

Quantitative Seismic Geomorphology of Fluvial Systems of the Pleistocene to Recent in the Malay Basin, Southeast Asia*

Faisal Alqahtani¹, Christopher Jackson¹, Howard Johnson¹, Alex Davis², and Ammar Ahmad¹

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Abstract

Outcrop data and satellite imagery of modern systems typically provide only 2D and quasi-3D data on the geometry, orientation and dimensions of reservoir sand bodies, which are critical elements for the construction of geologically meaningful, 3D, object-based reservoir models. 3D seismic data can also provide important data, although the ability to collate large, statistically valid datasets is limited by the tools that are available in standard seismic interpretation software packages. We present a new methodology for quantifying planform geometries and dimensions of fluvial channel sand bodies that are imaged in shallow, near sea-bed, 3D seismic datasets. Data capture has been semi-automated using ArcGIS, which allows fast and efficient mapping of these morphometric parameters. We have applied this methodology to a Pliocene-Pleistocene fluvial succession that is spectacularly imaged on a high-resolution, regionally extensive, 3D seismic survey from the Malay Basin, Southeast Asia, and we focus on the quantification of key channel parameters, such as meander channel width, meander belt width and meander wavelength. We demonstrate that the lower part of each seismic unit is characterised by wide, deep, low-sinuosity channels, which pass gradually upwards into narrower and thinner, high-sinuosity channels at the top. We speculate that a combination of sea-level changes and fluctuations in discharge and sediment load, both of which may have been linked to climate variations, may have controlled the observed stratigraphic organisation. Empirical equations developed on modern rivers have been tested on the channels identified in this study. The results suggest that existing empirical equations cannot be applied to describe the relationships between geometric parameters that characterise the fluvial channels in this particular geological setting. Hence, several new empirical relationships are proposed; they may be more applicable for predicting fluvial channel dimensions in humid-tropical settings. Our data have been used to constrain reservoir models for the deeper, oil- and gas-producing Miocene succession, which contains a large proportion of fluvial channel reservoirs but which is less clearly imaged on 3D seismic data. The study highlights the value of using high-quality, near sea-bed 3D seismic volumes for extracting analogue data on sand-body dimensions; datasets such as these are increasingly accessible to researchers from many parts of the world.

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AAPG Annual Meeting , Long Beach

Monday 23rd April, 2012

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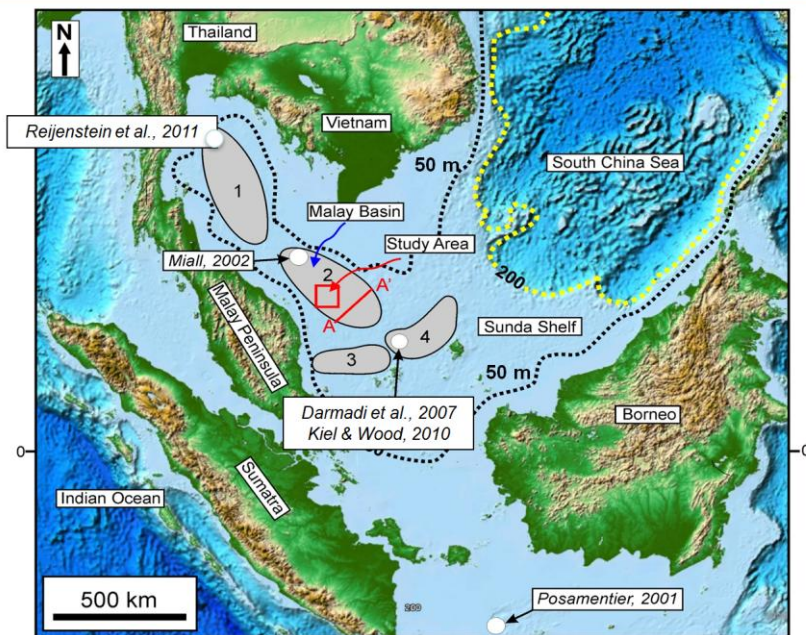


Presentation Outline



- Geological Setting & Project Background
- Pleistocene 3D Seismic Geomorphology
- Morphometric parameters and GIS applications
- Conclusions

Study Area Location & Previous Work



1: Pattani Basin; 2: Malay Basin; 3: Penyu Basin; 4: West Natuna Basin

Presenter's notes: The Sunda Shelf has an area of 125,000 km², making it the largest epicontinental area in the world that is located within a tropical humid climate setting:

The Sunda Shelf was exposed as far as the 200 m bathymetry level during the late Pleistocene lowstand of sea level.

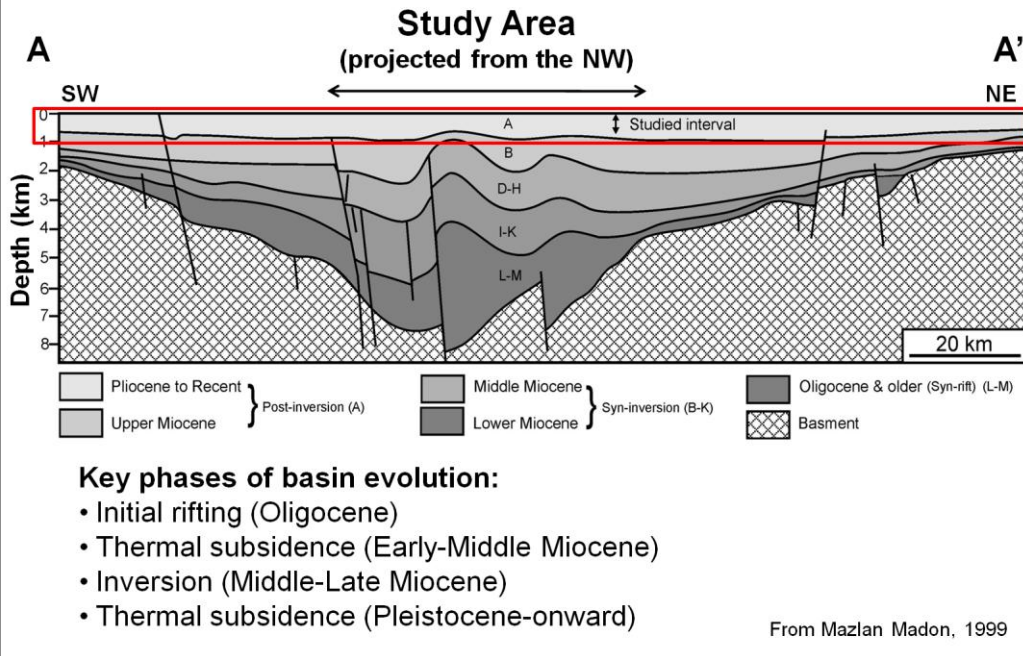
It now has an average water depth of 70 m and is characterised by an extremely low gradient (<0.1 degree).

