PSQuantitative Prediction of Sandbody Connectivity within Distributive Fluvial Systems Using Process-Based Numerical Modeling*

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Abstract

Fluvial deposits constitute a particularly challenging reservoir type due to their complex facies architecture. The primary control of reservoir performance is sandbody connectivity, which is a result of longitudinal, lateral, and temporal channel contacts. Advances in understanding the large-scale spatial distribution of fluvial facies from modern and ancient systems have led to the development of the Distributive Fluvial System (DFS) model. It provides a plan-view framework to predict the distribution of channel stacking patterns depending on location within the DFS (proximal, medial or distal). At present, the model is qualitative and excludes accommodation-driven controls predicted in the Leeder-Allen-Bridge (LAB) model. Quantifying the DFS model through outcrop analogues is difficult due to the limited number of case studies with exposure of the entire system. Flume tank experiments have full exposure and parameter control but introduce significant upscaling uncertainty. Process-based numerical models allow full exposure and parameter control at a range of scales. The Luna DFS out of the Ebro Basin in northwestern Spain was chosen as input for a suite of models. The fluvial parameters were taken from the High Island Creek in Minnesota, USA, a contributary to the Minnesota River. A base model that reproduced the sedimentary architecture of the input system was computed for the Luna DFS. To determine the impact of changing accommodation, sediment supply, and climate on the base cases, a suite of models was created that covers a range of these input parameters. The ranges were derived from literature studies. The process-based numerical software used are deterministic and thus create a single model for each input parameter set. To obtain a statistically sound sensitivity analysis, significant amounts of parameters sets were modelled. Sandbody connectivity analysis was undertaken to quantify the reservoir architecture of the different models. Preliminary results show a reduction in channel width and increase in channel number downstream. Using process-based numerical modelling to analyze the sensitivity of sandbody connectivity to governing parameters will result in a greatly improved understanding and predictability of reservoir connectivity in fluvial systems as a function of environmental and tectonic controls.

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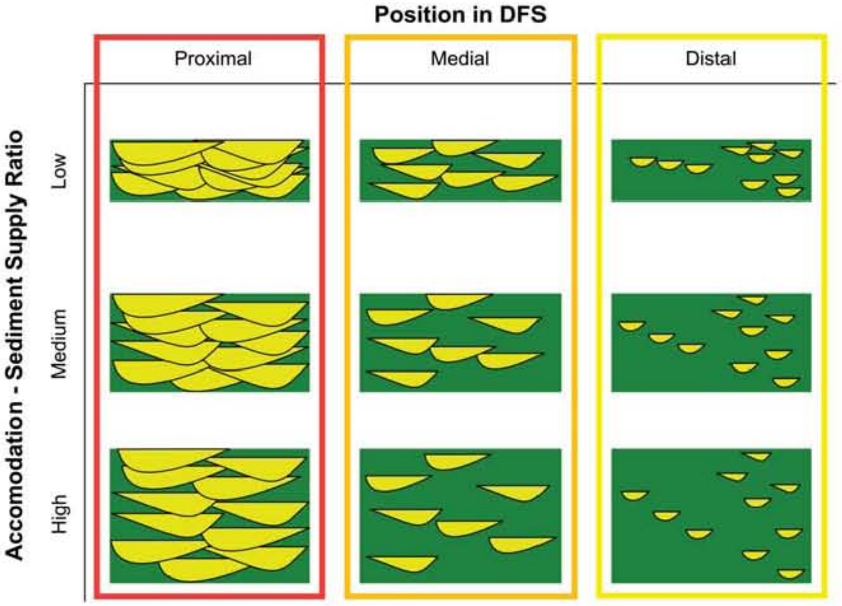
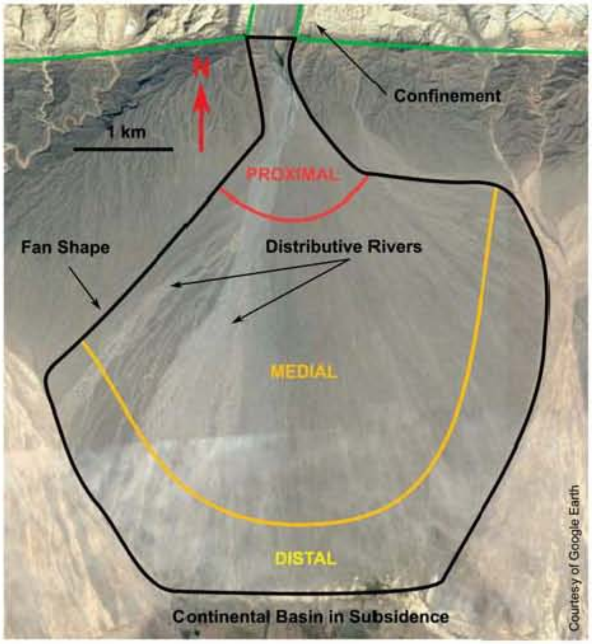
1. INTRODUCTION

