Three-Dimensional Surface-Based Modeling and Flow Simulation of Heterolithic Tidal Sandstone Reservoirs*

Benoît Y. G. Massart[1], Matthew D. Jackson[2], Gary J. Hampson[2], Berit Legler[2], Howard D. Johnson[2], Christopher A.-L. Jackson[2], Ayana M. Breheret[2], Justine Daboer[2], Ngozi Onokwai[2], Oluwole Talabi[2], Rodmar Ravnas[3], and Marcus Sarginson[3]

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[1]Department of Earth Science and Engineering, Imperial College London, UK (maspleben@gmail.com)
[2]Department of Earth Science and Engineering, Imperial College London, UK
[3]Norske Shell, Stavanger, Norway

Abstract

Tidal heterolithic sandstone reservoirs are highly heterogeneous across a wide range of length-scales. Consequently, effective flow properties may be poorly predicted using data that do not accurately represent the three-dimensional (3D) distribution of mudstone and sandstone within the reservoir. We present a novel, surface-based modelling approach, which honors the observed geometry of geologic surfaces that control such lithologic variability (e.g. contacts between laminae, beds, and facies units). Quantitative geometrical data to condition the models are obtained from an outcrop analogue, the Eocene Dir Abu Lifa Member (Western Desert, Egypt), which records deposition in a tide-dominated deltaic and estuarine setting.

The workflow uses template surfaces to represent heterogeneities in 3D depending on their geometry, rather than their length-scale. The region of interest is subdivided into "elemental volumes" that stack together, and in which heterogeneities have the same geometry. Different geometric input parameters are used to characterize the distribution and 3D orientation of template surfaces in the elemental volumes (e.g. laminae thicknesses within a cross-bed). Mudstones are modelled as mud drapes that line the heterogeneity surfaces, with their extent and continuity defined using a mudstone frequency function derived from the outcrop analogue.

Generic 3D mini-models (volume of 9 m^3) of sandy tidal bar deposits comprising stacked cross-beds have been generated with a range of mud drape coverage, which can be linked to a sandstone fraction observed in core. A cornerpoint grid conforming to the surfaces was generated, and the models were flow simulated until steady state was reached. Results show that effective permeability

measurements are highly dependent on the volume of rock considered, as heterogeneity surfaces are continuous at centimetre length-scale (e.g. core plugs) but discontinuous at metre length-scale (e.g. cross-beds). At metre length-scale, effective vertical permeability decreases faster than effective horizontal permeability as sandstone fraction decreases, because mud drapes become more laterally extensive. Effective horizontal permeability also decreases faster in the dip direction of the cross-beds than in their strike direction as sandstone fraction decreases. This pattern of 3D anisotropy is related to a higher density of mud drapes in the toesets, relative to the foresets, of cross-beds within sandy tidal bar deposits.

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[1] *Department of Earth Science and Engineering, Imperial College London, UK*

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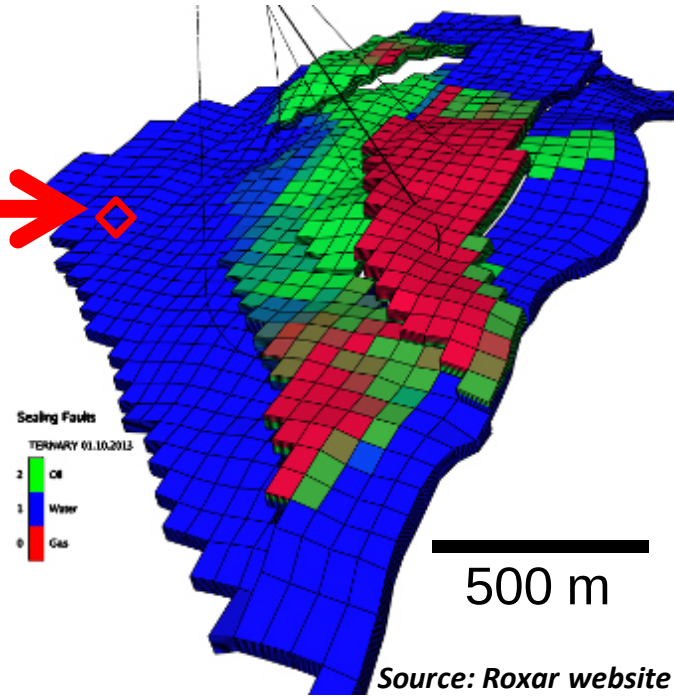
Rationale for the study

Subsurface data
(core-plug measurements or log-derived measurements)
Length-scale: cm to m

Reservoir model cell
Length-scale: 100m x 100m x 1m



Source: Roxar website

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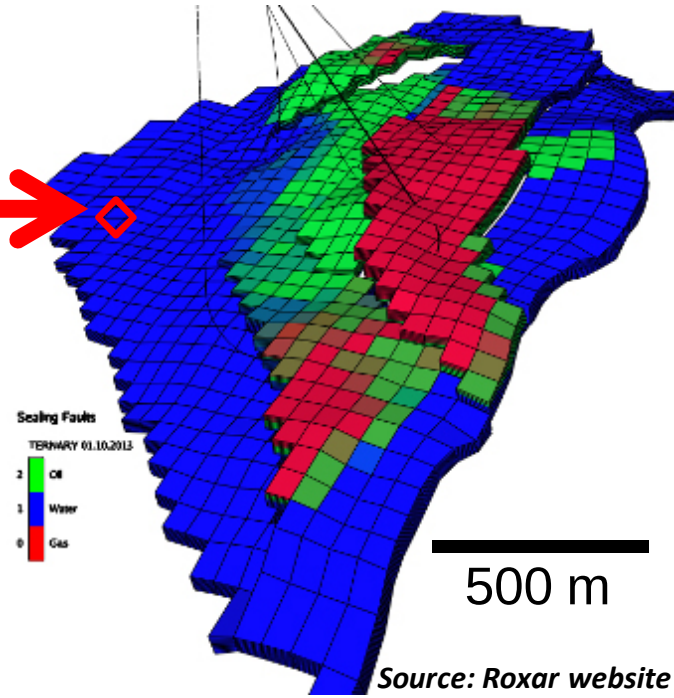


Source: Roxar website

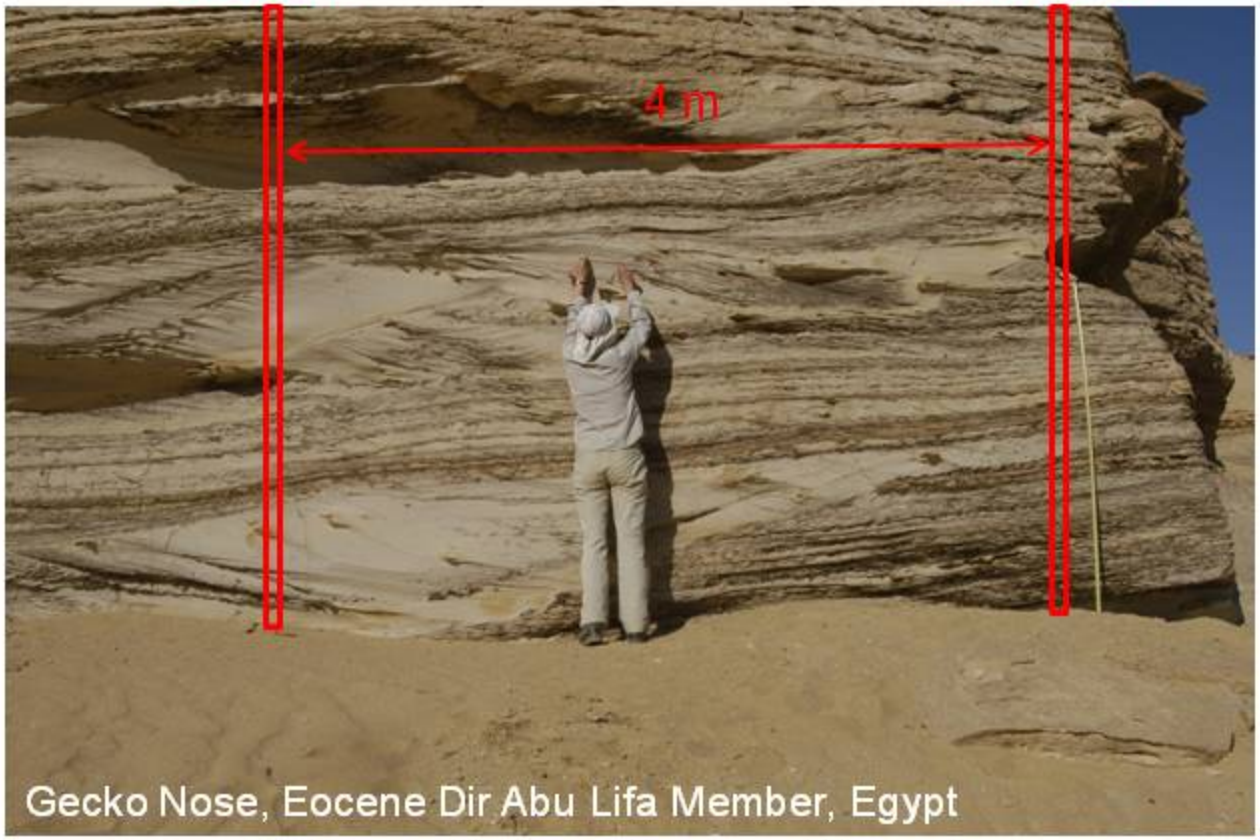
Previous studies highlighted **incorrect estimation of reservoir properties** based on core-plug measurements and log-derived measurements compared to high resolution models:

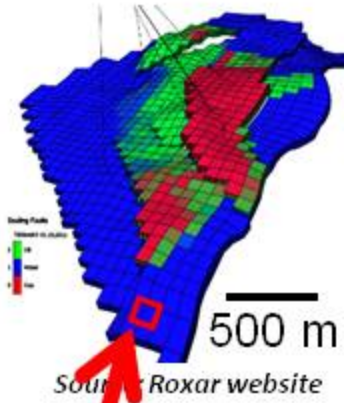
Core-plug measurements and log-derived measurements are not representative because the lateral and vertical variability of tide-influenced facies is not constrained.

Rationale for the study

CORE A

CORE B





Intermediate meter length-scale:
lateral and vertical facies variability
Closer to the REV (Representative Elementary Volume)

Rationale for the study

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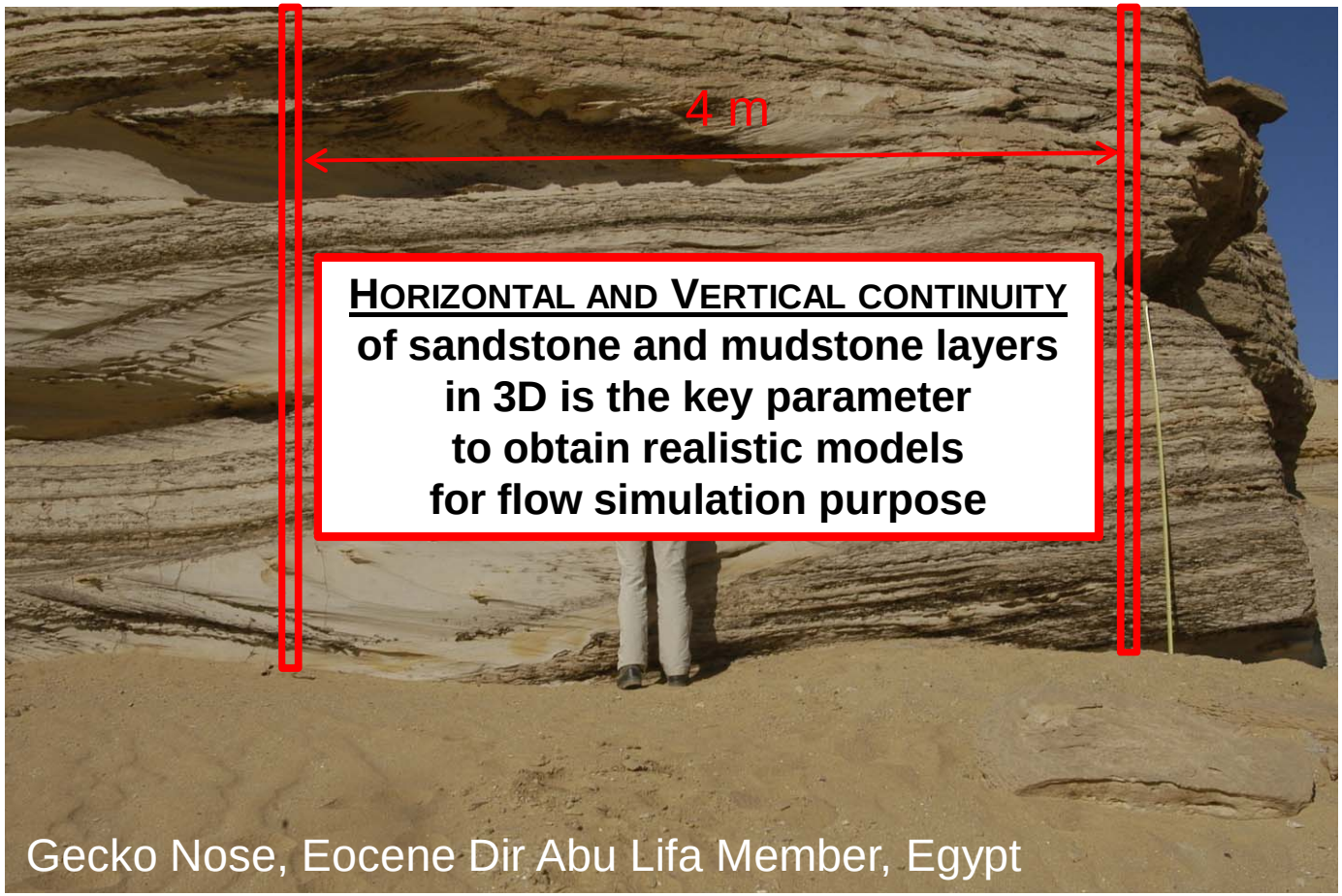
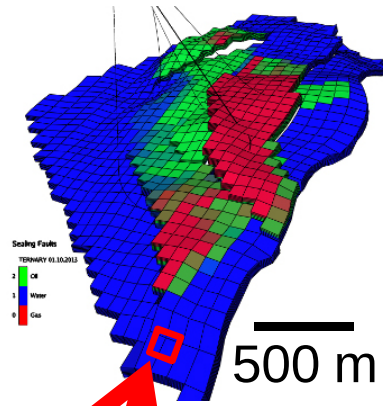
CORE B



HORIZONTAL AND VERTICAL CONTINUITY
of sandstone and mudstone layers in 3D is the key parameter to obtain realistic models for flow simulation purpose



Source: Roxar website

Intermediate meter length-scale:
lateral and vertical facies variability
Closer to the REV (Representative Elementary Volume)

Aim and objectives

- What do we want ?
  - ➢ Define effective reservoir properties for different facies of heterolithic tidal sandstones
- What do we need ?
  - ➢ Metre-scale mini-models of the different facies which capture key heterogeneity surfaces and realistic continuity of sandstone and mudstone layers
- How do we build models ?

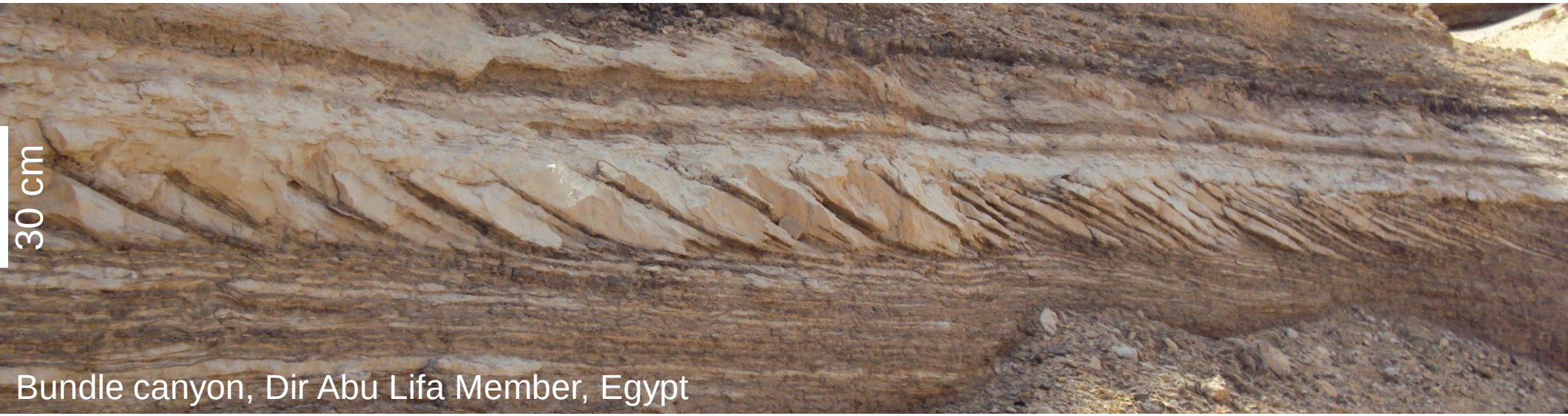
HORIZONTAL AND VERTICAL CONTINUITY
of sandstone and mudstone layers in 3D is the key parameter to obtain realistic models for flow simulation purpose

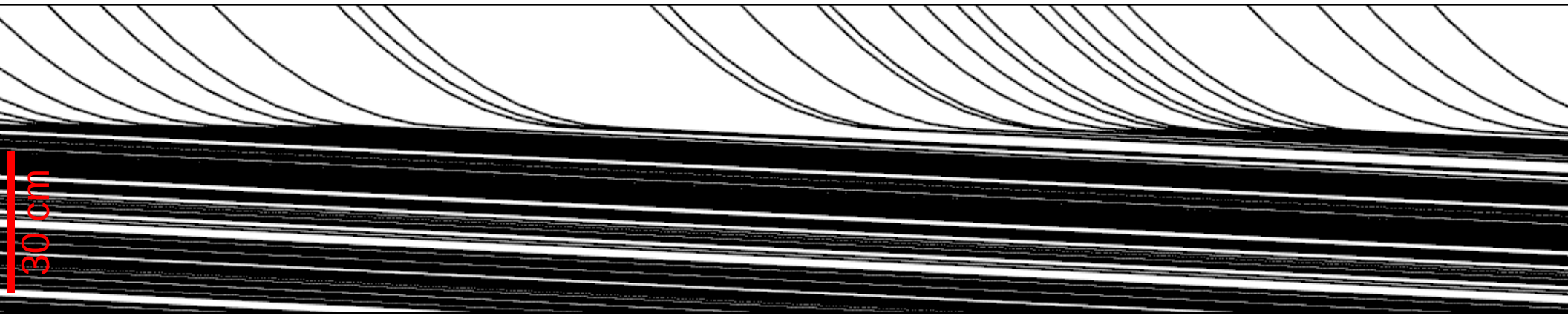
PROCESS-BASED MODELLING
SBED software available
Input parameters: flow velocity, sediment input rate, erosive current strength,...

