Characterizing Static Reservoir Connectivity of Deepwater Slope Deposits Using Sub-Seismic Outcrop-Based Facies Models, Tres Pasos Formation, Magallanes Basin, Chilean Patagonia*

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Search and Discovery Article #30416 (2015)**
Posted October 19, 2015

*Adapted from oral presentation given at AAPG Annual Convention & Exhibition, Denver, Colorado, May 31-June 3, 2015

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Abstract

As petroleum exploration ventures further offshore, the ability to more accurately predict and characterize the architecture of deep-water slope deposits is increasingly important. With well costs of 100's of millions of dollars, limited seismic resolution, and sparse well control, insight beyond well and seismic data is of increased importance. Leveraging outcrop analogs can aid in understanding the impact of inter- and intra-channel architecture on pay connectivity. Such architecture is generally below the resolution of subsurface seismic-reflection imaging and is difficult to deduce from well data.

A high-resolution digital model of stacked, deep-water channels from the Laguna Figueroa section of the Late Cretaceous Tres Pasos Formation in Chile was created. This model is based on > 1,600 meters of cm-scale measured section, > 100 paleoflow measurements, and 1,000's of dGPS points (10 cm accuracy) from a well-exposed outcrop belt 2.5 km long and 130 m thick. The model elucidates the effects of facies relationships and intra-channel architecture on channel connectivity. The model captures observed facies geometries at a resolution of 2 m horizontally and 1/4 m vertically (~600M cells). Emphasis was placed on accurate and detailed intra-channel architecture. Three channel width (200, 250, and 300 m) models and two channel base drape (CBD) scenarios were created, for a total of six models. Static connectivity analyses were performed on the models by: (1) calculating an overall model value, (2) by channel pair to assess connectivity through stratigraphy, and (3) down depositional-dip to capture planview connectivity variability. As such a fine-scale model would likely not be used in flow simulations, an upscaling analysis was performed to explore architecture degradation and its effects on connectivity. Results of the connectivity analysis show that the CBD scenarios strongly impact sandstone connectivity and that smaller channel widths are more susceptible to poor connectivity and disconnected sandstone. Net-to-gross was calculated to explore its relationship with connectivity metrics. Upscaling

the models consistently increases connectivity, and small changes in cell geometry impact architecture, which can artificially induce connectivity. Ultimately, this work aims to constrain uncertainty related to sub-seismic scale architecture and its impact on reservoir connectivity by providing concrete connectivity data and contributing to better predictive models.

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Agenda

- Introduction
- Geologic background
    - Previous work
- Research Questions
- Methods: model building
    - Facies, basal drape, and sizes
- Static connectivity analysis
    - Width
    - Drape
    - Stacking Pattern
- Conclusions

