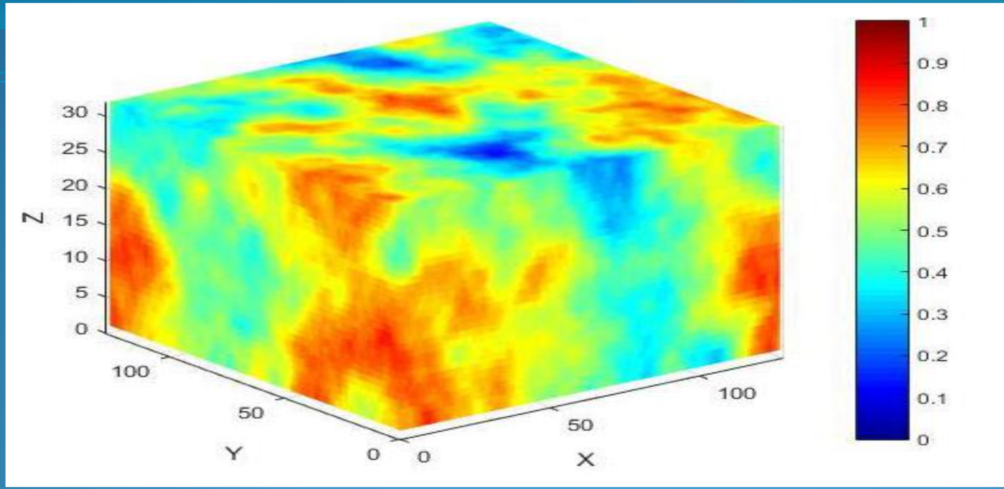


Modelling and Simulation of Heterogeneous and Anisotropic Formations using Advanced Fractal Reservoir Models

Piroska Lorinczi, Paul W.J. Glover, Saud Al-Zainaldin, Hassan Al-Ramadhan, Saddam Sinan, George Daniel, I. Obielum

Conventional Reservoir Modelling

A justified educated guessing game:

- Physical properties obtained from few wells
- Data incomplete and variability completely unknown at smaller scales (say < 50 m)
- Interpolated in the inter-well volume using variogram-filtered krigging
- No information available for accurate well placement
- No information about reservoir heterogeneity measured or used
- No information about reservoir anisotropy measured or used in modelling and simulation

Fractal Reservoir Modelling

- AFRMs can depict and control heterogeneity
- AFRMs can depict and control *xy*, *yz* and *zx* anisotropy
- AFRM accuracy can be verified
- AFRM allows generic sensitivity tests for heterogeneity, anisotropy, well placement and orientation
- AFRM is more accurate than conventional models in simulations
- AFRM contains information at all scales larger than cell size
- **AFRMs can be fully reservoir-conditioned**

… in this presentation

What fractals can do for you …

How to make Advanced Fractal Reservoir Model (AFRMs)

Generic fractal modelling

- The effect of heterogeneity on oil production data
- The effect of anisotropy on oil production data
- The effect of well placement and orientation

Conditioned fractal reservoir modelling

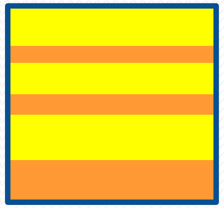
- How to use AFRMs with real reservoirs

The Future

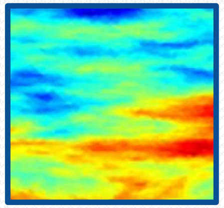
- Creating flexible software for modelling

Introduction to Fractals

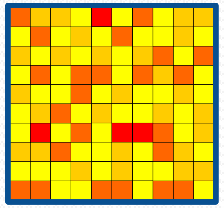
Structured objects exhibiting self-similar behaviour at all scales.



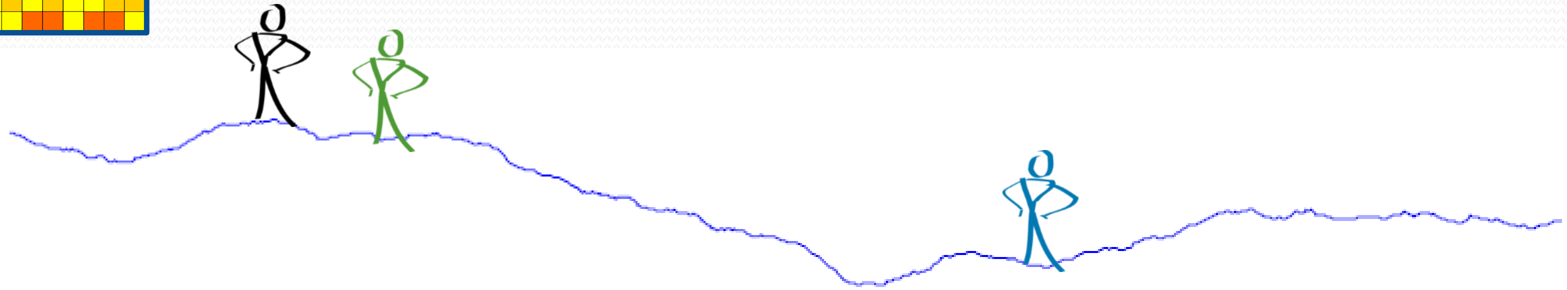
Well-defined structure at a given scale:
Full spatial correlation



Fractal:
Partial spatial correlation



Random distributions:
No spatial correlation

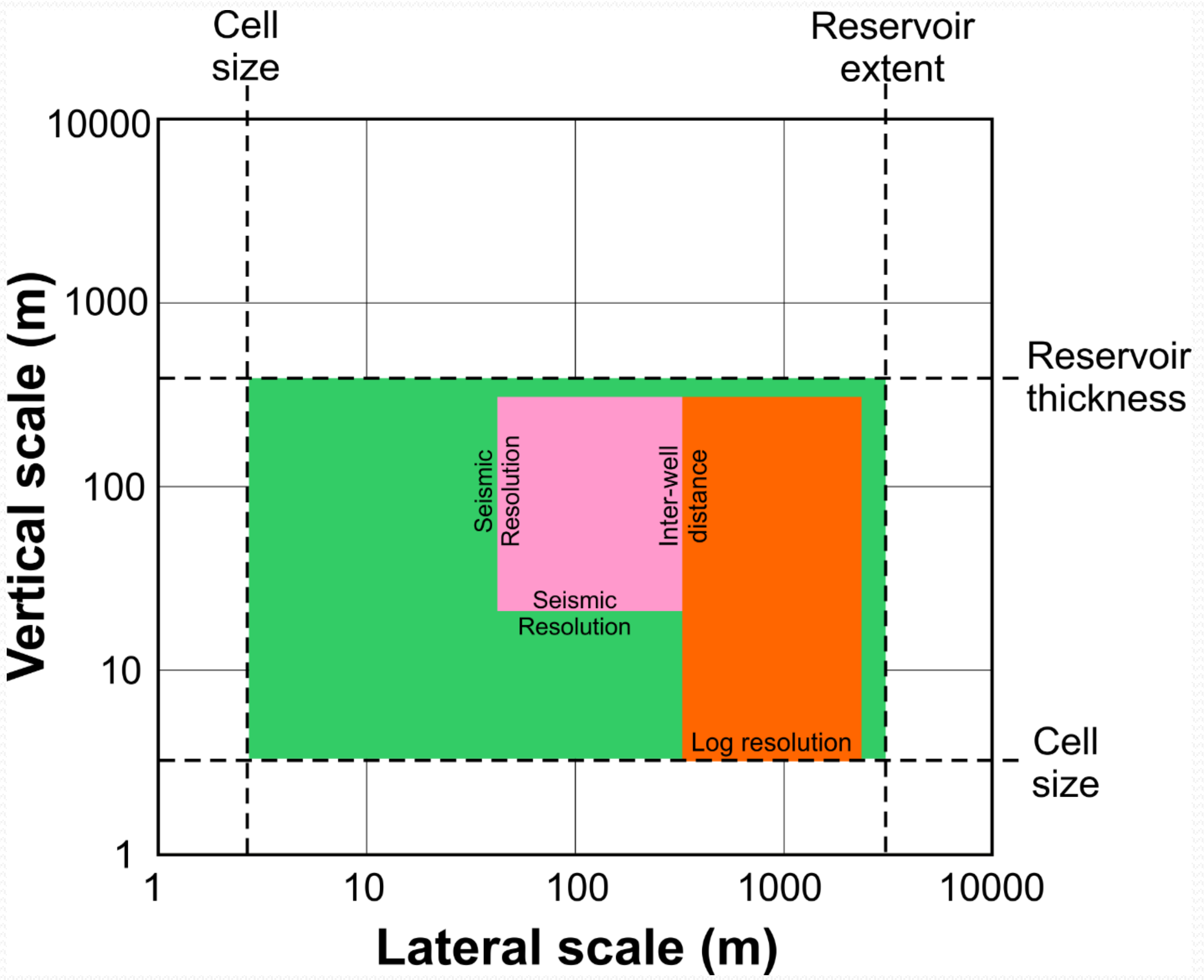


Scales and variability

Interpolation of wells:
Only large scale variability is taken account of

Interpolation of wells with seismic input: Range of scales in inter-well volume extended to seismic resolution

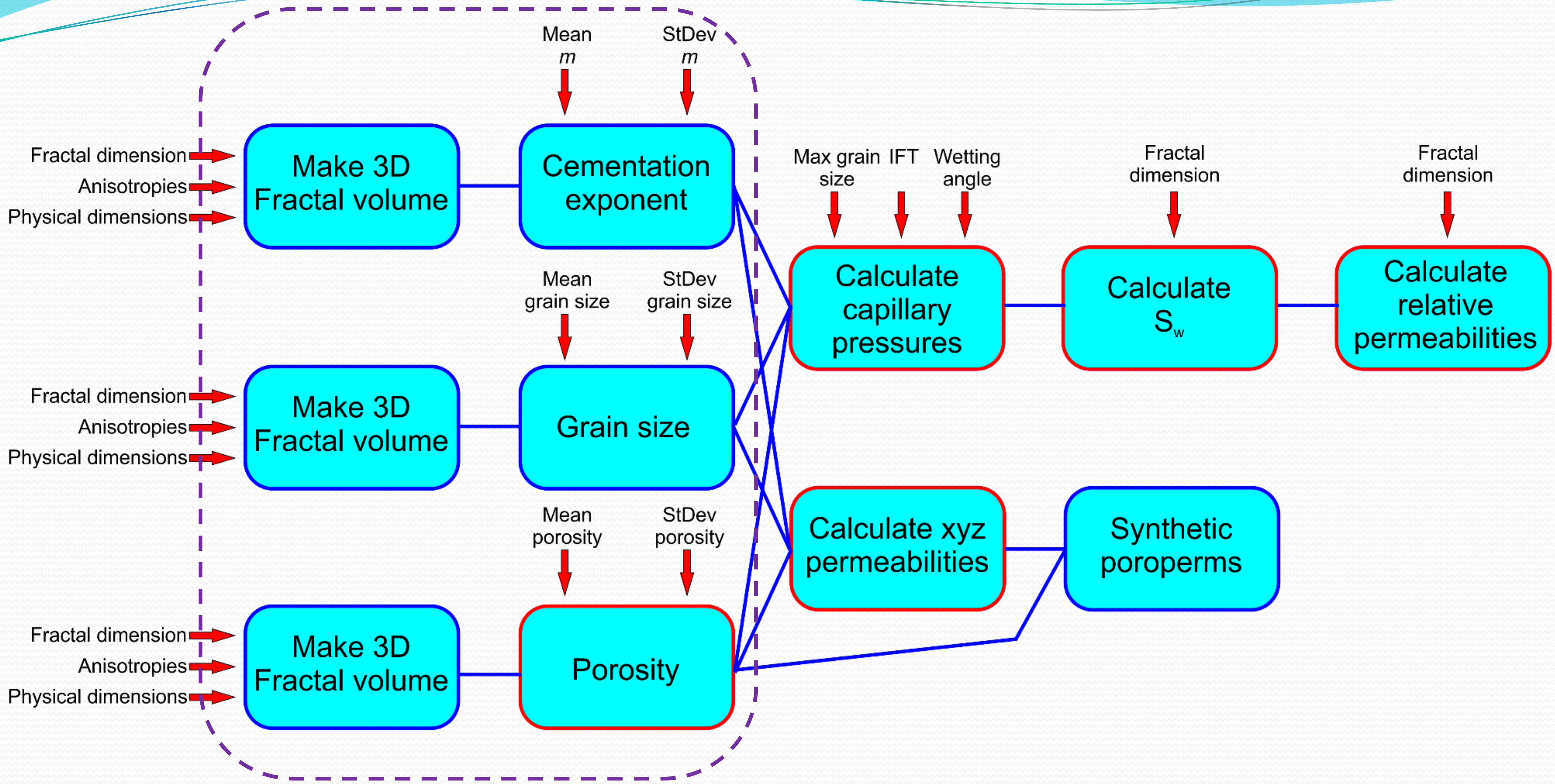
Fractal Interpolation (FSMA):
Takes account of all data from the reservoir scale to the cell scale



Making AFRMs

How is it possible to make fractal reservoir models which have:

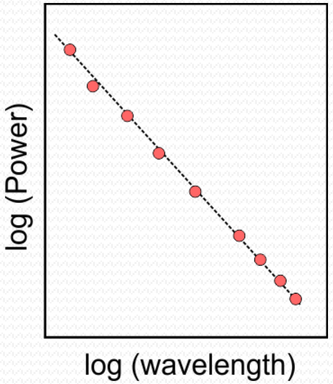
- 3D
- controlled heterogeneity
- controlled anisotropy
- can be fully validated, and
- can be used to model poroperm curves


Mean
m
StDev
m
Fractal dimension
Anisotropies
Physical dimensions
Make 3D Fractal volume
Cementation exponent
Mean grain size
StDev grain size
Fractal dimension
Anisotropies
Physical dimensions
Make 3D Fractal volume
Grain size
Mean porosity
StDev porosity
Fractal dimension
Anisotropies
Physical dimensions
Make 3D Fractal volume
Porosity
Max grain size
IFT
Wetting angle
Calculate capillary pressures
Fractal dimension
Calculate S_w
Fractal dimension
Calculate relative permeabilities
Calculate xyz permeabilities
Synthetic poroperms

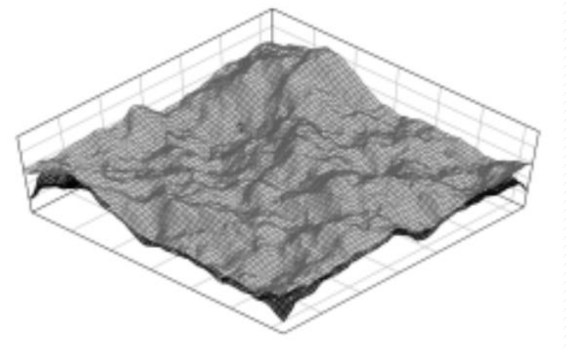
Fourier Filtering method in xD

1D

FT



2D



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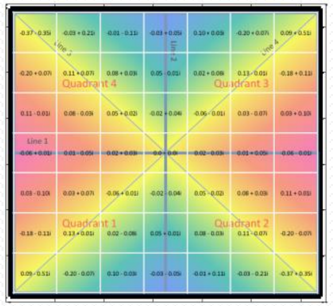
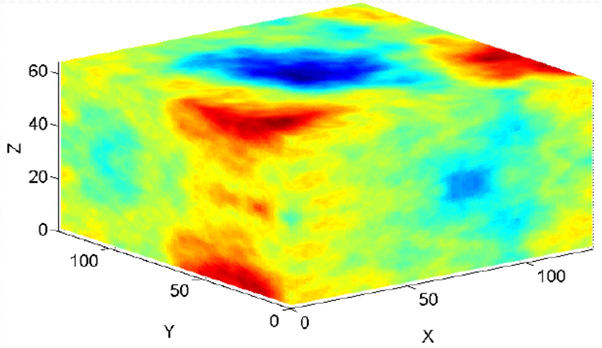