OR

SURFACE-BASED MODELLING
New modelling workflow presented here
Input parameters: purely geometric

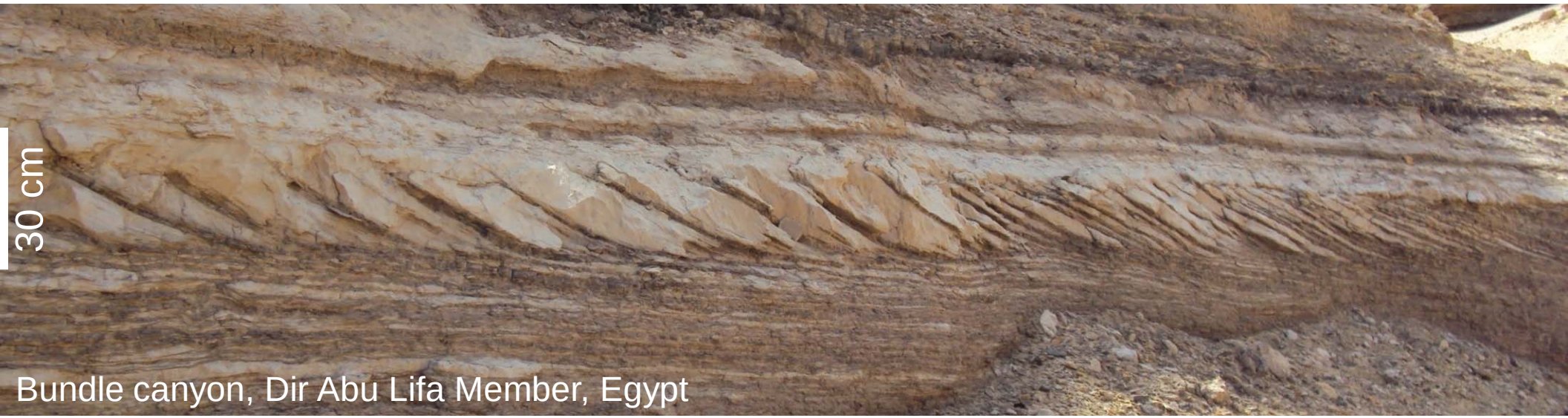
Surface-based modelling workflow
Comparison outcrop / model

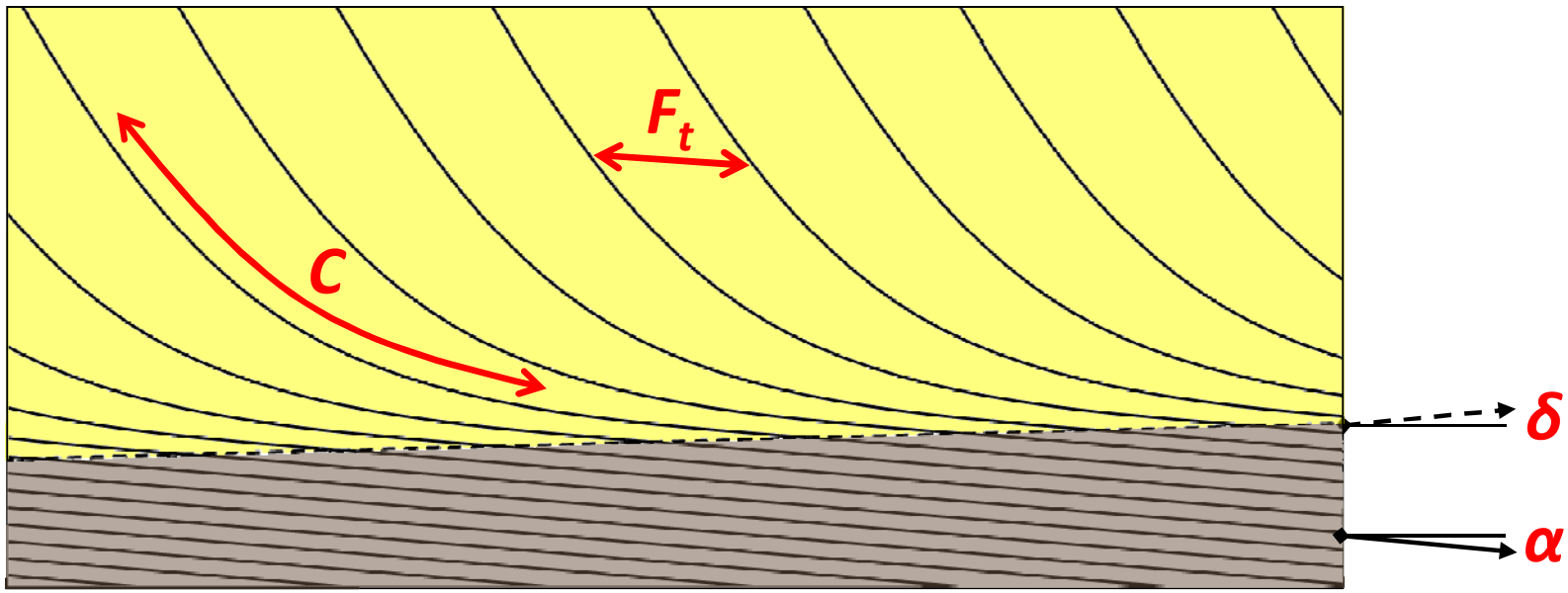




Dip cross-section in a cross-bed set using a dune cross-bedding template

Surface-based modelling workflow
Template surface: dune cross-bedding

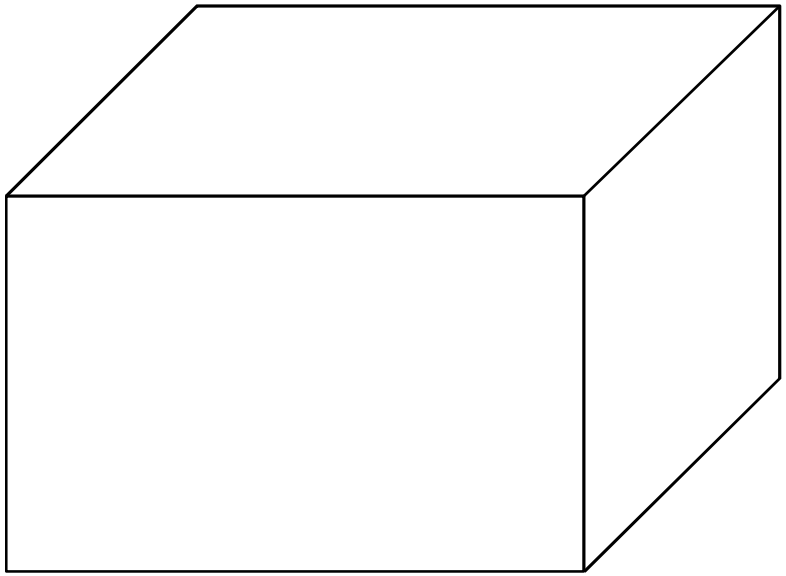


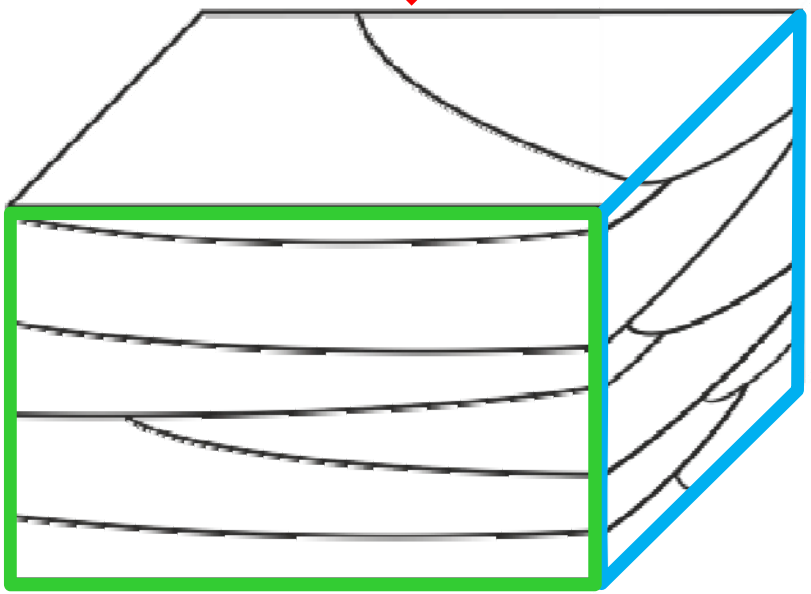


List of input parameters:

C	surface curvature
F_t	foreset thickness
δ	aggradation angle
α	toeset dip angle

Surface-based modelling workflow
1) Subdivision into elemental volumes

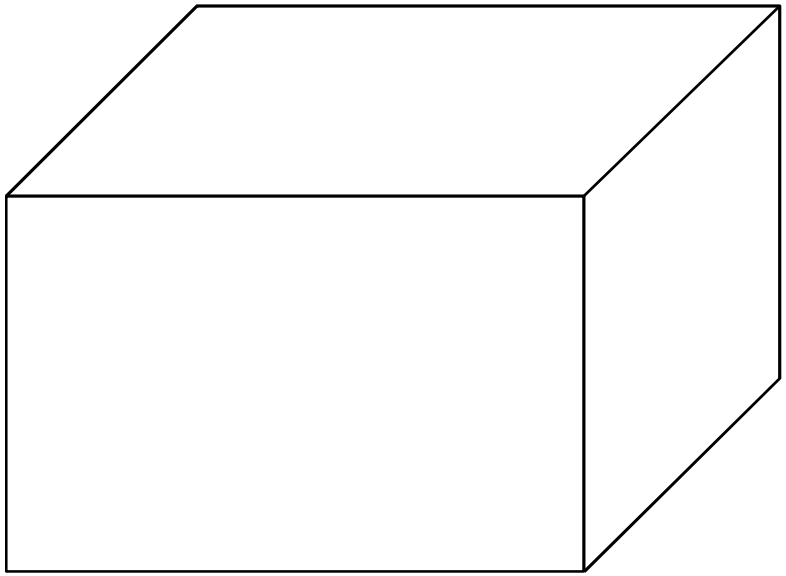


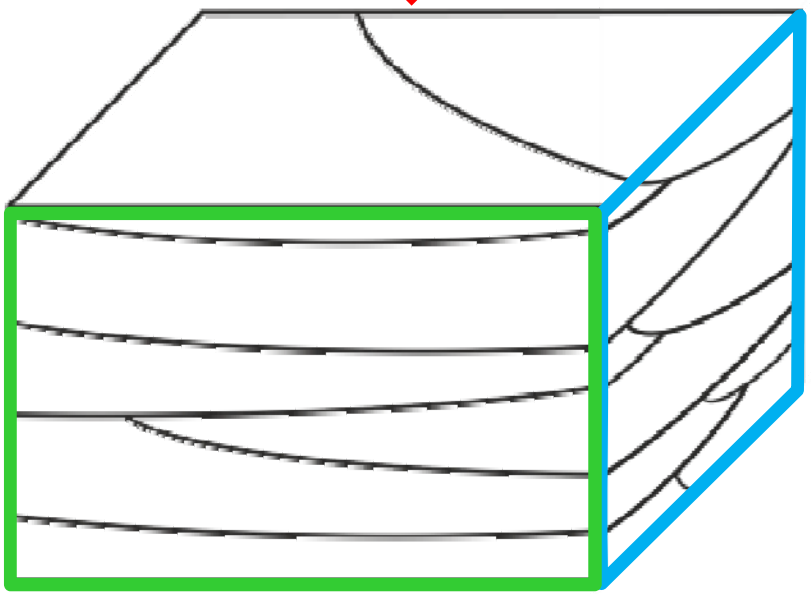


Dip cross-section:

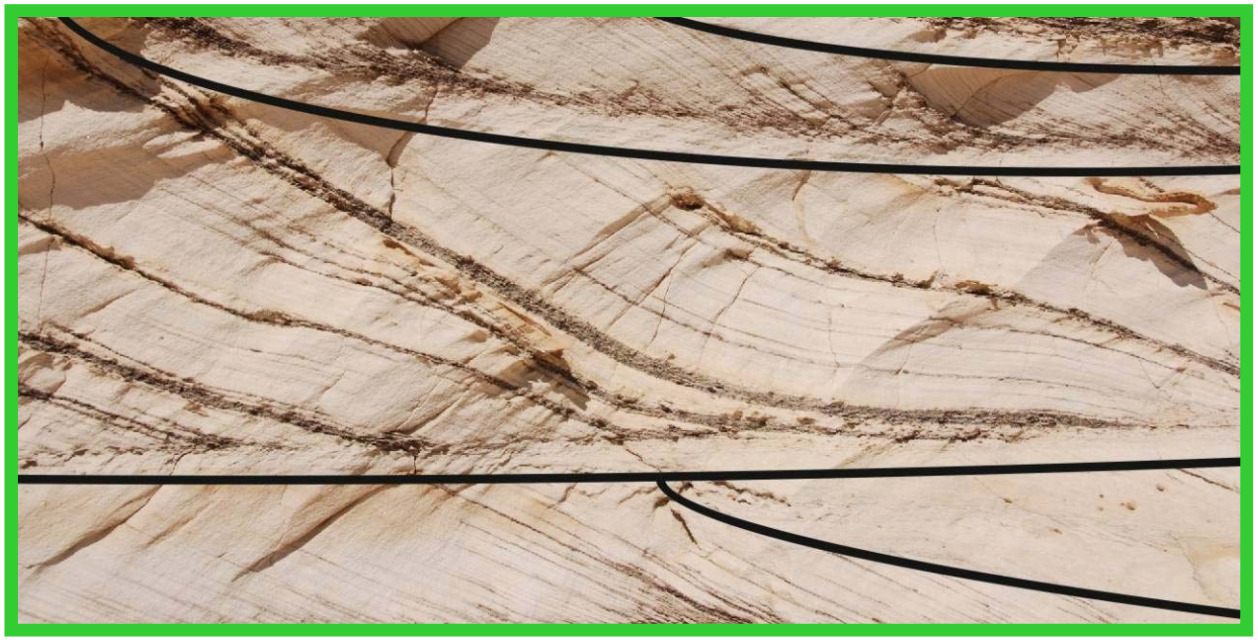
Strike cross-section:

Surface-based modelling workflow
1) Subdivision into elemental volumes





Dip cross-section:



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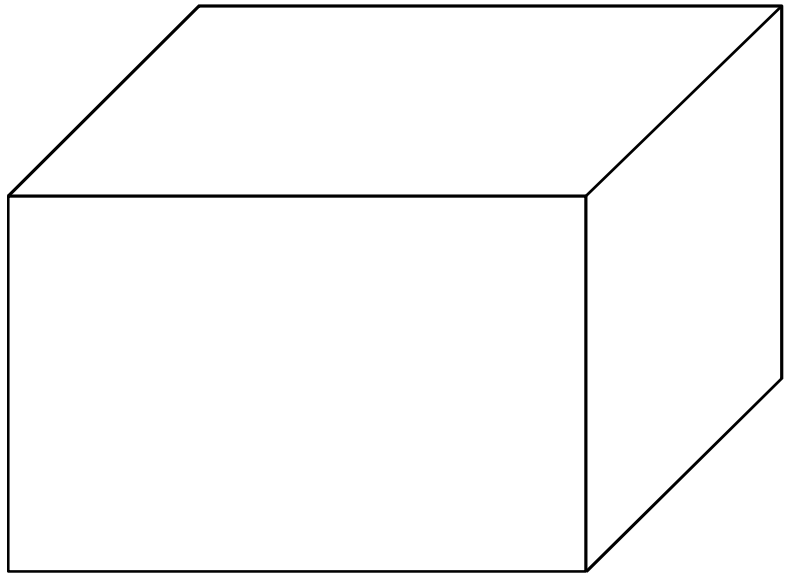

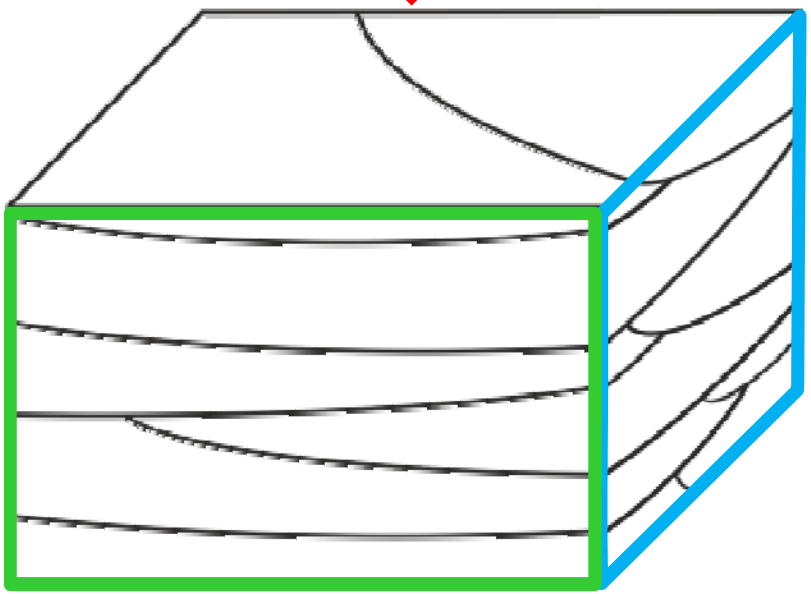

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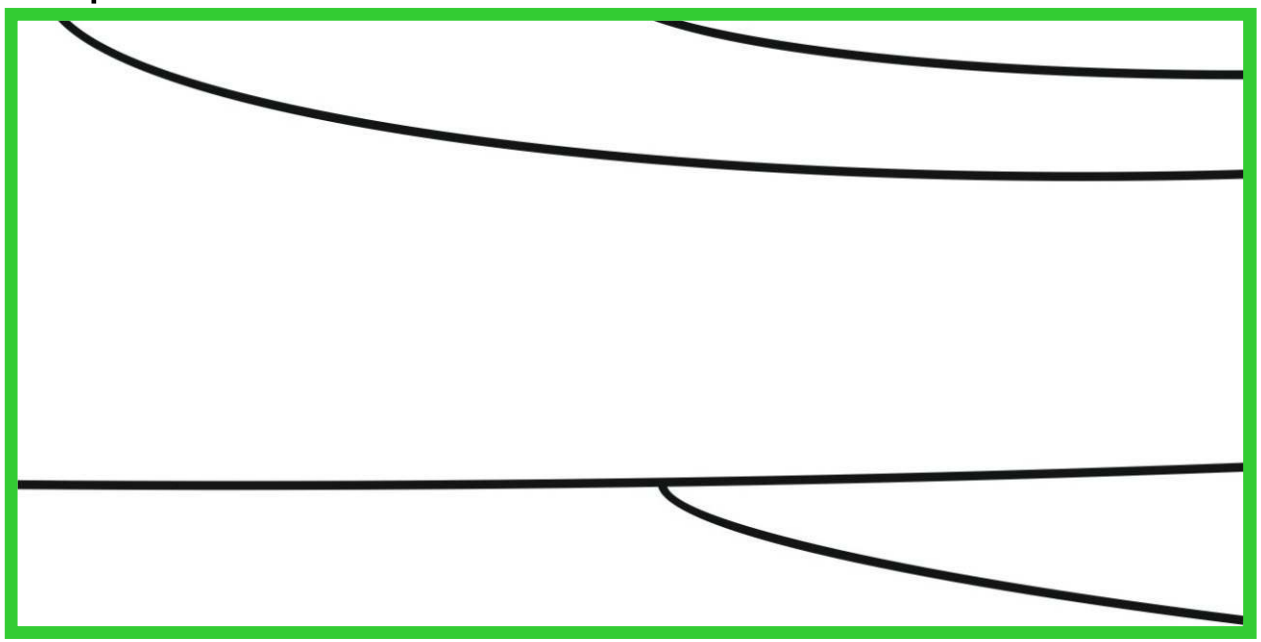