Study area is in the centre of the Malay Basin, which is one of several deeply buried Tertiary basins on the large Sunda Shelf: 500 km long & 250 km wide.

Sunda Shelf – end member: extremely wide, very high rates of sediment supply and high biodiversity.

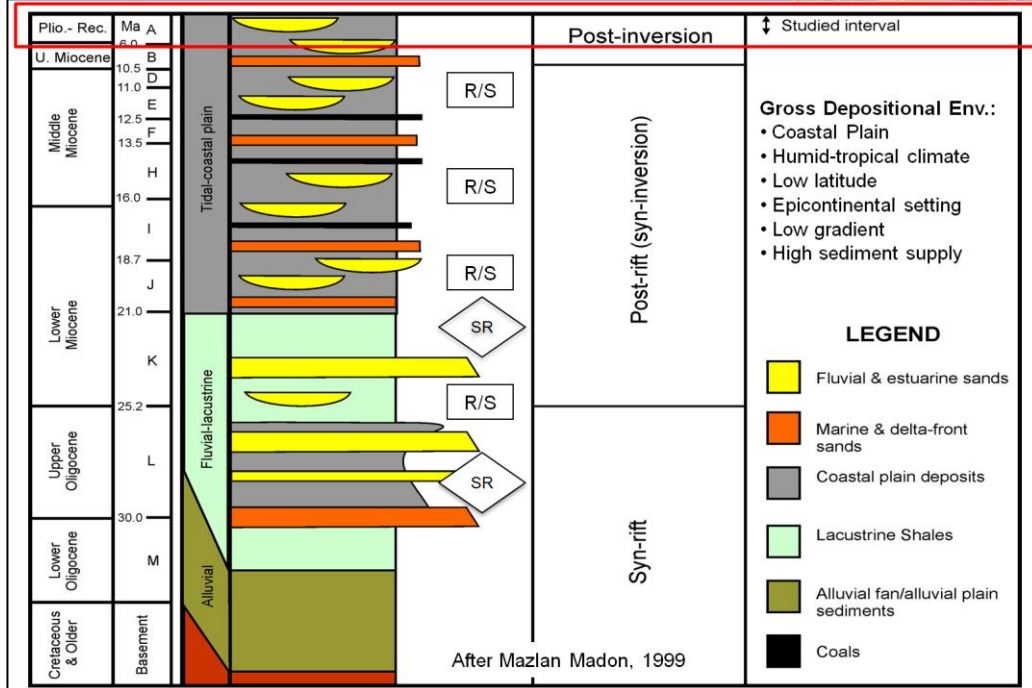
Previous studies highlight the following factors: 1. Non-glaciated, 2. Humid-tropical climate, 3. Large epicontinental area (tectonically-inactive), 4. Hinterland areas (e.g., Himalayas) tectonically active, and 5. Characterised by very high erosion & sedimentation rates.

Tectono-Stratigraphic Setting



Presenter's notes: The Malay Basin is a typical SE Asian basin that was initiated during Early Tertiary rifting, followed by thermal subsidence and inversion. From the late Pliocene/Pleistocene onwards it has been tectonically quiescent.

Stratigraphic Summary



Presenter's notes: Late Cenozoic basin-fill comprises Oligocene fluvial-lacustrine deposits that are overlain by coastal plain and marginal marine sediments. Productive oil and gas reservoirs occur mainly within the Miocene. The gross depositional environment of the Miocene continued into the Pliocene, and throughout this time the area was characterised by a humid tropical climate, without glaciation. Hence, sedimentary environments in the shallow sub-seabed part of the stratigraphy, which is Pliocene-Recent in age, mimics the deeper productive Miocene reservoirs.

Project Rationale and Aims

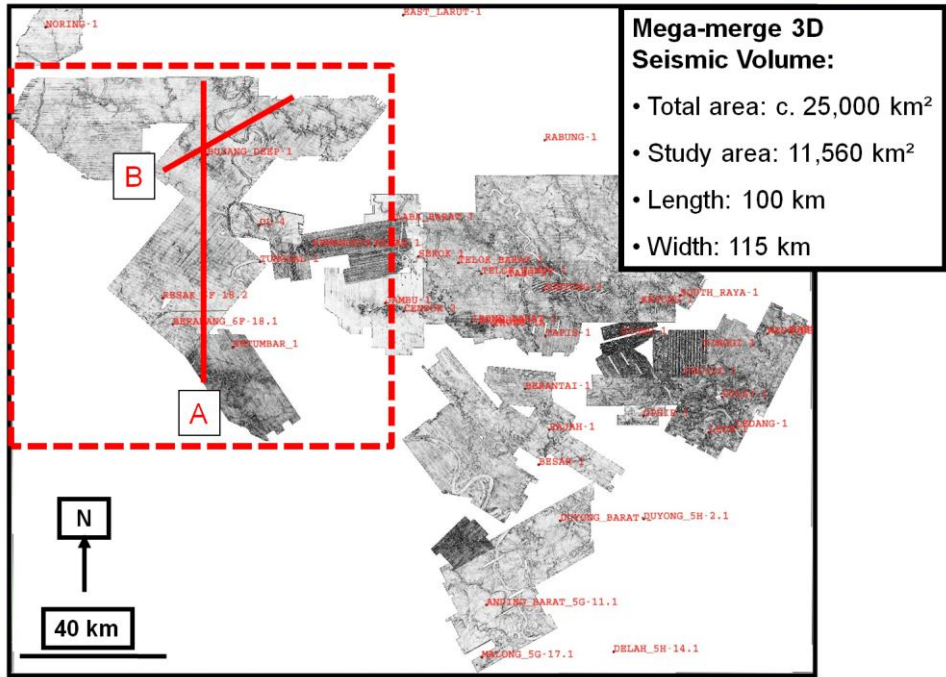
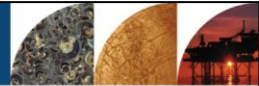


Rationale: The depositional characteristics of the Plio-Pleistocene succession of the Malay Basin mimics that of the deeper, hydrocarbon-bearing Miocene interval and can, therefore, be used for reservoir analogue purposes.