3D



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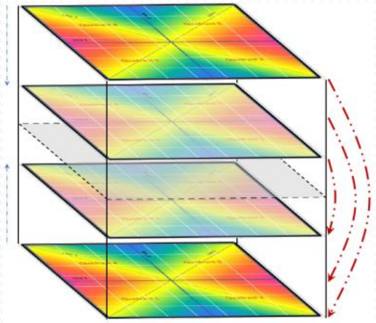
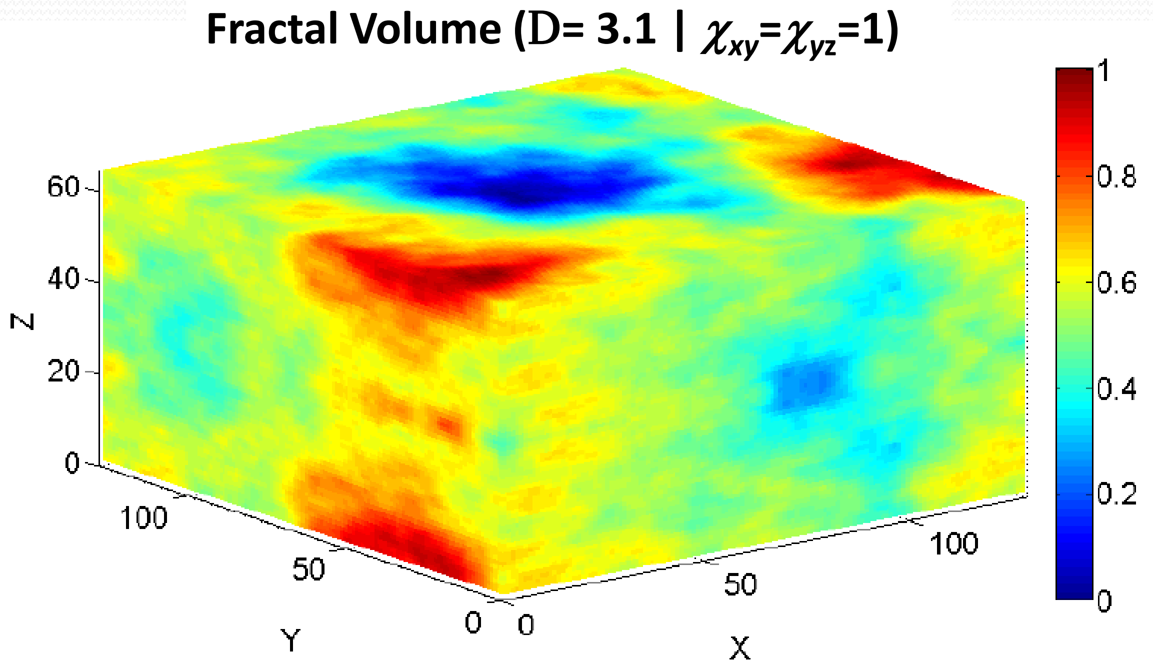
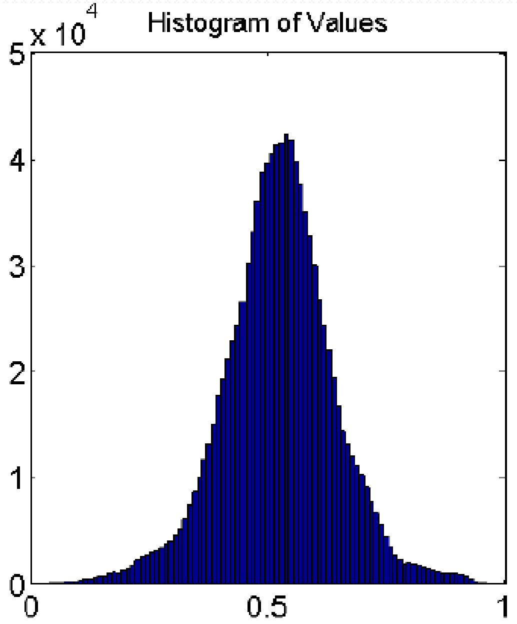


The Fourier Filtering method

Fractal dimension and anisotropy controlled

Exact and repeatable structure defined by a unique random number key



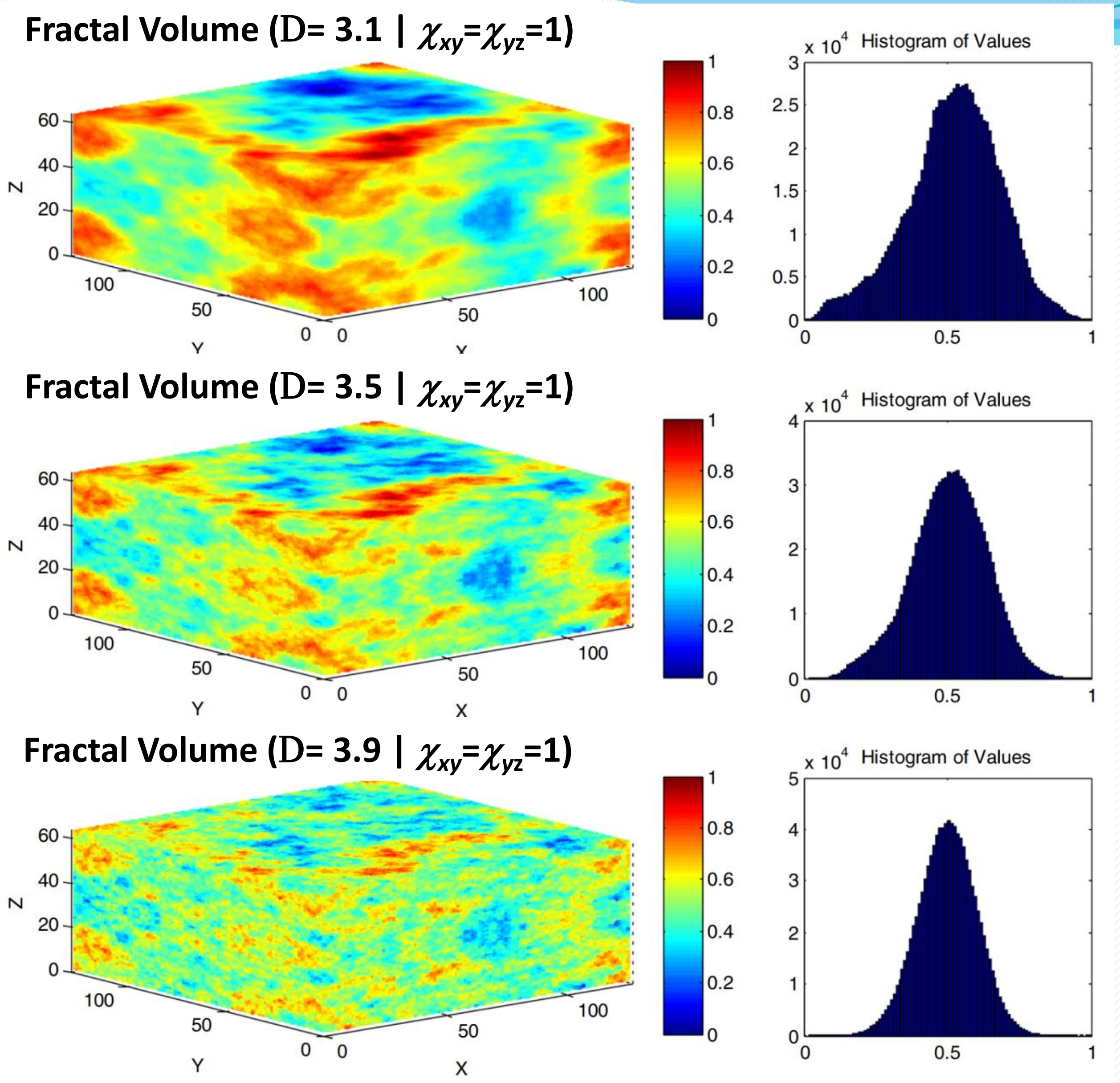


Data required: Physical and fractal dimension and two anisotropy factors

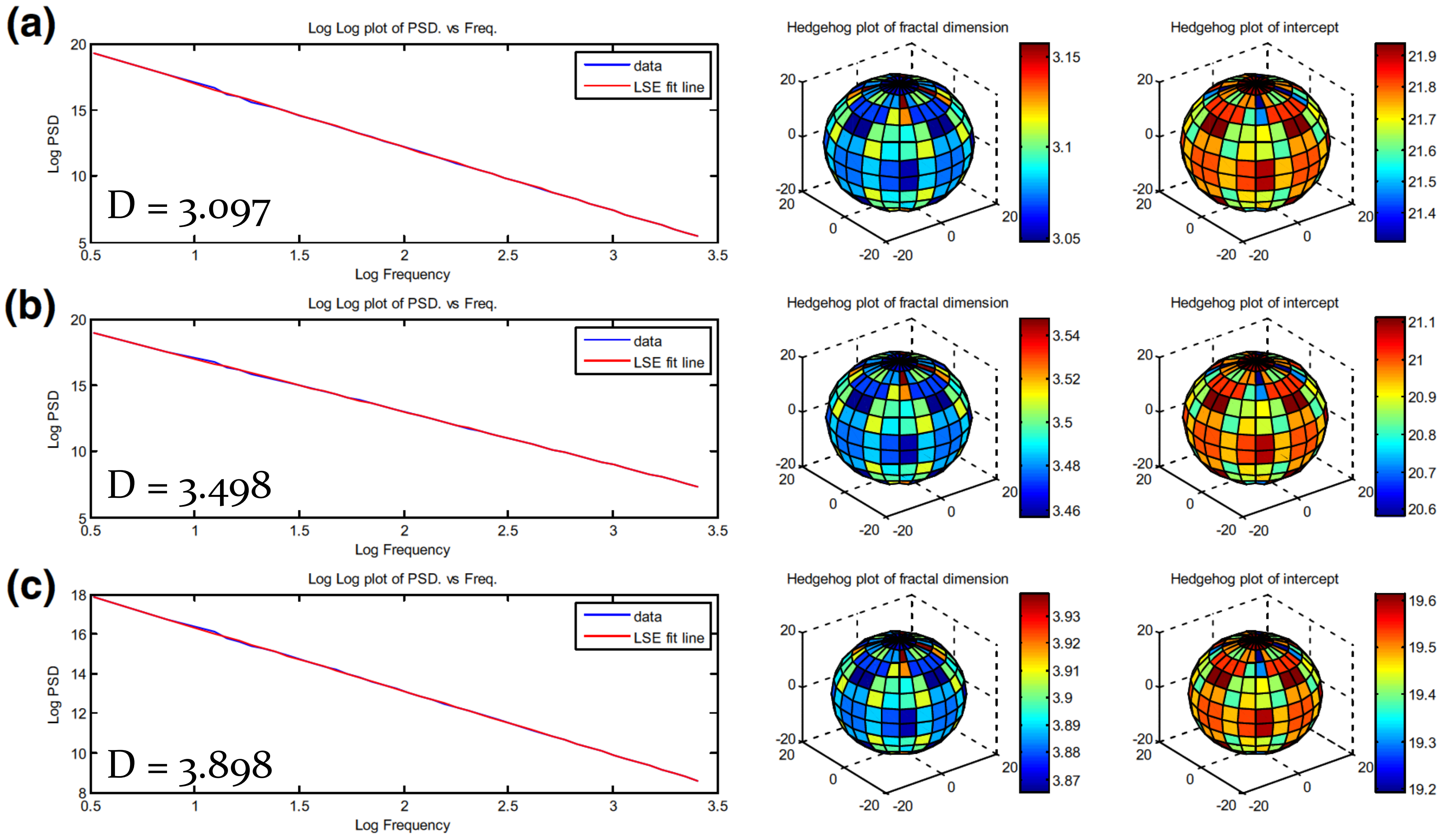
Fractal volumes for different heterogeneities (fractal dimensions) and the same isotropy

