Quantifying Heterogeneities and Their Impact from Fluid Flow in Fluvial-Deltaic Reservoirs: Lessons Learned from the Ferron Sandstone Outcrop Analogue*

Peter E. Deveugle[1], Matthew D. Jackson[1], Gary J. Hampson[1], Craig S. Calvert[2], Anthony R. Sprague[2], Michael E. Farrell[2], and Jonathan Stewart[2]

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[1]Earth Science and Engineering, Imperial College London, London, United Kingdom (peter.deveugle@imperial.ac.uk)
[2]ExxonMobil Upstream Research Company, Houston, TX

Abstract

Fluvial-dominated deltaic oil and gas reservoirs are economically important, but are characterized by complex facies architectures and flow behaviours. We have used a high resolution, reservoir-scale (4000 x 7000 x 50 m) geologic model of part of the Ferron Sandstone, an outcrop analogue for such reservoirs, to quantify key aspects of deltaic facies architecture, and to examine the impact of heterogeneity on fluid flow during production using streamline simulations directly on the model. The dimensions of delta lobes vary from 6 to 10 km in length, 2.5 to 9 km in width, and 4 to 30 m in thickness. A key control on recovery is the connectivity between delta lobes, which is affected by (i) the presence of distributary and/or fluvial channel sandstones, which can increase recovery by improving connectivity between delta lobes, but also decrease recovery if the permeability contrast between channel and delta lobe facies is large, and (ii) the continuity of distal delta front facies, which controls the sweep of lobes that are not penetrated by wells. Recovery is also affected by well spacing, because this dictates the degree of cross-flow between delta lobes, and by the orientation of channels with respect to injector-producer well pairs, because channel sandstones can act as thief zones. Quantification of stratigraphic architecture and associated fluid flow has enabled the representation of various geologic heterogeneities and their relative impact on recovery to be evaluated. Guidelines for reservoir geologists and engineers seeking to build quantitative models in a similar geologic setting are presented.

Imperial College London

ExxonMobil Upstream Research

Quantifying heterogeneities and their impact on fluid flow in fluvial-deltaic reservoirs

Lessons learned from the Ferron Sandstone outcrop analogue

PhD project 2005-2008

Imperial College
Matthew D Jackson
Gary J Hampson

ExxonMobil URC
Craig S Calvert
Anthony R Sprague
Michael E Farrell
Jonathan Stewart

Peter Deveugle
AAPG San Antonio, 22 April 2008

Research questions

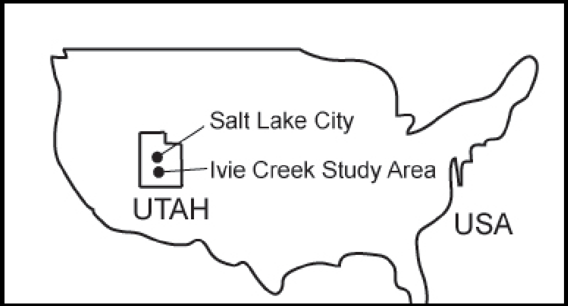
What are the typical dimensions for the building blocks of a fluvial-dominated delta, useful to build three-dimensional geologic models with ?

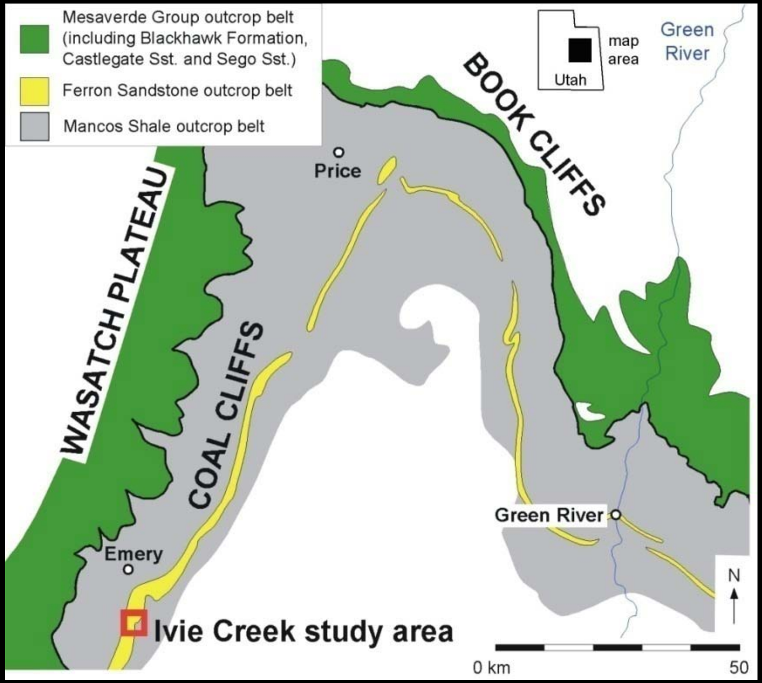
Which heterogeneities have an important impact on fluid flow (and at which scale) ?

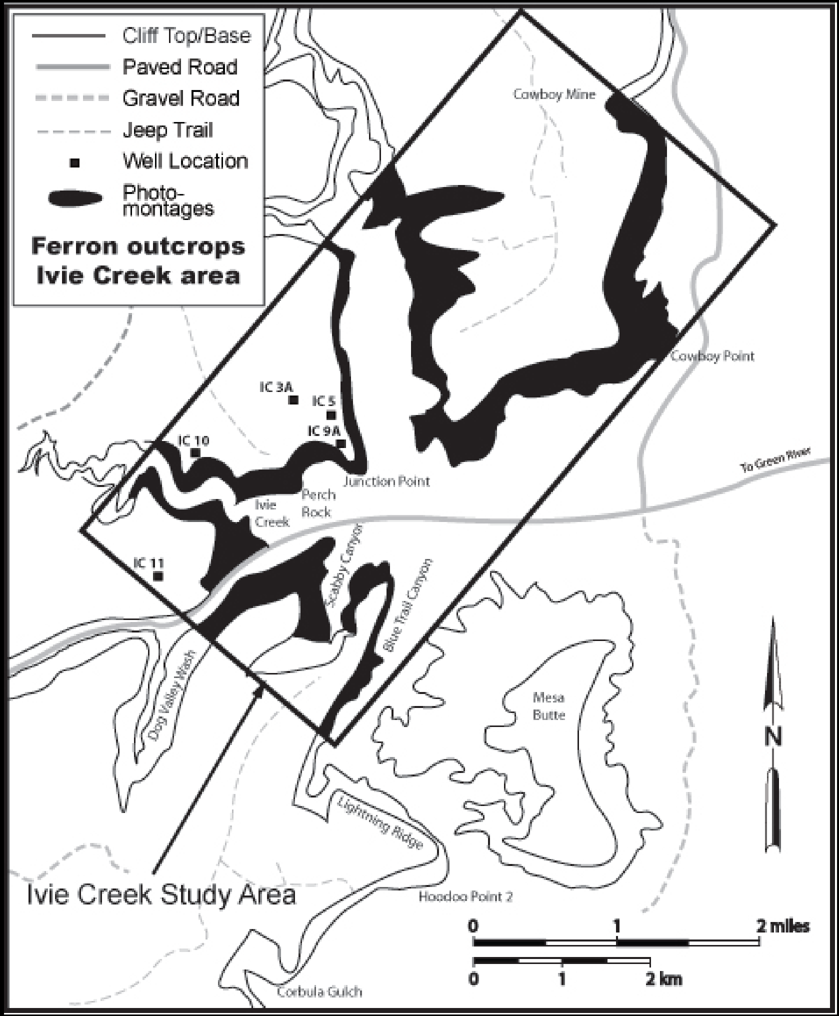
Which stochastic modeling technique best reproduces the reference model ?

What are the relative influences of modeling decisions on fluid flow simulations ?