Project aims: To describe and interpret a large, shallow (mega-merge) 3D seismic data volume, especially documentation of the size, geometry and architecture of fluvial channel systems in the Plio-Pleistocene succession, in order to:

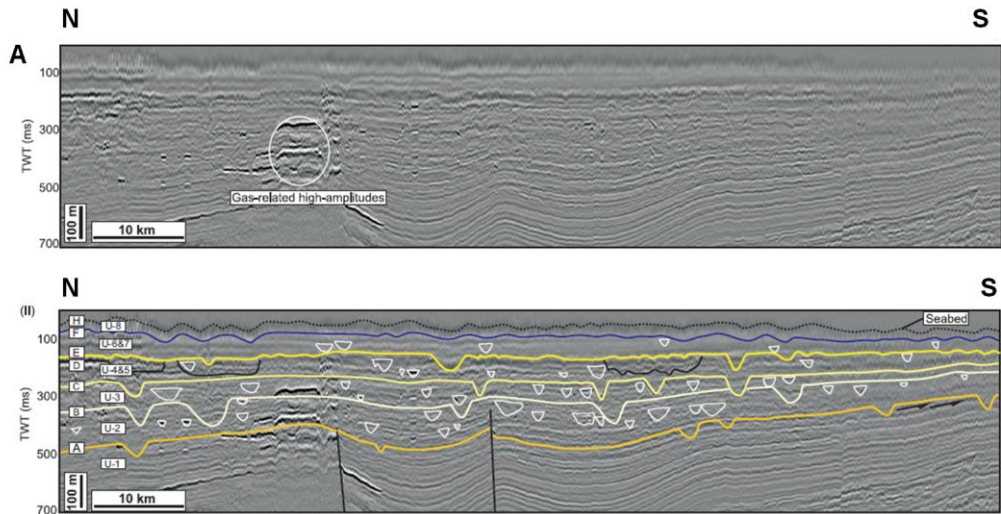
- Improve insight into fluvial channel architecture, stacking patterns and stratigraphic evolution
- Guide sub-regional horizon-slice-amplitude interpretations at deeper, prospective Miocene levels
- Develop a quantitative reservoir analogue database of Pleistocene fluvial channel-body types, dimensions and geometries using GIS
- Establish a quantitative database for humid-tropical fluvial channel reservoirs to constrain input into 3D reservoir models

Mega-Merge 3D Seismic Datasets, Malay Basin



Presenter's notes: Study area based on 10 separate 3D surveys merged into a single interpretable volume. They have different acquisition and processing characteristics.

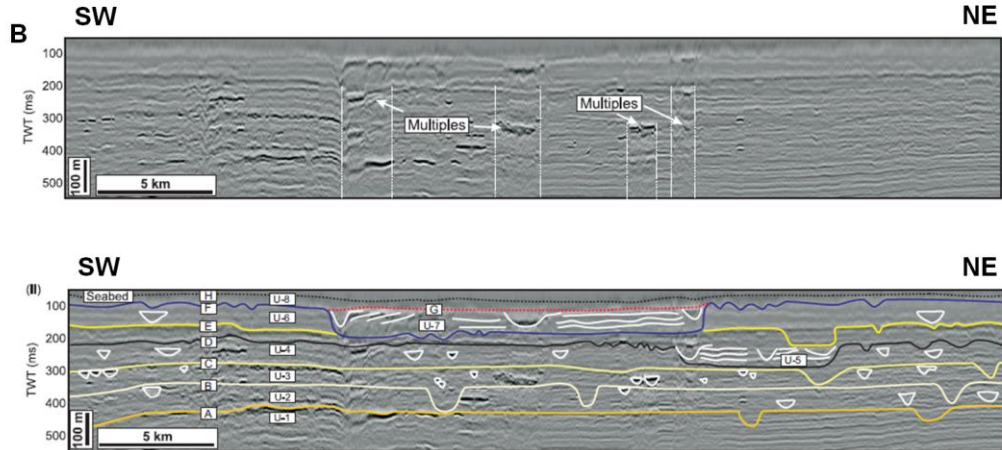
Seismic Stratigraphic Framework



Presenter's notes: (I) Uninterpreted and (II) interpreted regional seismic section through the 3D seismic dataset illustrating the seismic units and the bounding surfaces.

- Cross-sectional profiles of the largest, seismically-detectable, channel systems are shown: white 'u' and 'v' shapes plus two large IVF.
- The main bounding surfaces are characterised by prominent incisions.
- Truncation at base of Unit A.

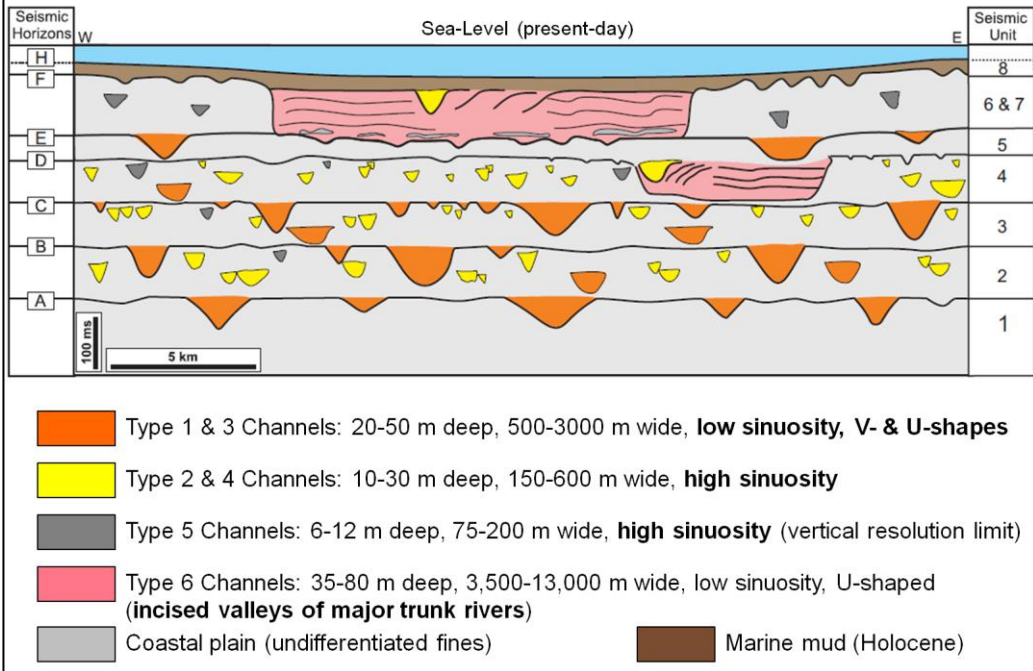
Seismic Stratigraphic Framework



Presenter's notes: (I) Uninterpreted and (II) interpreted seismic section through the 3D seismic dataset illustrating the Units and the bounding surfaces.