Data required:
Physical and fractal dimension and two anisotropy factors

Increasing Heterogeneity

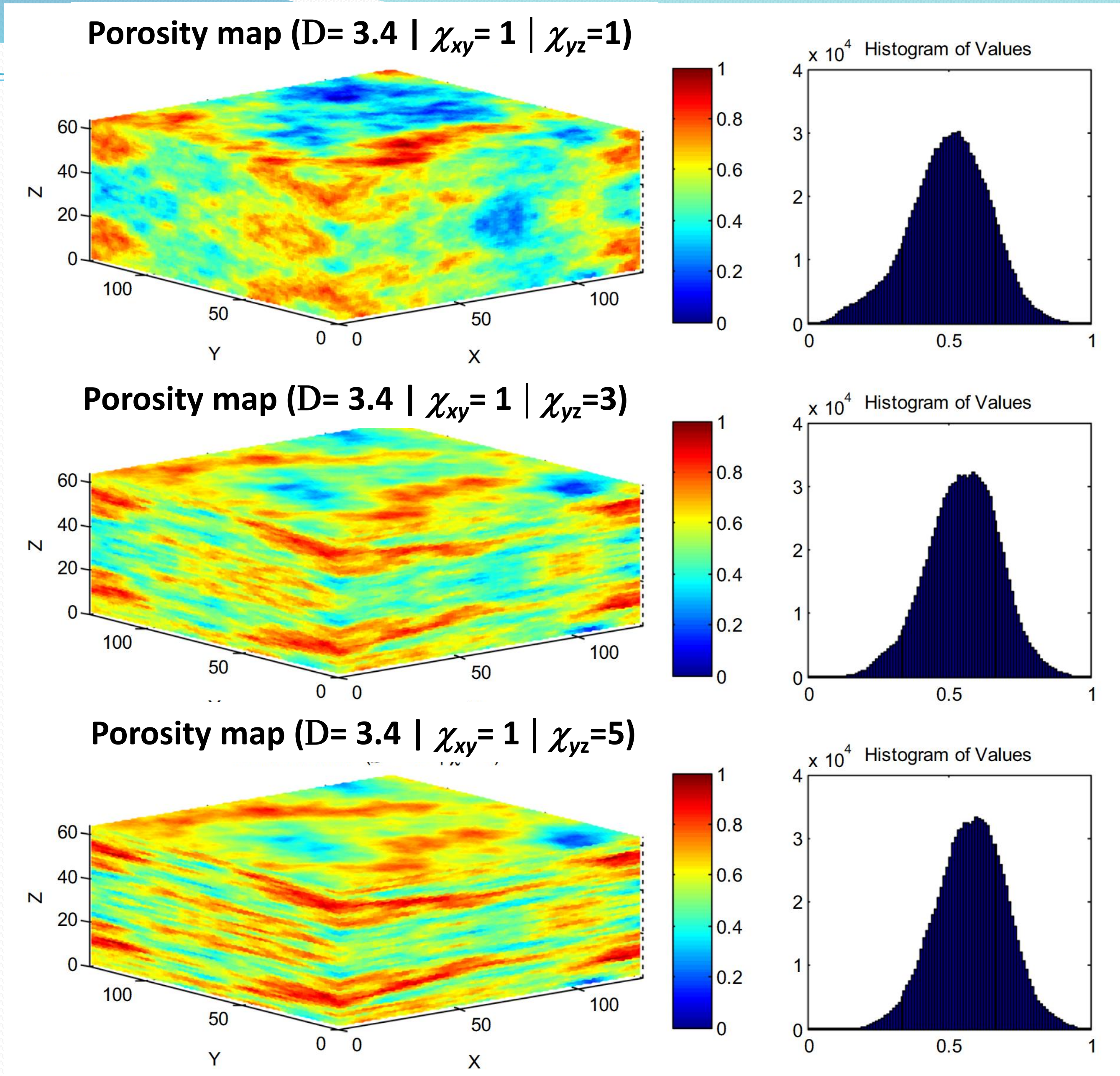


Testing the fractal dimensions

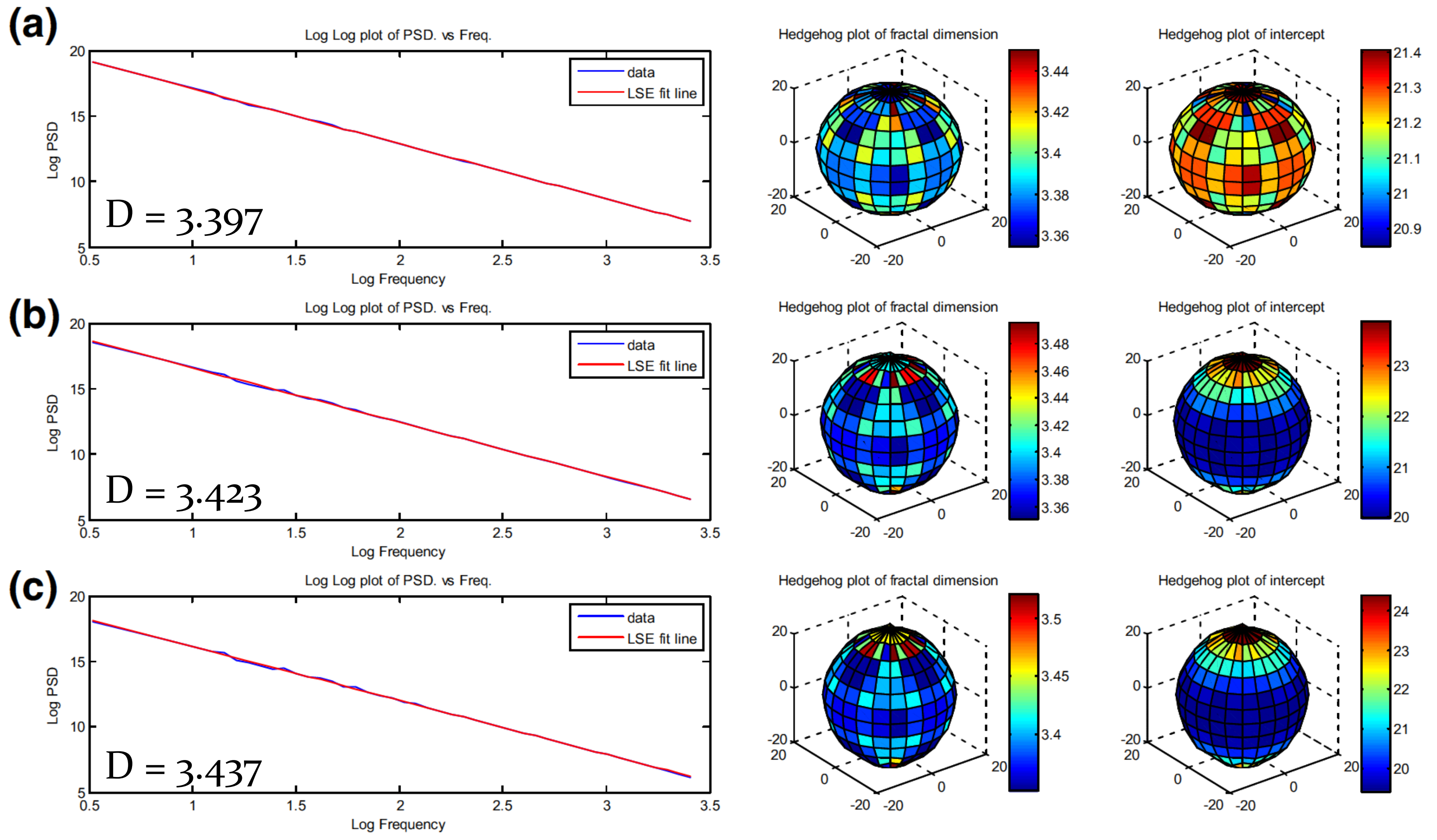


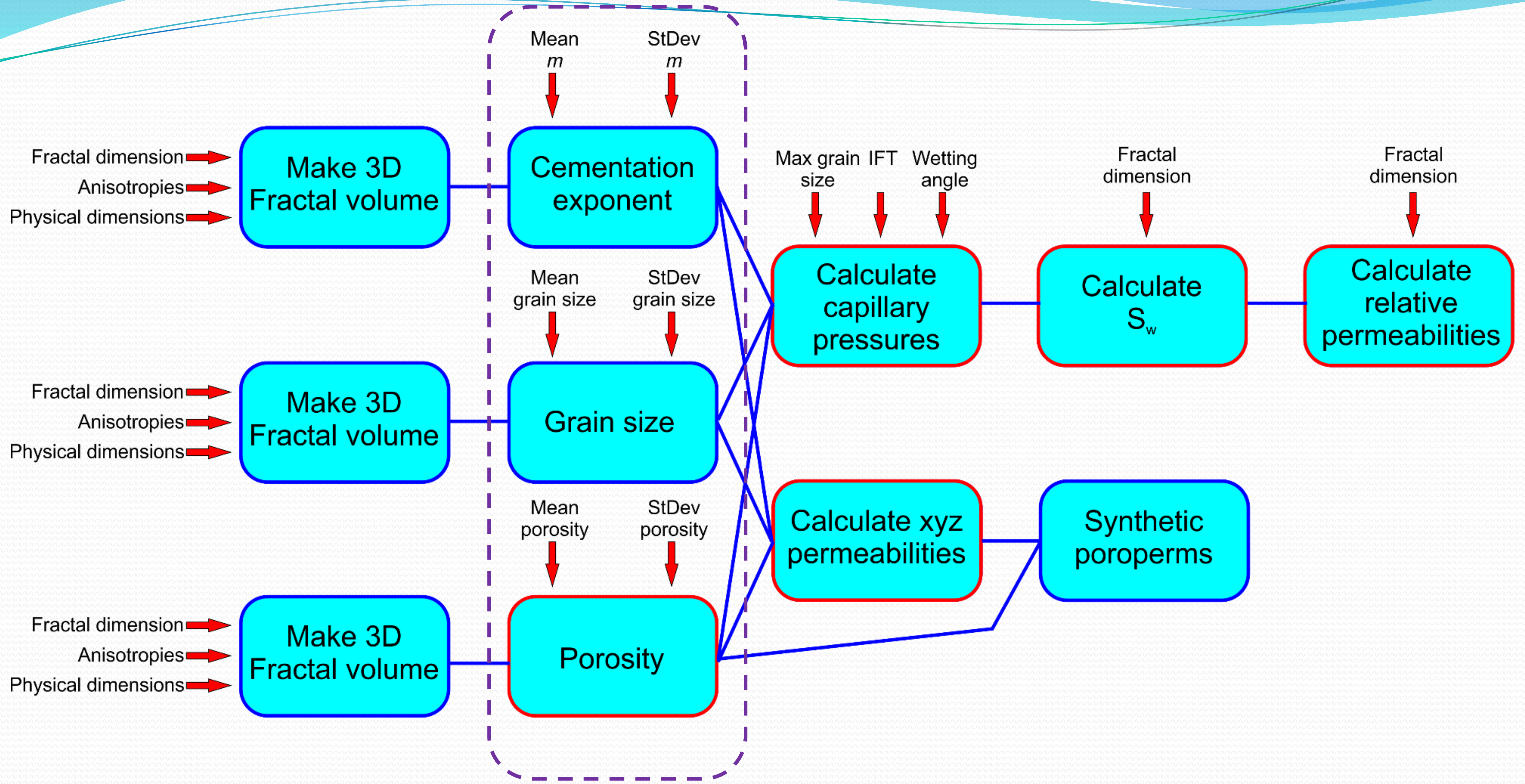
Fractal volumes for different heterogeneities (fractal dimensions) and the same isotropy

Increasing Anisotropy



Testing the anisotropies




Mean
m
StDev
m
Fractal dimension
Anisotropies
Physical dimensions
Make 3D Fractal volume
Cementation exponent
Max grain size
IFT
Wetting angle
Fractal dimension
Fractal dimension
Calculate capillary pressures
Calculate S_w
Calculate relative permeabilities
Mean grain size
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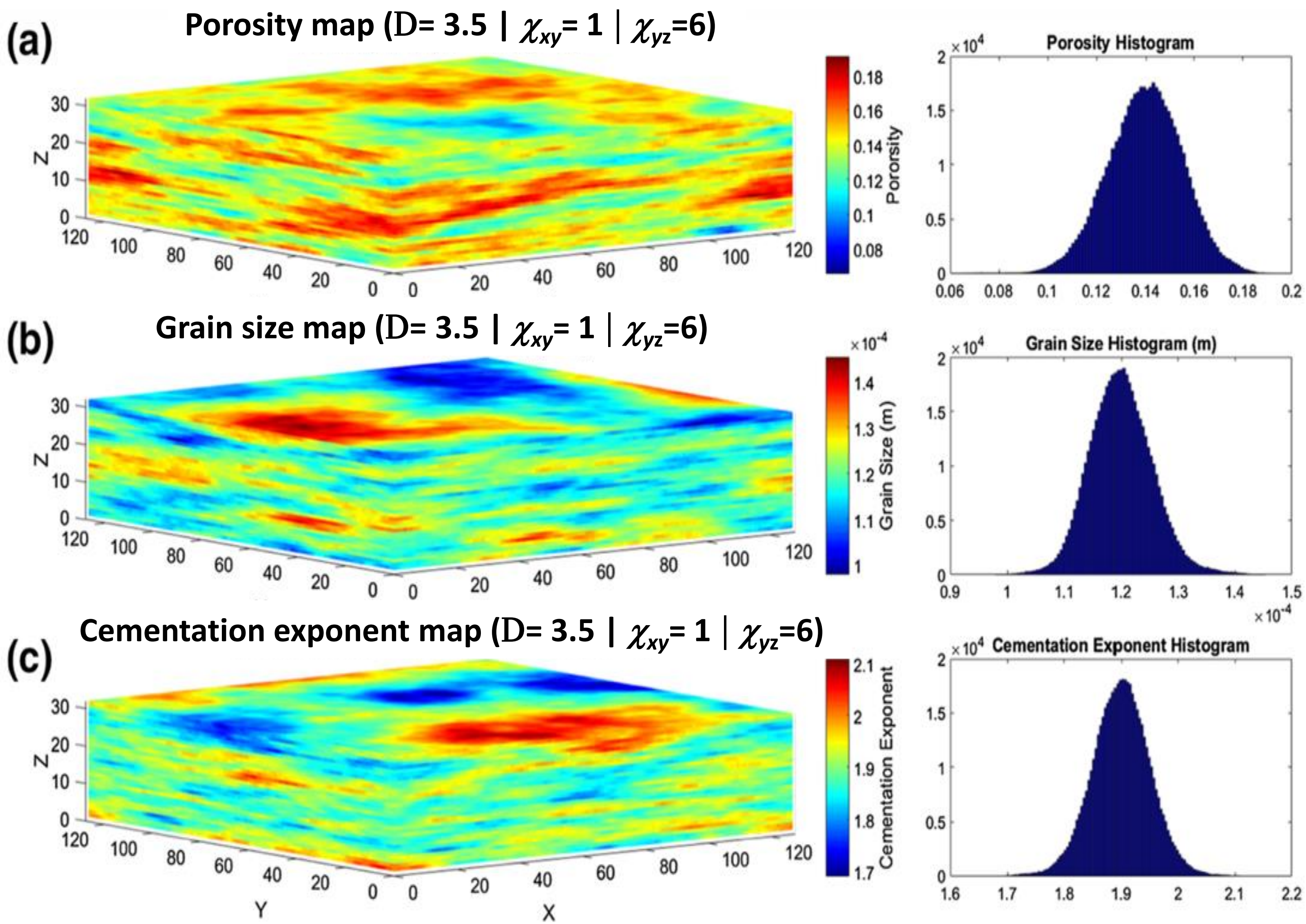
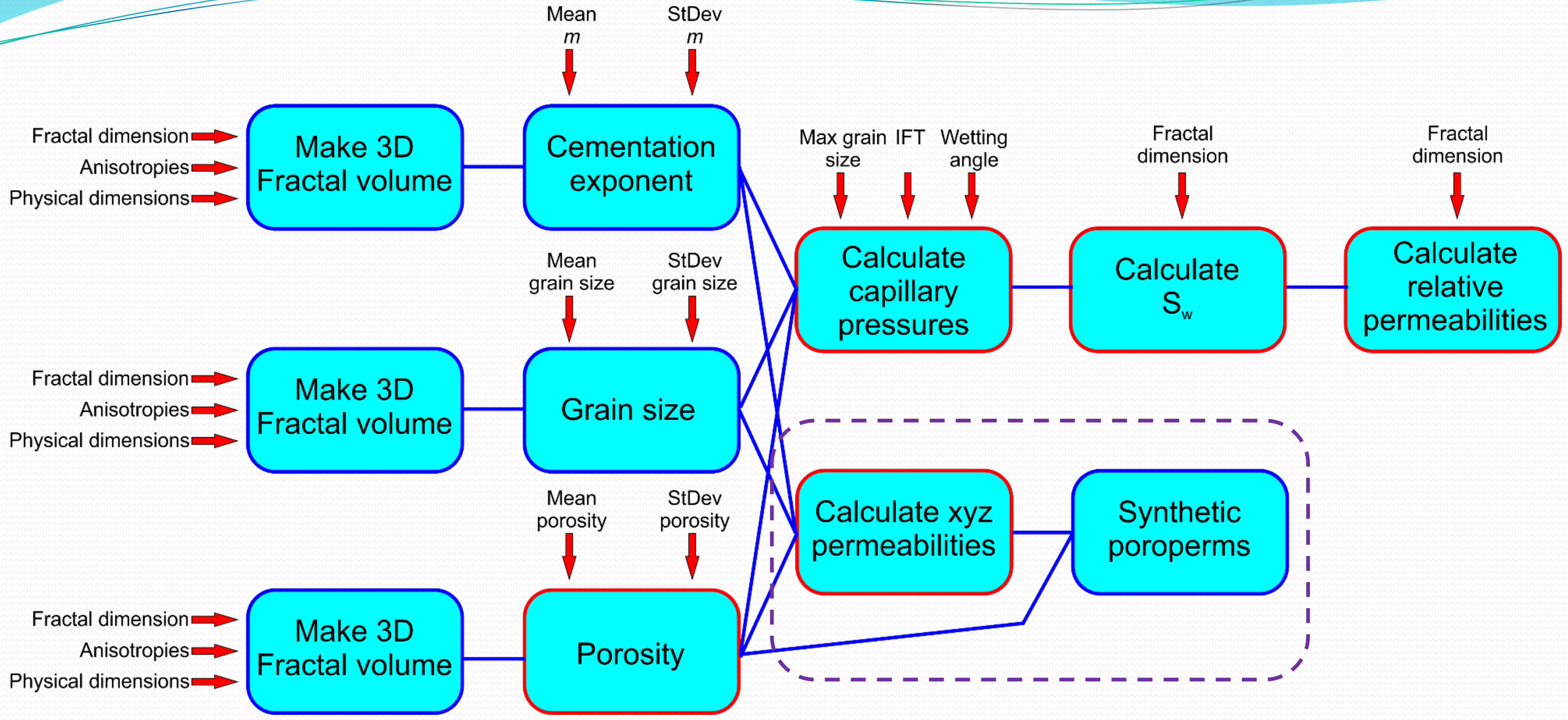
Anisotropies
Physical dimensions
Make 3D Fractal volume
Grain size
Mean porosity
StDev porosity
Calculate xyz permeabilities
Synthetic poroperms
Fractal dimension
Anisotropies
Physical dimensions
Make 3D Fractal volume
Porosity

