PS The Influence of Intra- and Inter-Channel Architecture in Selecting Optimal Gridding for Field-Scale Reservoir Simulation*

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Abstract

Sub-seismic scale heterogeneity in channelized deep water reservoirs can lead to significant uncertainty in reservoir connectivity and predicted performance. Though bed-scale heterogeneity can influence reservoir performance, reservoir simulation typically requires cell sizes much greater than the scale of internal channel architecture. Simple fine-scale sector modeling studies can be used to investigate the influence of bed-scale architecture and channel stacking on flow and connectivity and to identify optimal gridding and effective property modeling for field-scale volumetrics and flow simulation.

Fine-scale simulations were performed using sector models developed from an outcrop analogue in the Tres Pasos Formation of the Magallanes Basin in Chilean Patagonia. These models represent a 550 m long segment of a single channel element, then two stacked channel elements. The influence of intra-channel architecture within a channel element was investigated using three different channel fills, each with an increasing level of detail: (1) single homogenous fill populated with average reservoir properties, (2) three depositional facies (axis, off-axis and margin) characterized by vertical boundaries and distinct average reservoir properties, and (3) distributed reservoir properties populated according to observed facies proportions, architecture, and trends. Reservoir performance testing was performed using a single injector-producer pair at a constant well spacing. The impact of well placement on reservoir performance was tested by systematically moving each well through a range of locations from the axis to margin of each channel. The influence of inter-channel architecture was investigated using stacked channel segments. The experiment above was repeated on the stacked segments by varying both internal channel fill and well placement. Variations in channel stacking were tested by changing the offset angle and distance between the two channel segments. End members of the stacked channel simulations were selected to identify an optimal cell size and effective properties for building coarse grid models. Primary conclusions include:

(1) reduced detail in the representation of intra-channel architecture, including upscaling, tends to under-emphasize the critical role marginal facies play in inter-channel connectivity, and (2) error introduced by flow-averaged properties decreases as stacked channels become more vertically aligned.

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Objectives:

1) Quantify the influence of inter- and intra-channel architecture on reservoir performance using high-resolution outcrop-based geocellular modeling.

2) Investigate how the character of internal channel fill and channel stacking may impede connectivity by creating reservoir compartmentalization.

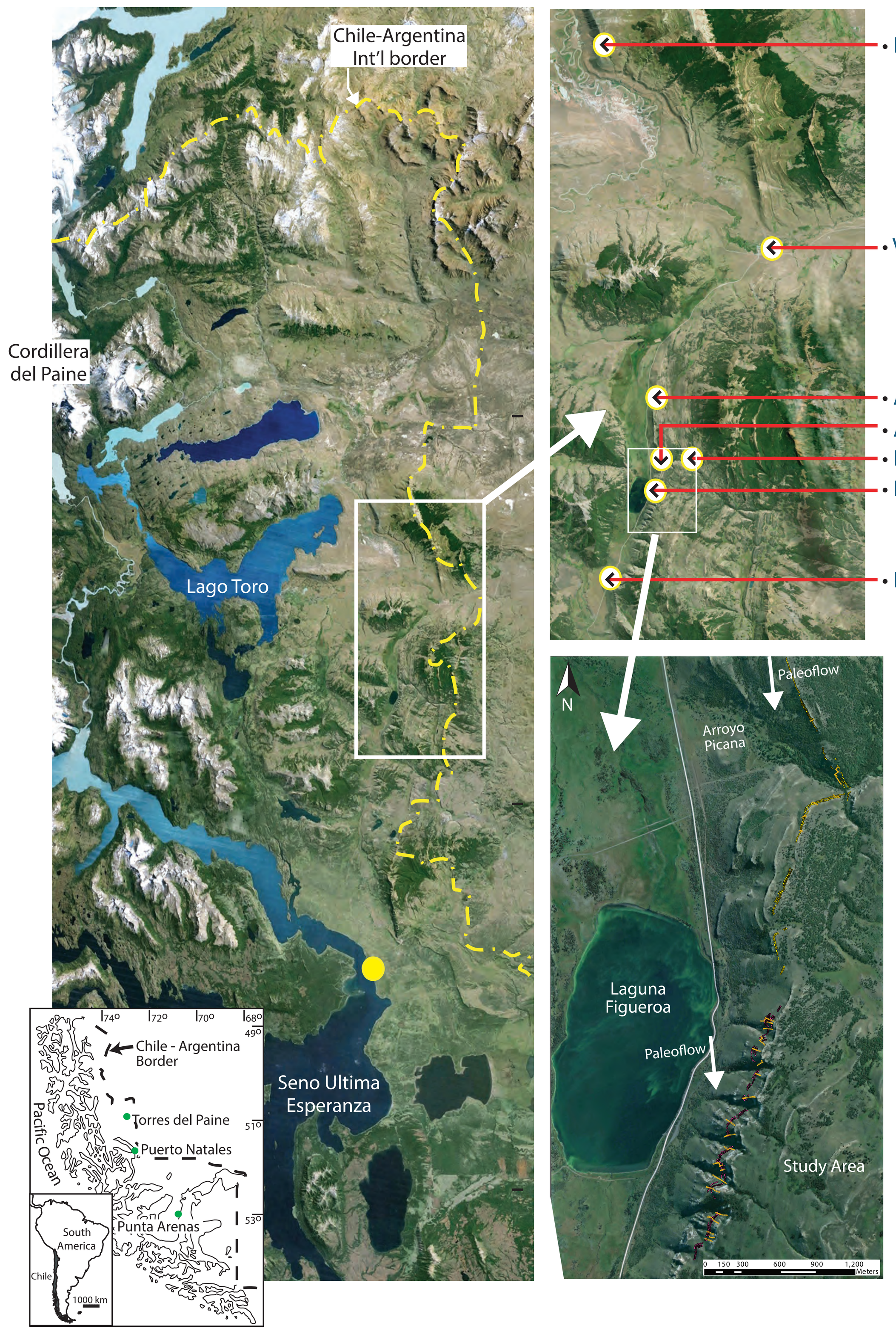
3) Quantify the impact of asymmetric channel fill on reservoir connectivity and performance.

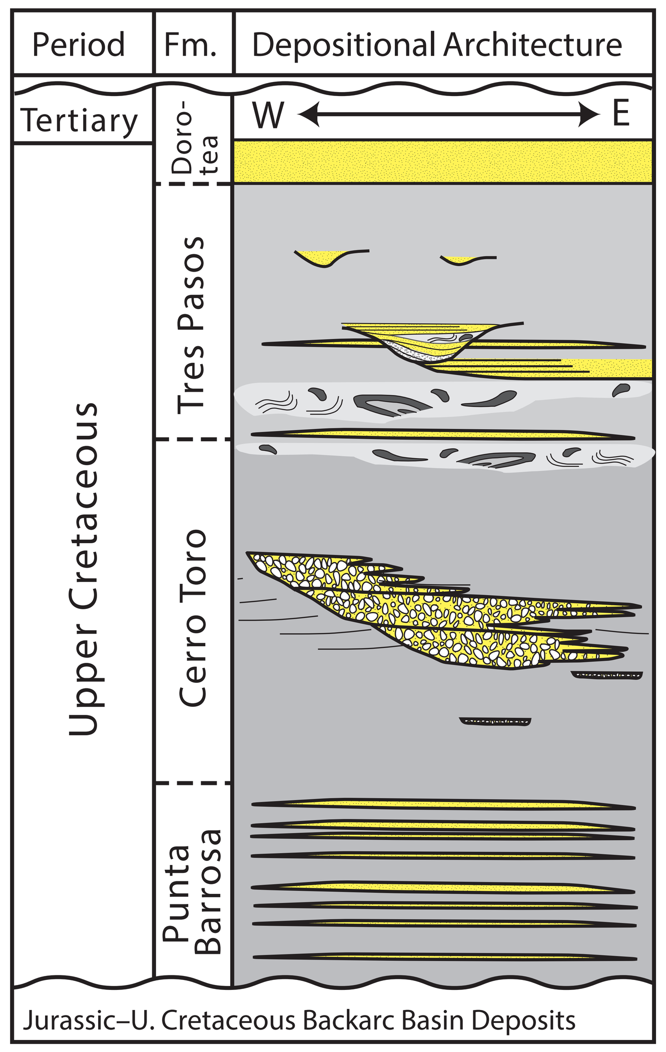
4) Elucidate the impact of upscaling inter- and intra-channel architecture on flow.

