Matrix Solutions Inc.
ENVIRONMENT & ENGINEERING

Quantifying Risk for Groundwater Modelling

From Deterministic to Stochastic Geo-models

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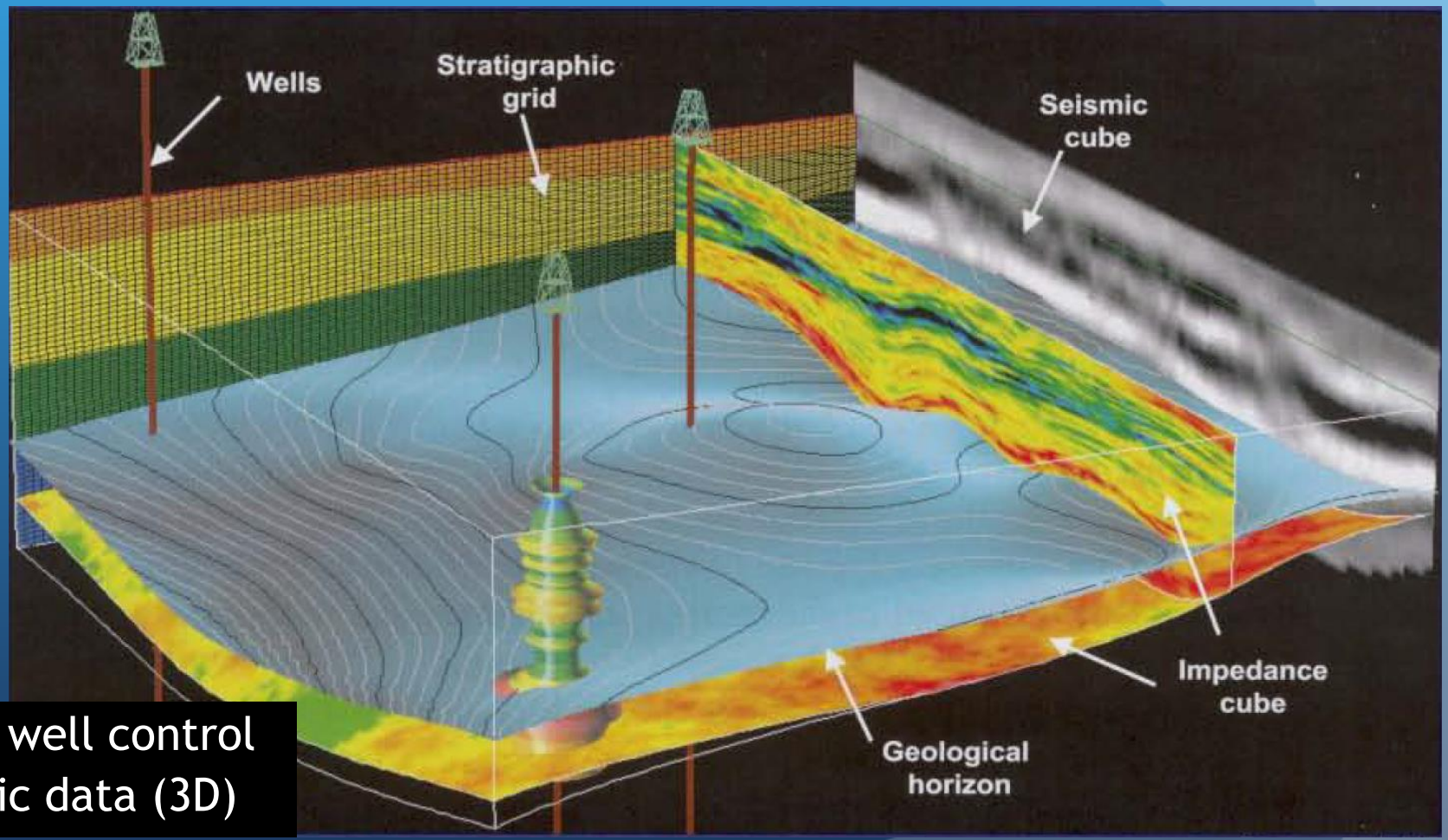
Objective

- Discuss the role for stochastic geo-models in hydrogeologic studies

Background

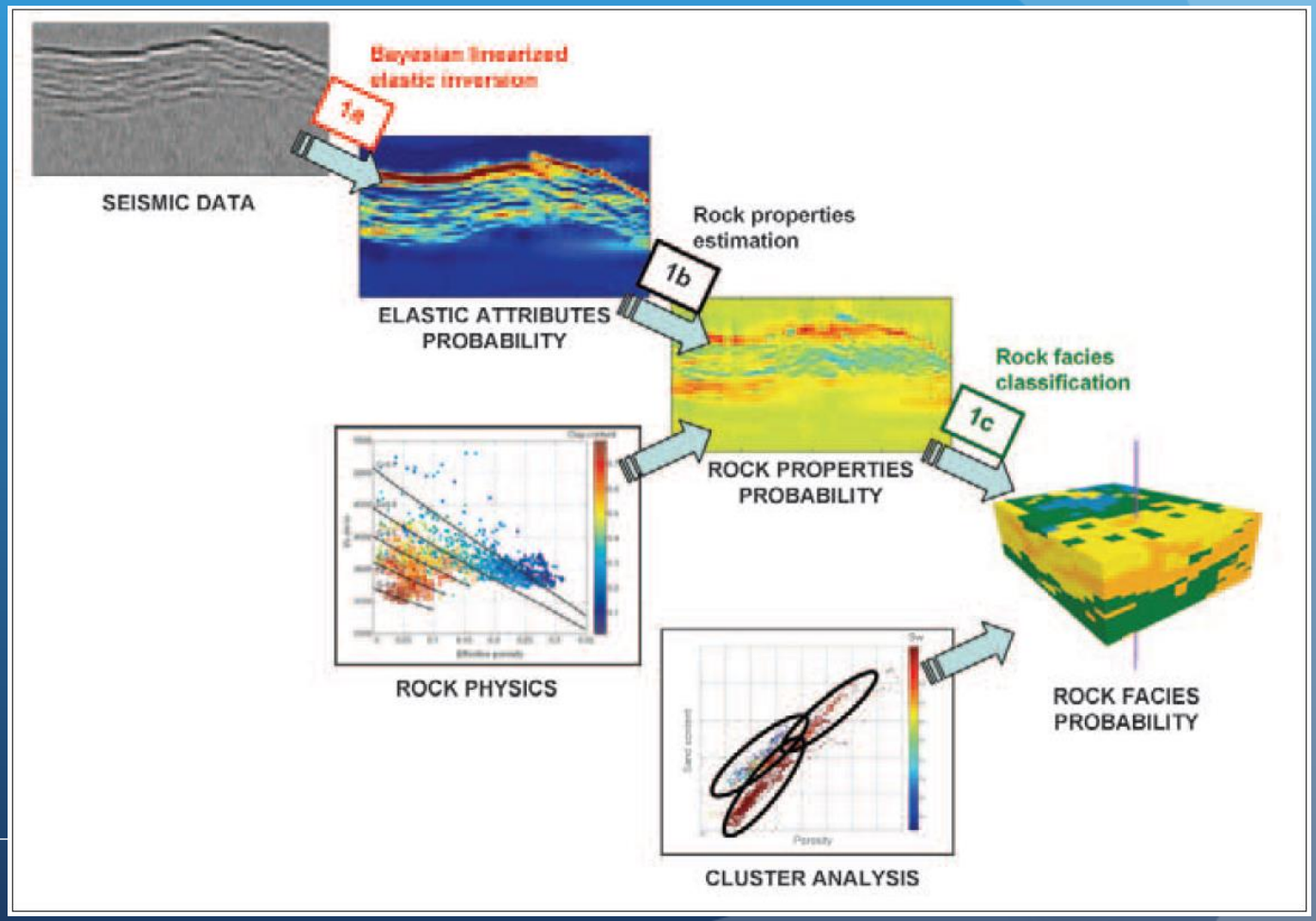
- From reservoir modelling…
  - Dubrule (2003): Geostatistics for Seismic Data Integration in Earth Models.



- Great well control
- Seismic data (3D)

Background

- From reservoir modelling…
  - Grana and Dvorkin (2011): Geostatistical simulations in seismic reservoir characterization studies



Background

- … to hydrogeology studies

- Scale of the problem
  - Regional study: 10's to 1000's **km** (water supply)
  - Local study: 10's to 100's **m** (solute transport, wastewater)

- Level of heterogeneity

- Well control
  - Hydraulic parameters availability

- Time / economic incentive

Background

- … to hydrogeology studies
  - Heterogeneity vs Data / Model Resolution

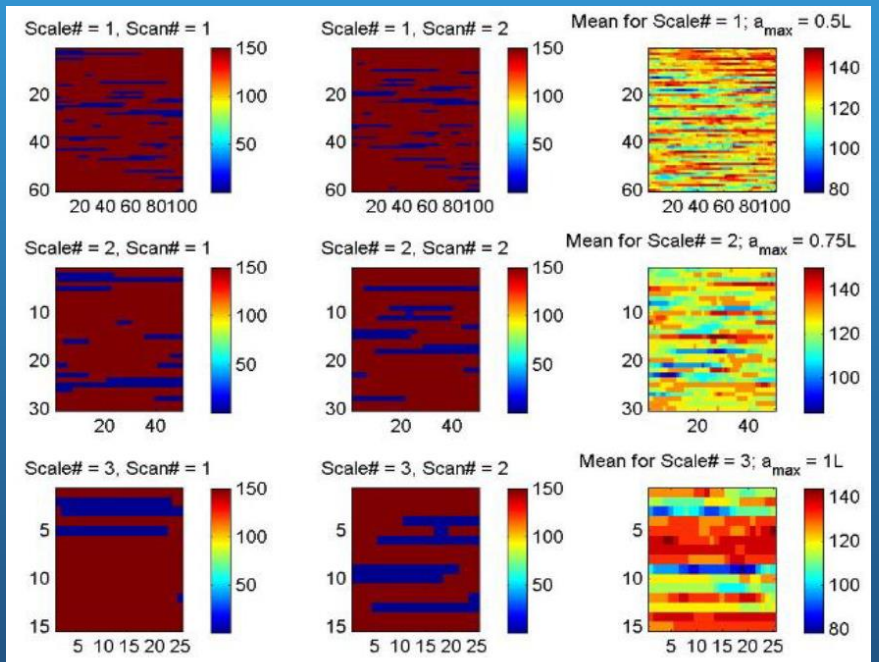


Figure 7: Realizations of permeability and their mean with different scales of heterogeneity extracted from realizations of 200 x 100 scale models

(Singh and Srinivasan, 2014)

