Effective Permeability in Tidal Heterolithic Cross-Bedded Sandstones*

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Abstract

Tidal heterolithic sandstone reservoirs are heterogeneous at the sub-metre scale, often due to the presence of mud drapes of varying frequency and continuity along the foresets and toesets of cross-beds. It is well known that permeability is highly scale-dependent in such heterogeneous rocks, and conventional permeability measurements fail to sample a representative volume. Previous studies have used ‘mini-models' to calculate permeability values at appropriate length-scales in flaser-wavy-lenticular bedded intervals, but no studies have modeled tidal heterolithic cross-bedded sandstones. We investigate the impact of mud-drape distribution on effective permeability, using 3-D mini-models that accurately capture the geometry of cross-beds.

The surface-based modeling methodology uses template surfaces to represent the geometries of cross-bed set and foreset-toeset lamina boundaries. Geometrical input parameters are extracted directly from subsurface and outcrop analog data. The impact on effective permeability of seven parameters that characterize heterogeneity has been determined: (1) total sandstone fraction (‘net-to-gross'), (2) thickness of sand laminae, (3) mud drape continuity, (4) toeset dip, (5) angle of climb between successive foreset-toeset surfaces, (6) proportion of foresets to toesets, and (7) the trough or tabular geometry of the cross-beds.

Calculated permeability decreases as the sandstone fraction decreases and is highly anisotropic: the vertical permeability (averaged over the other 6 parameter values) falls to c. 0.5% of its value in a sandstone-dominated plug, while the horizontal permeability falls to c. 5% and c. 50% of the sandstone value in the dip and strike directions, respectively. A relationship between sandstone fraction and calculated permeability in each direction can be identified, although there is considerable spread, because the other 6 parameters investigated can each have a significant impact, depending upon the flow direction and sandstone fraction. The calculated permeability also depends strongly on model volume, but it converges to consistent (effective) values at the largest volumes investigated. The results yield improved estimates of effective

permeability in cross-bedded, heterolithic intervals, which can be used to populate reservoir-scale model grid blocks, using estimates of sandstone fraction obtained from wireline or core data, and geometrical parameters obtained from core data or outcrop analogs.

References Cited

Bear, J., 1972, Dynamics of Fluids in Porous Media: American Elsevier, 764 p.

Jackson, M.D., D. Yoshida, A.H. Muggeridge, and H.D. Johnson, 2005, Three-dimensional reservoir characterization and flow simulation of heterolithic tidal sandstones: AAPG Bulletin, v. 89, p. 507-528.

Ringrose, Ph., K. Nordahl, and R. Wen, 2005, Vertical permeability estimation in heterolithic tidal deltaic sandstones: Petroleum Geoscience, v. 11, p. 29-36.

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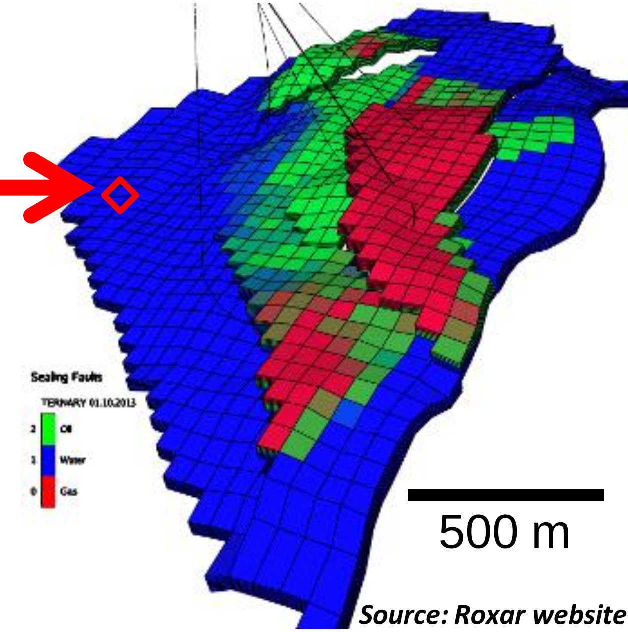
Rationale for the study

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

UPSCALING

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



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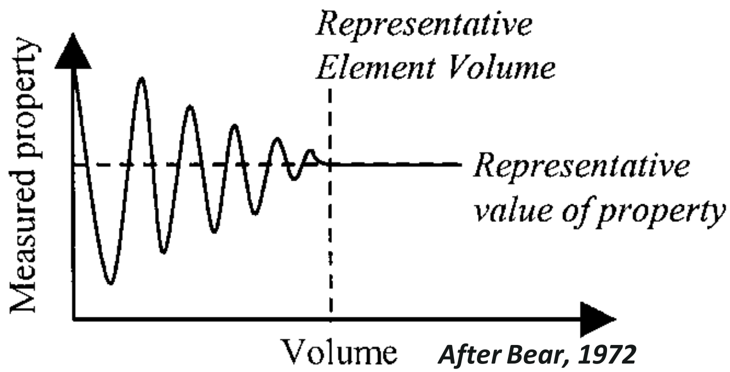
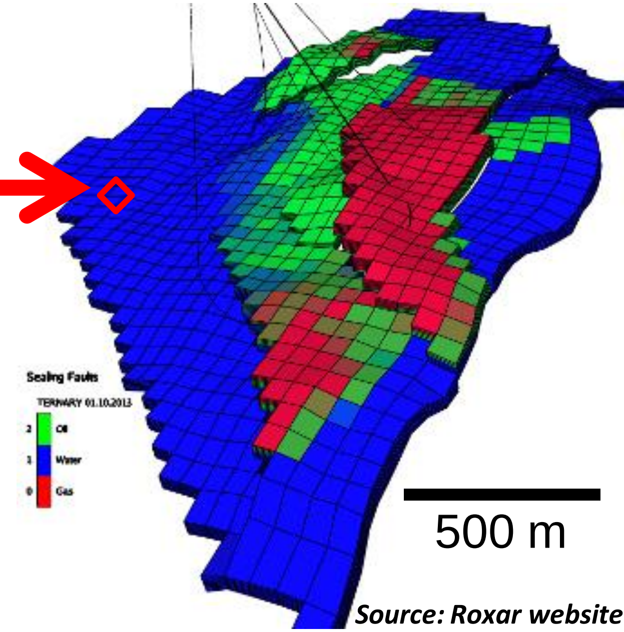




Previous studies highlighted **incorrect estimation of reservoir properties** based on core-plug measurements and log-derived measurements compared to high resolution models:

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

Aim and objectives

Aim of the study

Determine the impact of heterogeneities on effective permeability in tidally influenced cross-bedded sandstone reservoirs

Objectives:

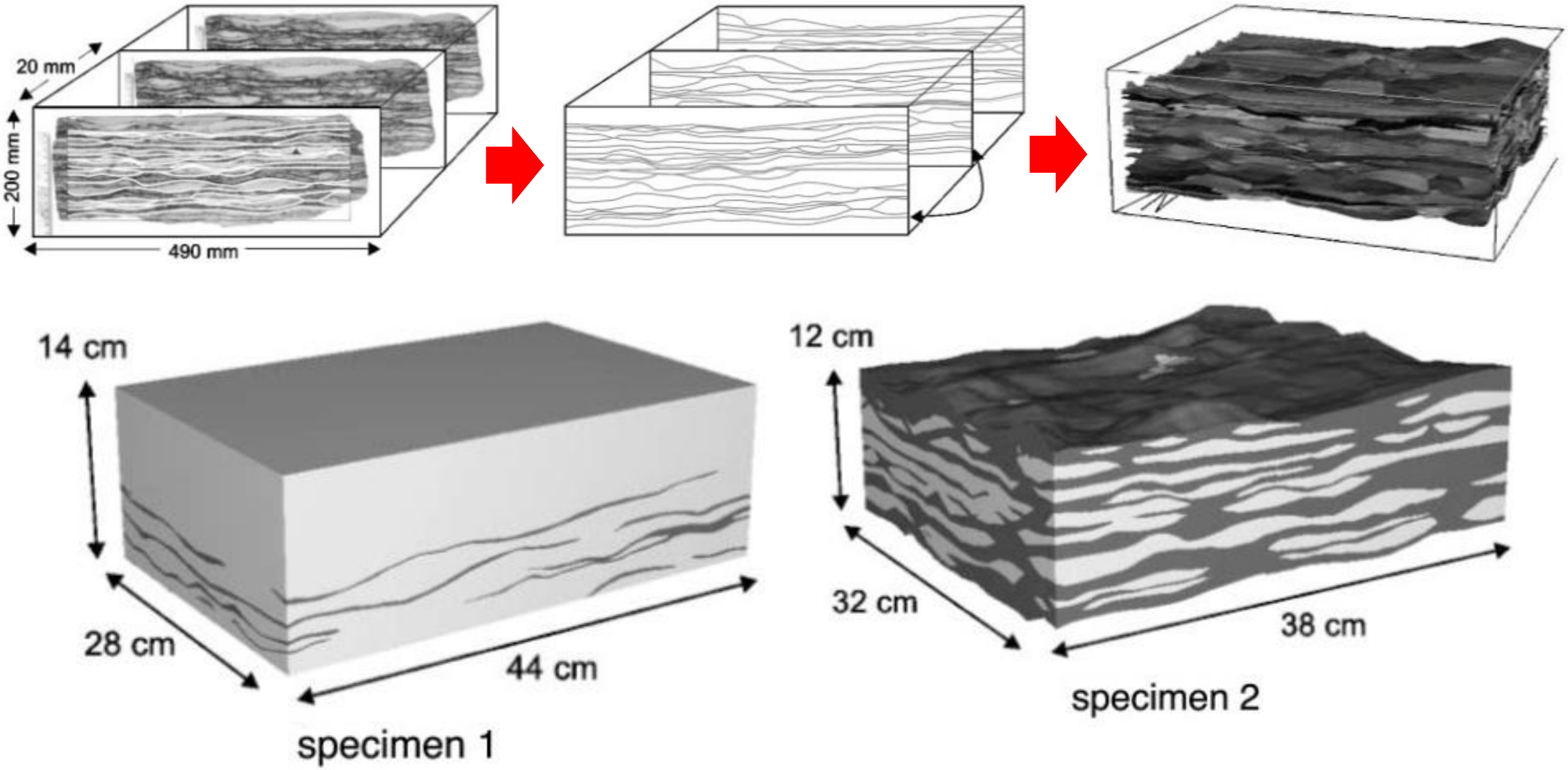
- Quantify the impact of mud-drape coverage along cross-bedding on effective permeability.

- Define the relative impact of the different geological parameters on their influence on effective permeability.

3D model generation for flow simulation

How to generate such models?

1) Reconstruction of a rock sample:

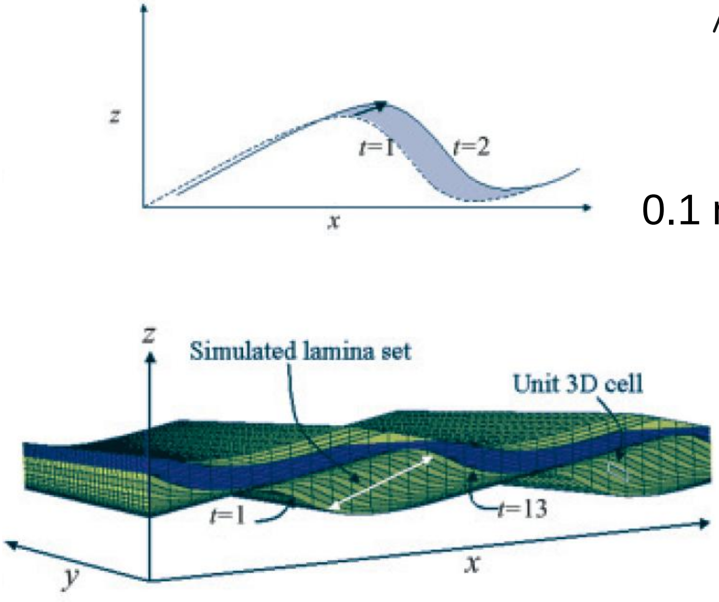


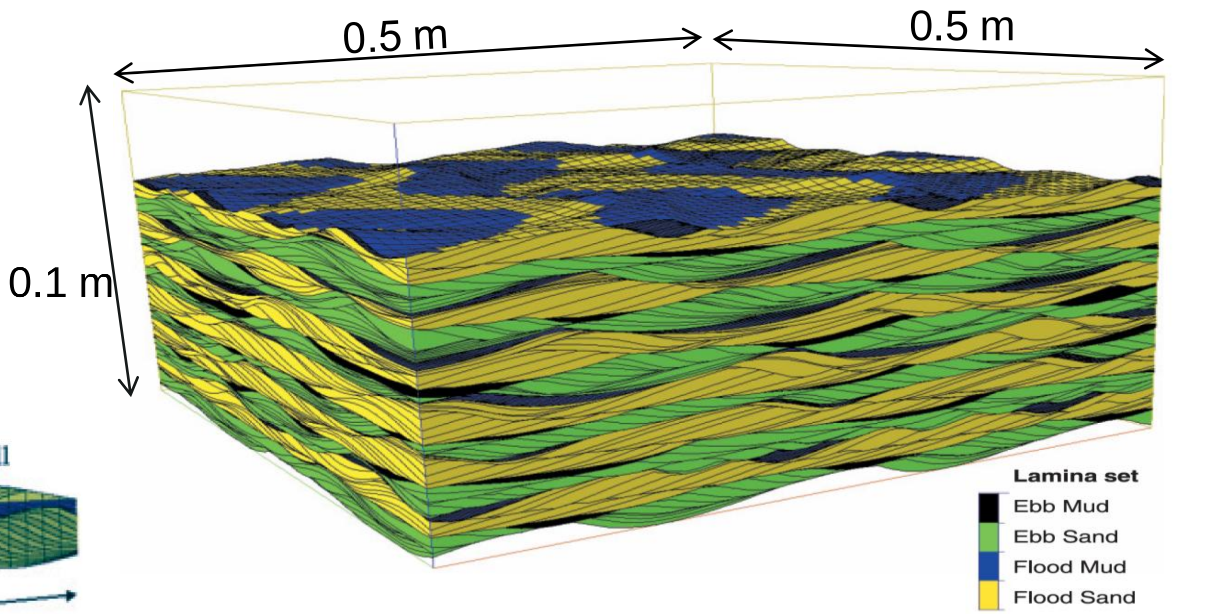
Jackson et al., 2005

3D model generation for flow simulation

How to generate such models?

1) Reconstruction of a rock sample
2) Forward modeling:





SBED model of Flaser Bedding

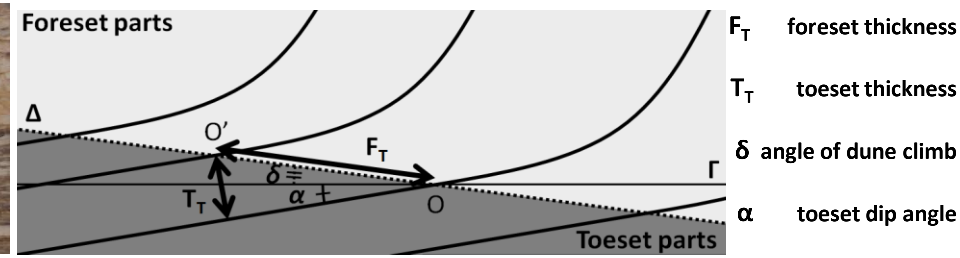
Ringrose et al., 2005

3D model generation for flow simulation

How to generate such models?