Project Overview

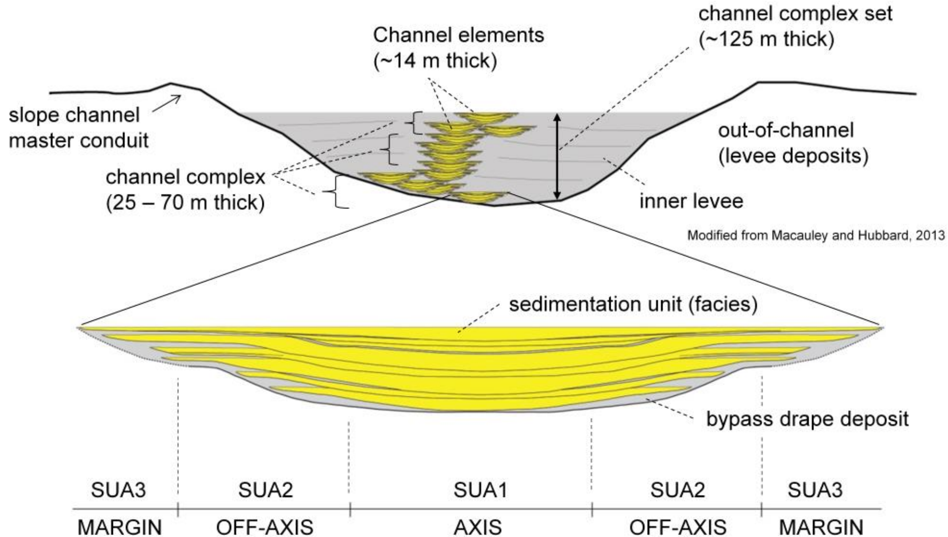
Motivation

- Deep-water slope deposits are increasingly important reservoirs worldwide
- Subsurface data are insufficient for understanding these deposits
    - High resolution (~10m) 3D seismic
    - Conventional core, well log data, biostratigraphy, etc.
- Sub-seismic scale architecture remains difficult to capture
    - Controls reservoir flow and connectivity
- Outcrop analogs allow for detailed study of these deposits

Objectives

- Model a well exposed section of the Tres Pasos Formation, Chile
- Modeling goal: Create a facies model that honors outcrop data and reflects observed bed scale architecture of channelized slope systems
- Leverage outcrop analog model to examine static connectivity

Deep Water Channels: Hierarchy



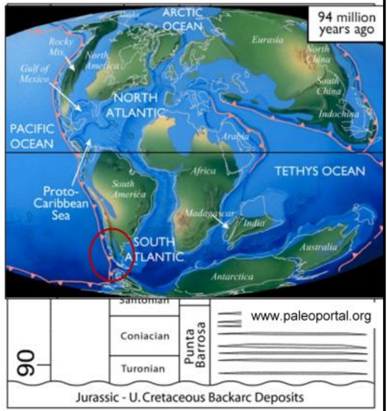
Presenter's notes: Sedimentation Unit Associations (SUAs):

- Groups of sedimentation units
    - The fundamental architectural unit and are deposits produced from a single gravity flow event
    - Similar to sedimentary facies
- 3 identified at Laguna Figueroa

Magallanes Basin, Chilean Patagonia

Tres Pasos sedimentology

- Magallanes Basin:
  - Retroarc foreland basin
  - Infilled in the Upper Cretaceous
    - 5,000 m in 20 Ma



Hubbard, 2010

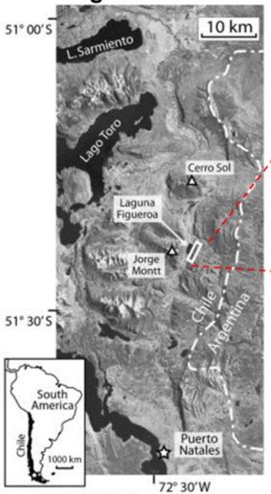
- 4 marine formations in the basin
  - Tres Pasos Formation
    - Over 2km of stratigraphy
    - High clinoform relief (>800m)
    - Toe of slope deposits in study area

Presenter's notes:

- Punta Barrosa
  - First turbidites in this basin
  - Cerro Torro (2,500 m thick)
  - Shale with occasional conglomeratic intervals
- Tres Pasos (1,200 to 1,500 m thick)
  - Last turbidite phase in the basin
  - Dorotea Formation (300 m thick)
  - Sandstone-rich, grades upwards from shallow marine to deltaic and non-marine
- These formations may represent a southward prograding slope system, and likely capture the entire basin infilling sequence, recording the transition from deep-water sedimentation to terrestrial deposition (Hubbard et al., 2010; Romans et al., 2011).

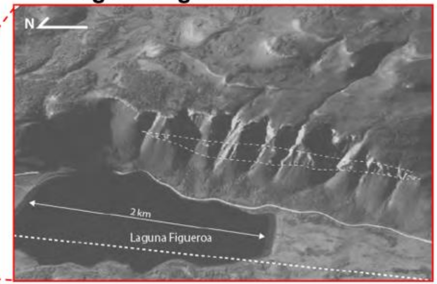
Tres Pasos Formation, Chilean Patagonia

Magallanes Basin



Hubbard, 2010

Laguna Figueroa View to East

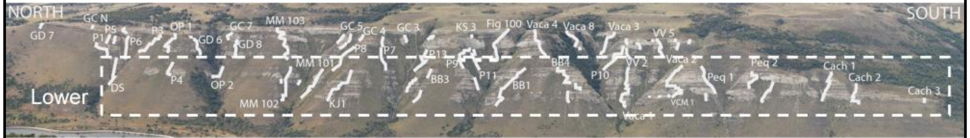


Hubbard, 2010

- Study section is 130 m high and 2500 m long
- Exceptional exposure
    - Can project channels in and out of the outcrop

Presenter's notes: Where we are in the world, what the Tres Pasos is…
This is just the Laguna Figueroa section of the TP. The TP formation outcrops a long distance north, revealing slope deposits that connect up to the shelf.