Geologic Background and Study Area

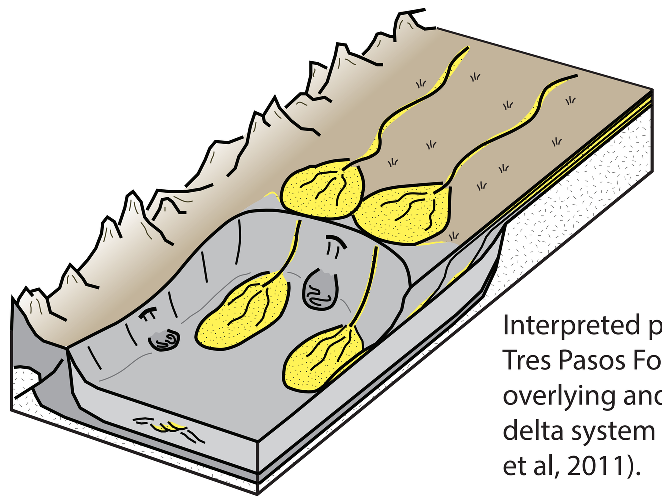
The Late Cretaceous Tres Pasos Formation consists of a turbidite-dominated succession that records the terminal phase of deep-water deposition in the Magallanes foreland basin, southern Chile. Slope channel deposits accumulated along a high-relief margin (>1 km relief) along a depositional profile >40 km long (Hubbard et al., 2010). This study focuses on a 120 m thick and 2.5 km long sandstone-rich succession of slope channel strata located adjacent to Laguna Figueroa. 3D exposures along a depositional-dip oriented transect enables well-constrained mapping of channel architecture.

GoogleEarth images of the Ultima Esperanza District with CSS JIP study areas highlighted. Inset map at lower left shows location of study area with respect to southern South America (compare locations of the Torres del Paine and Puerto Natales).



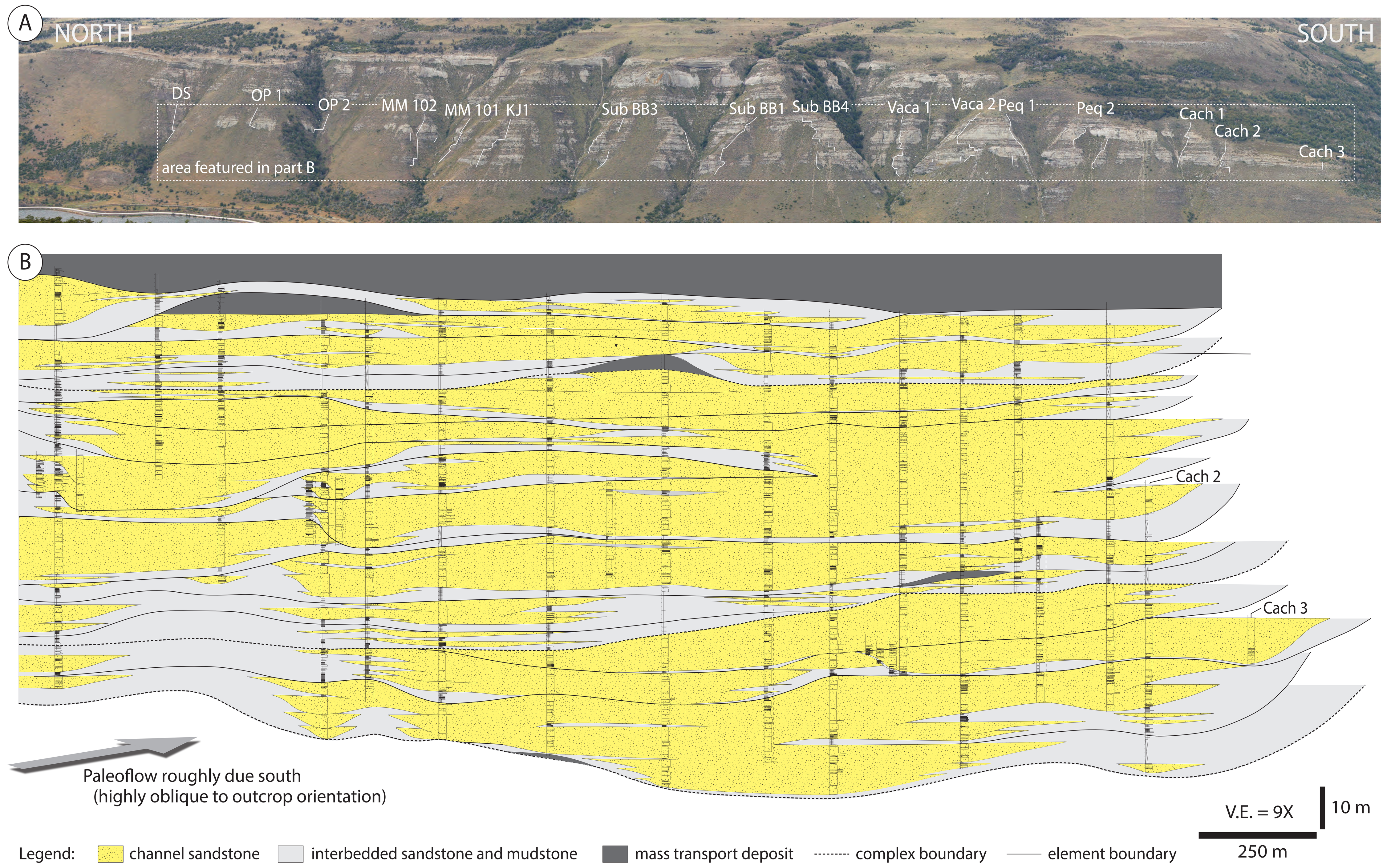


Stratigraphy of the Magallanes Basin (Romans et al, 2011). This study focuses on the Lower portion of the Tres Pasos Formation.



Interpreted paleogeographic setting for the Tres Pasos Formation slope system, and overlying and genetically linked shelf-edge delta system of the Dorotea Formation (Romans et al, 2011).