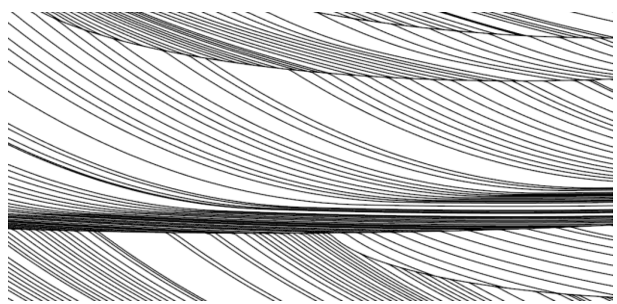
1) Reconstruction of a rock sample
2) Forward modeling
3) Geometric modeling – outcrop-based dataset

Bundle canyon, Dir Abu Lifa Member, Egypt

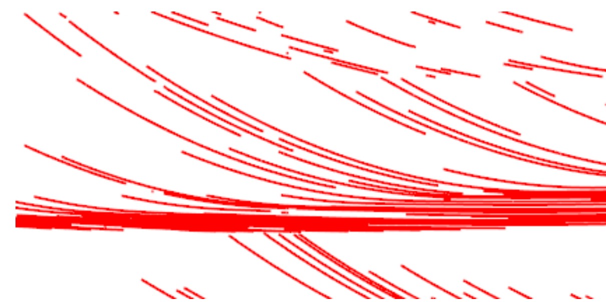


Input parameters derived from outcrop dataset

Outcrop – dip section



Surface modeling



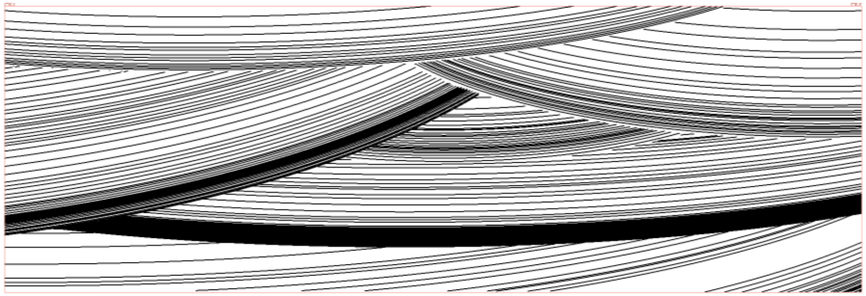
Mud drape modeling

Massart et al., in review

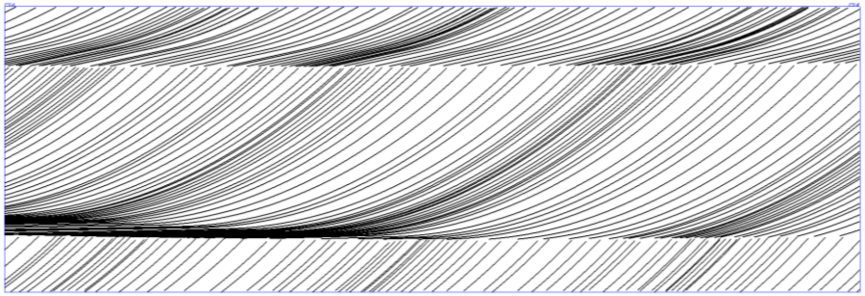
Generic 3D model of tidally influenced cross-bedded sandstones

Gecko Nose outcrop, Dir Abu Lifa Member, Egypt

Strike cross-section:

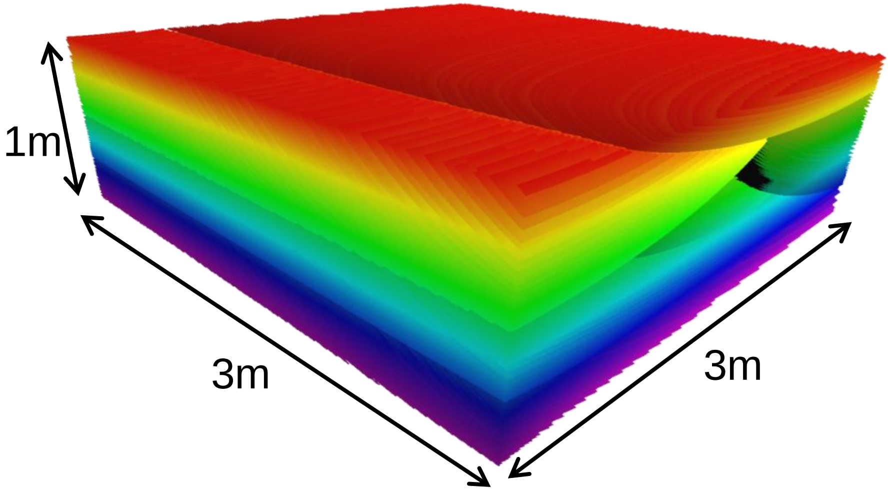


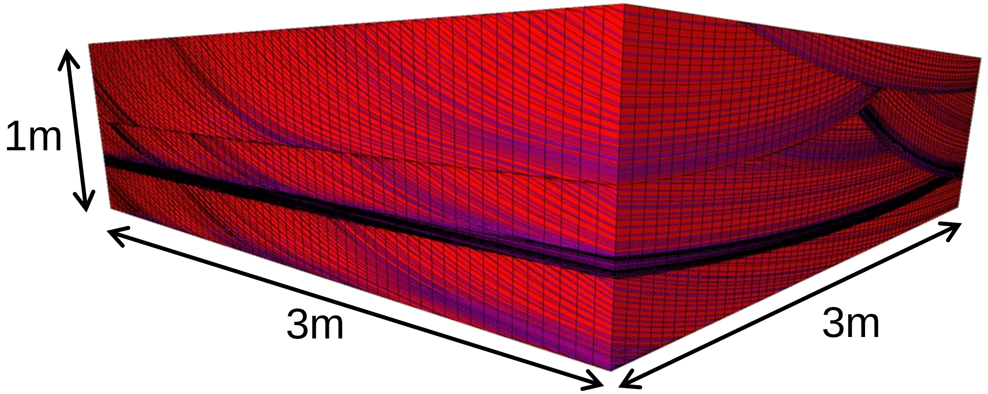
Dip cross-section:



Generic 3D model, geometry after Gecko Nose outcrop

Parameters	Gecko Nose generic model
Toeset dip angle	2-12° (Gaussian distribution)
Foreset thickness	5.9cm ± 3.9 cm
Foreset : toeset ratio	3 : 1
Angle of dune climb	0-5° (Gaussian distribution)
Mud patch size	10 - 30cm (Gaussian distribution
Style of cross-bedding	Trough cross-bedding

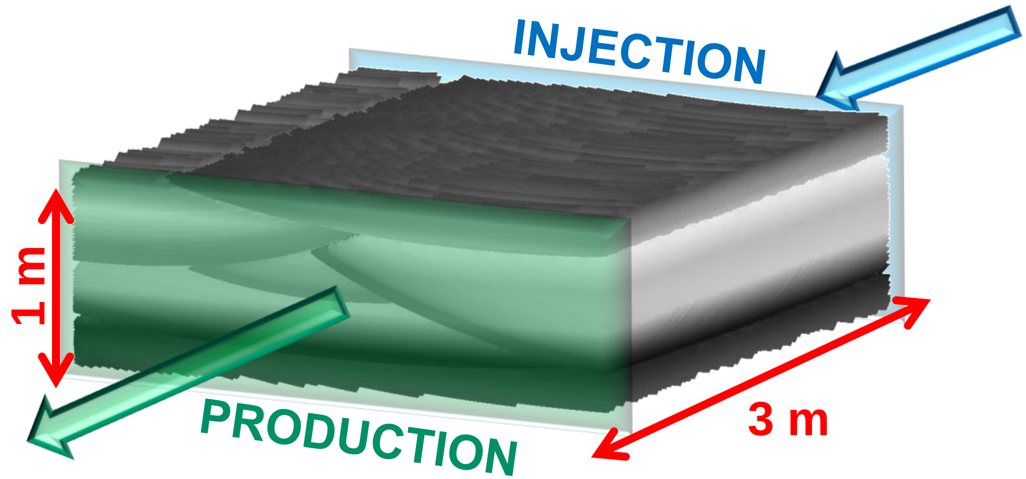




Calculation of effective permeability

Flow simulation reproduces the conditions of a core-plug triaxial test:
4 no-flow faces, 2 opposite faces with flow

- Horizontal flow oriented parallel to the sedimentary structures: measure of $K_{H\ (DIP)}$