Conditioning to reservoir properties



Data required: Mean and standard deviation of each parameter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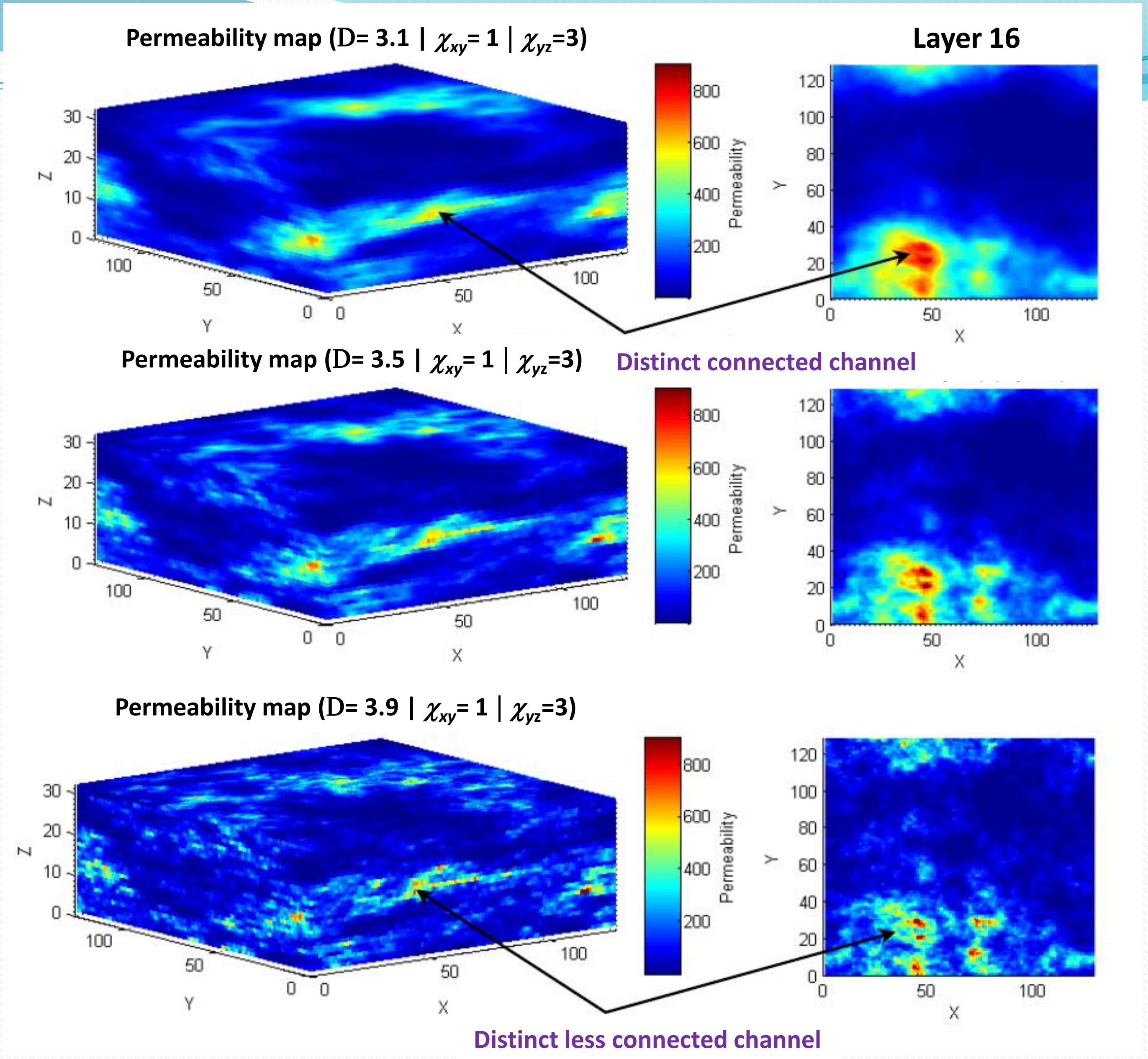
Porosity

Calculating permeability

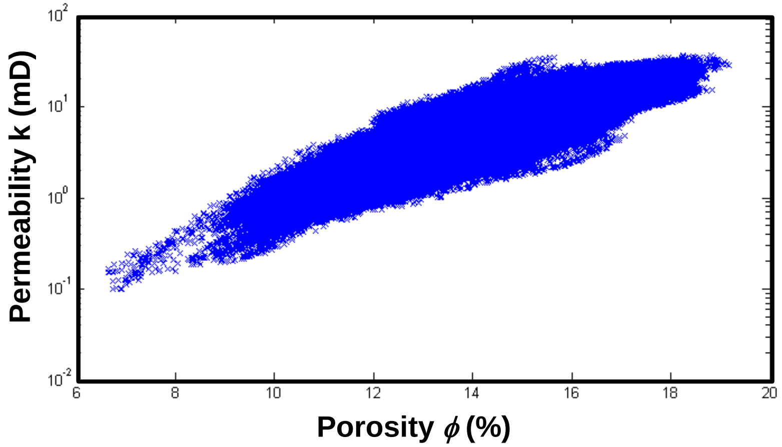
Using the RGPZ method for clastic rocks

$$k = \frac{d_{grain}^2 \phi^{3m}}{4am^2}$$

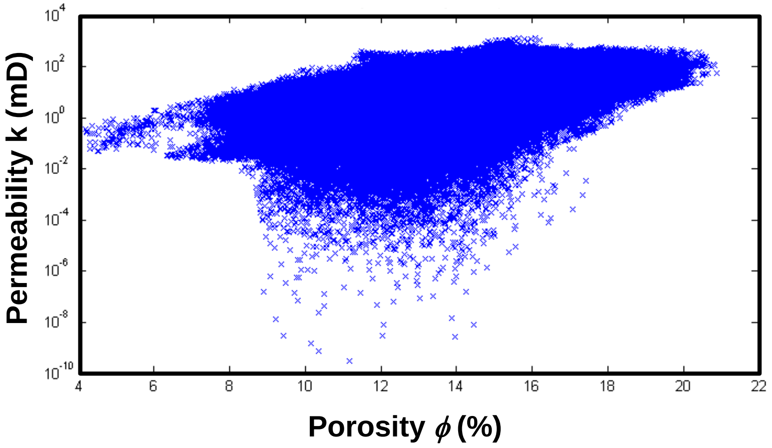
or its carbonate or generic modifications appropriately.



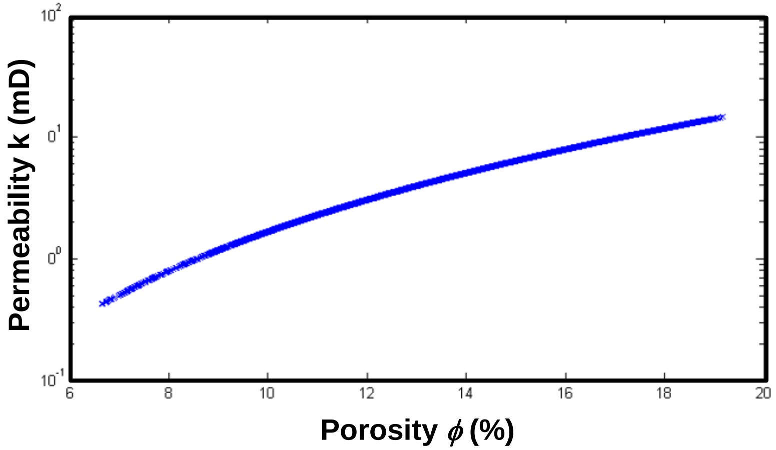
Synthetic poroperm plots



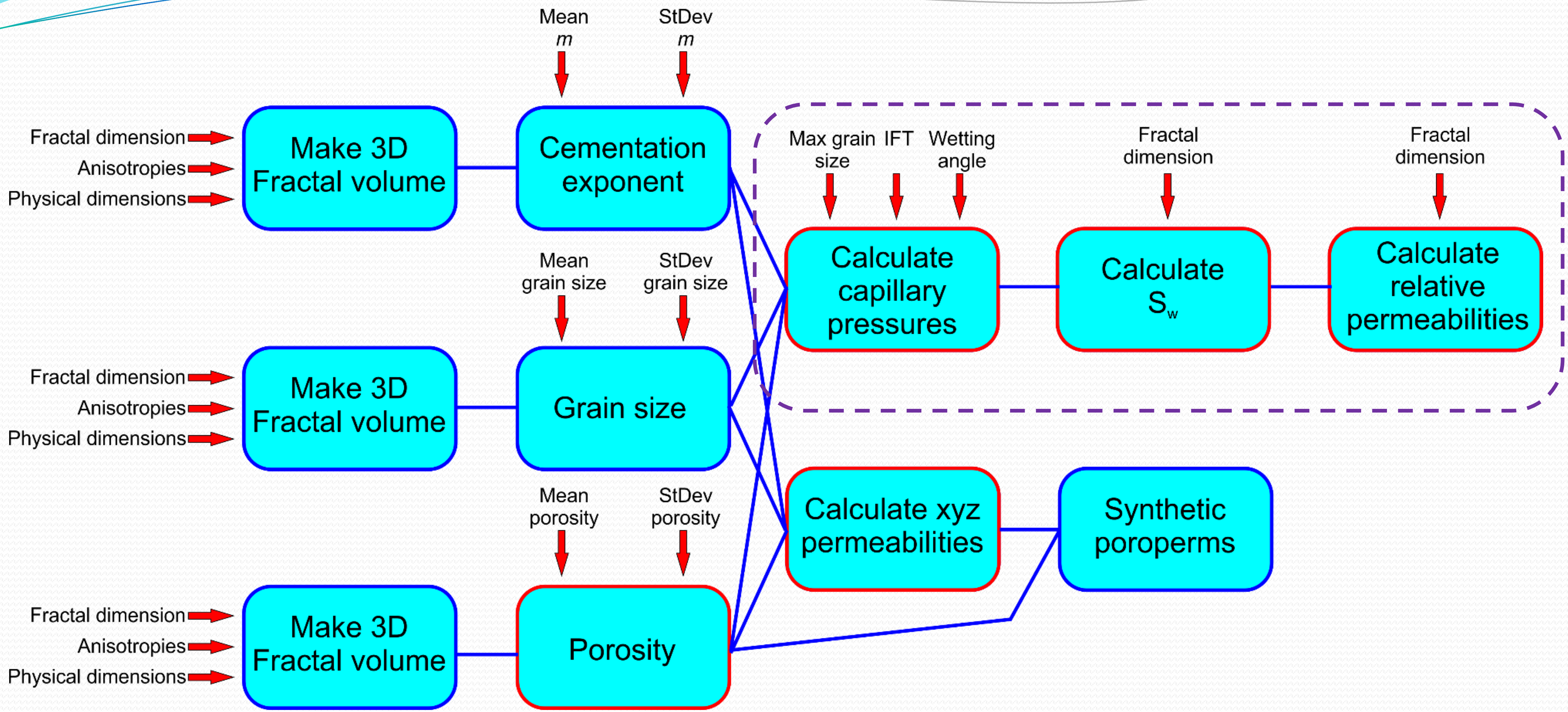
Typical poroperm plot for *D*=3.4, different fractal volumes of main parameters and typical standard deviations of input fractal volumes



Increasing standard deviations of input fractal volumes increases scatter



Using the same map for all input parameters collapses the poroperm plot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Porosity

Capillary pressures

Capillary pressure

$$P_c = \frac{2A\sigma\cos\theta}{d_{grain}}\sqrt{\frac{am^2}{2\phi^{2m}}}.$$

Entry pressure

$$P_e = \frac{2A\sigma\cos\theta}{d_{largest\ grain}}\sqrt{\frac{am^2}{2\phi^{2m}}},$$

Water saturation

$$S_w^* = \left(\frac{d_g}{d_{g,max}}\right)^{3-\mathfrak{D}}$$

$$\lambda = 3 - \mathfrak{D}$$

Relative permeabilities

Brooks-Corey-Mualem

$$k_{\mathrm{rw}} = \left(S_{\mathrm{w}}^*\right)^{\frac{4+5\lambda}{2\lambda}}$$

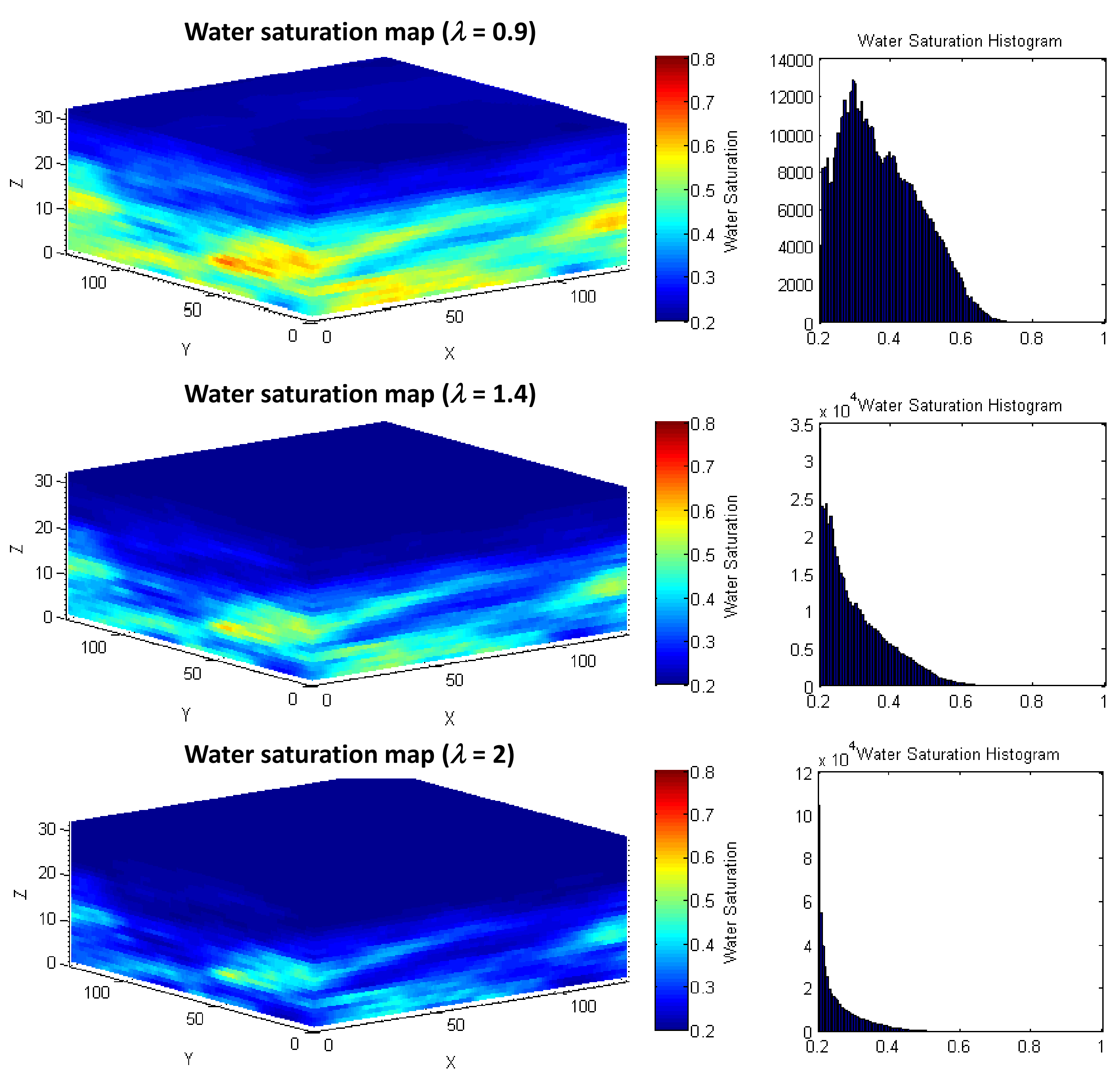
$$k_{\mathrm{rnw}} = \left(1 - S_{\mathrm{w}}^*\right)^{\frac{1}{2}}\left[1 - \left(S_{\mathrm{w}}^*\right)^{\frac{1+\lambda}{\lambda}}\right]^2$$