Tres Pasos at Laguna Figueroa



Macauley and Hubbard, 2013

- 2 Channel Complex Sets
- Study based on the Lower Channel Complex Set

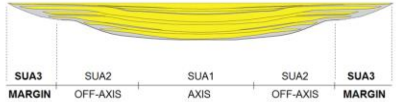
- 18 Channel elements, which are:
  - 200 to 300 m width, 12 to 16 m thick
    - low sinuosity (1.01 – 1.05)
  - Symmetric elements and facies fill
  - Negligible variability
    - between the channel elements
    - down slope

Presenter's notes:

- 1607 meters of section measured at the cm-scale
  - >100 paleoflow measurements from 53 outcrop locations
  - Mostly sole marks
- Thousands of high-resolution differential GPS data points
  - 10-cm accuracy
  - records major stratigraphic horizons
- Channel locations were mapped using:
  - Cross-section interpretations
  - High resolution satellite images and photomosaics

Sedimentation Unit Associations

(SUA)



SUA[illegible]:

- [illegible] sandstone.
  - [illegible] to 2 m thick
  - [illegible] interbedded with silt- and mudstone.
- **Represe**[illegible]planar laminations (T_b) and ripples or cross-laminations (T_c)
- Bypass deposits
  - Represents the tails of high energy bypass deposits

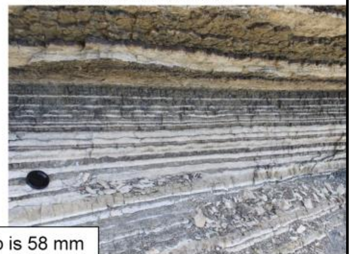
Thick massive sandstone of SUA1.

Tape bands=10cm

Thin interbedded sand- and mud-stones of SUA2.

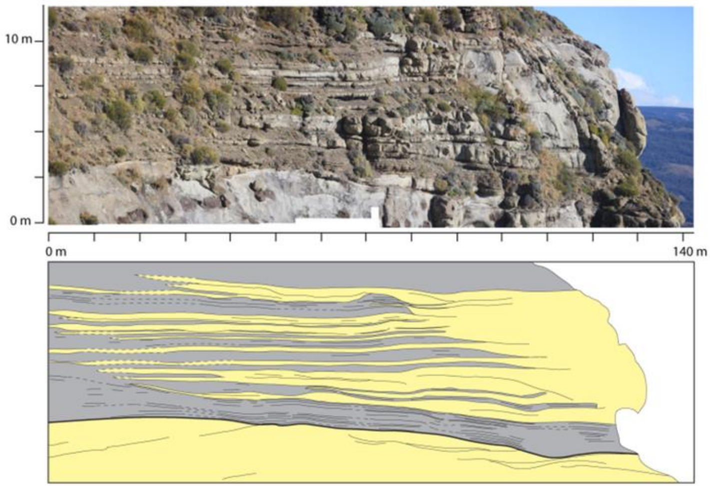
Lens cap is 58 mm in diameter.

Thinly interbedded sand-, silt-, and mudstone beds of SUA3.



