regardless of the number of channel threads, rivers tend to produce low to high rugosity channel belts depending on the channel sinuosity (amount of lateral accretion). A) Rio Colorado, B) Lena River, C) Mississippi River, D) Brahmaputra River.

Suggested Quantification Approach:

Rugosity (f_r) is a measure of small-scale variations or amplitude in the height of a surface. In the case of channel belts, this is the difference between the distance along the channel belt margin relative to a smoothed centre line (L3)



Both sides of the channel belt need to be considered in calculation of average rugosity. Where the channel belt as a whole wanders significantly across the floodplain, this will also increase the calculated edge Rugosity when compared with the straight line distance. In such cases it is useful to separate reaches along the edge trace; to distinguish lengthening related gradual channel belt wandering from that due to channel-bend-scale edge rugosity.

Channel Belt Rugosity (*R*) is defined as:

$$R=(L1+L2)/(2*D)$$

where L1 and L2 are the lengths of the channel belt margins and D is the straight line distance between the measured length.

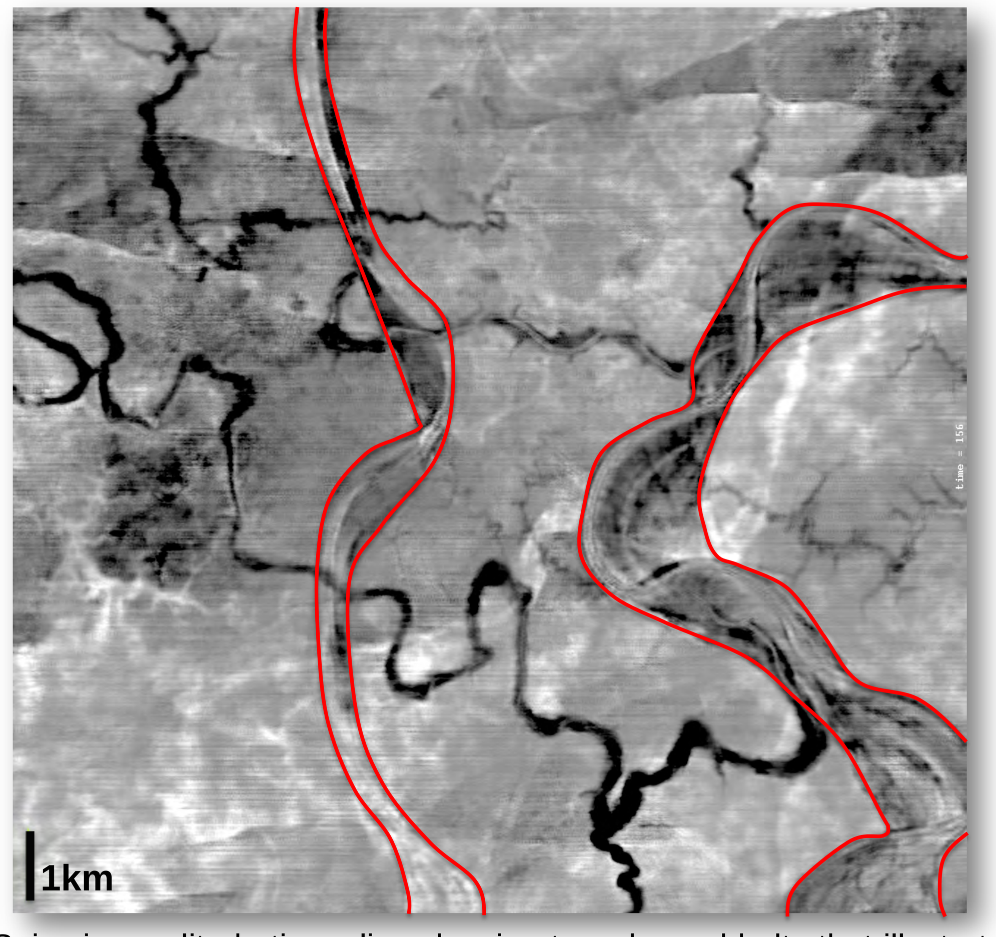
Channel Belt Wandering (W) is defined as:

$$W=L3/D$$

Where L3 is the length of the channel belt center line and D is the distance between the two L3 endpoints.