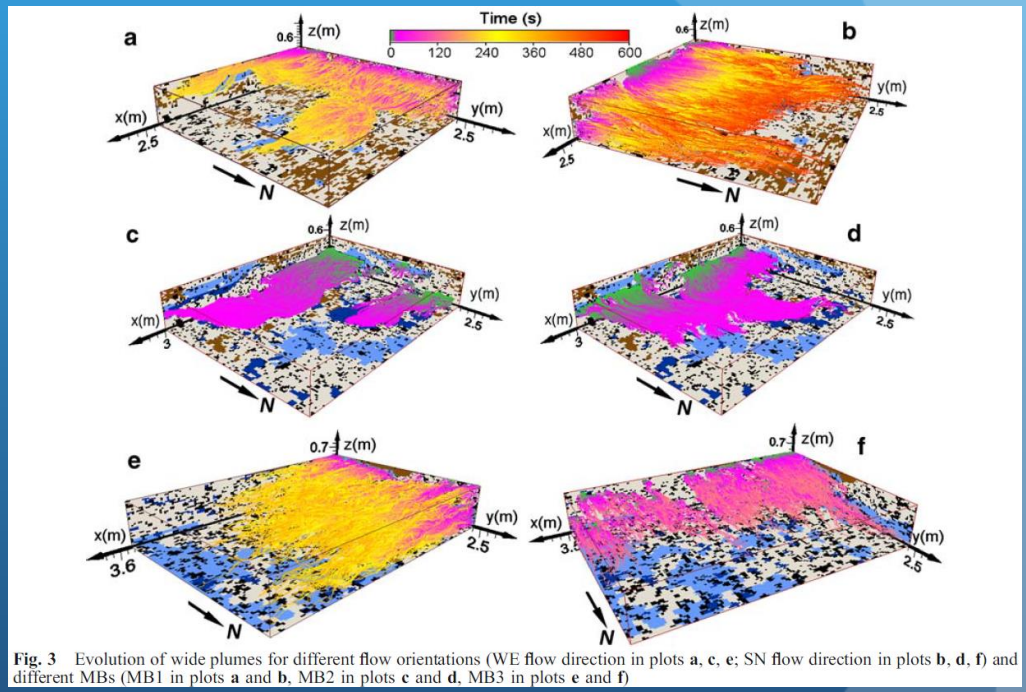
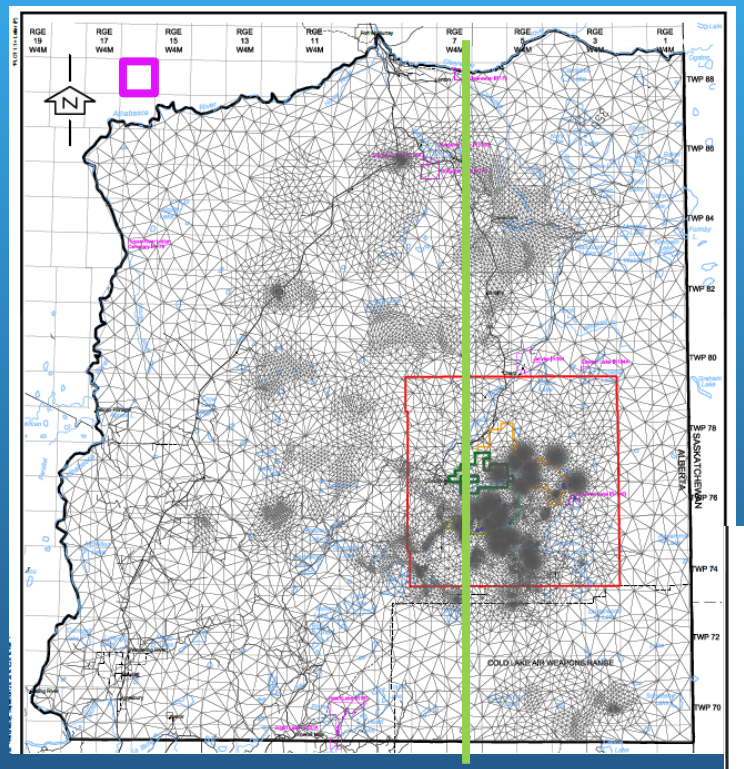


Fig. 3 Evolution of wide plumes for different flow orientations (WE flow direction in plots **a**, **c**, **e**; SN flow direction in plots **b**, **d**, **f**) and different MBs (MB1 in plots **a** and **b**, MB2 in plots **c** and **d**, MB3 in plots **e** and **f**)

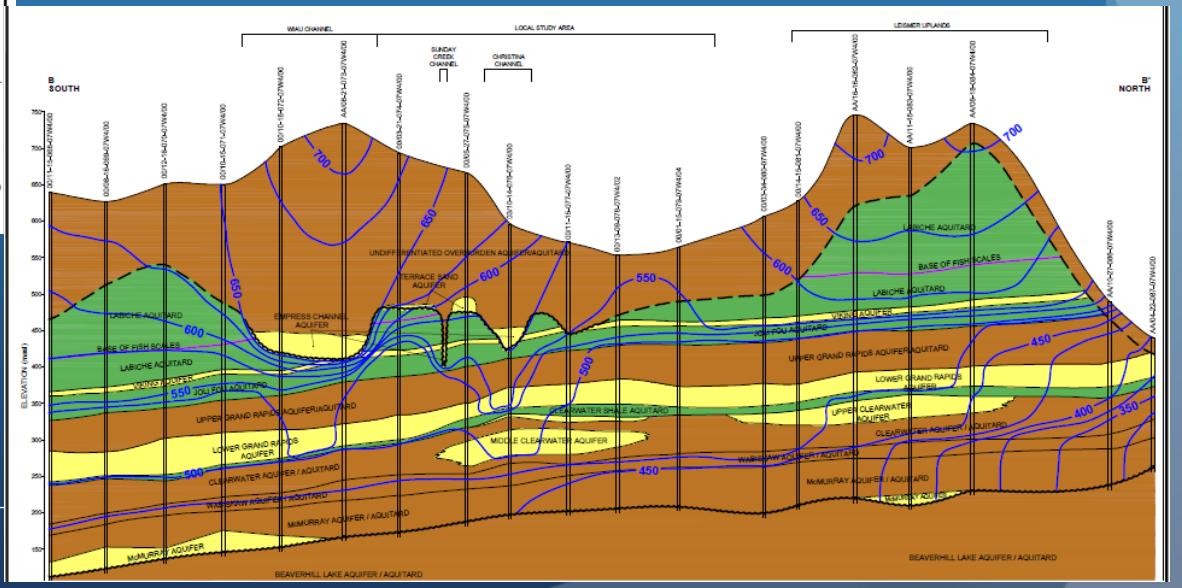
(Vanessa et al., 2009)

Regional Models

- Interpolation of 2D horizons from well picks, constrained by knowledge of geology
  - Build 3D grid model by filling between the surfaces (Gocad)
- Model is the “most-likely” representation of stratigraphy / hydrostratigraphy at regional scale
  - Averaging local groundwater flow pattern

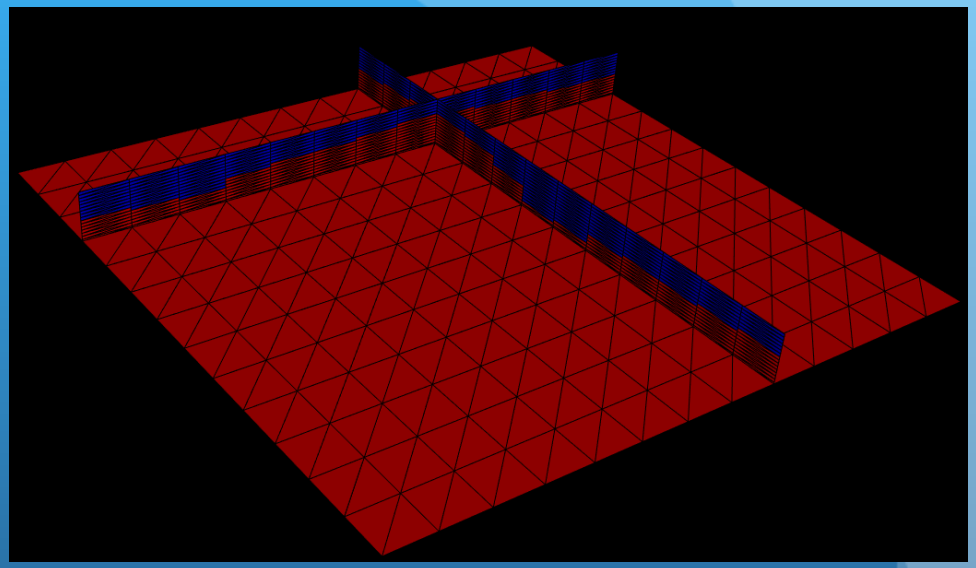


CLRWMA Model (Matrix 2012)

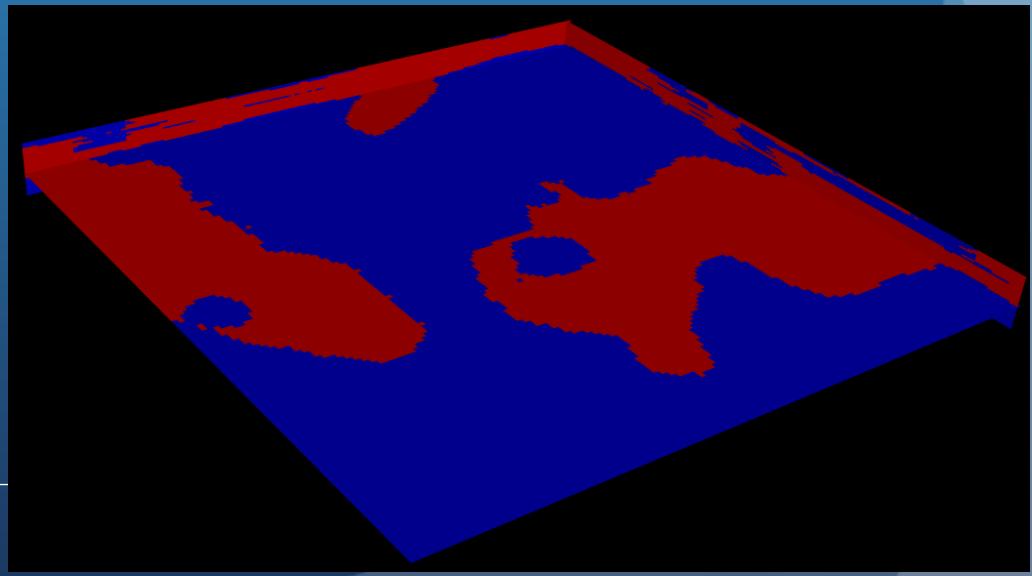


Definition of geo-model

- 3D model representation of facies representing:
  - geology
  - petrophysics
  - hydrostratigraphy