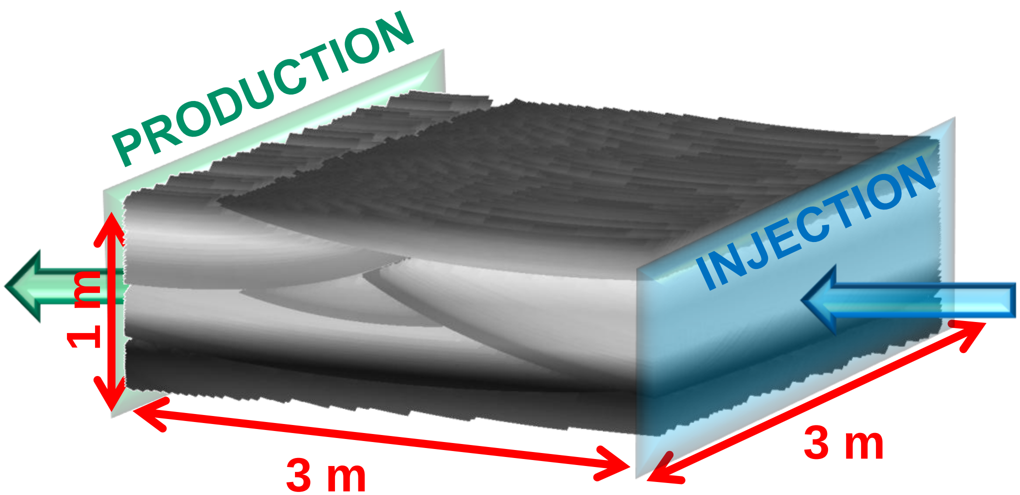
Model dimensions: 9m³
3m x 3m x 1m
590.000 active cells
(cells: 5cm x 5cm x 1cm)

- Buffer zones with high permeability to insure uniform flow
- $K_{SANDSTONE}/K_{MUDSTONE}$ >>> 1

Calculation of effective permeability

Flow simulation reproduces the conditions of a core-plug triaxial test:
4 no-flow faces, 2 opposite faces with flow

- Horizontal flow oriented perpendicular to the structures: measure of $K_{H\ (STRIKE)}$



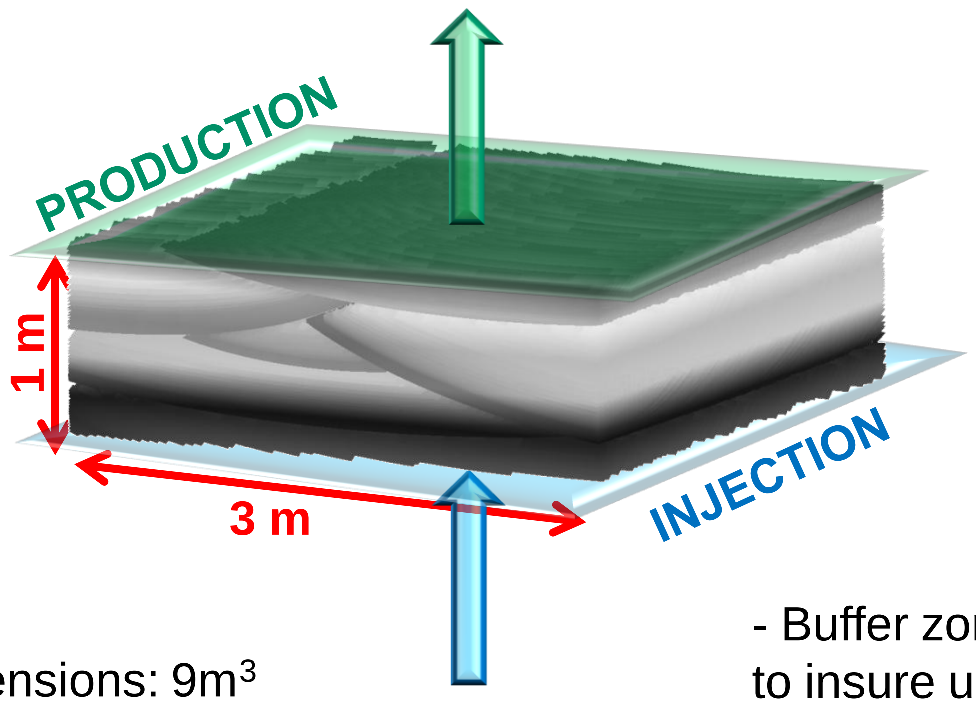
Model dimensions: $9m^3$
3m x 3m x 1m
590.000 active cells
(cells: 5cm x 5cm x 1cm)

- Buffer zones with high permeability to insure uniform flow
- $K_{SANDSTONE}/K_{MUDSTONE} >>> 1$

Calculation of effective permeability

Flow simulation reproduces the conditions of a core-plug triaxial test:
4 no-flow faces, 2 opposite faces with flow

- Vertical flow: measure of $\mathbf{K_V}$

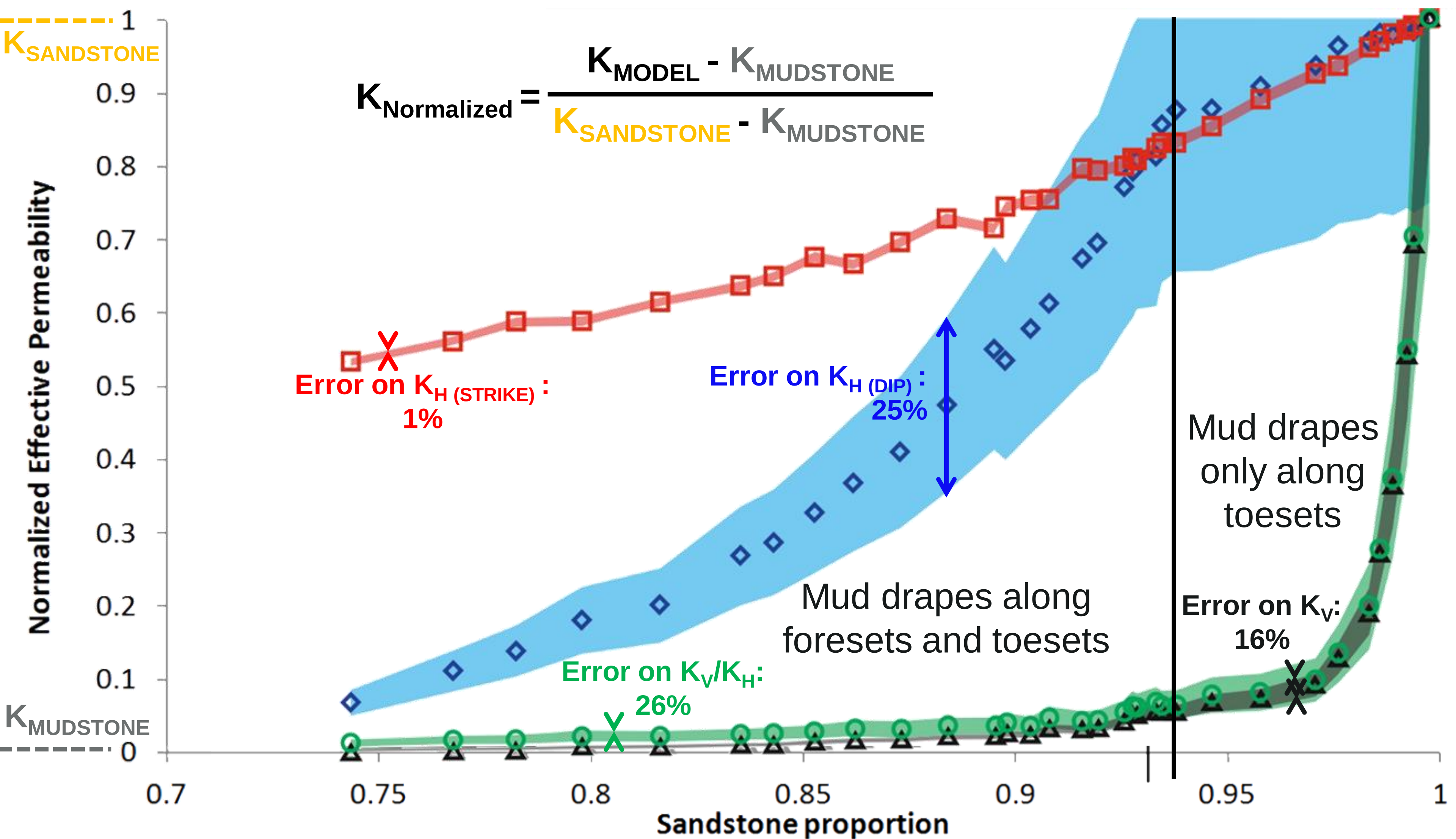


Model dimensions: $9m^3$
3m x 3m x 1m
590.000 active cells
(cells: 5cm x 5cm x 1cm)