If channel belt wandering is large, the Rugosity of a channel belt might be better described as the Rugosity and Wandering (R_W):

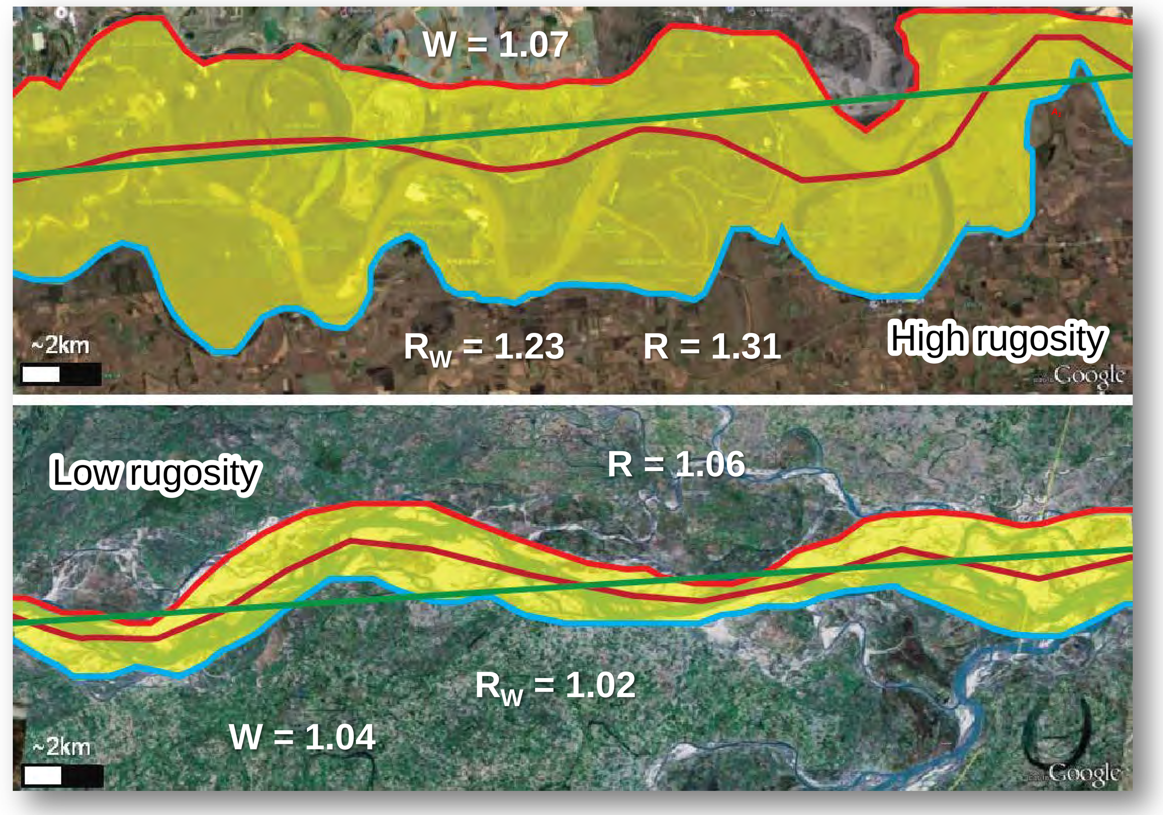
$$R_W = (L1+L2)/(2*L3)$$



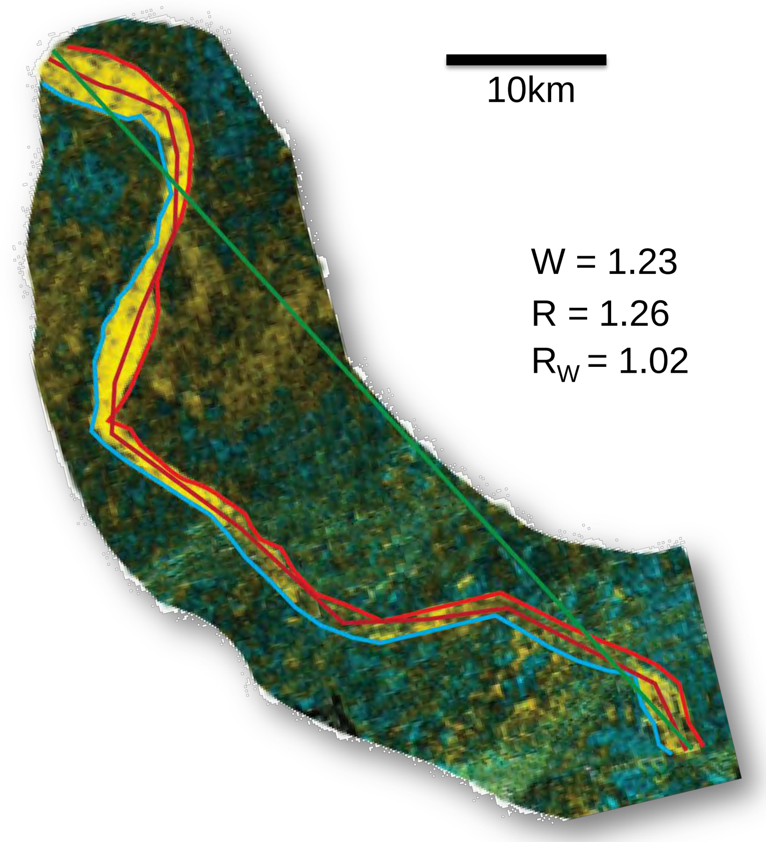
Seismic amplitude time slice showing two channel belts that illustrate the effect of increased lateral migration on channel belt rugosity. The center left channel belt shows little width variations and pinching and swelling, while the right does. Increase in the amount of lateral accretion leads to increase in pinch and swell, widths variations and "bulging" of the channel belt margin.