- Fluvial reservoirs difficult to characterize due to complex facies architecture
- Sandbody connectivity primary **control of reservoir performance**
  → **Channel stacking pattern**
- Distributive Fluvial System (DFS) model (Hartley et al., 2010; Weissmann et al., 2010) predicts channel stacking patterns depending on location within DFS (proximal, medial or distal)
- **Quantify effect of accommodation – sediment supply ratio** (A/S) **on sandbody connectivity**



2. DISTRIBUTIVE FLUVIAL SYSTEMS

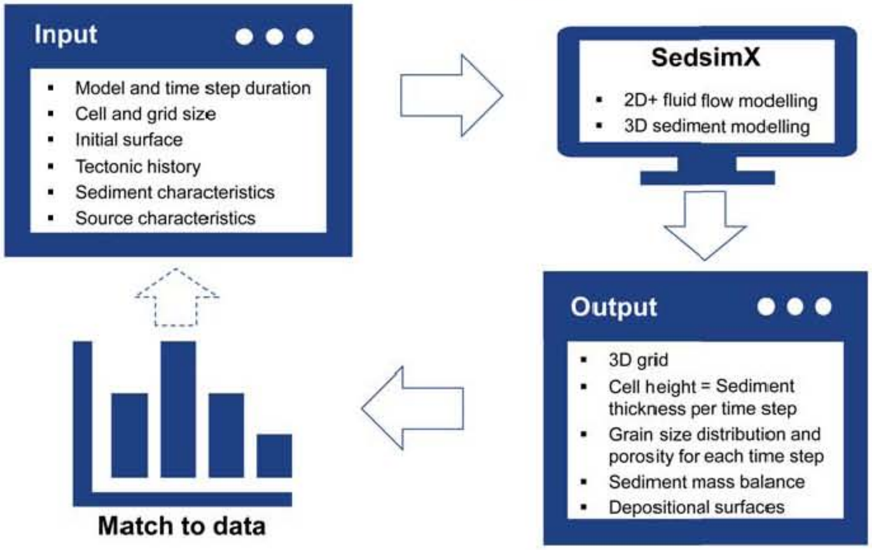
- **Dominate fluvial rock record**
- Occur in **all basin types**, **tectonic settings** and **climate zones**
- Range in sizes from small-scale alluvial fans to large-scale fluvial mega-fans
- Control on development
  - Primary: Capacity of system to expand laterally from confinement
  - Secondary: A/S, gradient and discharge
- Modern examples: Tarim Basin, China (below) and Okavango Delta, Botswana



Courtesy of Google Earth

3. PROCESS BASED SOFTWARE

- **SedsimX** commercialized by StrataMod
- **3D stratigraphic forward-modelling** software
- Fully **scalable** in time and space
- **Deterministic** but apparently chaotic due to highly sensitive parameters
- **Fluid flow** modelled in **2D** with shallow water assumption
  - Simplification of Navier-Stokes equation
  - Modelled as open channel flow in two horizontal dimensions with a depth-averaged parameter of flow → Constant flow velocity with depth
  - Friction along channel/water interface approximates drag
- **Sediment** modelled in **3D**
  - Erosion, transport, and deposition computed for every cell at each time step
  - **4 clastic sediment types** characterized by grain size, density and transport type
  - **No cohesion**
  - Sedimentary features much shorter than flow depth cannot be modelled



Input

- Model and time step duration
- Cell and grid size
- Initial surface
- Tectonic history
- Sediment characteristics
- Source characteristics