- Buffer zones with high permeability to insure uniform flow
- $K_{SANDSTONE}/K_{MUDSTONE}$ >>> 1

Impact of mud drape coverage on flow

Variation of $K_{H\ (DIP)}$, $K_{H\ (STRIKE)}$, K_V and K_V/K_H with Sandstone proportion in generic Gecko Nose outcrop model



Predicting effective permeability in subsurface reservoirs

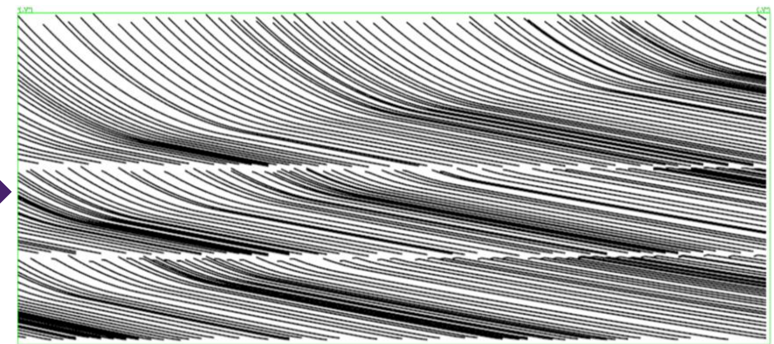
<u>Hypothesis 1:</u>

Can effective permeability in cross-bedded tidal sandstones be predicted from a parameter, simple to measure, such as sandstone fraction (NTG)?

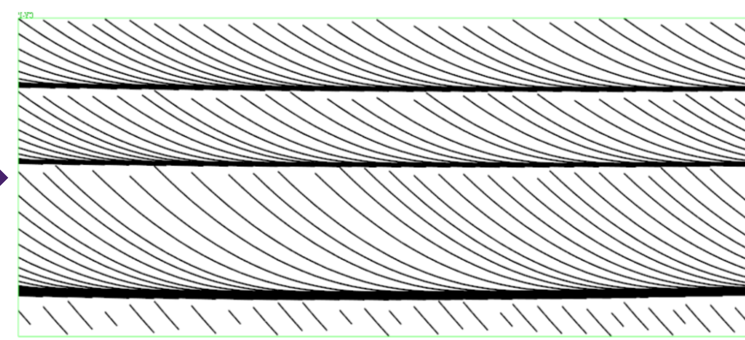
Impact of geological parameters on flow

Parameters	Muddy case Settings “A”	Sandy case Settings “B”
Toeset dip angle	8°	1°
Foreset thickness (mean value)	5.9cm	10cm
Foreset : toeset ratio	2 : 3	20 : 1
Angle of dune climb	5°	0°
Mud patch size	10-100cm	10-20cm
Style of cross-bedding	Trough	Tabular

Muddy case end member

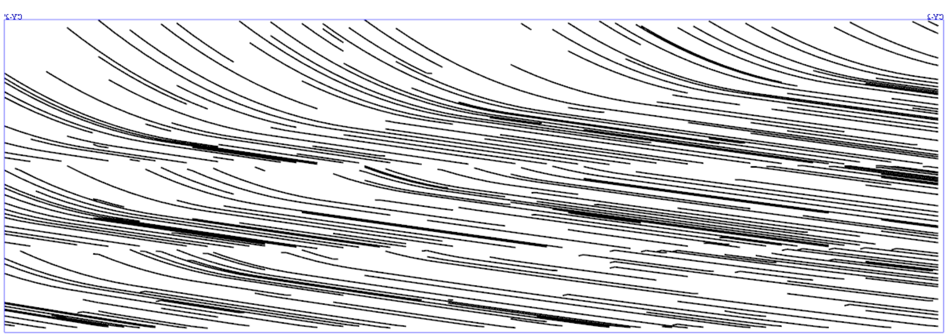


Sandy case end member

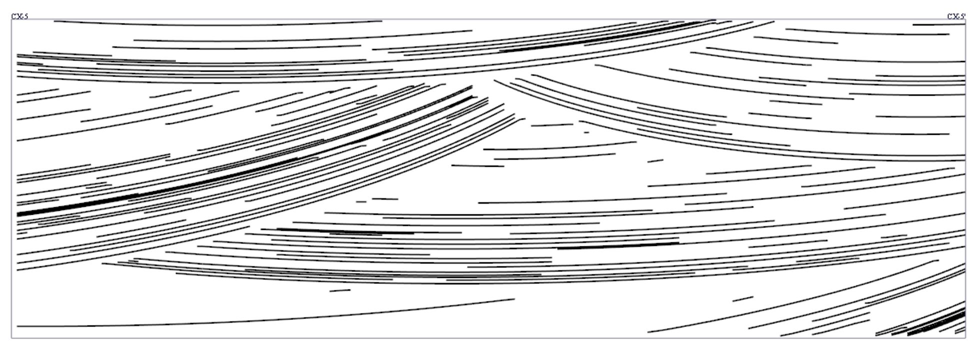


Impact of geologic parameters on flow

Gecko Nose outcrop, muddy trough cross-bedding example, Dir Abu Lifa Member, Egypt