A proposed workflow is to:

- Create a plan view map of the channel belt (e.g. from seismic).
- Determine area of interest (*Note: smaller sample area can approach R = 0*);
- Define L1, L2, L3 and D consistently. Consider the wavelength of the river and of the channel belt.
- Determine if the channel belt wanders significantly and select R or R_W
- Calculate channel belt rugosity.



Satellite images illustrating differences in Rugosity (R) between meandering (upper) and braided (lower) rivers. Measurements of rugosity can be influenced by the wandering of a channel belt, However, in this example Wandering is low, and hence negligible. *Base images from Google Earth.*



Example of a rugosity measurements along a reach of the seismically-imaged channel belt, Triassic NWS, Australia. Note the difference between R and R_w due to channel belt wandering.

Channel Belt Rugosity in Reservoir Characterization

Alternative Quantification Approaches:

Several alternative quantification approaches have been investigated, each with it's own strengths and weaknesses

What is the best way of quantifying channel belt edge roughness more generally? Rugosity is defined in other sciences in a specific way. For marine biologists, rugosity is basically the same as sinuosity applied to a surface, defined by laying a chain of know length on the sea floor and measuring its horizontal span across the water surface, Like sinuosity, it is a dimensionless number (length/length) greater than 1. In materials science, rugosity is more or less the same, but is measured digitally from surface projections. In this case, rugosity is the area of a segment on the surface divided by the area of the vertical projection of that surface segment. Note that projected areas are always equal to or less than the original surface, and thus, just as for the case of line sinuosity, rugosity of a surface has a dimensionless (area/area) value less than 1.

The problem of defining a measure of channel belt edge rugosity centers on the need to define an orthogonal projection plane (without a horizontal "sea level" reference) and what to do with the two surfaces (each side of the channel belt) rather than having just one. The latter question depends on what you want to measure: 1) a metric of the true size of the irregularities or 2) a shape indicator such that edge irregularities are defined relative to the size of the belt (example, a percent of channel belt width). Possible alternatives include:

1) The easiest and most "true to the definition" measure of Rugosity is just a measure of the external edge sinuosity: Rugosity (Fr) = P/2D, where P is polygon perimeter length and D is the distance between the two points farthest apart on the polygon. The resulting measure appears to scale, in that Rugosity appears to stay the same when the same shape is simply enlarged. There are two potential problems: 1) One needs to define the projection, the straight line distance, which can be impacted when the belt wanders along the floodplain, and 2) A wide channel belt and a narrow one with otherwise the same edge geometry would have almost the same Rugosity even though the wider one would appear relatively smoother. So this provides a measure of true roughness rather than a measure relative to average width.

2) Perimeter Length/Area. This method does not seem to work for very elongate objects like a channel belt. The test was to calculate this ratio on a channel belt trace polygon and then calculate it again for 1) two of the exact same polygons attached end to end, and the same shaped polygon enlarged in size. It is undesirable to have a rugosity measure dependent on measurement length.

3) Channel belt width variation. The upside is that it can be used to define a number of different roughness measures (including rugosity). The downsides are the problem of defining width measures perpendicular to the channel centreline along a wandering channel belt and on developing an automated process. Once width measurements are made, the rest is fairly easy: one can use the resulting data to calculate rugosity, magnitude of edge changes, and wavelength of variations. To measure rugosity from evenly spaced width measures, sum the obsolete value of the difference in successive widths and calculate the length of the hypotenuse of a right triangle with horizontal distance on one side and sum of vertical changes on the other. Divide this hypotenuse length by the horizontal distance.