SedsimX

- 2D+ fluid flow modelling
- 3D sediment modelling

Output

- 3D grid
- Cell height = Sediment thickness per time step
- Grain size distribution and porosity for each time step
- Sediment mass balance
- Depositional surfaces

Match to data

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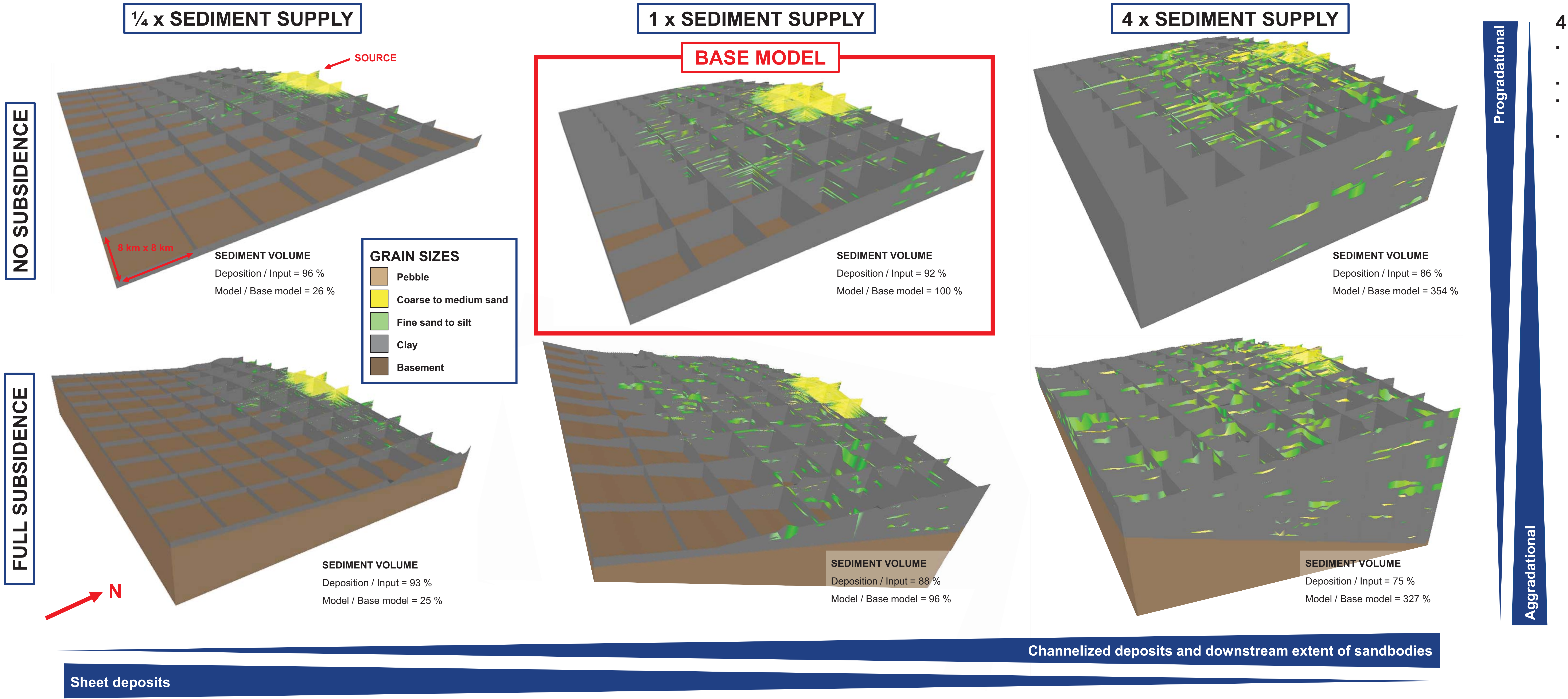