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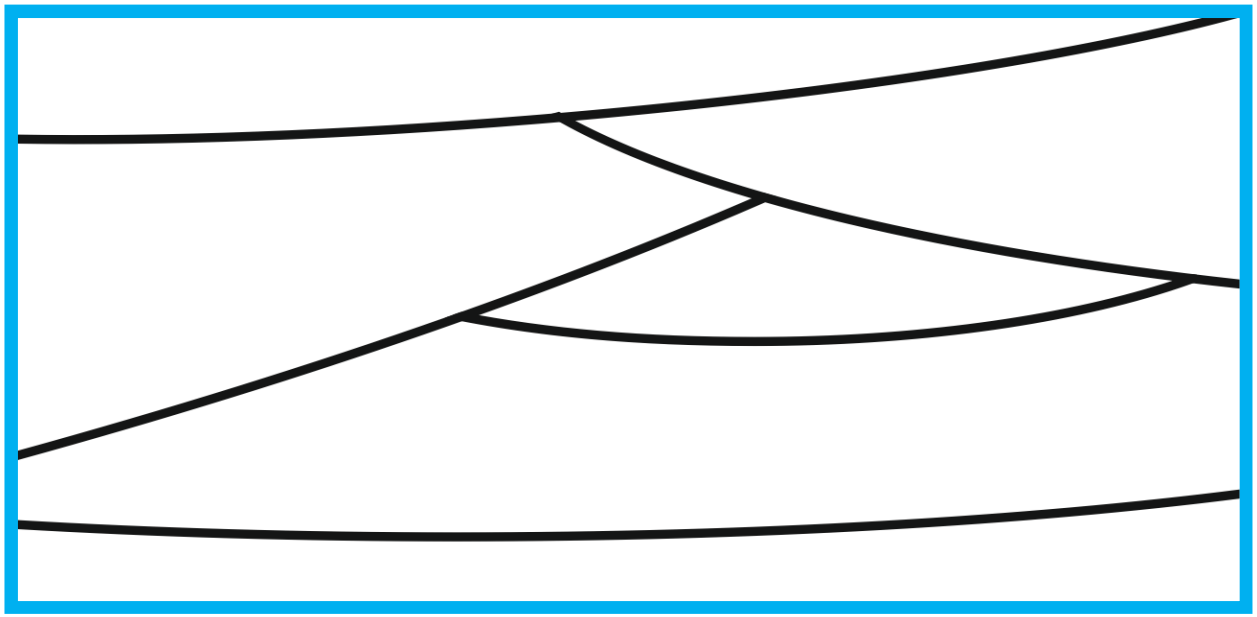
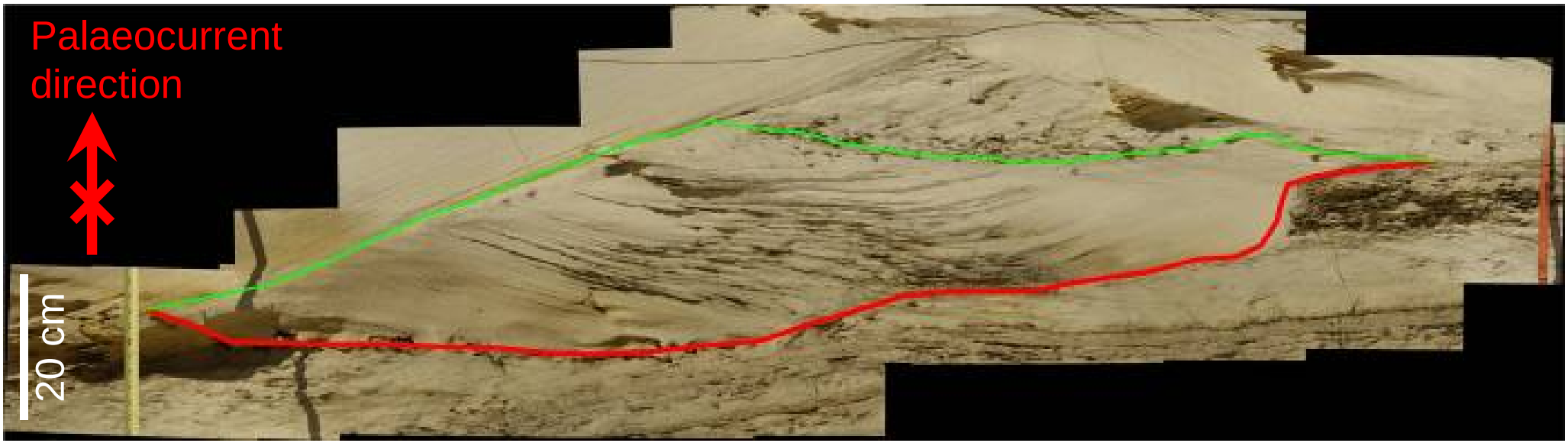


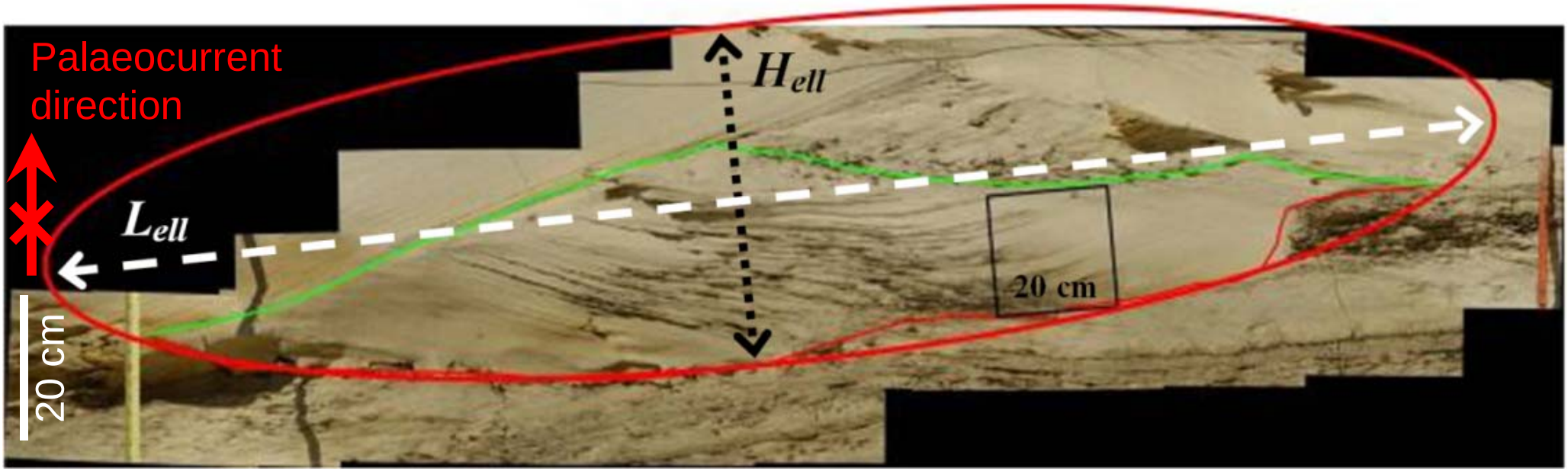
Surface-based modelling workflow
1) Subdivision into elemental volumes

Elemental volume dimensions distributions

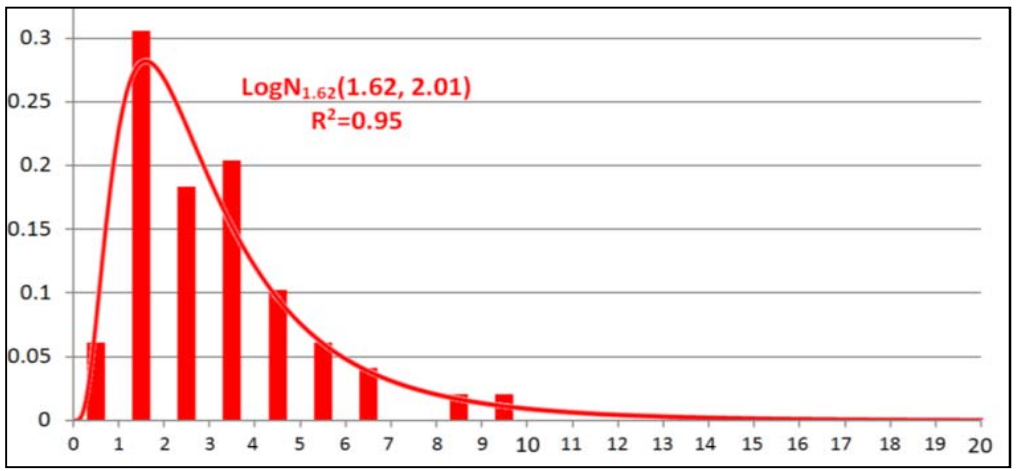


Surface-based modelling workflow
1) Subdivision into elemental volumes

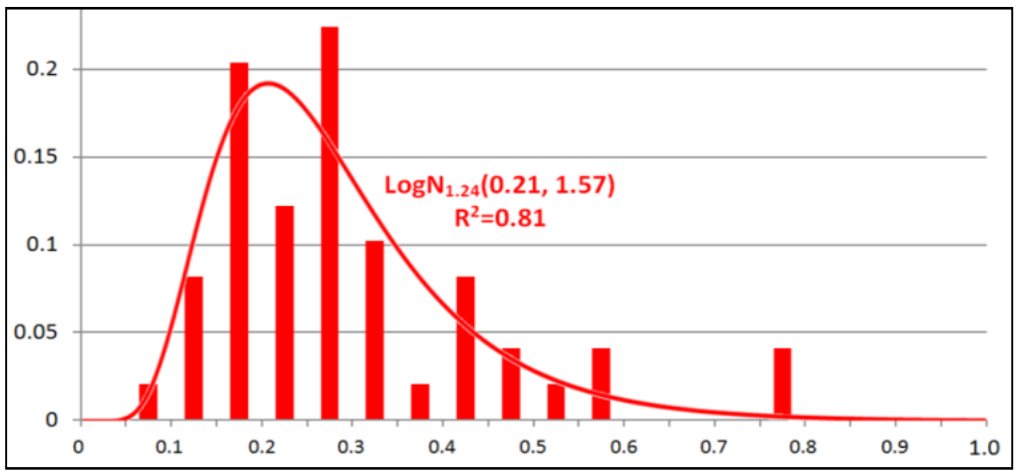
Elemental volume dimension distributions in the strike direction



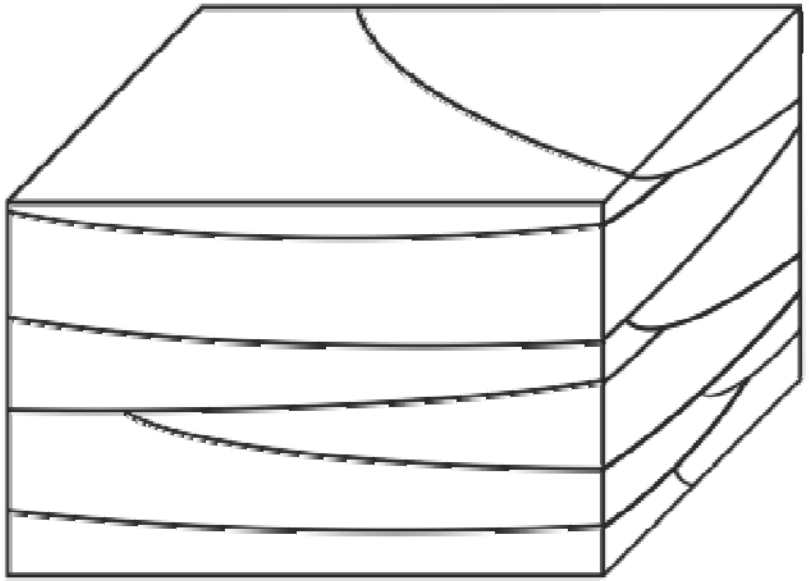
Length L_{ell}

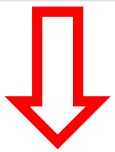


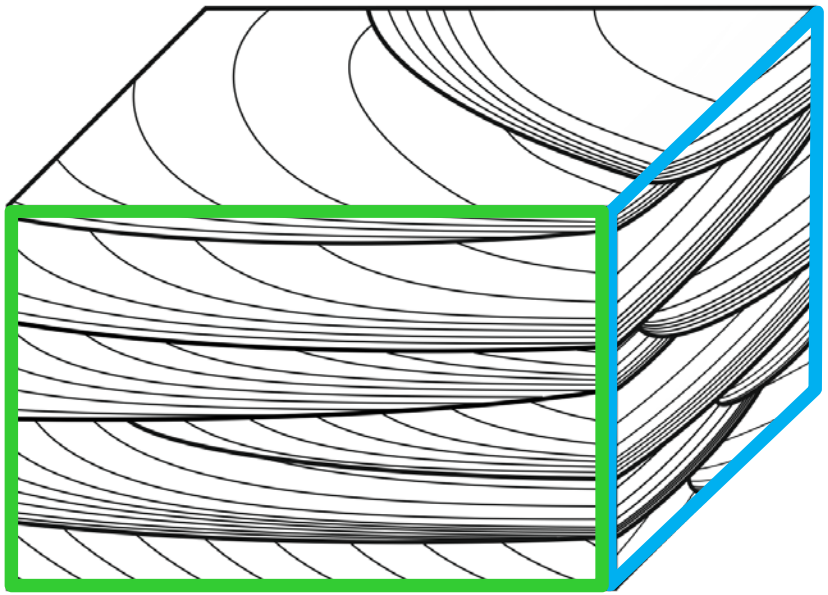
Height H_{ell}



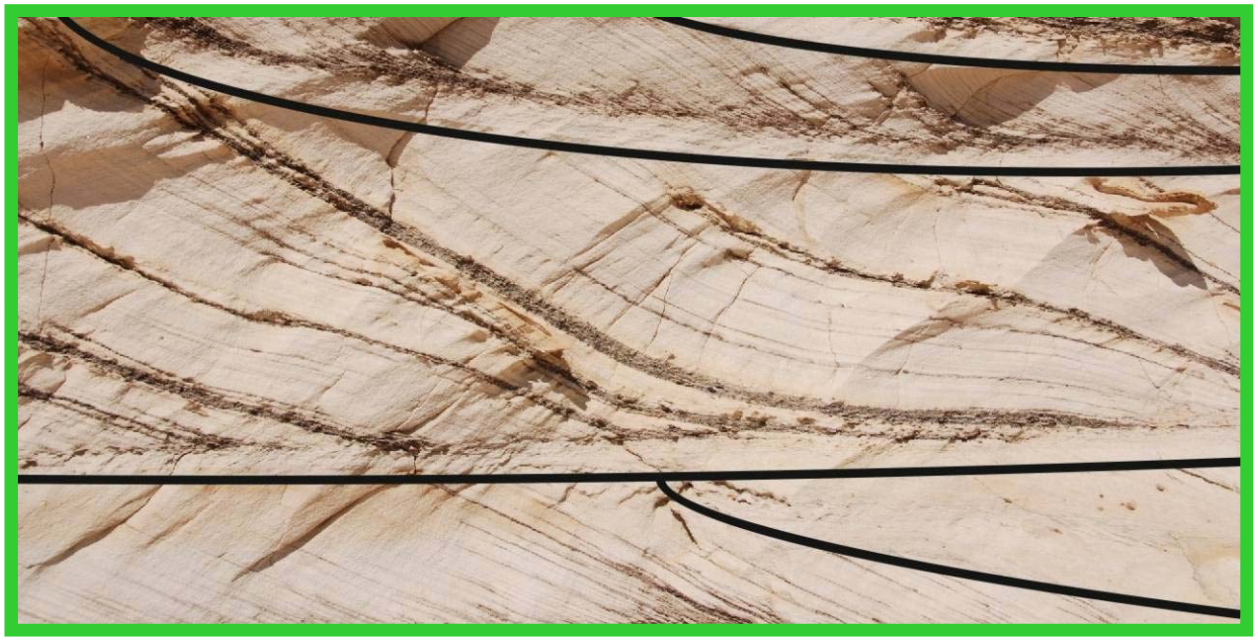
Surface-based modelling workflow
2) Template surface modelling





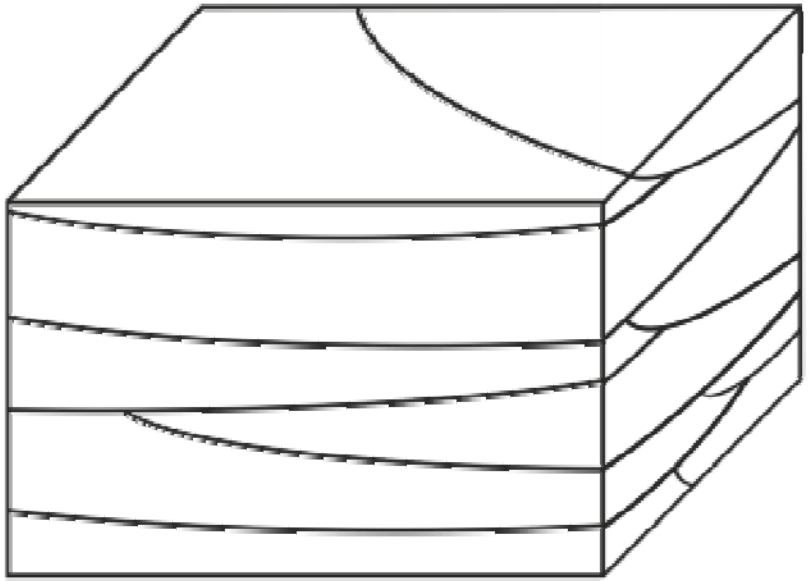


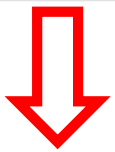
Dip cross-section:

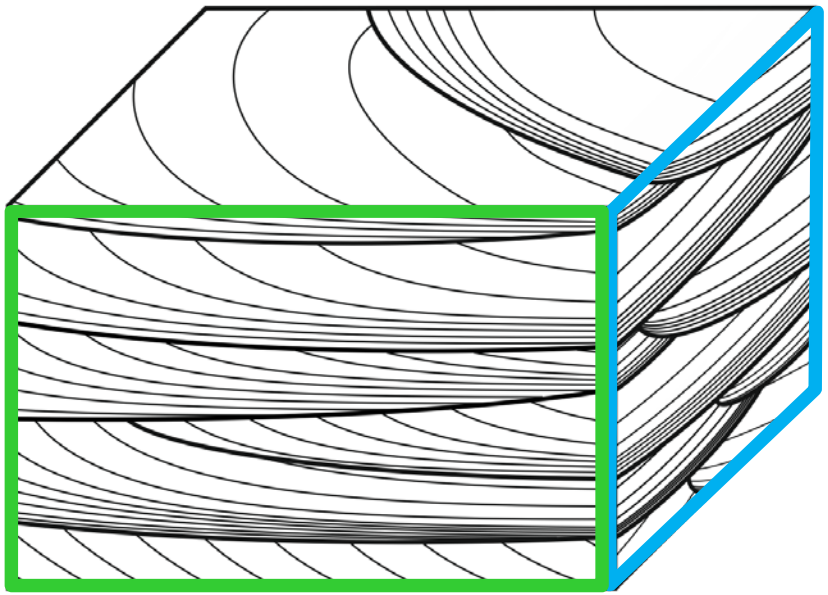


Strike cross-section:

Surface-based modelling workflow
2) Template surface modelling







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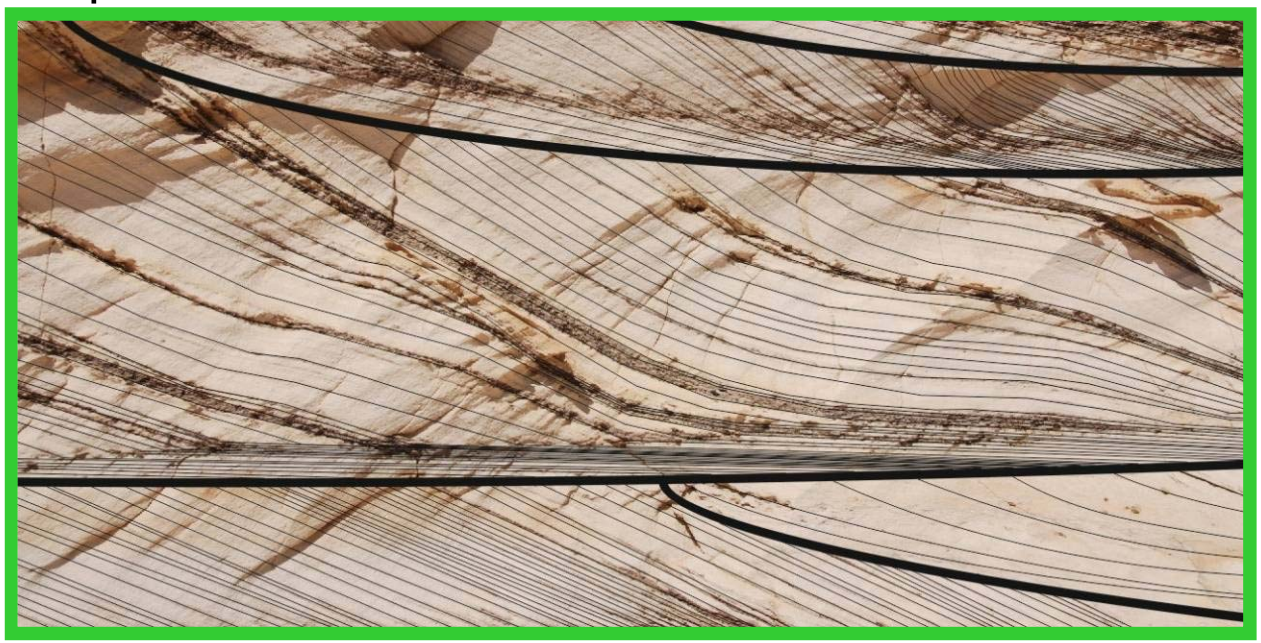

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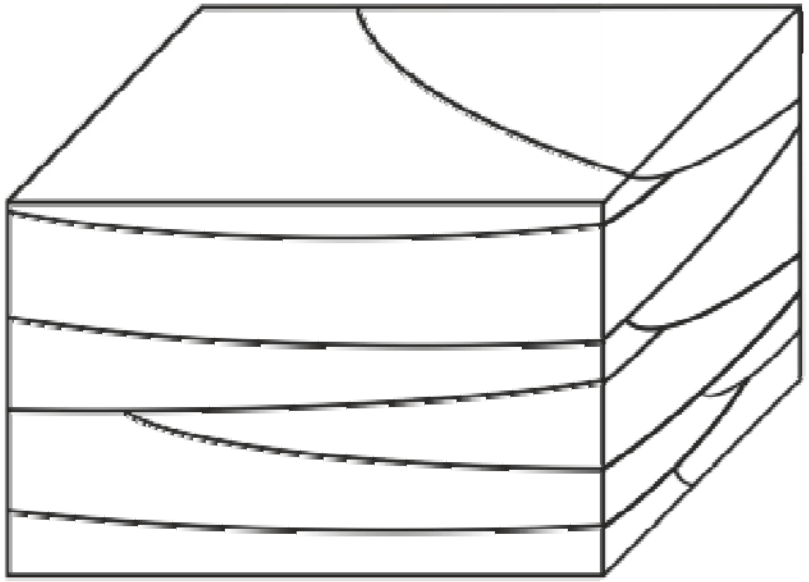

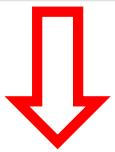

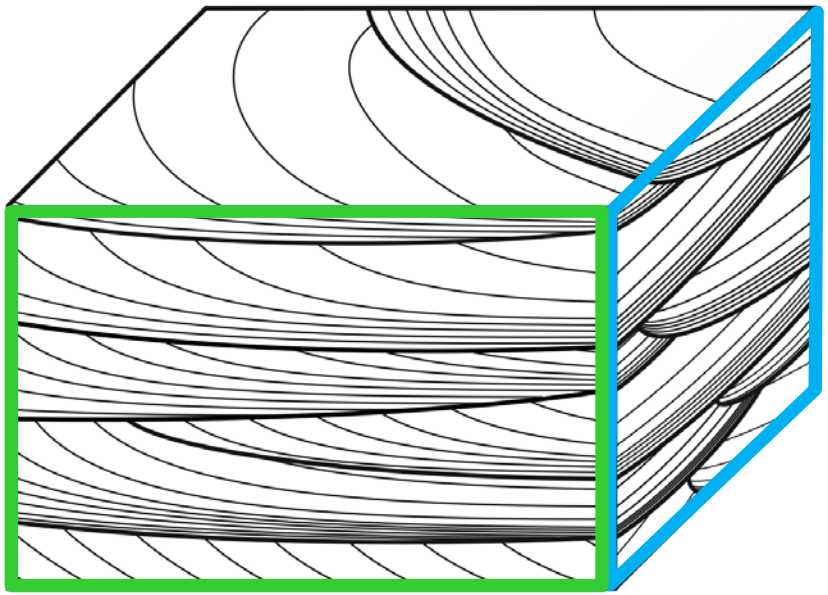

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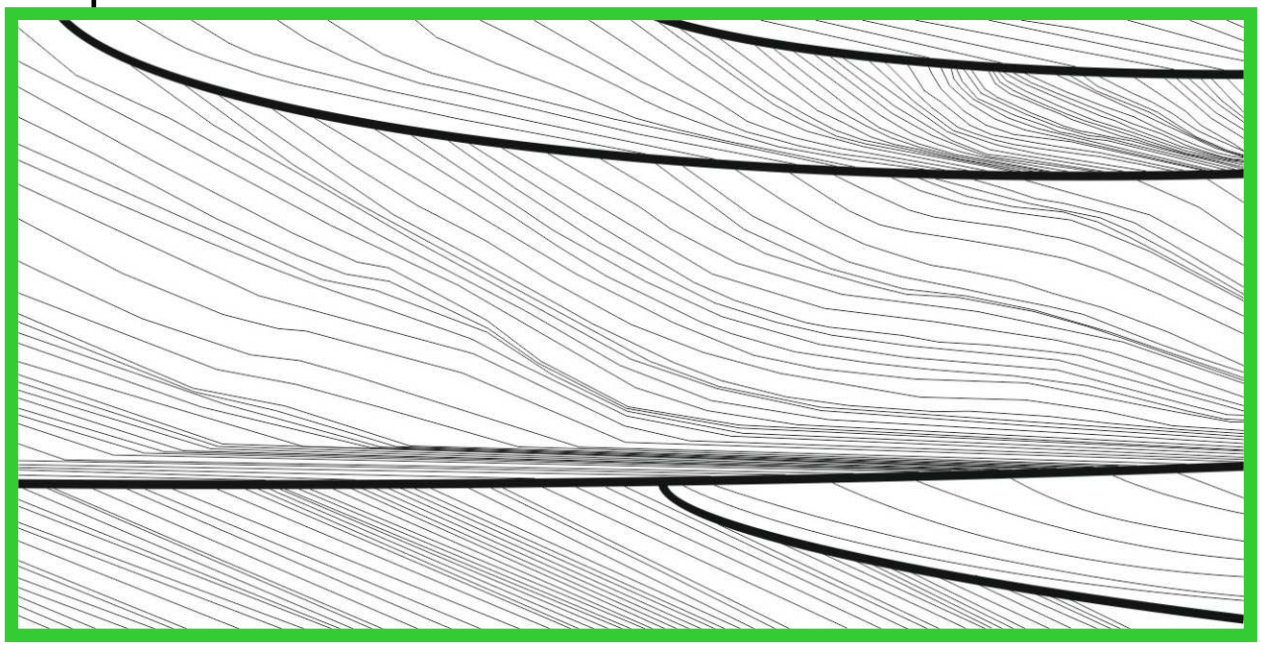

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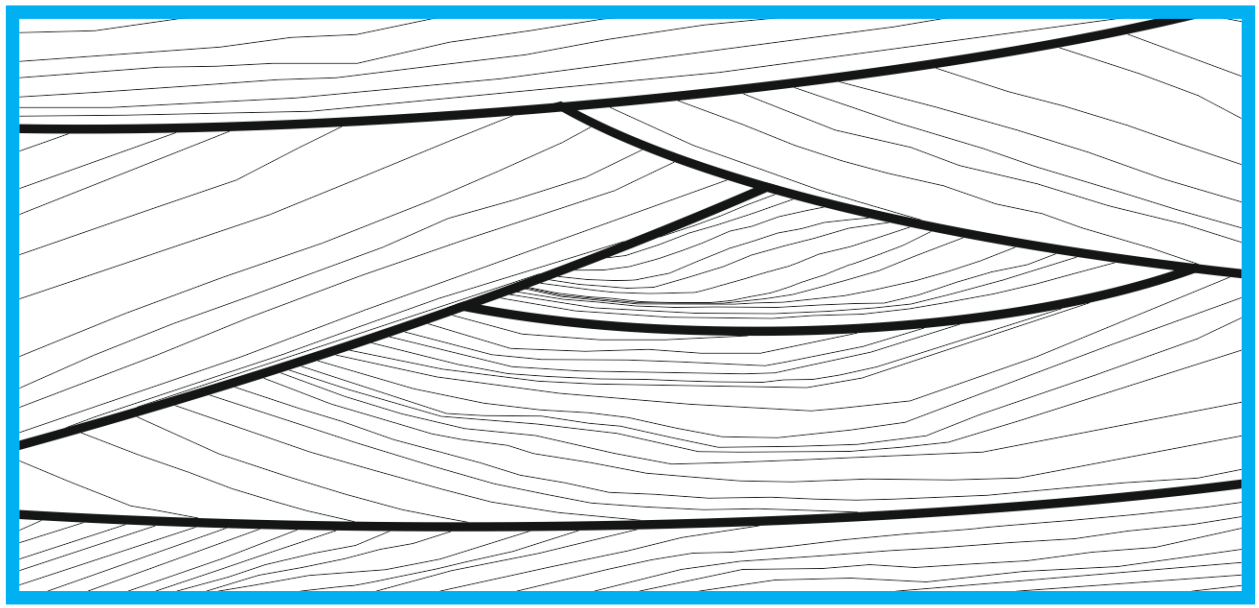

Surface-based modelling workflow
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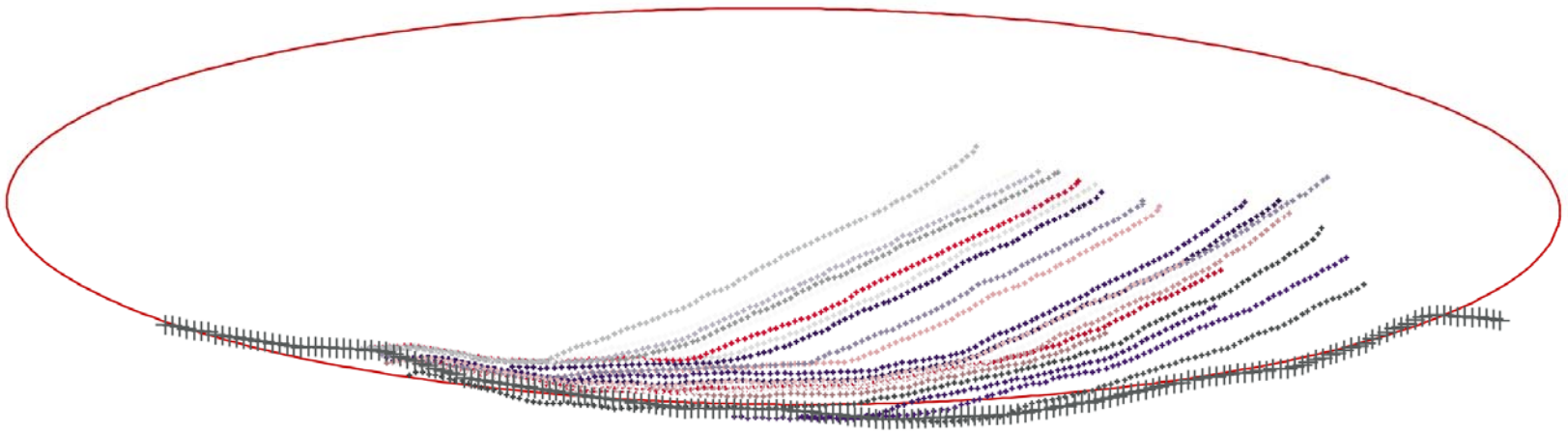
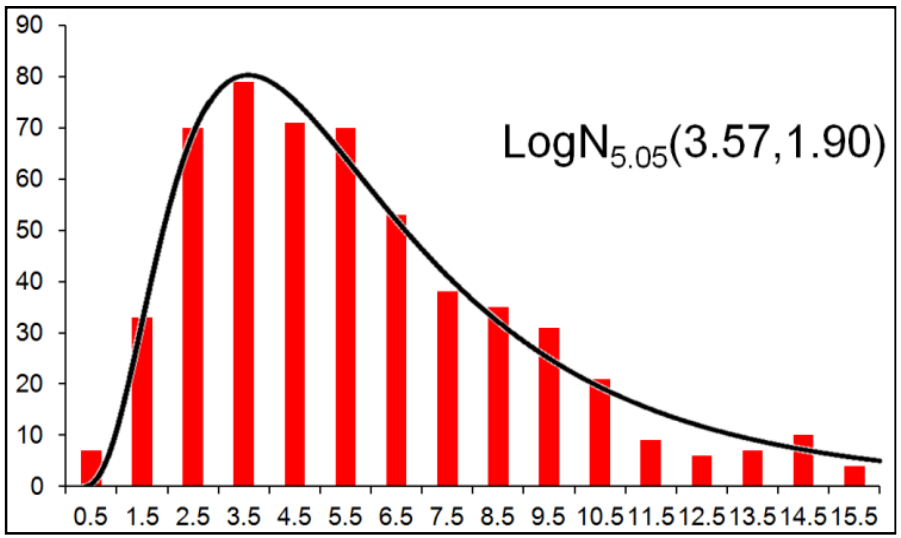
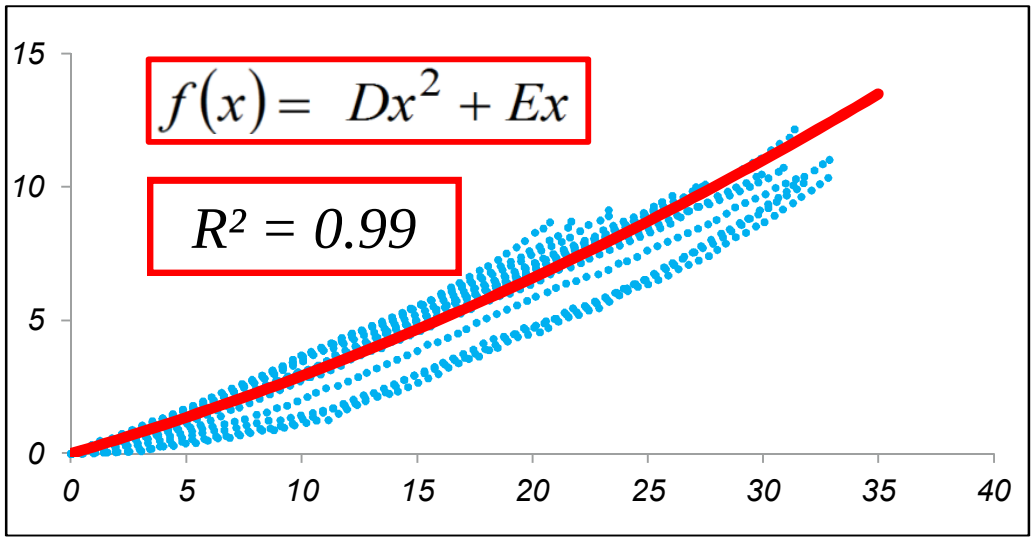


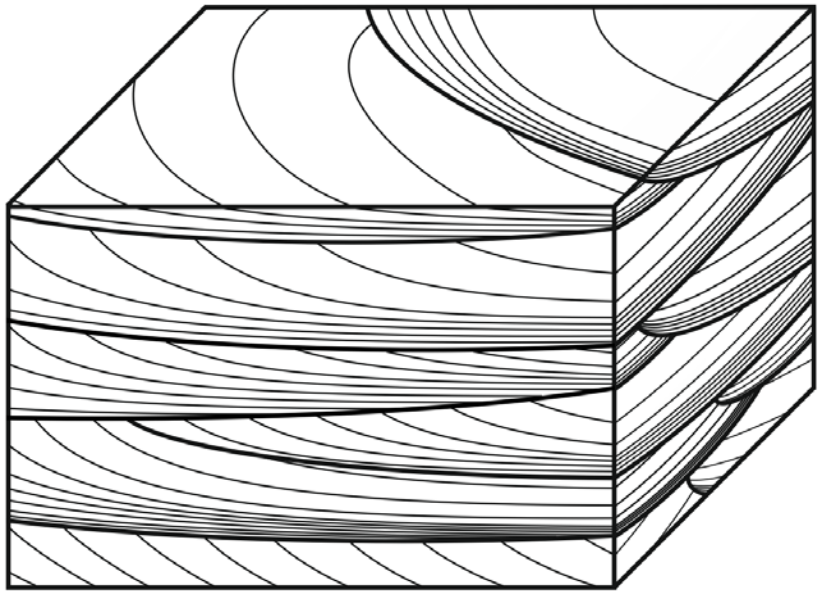


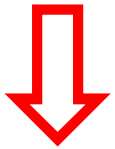
Foreset thickness Ft distribution (cm)

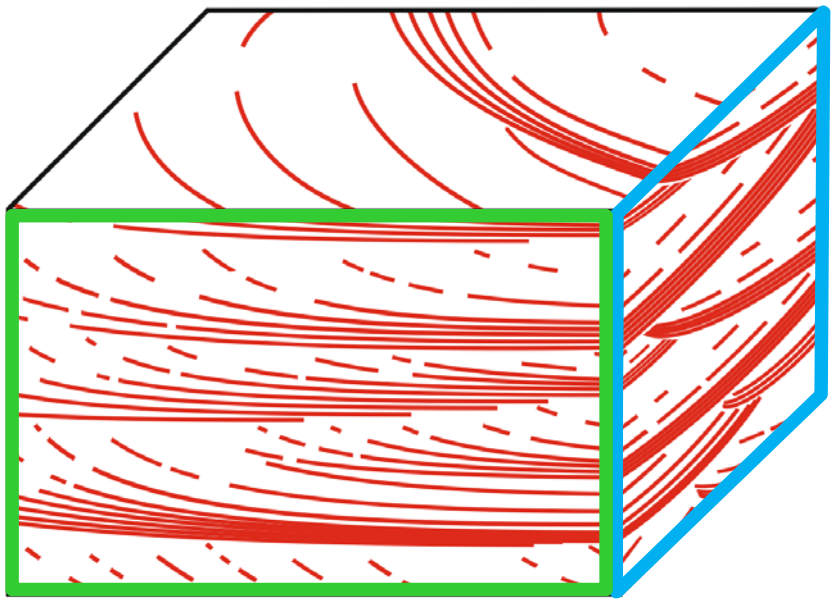


Foreset geometry and curvature (cm)