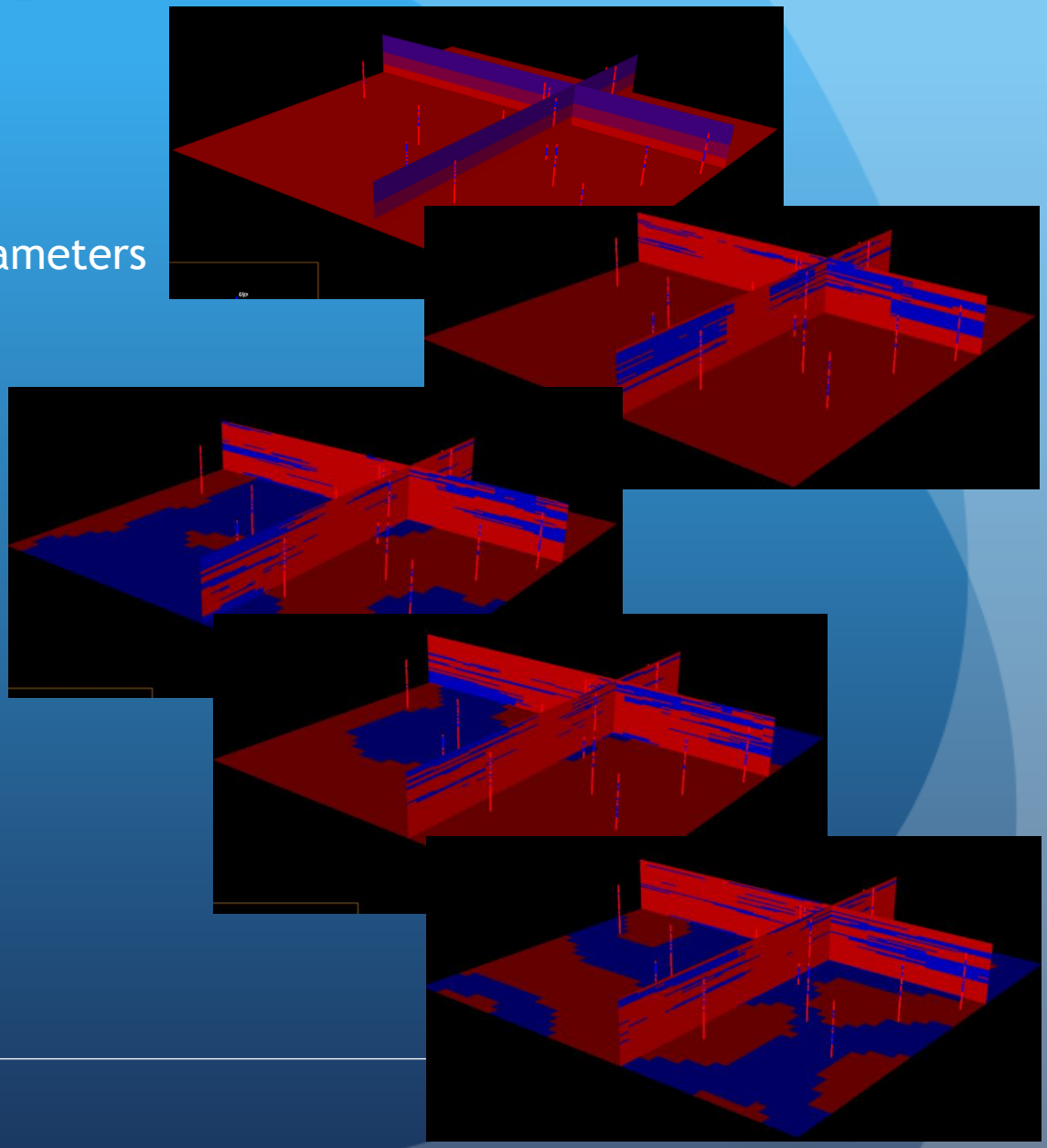


- Assignment of facies to all cells of the 3D model representation
  - How to assign facies?



Definition of geo-model

1. Deterministic Approach:
   - 1 facies per unit
     - Assume homogeneous parameters for each unit / layer
     - No uncertainty
   - Kriging
     - 1 best-fit model (least error)
     - Uncertainty evaluated but not considered
2. Stochastic Approach:
   - Multiple realizations
   - Uncertainty considered



Problematic

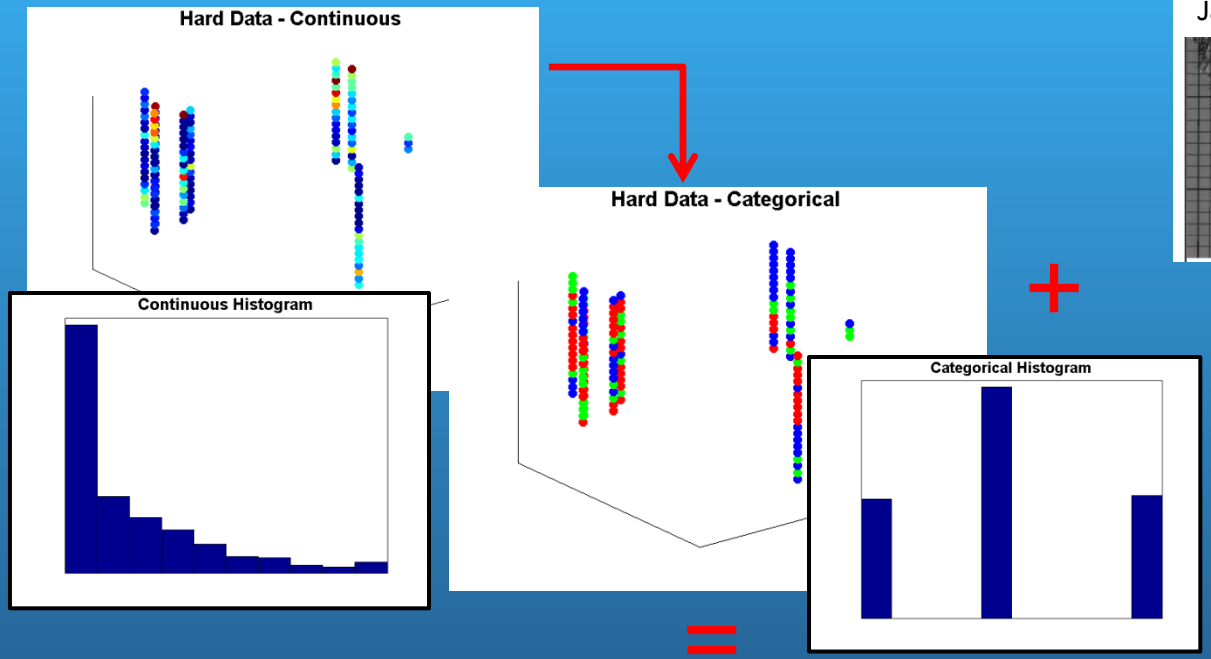
Deterministic Geo-models vs Stochastic Geo-models

	Deterministic	Stochastic
Properties	Honors wells	Honors wells Honors histogram and probability
Output	One unique “best-fit” geo-model	Multiple “equally probable” geo-models
Use	Mapping Regional-scale geo-models	Heterogeneity modelling Local-scale geo-models Uncertainty quantification

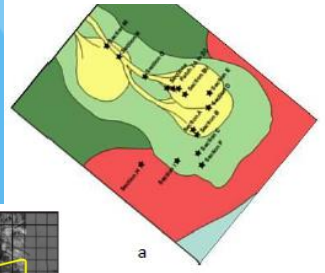
modified from Dubrule (2003)

Stochastic Geo-models

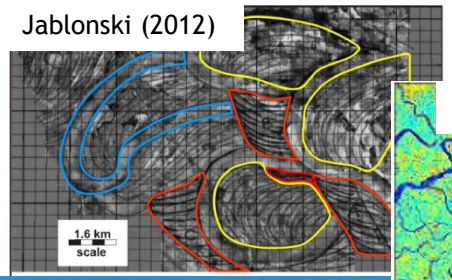
- Objective: Build several “equally-probable” geo-models



Doliguez et al. (2014)



Jablonski (2012)



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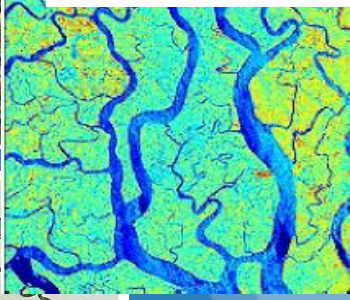
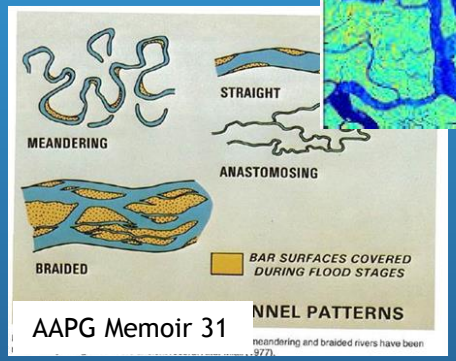
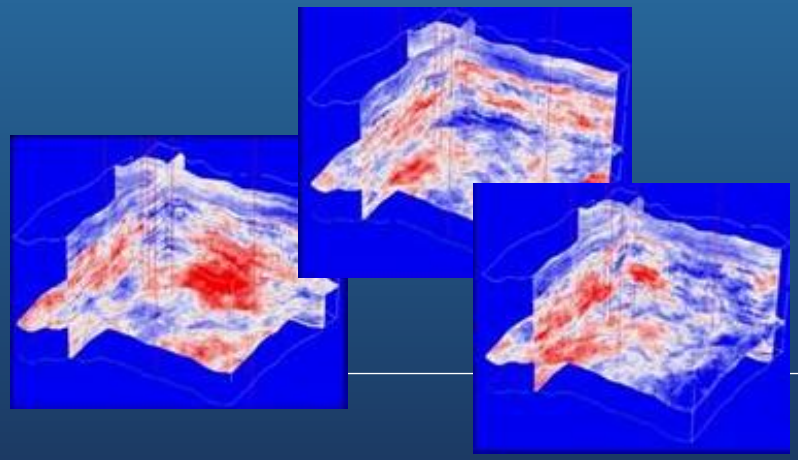




AAPG Memoir 31



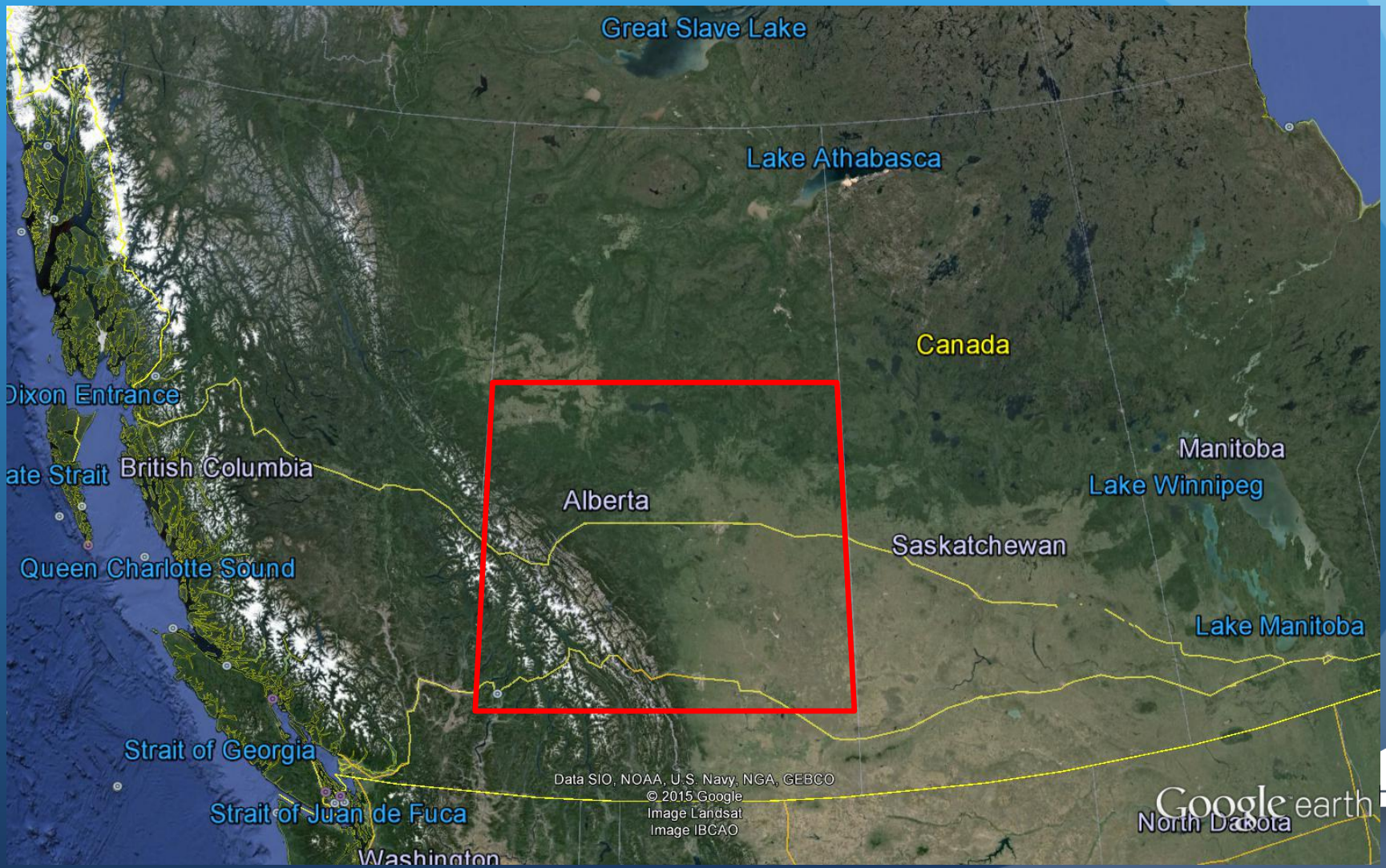
- All realizations are equally probable, even if one “looks” better
- Probabilistic approach of uncertainty and risk analysis for:
  - groundwater modelling
  - Solute transport problems