4) Area difference defines an outer boundary through the edge maximum around the trace of the polygon. The ratio of the areas of the inner and outer boundaries measures the maximum/mean polygon width values, or at least it would except that the outer boundary definition is constantly changing along the channel belt. So one could say it defines the ratio of the average channel belts width relative to a localized estimate of maximum width. This method does provide a scalable measure of surface roughness in that two channel belts with the exact same wall irregularities, but one with the walls farther apart than the other, would produce very different roughness measures. The challenge is that this is a behaviour not found in a measure of rugosity (more of a measure of normalized variance of some kind). Also the method is prone area, both because different operators will define different tie points and because when there is nested scales of edge irregularities the larger scales with hold the max width value out even when there are variable amounts of smaller-scale interstices between the tie points which will be poorly sampled by this measure.

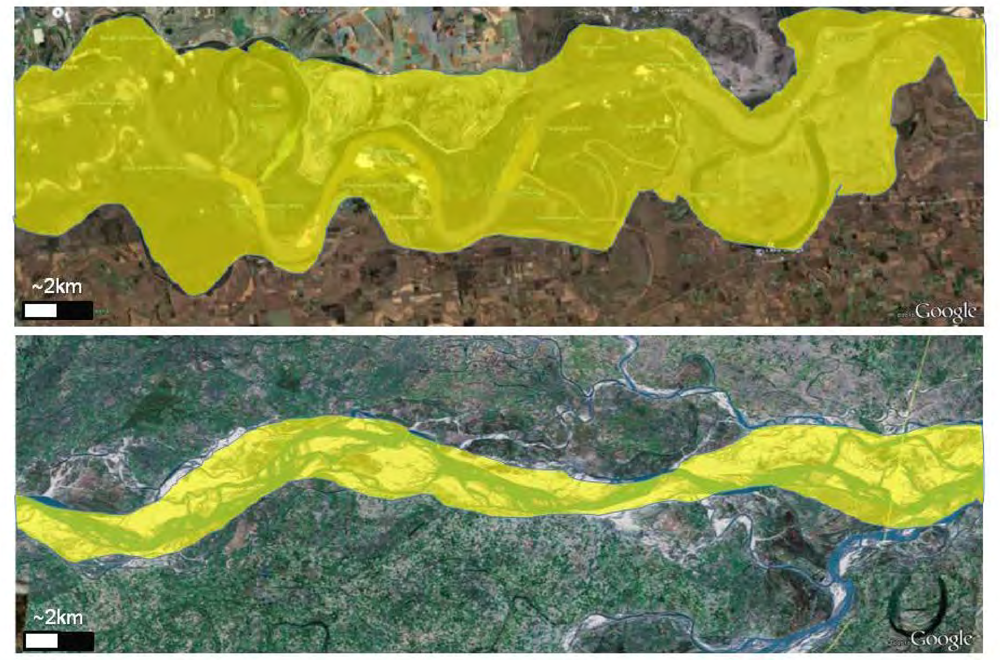
5) A simple Rugosity Index (RI) could be defined based on the maximum channel belt width divided by the minimum channel belt width, similar to a sinuosity index. The challenge with this methodology is that the margin of a channel belt is not a wave form, and the measure could be a local phenomenon not representative of the entire channel belt.

Rugosity Index:

$$RI = CB_{max} / CB_{min}$$

where CB_{max} is the maximum channel belt width and CB_{min} is the minimum channel belt width.

- Low rugosity = 1 to 1.5
- Moderate rugosity = 1.5 to 3
- High rugosity = >3



Perimeter Length/Area:

Initial tests of parameter looked promising

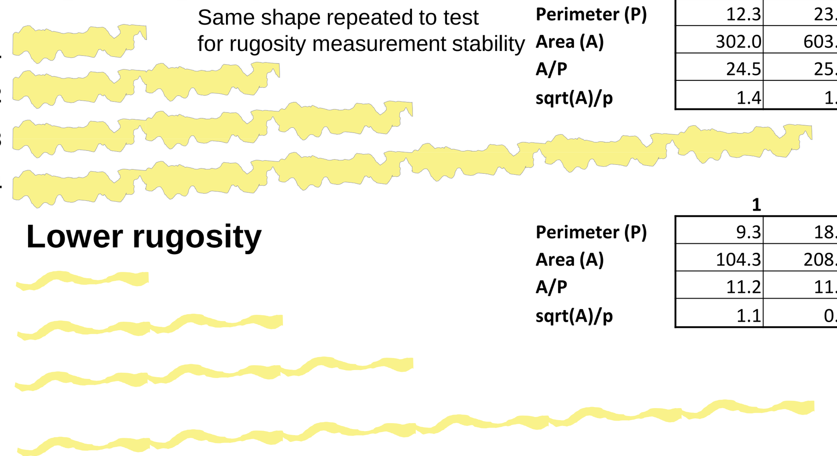
Higher rugosity

Same shape repeated to test for rugosity measurement stability

	1	2	3	6
Perimeter (P)	12.3	23.9	35.2	69.5
Area (A)	302.0	603.6	904.8	1809.5
A/P	24.5	25.3	25.7	26.0
sqrt(A)/p	1.4	1.0	0.9	0.6