Photos: A. Jackson

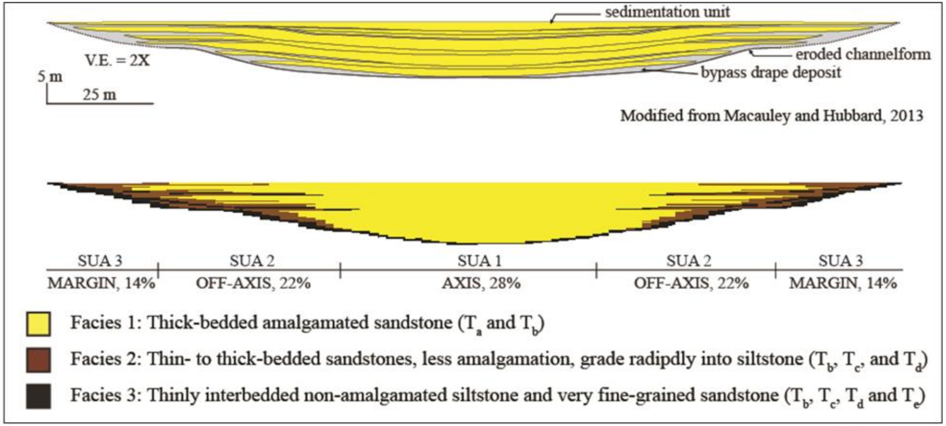
Tres Pasos at Laguna Figueroa



CSS Consortium Material

Model Building: Facies Template

- Cell size: 2 m by 2 m aerially, 0.25 m vertically
- Channel fill symmetric, constant between elements
- 14 m thick by 200, 250, and 300 m wide



Jackson, *in prep*

Presenter's notes: Ryan says: Through observations of numerous margins, it is "evident that channels are characterized by cross-sectional fills that are symmetric to slightly asymmetric"

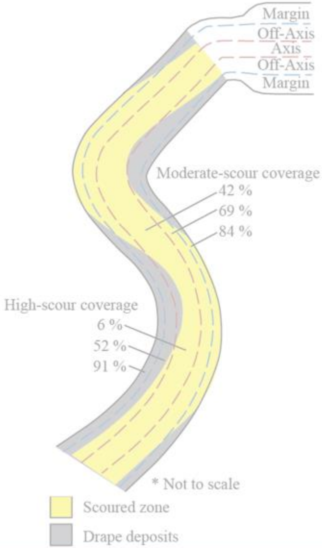
- MATLAB script used to generate property files
- Seeding from left margin
- Planview curvilinear grid -> square Cartesian grid

Say each channel gets its own grid so as to preserve channel width and geometry with the template is seeded. Each channel's grid is designed to follow the channel's left and right margins. Once these 18 are done, they are all merged onto the same grid, and overlying channels are scoured into underlying channels to create the model.

Curvilinear in planview, Cartesian in x-section.

Model Building: Basal Drape Configurations

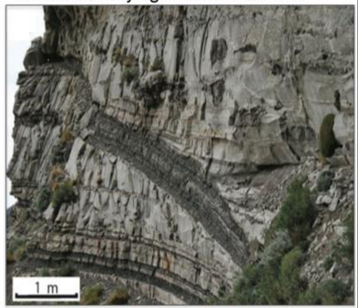
1. Geometry based on flume[1], modern analog[2], and modeling studies[3]
2. Coverage constrained by Tres Pasos outcrop statistics



Moderate scour total drape coverage: 72 %

High scour total drape coverage: 58 %

Thick (~1m) bypass drape deposit lining base of overlying channel element.



Hubbard, 2010

1. Amos et al., 2010
2. Conway et al., 2012
3. Sylvester et al., 2010

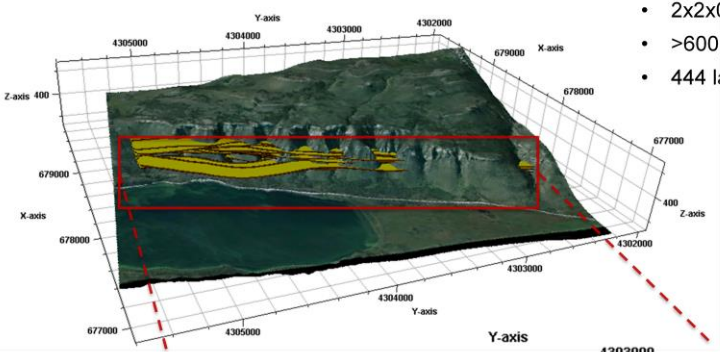
Presenter's notes:

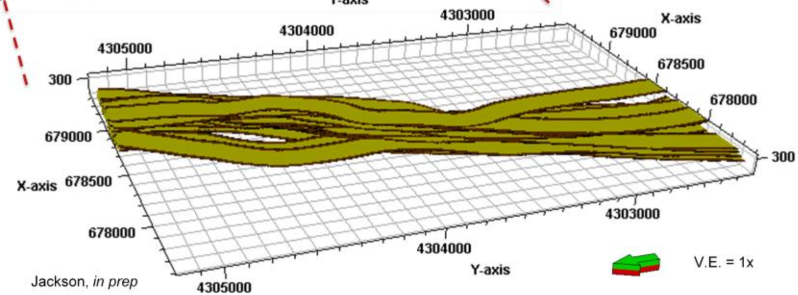
-Cannot get geometry from outcrop analog because we cannot see in 3D.

-There are two governing factors for how the drape configurations were generated. First, there is the analog and flume work, which gives the conceptual locations for areas of scour vs. preservation (scour occur on the outside bends, deposition or non-erosion on the inside). Then, while maintaining this geometry, the drapes were scaled to match statistics from the field.

The Model

- 2x2x0.25 cell size
- >600,000,000 cells in grid
- 444 layers vertically





Jackson, *in prep*

6 Model Scenarios

		Drape Configuration	
		Moderate-scour	High-scour
Element Width (m)	200	Moderate-scour, 200 m width model	High-scour, 200 m width model
	250	Moderate-scour, 250 m width model	High-scour, 250 m width model
	300	Moderate-scour, 300 m width model	High-scour, 300 m width model

Width

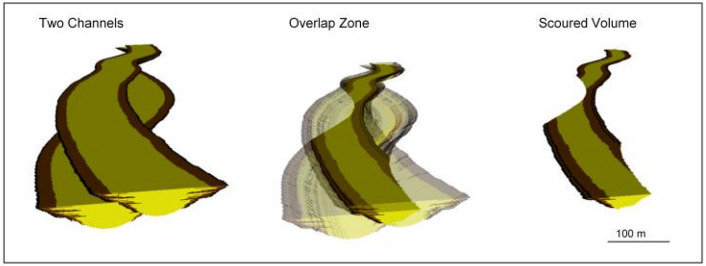
Basal drape

What are the effects on connectivity of:

1. **Element width**
2. **Intra-channel architecture (drape facies)**
3. **Inter-channel architecture (stacking patterns)**

Scour Volumes

•Scour volumes: overlap volume between a channel element pair

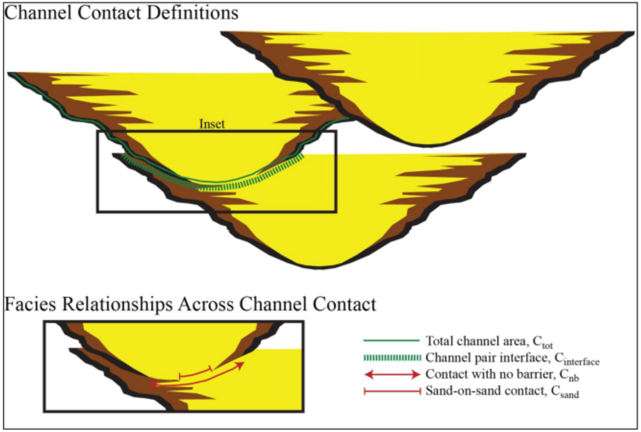


Jackson, *in prep*

Margin and Sand-on-sand Connectivity (C_m and C_s)

2D → 3D Statistics

- Funk et al. (2012): 2D metrics to quantify facies relationships across an interface
- Connectivity is a 3D problem
- Extend to 3D, add global connectivity, C_g



3D

$$C_s = (\sum C_{sand})/C_{interface}$$

$$C_m = (\sum C_{nb})/C_{interface}$$

$$C_g = (\sum C_{interface})/C_{tot}$$

Jackson, *in prep*

Presenter's notes:

- Cg: Describes amount of potential surface area available for fluid flux as a fraction of the total channel element basal surface area.
- Cm: is the amount of surface area shared by two elements that is available for fluid transfer (not draped) as a ratio of the total contact area between channels.
- Cs: is the amount of sand-on-sand surface area between two elements available for fluid transfer as a ratio of the total contact area between channels.