3 Case Studies
Stochastic Geo-models

- Quantify risk for groundwater modelling in 3 different contexts:
  - Site 1:
    Water Quality Impacts to a residential well
  - Site 2:
    Thermal plume migration and potential surface water/groundwater interaction from a Steam-Assisted Gravity Drainage (SAGD) Project
  - Site 3:
    Wastewater migration away from disposal wells toward nearby source well in same aquifer

Site 1: Project Area

- for confidentiality purposes:

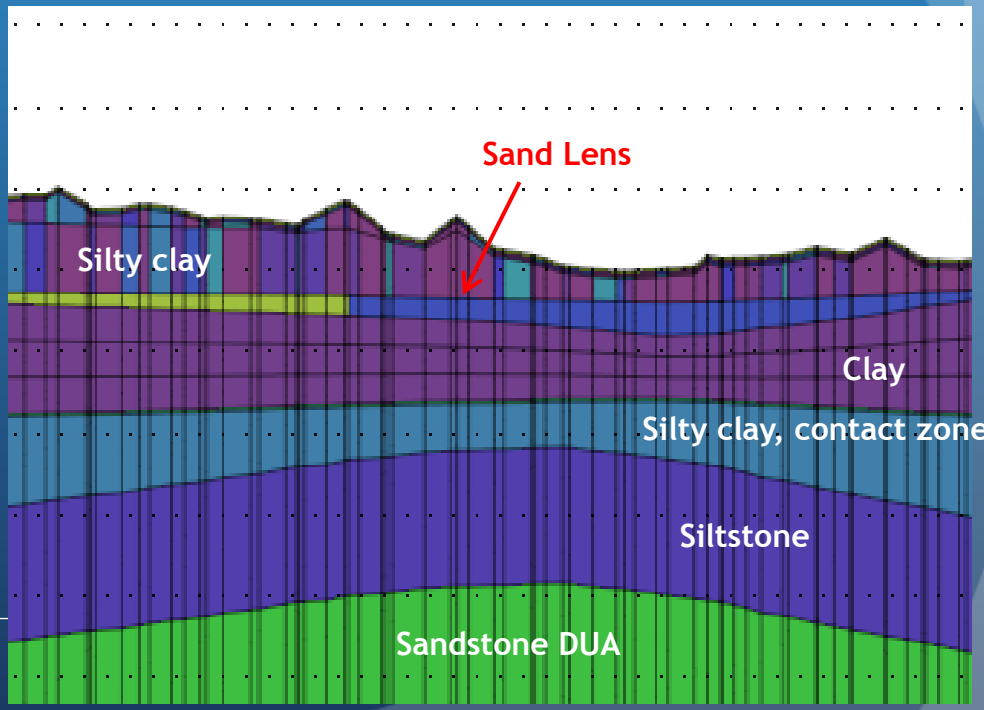


Site 1: Project Area

- Regional Model
  - 2.0 km x 2.5 km
- Local Model
  - 400 m x 300 m
  - Assess risk of near-surface water quality impacts

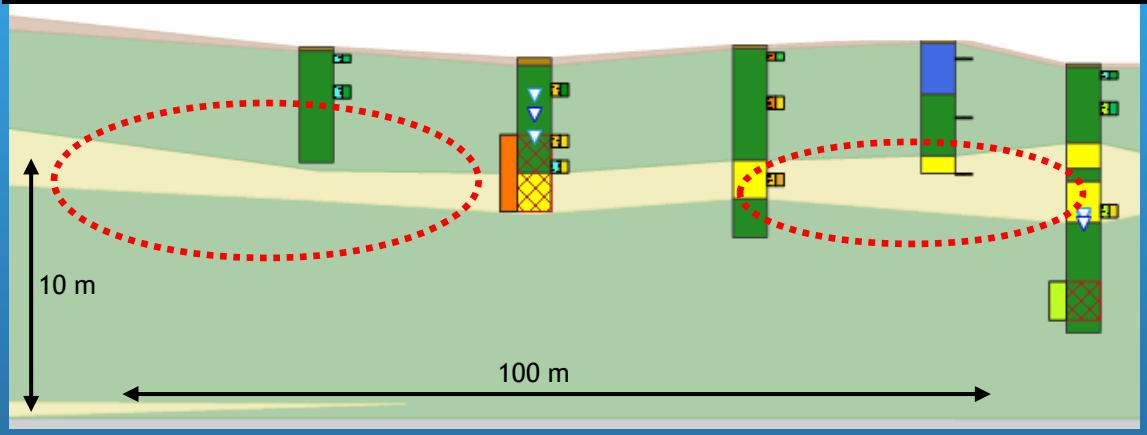
Site 1: 3D Groundwater Flow Model

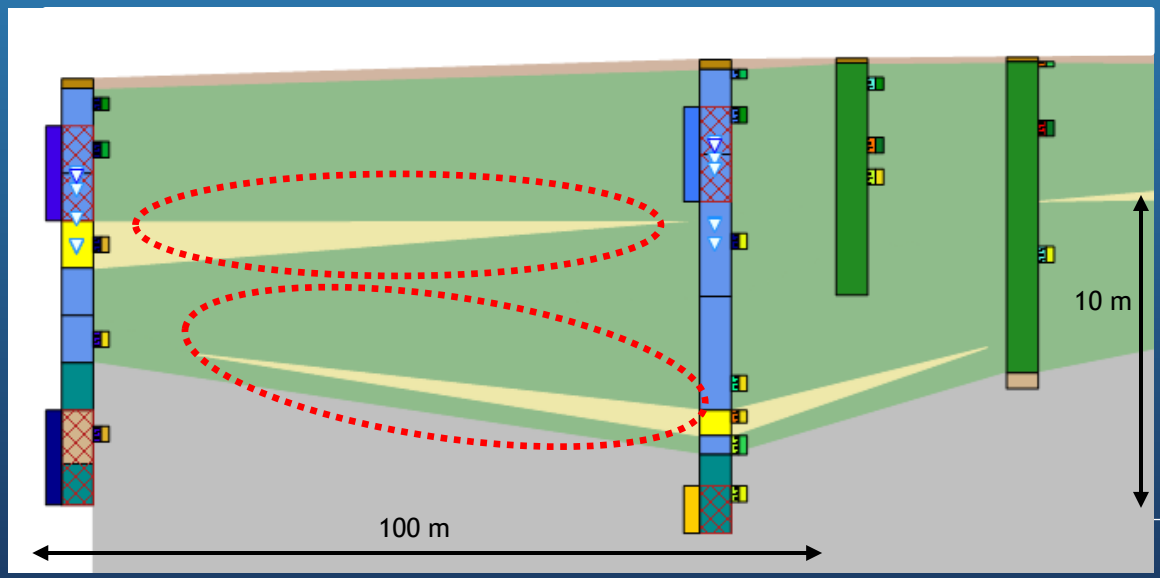
- Layered model with sandstone domestic use aquifer (DUA) at base
- Structure intended to capture presence of sand lenses
  - critical in characterizing groundwater travel and migration of chloride plume concentrations
- Some heterogeneity
  - random Kzone assignments to upper Till unit
  - K value of each zone tuned by PEST (Model Independent Parameter Estimation)



Site 1: Model Conceptualization

- Hydrogeologic units interpreted along NS (top) and EW (bottom) sections
  - Clay - Clay Till - Sand, silty sand - Sandstone -Siltstone





2D cross-sections

What in 3D? out of 2D plane?

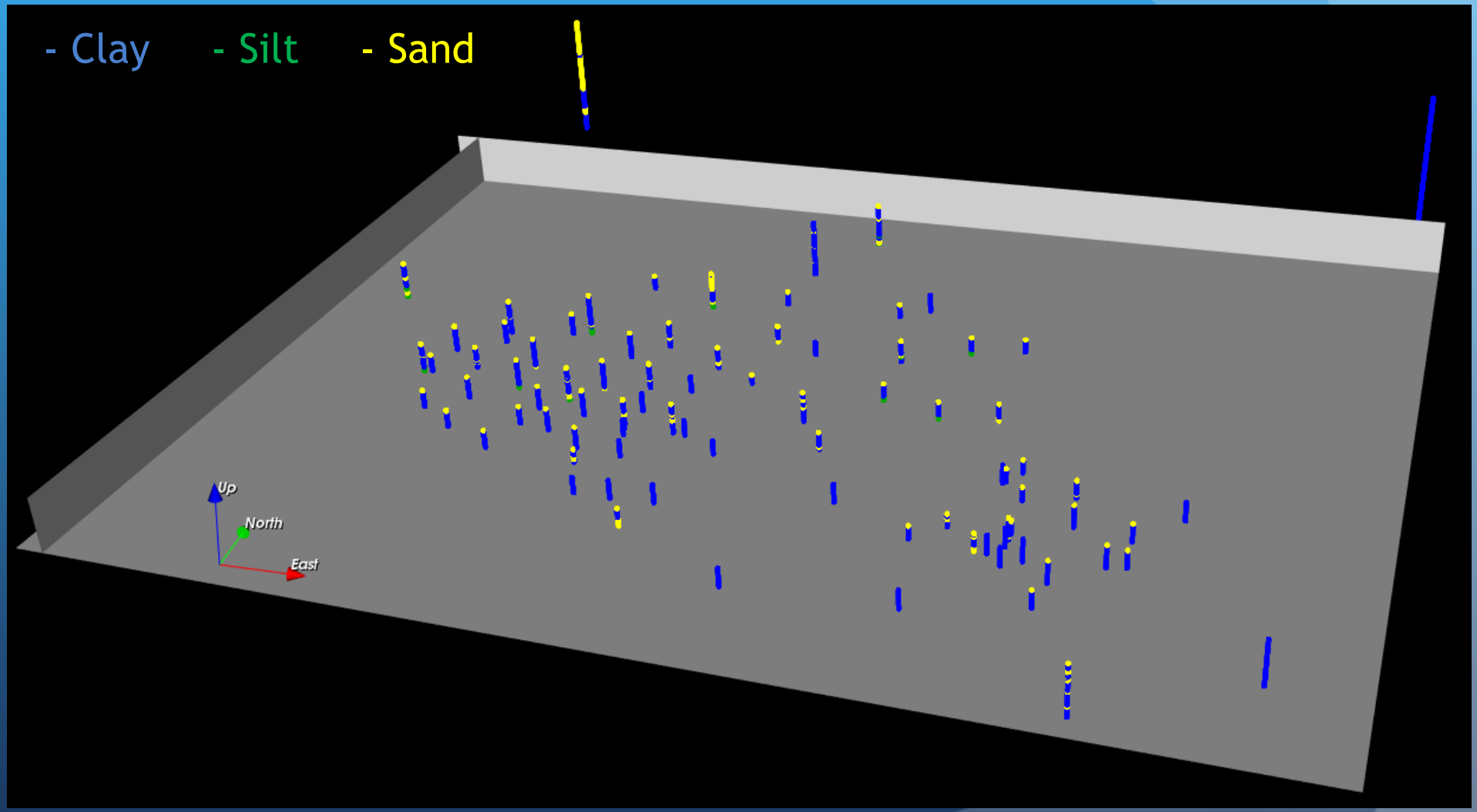
Site 1: Objectives

- Build probable representations of hydrofacies distribution
  - Integrate “hard” knowledge at boreholes with “soft” knowledge of geology (trends, regional geology…)
  - Heterogeneous models of geology
    - Sand vs Till facies