Lower rugosity

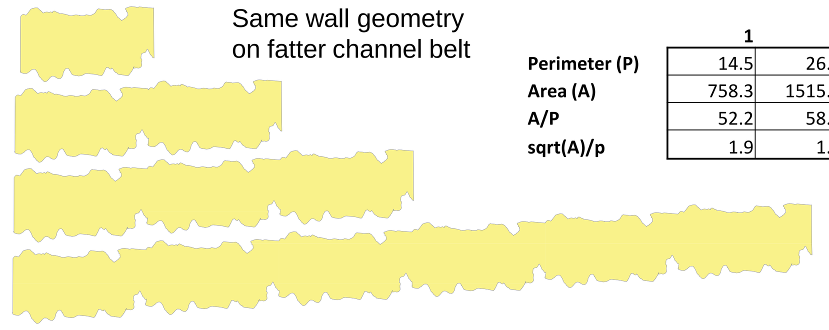
	1	2	3	6
Perimeter (P)	9.3	18.3	27.4	54.5
Area (A)	104.3	208.9	313.4	627.2
A/P	11.2	11.4	11.4	11.5
sqrt(A)/p	1.1	0.8	0.6	0.5

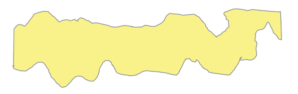


Further tests showed variations in measurement value with scaling unrelated to rugosity

Same wall geometry on fatter channel belt

	1	2	3	6
Perimeter (P)	14.5	26.1	37.4	71.7
Area (A)	758.3	1515.9	2259.9	4544.4
A/P	52.2	58.1	60.4	63.4
sqrt(A)/p	1.9	1.5	1.3	0.9

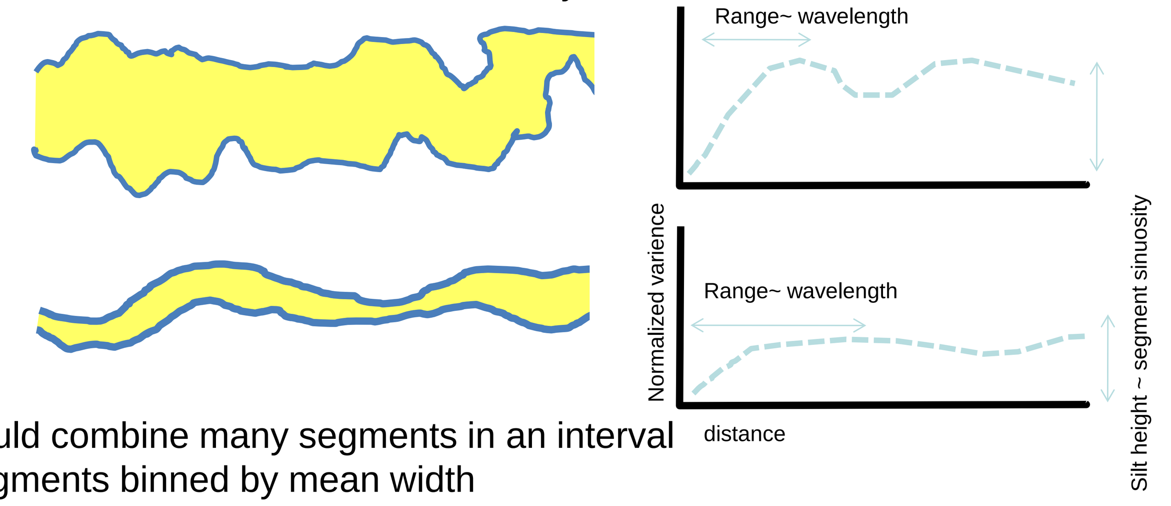




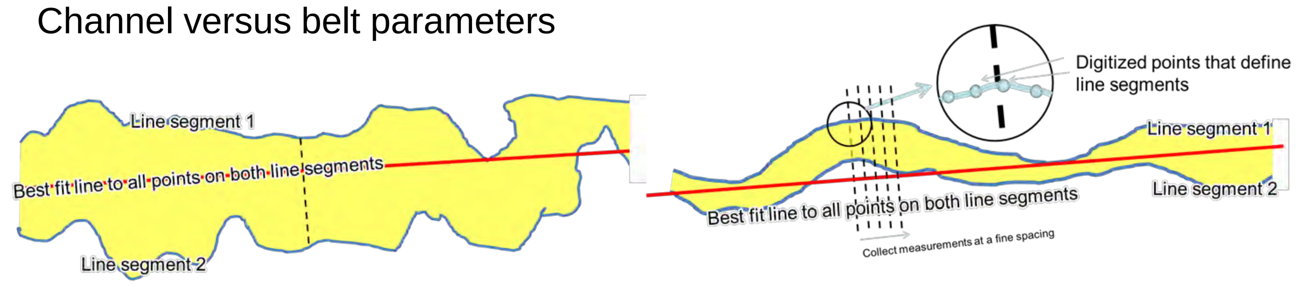
Perimeter (P)	2459.33
Area (A)	120800.7
A/P	49.11937
sqrt(A)/p	0.00285