Tres Pasos Formation, lower Laguna Figueroa section



The Laguna Figueroa Outcrop Belt. Two-large-scale (>100m thick), composite channel complex sets have been delineated in the Laguna Figueroa area, which are comparable to channelized slope systems explored off numerous continental margins. The lower of the two is the focus of this analysis (Macauley and Hubbard, 2013)

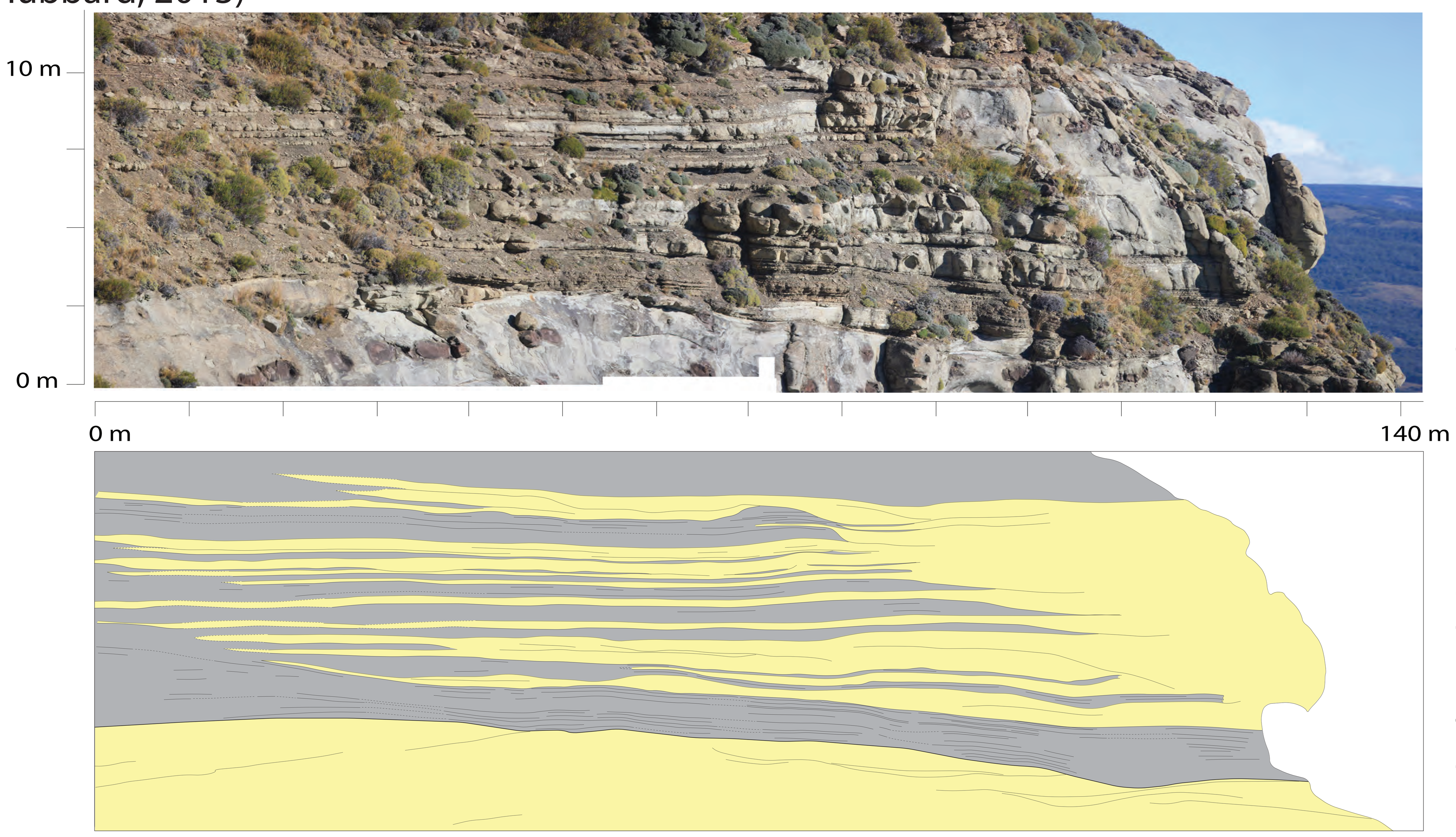
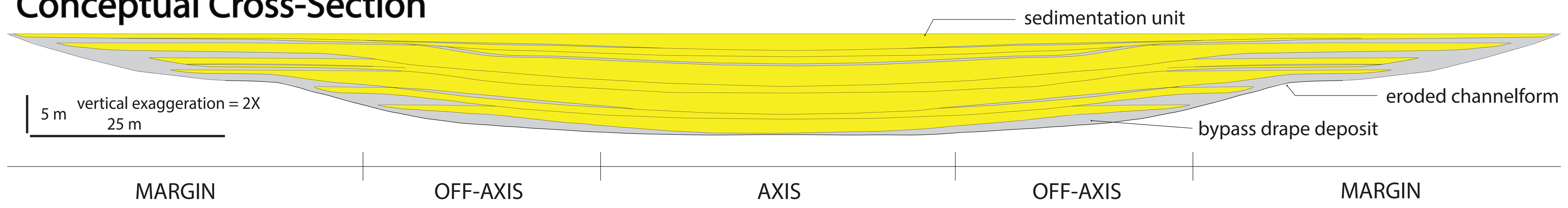


Photo (top) and line-drawing trace (below) of a channel, the primary building block for modeling. Note the more axial amalgamated sandstone (at right) transitions to non-amalgamated and finer facies to the left. This relationship is further depicted in the conceptual cross-section below (bottom).

Conceptual Cross-Section



Macauley and Hubbard, 2013

The Influence of Intra- and Inter-Channel Architecture in Selecting Optimal Gridding for Field-Scale Reservoir Simulation, Tres Pasos Formation, Magallanes Basin, Chile

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Modeling Approach

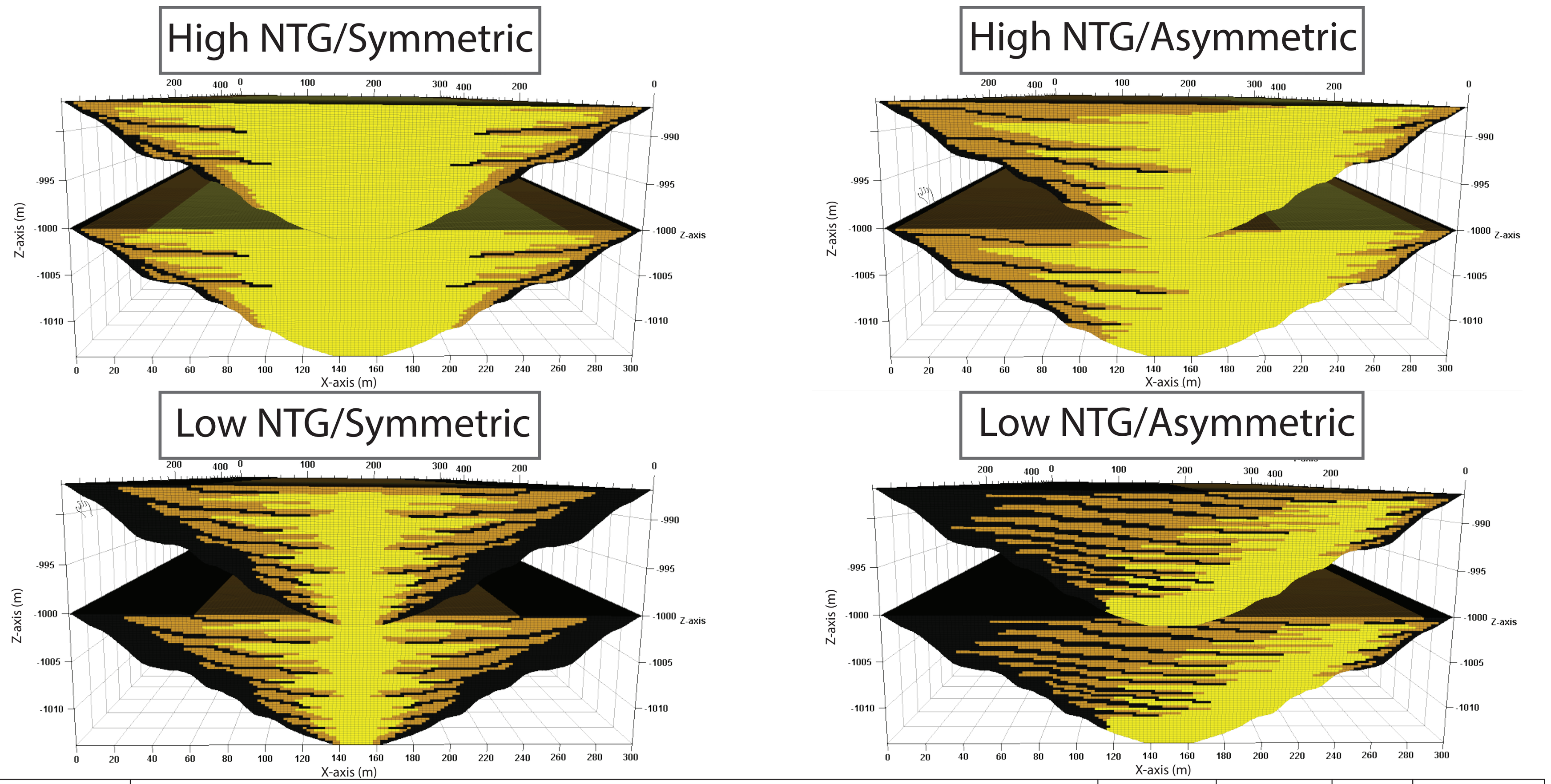
1) Develop static and dynamic models (channel element to channel complex set scale) based on outcrop characterization, expanding beyond the high net symmetric channels of Laguna Figueroa to include asymmetric channel fill and lower net variations.