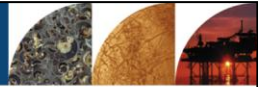
- Note the seismic expression within the deep incision is different from the adjacent strata. 'V'-shaped channel morphology associated with accretion surface is also shown

Fluvial Channel Style: Summary

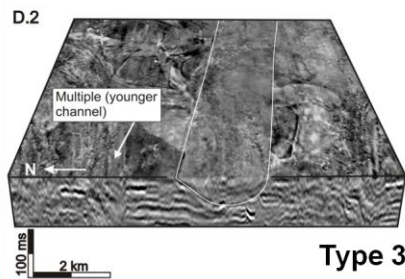
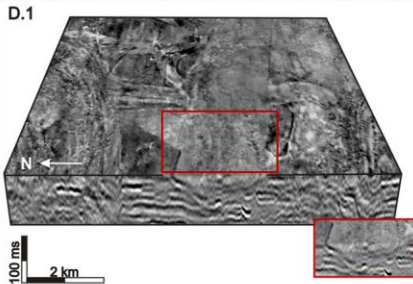


Presenter's notes: 6 different channel types identified from width (W), depth (D), sinuosity (SI) & cross-sectional geometry (U- and V-shapes). Vertical resolution limit at c. 7-8 m.

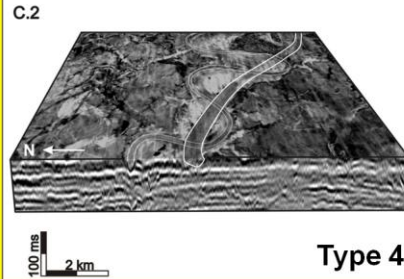
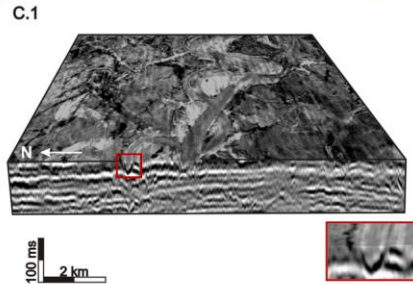
Channel Seismic Expression and Morphology



Type 1 & 3 Channels

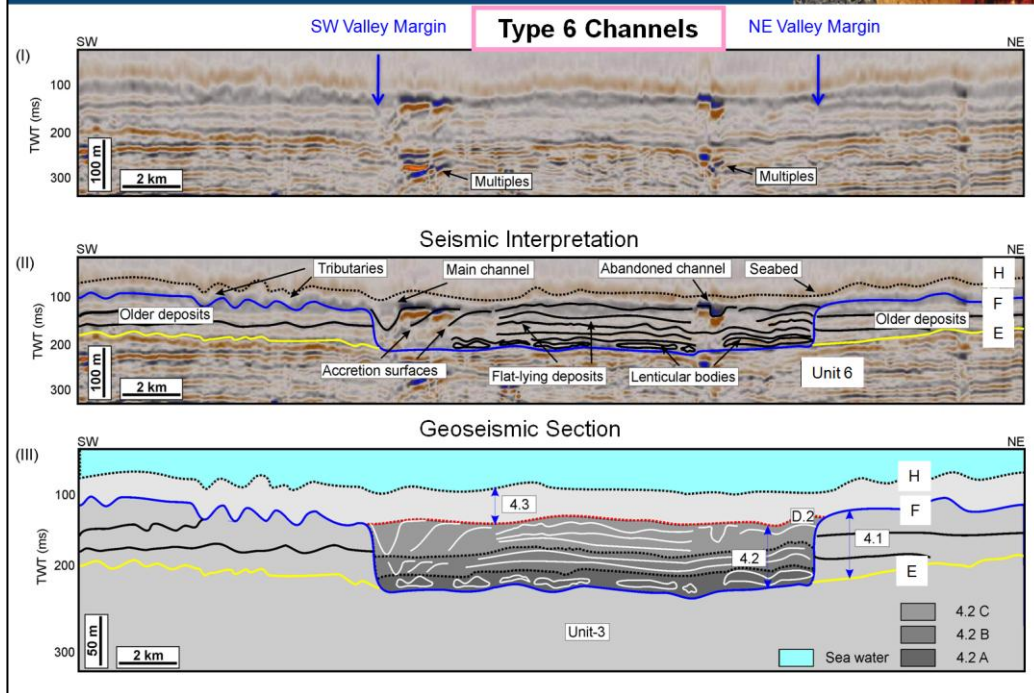


Type 2 & 4 Channels



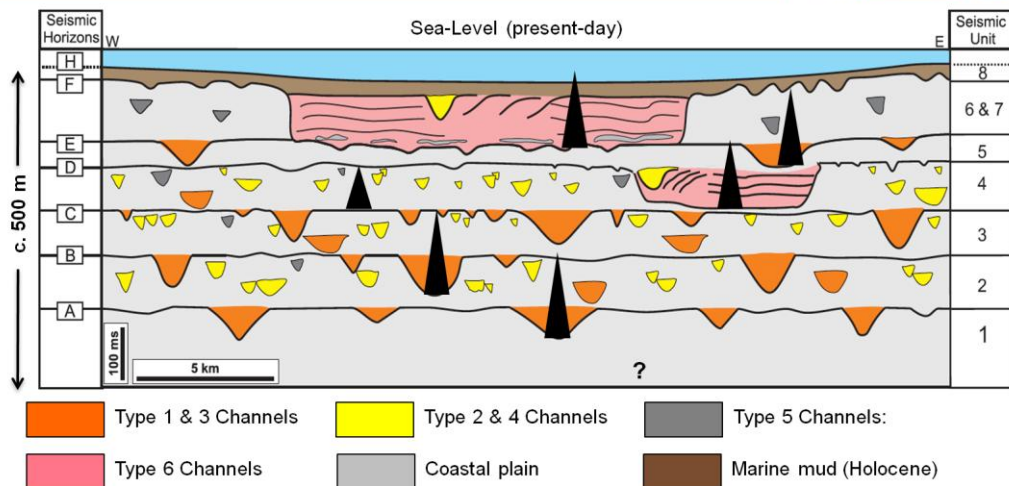
Presenter's notes: Type 3 (Type 1 not shown) is characterised by u-shaped, infilled with variable-amplitude, laterally continuous seismic reflections. These types are common in association with major low-sinuosity channels. Type 4 (Type 2 not shown) is characterised by narrow, shallow, u-shaped, with a clear erosional base and sub-seismic infill. These types are common in association with medium-scale, high-sinuosity channels.