Data required: Pore throat conversion factor, interfacial tension, wetting angle

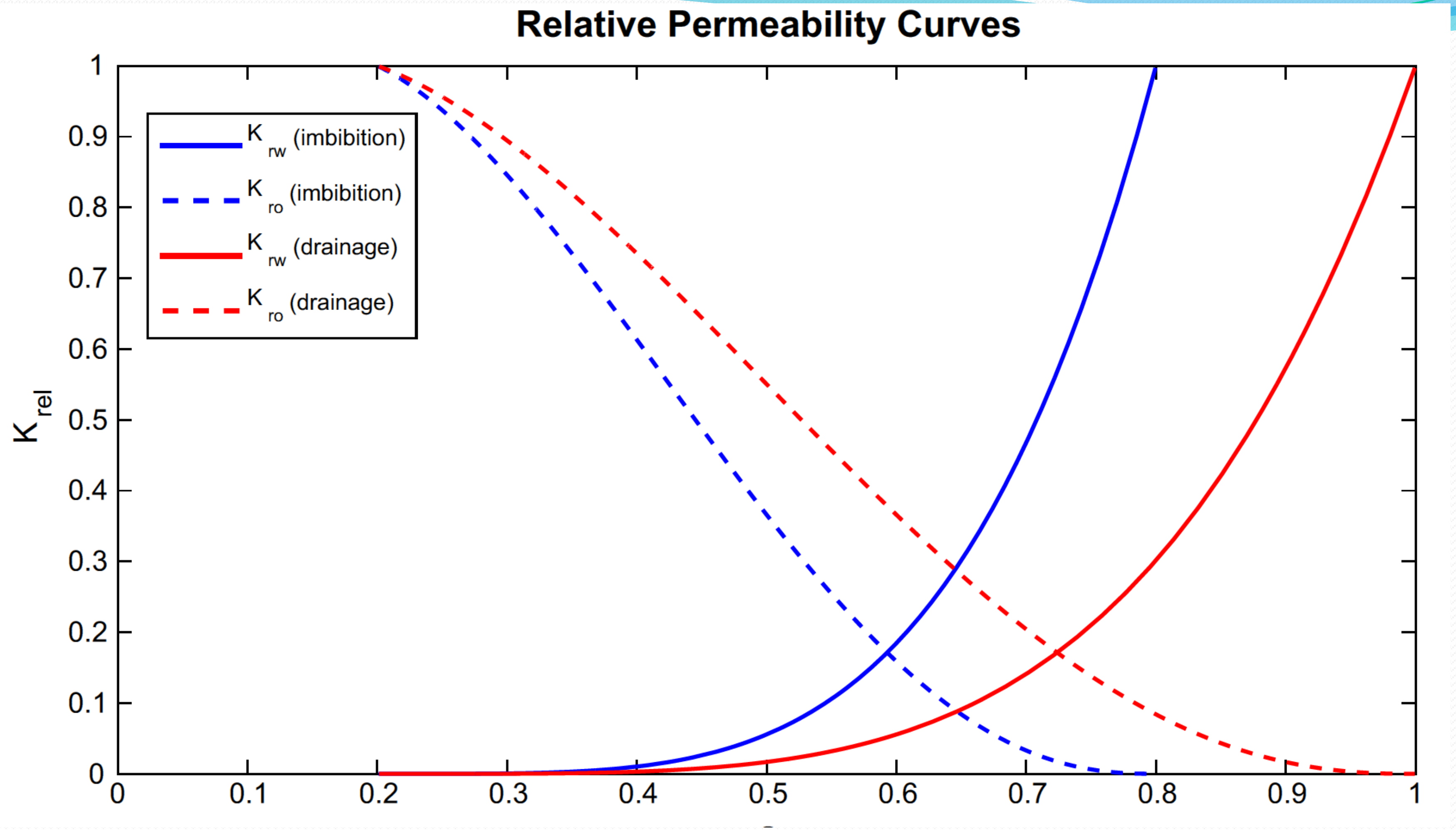
Water saturation

Water saturation depends on λ, which depends on the fractal dimension

$$\lambda = 3 - \mathfrak{D}$$



Relative permeabilities



Can be calculated with any of the 4 main models – here the Brooks-Corey-Mualem model

Generic modelling

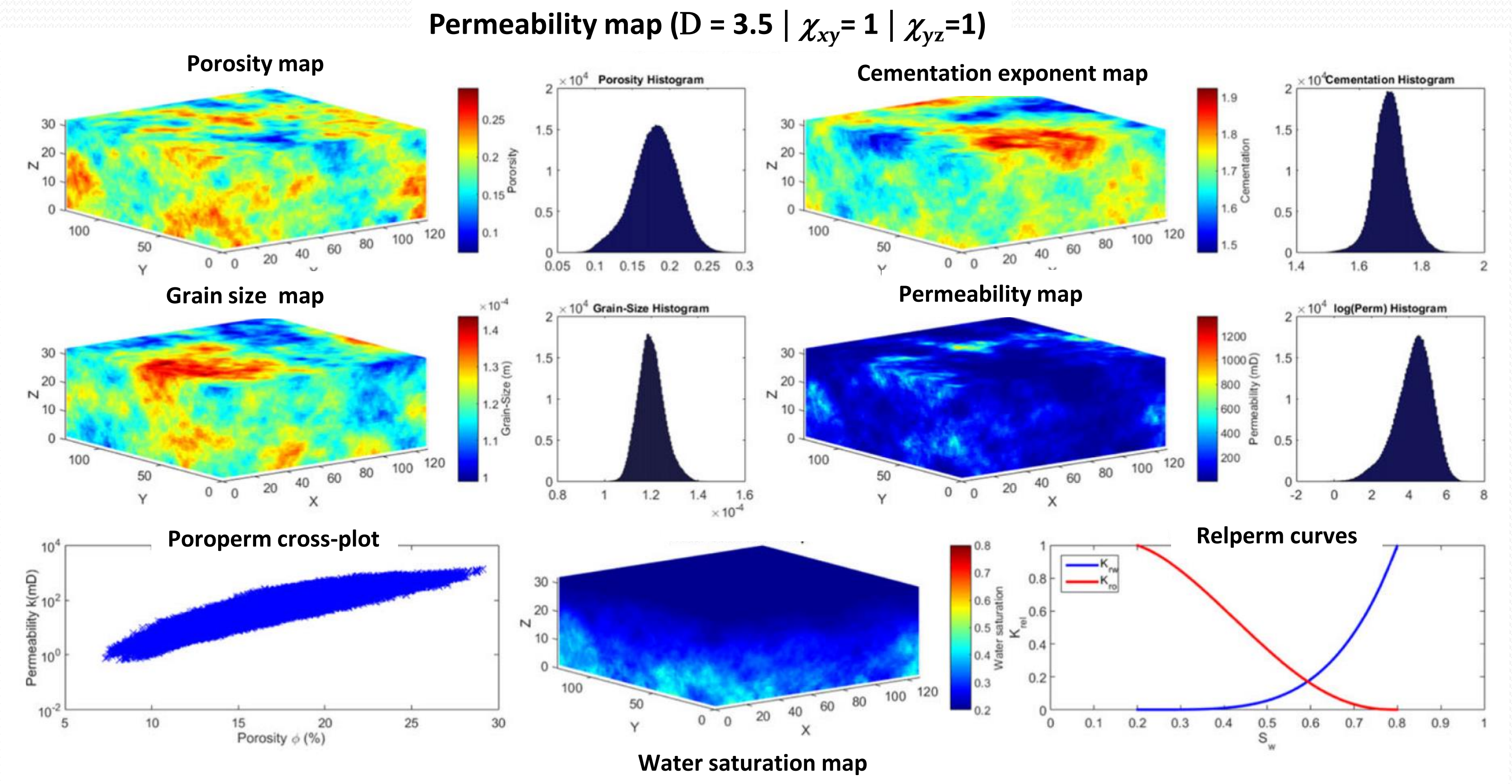
What is the effect of:

- Heterogeneity
- Anisotropy
- Well Placement
- Orientation

on reservoir production from a model reservoir?

Saud Al-Zainaldin, George Daniel, Saddam Sinan, Piroska Lorinczi

A Typical Finished AFRM



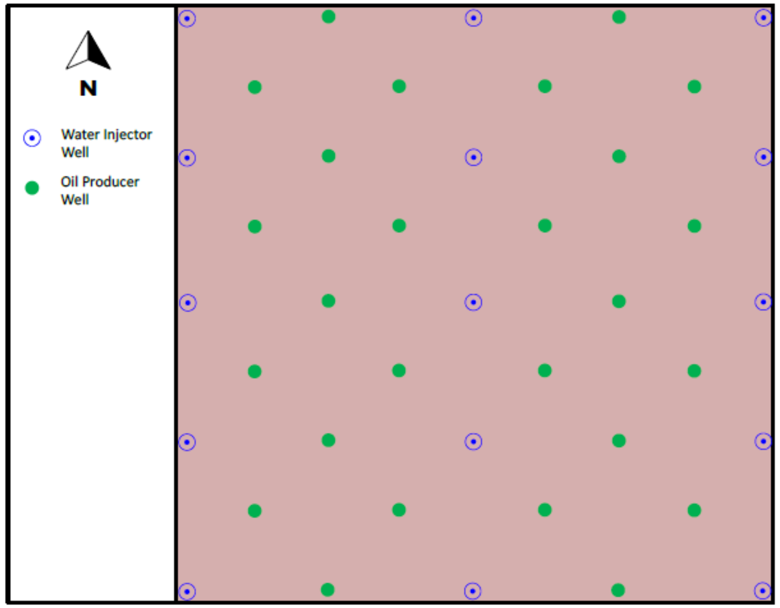
Water saturation map

All the input parameters needed for full simulation.

Fully specified, unique structure, repeatable model. Not stochastic.

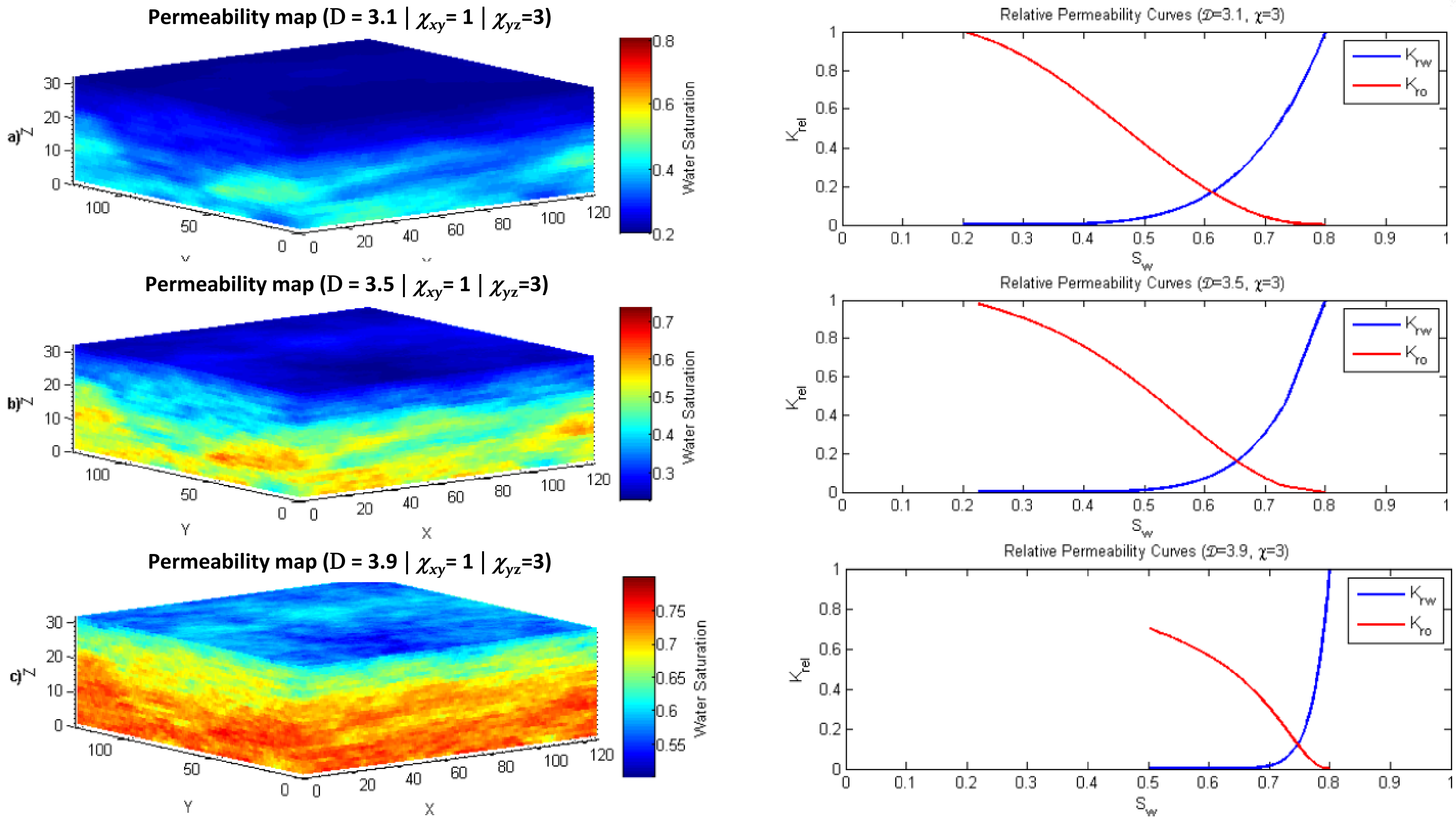
Simulation for testing the effect of heterogeneity and anisotropy

- **Finite-difference Roxar Tempest® Black-Oil simulator (ver. 7.0.4)**
- **Anisotropy causes striping in the *x*-lateral direction**



Parameter	Value
Number of grid blocks	128 × 128 × 32; 524288 voxels
Reservoir dimensional extent	12.8 km laterally and 96 m vertically
Depth of top reservoir	2000 ft
Layers thickness	3 m
Oil-water contact depth	2096 ft