¼ x SEDIMENT SUPPLY

1 x SEDIMENT SUPPLY

4 x SEDIMENT SUPPLY

NO SUBSIDENCE

FULL SUBSIDENCE

SEDIMENT VOLUME
Deposition / Input = 96 %
Model / Base model = 26 %

SEDIMENT VOLUME
Deposition / Input = 92 %
Model / Base model = 100 %

SEDIMENT VOLUME
Deposition / Input = 86 %
Model / Base model = 354 %

SEDIMENT VOLUME
Deposition / Input = 93 %
Model / Base model = 25 %

SEDIMENT VOLUME
Deposition / Input = 88 %
Model / Base model = 96 %

SEDIMENT VOLUME
Deposition / Input = 75 %
Model / Base model = 327 %

GRAIN SIZES

🟫	**Pebble**
🟨	**Coarse to medium sand**
🟩	**Fine sand to silt**
⬜	**Clay**
🟫	**Basement**

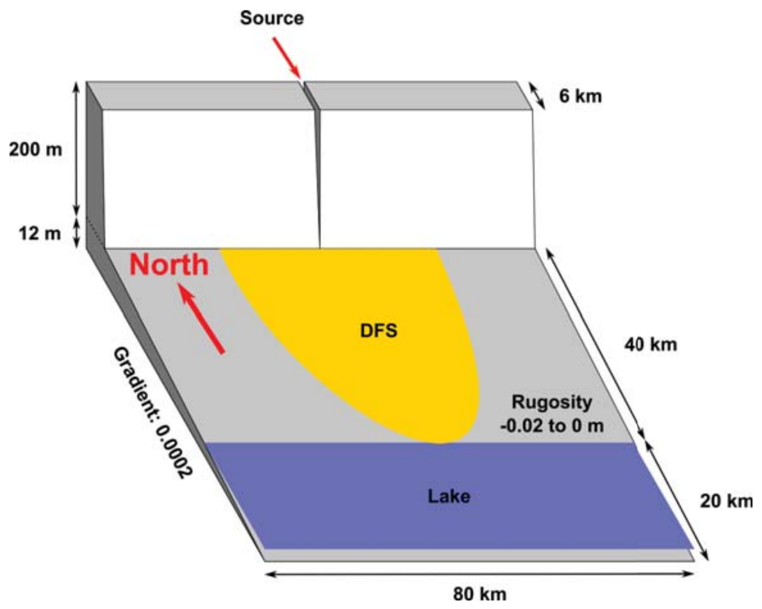
Channelized deposits and downstream extent of sandbodies

Sheet deposits

4. MODEL DESCRIPTION

- Sediment grain sizes: Pebble, coarse to medium sand, fine sand to silt and clay
  → Coarsest two as bed load transport
- Most parameters derived from literature study of the Luna DFS
- Source parameters from High Island Creek, MN (Groten et al., 2016)
  → Measurements include **centennial flood**
- **A/S scenario model ranges**
  - **Sediment supply**: ¼ x, 1 x and 4 x discharge (→ sediment supply) of base model
  - **Subsidence**: Zero and differential subsidence: All subsidence at basin margin = Total sediment thickness of non-subsidence model AND no subsidence distally

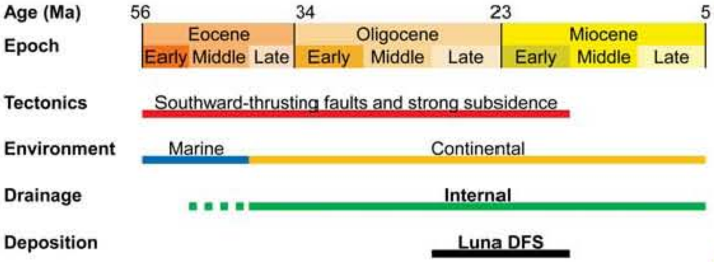
INPUT PARAMETERS		Values	
Time	Model duration (years)	500 000	
	Time step duration (years)	100	
	Display interval (years)	1 000	
Grid	Spacing (m)	1 000	
	North-south extent (km)	66	
	East-west extent (km)	80	
Sources	Stage type	Normal	Flood
	Stage length (years)	500 000	100
	Number of stages	1	300
	Discharge (m^3/s)	16	210
	Flow velocity (m/s)	0.6	1.4
	Sediment concentration (kg/m^3)	1	1.1
	Grain size distribution coarsest to finest (%)	0, 0, 0, 100	2, 20, 9, 69
Model boundaries		Open	