2) "Bottom-up" methodology where high-resolution (2 m x 2 m x 0.25 m cell size) single and double channel sector models are used to isolate behaviors, quantify uncertainty/error, and identify optimal grid sizes for larger-scale simulations.

3) Assume constant rock properties for each facies, and hold rock and fluid properties constant for all simulations.

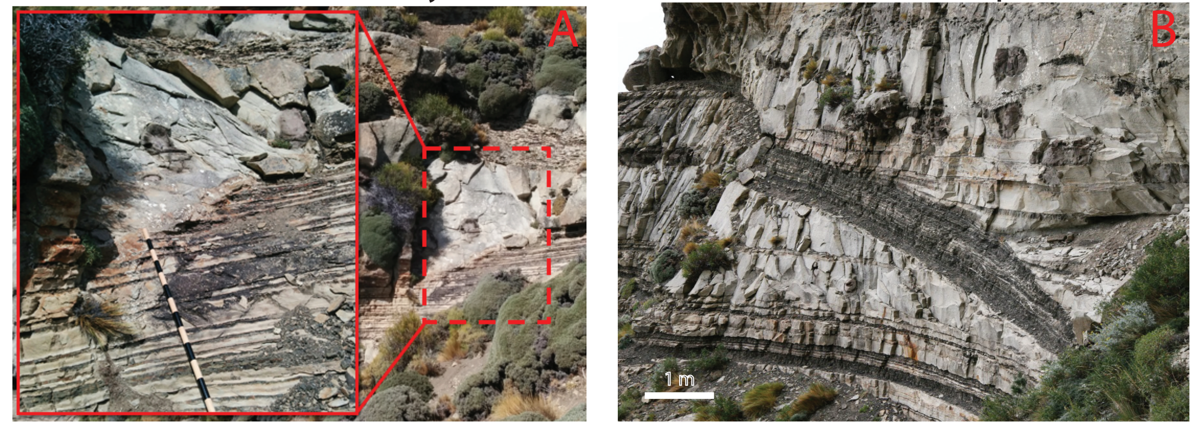
4) Test impacts to reservoir performance from: a) internal channel architecture, b) facies proportions (net-to-gross), and c) channel stacking angle and offset (mobility).

Variations in Internal Channel Architecture



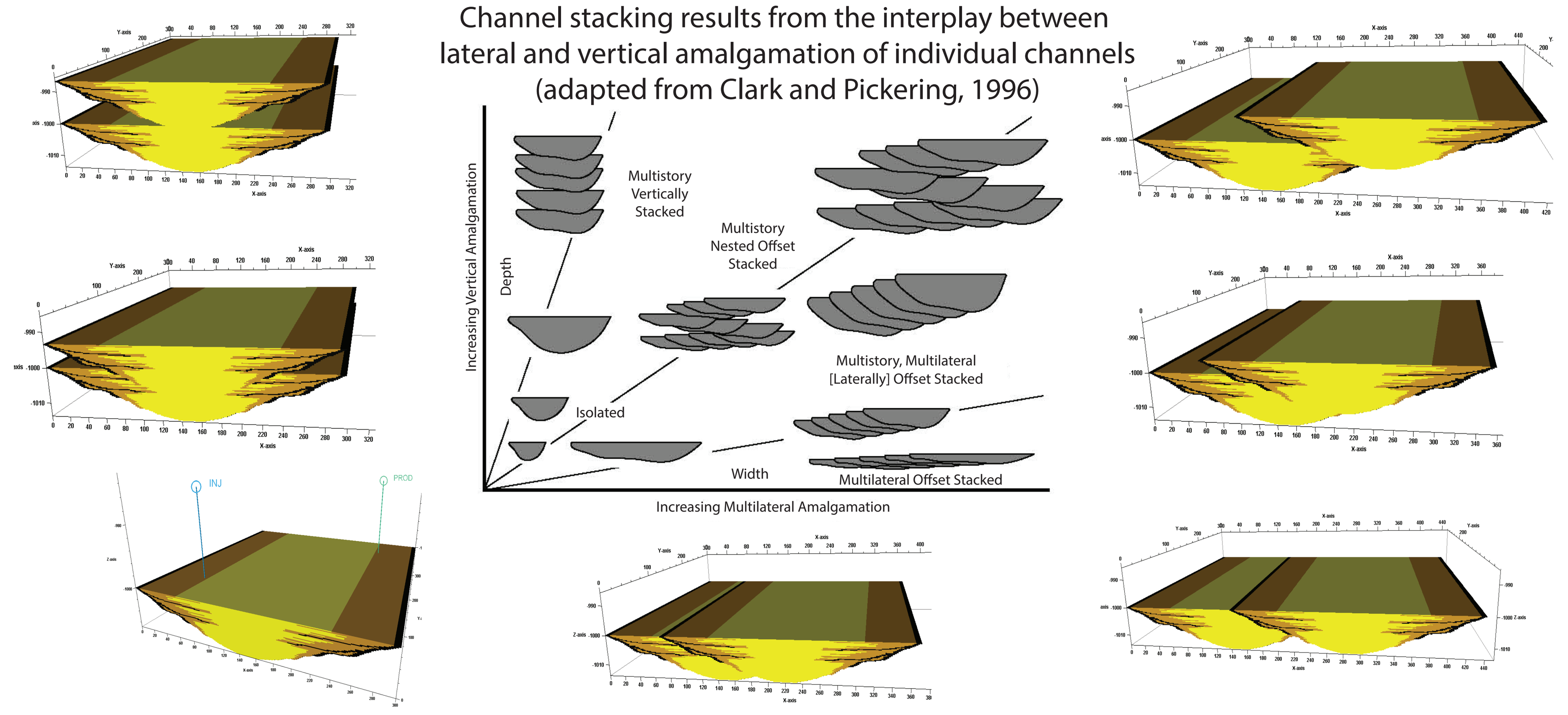
Depofacies	Facies Description	Kxy (mD)	Kz (mD)	Φ	Net:Gross
Axis	Thick-bedded amalgamated sandstone (Ta and Tb)	1000	200	0.3	0.9
Off-Axis	Thin- to thick-bedded sandstones, less amalgamation, grade rapidly to siltstone (T_b, T_c, and T_d)	100	10	0.2	0.7
Margin	Thinly interbedded non-amalgamated siltstone and very fine-grained sandstone (T_b, T_c, T_d, and T_e)	0	0	0.1	0.3

Four deterministic end-members capture a range of potential variations in depofacies proportions and internal architecture at the channel element scale. The "High NTG/Symmetric" case is characteristic of fill patterns and proportions (68% axis, 24% off-axis, 8% margin) observed at the Lower Laguna Figueroa outcrop. Equal facies proportions in the "Low NTG" cases represent a lowest end-member condition. Asymmetric cases contain the same facies proportions as their symmetric counterparts and are used to quantitatively assess the influence of asymmetric channel fill on reservoir performance.