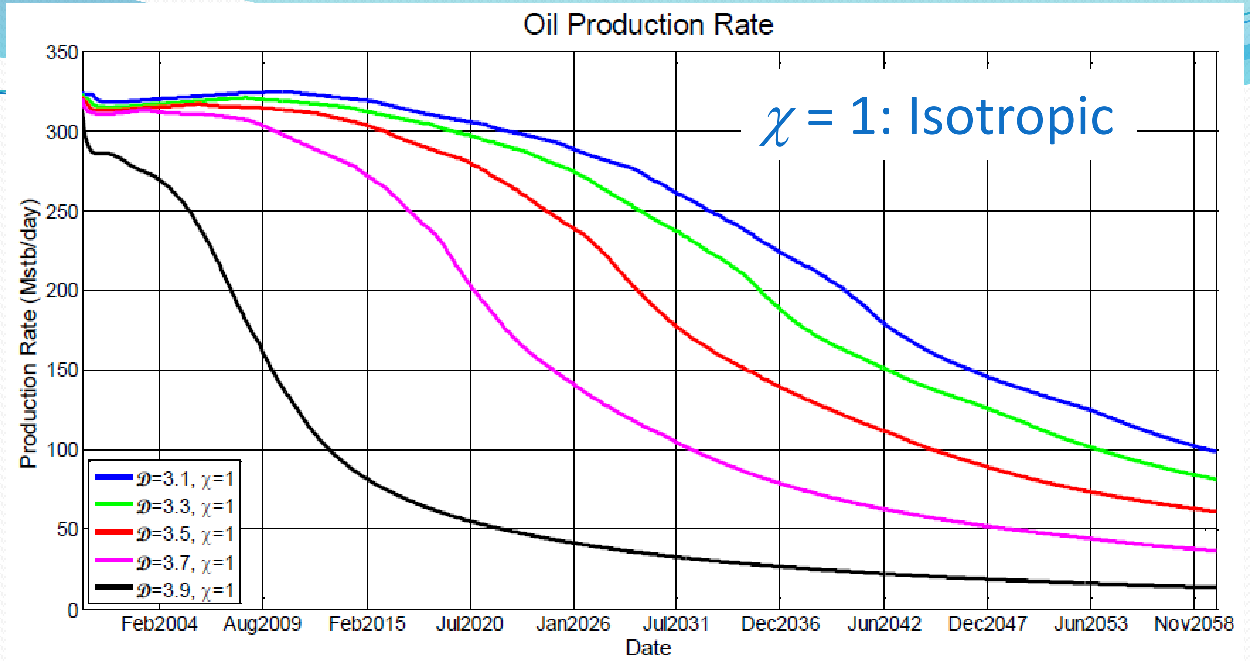
Fractal capillary pressure and water saturations

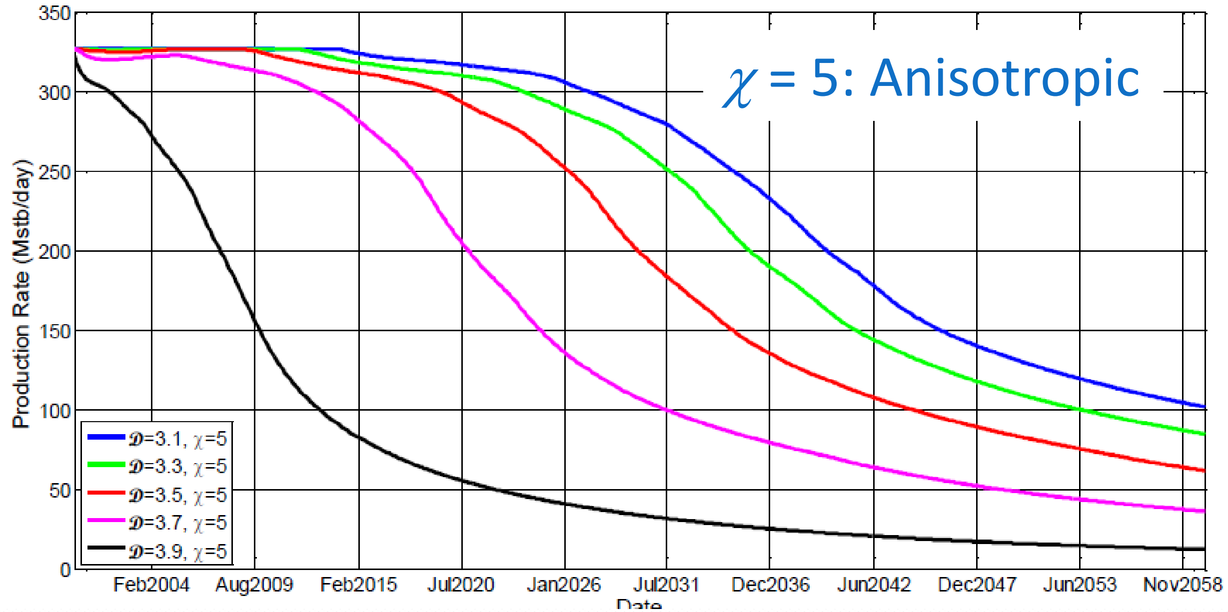


Effect of changing heterogeneity: Oil Production Rates

Homogeneous reservoirs (low $\mathcal{D}$) produce at a **higher rate** for **longer** than heterogeneous reservoirs (higher $\mathcal{D}$)

Greater anisotropy χ reduces production rate slightly at each time point

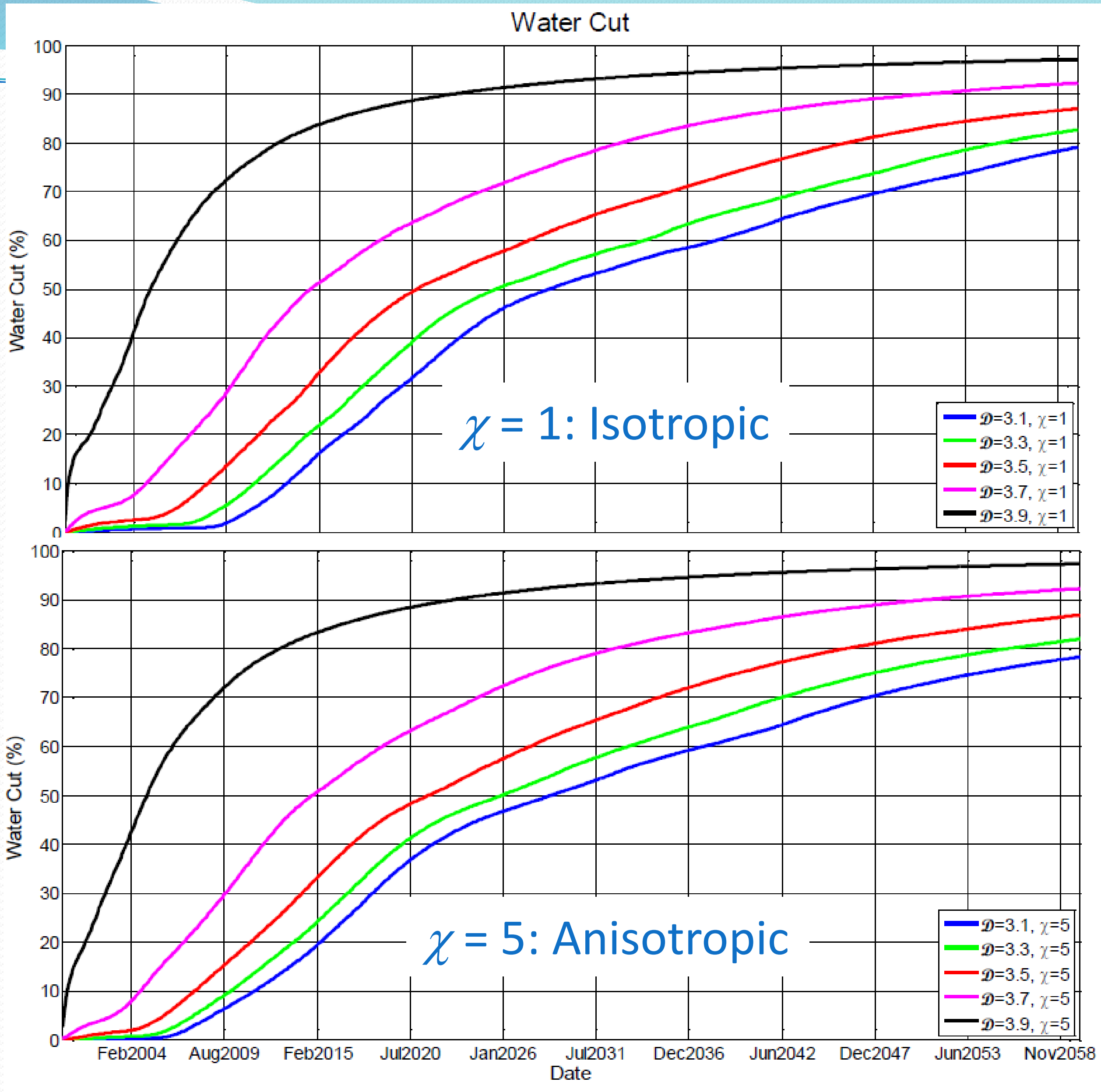




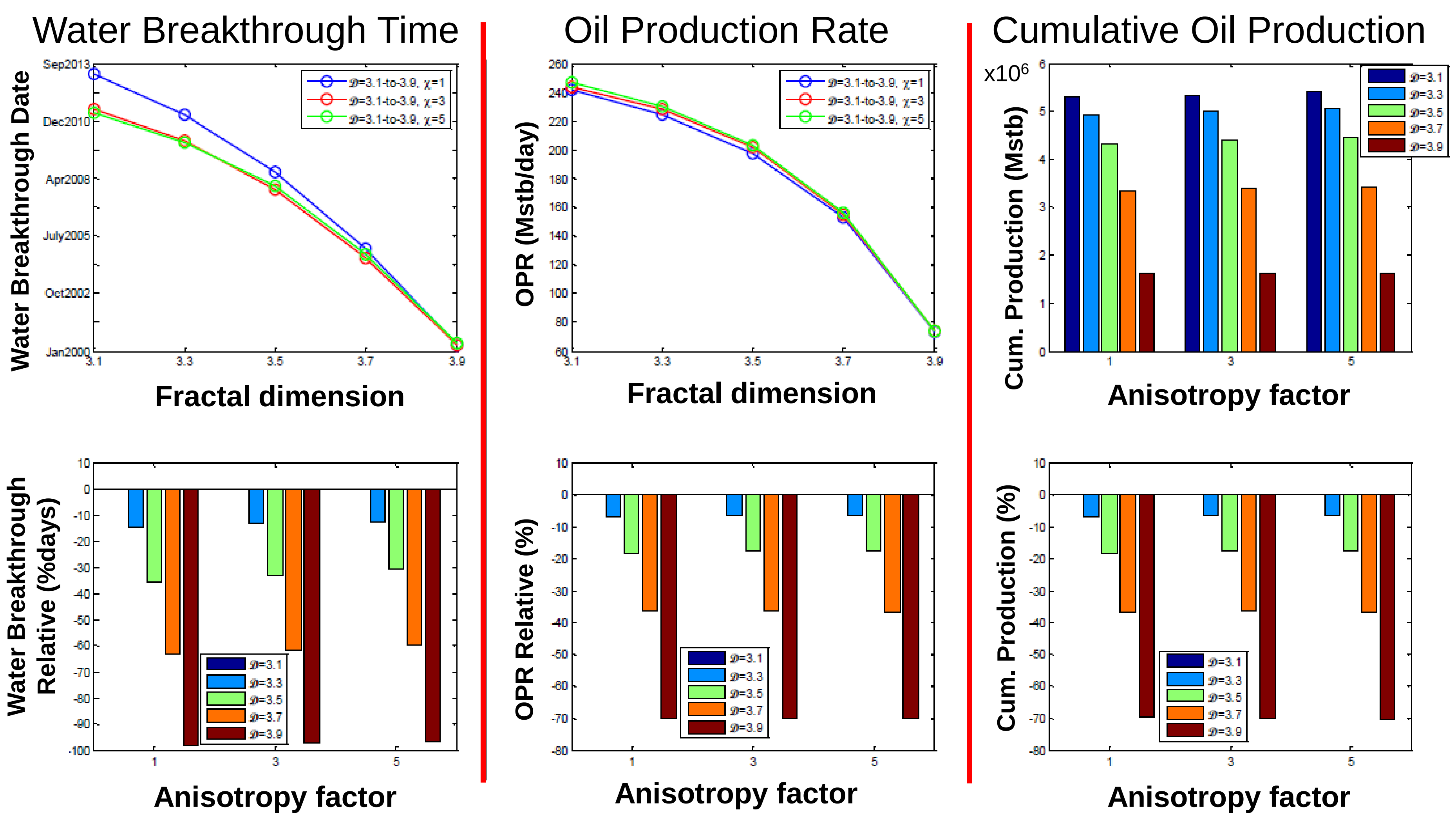
Effect of changing heterogeneity: Water cut

Homogeneous reservoirs (low $\mathcal{D}$) keep the water cut **lower** for **longer** than heterogeneous reservoirs (higher $\mathcal{D}$).

Greater anisotropy χ leads to earlier water breakthrough



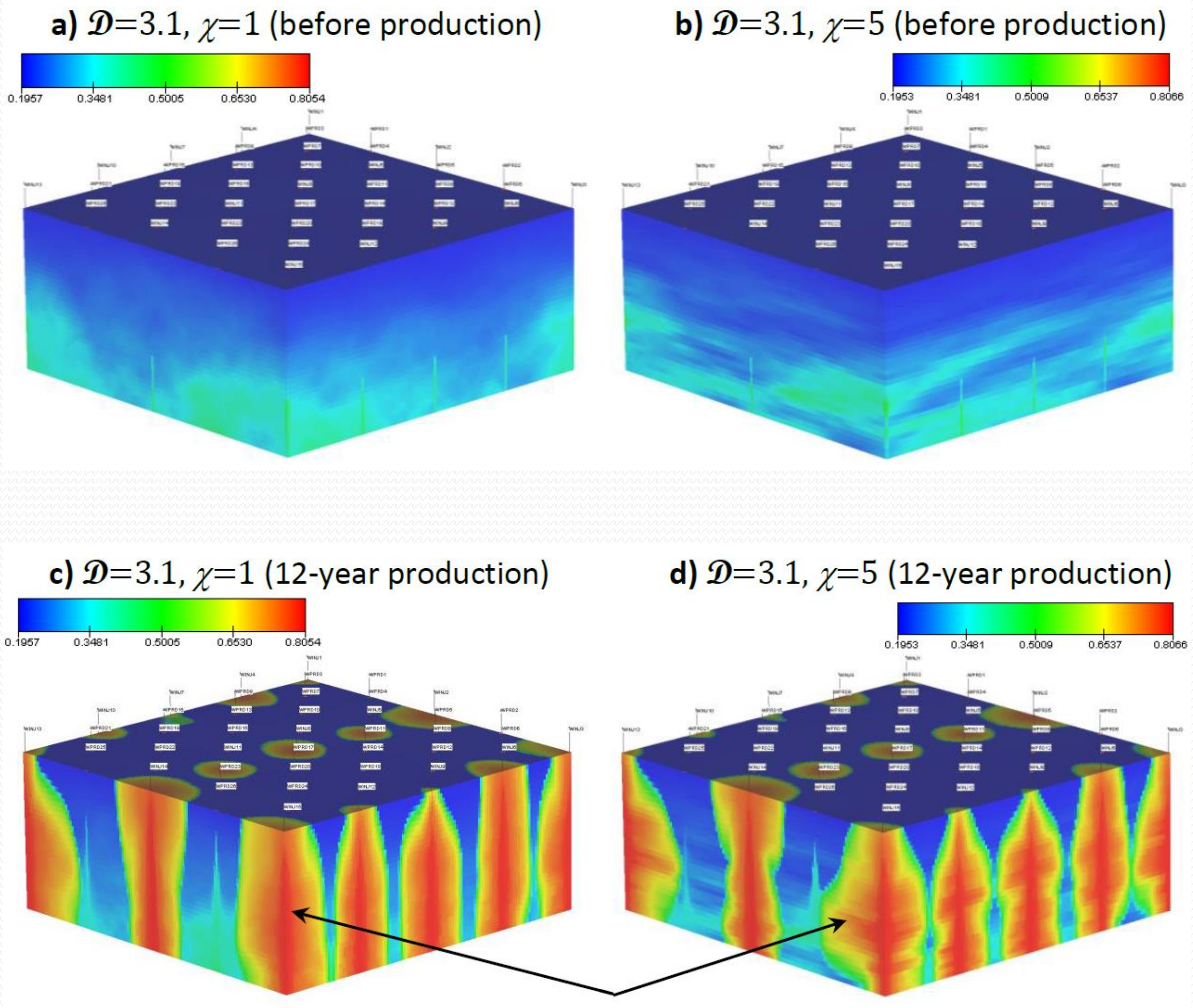
Effect of changing heterogeneity & anisotropy