Location of study area

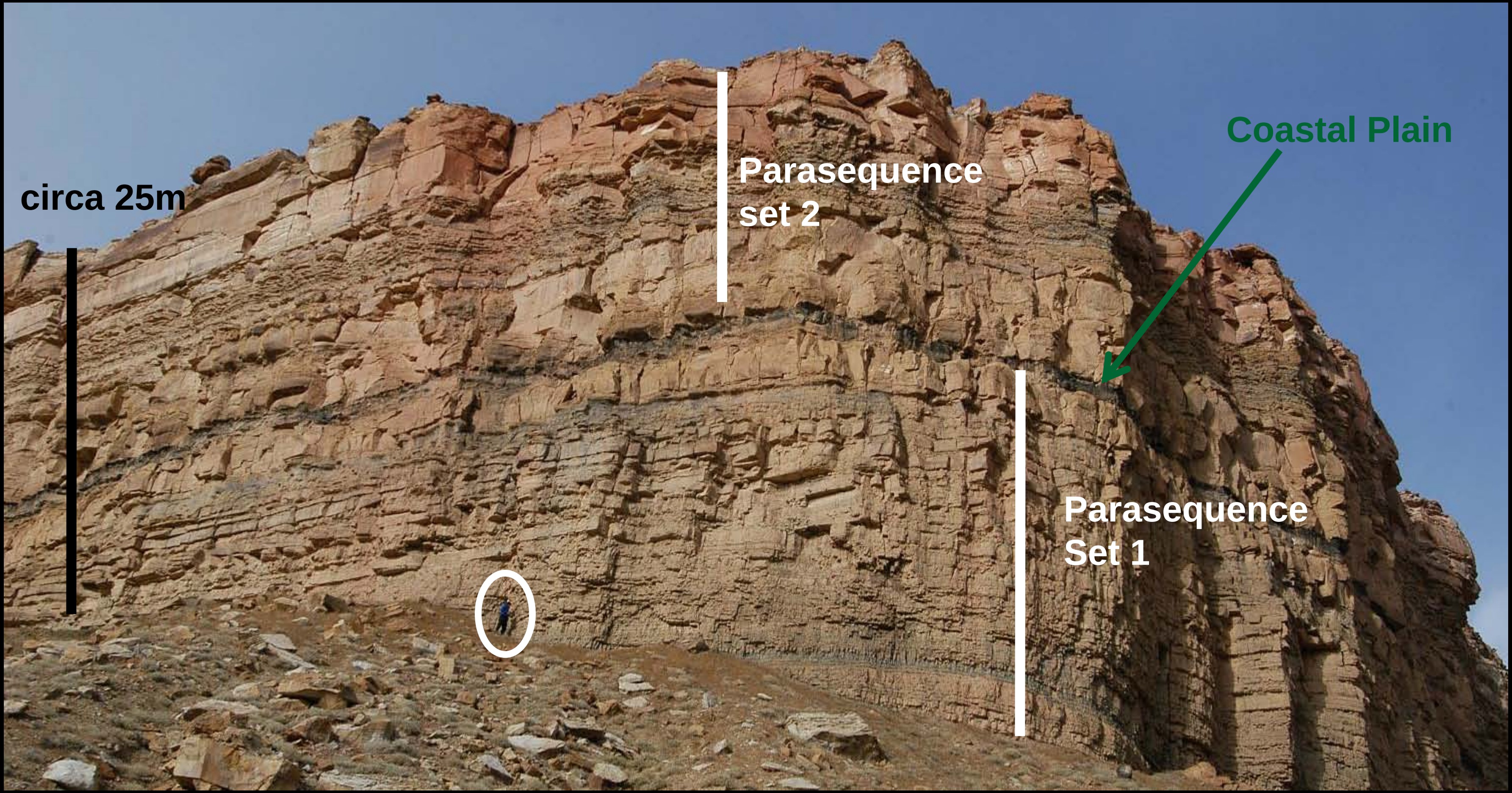






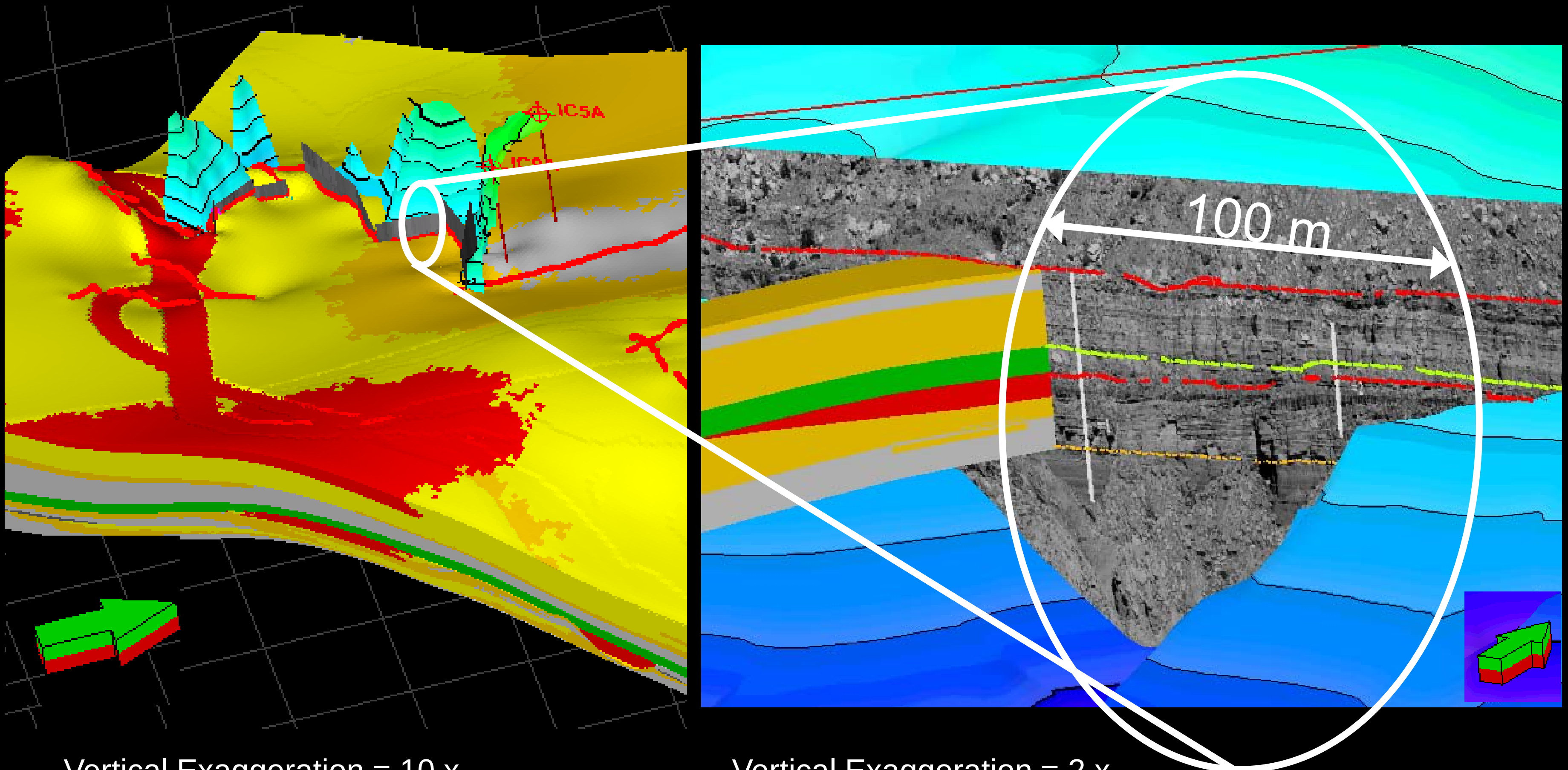
Reference model	Dimensions	Fluid flow	Summary

Outcrop architecture



Two parasequence sets (1.3-1.8 and 2.1-2.5) separated by a coastal plain section, marked by a continuous coal layer at the top

Ferron Sandstone 3D geologic model

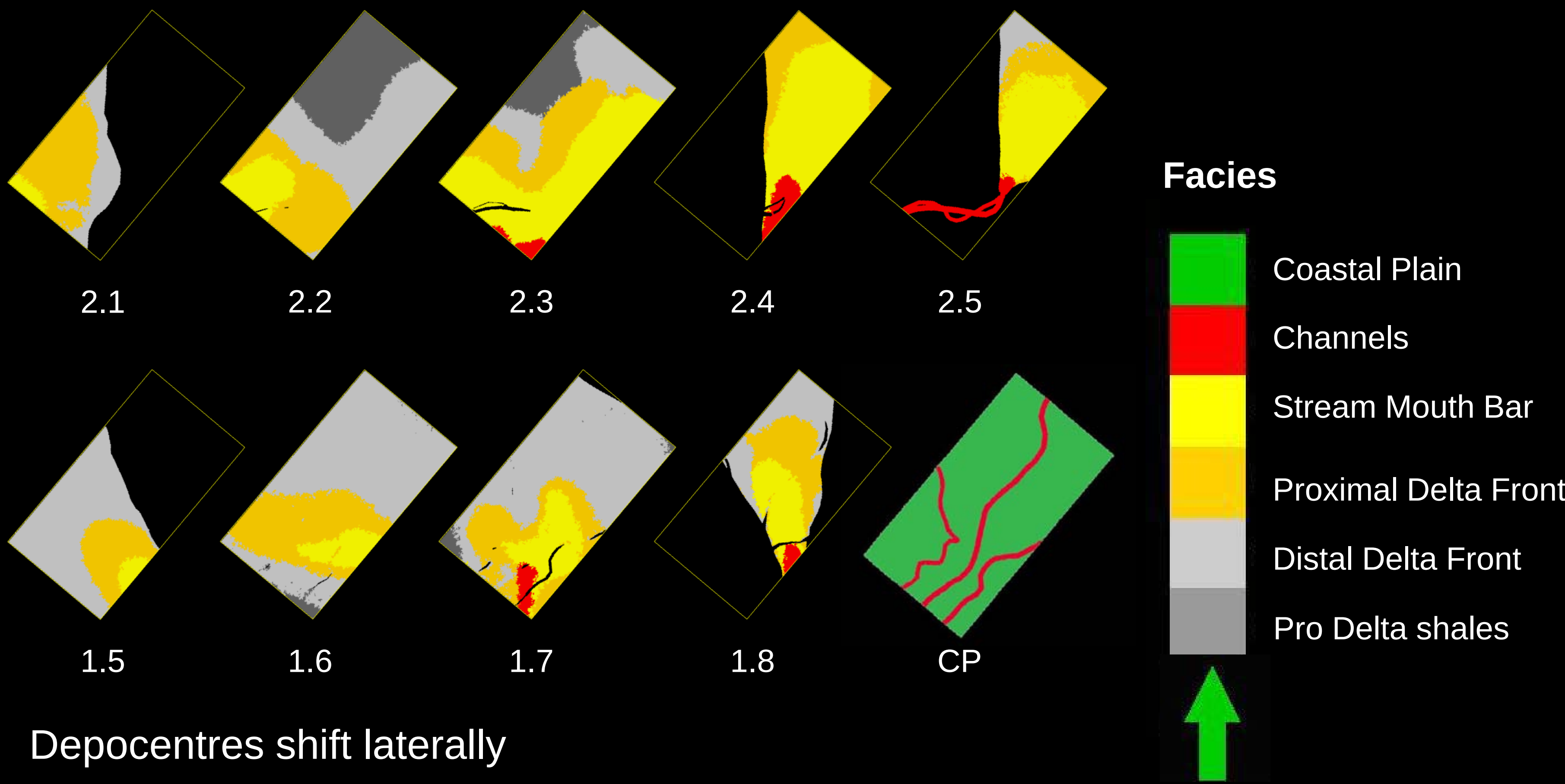


Vertical Exaggeration = 10 x

Vertical Exaggeration = 2 x

Three-dimensional facies model integrating satellite photos, photopanoramas, wireline logs and cores, measured sections along outcrop faces, …