(A) Despite reduced overall NTG, off-axis interbedded sands appear connected to amalgamated axial sands. (B) Shale drapes associated with the margin facies can significantly reduce connectivity between stacked channels.

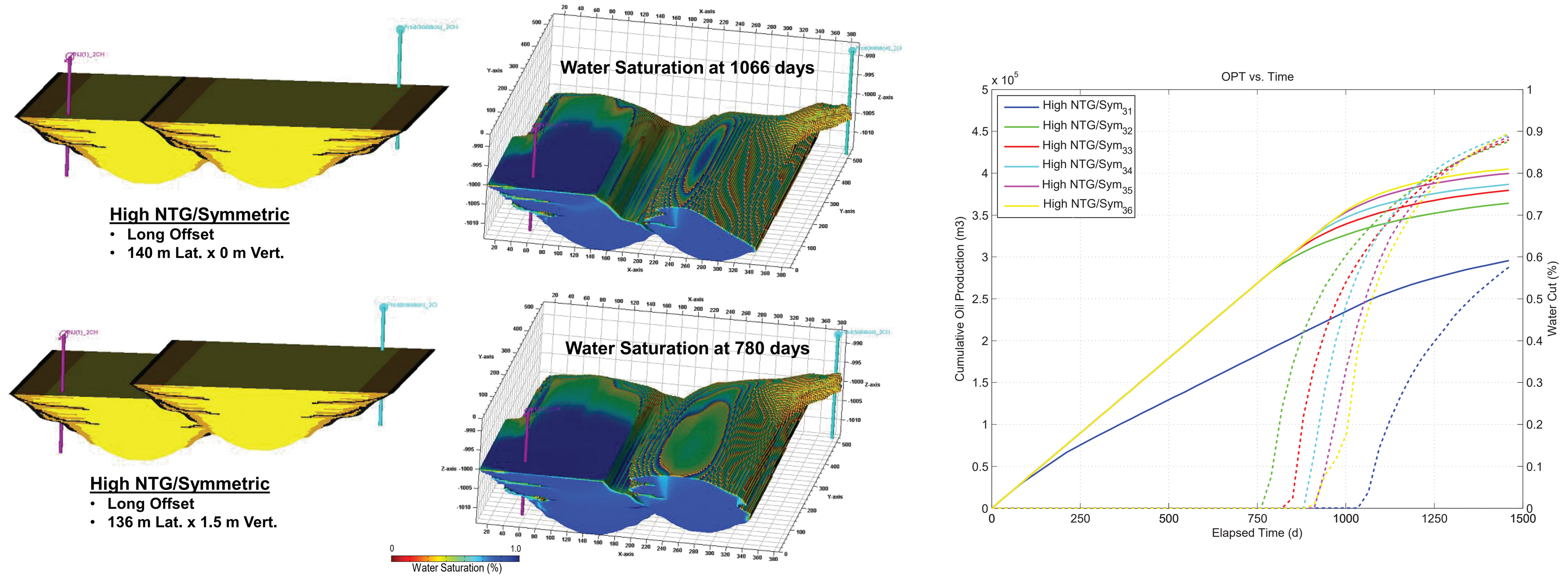
Inter-Channel Architecture: Stacking Angle and Offset



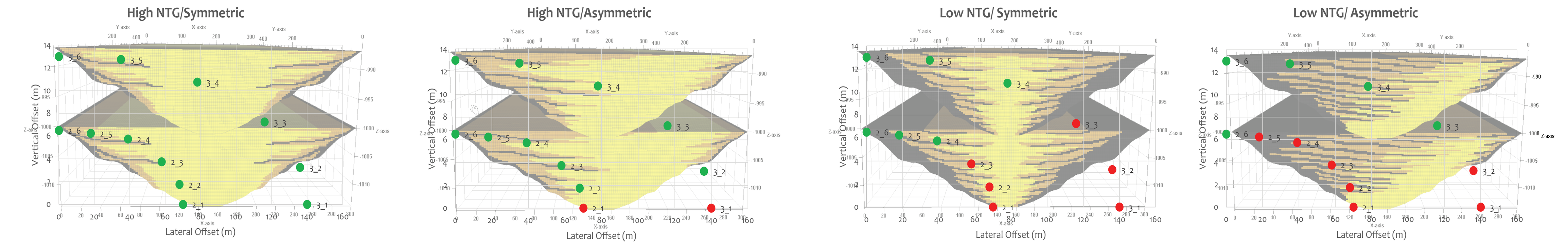
Twelve stacking patterns were created to capture a range of possible behaviors. Offset angle varies from 0° (lateral) to 90° (vertical). Offset distance is either short (1/4 channel width/thickness) or long (1/2 channel width/thickness).

Marginal Facies: Potential Baffle/Barrier to Flow

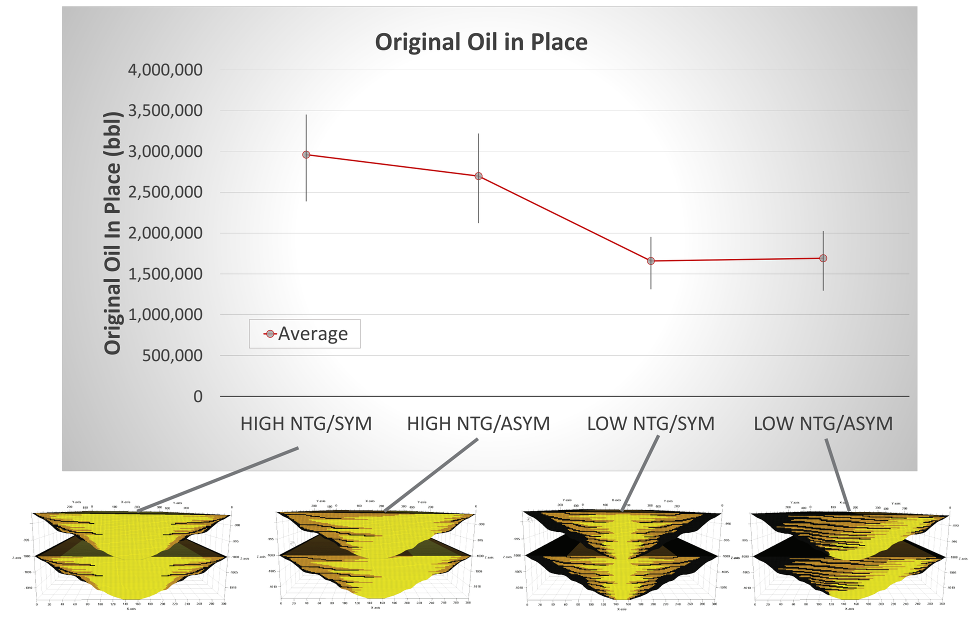
Marginal facies have the greatest impact on inter-channel connectivity in scenarios where channels are predominantly laterally stacked.