Effect of anisotropy: Production

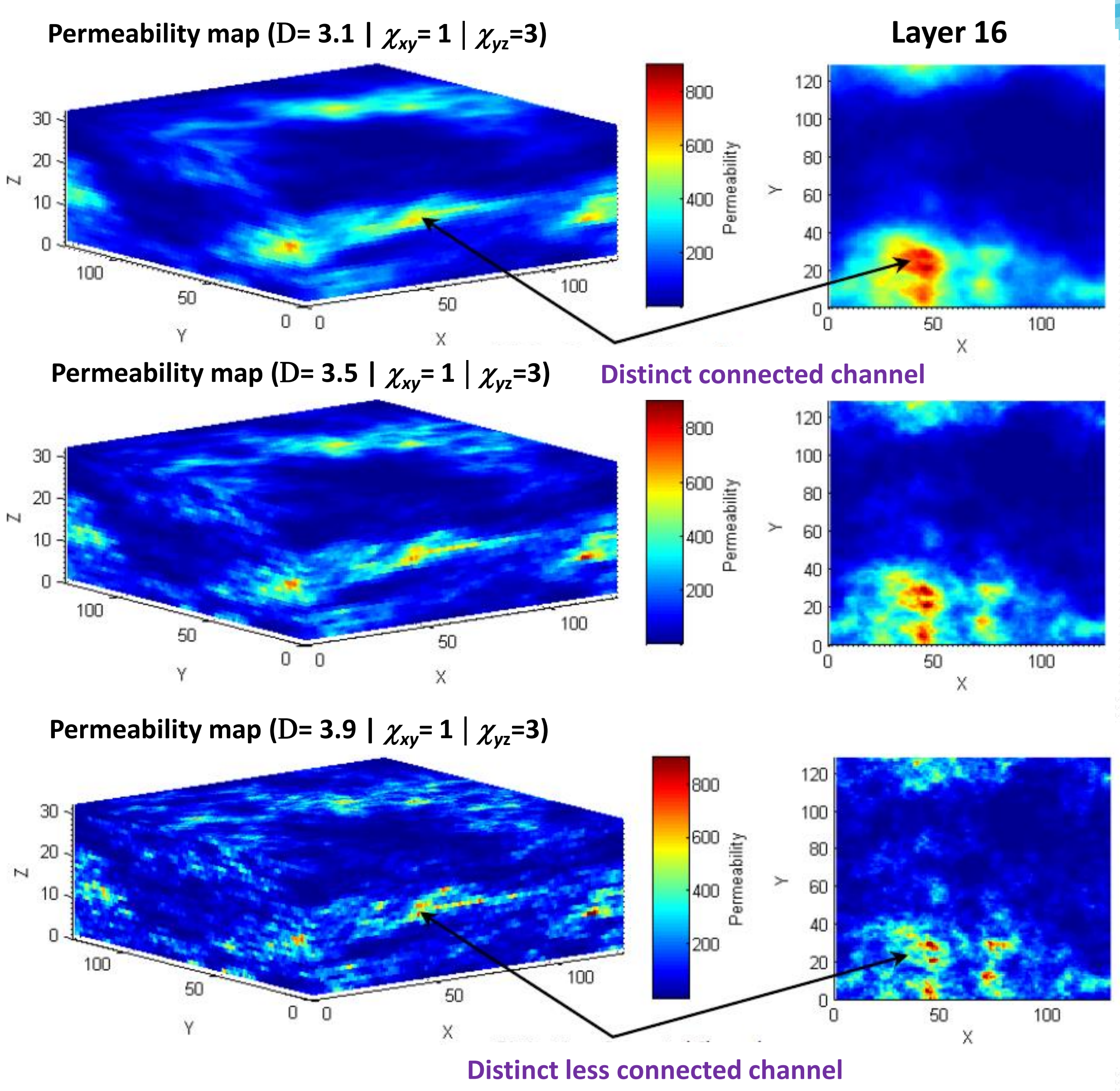
Water saturation maps

- Higher anisotropy
- Higher anisotropic flow
- Advance water break-through
- Slightly increased residual oil
- No change in production rates



Effect of heterogeneity: Production

- Higher heterogeneity
- Higher fractal dimension
- Less spatial correlation
- Less distinct channels of high permeability
- Lower production rates

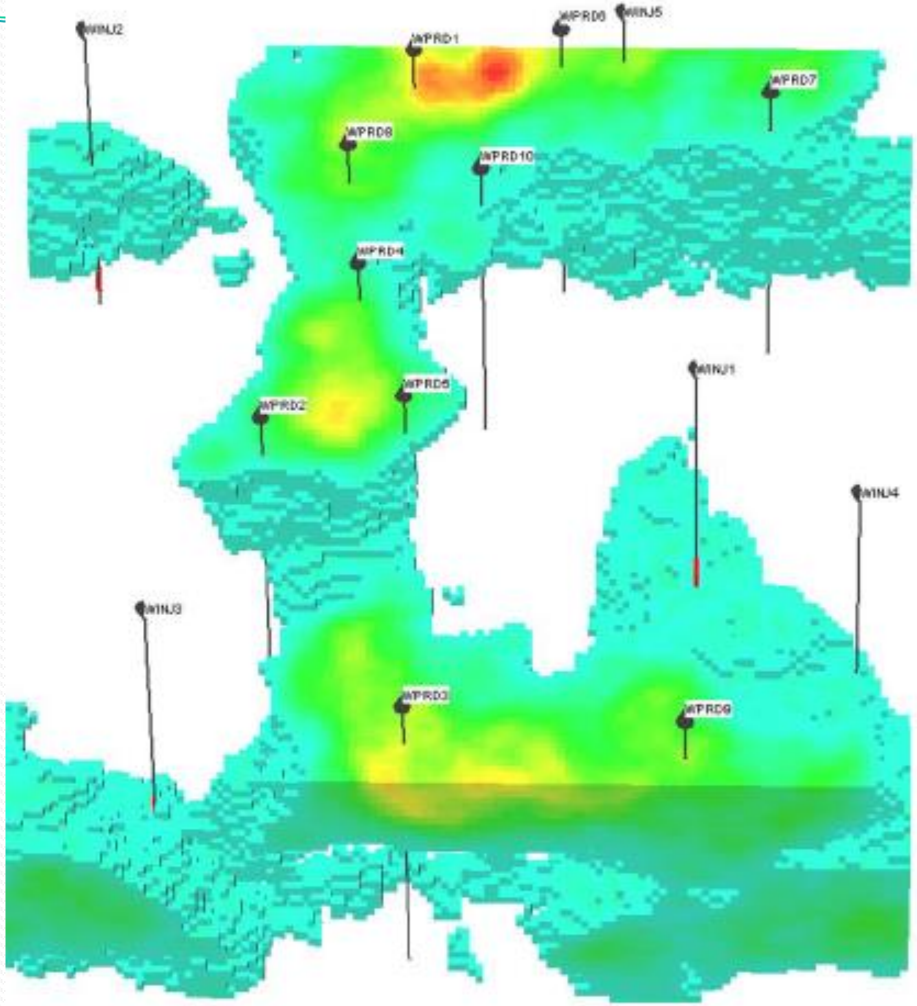


Well placement in isotropic reservoirs

Tests done for:

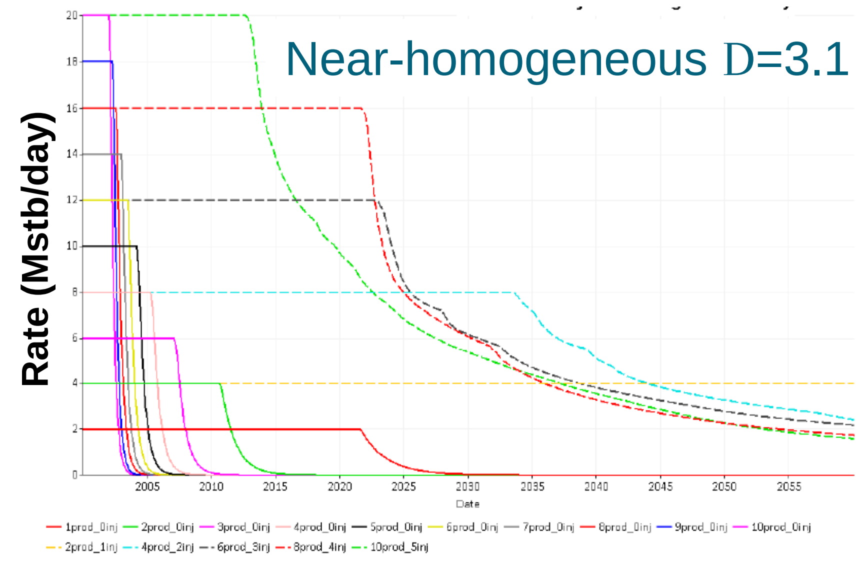
- 3 configurations of random well placement
- Combinations of Injectors *I* and/or producers *P* in low or high permeability zones
- 1 to 10 producers and 1 to 5 Injectors
- For conventional and tight reservoirs
- Fractal Dimensions 3.1, 3.5 and 3.9
- Oil production profile, Oil recovery factor, Water cut

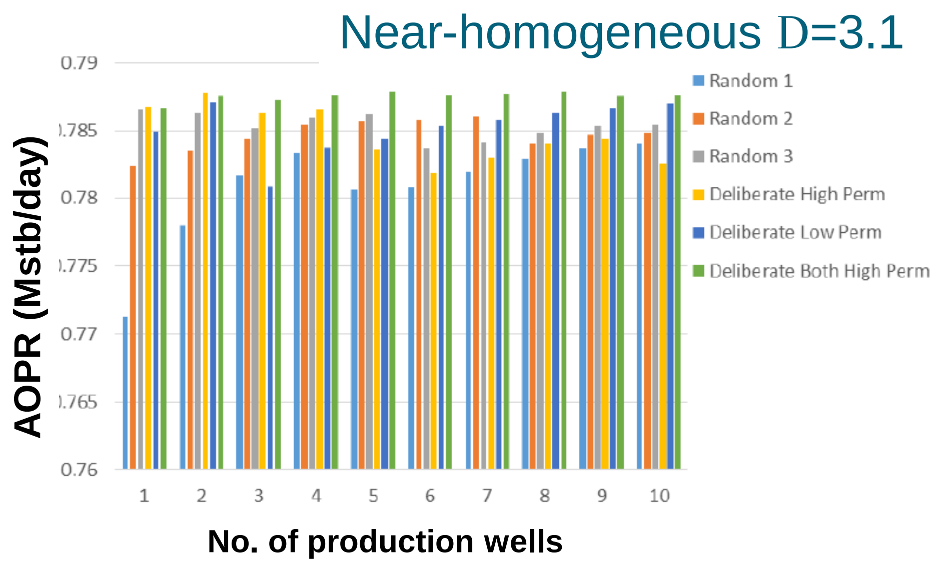
54 profiles, each with 15 curves

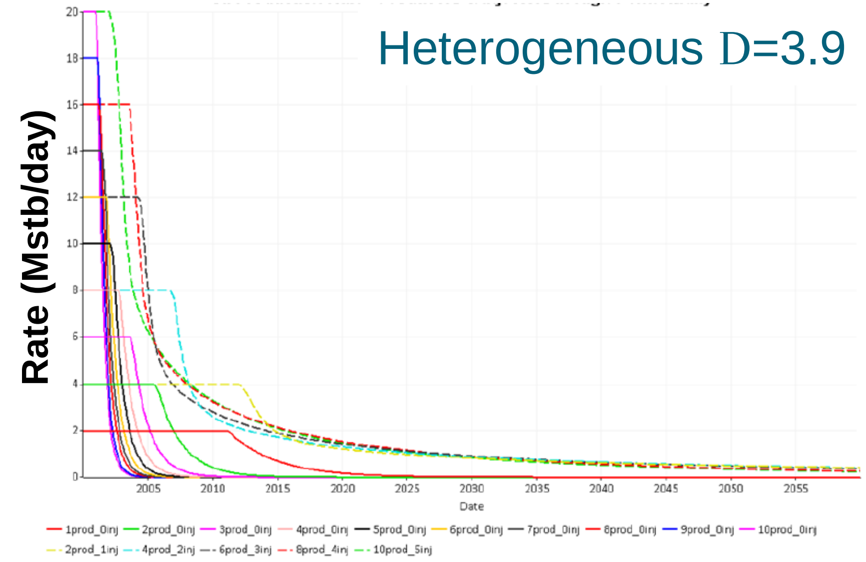


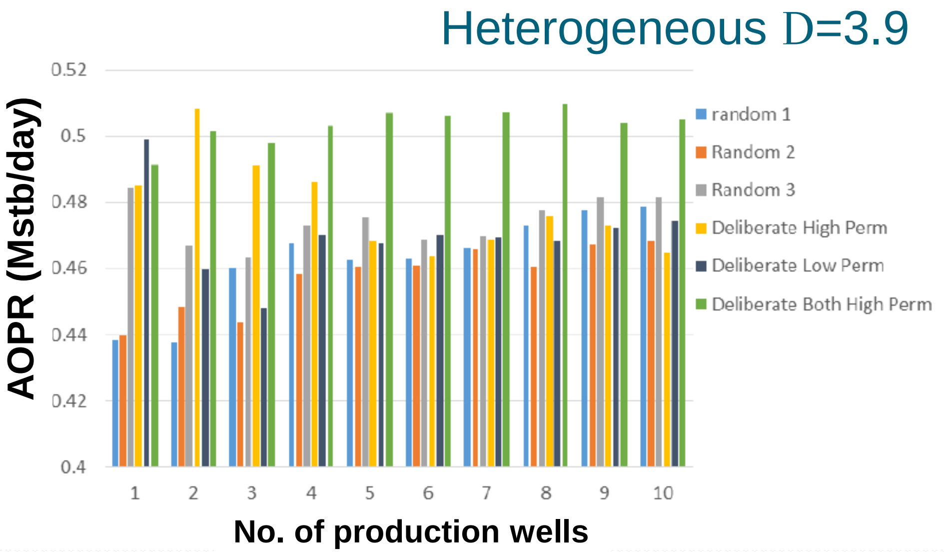
Well placements *I* and *P* in high permeability (k>120 mD cut-off)

Typical well placement results









Well placement conclusions

- Well numbers important but well placement not important for producer only scenarios (irrespective of reservoir type or fractal dimension)