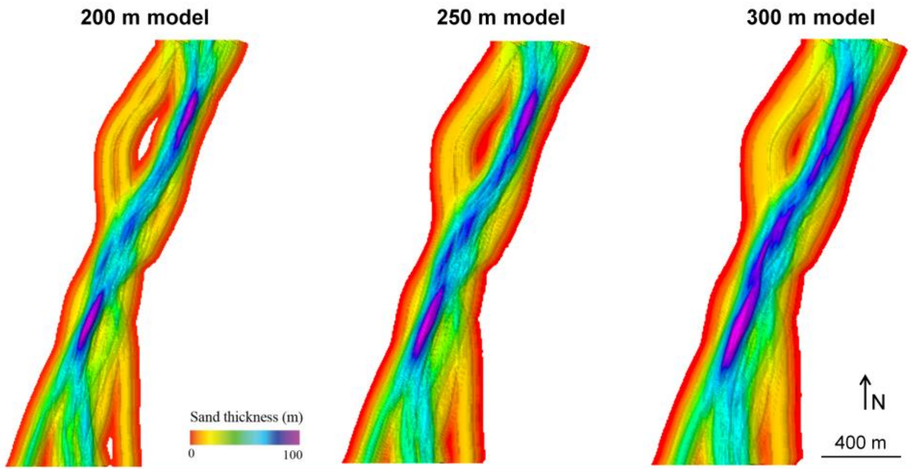
1. What is the impact of element width on connectivity?

As individual channel elements are typically below seismic resolution, understanding the implications of uncertain channel width is key for reservoir modeling.

– Is connectivity affected linearly by increases in element width?

Width

- Net sand maps for SUA1
  - total thickness of the thick-bedded amalgamated sandstone facies
- Areas of thick net sand increase with increased with
  - Increase not linear



Presenter's notes: **1. Thick sand increases a lot with width**

Net sand maps for Facies 1 (total thickness of the thick-bedded amalgamated sandstone facies) were generated for all three element width models (Figure 7a). This provides the opportunity to tie segment-based statistics to a net-to-gross (NTG), a metric that could be derived from a seismic amplitude map. The net sand maps show that areas of thick net sand increases with increasing element width. For example, the 200 m width has two distinct areas (total area = 4.88E4 m^2) of net sand $\geq$ 75 m. The 250 m width has four of these areas (total area = 1.81E5 m^2), which constitutes a 272% increase area of net sand $\geq$ 75 m. The 300 m width increases area of net sand $\geq$ 75 m by only 7% from the 250 m model (1.95E5 m^2).

2. Variability decreases with width

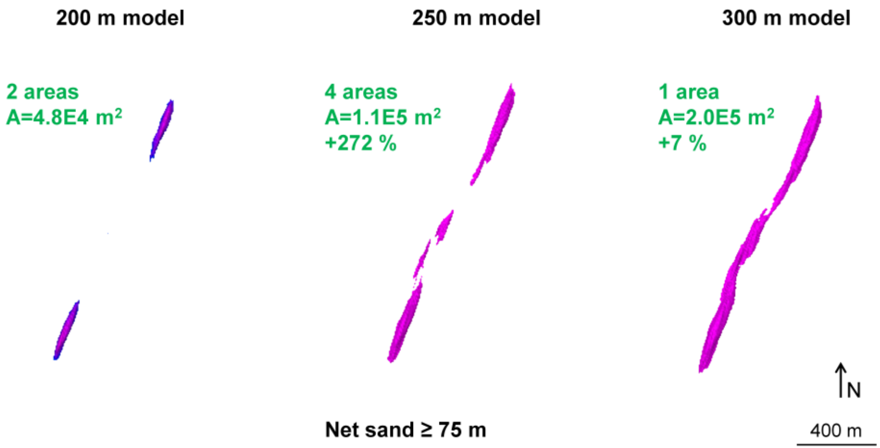
The range in values for non-draped connection (C_m) and non-draped sand connection (C_s) for each channel element pair invariably decreases with increasing channel element width. From 200 to 250 m width, the average decrease in Cm and Cs connectivity range is 18%, and from 250 to 300 m width, the average decrease in range is 10%. This suggests that the increase in connectivity with increased element width is accompanied a convergence towards the average of the C_m and C_s values themselves.