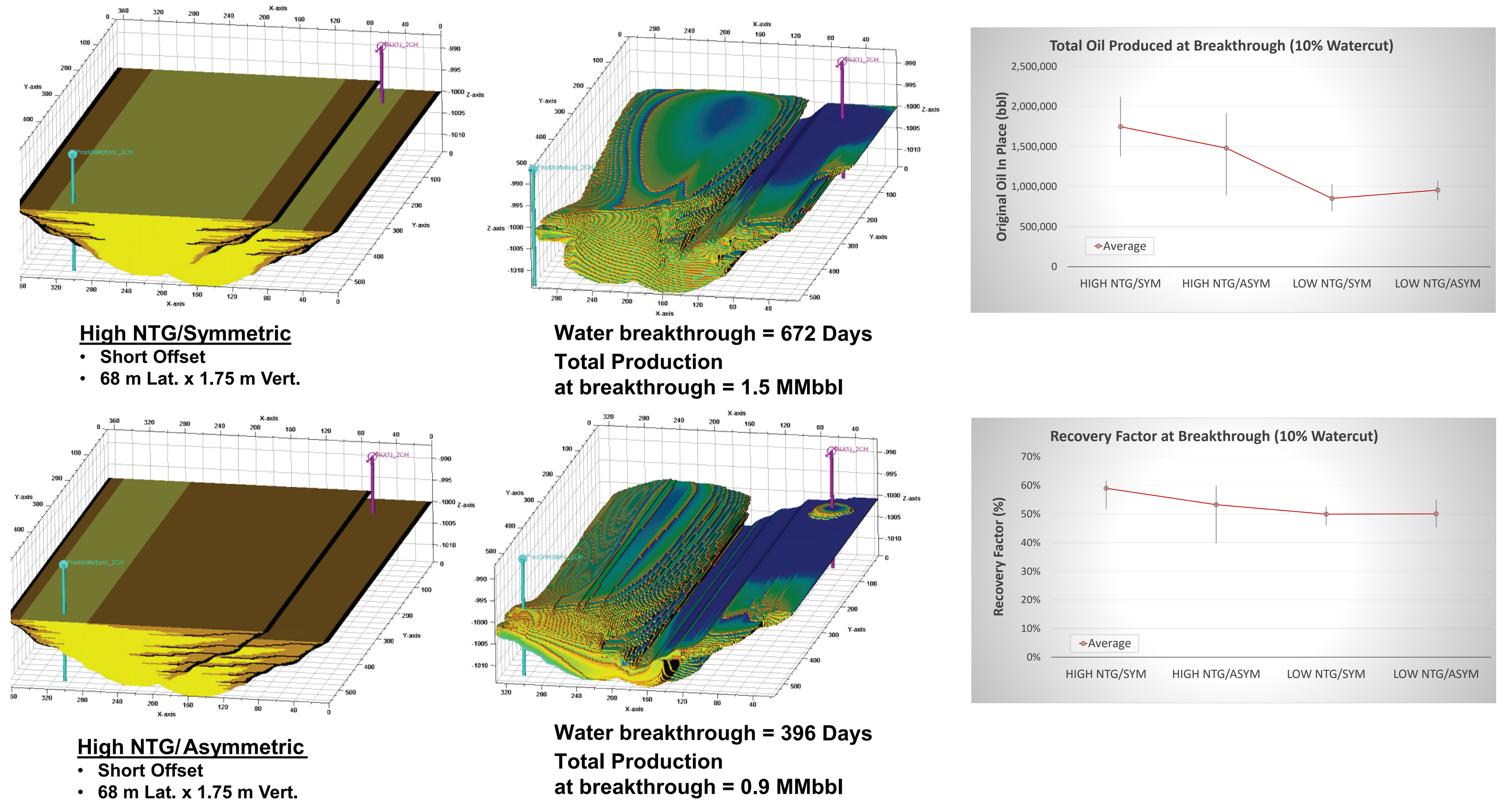
Above: In the long offset, laterally stacked "High NTG/Symmetric" scenario above, oil production and water breakthrough are slowed by the baffling effect of marginal facies. Introducing 1.5 meters of vertical offset increases the average production rate by 20%, also resulting in water breakthrough 284 days earlier. Below: XY-plots depict lateral (x-axis) vs vertical (y-axis) offset for each of 48 total simulations. Red dots represent no connectivity between channels, while green dots represent intra-channel connection. Results suggest increased risk of reservoir compartmentalization with the introduction of asymmetric internal architecture and reduced net to gross.



Sensitivity Analysis: Volumetrics and Recovery Factor

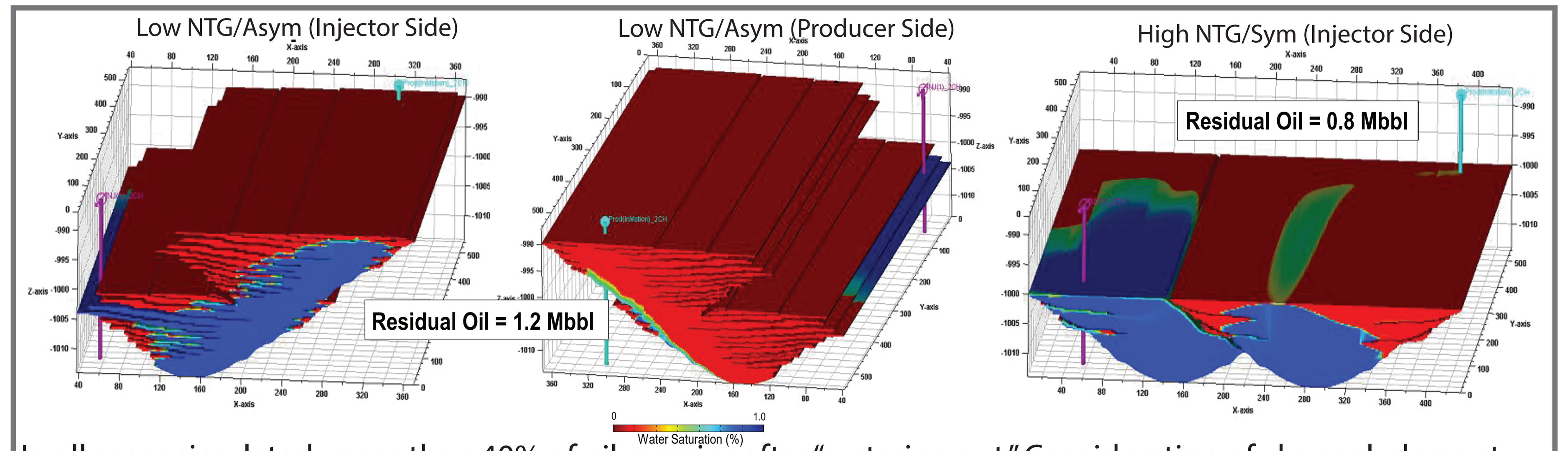


Whisker-plot showing the range and average original oil in place (OOIP) for all 48 simulations, grouped by internal architecture. Although facies distributions are held constant for individual channel fills (either high or low NTG) volumetrics are highly sensitive to the interaction of internal architecture with stacking, as the second channel is assumed to incise the first, potentially replacing desireable axis sands with margin facies, or vice-versa. OOIP is reduced 10% on average (11-22%) with the introduction of asymmetry. OOIP is reduced by 45% on average from high to low net:gross.



Above: Facies and water saturation volumes showing the impact of asymmetry on volumetrics and recovery factors. Asymmetry reduced average total production at breakthrough by 43% for the high net scenarios, but increased it by 9% for the low net scenarios. Recovery factors vary up to +/- 10%, with the greatest impacts to more laterally stacked scenarios.