Type 6 Channels Morphology & Dimensions



Presenter's notes: Erosional relief of the F reflector (base sequence 7) = up to 90 m. Width of the valley - up to 18.5 km.

Fluvial Sequence Stratigraphy & Architecture



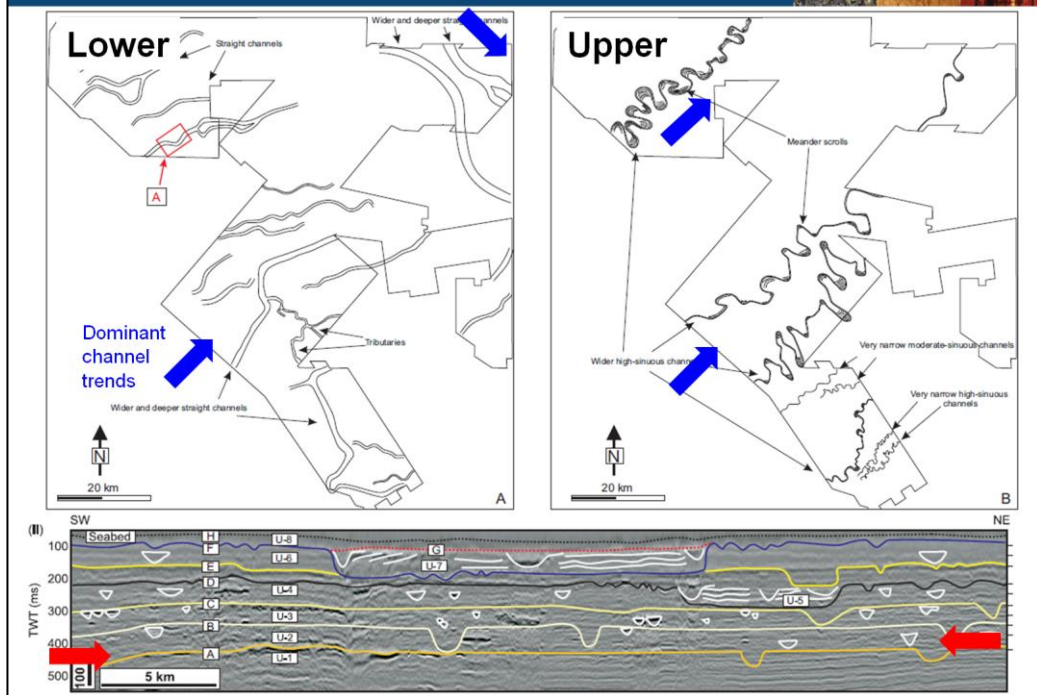
Summary:

- 6 regionally mappable erosion surfaces: A-F (old to young)
- 6 main erosively bounded stratigraphic units: Units 2-7 (c. 50-150 m thick)
- Prominent U- and V-shaped incisions define most major erosion surfaces
- Occasional major, NW-SE oriented trunk rivers are preserved (Type 6)

Erosively based,
fining-upward
successions

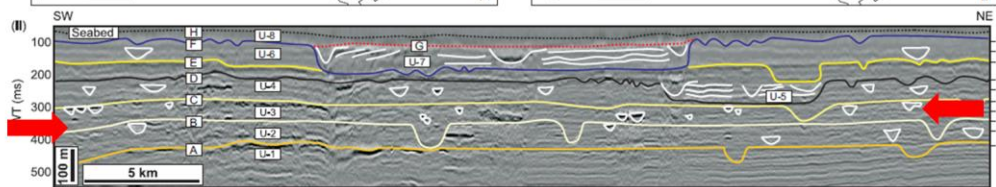
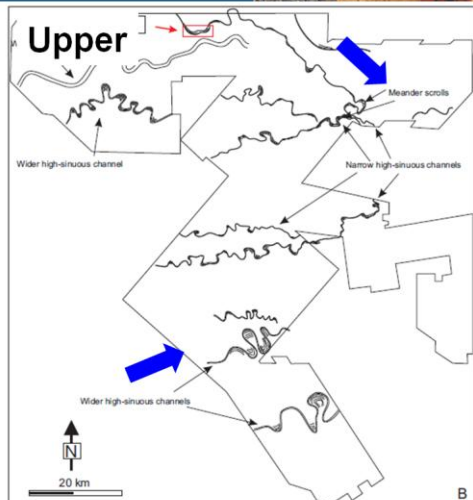
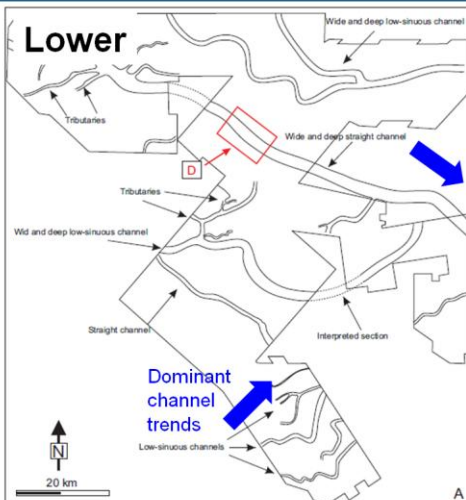


Sequence 2 – Channel trends & geometries

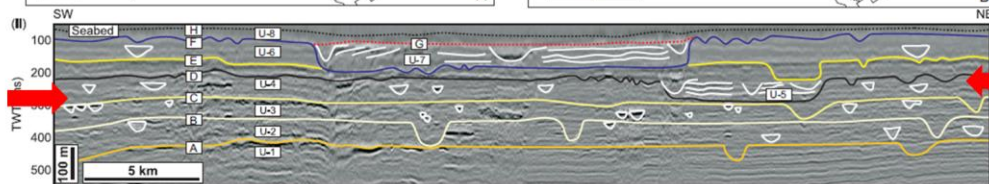
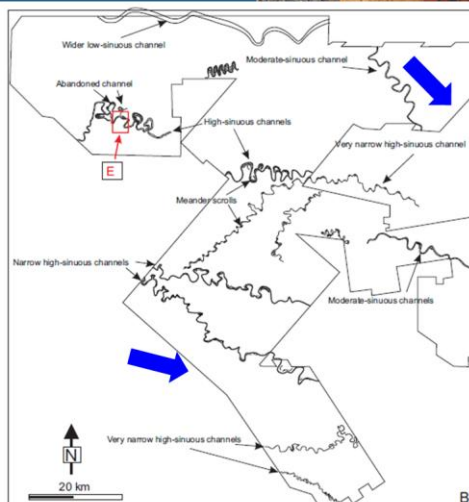
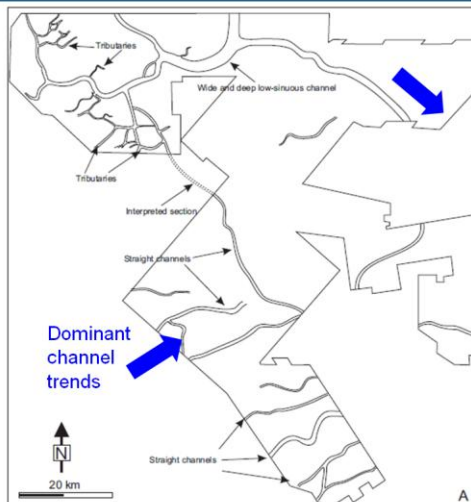


Presenter's notes: This is the first of three summary slides.