Parasequence architecture

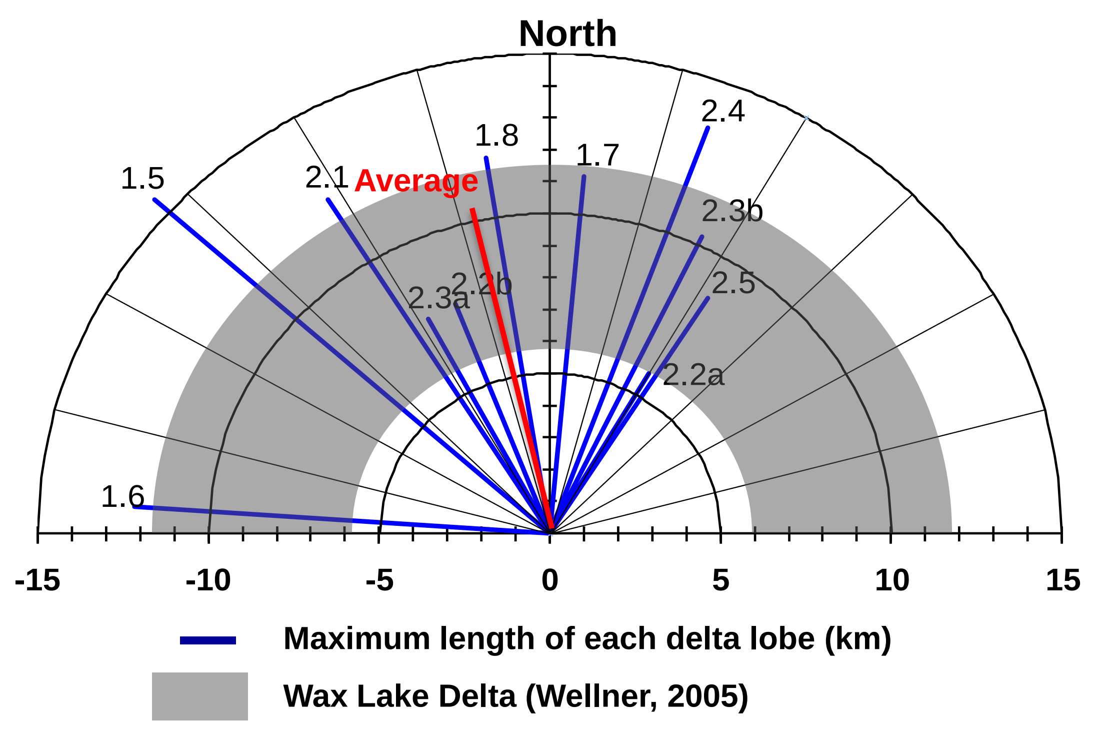


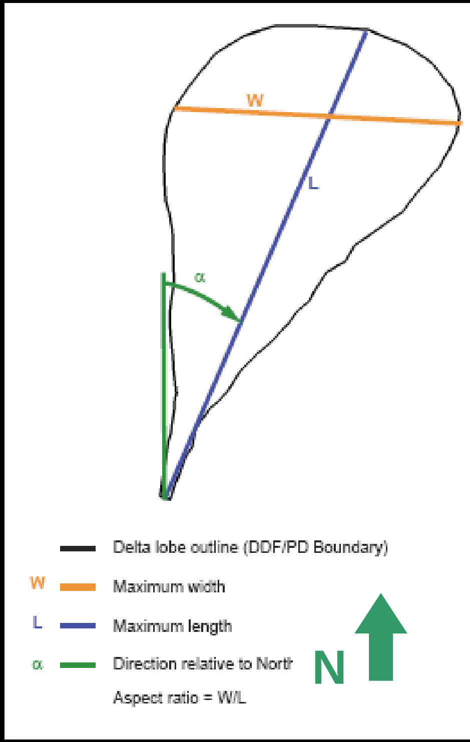
Depocentres shift laterally

Sediment sources (distributary channels) shift laterally

Interpretation of channels as distributary or fluvial potentially has great impact

Lobe length and orientation



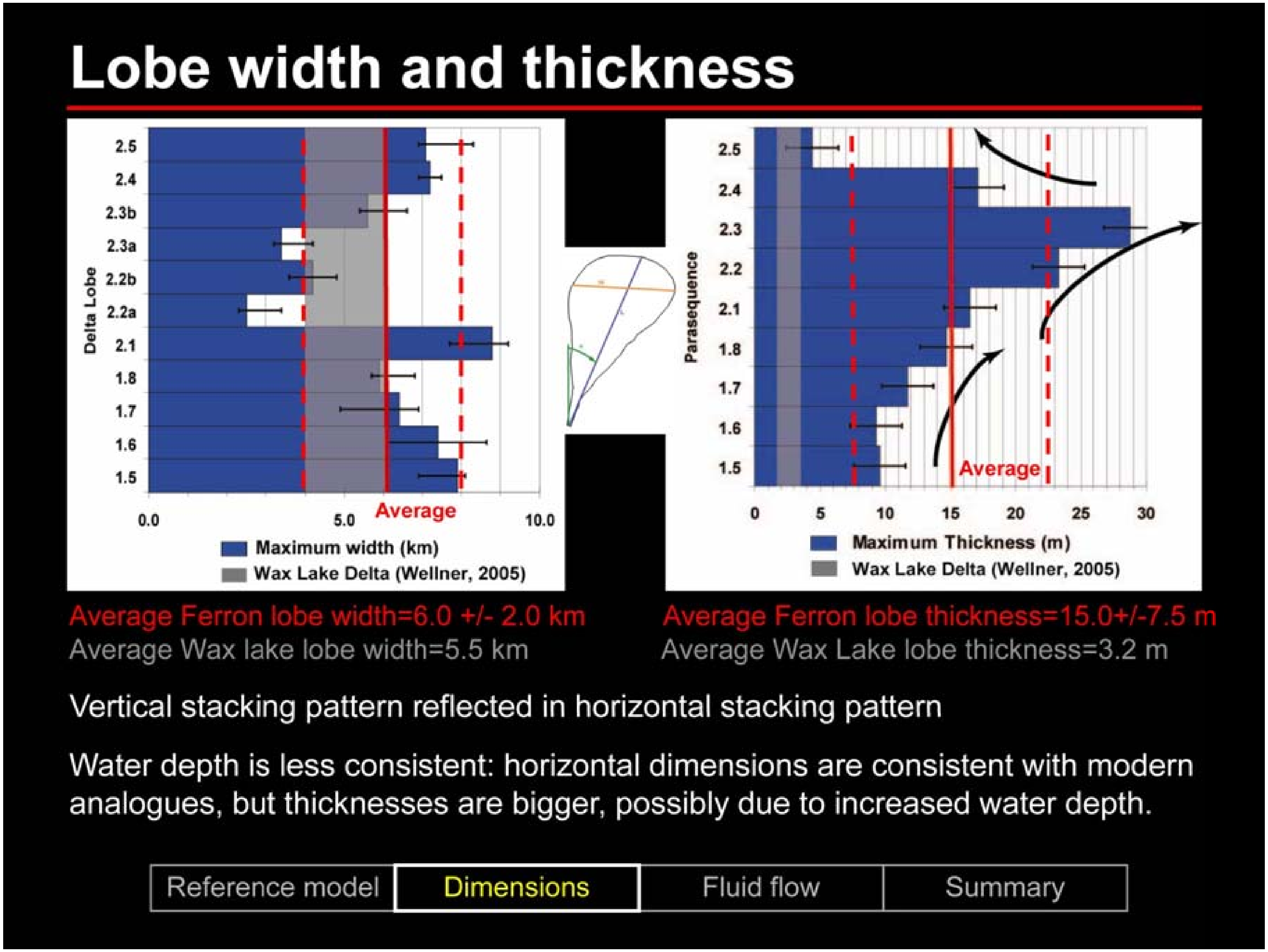


Average Ferron lobe length = 10.6 +/- 2.9 km

Average Wax Lake lobe length = 9.8 km

Lobe-switching directions vary around progradation direction (up to100º)

Evidence for partial compensational control on lateral stacking pattern (topographical bypass) with similarly sized lobes filling up the available space



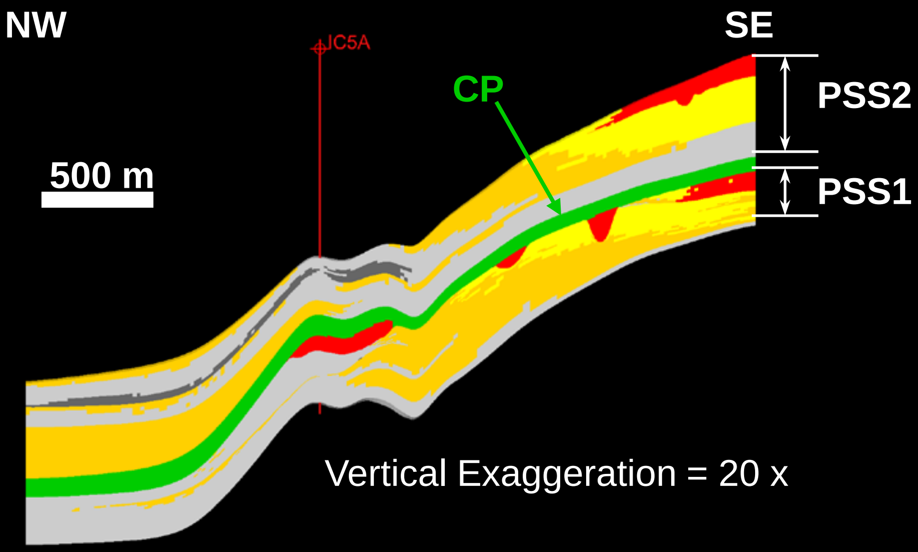
Notes by Presenter: 3D correlation dimensions for delta lobes need to be consistent with inferred depositional environment (here: on average 15 km long by 6 km wide)