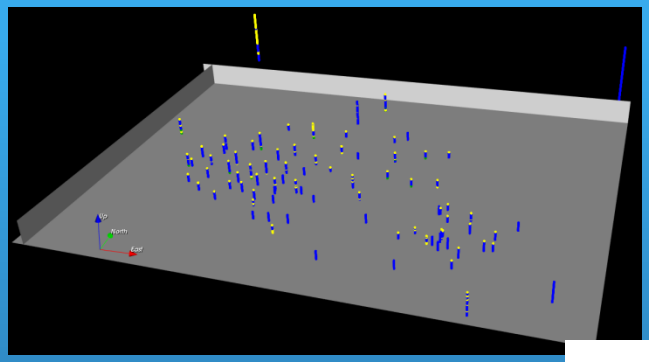
- Quantify uncertainty:
  - Geology
  - Hydraulic parameters

Site 1: Initial Parameters

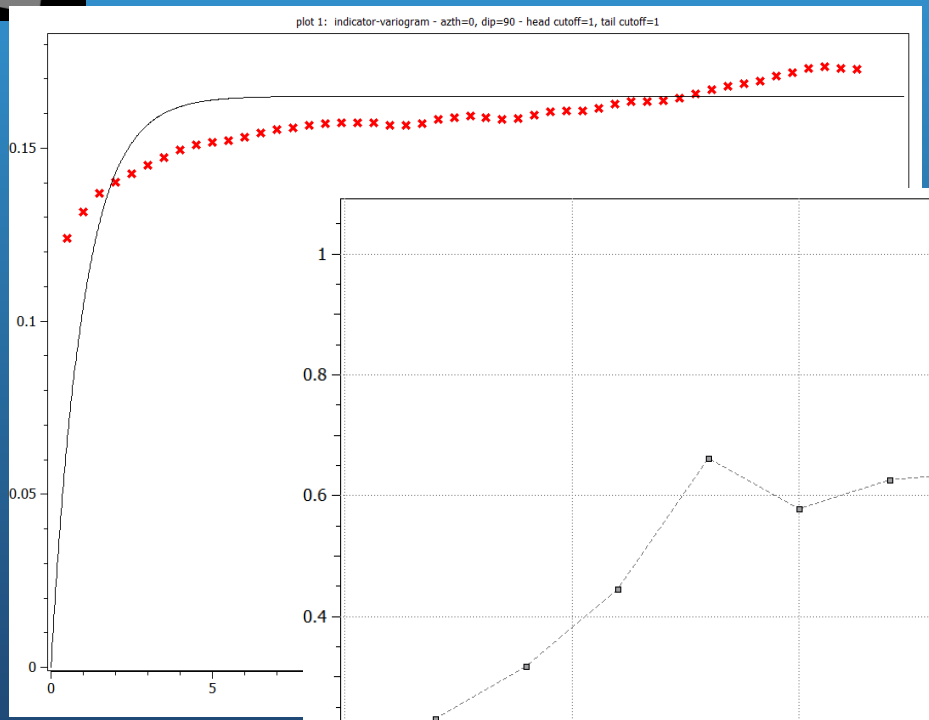
- 3D Cartesian Grid 40 x 30 x 80 cells
- Use boreholes to develop layer structure and units thickness

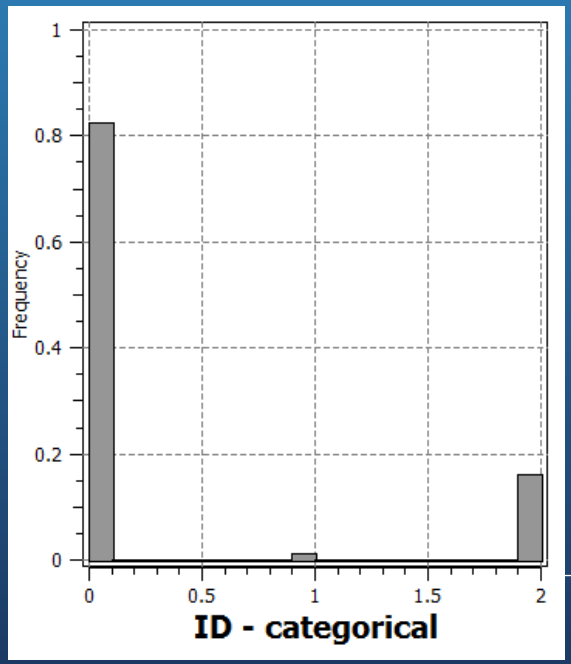


Site 1: Initial Parameters



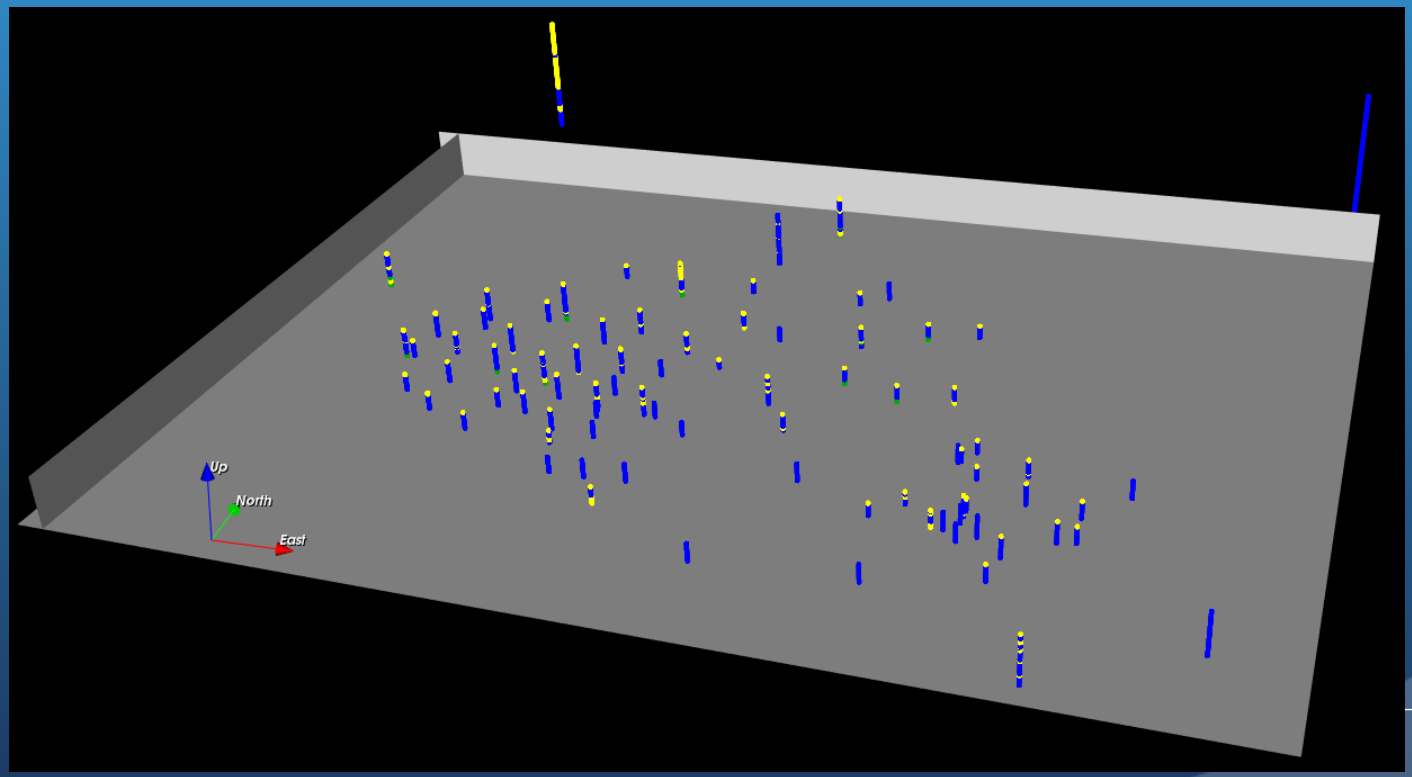
- Proportions of hydrofacies: Histograms
- Geometrical trend: Indicator Variograms
  - vertical
  - horizontal





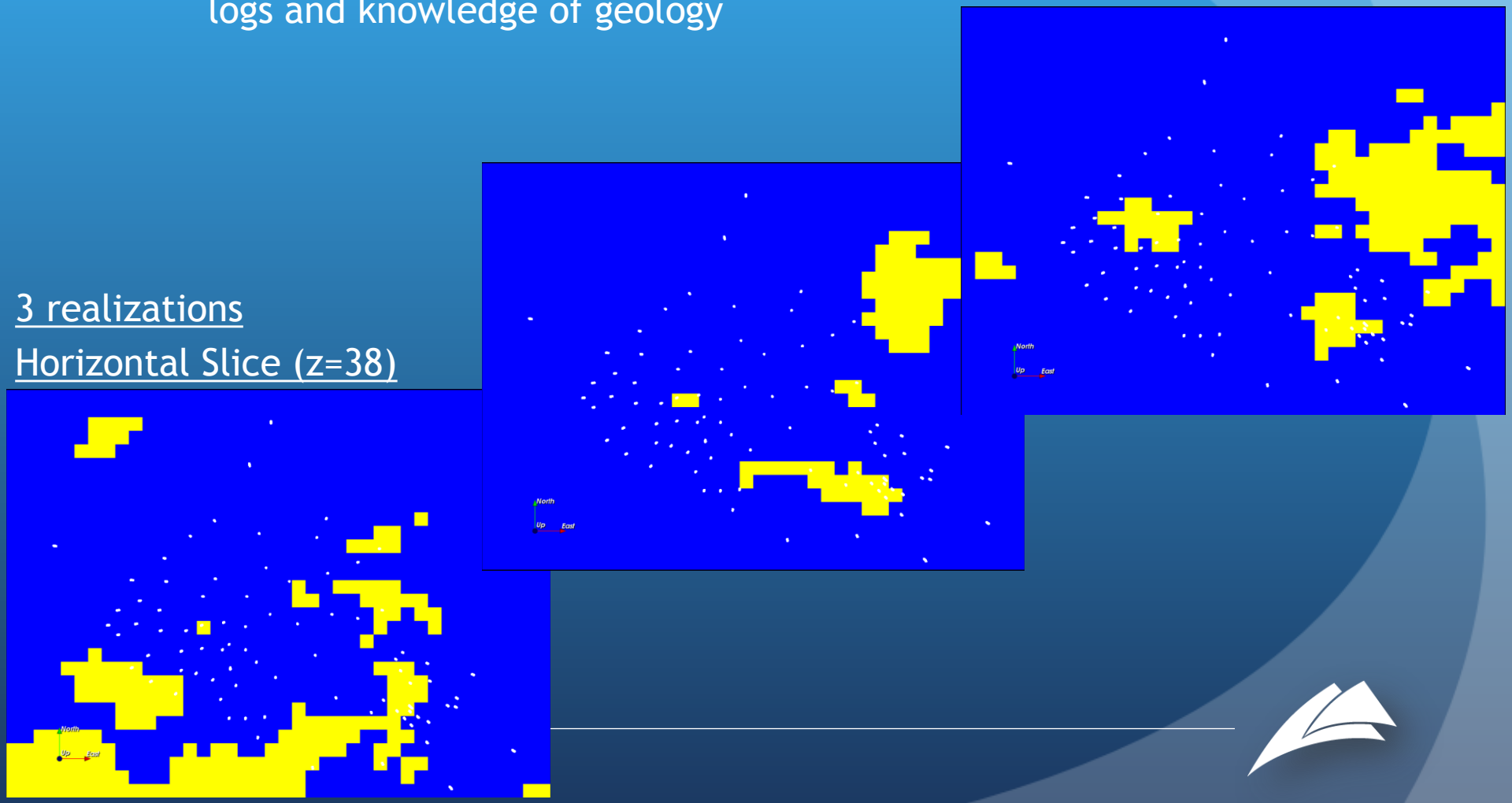
Site 1: Initial Parameters

- Data at local scale, not good to determine larger scale structures
- Knowledge of geology: sand bodies with trend in EW direction
  - Discussions with the project's geologist
  - To replace parameters for horizontal variograms