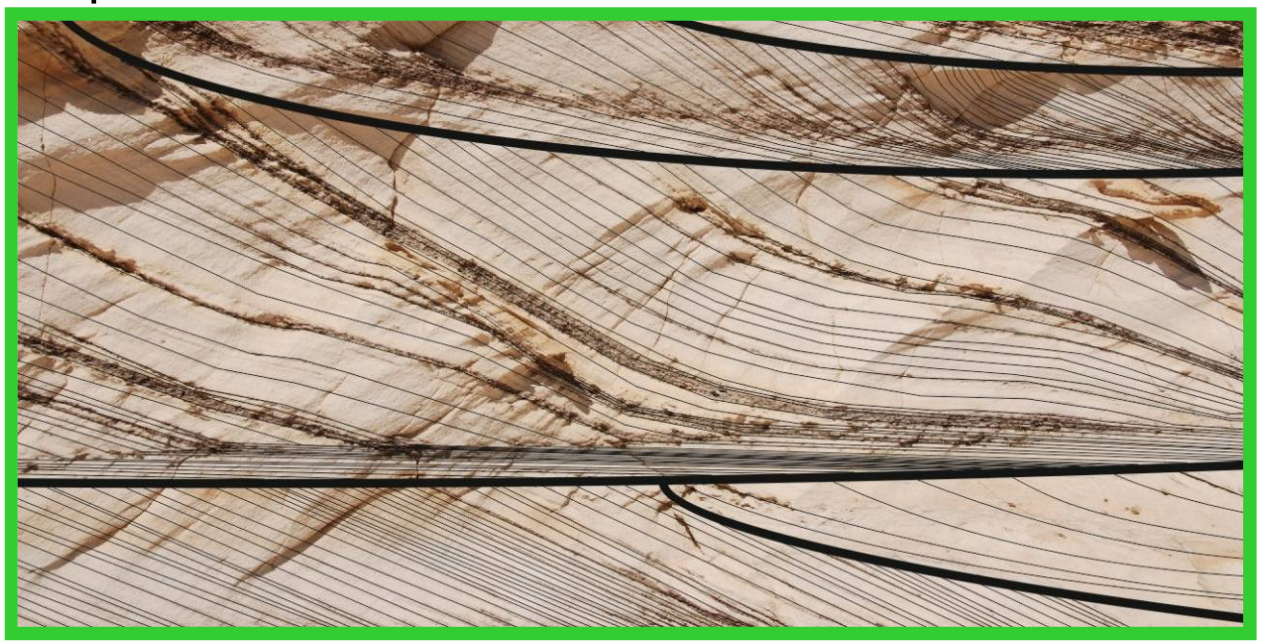
Surface-based modelling workflow
3) Mudstone modelling





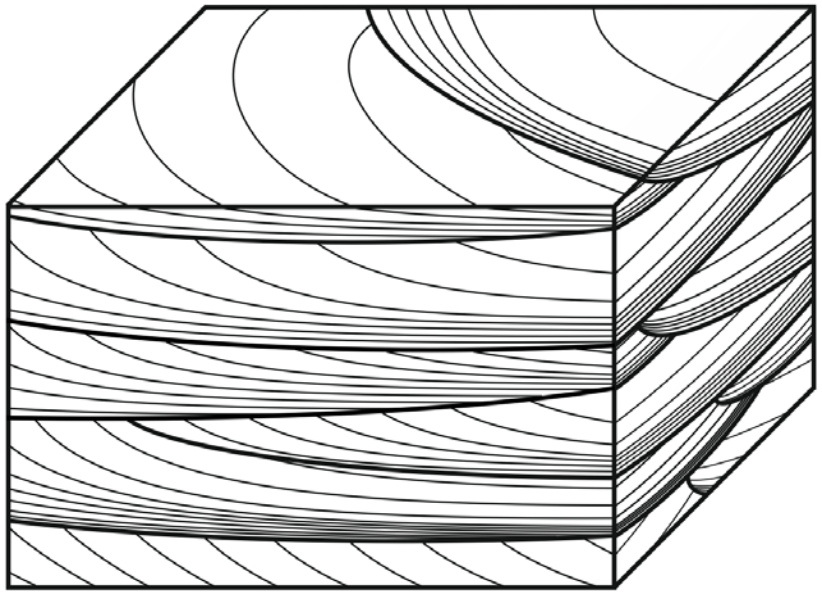


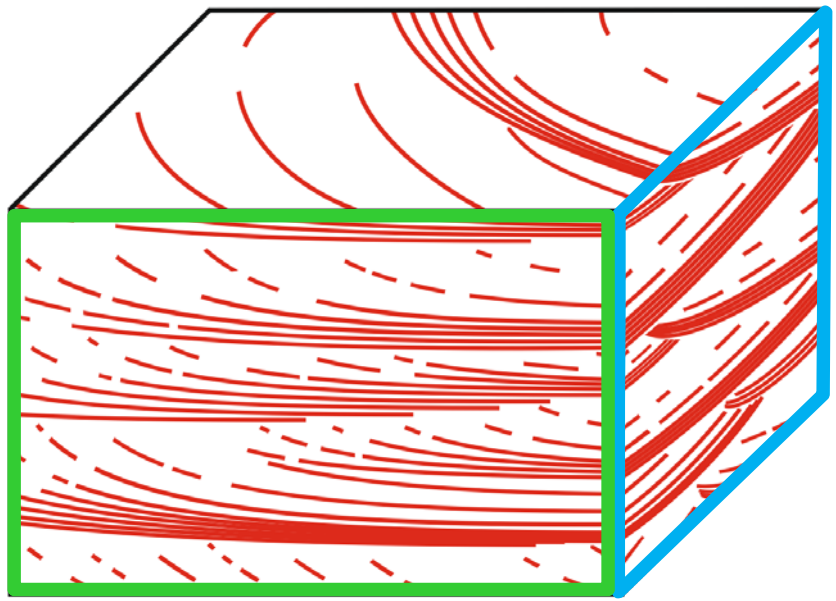
Dip cross-section:



Strike cross-section:

Surface-based modelling workflow
3) Mudstone modelling

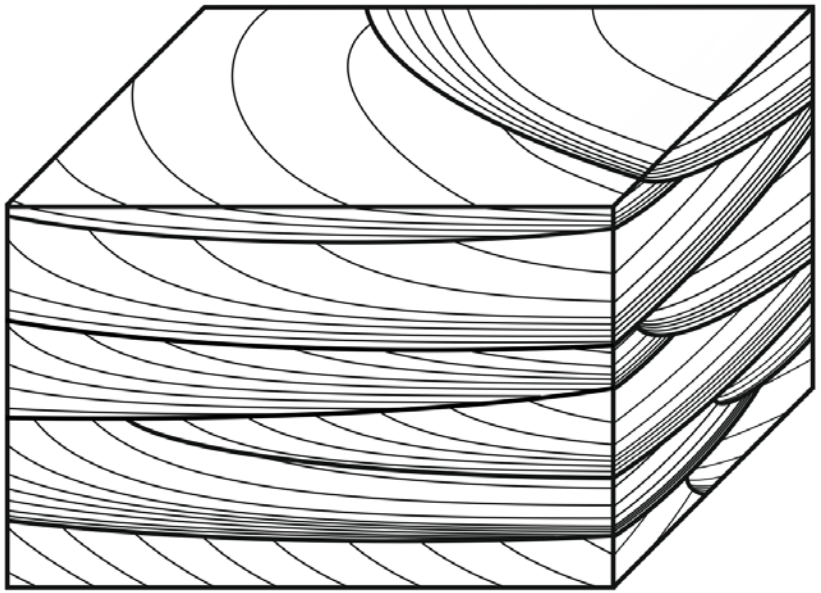


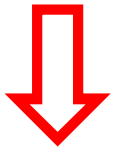


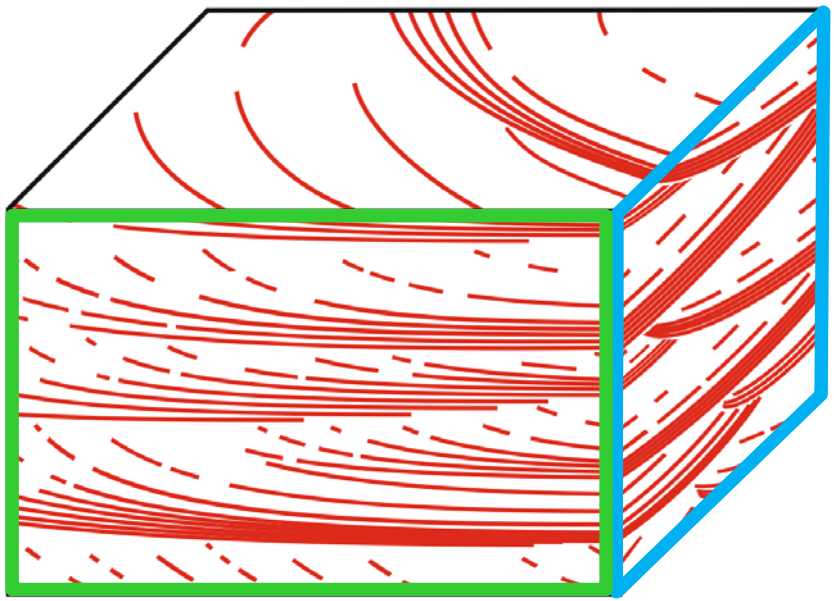
Dip cross-section:

Strike cross-section:

Surface-based modelling workflow
3) Mudstone modelling



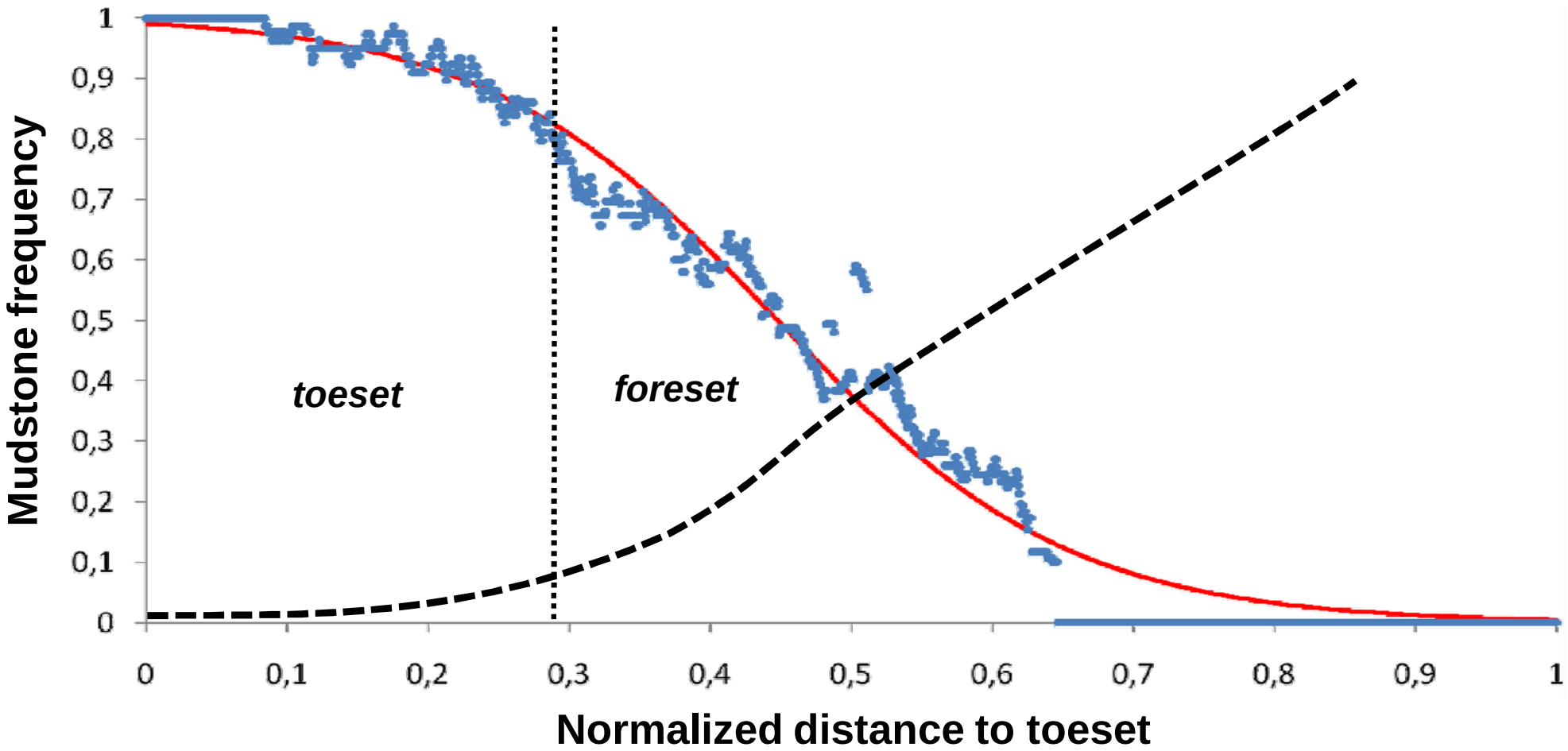




Dip cross-section:

Strike cross-section:

Surface-based modelling workflow
3) Mudstone modelling

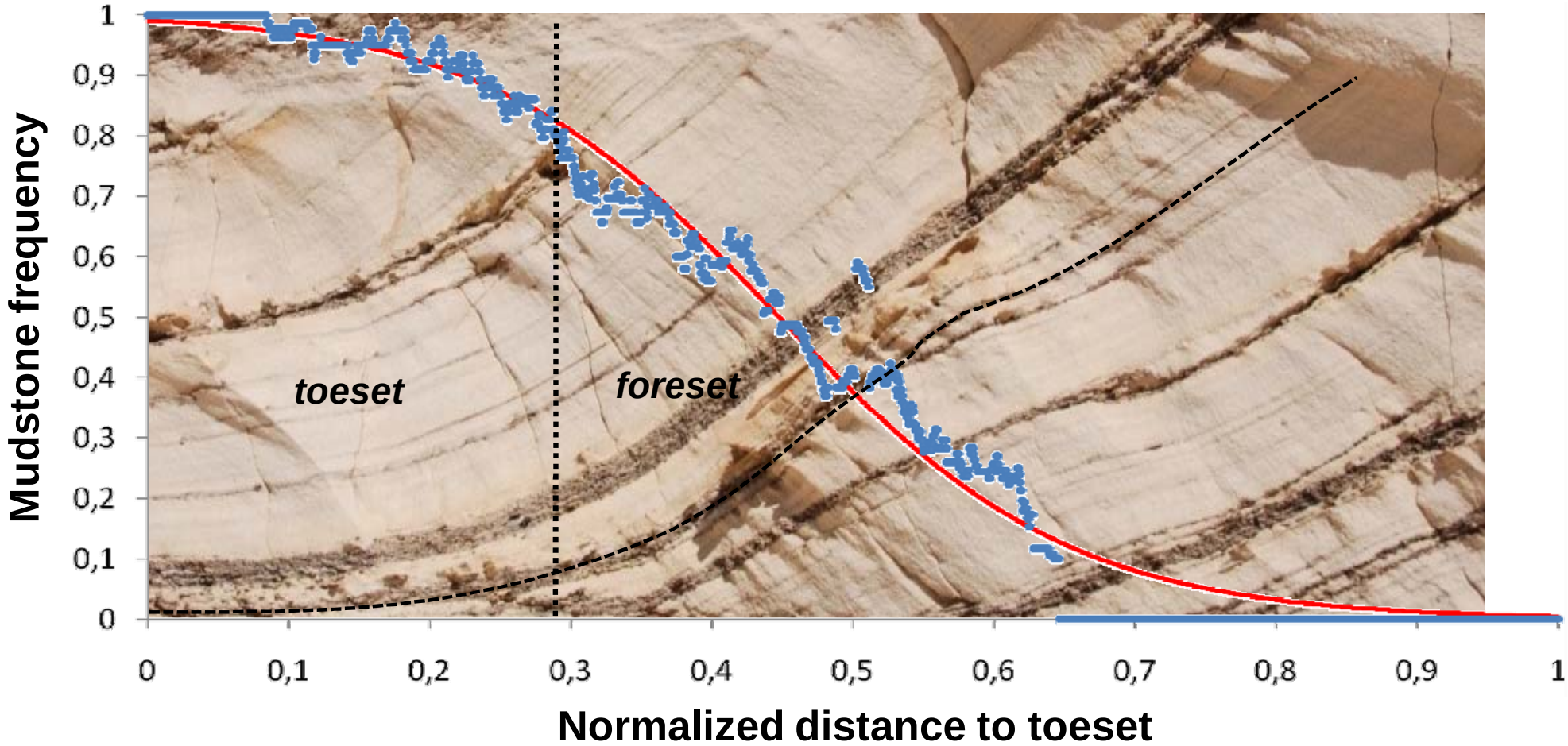


Mudstone frequency function extraction

$$f(x) = \frac{G}{1 + e^{(Hx+K)}}$$

$$R^2 = 0.99$$

Surface-based modelling workflow
3) Mudstone modelling



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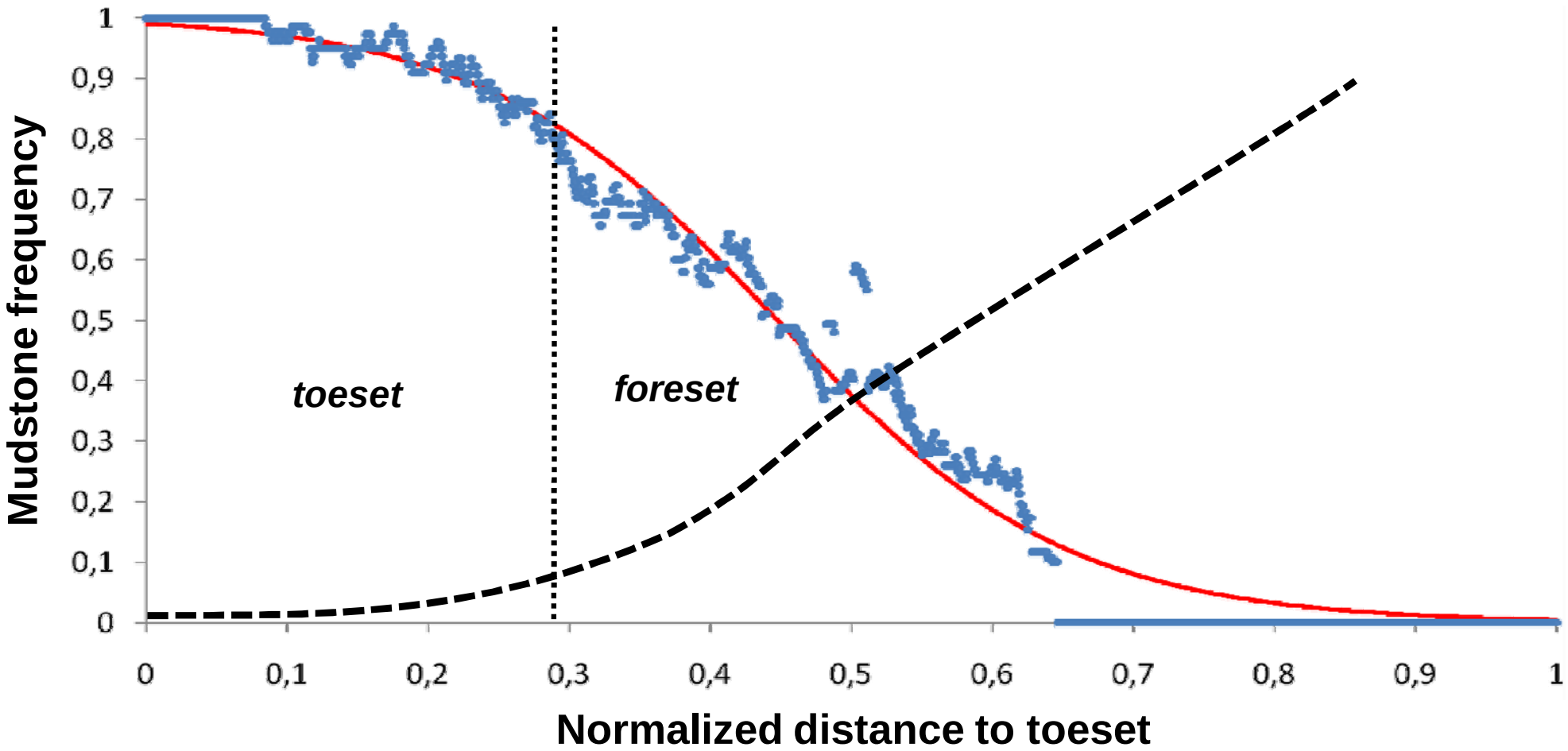
3) Mudstone modelling