Streamline simulations

Streamline based tracer simulation approximates a waterflood production scheme (no capillary & gravity effects)

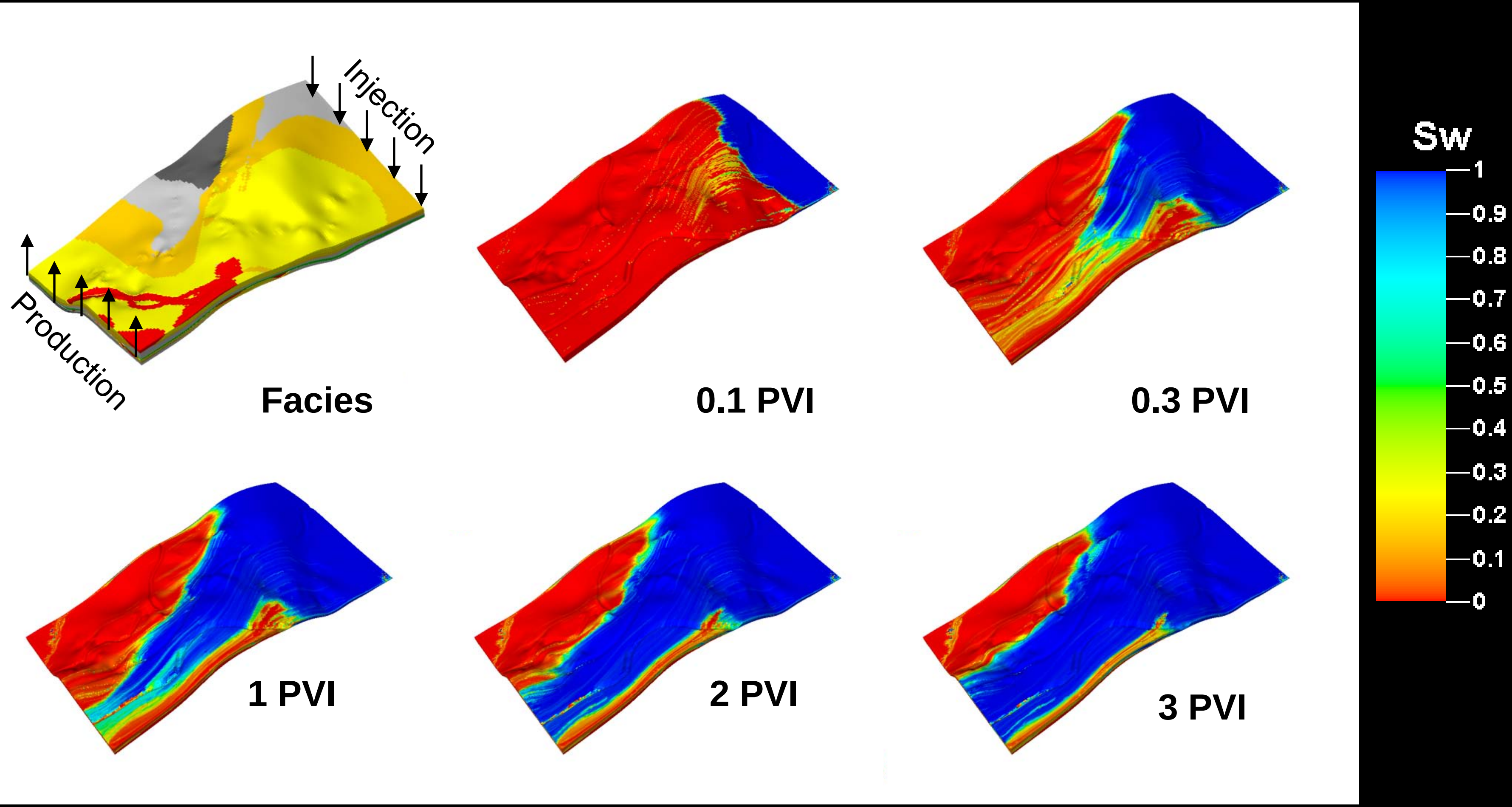
Parasequence sets simulated separately as they are interpreted to be hydraulically isolated (PSS2 &PSS1)

Constant porosity and permeability values per facies from mature subsurface analogue (South Timbalier field, Gulf of Mexico)



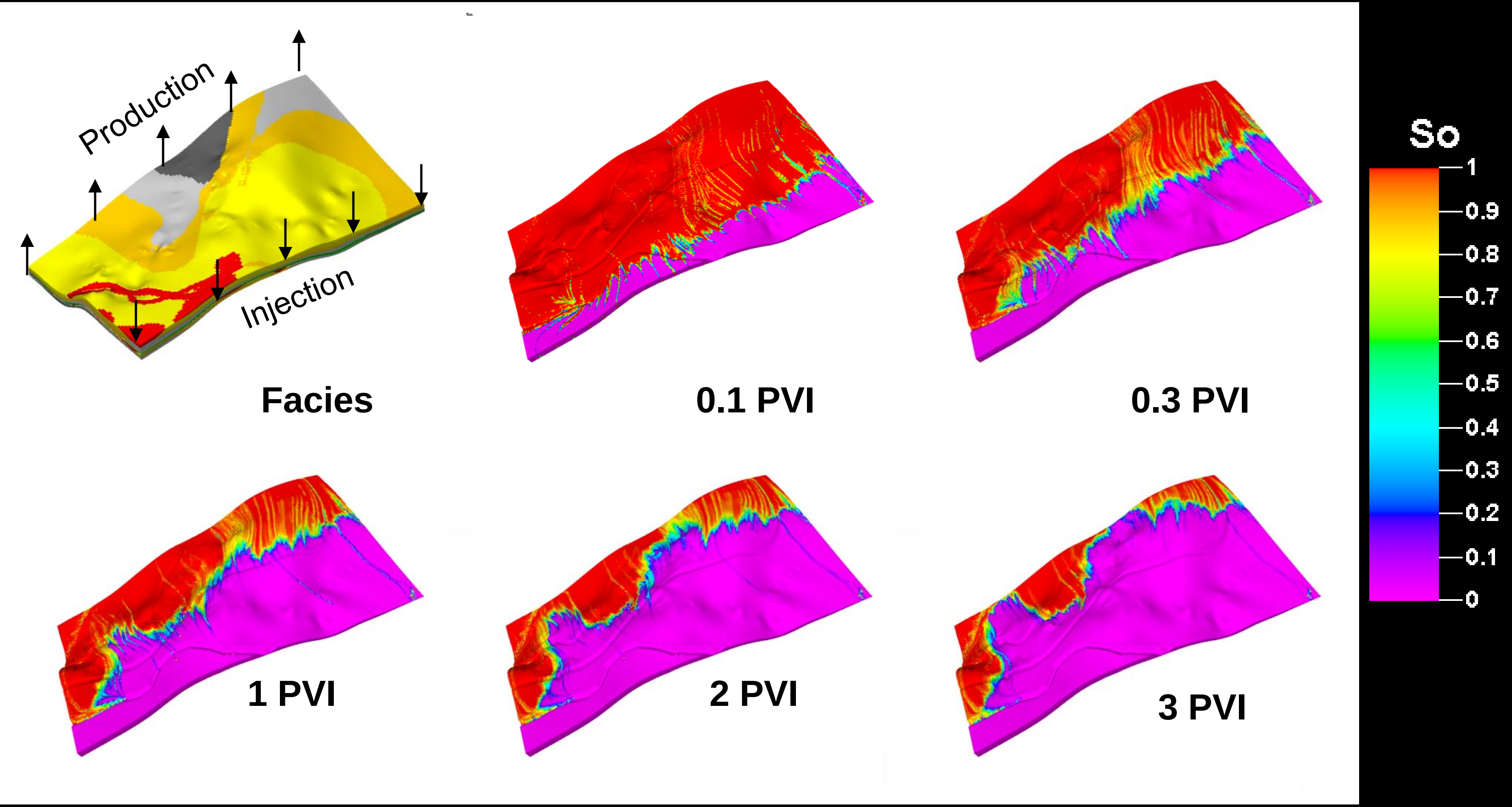
Facies	Porosity (%)	K_{mean} (mD)	Kv/Kh (-)
FC/DC	28	1793	0.9
SMB	28	1793	0.9
CP	NA	NA	NA
PDF	27	433	0.75
DDF	18	71	0
PD	NA	NA	NA

Pattern 1 (NE-SW)