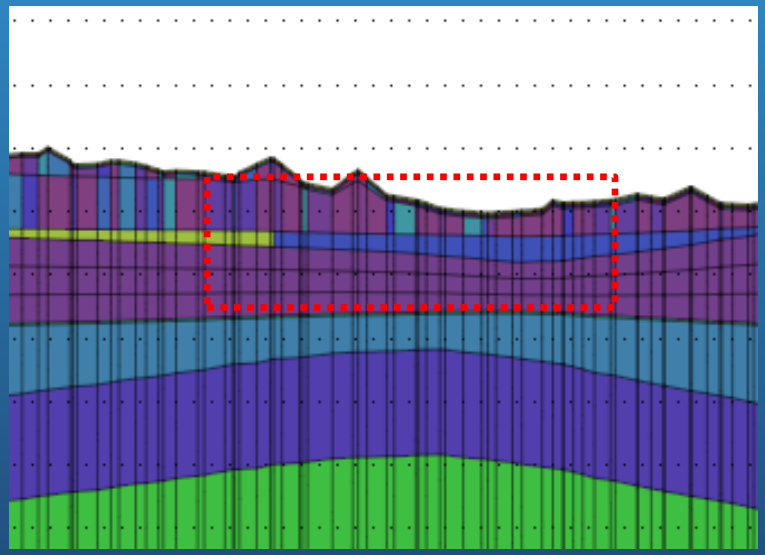
Site 1: Hydrofacies Modelling

- Sequential Indicator Simulations (SIS)
  - Simulate many realistic geo-models based on statistics from borehole logs and knowledge of geology



Site 1: Hydraulic Parameters

- Simulate the initial spatial distribution of hydraulic parameters within each hydrofacies
  - For input in FeFlow (PEST calibration)
  - Optimization of hydraulic conductivity parameters: K or a proxy to K (soil saturation %)



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3 selected realizations (cross-section)

Site 1: Hydraulic Parameters

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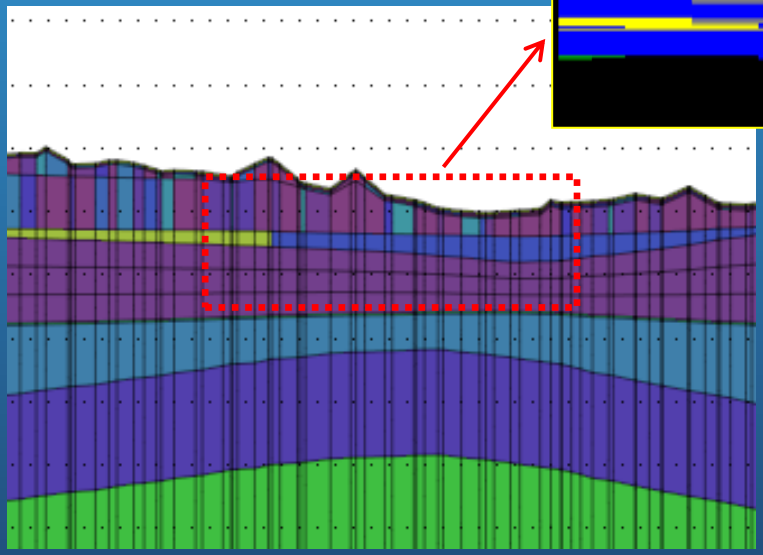

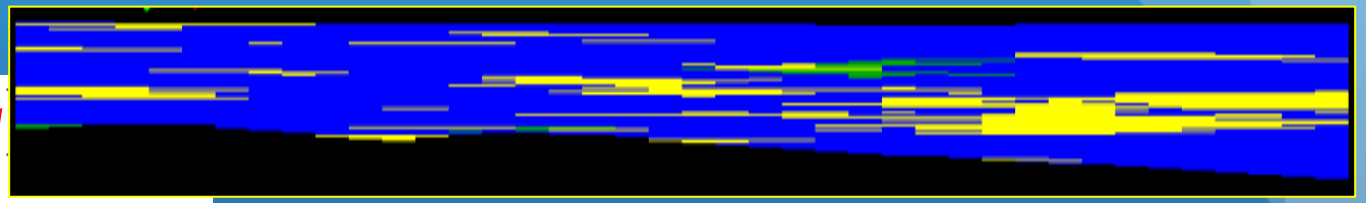

From 1 realization…

Site 1: Hydraulic Parameters

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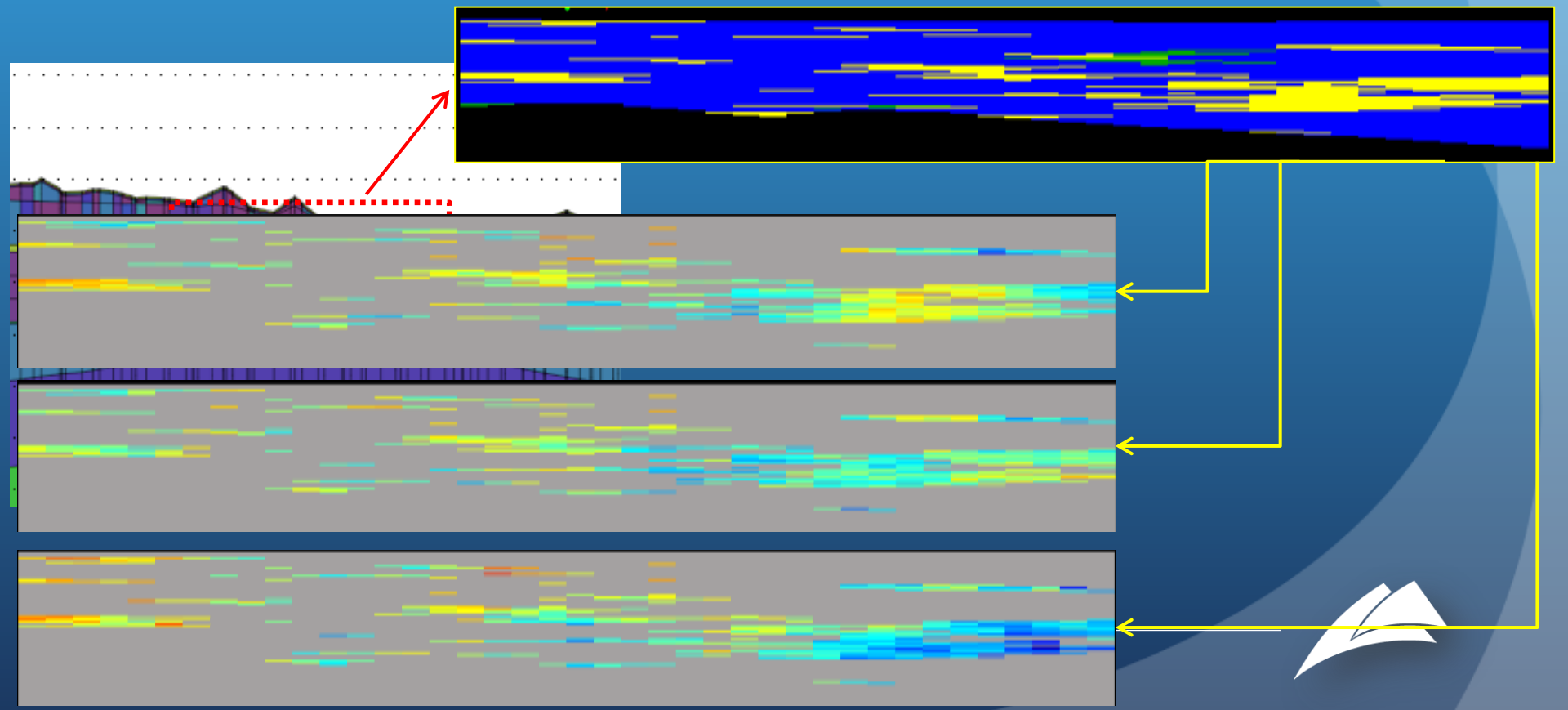
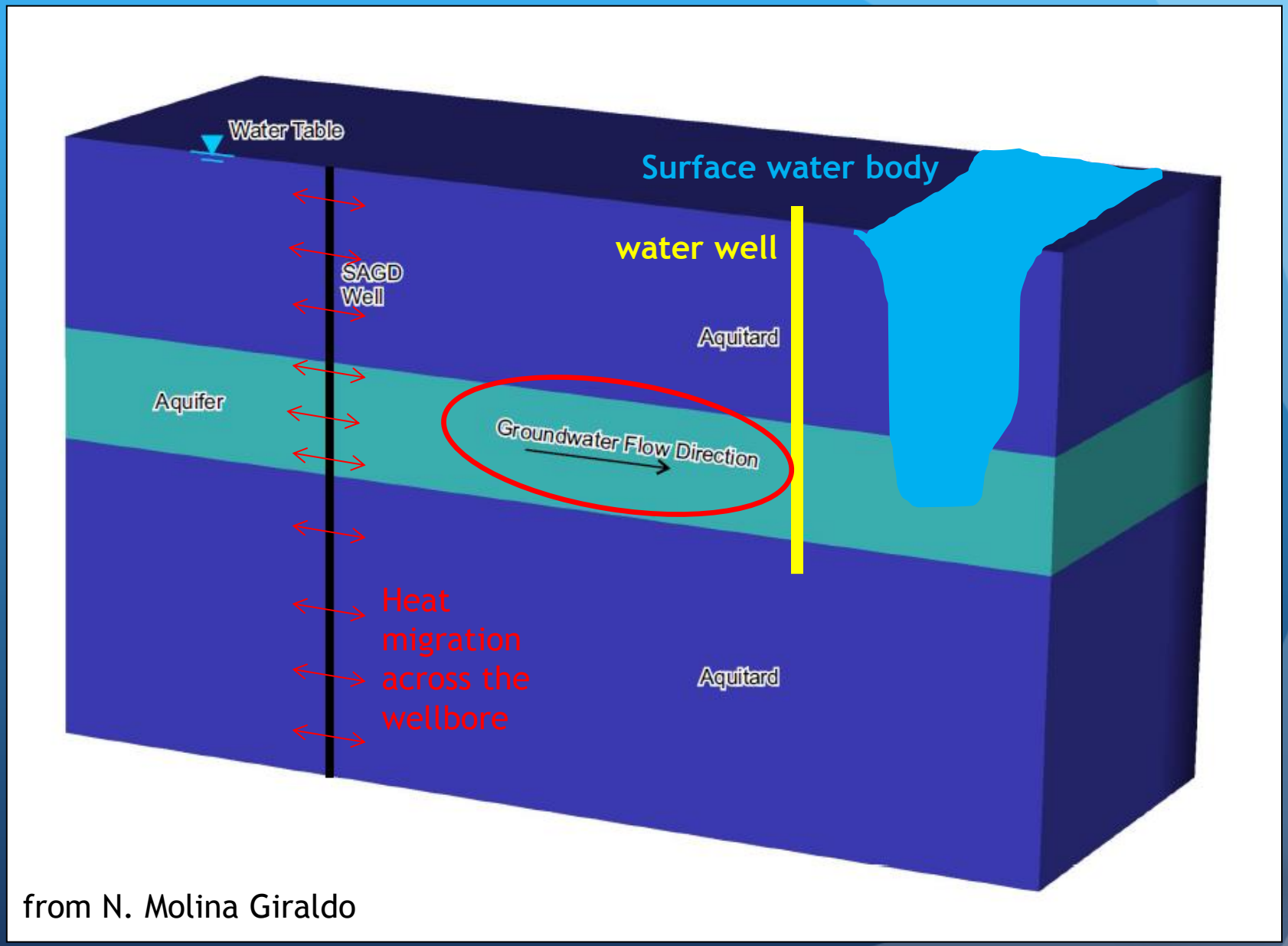