Residual Oil Volume and Distribution Estimation



In all cases simulated, more than 40% of oil remains after "watering out." Consideration of channel-element scale heterogeneity will play an important role in improving risk assesment and field development strategies.

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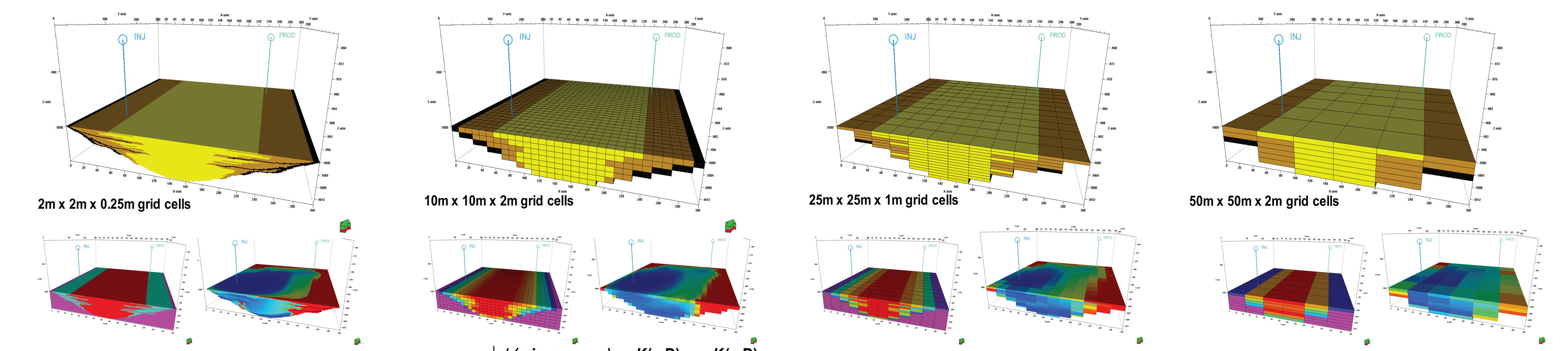
Upscaling: Optimal Grid Selection



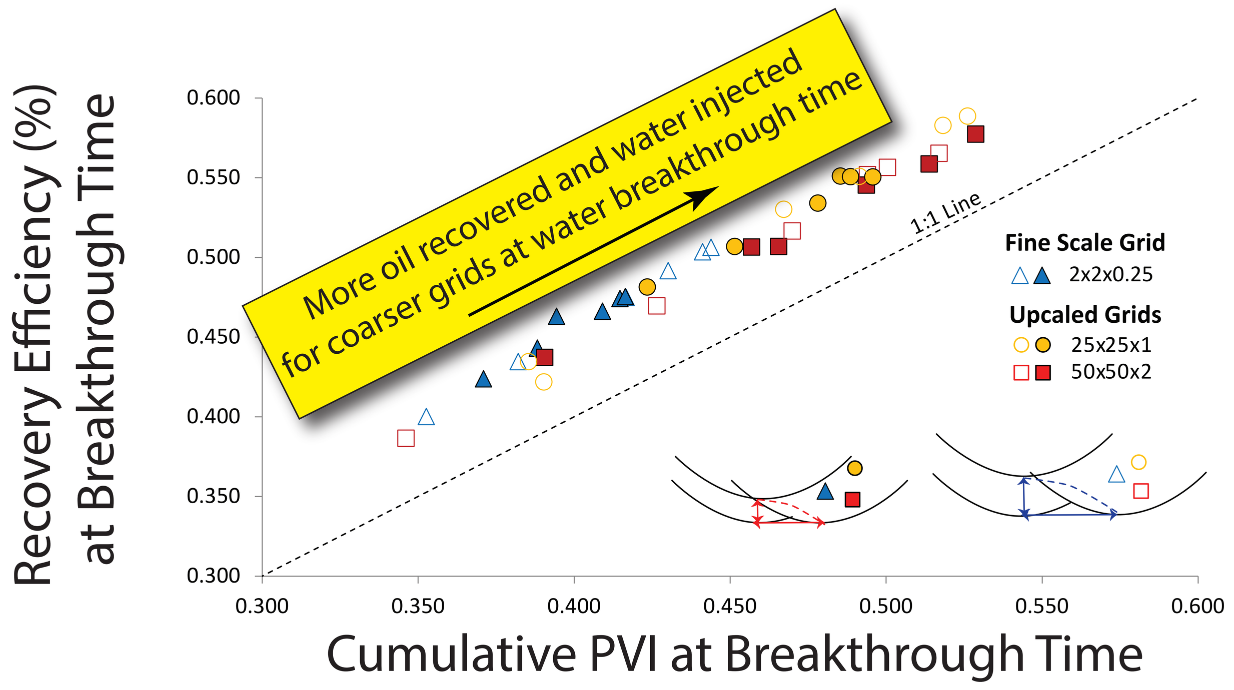
ϕ	K_{xy} (mD)	K_z (mD)
0.3	50	25
0.28	10	1
0.0	0	0

UPSCALING
ϕ Volumetric averaging
$K_{xy,z}$ Flow-based upscaling

	ϕ (min-max,avg)	K(mD)	K(mD)
yellow	0.03-0.3, 0.28	2-50, 44	0-50, 37
brown	0.0-0.29, 0.21	0-27, 11	0-16, 4
black	0.0-0.12, 0.03	0-3, 0.6	~0

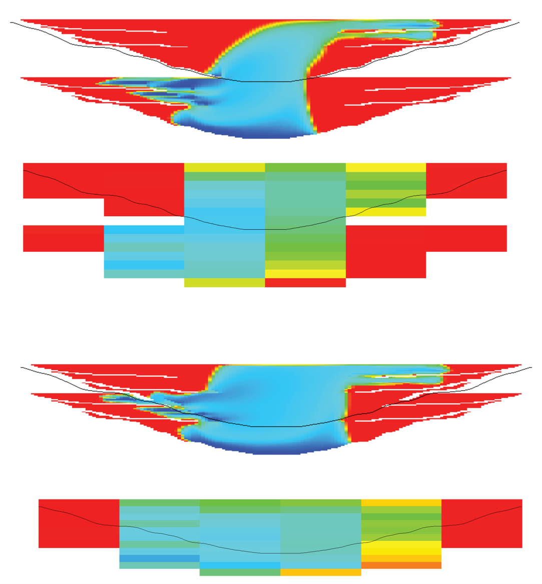
	ϕ (min-max,avg)	K(mD)	K(mD)
yellow	0.16-0.3, 0.29	17-50,45	1-50, 43
brown	0.14-0.29, 0.23	3-25,11	0-17,7
black	0.06	0.3	~0

	ϕ (min-max,avg)	K(mD)	K(mD)
yellow	0.13-0.3, 0.27	13-50, 42	1-50, 40
brown	0.01-0.26, 0.15	0.1-21, 7	0-6, 3
black	0.03	0.2	~0

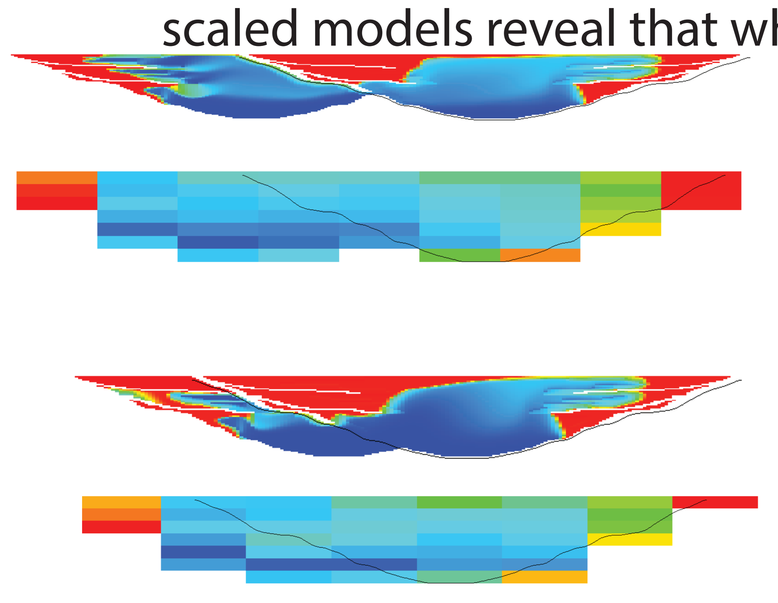


Above: Each of the 12 offset models for the "High NTG/Symmetric" realization were up-scaled and re-run to evaulate the impact of upscaling on reservoir performance as a function of channel stacking pattern . Single channel representations are shown to highlight gridding.