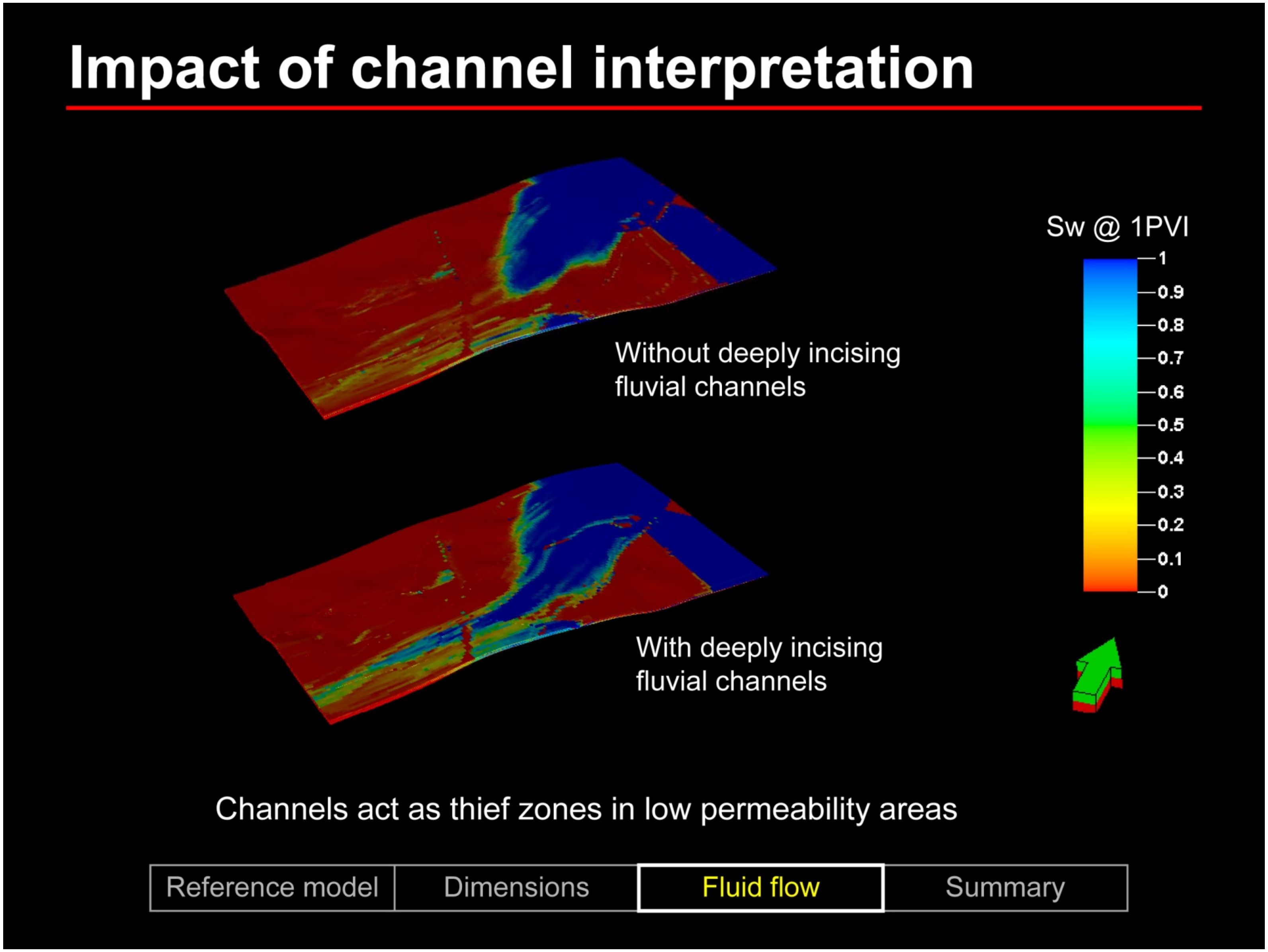


Injection and production from opposite faces

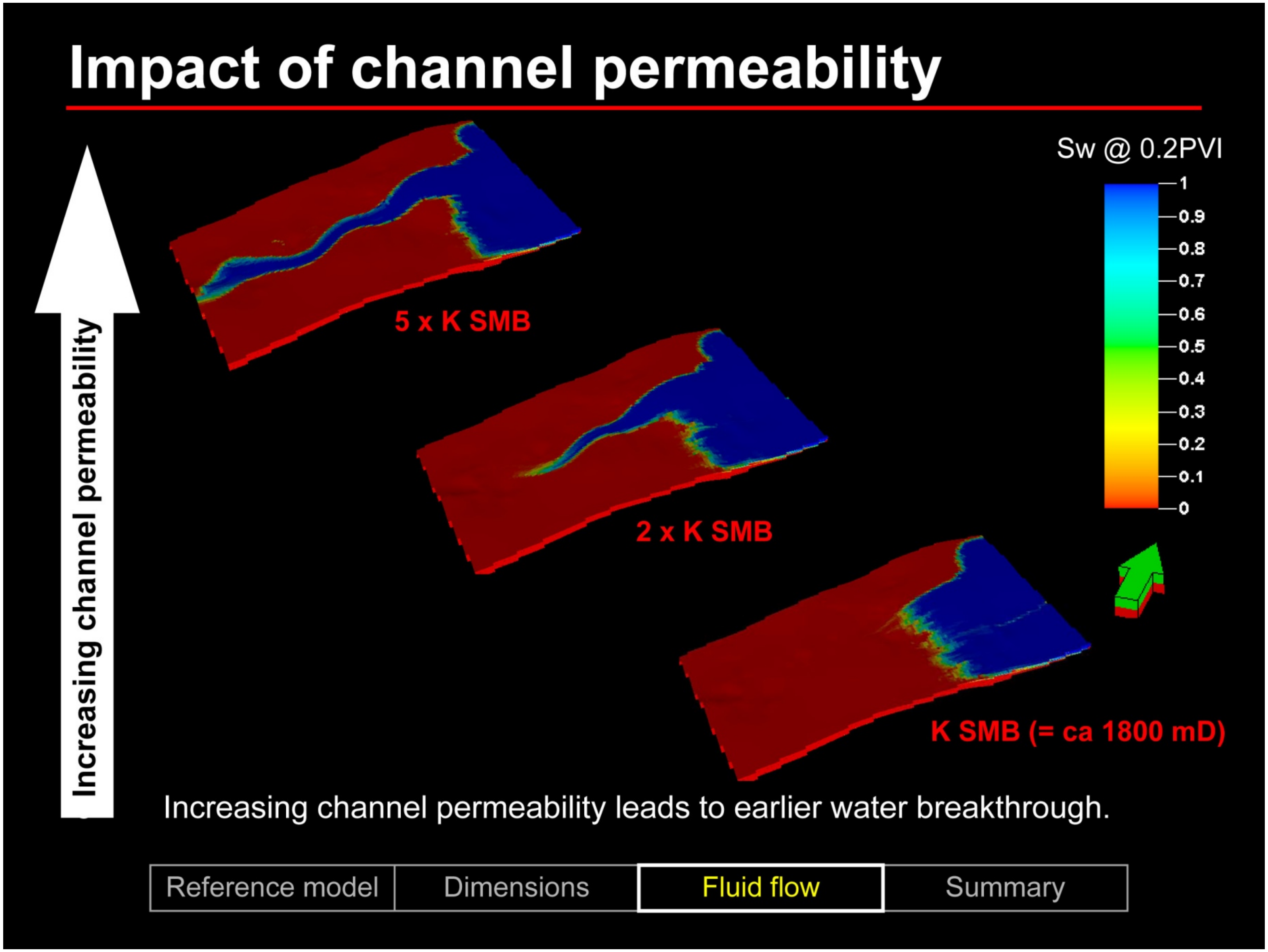
Pattern 2 (SE-NW)



Injection and production from opposite faces – reduced well spacing

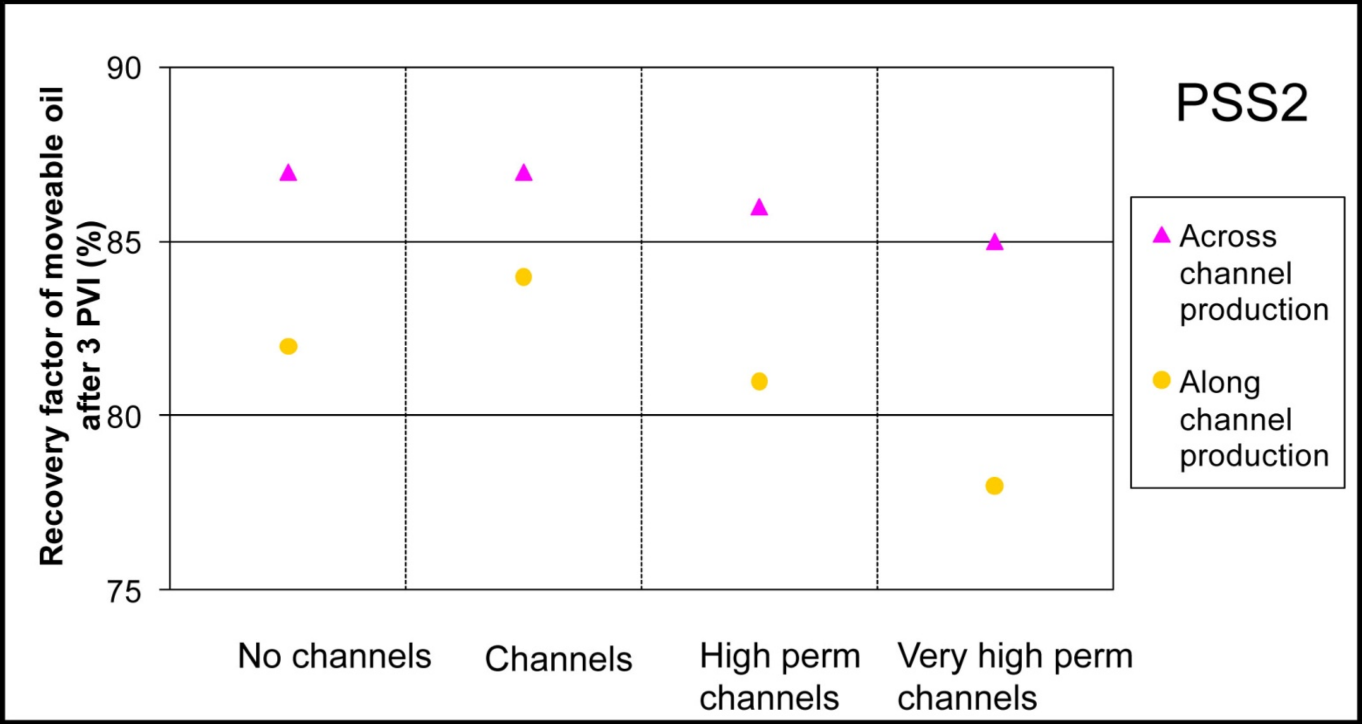


Notes by Presenter: Presence of channels improves recovery (due to its higher pore volume); however, increase of channel permeability decreases recovery (due to earlier water breakthrough).