Mudstone frequency function extraction

$$f(x) = \frac{G}{1 + e^{(Hx+K)}}$$

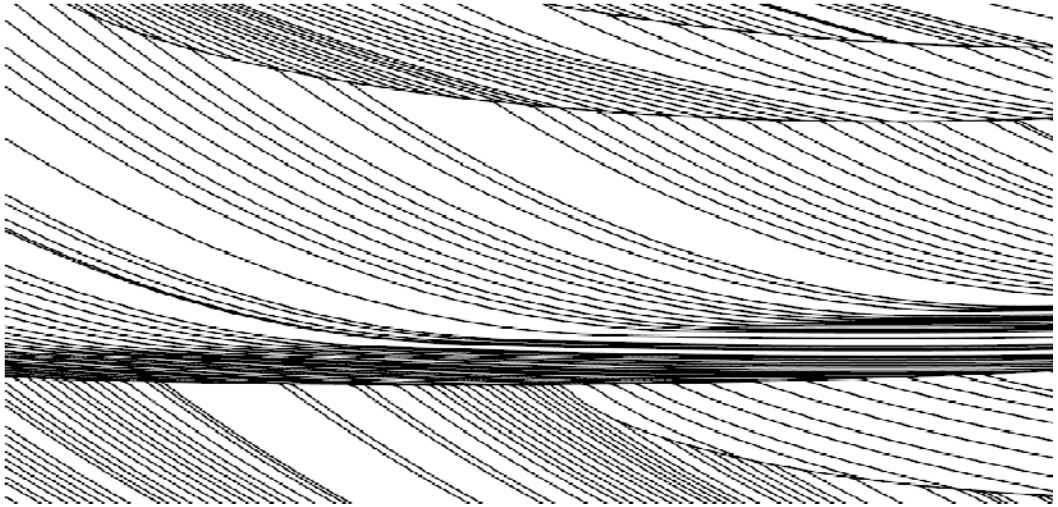
$$R^2 = 0.99$$

Comparison model/outcrop

Dip cross-section:

OUTCROP

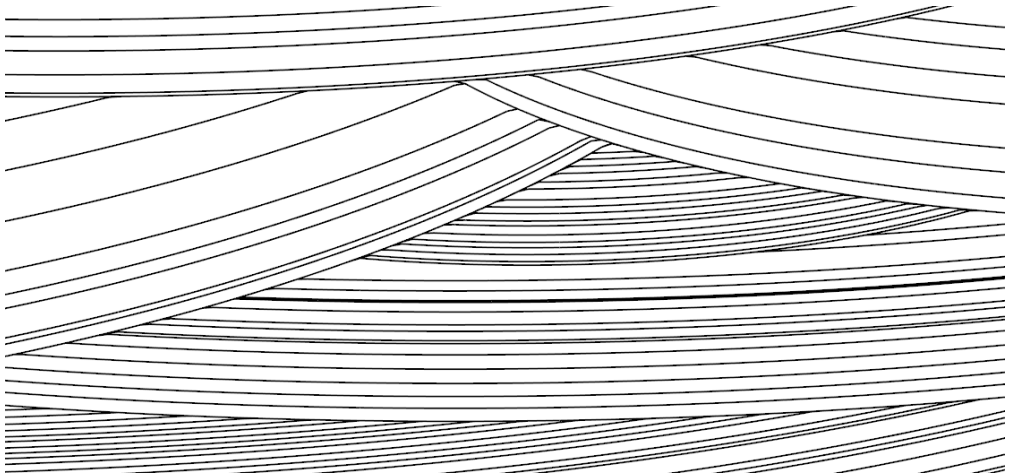
MODEL



Strike cross-section:

OUTCROP

MODEL

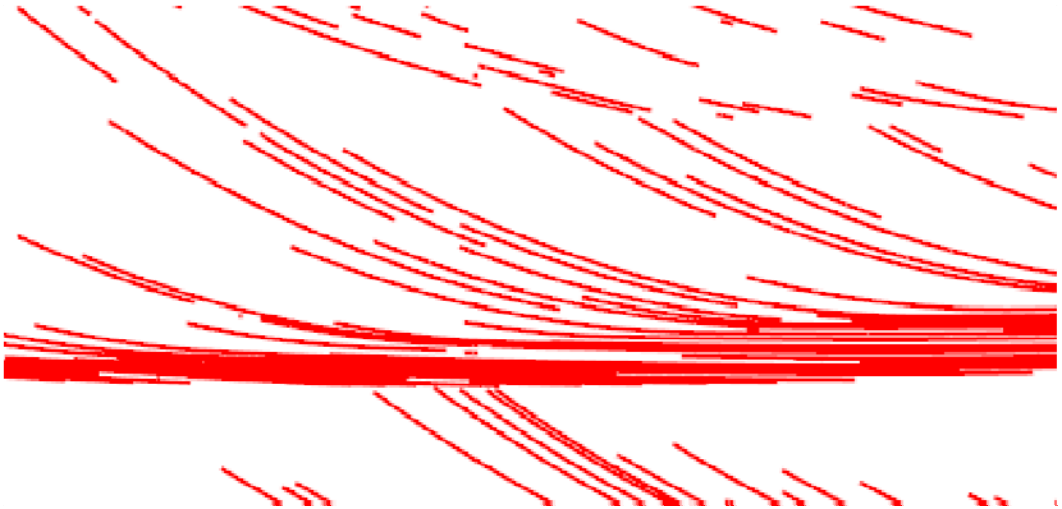


Comparison model/outcrop

Dip cross-section:

OUTCROP

MODEL



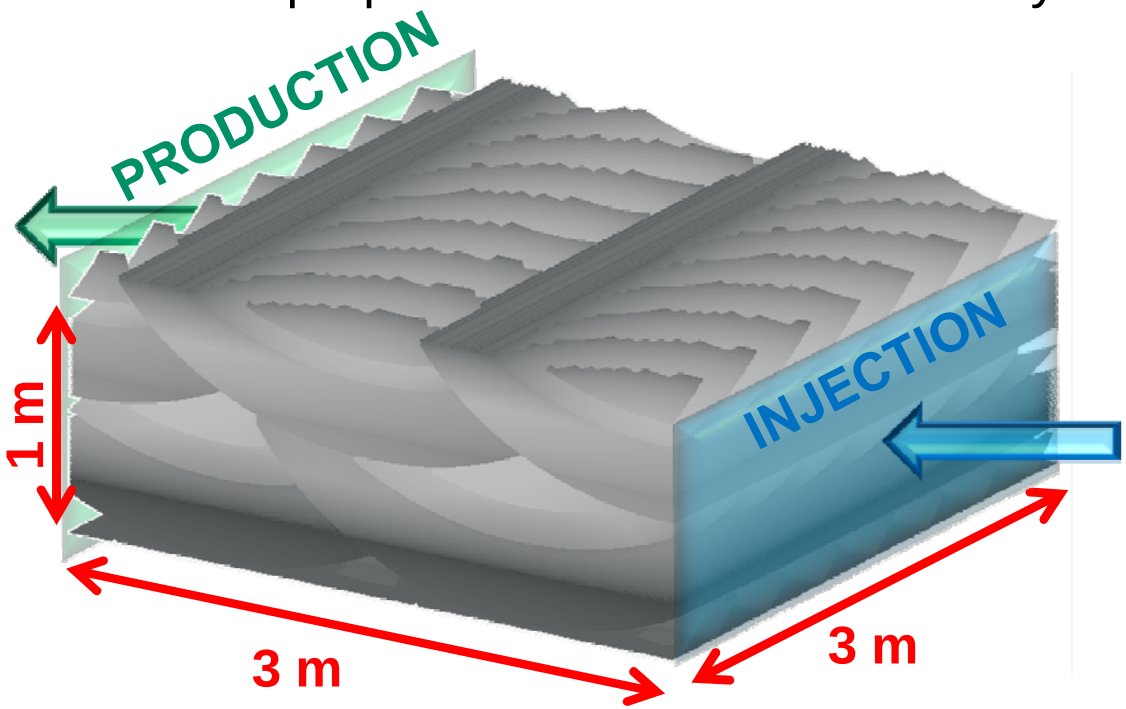
Strike cross-section:

OUTCROP

MODEL

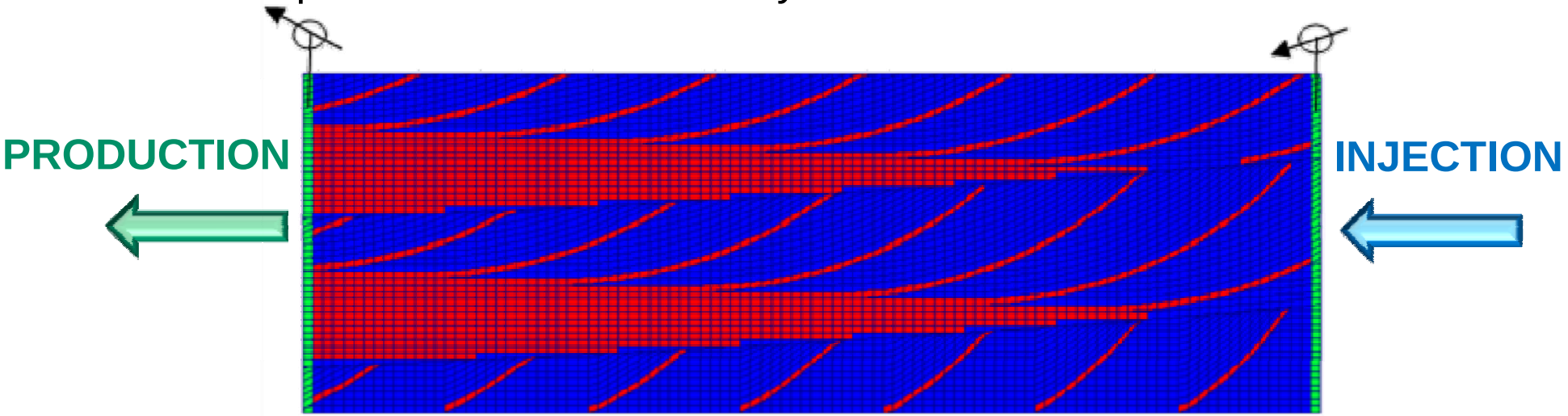
Flow simulation model

- Flow oriented perpendicular to the sedimentary structures:

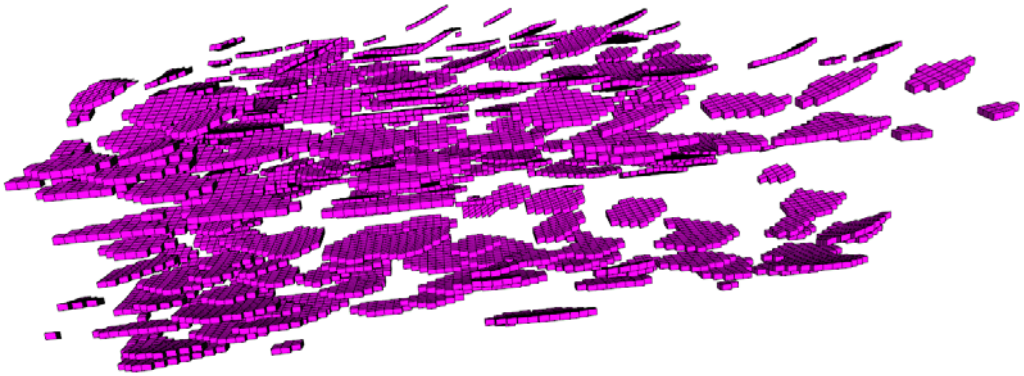


Model dimensions: $9m^3$
3m x 3m x 1m
590.000 active cells
(3cm x 3cm x 2cm)

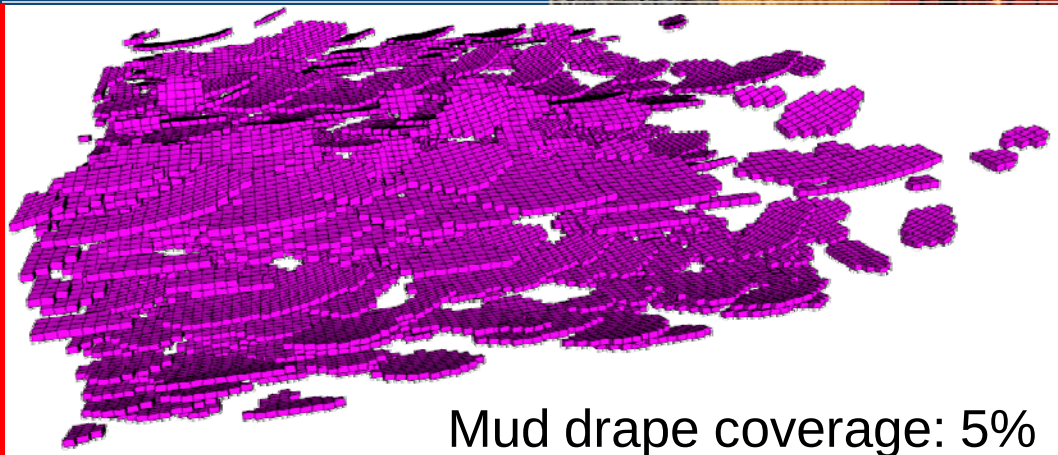
- Flow oriented parallel to the sedimentary structures:



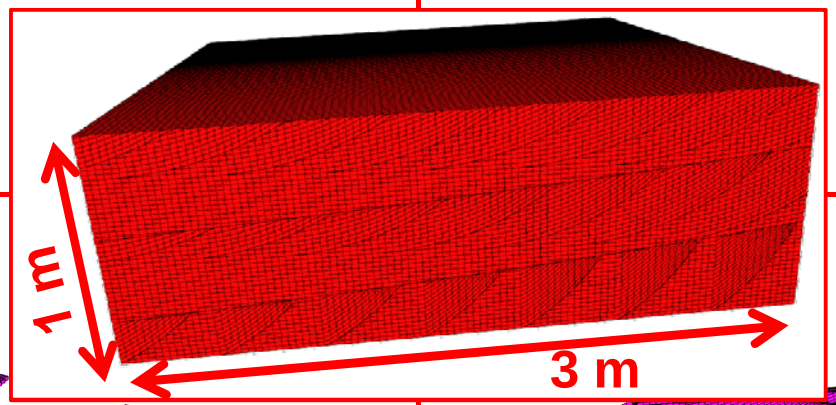
Mud drape coverage parameter variability

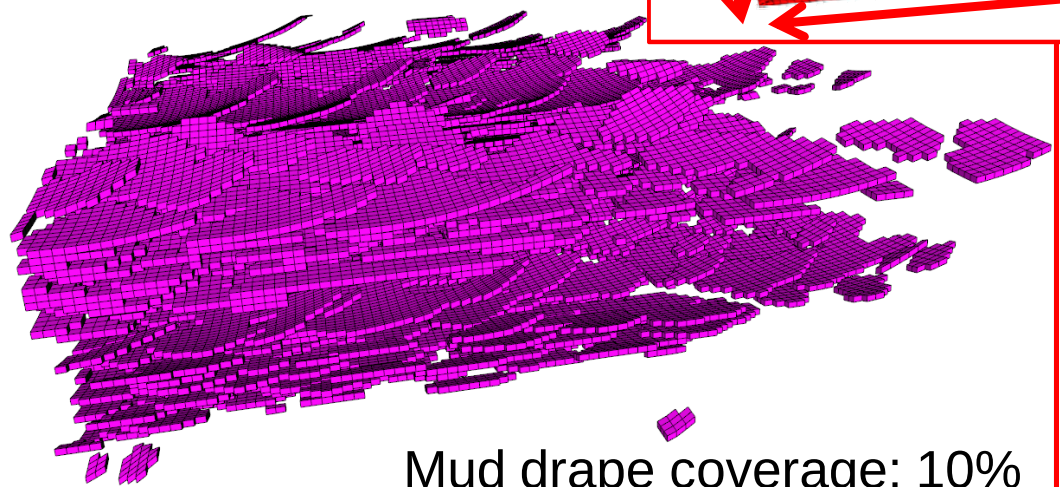


Mud drape coverage: 2.5%
Sand proportion: 98%

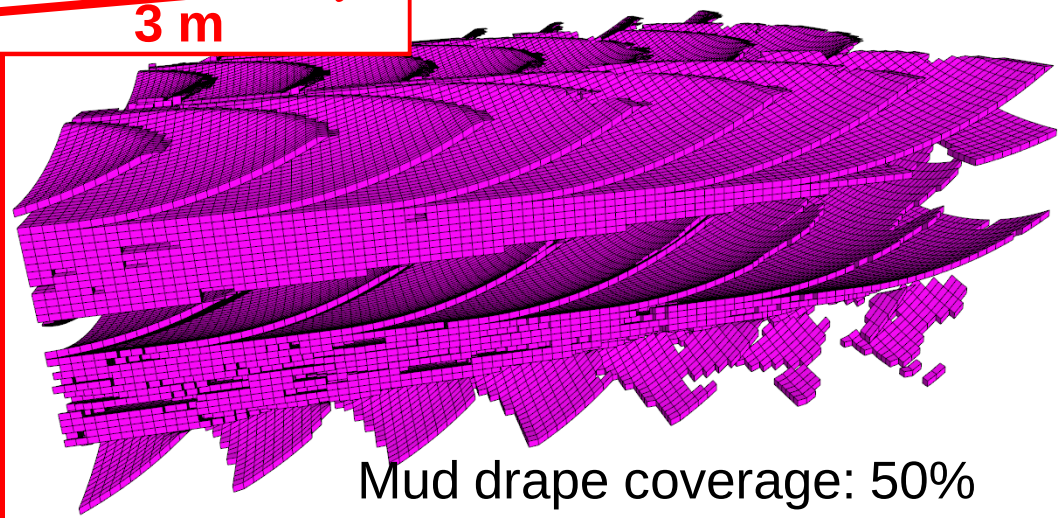


Mud drape coverage: 5%
Sand proportion: 96%





Mud drape coverage: 10%
Sand proportion: 92%



Mud drape coverage: 50%
Sand proportion: 70%

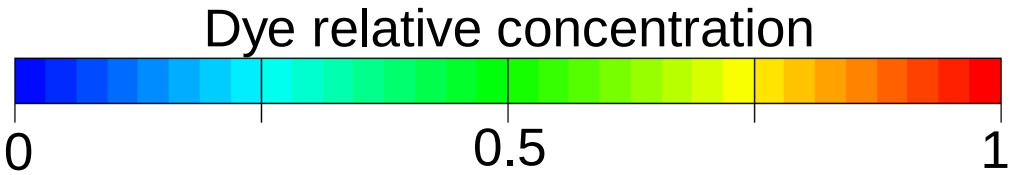
Flow simulation: first results

10 % of pore volume injected

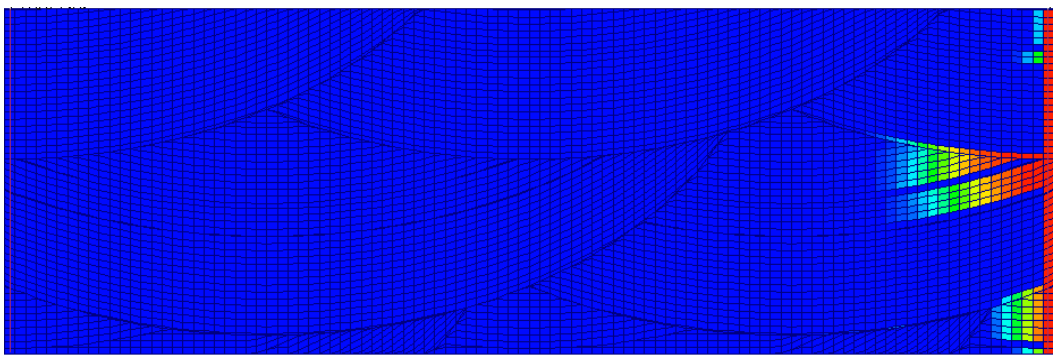
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