Thus, not only does increasing widths exponentially increase thick sand zones, it also renders understanding detailed, localized connectivity variability less important.

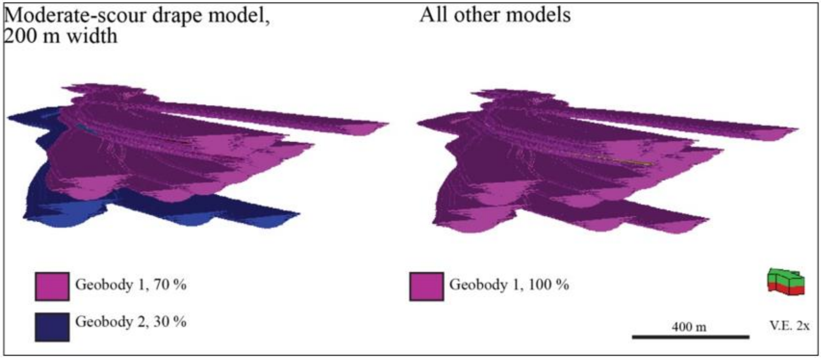
Width

- Net sand maps for Facies 1
  - total thickness of the thick-bedded amalgamated sandstone facies

- Thick net sand areas do not increase linearly with increased with



Width + Drape



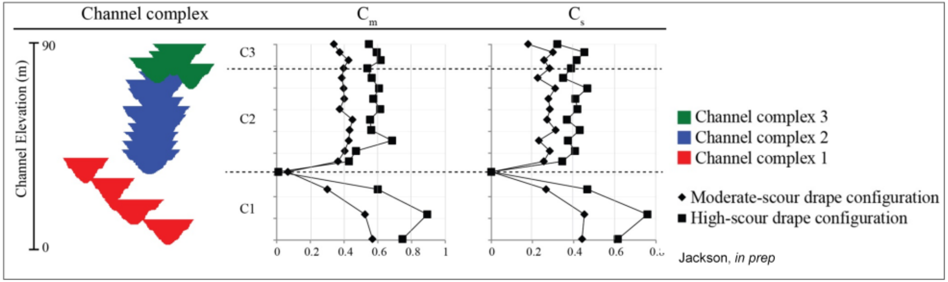
Jackson, *in prep*

2. What is the impact of intra-channel architecture (drape facies) on connectivity?

- *how do facies relationships across channel boundaries affect connectivity?*
- *is capturing the basal drape play important?*

Impact of intra-channel architecture on connectivity (facies)