Same shape as A1, just larger, leads to a much lower value of both A/P and Sqrt(A)/P.

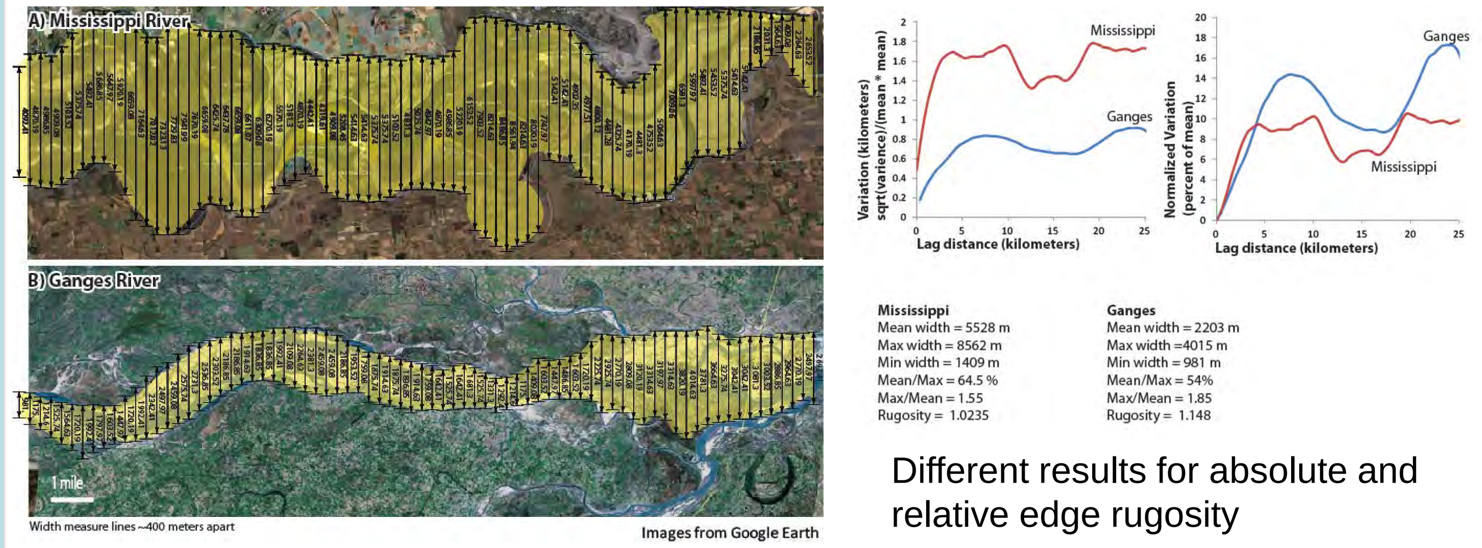
Channel Belt Width (Centreline) Variations:



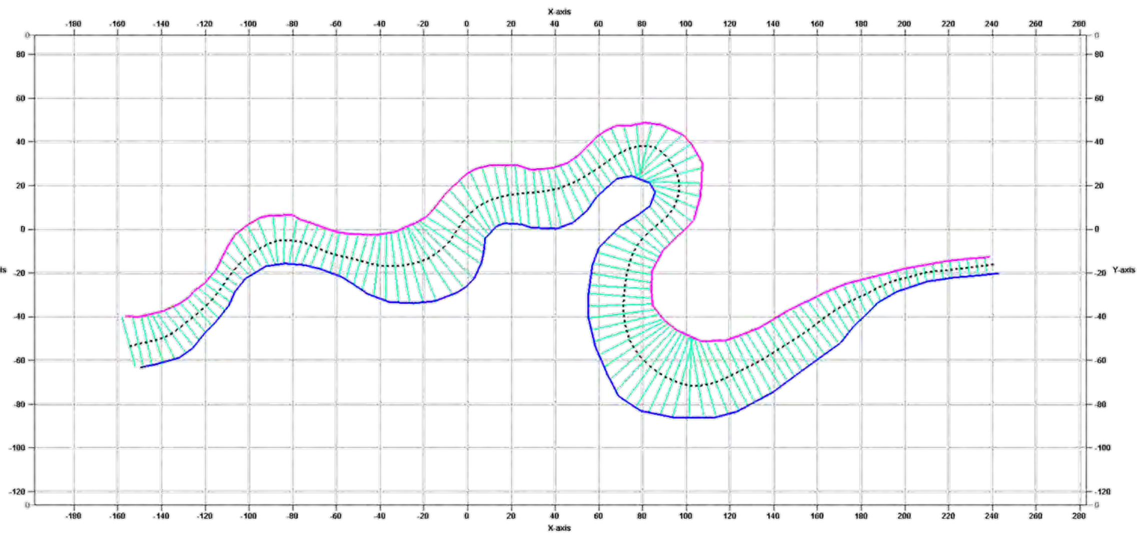
Could combine many segments in an interval
Segments binned by mean width
Channel versus belt parameters