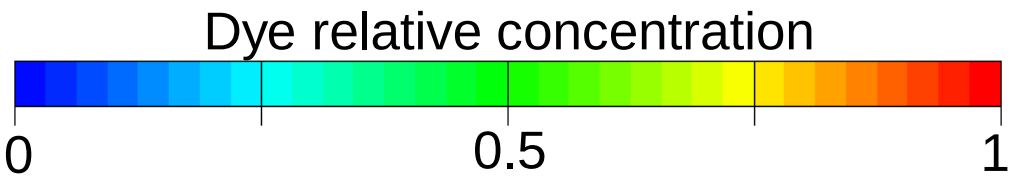
Flow simulation: first results

25 % of pore volume injected

Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage

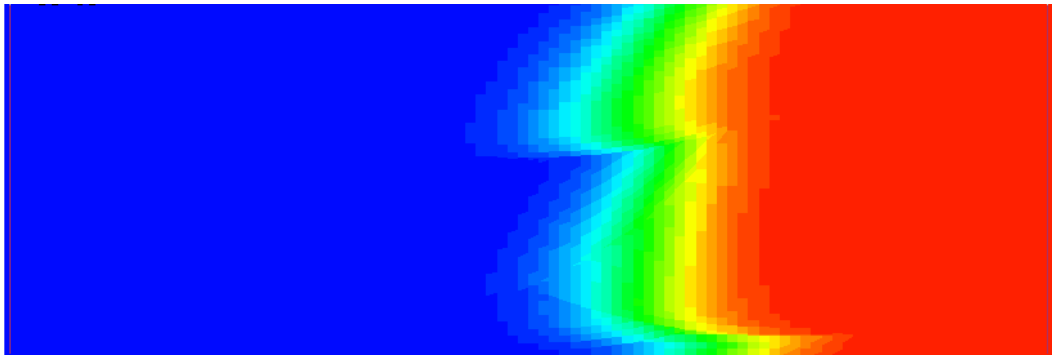
Flow simulation: first results

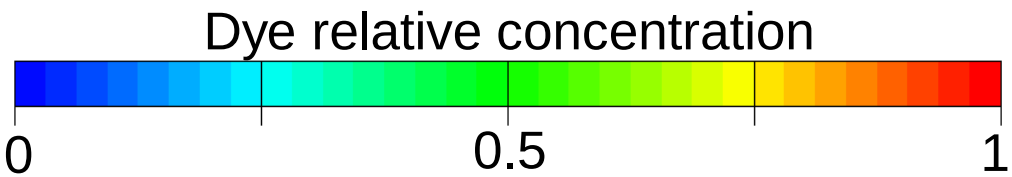
40 % of pore volume injected

Facies model

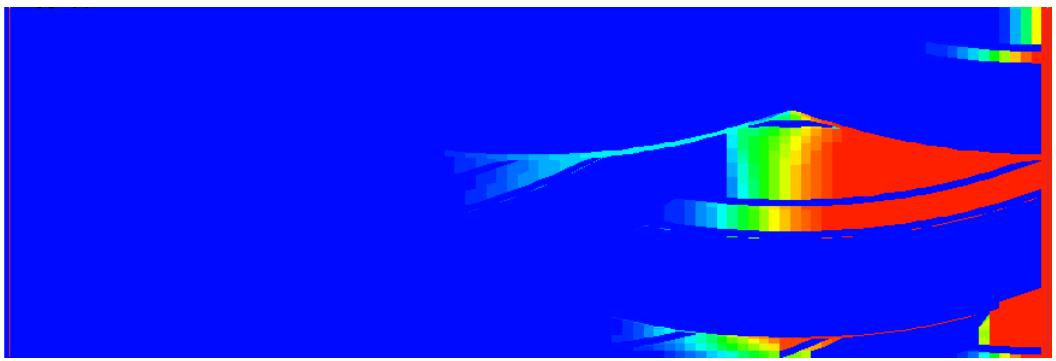
Flow simulation

- Pure sandstone model





- 100 % Mud drape coverage



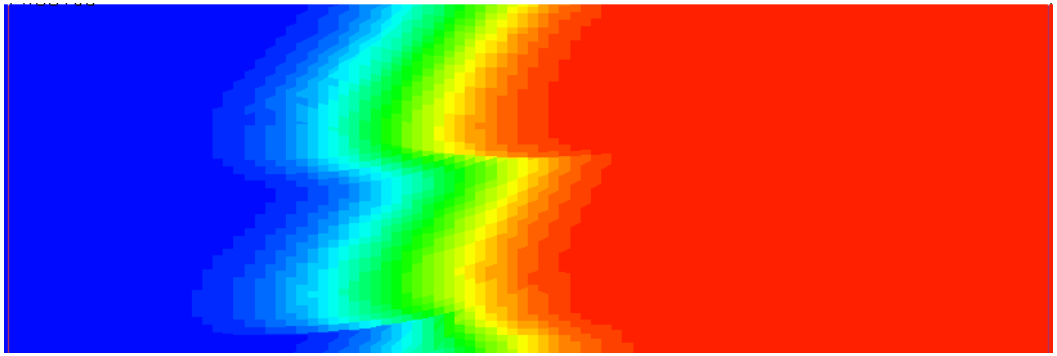
Flow simulation: first results

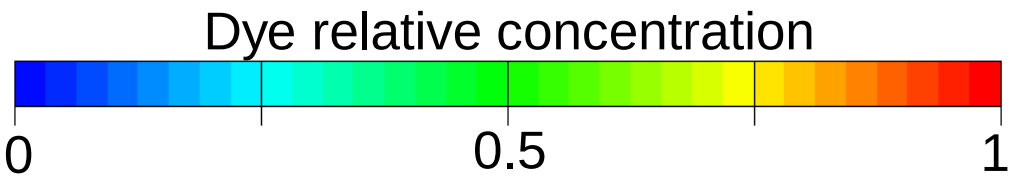
60 % of pore volume injected

Facies model

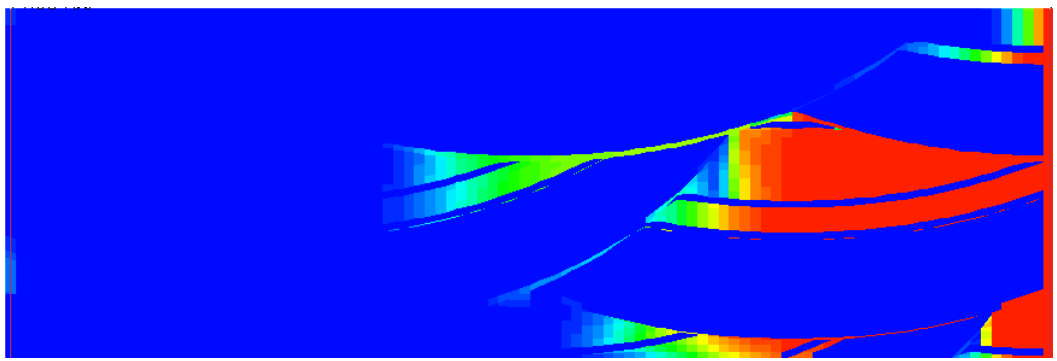
Flow simulation

- Pure sandstone model





- 100 % Mud drape coverage



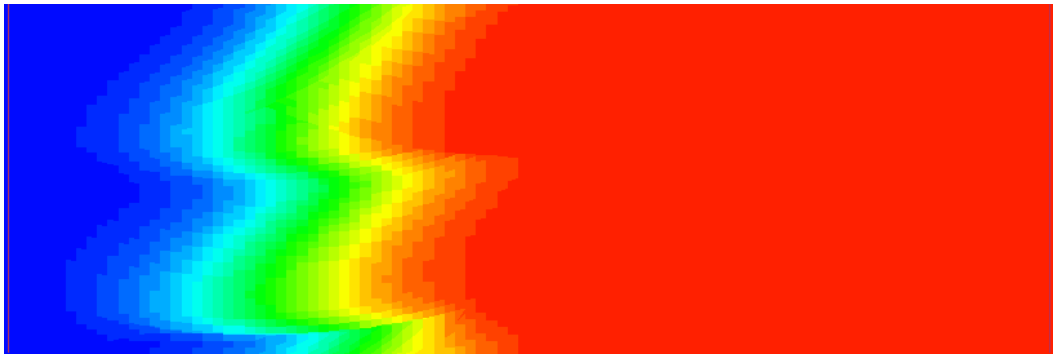
Flow simulation: first results

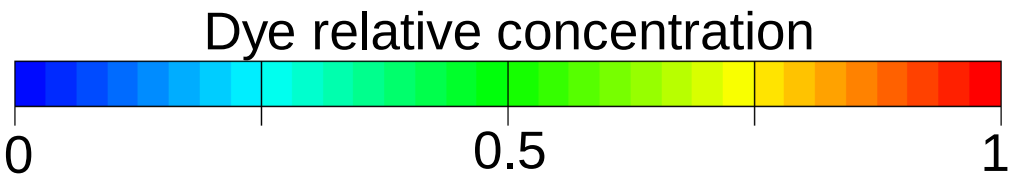
75 % of pore volume injected

Facies model

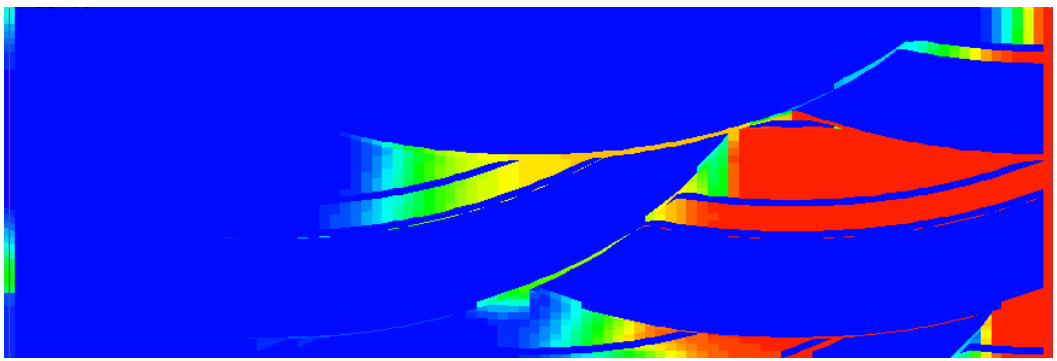
Flow simulation

- Pure sandstone model





- 100 % Mud drape coverage



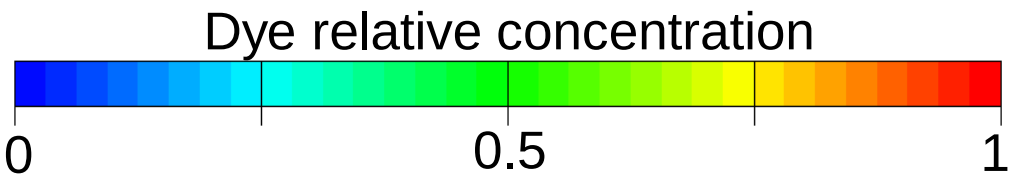
Flow simulation: first results

90 % of pore volume injected

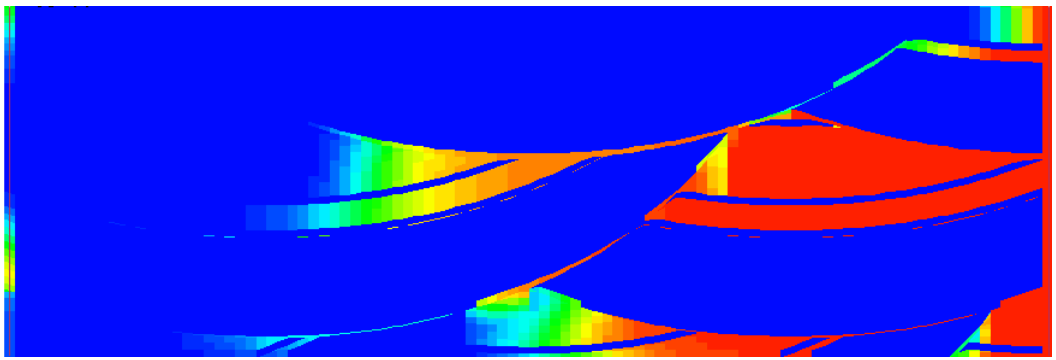
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



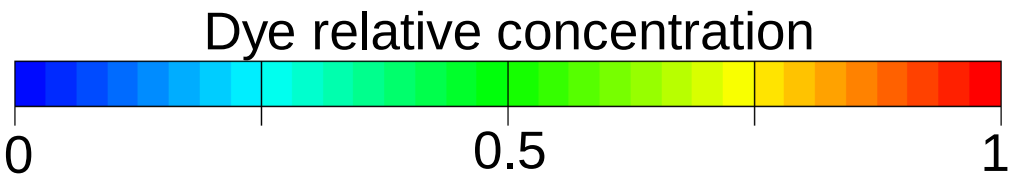
Flow simulation: first results

110 % of pore volume injected

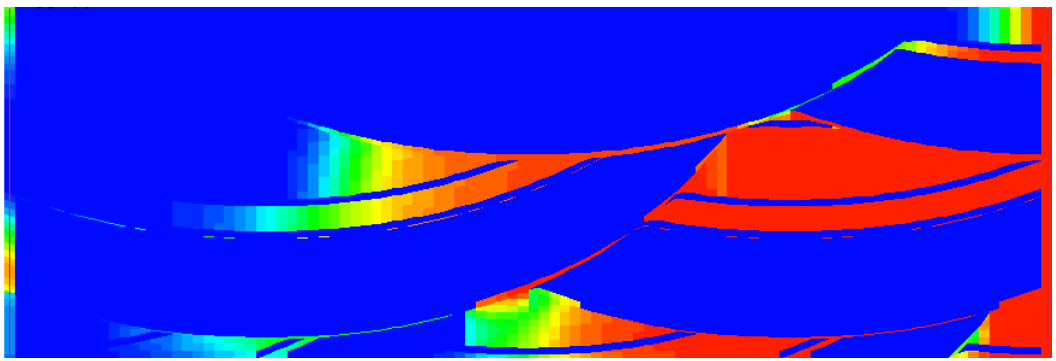
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



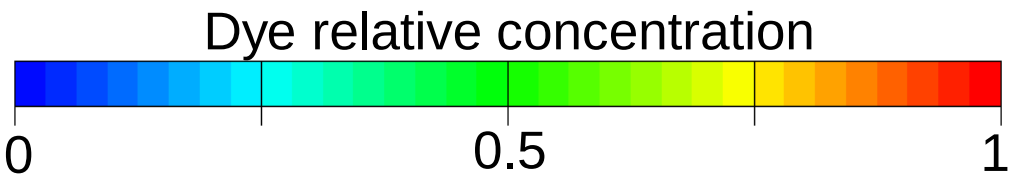
Flow simulation: first results

130 % of pore volume injected

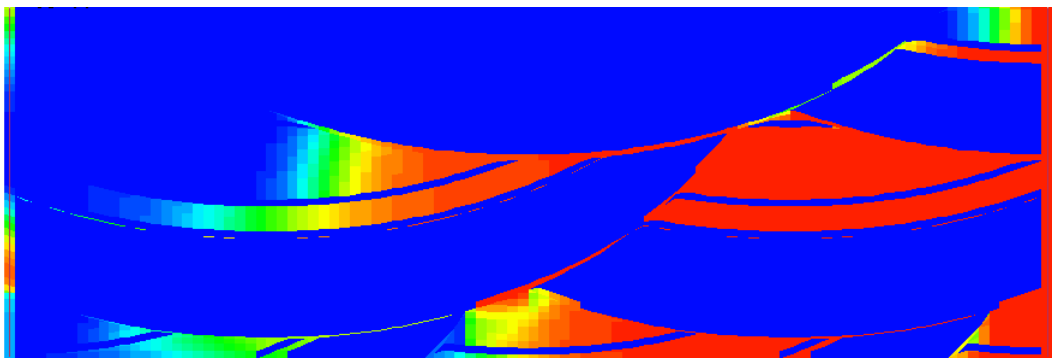
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



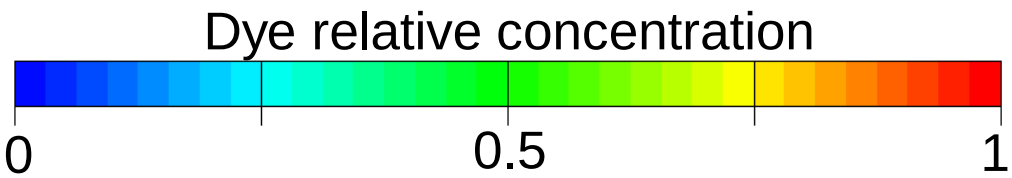
Flow simulation: first results

145 % of pore volume injected

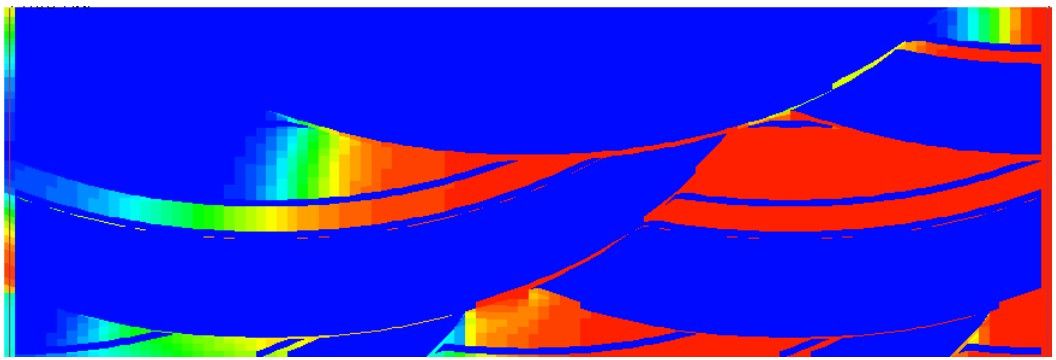
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



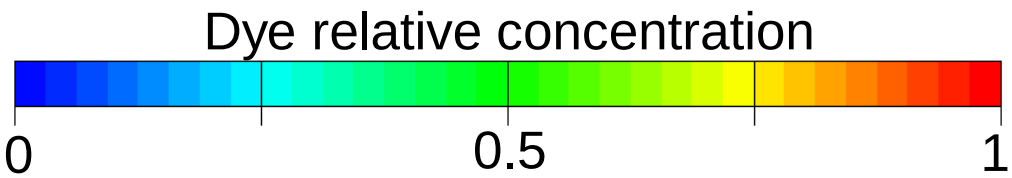
Flow simulation: first results

160 % of pore volume injected

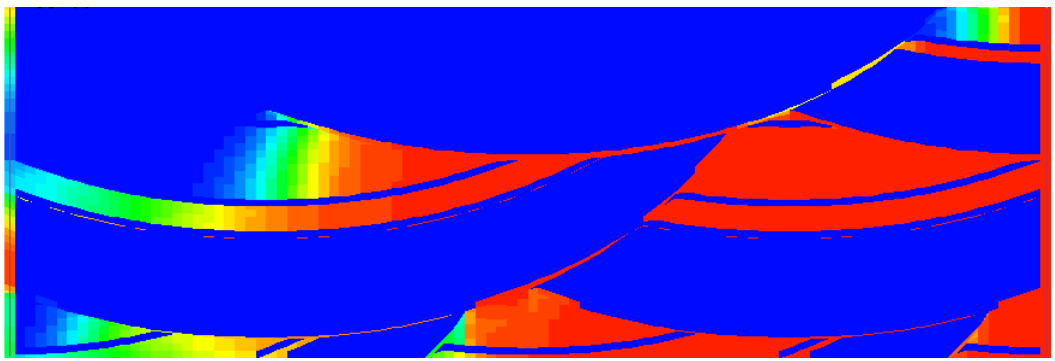
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