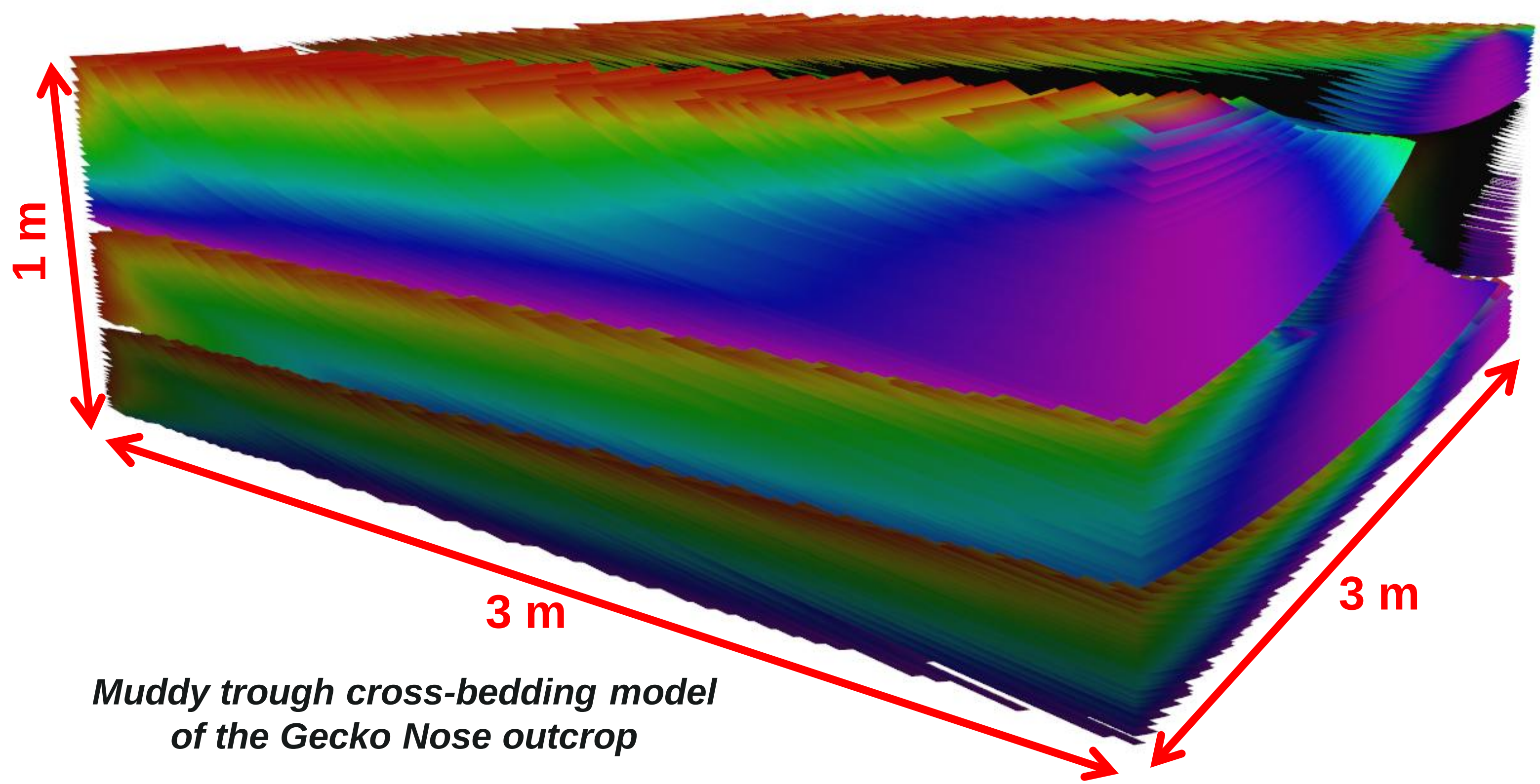


Dip cross-section of the model

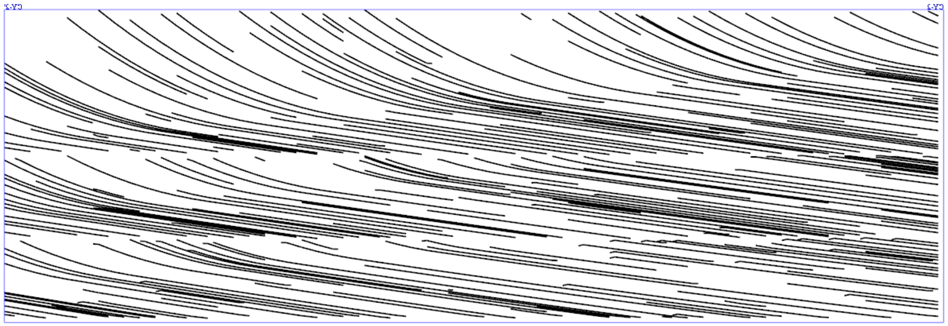


Strike cross-section of the model

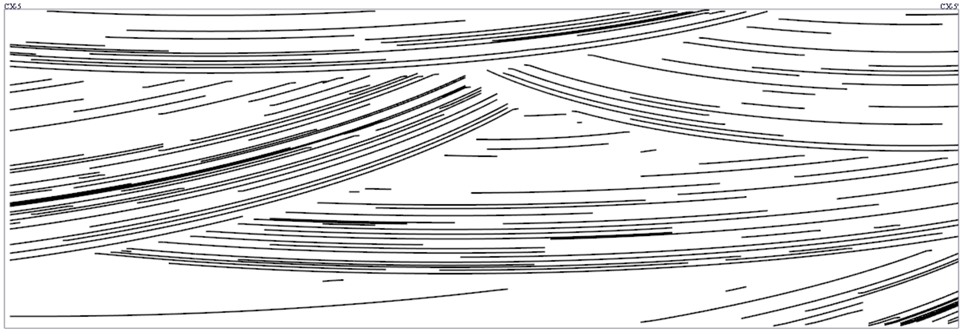
Impact of geologic parameters on flow



Muddy trough cross-bedding model of the Gecko Nose outcrop



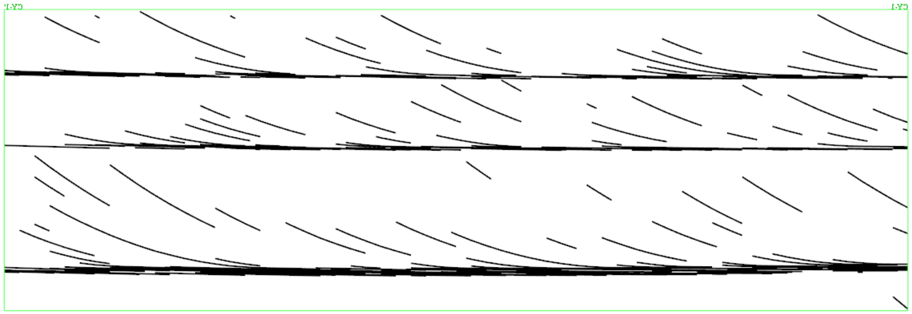
Dip cross-section of the model



Strike cross-section of the model

Impact of geologic parameters on flow

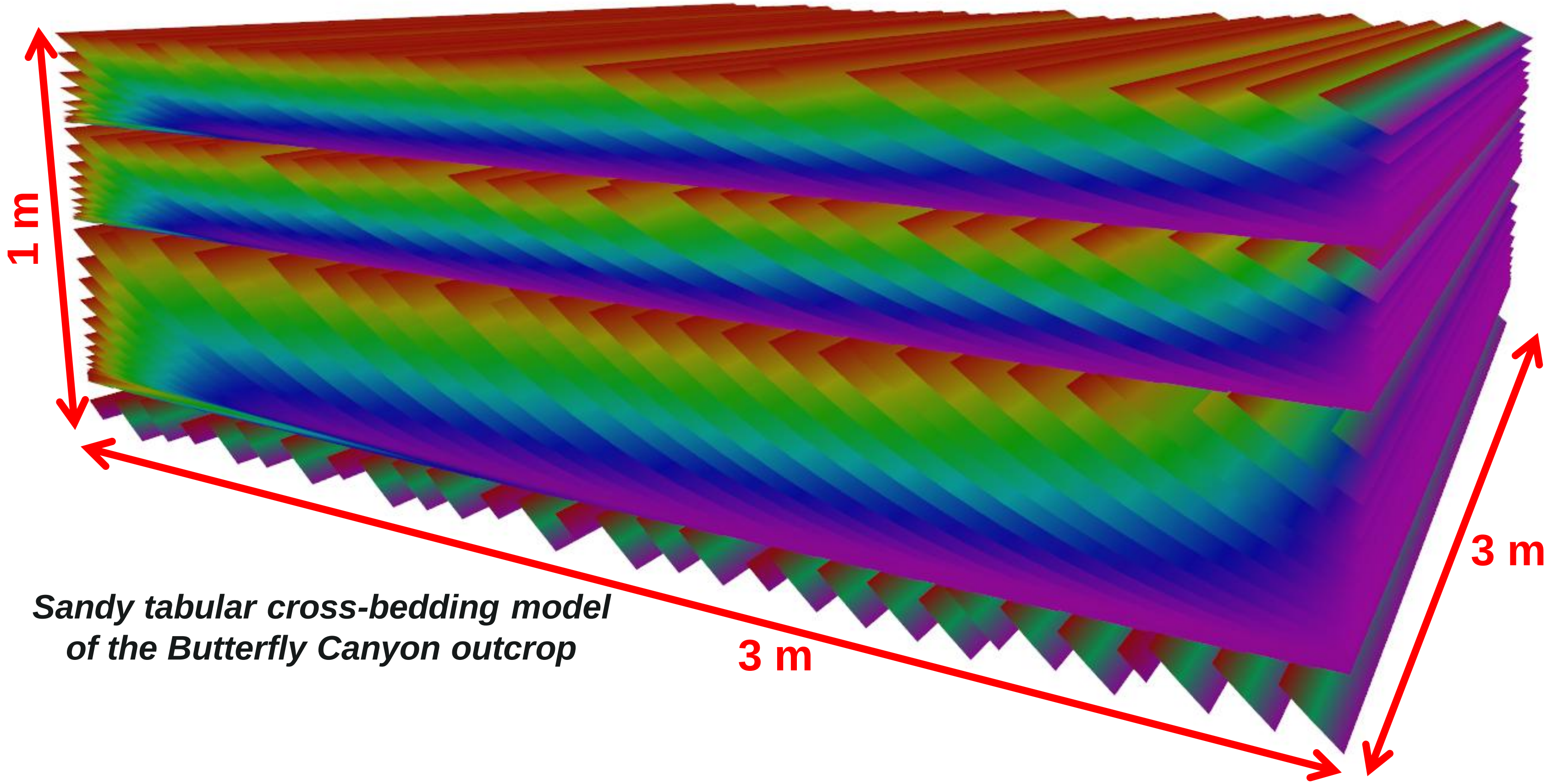
Butterfly canyon outcrop, sandy tabular cross-bedding example, Dir Abu Lifa Member, Egypt