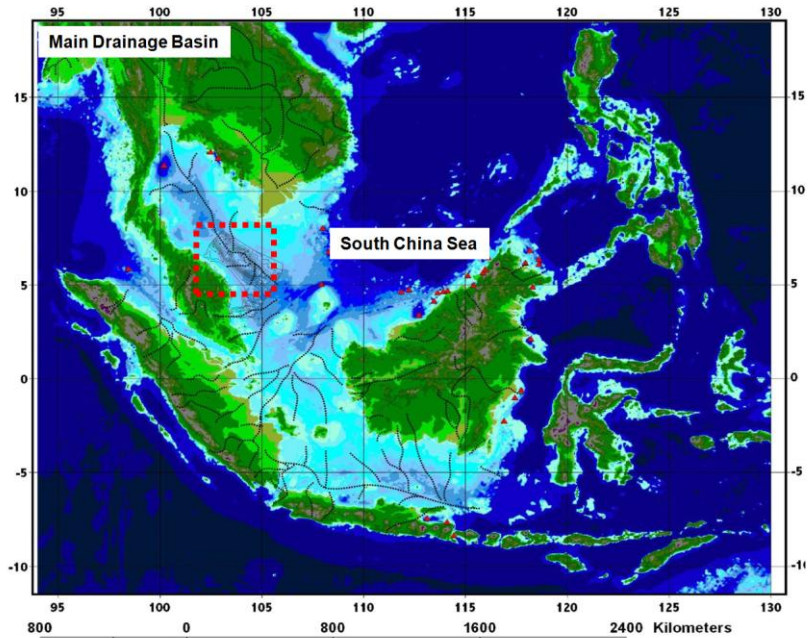
Sequence 3 – Channel trends & geometries



Sequence 4 – Channel trends & geometries



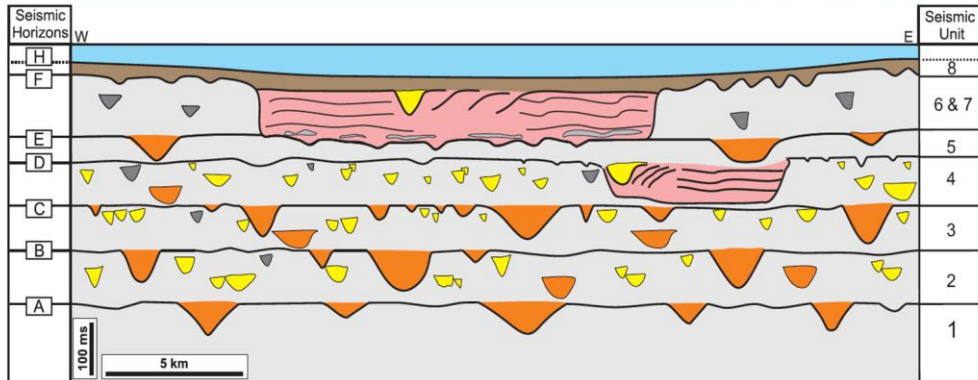
Present-Day Topography & Bathymetry



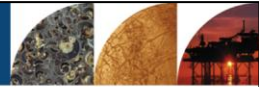
From Voris (2000); Sathiamurthy & Voris (2006)

Presenter's notes: Work by Voris and others have defined a network of fluvial systems based on high-resolution sea-bed bathymetry data; the Chao Praya-Johore drainage system, the largest system, trended along the axis of the earlier rift/sag basins.

Summary

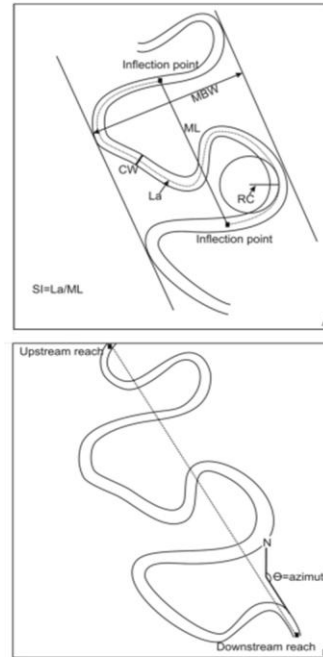
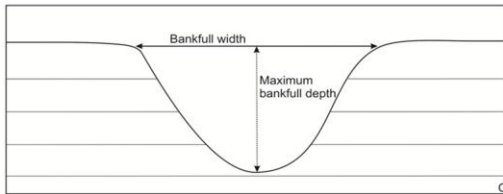


1. Several different channel types have been identified in the Pleistocene succession of the Malay Basin
 2. Marked vertical variability (stacking patterns) in channel types, dimensions and orientations, but with repeated vertical organisation
 3. How do we **permanently capture** and **quantify** this variability?
- = GIS applied to interpreted seismic time-slices and/or horizon-slices:
(1) Easier, (2) More accurate, & (3) Faster



Morphometric Parameters:

- Channel width (CW)
- Meander-belt width (MBW)
- Channel depth (CD)
- Channel length (L)
- Channel meander wavelength (MLW)
- Channel sinuosity (SI)
- Radius of curvature (RC)
- Valley width (VW)
- Valley length (VL)
- Valley depth (VD)



Presenter's notes:

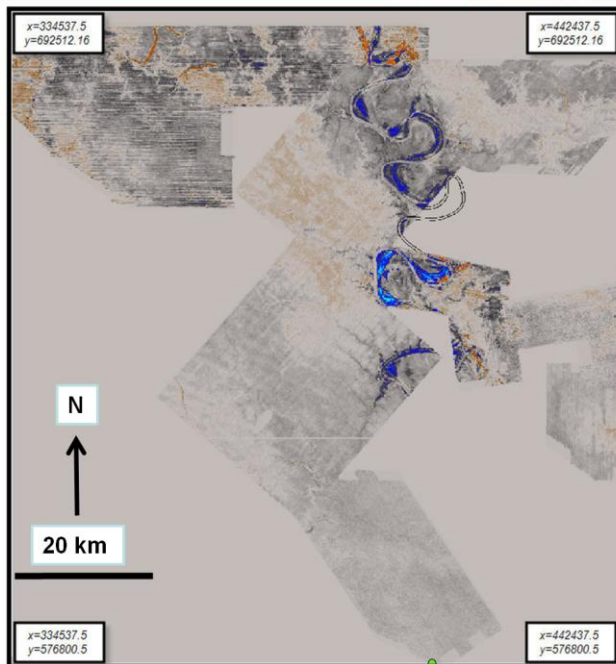
- Seismic interpretation software is not designed to make accurate and spatially-constrained measurements of fluvial channel dimensions.
- Existing methods for measuring fluvial channels dimensions are time-consuming and inaccurate.
- Two new methods presented here utilise seismic time-slices and interpreted seismic horizons: (1) Easier, (2) More accurate, & (3) Faster.