Automate channel belt measurements perpendicular to belt axis so that finely spaced measurements can be sampled.

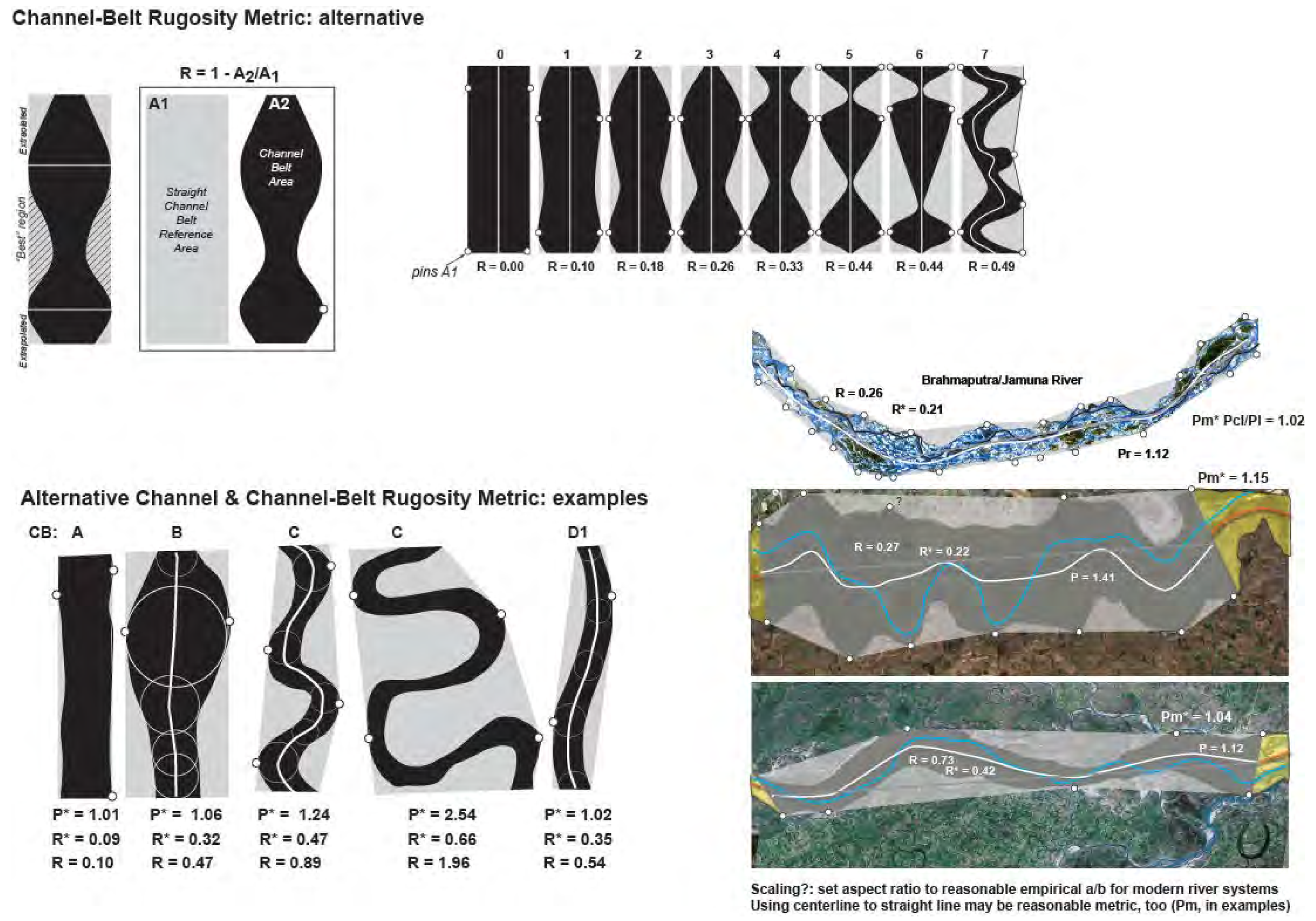


Different results for absolute and relative edge rugosity

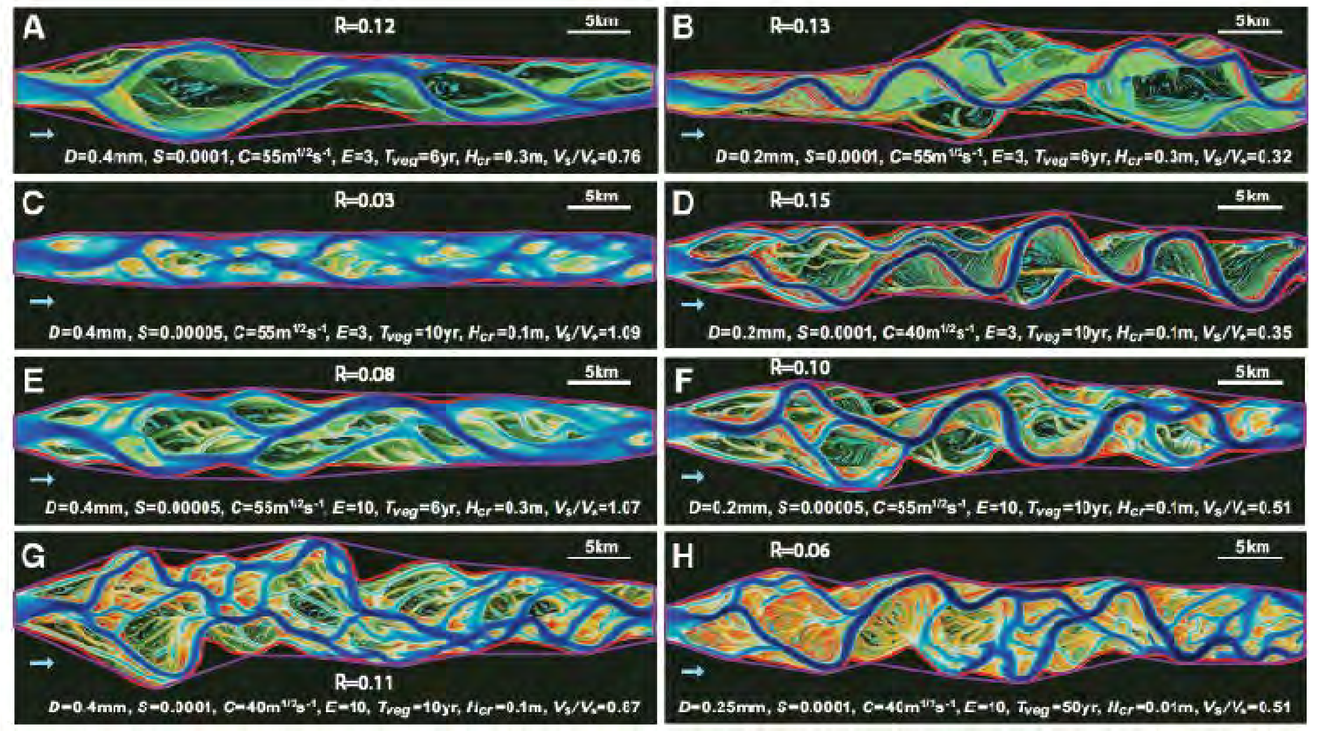


Alternative width measure is to define distance along tangents to the centerline. To define centerline in Petrel™ set the elevation of one channel belt margin line to -1 and the other to 1, fit a surface to the lines, and define the intersection of this surface with zero. Calculate the direction of steepest slope on the surface from for each specified point on the centerline.

Area Difference of Channel Belt vs. a Straightened Belt:



Morphodynamic diversity of the world's largest rivers, Andrew Nicholas, April 2013
Figure 3 rugosity measurements



River name	A2	A1	(A1-A2) Gray	%Gray	R=1-A2/A1
	mm2	mm2			
A	1654.42	1888.02	234	12%	0.12
C	1298.74	1335.49	37	3%	0.03
E	1750.57	1911.74	161	8%	0.08
G	2306.81	2578.73	272	11%	0.11
B	1817.39	2079.68	262	13%	0.13
D	1672.09	1962.62	291	15%	0.15
F	1900.85	2123.14	222	10%	0.10
H	2065.24	2207.93	143	6%	0.06