Notes by Presenter: Increasing channel permeability leads to earlier water breakthrough.

Impact of channels



Presence of channels increases recovery (higher pore volume)
Increase of channel permeability decreases recovery (earlier water breakthrough)

Reference model	Dimensions	Fluid flow	Summary

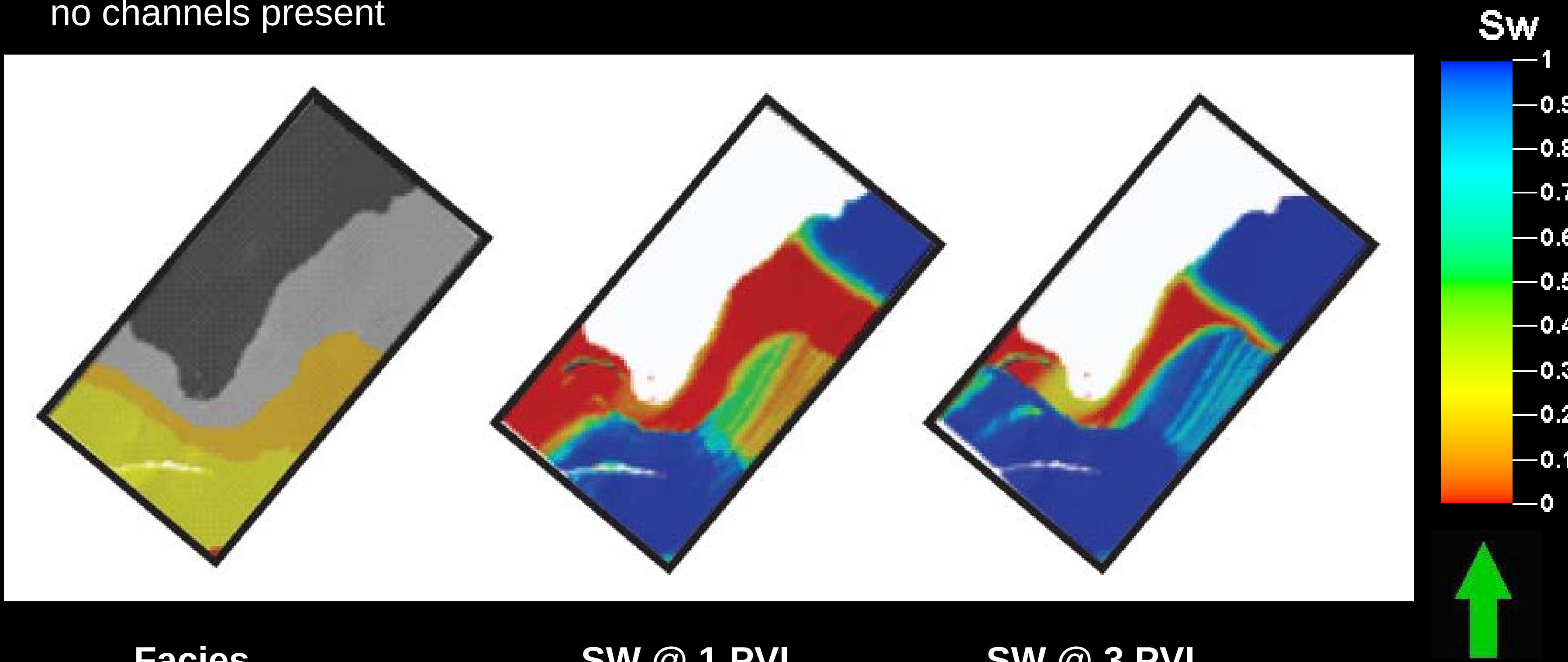
Notes by Presenter: Presence of channels improves recovery (due to its higher pore volume); however, increase of channel permeability decreases recovery (due to earlier water breakthrough).

Kv/Kh in Distal Delta Front

Continuity of small shale layers in Distal Delta Front (DDF) impacts on vertical permeability

Kv/Kh in Distal Delta Front

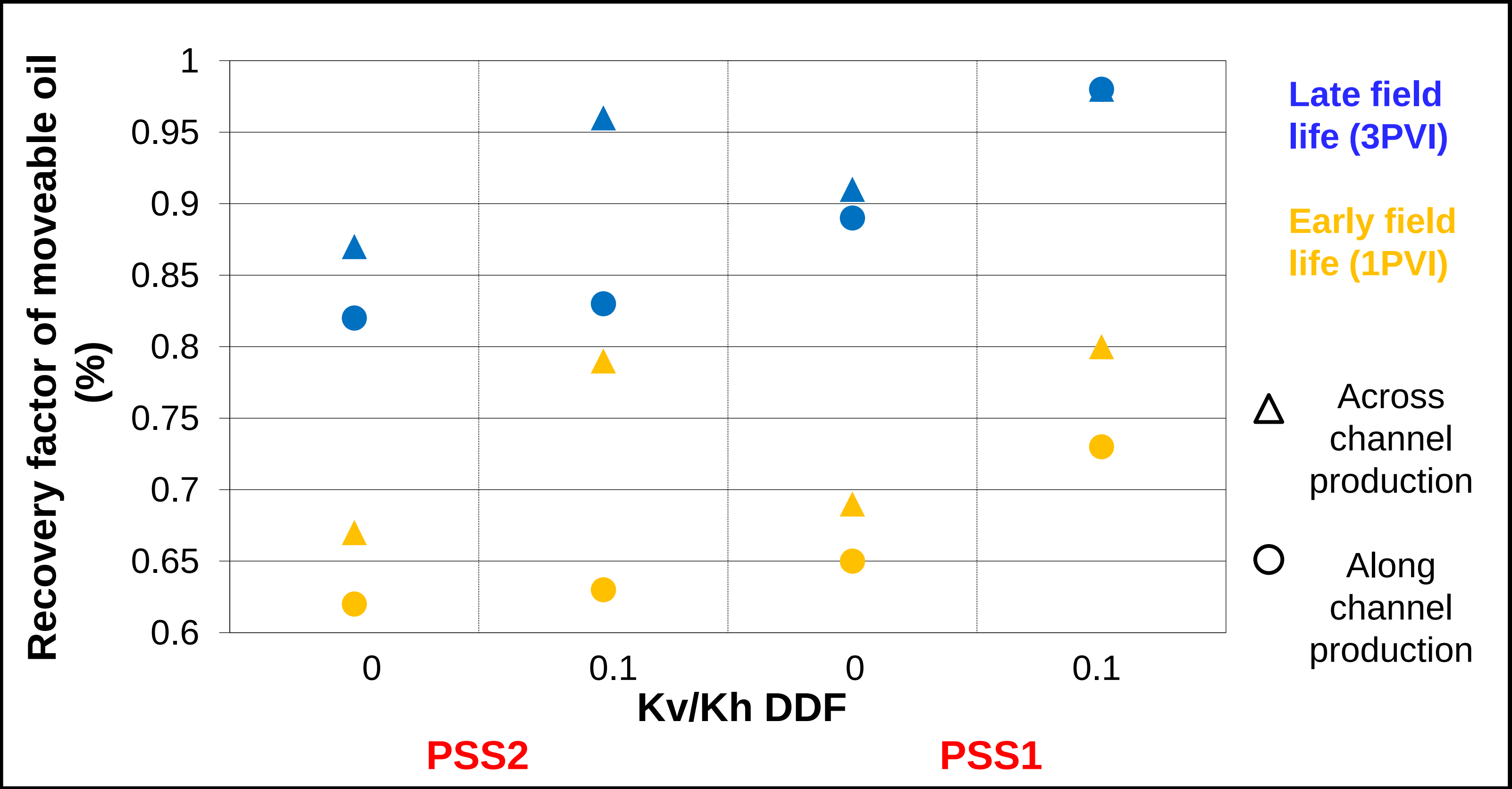
Layer 49 in zone PS 2.3 of PSS2, Kv/Kh DDF =0,
production along the long axis (NE-SW),
no channels present