Site 1: Conclusions

- Ability to assess different probable scenarios of contamination at local scale
  - Evaluate possible volumes of contaminant
  - Quantify risk by evaluating the whole range of possible outcomes
- Conduct risk analysis by simulating different scenarios of propagation of contaminant in the near-surface geology
  - Evaluate probable paths of propagation

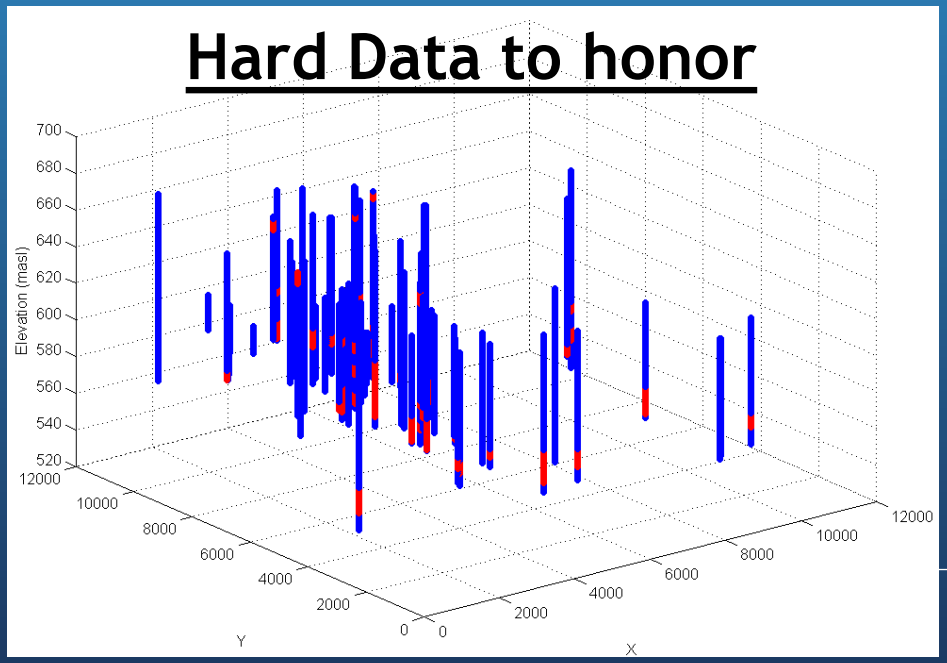
Site 2: SAGD Project



from N. Molina Giraldo

Site 2: Stochastic Geo-modelling

- Multiple-Point Statistics simulations (MPS)
  - Training Image: Knowledge of depositional trends to guide simulations (can be hand-drawn image, seismic-derived image…)
    - Channel-type structure
    - Not regionally correlatable - limited length and width
    - Maximum thickness 25m (based on well logs)
    - 10% sand (based on well logs)



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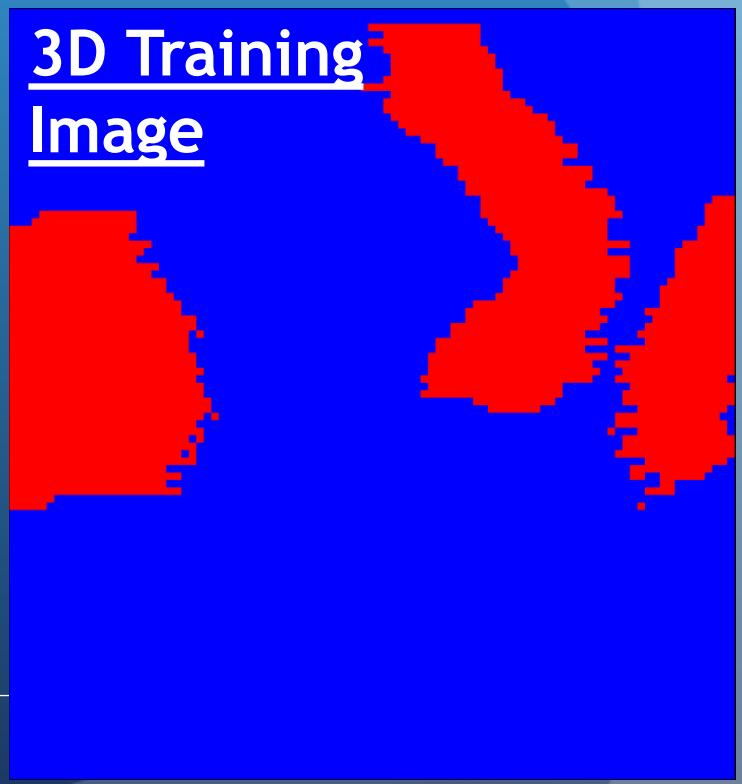
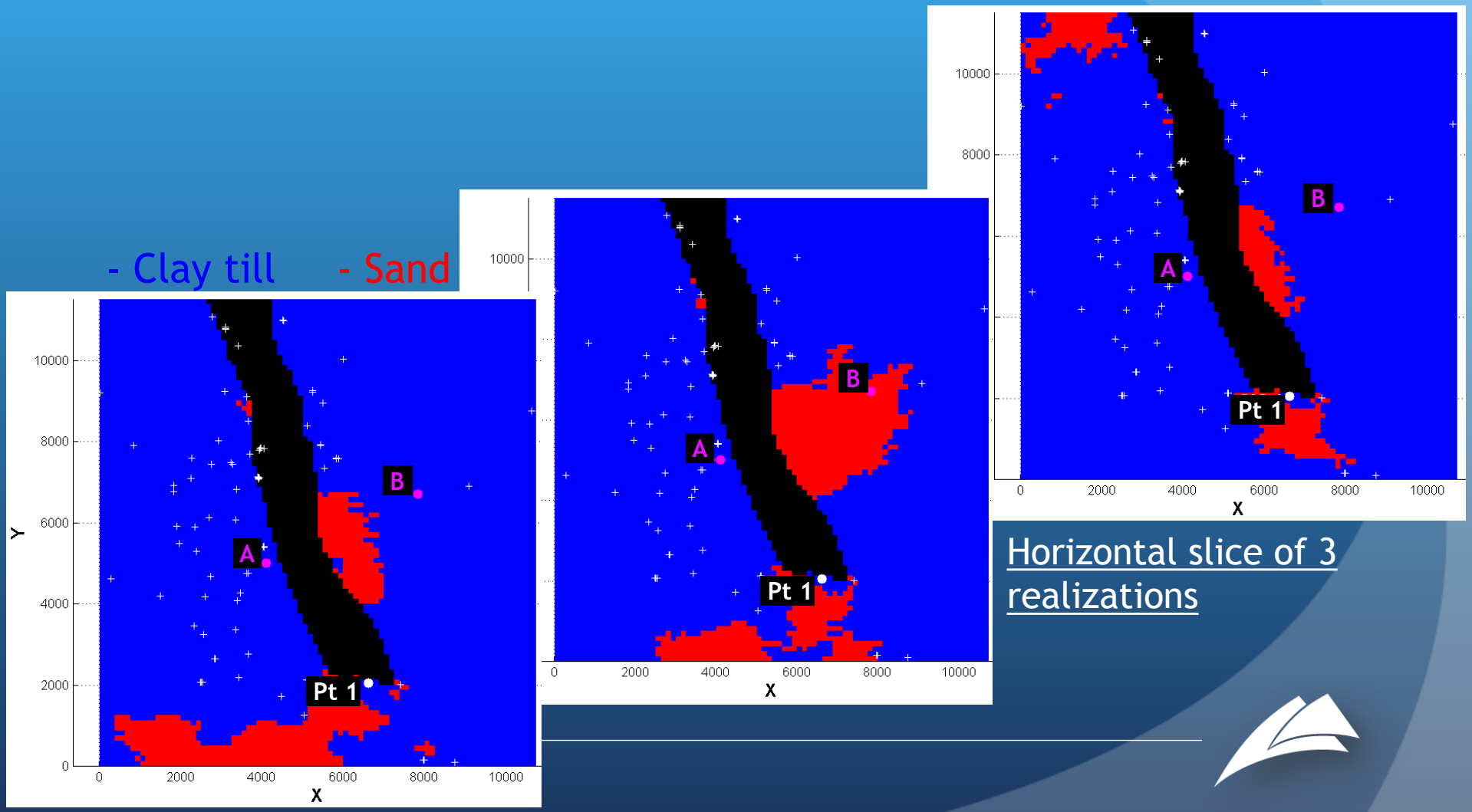


Site 2: Connectivity of Sand Hydrofacies

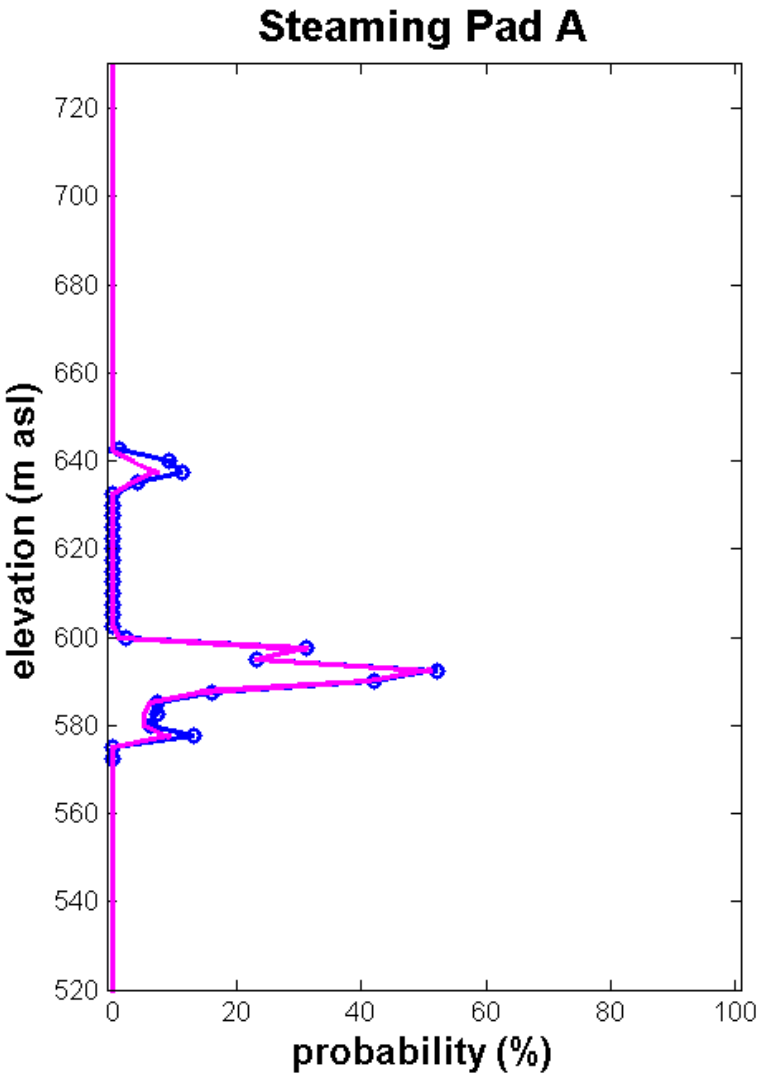
- Simulate 100 probable scenarios of sand facies distribution