200 m width



1. For all scenarios, lower drape preservation translates to increased C_m and C_s

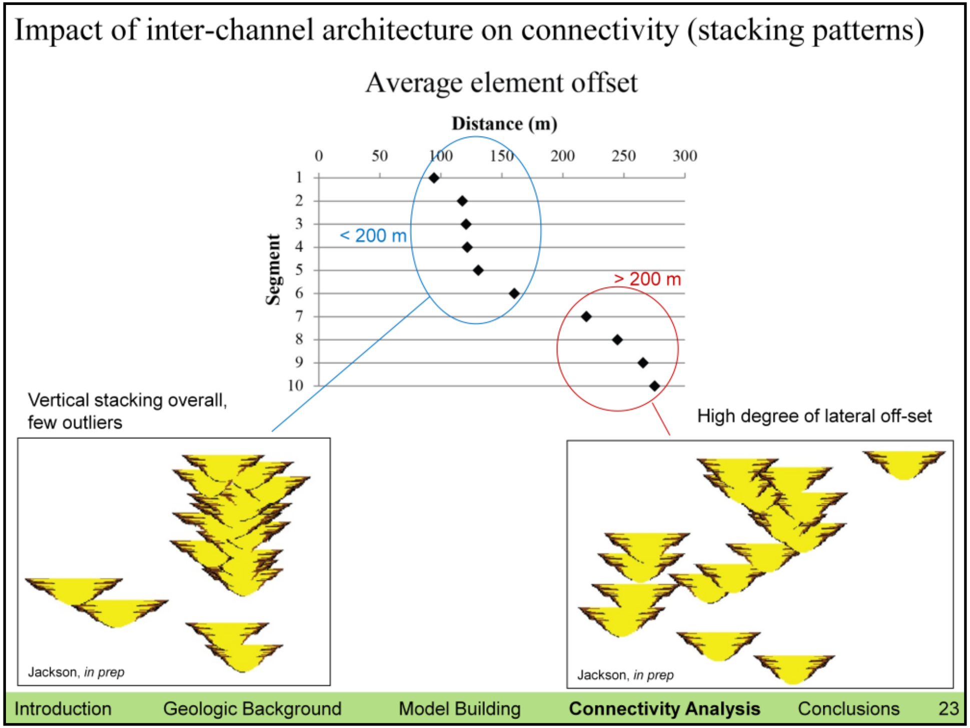
2. Different basal drape configurations do not affect connectivity trends

Implication: For every 10% increase in drape, C_m decreases by a minimum of 22 % and up to 25 % for C_s (optimal permeability) areas

Presenter’s notes: DH is consistently higher, whether by seg or channel pair, BUT they show the same trends.

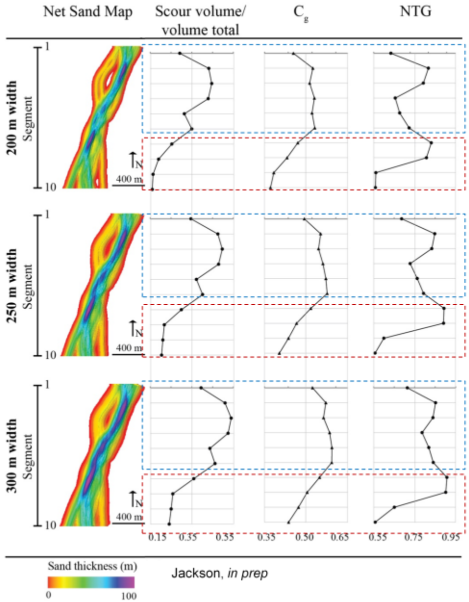
3. What is the impact of inter-channel architecture (stacking patterns) on connectivity?

– *Can we relate channel stacking patterns to connectivity?*



Presenter's notes: The decrease may be tied to this section of the net sand map, which here displays thinner sand accumulations in a broader east-west area. This character, along with the lower scour proportions and decreased area of element connection with no drape present (C_g), suggests less vertical stacking patterns causing the reduced connectivity in the bottom section.

Stacking patterns



Jackson, *in prep*

< 200 m, dominantly vertical

> 200 m, dominantly lateral

Transitioning from vertical to lateral stacking caused:

- -45 % decrease in scour proportion
- -18 % decrease in Cg
- -5.4 % decrease in NTG

< 200 m, dominantly vertical

> 200 m, dominantly lateral

•Once stacking laterally, every 10 m increase in offset decreases C_m by 5%.

< 200 m, dominantly vertical

> 200 m, dominantly lateral

Presenter's notes:

- Even small widths may be totally connected if basal drapes are scarce or not preserved.
- Note break at complex level for 200DS.

Conclusions

- Width: For widths of 200 m or less, risk of compartmentalized sandstone, segmentation at complex boundaries, and exponential decreases in pay zones is high

- Drape: This work shows that accounting for basal drapes does matter for connectivity
  - Especially important when combined with small element widths
  - Critical for reservoirs with pronounced basal drapes
    - e.g. Karoo Basin (South Africa) or Brushy Canyon Formation (Texas)

- Stacking Patterns: Able to document and quantify changes in stacking patterns and its effect on connectivity

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