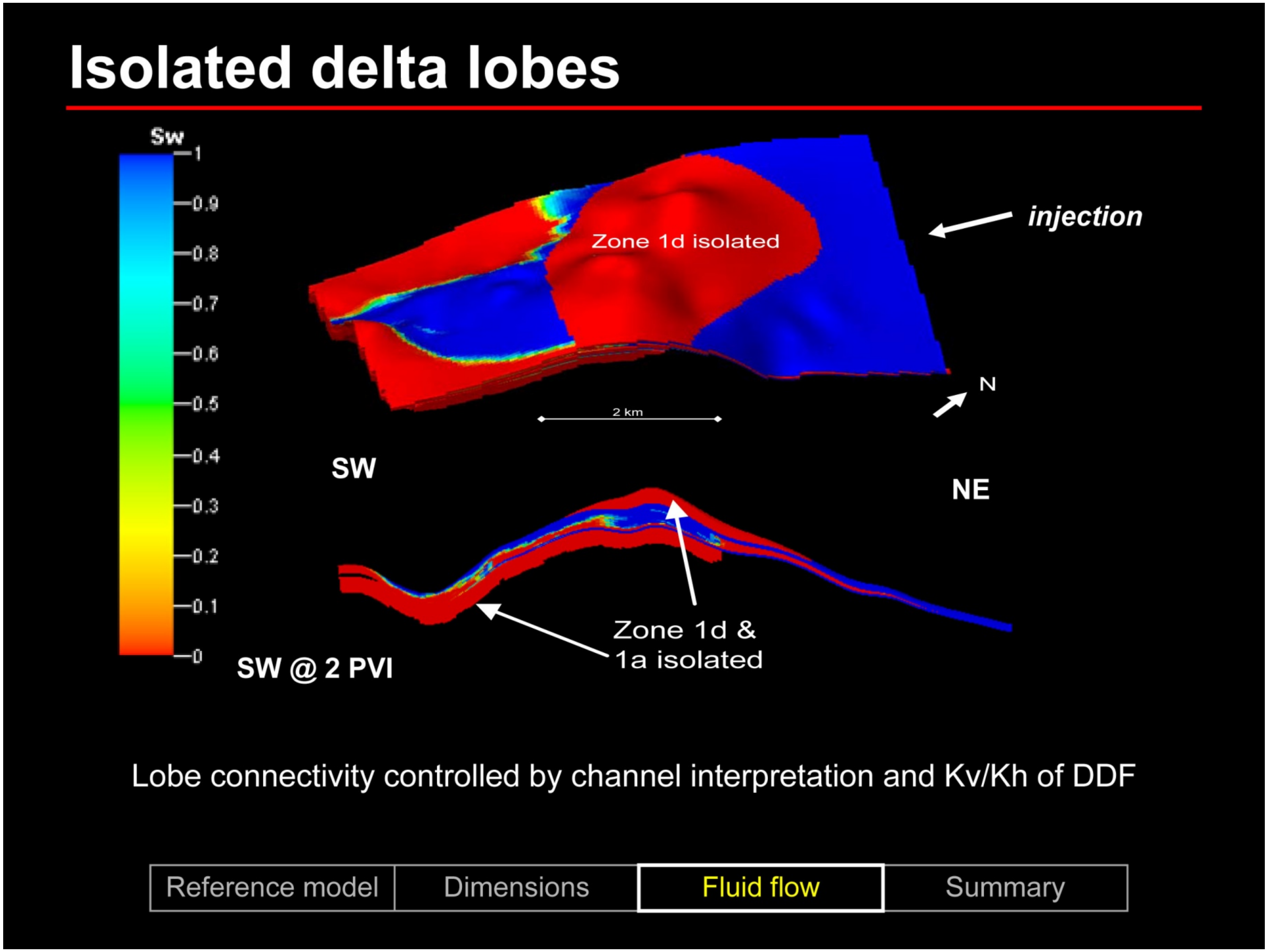
Facies **SW @ 1 PVI** **SW @ 3 PVI**

Oil is left unswept in delta lobes isolated by PD / DDF with zero Kv

Kv/Kh in Distal Delta Front

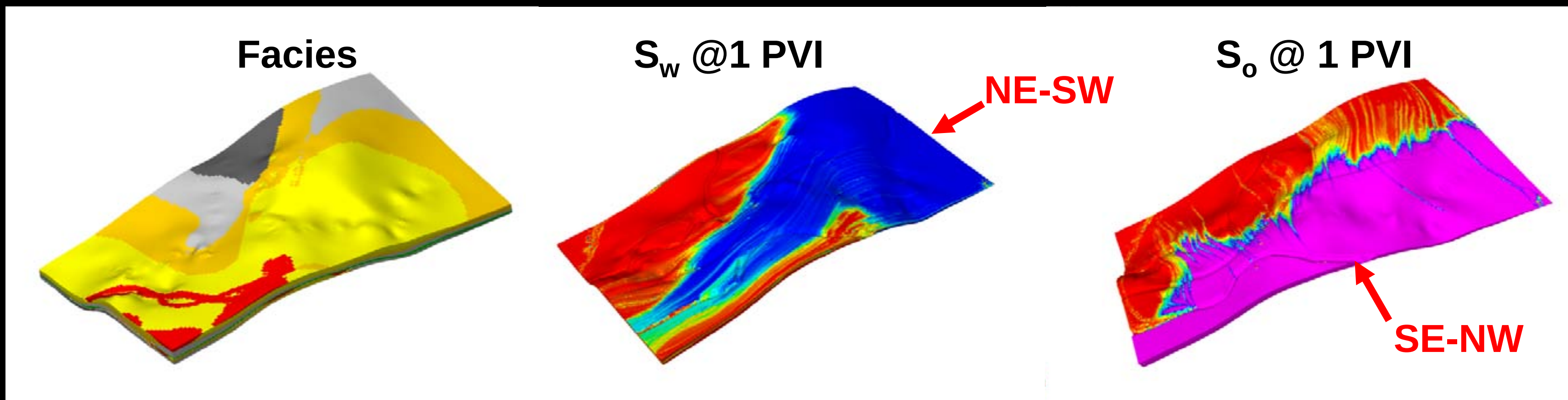


Continuity of distal delta front facies controls the sweep of delta lobes not connected by wells



Notes by Presenter: Due to interbedding of shale layers in DDF, its KV/Kh of 0.1 was introduced. The recovery increases as shown in pic; isolated zones get connected by considering DDF kv/kh =0.1.

Orientation of line drive /heterogeneities



NE-SW	RF(%) @1PVI	RF(%) @3PVI	BT in %PVI
PSS2	62	82	0.36
PSS1	63	80	0.22

SE-NW	RF(%) @1PVI	RF(%) @3PVI	BT in %PVI
PSS2	67	87	0.3
PSS1	79	96	0.41

Injection along long axis yields lower recovery and earlier breakthrough. The sweep efficiency is lower because lobes may be isolated and channels act as thief zones.

Injection along short axis yields higher sweep efficiency because all lobes are penetrated by injector-producer well pairs.

Conclusions

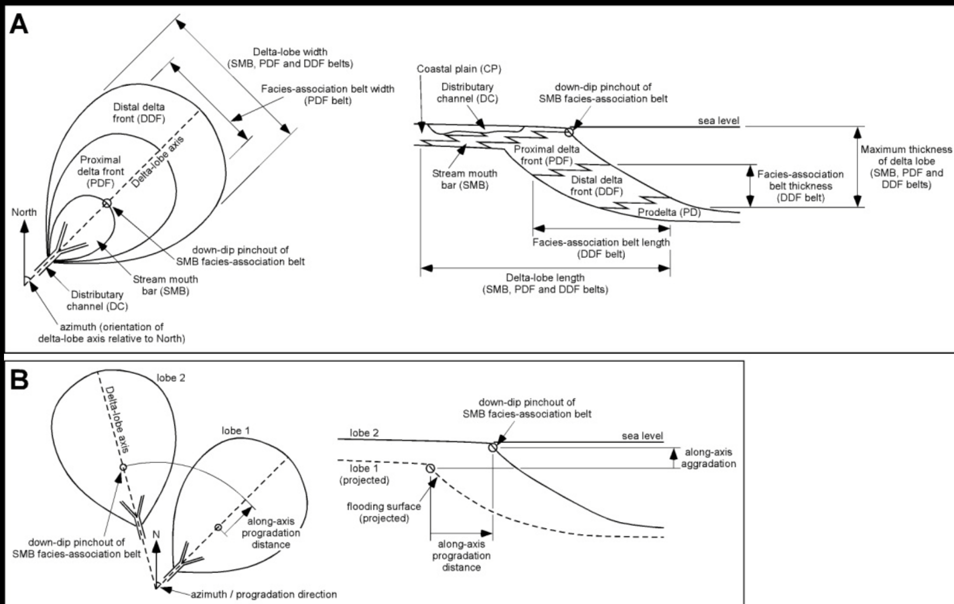
Dimensions:

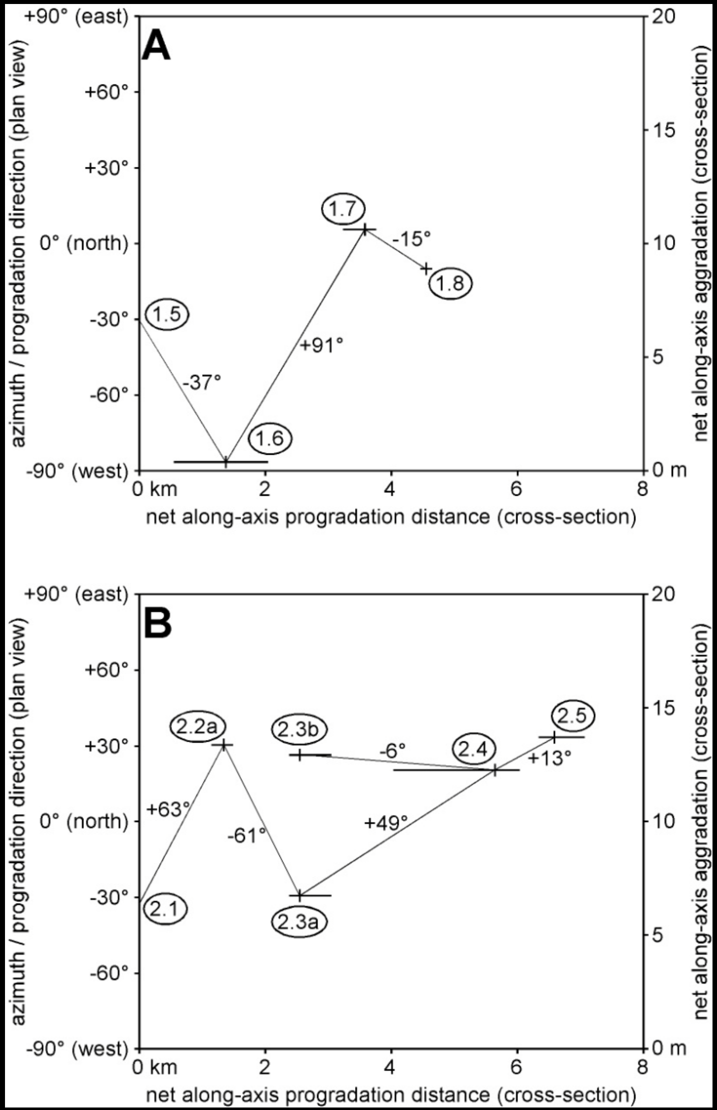
- Three-dimensional correlation delivers dimensions of individual delta lobes: on average 10.6 +/- 2.9 km long by 6 +/- 2 km wide by 15 +/- 7.5 m thick
- Evidence for mix of allocyclic (sea level, tectonic, …) and autocycylic (compensational stacking) controls on deposition