1) Schematic drawing showing the methodology adopted to measure the morphometric parameters of the fluvial systems (A) and the channel orientation (B). The morphometric parameters include channel width (CW), channel depth (CD), meander belt width (MBW), radius of curvature (RC), meander wavelength (ML), and channel length (La). Sinuosity (SI) is calculated as the length along the channel course (La) divided by the meander wavelength (ML). The channel orientation is determined by defining the azimuth of a line that has been drawn between two points of the upstream and downstream reaches.

2) Schematic drawing showing the methodology adopted to measure the channel depth (CD) from the seismic section. In this study, the channel depth is measured as the maximum thickness of channel incisions, which is the vertical distance between the top and base of the incision feature.

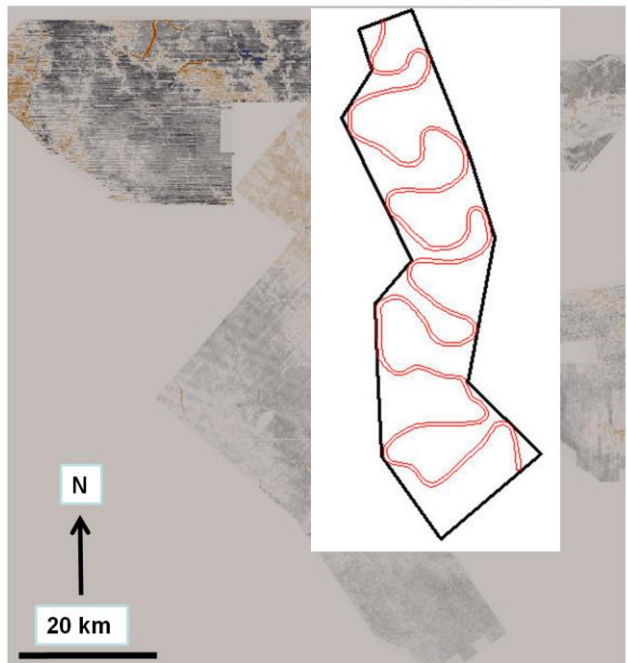
GIS Methodology – brief summary

(1) Import **spatially referenced seismic time-slices** into ArcGIS using the *Georeferencing Tool*



GIS Methodology: e.g. meander belt width

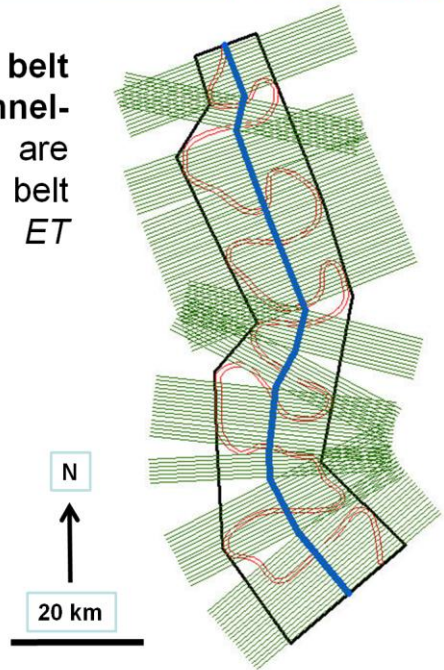
(2) & (3) Digitise **channel edges** (red lines) & the **meander belt** (black polygon) using the *Editor Tool*



GIS Methodology: e.g. meander belt width

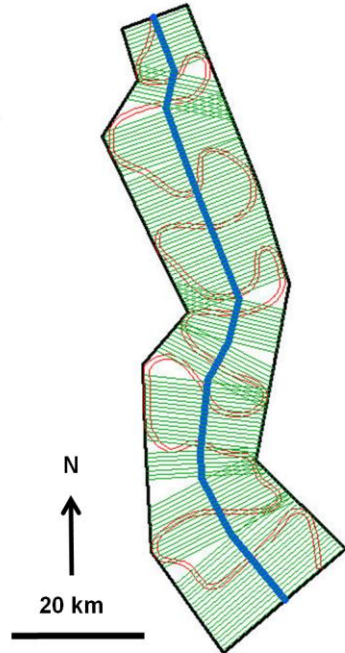
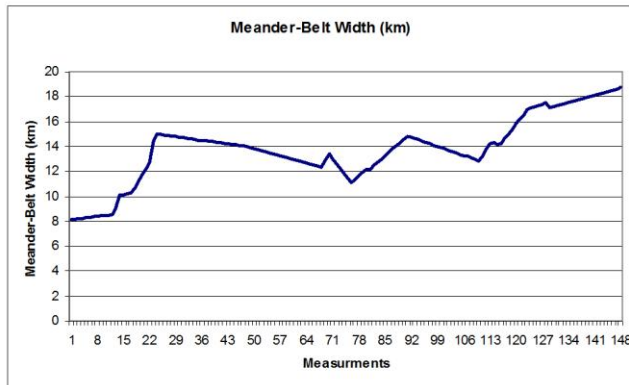


(4) & (5) Create **meander belt centreline** (blue line) **channel-perpendicular lines** which are perpendicular to the meander belt centreline (green lines) using *ET GeoWizard*