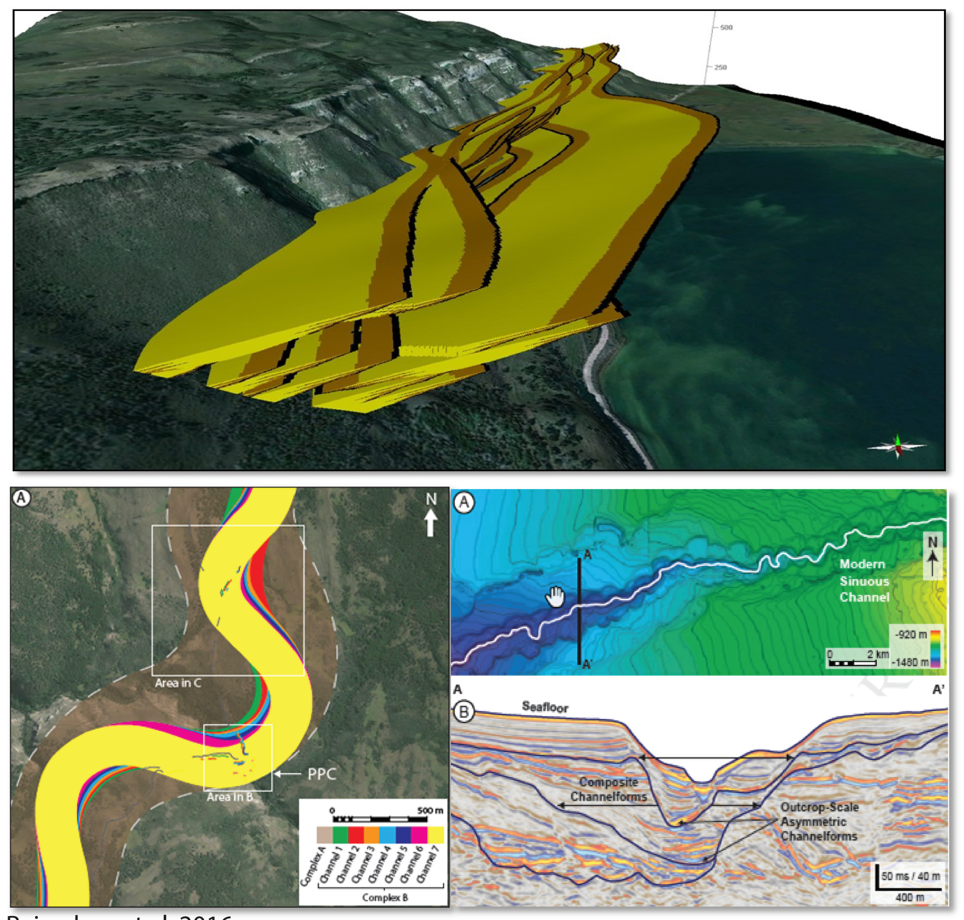
Left Plot: Cumulative pore volumes of water injected (PVI) at the time of water break-through as a function of the amount of oil re-covered at water breakthrough. The up-scaled models reveal that when water breaks through, more water has been injected and more oil recovered than in the fine-scale models.



Upscaling multiple channels degrades the ability to represent the marginal facies and limits the marginal facies impact on flow. The effect is stronger in laterally staced channels than in vertically stackaed channels.



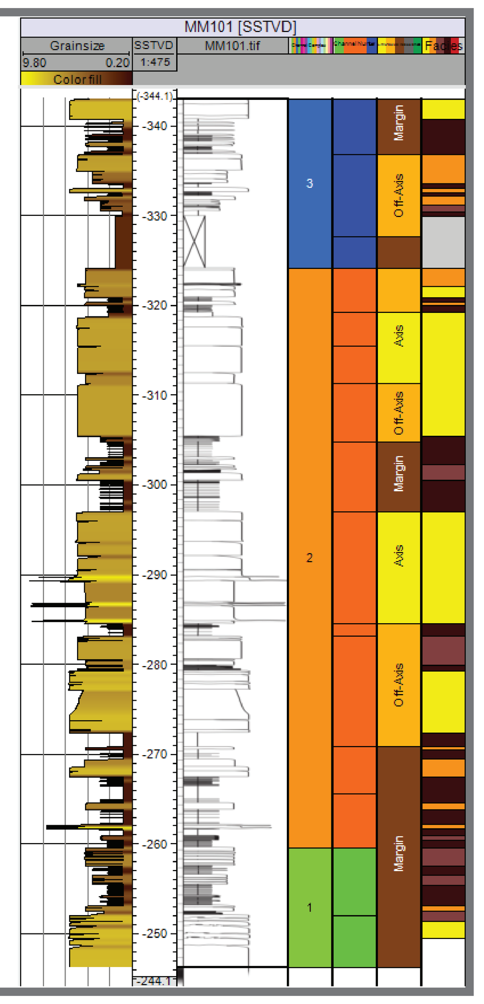
Reservoir Performance Investigation: Future Directions



Reimchen et al, 2016

Left: Ongoing research will expand into reservoir-scale modeling at both Laguna Figueroa and Arroyo Picana locales. Sea-floor morphometrics relating channel sinuosity and channel fill asymmetry (Reimchen et. al, 2016) will be used to develop channel fills for the sinuous Arroyo Picana channels.

Right: We continue to collect new data and develop methodologies for creating useful metrics to quantitatively describe sedimentologic relationships observed in outcrop.



Drones, Photogrammetry, and 3D Outcrop Models

The Chile Slope Systems Team has begun testing new hardware and software technologies for the development of 3D digital outcrop models. The primary purpose of this effort is to facilitate qualitative and quantitative outcrop characterization.

Following the 2016 field season, the team has begun developing high resolution 3D outcrop models and is testing geometric data extraction and interpretation from the models. This effort has already enhanced outcrop interpretation and outreach.

Data and models created will inform future reservoir-scale modeling, enhancing efforts to elucidate the influence of reservoir architecture on performance.

Right: 3D high resolution outcrop models of exposures at Laguna Figueroa. Models are scaled and located in real-world coordinates, facilitating data extraction and interpretation.

Conclusions

1) Original oil in place (OOIP) is highly sensitive to channel stacking, varying +/- 20% of average when internal architecture is held constant.

2) Representation of asymmetric channel fill in reservoir simulations (where appropriate), may reduce error in total production estimates by 10-30%.

3) Decreasing net:gross may result in increased reservoir compartmentalization, especially where channel migration/amalgamation is mostly lateral.

4) Reservoir performance is strongly impacted by marginal facies when channels are laterally stacked.

5) Upscaling tends to under-represent marginal facies resulting in over-prediction of reservoir volumes and performance (total production, recovery efficiency, water breakthrough timing).

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