Fluid flow:

- Connectivity of delta lobes controlled by
  - Interpretation of channels (extent, orientation & characteristics)
  - Vertical permeability of heterolithic distal delta front
- Orientation of main fluid flow direction with regards to the orientation of the heterogeneities impact significantly on the sweeping pattern

Spatial distribution of building blocks



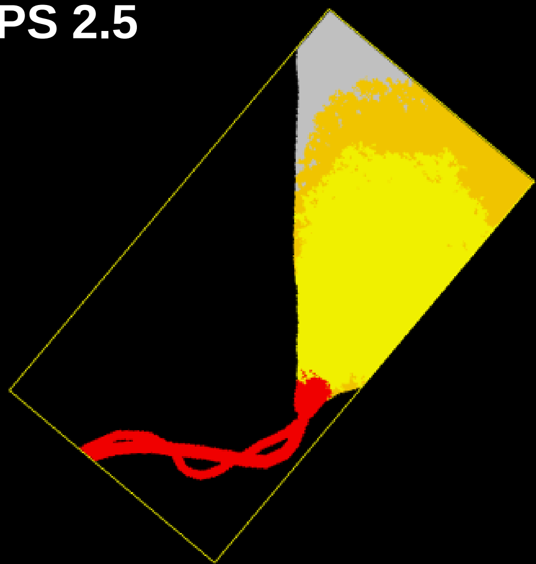


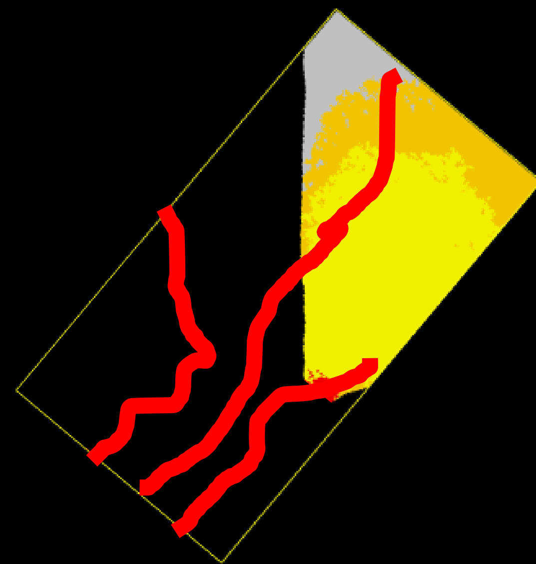
The delta lobes build out in steps towards the overall progradation direction, with a significant spread

The vertical stacking pattern is reflected in the horizontal progradation sequence

Channel interpretation

PS 2.5

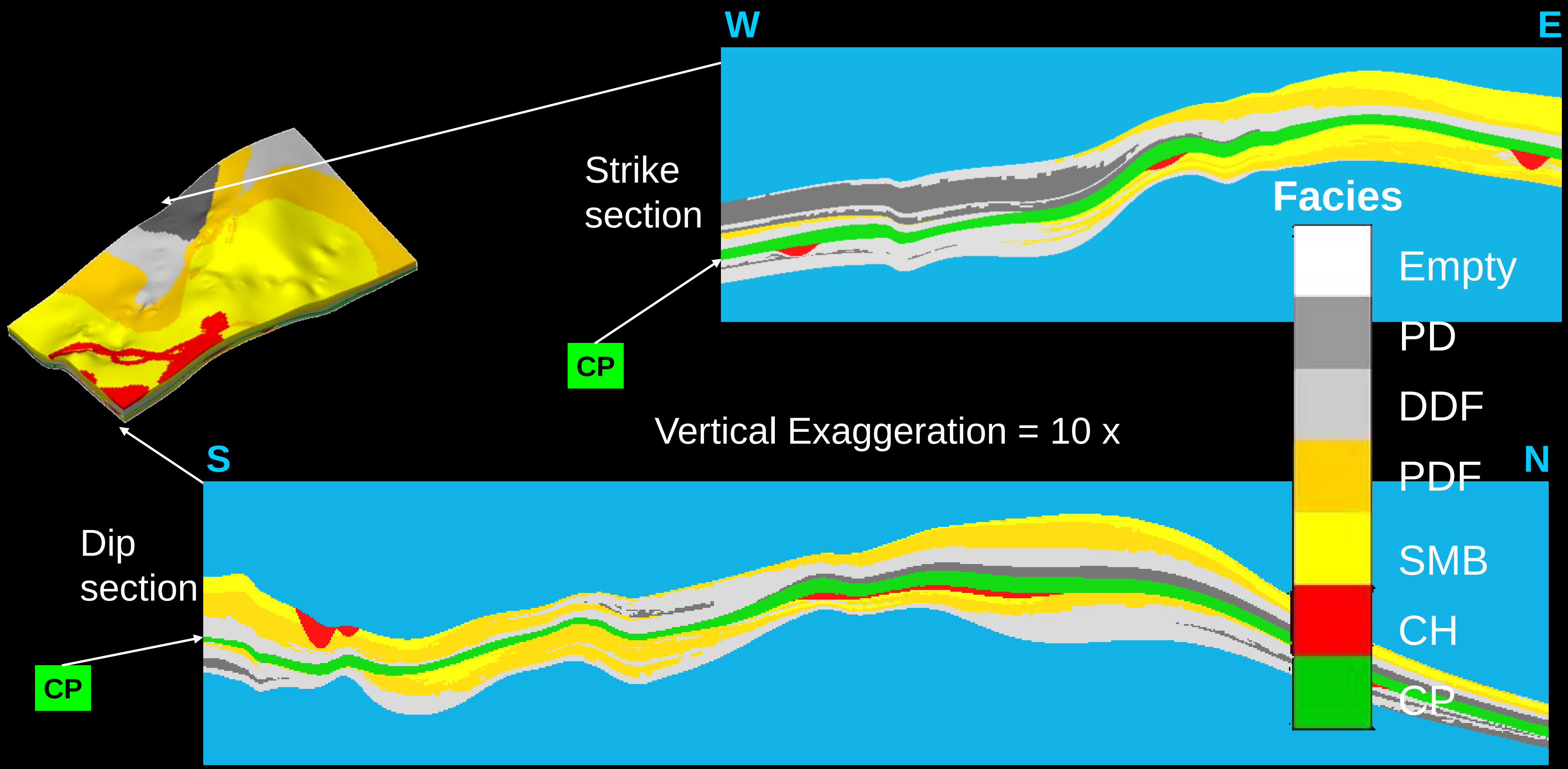




Channel facies encountered in well interpreted as distributary

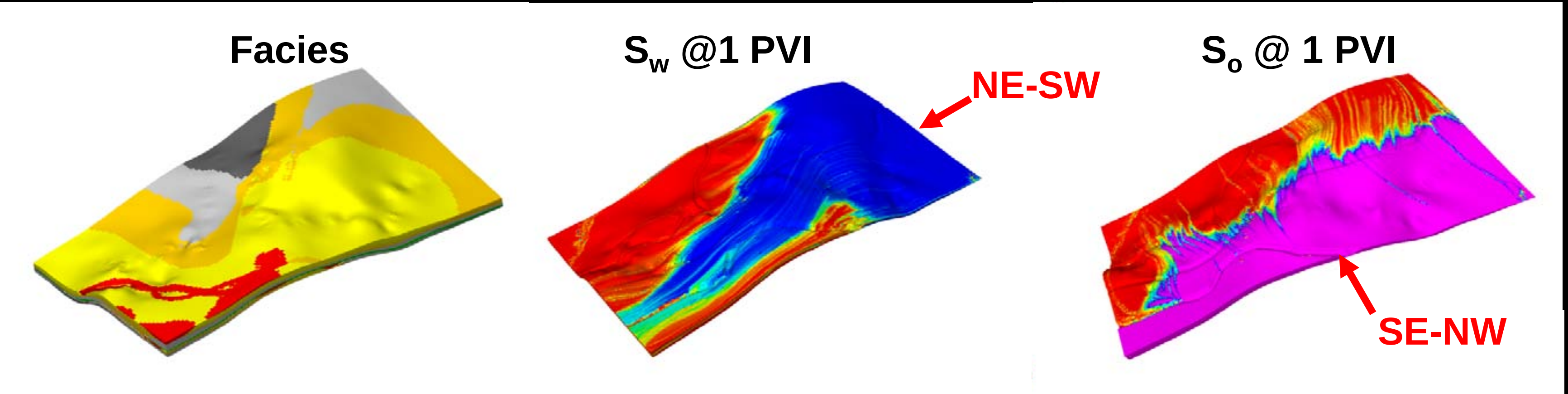
Channel facies encountered in well interpreted as fluvial

Orientation of line drive/heterogenities



More pinchouts along the long axis (N-S) reduces connectivity

Orientation of line drive /heterogenities



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Line drive along the long axis is along the main channel and lobe directions
Line drive along the short axis is across the main channel and lobe directions
The shorter well pattern increases total recovery (more sweep)
and breakthrough times longer ~ Concentration of streamlines
~ Local heterogeneities (Pro Delta)