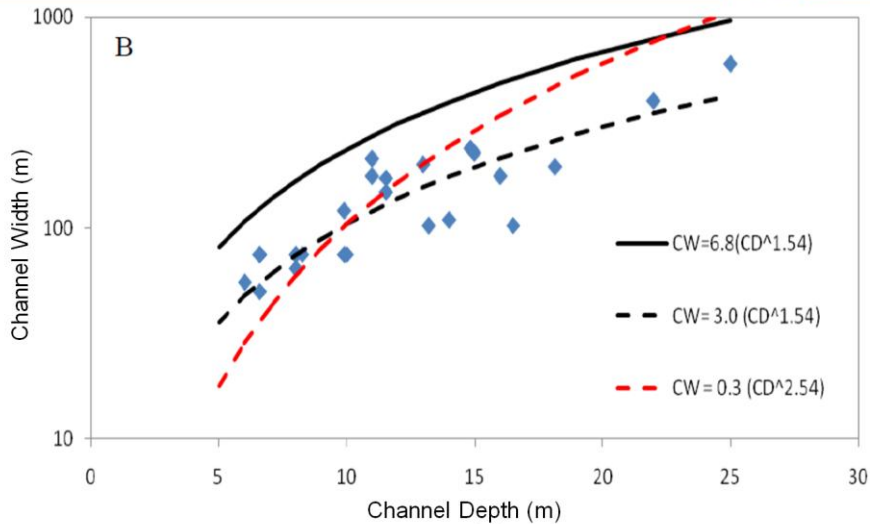




6) – Clip channel-perpendicular lines to meander belt with using *Analysis Tools*: **meander-belt width can now be measured** (148 measurements; MBW = 8-18.5 km)



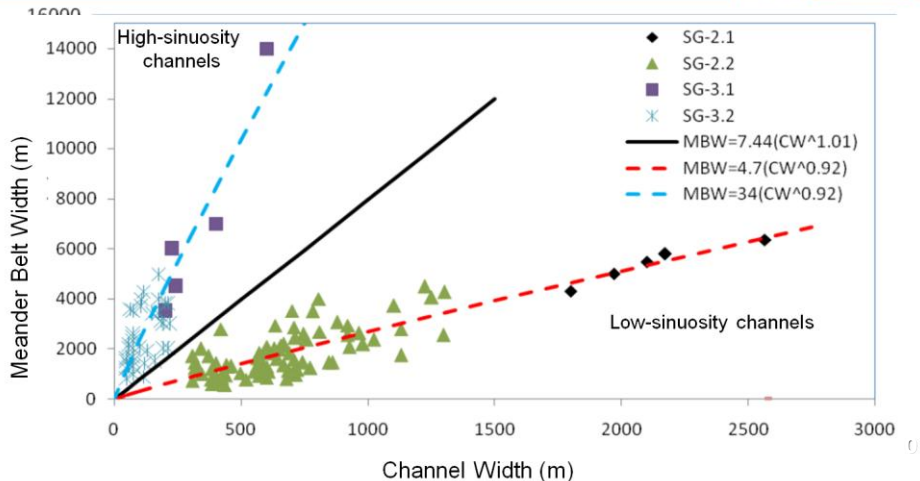
Channel Depth vs. Channel Width



- Existing equation (red dashed line) defines key parameter trend
- Leeder (1973) (solid black line) overestimates CW
- Generation of a 'bespoke' equation (dashed black line) for high SI channels
- CW and CD display a (predictable) positive relationship over several orders of magnitude
- Definition of a new equation to define this relationship

Presenter' notes: (a) Cross-plot of channel depth (CD) versus channel width (CW) shows that as CW increases so does CD. This relationship allows for a new empirical equation to be developed (dashed-line). The developed equation is $CW = 0.3(CD^{2.54})$. (B) Approximately 130 channels were measured in detail.

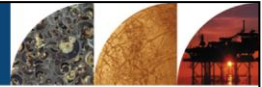
Channel Width vs. Meander Belt Width



- Equation of Lorenz et al. (1985) ($MBW=7.44CW^{1.01}$) under-estimates for high-sinuosity channels and over-estimates for low-sinuosity channels
- Two 'bespoke' equations are developed for the two sub-populations:
 - $MBW=4.7CW^{0.92}$ for the low-sinuosity channels (Gp-2; red dashed-line)
 - $MBW=4.77CW^{0.92}$ for the high-sinuosity channels (Gp-3; blue dashed-line)
- CW and MBW display positive a relationship
- Two 'sub-populations' of this relationship are observed
 - Low SI systems (Gp-2) (low slope=low rate of parameter increase)
 - High SI systems (Gp-3) (high slope=high rate of parameter increase)

Presenter's notes: Cross-plot of channel width (CW) versus meander belt width (MBW). This graph shows a direct relationship whereby MBW increases as CW increases (A). In addition, it shows two main populations: one with small slope (rate of increase) corresponding to the low-sinuosity channels (Group-2), and another with a larger slope representing highly sinuous channels (Group-3).

Summary



- (1) Empirical equations developed from studies of modern rivers have been tested on the humid-tropical coastal plain channels identified in this study and show significant deviations
- (2) Several new empirical relationships have been established based on our dataset, which may be more applicable to humid-tropical humid climate settings, including both the Plio-Pleistocene and Miocene of SE Asia
- (3) The deviations from established trends may reflect:
 - **(i) type of the channels** - sand-bed alluvial rivers in semi-arid and sub-humid (many modern studies) vs. mud-rich coastal plain channels in humid-tropical conditions (this study)
 - **(ii) basin-specific controls** – variations in sea level, tectonics, climate, vegetation and bedrock type all will have contributed. In relation to the study area; climatic fluctuations, affecting the rainfall, discharge, erosion and sediment supply, may have been most significant
 - **(iii) methodology** - errors associated with measurement of values from seismic reflection datasets, vertical and lateral resolution uncertainties and/or differences in measurement techniques

Conclusions



- The mega-merge 3D seismic dataset has enabled reconstruction of late Pleistocene river systems in the Malay Basin
- The c. 500 m-thick Plio-Pleistocene comprises approximately 6 erosion-bounded seismic stratigraphic units, each recording cycles passing from higher energy, low-sinuosity channel systems (including major NW-SW-oriented trunk rivers) into lower energy, probably finer grained, high-sinuosity channel systems
- It has not been possible to uniquely discriminate controls on these fluvial cycles, with both drainage basin conditions (rainfall, discharge, tectonics, etc.) and sea-level fluctuations (in the South China Sea) being influential
- A GIS-based method for quantify fluvial geomorphic features from 3D seismic reflection data has proven to be a more efficient and accurate method when compared to established methods
- Several 'bespoke' empirical relationships have been established for different fluvial parameters; these may aid quantitative predictions of deeper, productive Miocene fluvial channel sand bodies in the Malay Basin and in other humid-tropical fluvial systems elsewhere

Acknowledgments



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2. PETRONAS (Petroleum Management Unit) are thanked for providing the 3D seismic dataset and approving this presentation.
3. PETRONAS Research Snd. Bhd. kindly supported part of this research.
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