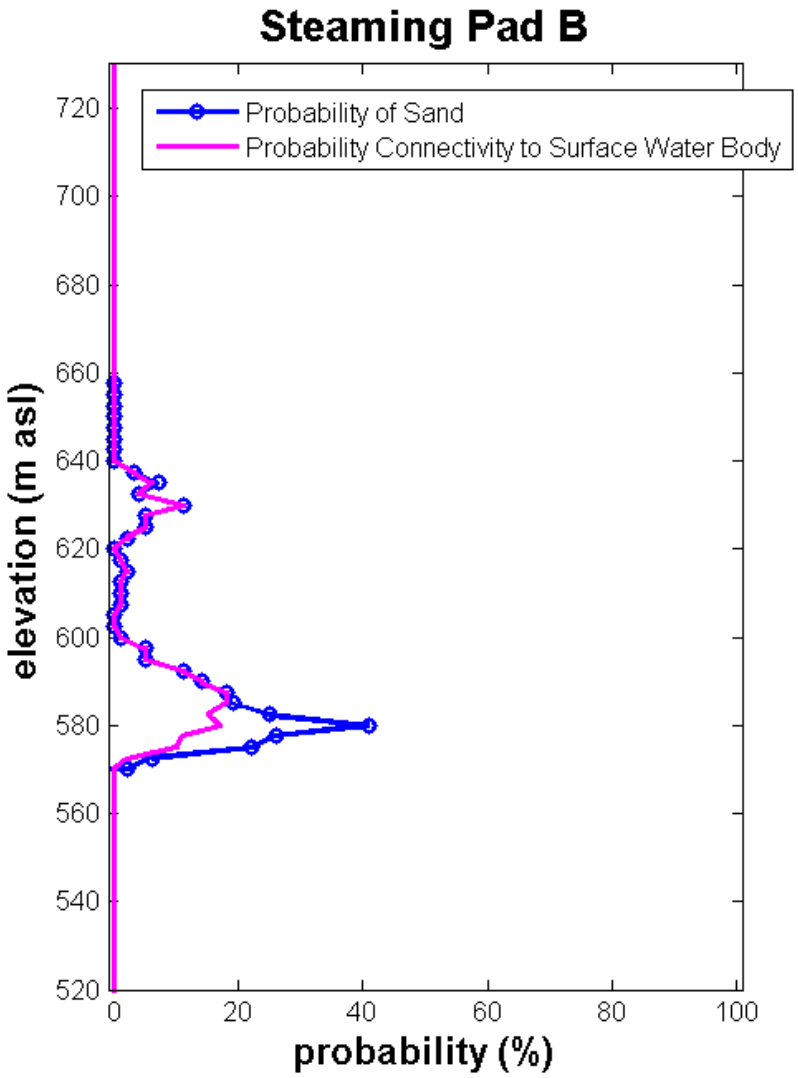


Horizontal slice of 3 realizations

Site 2: Connectivity of Sand Hydrofacies

- Probability of connectivity to surface water body

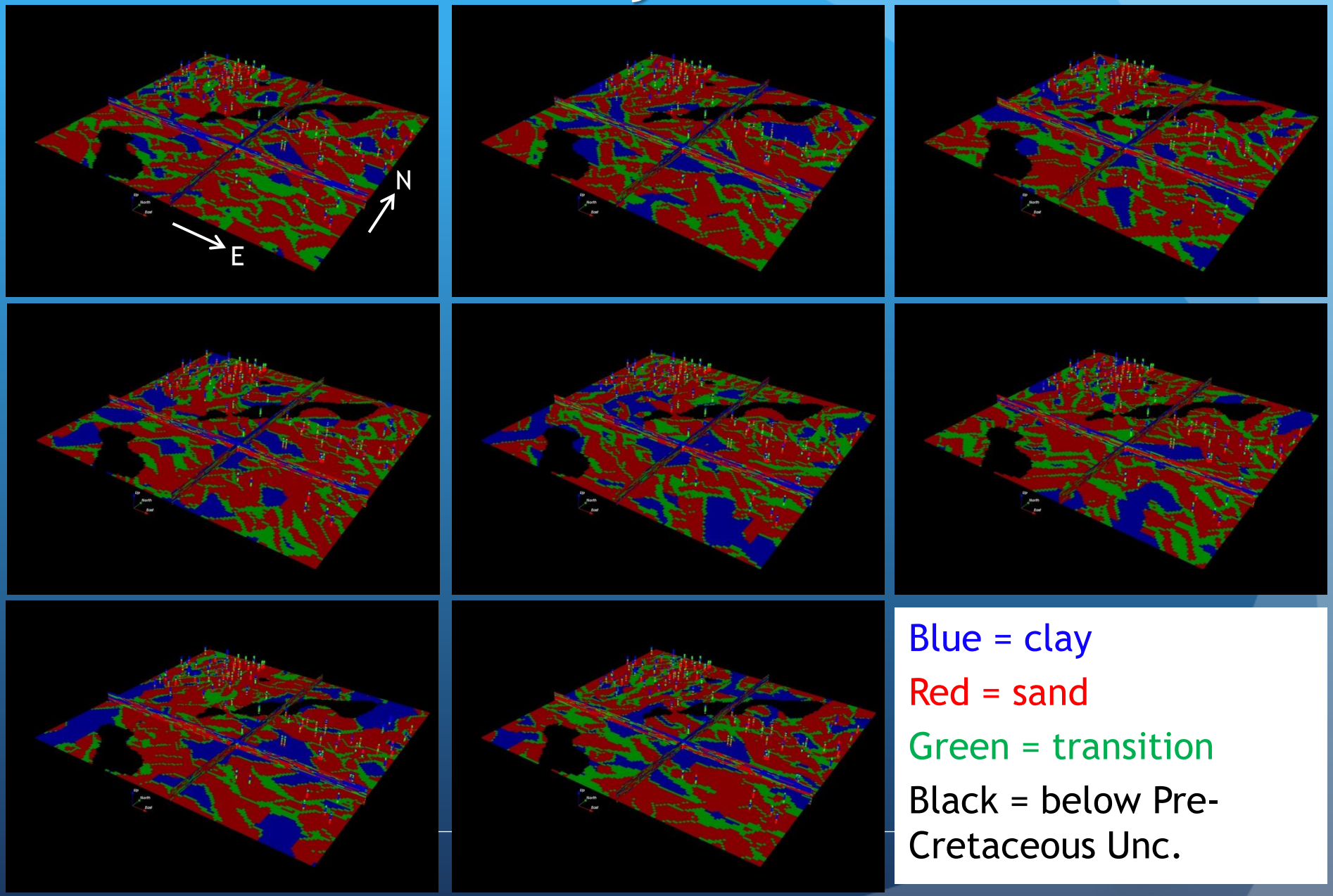




Site 3

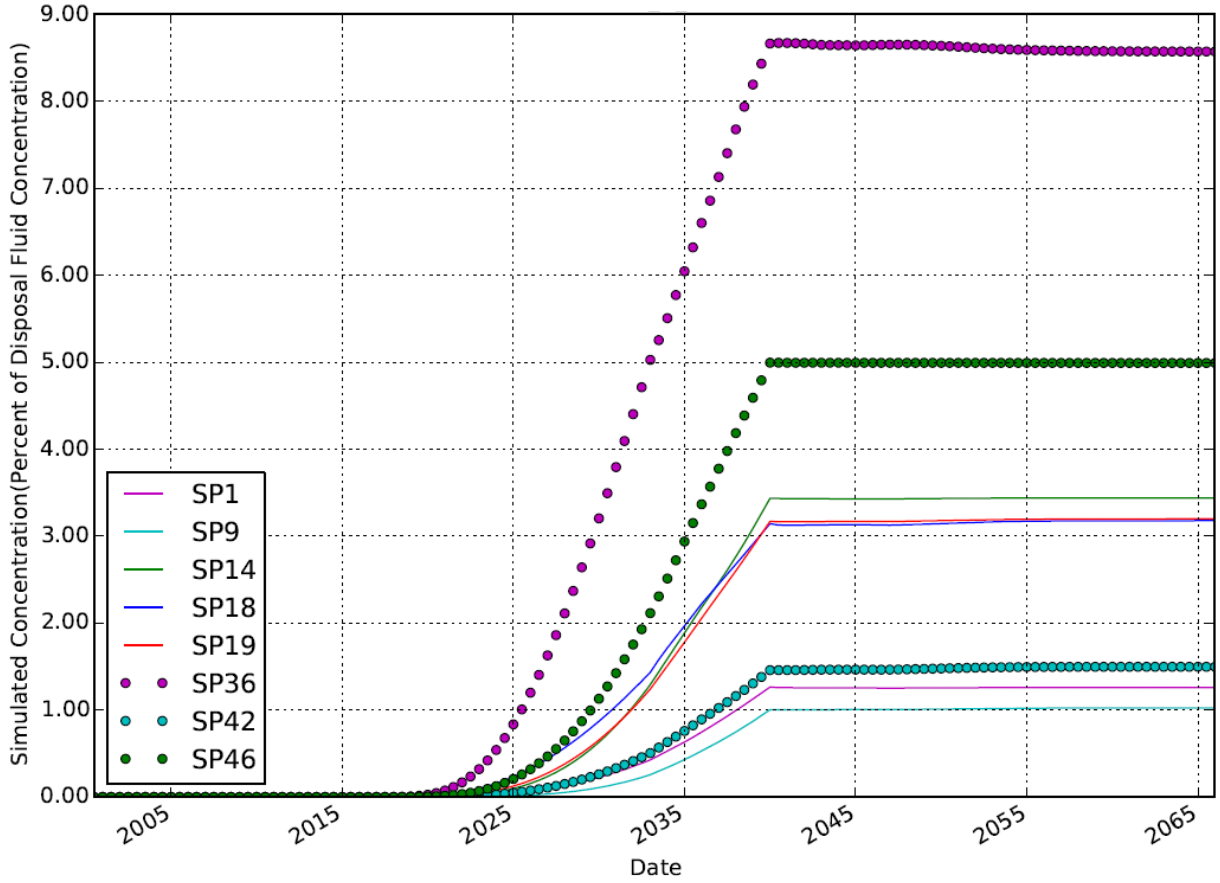
- Evaluate rate and extent of wastewater migration away from disposal wells toward nearby source well in same aquifer.
  - Assess differences in disposal fluid arrival time and concentration at source well

Site 3: Variability of Geo-models



Site 3: Variability of flow models

- Simulated Concentration of disposal fluid at source well
- Stochastic geo-modelling allows computing the range of concentrations likely to be sourced



To conclude…

- Find best way to integrate available data
  - Deterministic or Stochastic Approach
  - Honor hard data
  - Hydrofacies (sand vs clay)
  - Respect geological knowledge from geologist

- Stochastic Geo-models allow to run Connectivity Analysis
  - Probability of:
    - Facies occurrence
    - Connectivity between Source/Receptor

To conclude…

- Quantify risk by considering the uncertainty and evaluating the variability of stochastic geo-models

- Compute range of possible outcomes
  - minimum – mean – maximum volumes
  - P10 – P50 – P90

Any Questions?

Please ask…

or contact me:

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