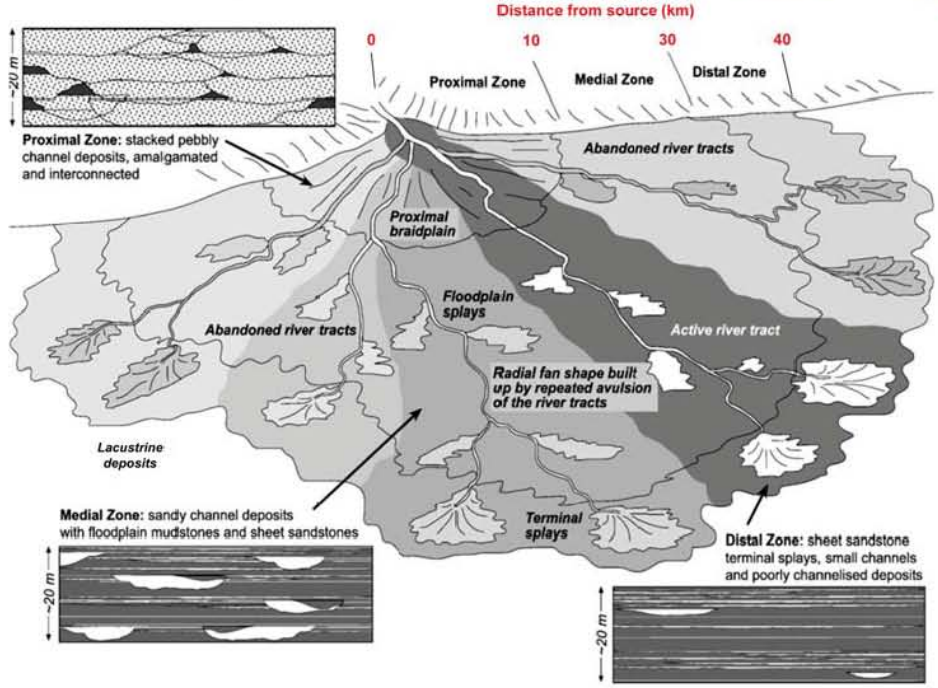
5. LUNA DFS (EBRO BASIN)

- Part of **southern Pyrenean foreland basin**, Northern Spain
- **Luna DFS** developing from northern **basin margin** (Nichols, 1987)
  - Aggradational after initial progradation
  - Little structural overprint (Hirst & Nichols, 1986)
  - Semicircular shape with 40 km radius
  - Mesozoic basement dips to NNE with 2.5° (Gaspar-Escribano et al., 2001)
  - Well defined apex location from paleocurrent measurements (Jupp, 1987)
- **Lacustrine deposits** in basin center → **Mud dominated**
  - Sedimentation rates range from 68 to 107 mm/ka (Pérez-Rivarés et al., 2002)
- Humid continental climate (Hamer et al., 2007)

GEOLOGICAL HISTORY



SEDIMENTOLOGY (after Nichols and Fischer, 2007)



6. WORKFLOW

Test process-based modelling software

⇩

Select and model DFS analogue

⇩

Find and model A/S scenarios

⇩

Quantify sandbody connectivity in each scenario model

⇩

Analyse effect of A/S on sandbody connectivity

⇩

Test findings in subsurface analogue

7. CONCLUSIONS

- **Base model criteria**
  - DFS plan-view extent
  - Sedimentation rate of lake deposits within range of measured values
  - Correct grain size distribution and sedimentology in proximal, medial, distal and lake facies associations
  - → All met **except more tabular sandbodies** needed in medial part
- **Sandbody connectivity**
  - **Mainly influenced by sediment supply**
  - **→ High supply reduces sandbody connectivity**
  - Differential subsidence influences stacking pattern
  - **→ Higher differential subsidence leads to aggradational stacking pattern**

8. OUTLOOK

- **High resolution grids**
  - 1 km x 1 km size
  - Channel width resolution → 10's of meters
  - Located in proximal, medial, distal and lake parts
  - Used for sandbody connectivity measurement through connected volumes in Petrel
- Create **statistically significant** amounts of **scenario models**
  - Use machine learning to automate sensitivity analysis
- **Link A/S to sandbody connectivity** through empirical formulas
- **Test validity of formulas on outcrop analogues** in different tectonic and climatic settings, on **modern DFS** and **subsurface DFS**

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