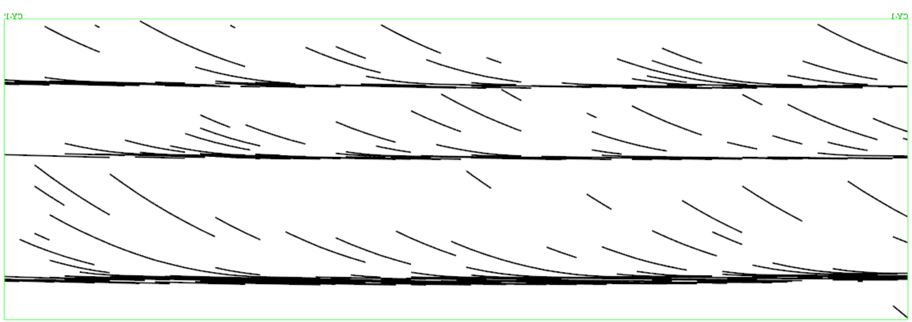
Dip cross-section of the model

Strike cross-section of the model

Impact of geologic parameters on flow



Sandy tabular cross-bedding model of the Butterfly Canyon outcrop



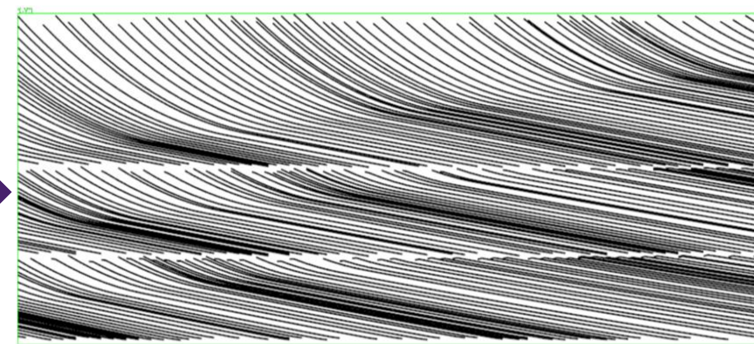
Dip cross-section of the model

Strike cross-section of the model

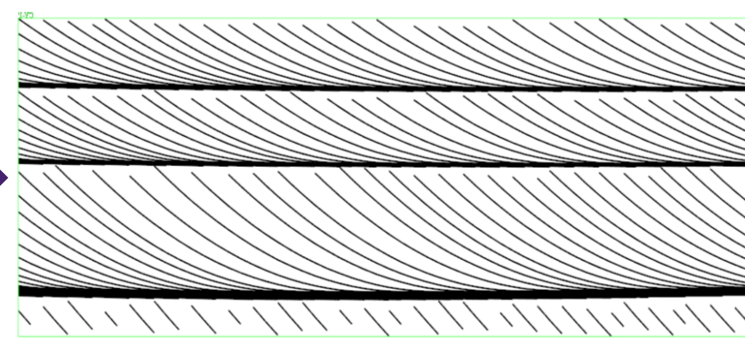
Impact of geological parameters on flow

Parameters	Muddy case Settings "A"	Sandy case Settings "B"
Toeset dip angle	8°	1°
Foreset thickness (mean value)	5.9cm	10cm
Foreset : toeset ratio	2 : 3	20 : 1
Angle of dune climb	5°	0°
Mud patch size	10-100cm	10-20cm
Style of cross-bedding	Trough	Tabular

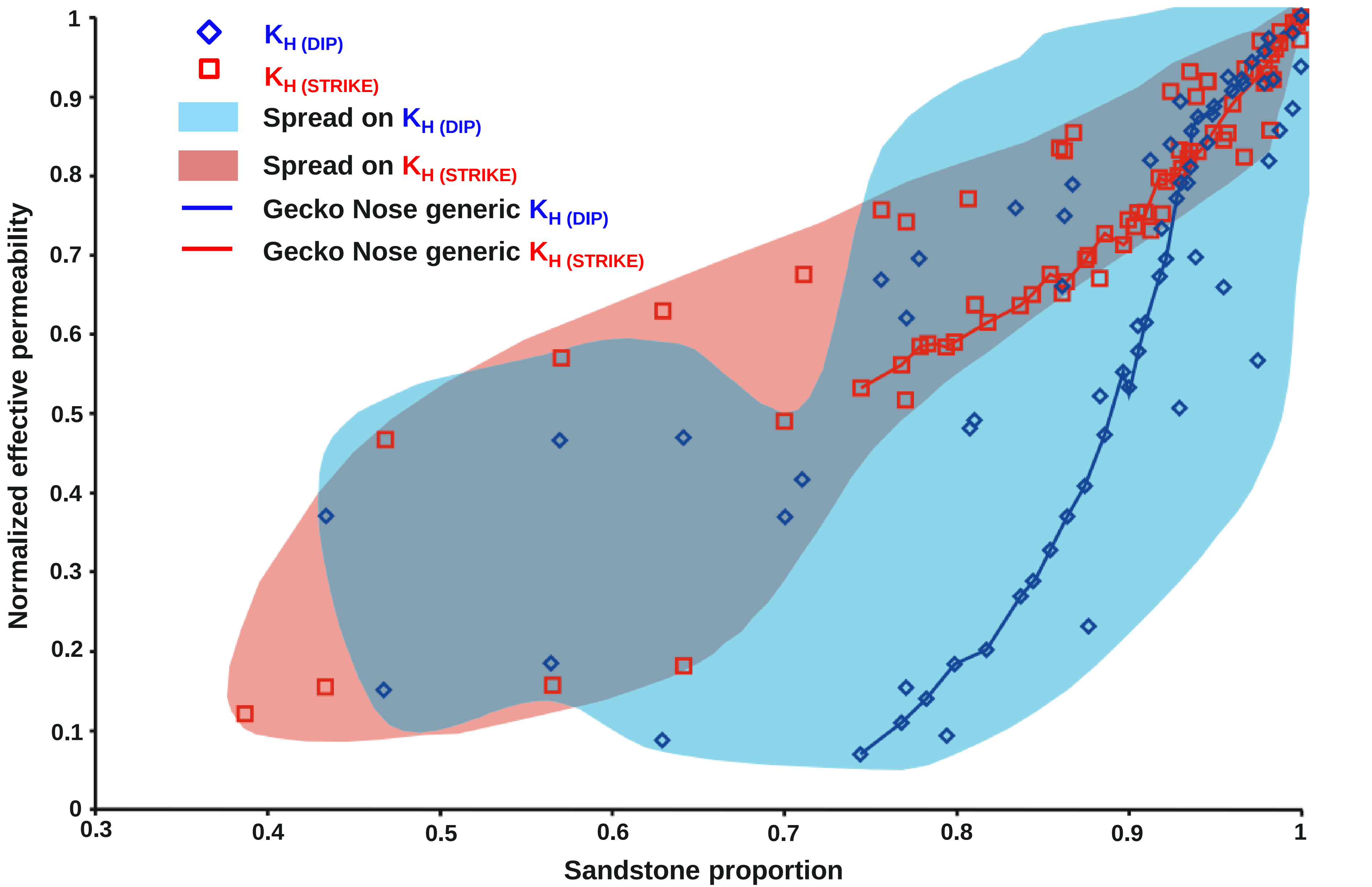
Muddy case end member



Sandy case end member



Relative impact of geologic parameters on effective permeability



Predicting effective permeability in subsurface reservoirs

<u>Hypothesis 1:</u>

Can effective permeability in cross-bedded tidal sandstones be predicted from a parameter, simple to measure, such as sandstone fraction (NTG)?

NO

<u>Hypothesis 2:</u>

Do a small number of additional parameters play the key role in controlling effective permeability?