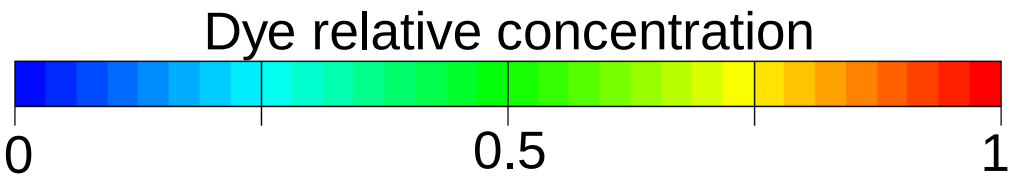
Flow simulation: first results

180 % of pore volume injected

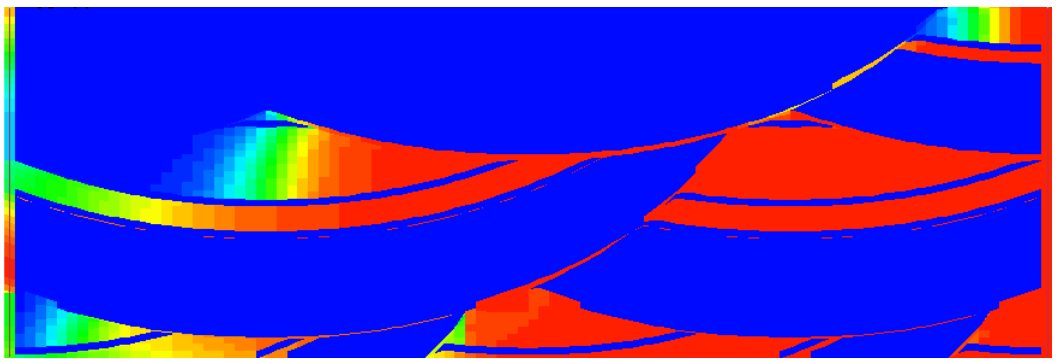
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



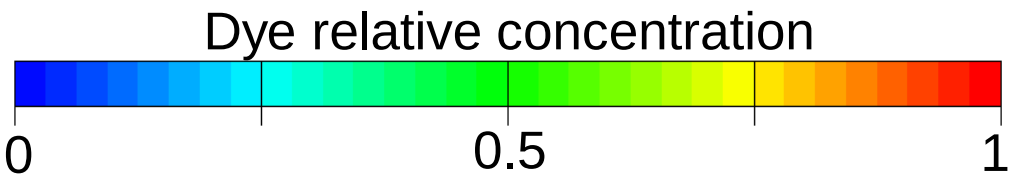
Flow simulation: first results

200 % of pore volume injected

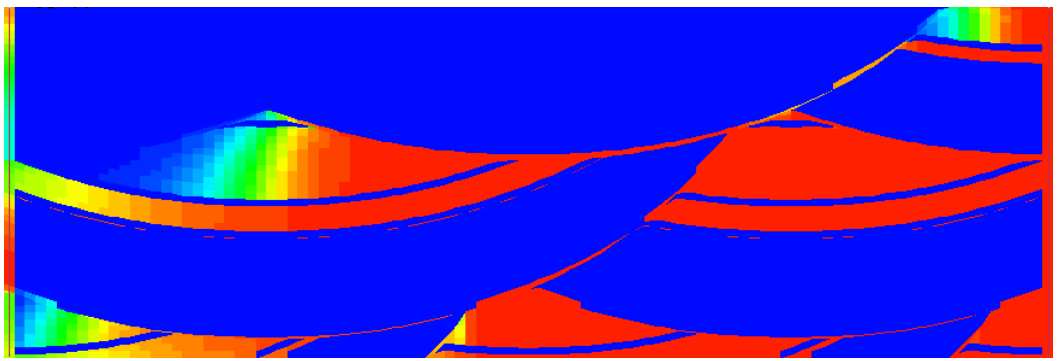
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



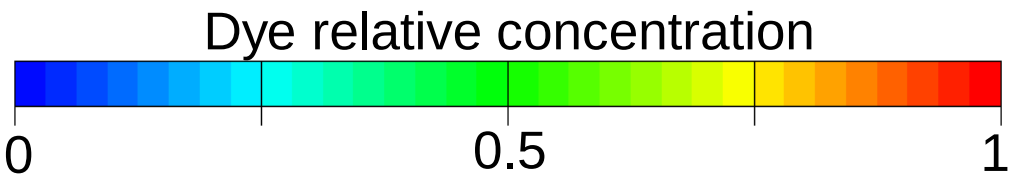
Flow simulation: first results

210 % of pore volume injected

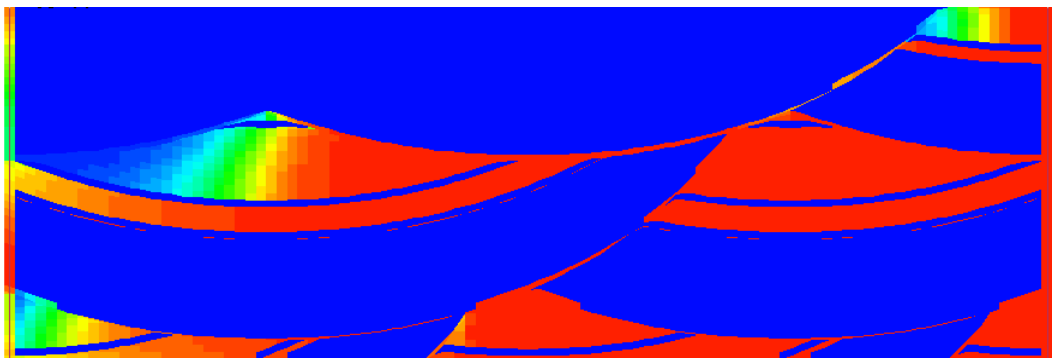
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



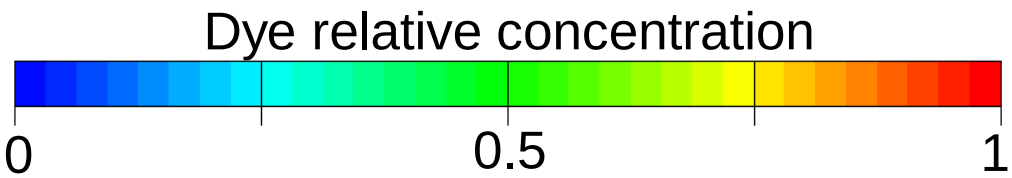
Flow simulation: first results

230 % of pore volume injected

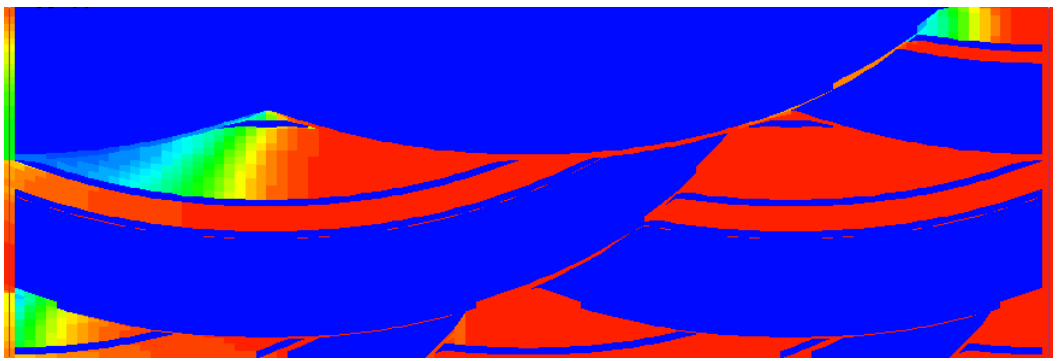
Facies model

Flow simulation

- Pure sandstone model



- 100 % Mud drape coverage



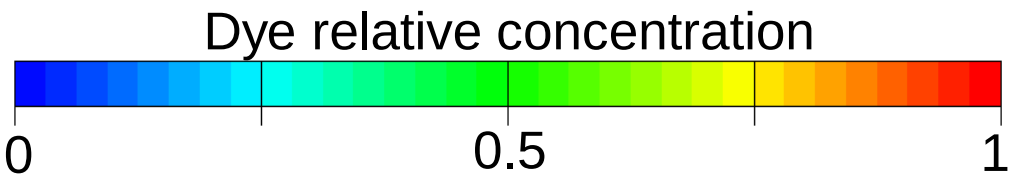
Flow simulation: first results

250 % of pore volume injected

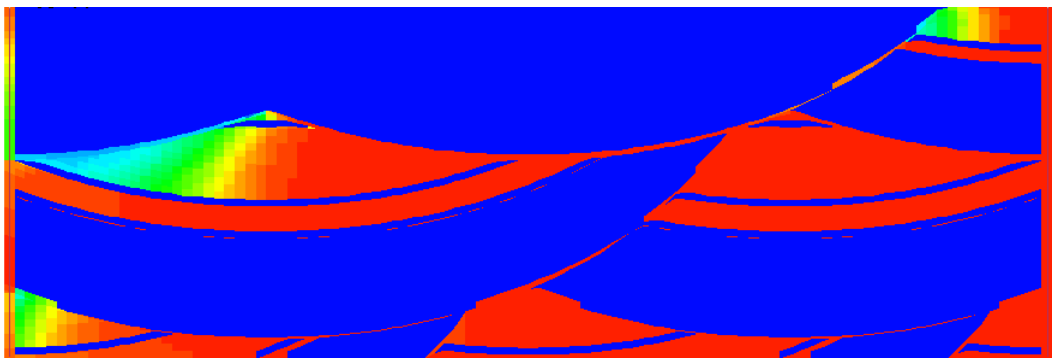
Facies model

Flow simulation

- Pure sandstone model

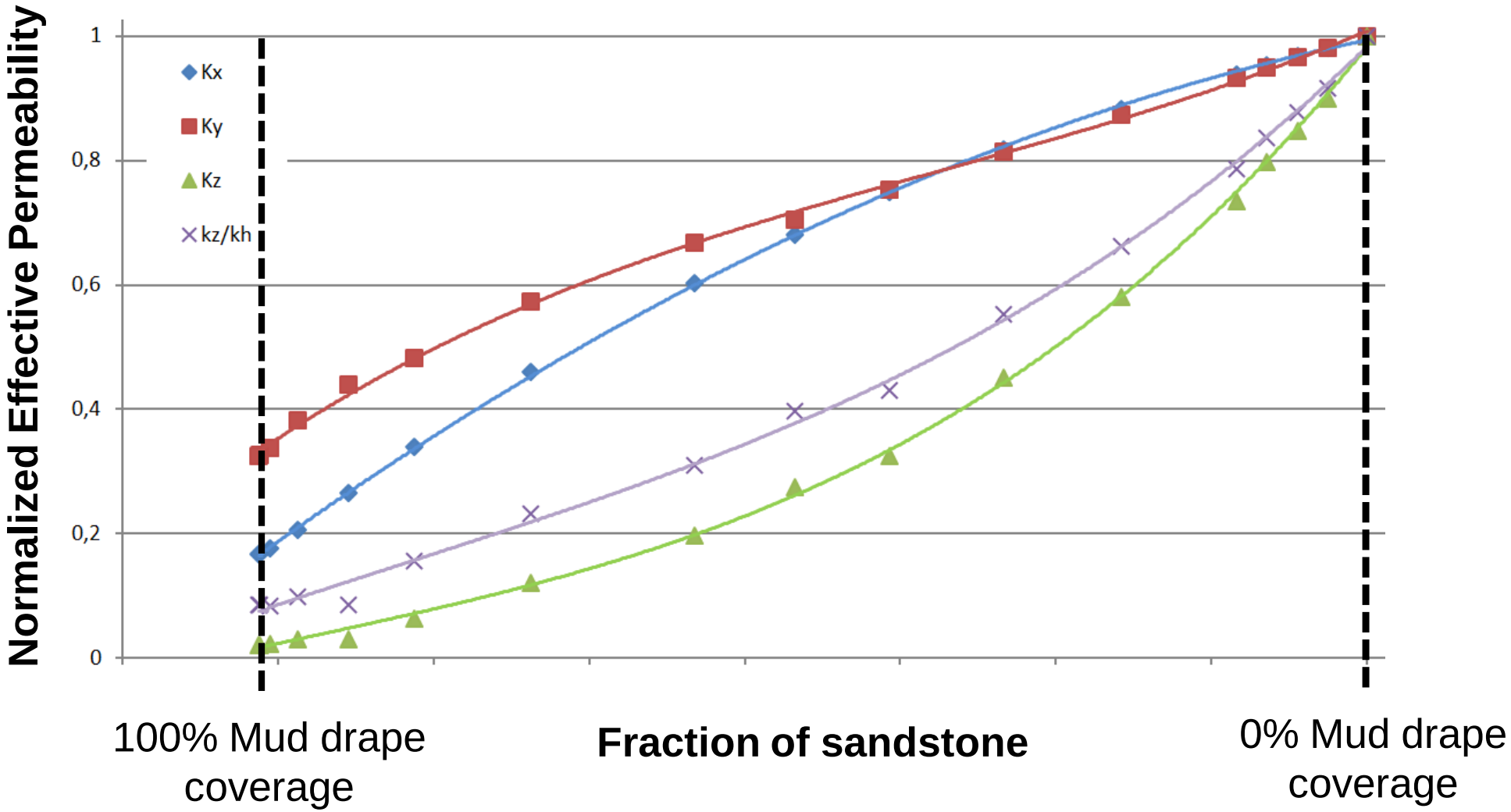


- 100 % Mud drape coverage



Flow simulation: first results

Effective permeability simulation results
Variation of *knx, kny, knz and knz/knh* with NTG



Conclusions

- New surface-based modelling workflow developed to reproduce heterogeneities in 3D of the different tide-influenced heterolithic sandstone facies: purely geometric input parameters, extracted from outcrop analogue observations.

- Dune cross-bedding template created with 4 geometric input, with distributions extracted from outcrop analogue statistics:
  - o Foreset thickness F_t
  - o Curvature C : Parabolic curve Dx^2+Ex
  - o Aggradation angle δ
  - o Toeset dipping angle α

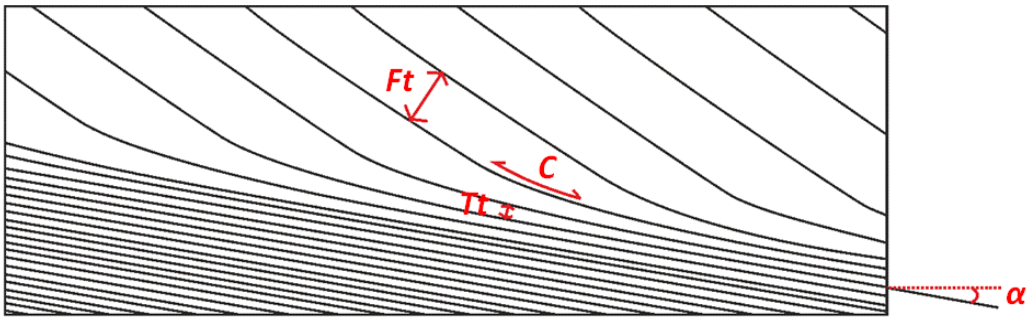
- Mudstone frequency function derived from outcrop analogue statistics. Mud drapes generated until a specific coverage (surface) is reached.

- Mini-model ($9m^3$) is flow simulated. At metre length-scale, effective vertical permeability decreases faster than effective horizontal permeability as sandstone fraction decreases, because mud drapes become more laterally extensive.

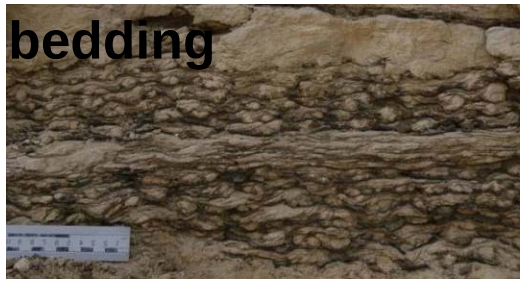
- Vertical permeability stays quite high (2% of the sand-only model) as erosive surfaces at the base of dune cross-bed sets allow the flow to cross through stacked sandy foreset zones.

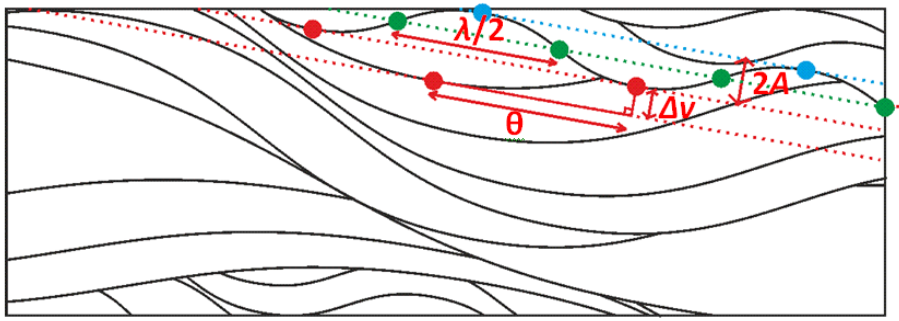
Future work: application of the surface-based modelling to other heterogeneities

1) Dune cross-bedding

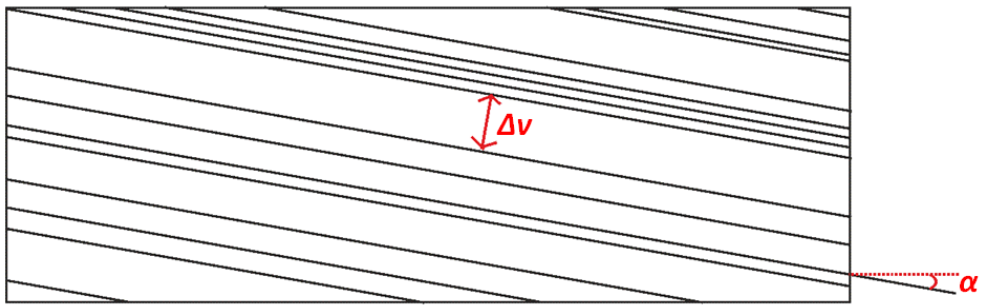


2) Wavy bedding

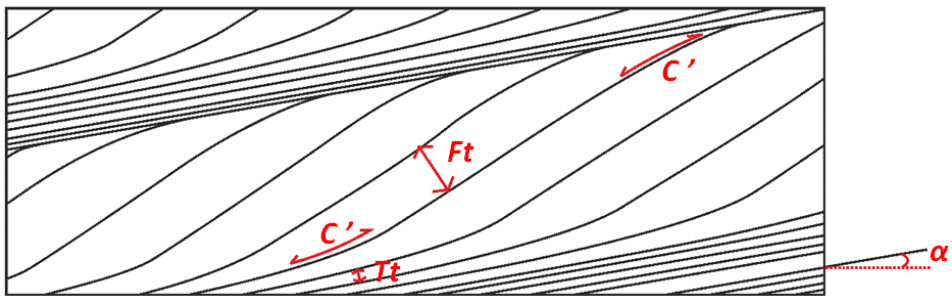




3) Parallel bedding



4) Sigmoidal bedding



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- Mudstone frequency function derived from outcrop analogue statistics. Mud drapes generated until a specific coverage (surface) is reached.

- Mini-model ($9m^3$) is flow simulated. At metre length-scale, effective vertical permeability decreases faster than effective horizontal permeability as sandstone fraction decreases, because mud drapes become more laterally extensive.

- Vertical permeability stays quite high (2% of the sand-only model) as erosive surfaces at the base of dune cross-bed sets allow the flow to cross through stacked sandy foreset zones.