Relative impact of geologic parameters on effective permeability

Parameters	Muddy case Settings "A"	Sandy case Settings "B"
Toeset dip angle	8°	1°
Foreset thickness (mean value)	5.9cm	10cm
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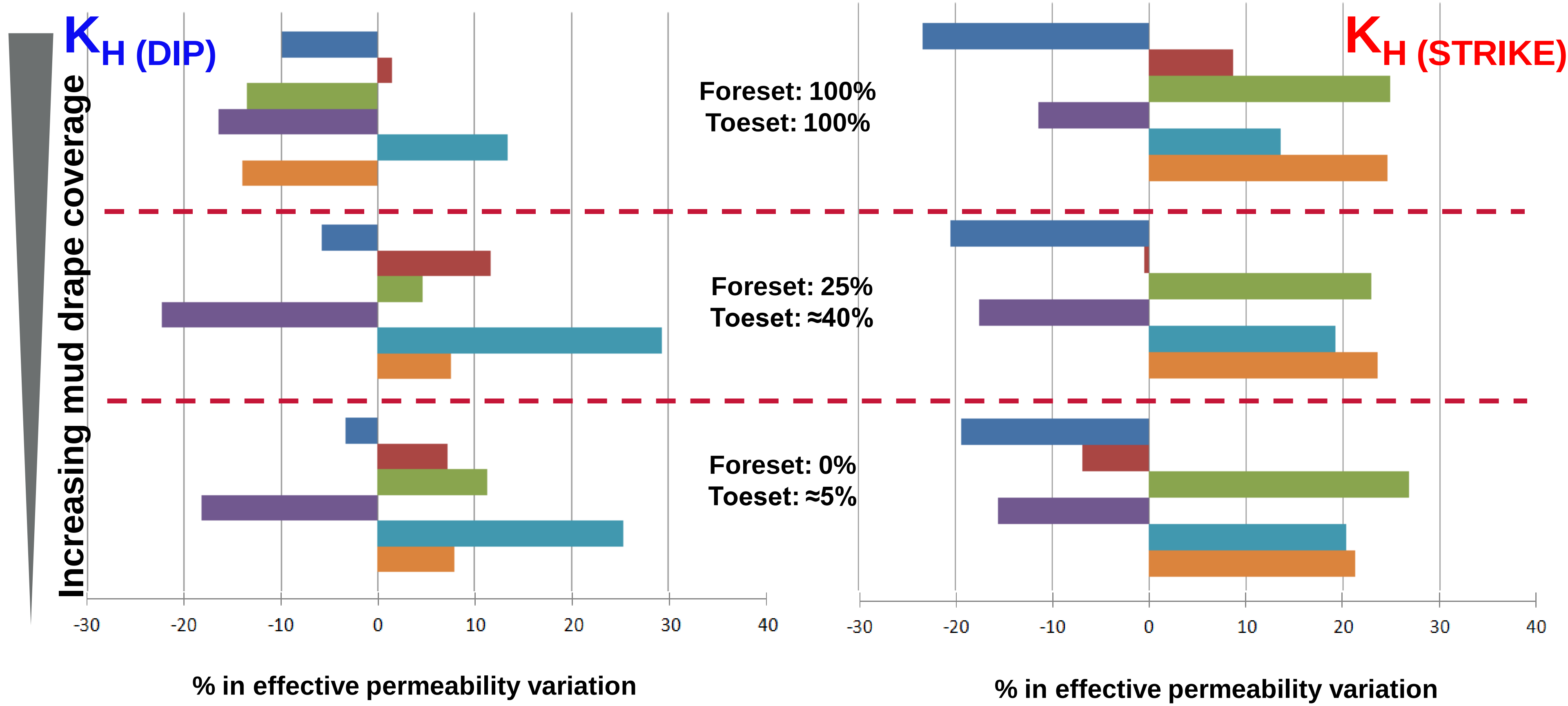
Mud patch size	10-100cm	10-20cm
Style of cross-bedding	Trough	Tabular



Predicting effective permeability in subsurface reservoirs

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NO

<u>Hypothesis 2:</u>

Do a small number of additional parameters play the key role in controlling effective permeability?

NO

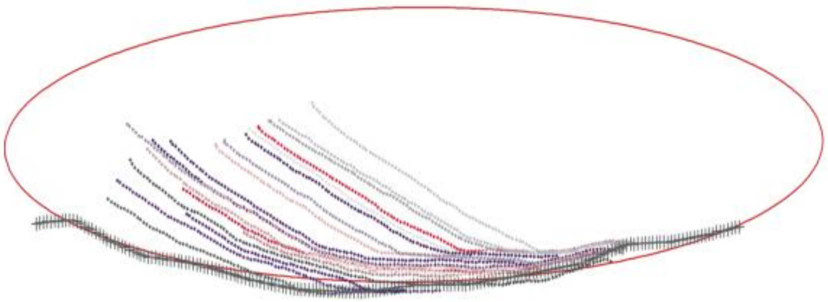
Will need to construct ‘bespoke’ mini-models for a given reservoir or interval. Is this possible from available data?

Application to subsurface reservoirs

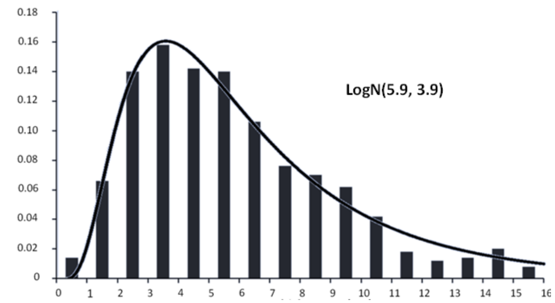
Direct core observation

1) Toeset dip angle
2) Foreset thickness
3) Foreset : toeset ratio
4) Angle of dune climb
5) Mud patch size
6) Style of cross-bedding

Outcrop analog dataset selected to match depositional environment



Extraction of cross-bedding from photomontage

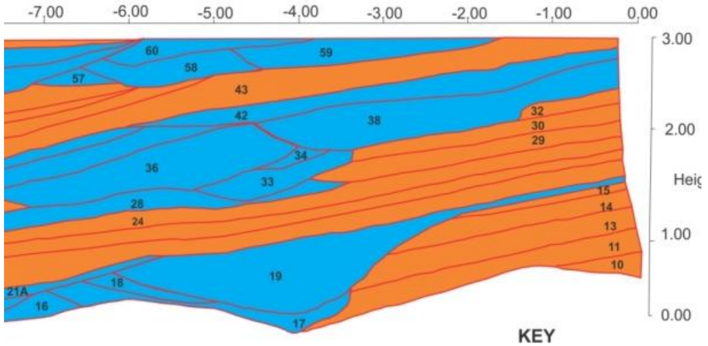


Foreset thickness Ft distribution (cm)

1) Toeset dip angle 3) Foreset : toeset ratio

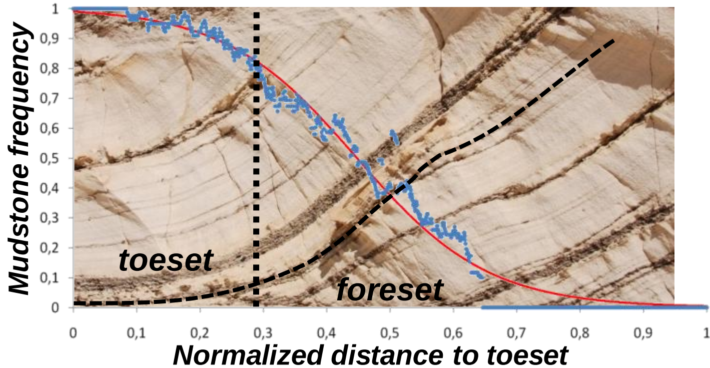
4) Angle of dune climb

2) Foreset thickness



Interpretation of style of cross-bedding at Gecko Nose outcrop, Dir Abu Lifa Member, Egypt

6) Style of cross-bedding



5) Mud patch size

Predicting effective permeability in subsurface reservoirs

Hypothesis 1:

Can effective permeability in cross-bedded tidal sandstones be predicted from a parameter simple to measure such as sandstone fraction (NTG)?

NO

Hypothesis 2:

Do a small number of additional parameters play the key role in controlling effective permeability?

NO

Will need to construct ‘bespoke’ mini-models for a given reservoir or interval. Is this possible from available data?

YES

Many key data types obtained directly from subsurface measurements supplemented by data from relevant outcrop analogues

Conclusions

- At the metre-scale, effective vertical permeability decreases faster than effective horizontal permeability as sandstone fraction decreases, because mud drapes become more laterally extensive
    - Example: in the generic Gecko Nose model, vertical permeability falls to c. 0.5% of the sandstone value, while the horizontal permeability falls to c. 5% and c. 50% of the sandstone value in dip and strike directions, respectively

- Across all models, calculated permeability broadly increases with sandstone fraction in each direction, but there is a considerable spread in values reflecting sensitivity to the geologic parameters that control mud drape continuity and connectivity

- None of the tested geologic parameters has a predominant impact on effective permeability compared to the others

- In subsurface reservoirs, many geologic input parameters required for the modeling process can be estimated or directly measured from core data