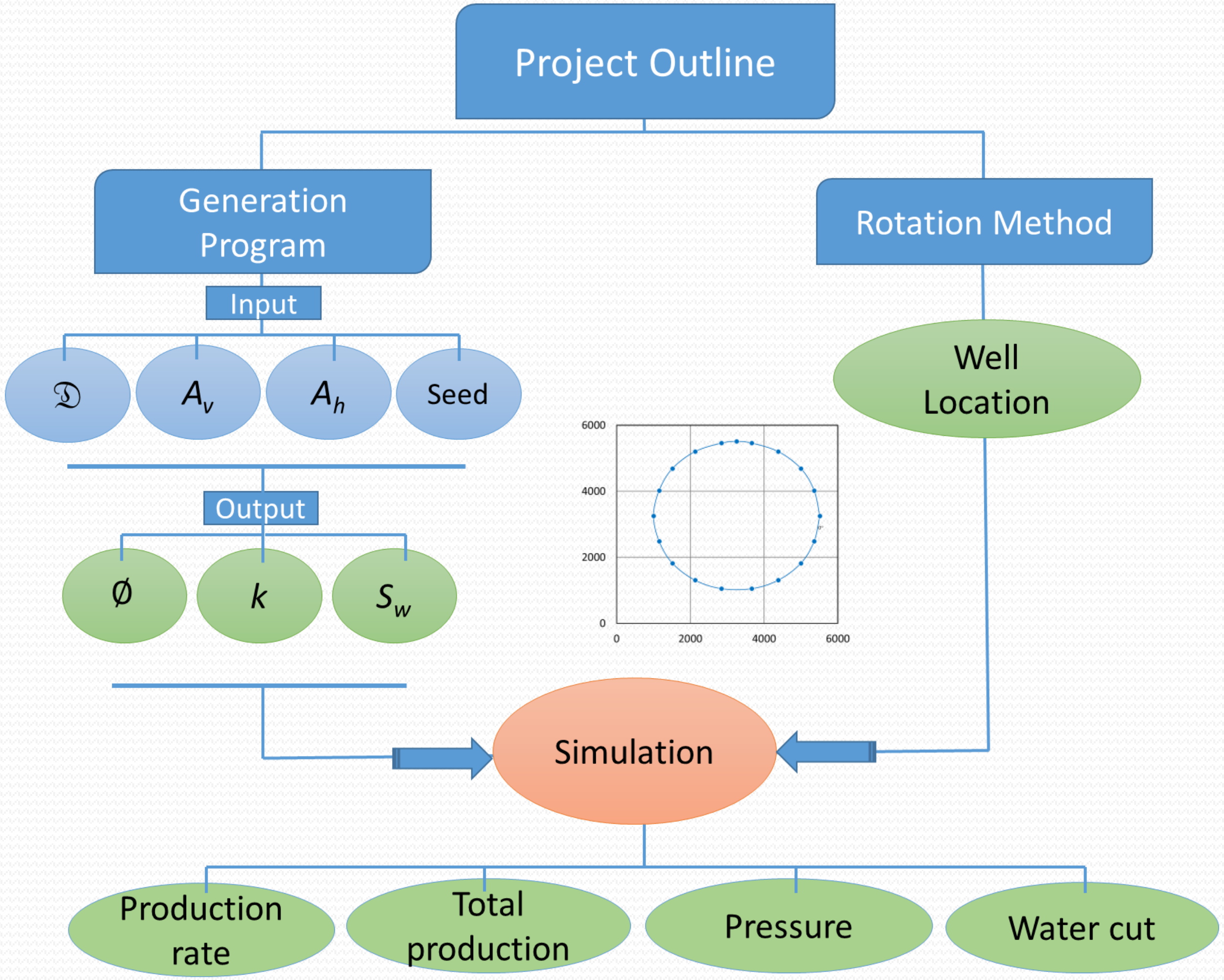
- AOPR increases significantly by adding injector wells (irrespective of reservoir type or fractal dimension)

- AOPR benefits from placing both producers and injectors in high permeability zones

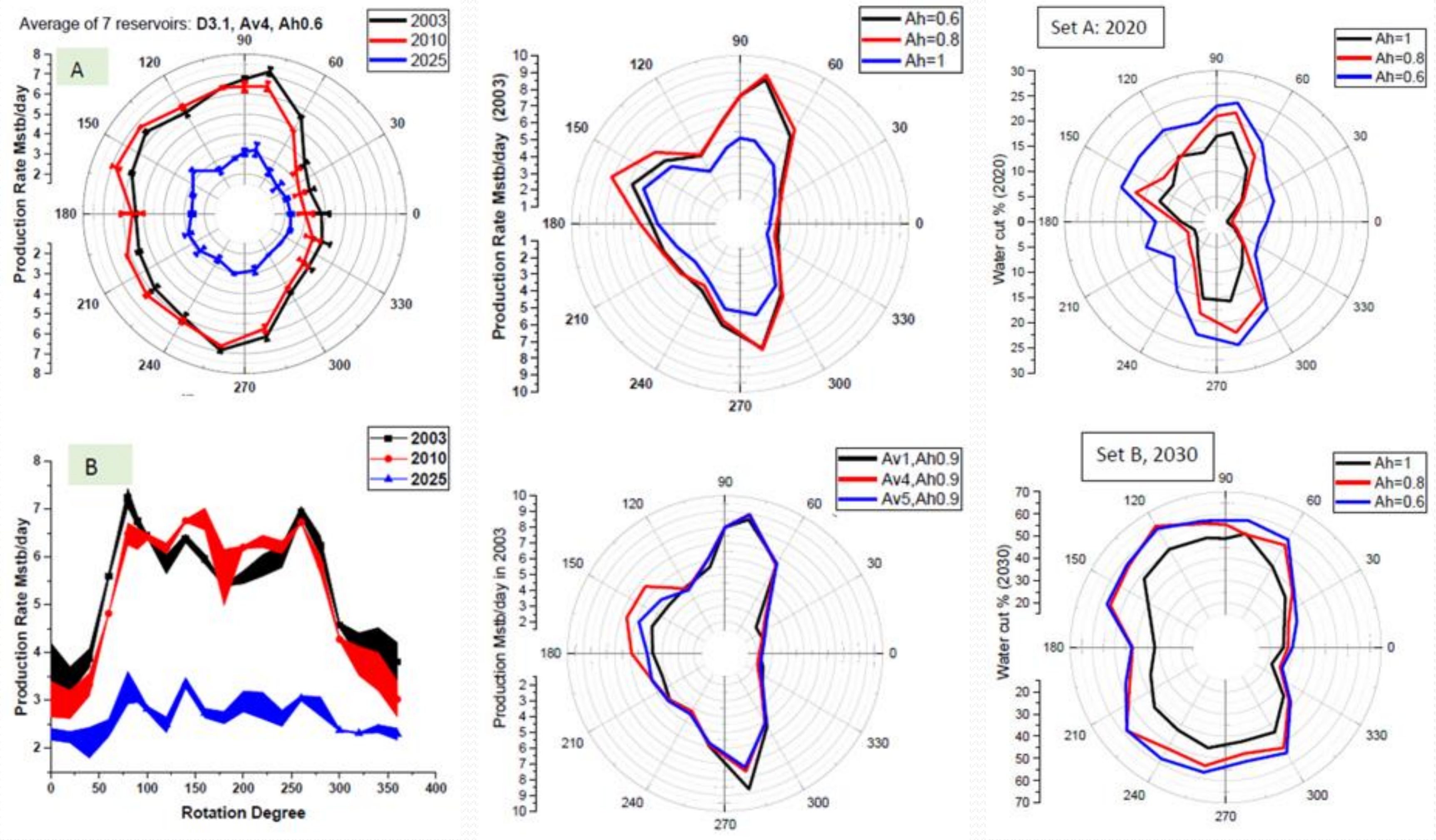
- Time to water break-through not consistently related to a particular well placement but is affected by heterogeneity

Well Orientation and Anisotropy

- **AFRMs created with different heterogeneities and anisotropies**
- Define simple injector-producer well pattern
- **Rotate well pattern with respect to AFRM**
- Simulate major reservoir production parameters at each orientation



Well orientation and anisotropy



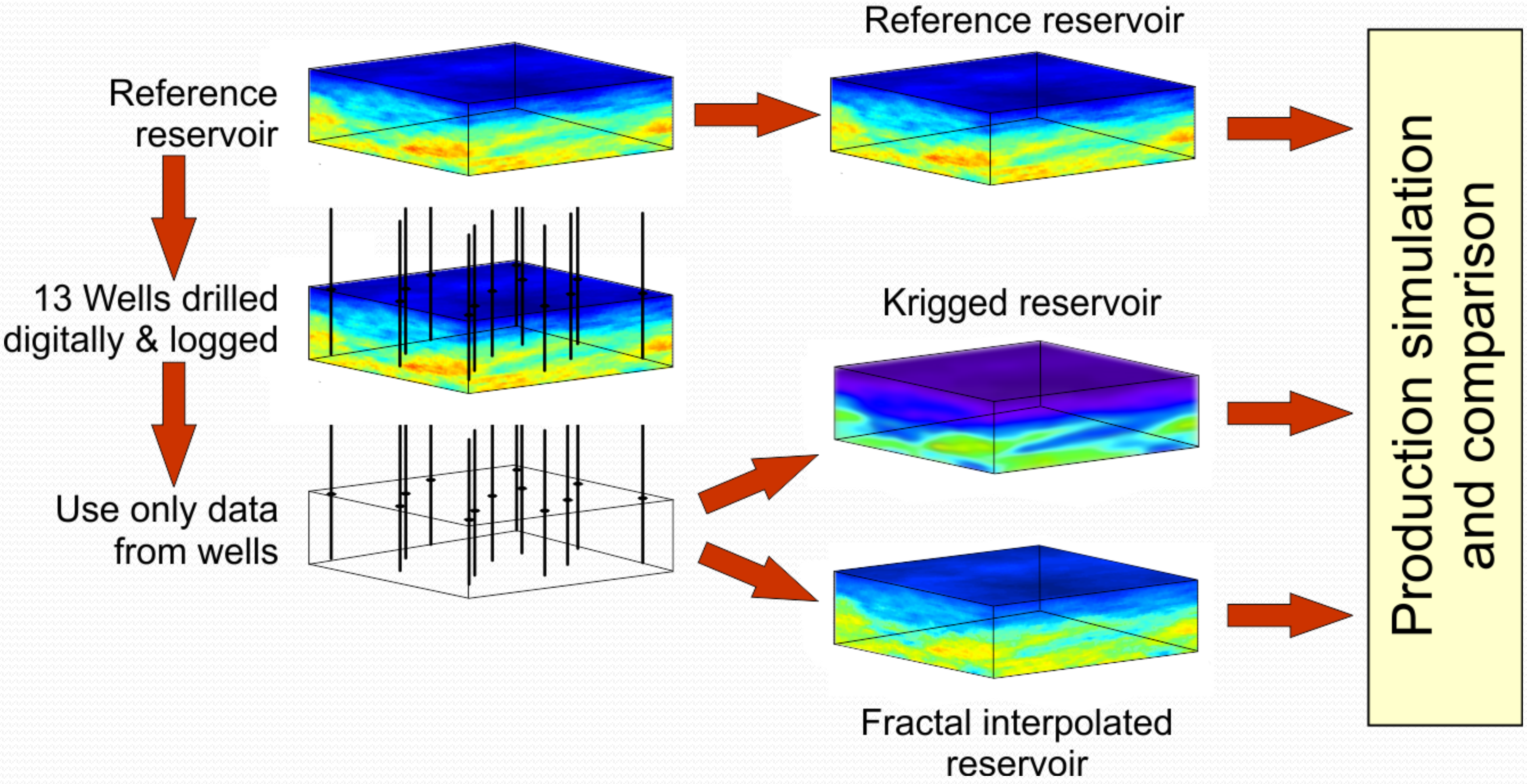
Production rate initially higher in anisotropic direction, becoming isotropic by late production

Conditioning to real reservoirs

How can AFRMs be used to represent real reservoirs?

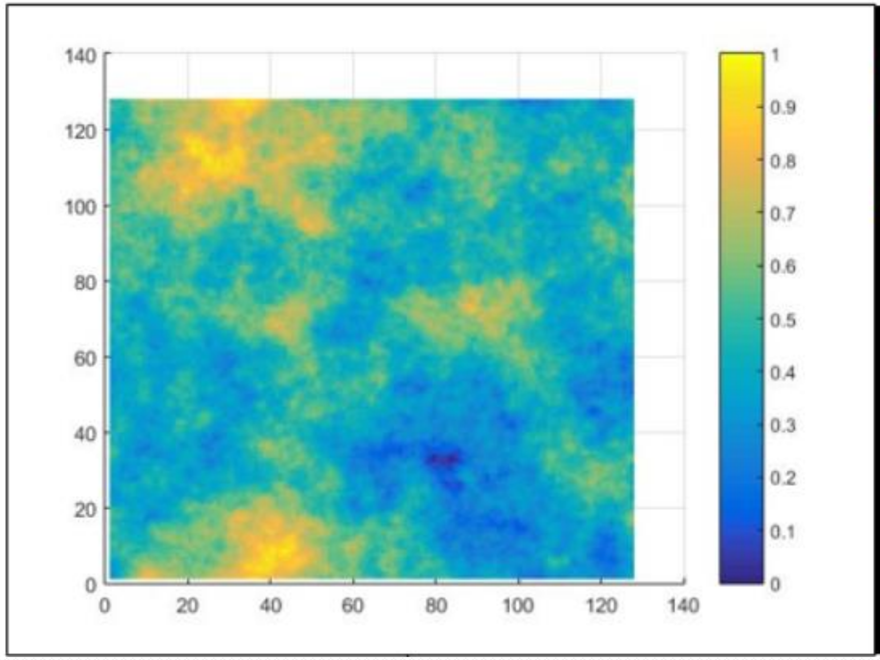
Hassan Al-Ramadhan, Piroska Lorinczi

Conditioning to real reservoirs

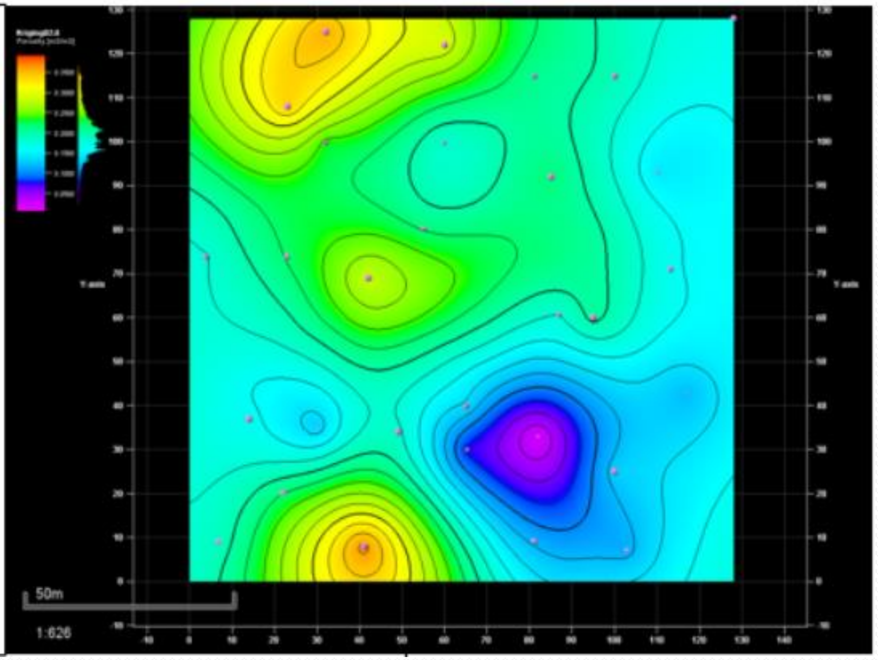


The fractal interpolation method allows data to be retained at all scales.

Fundamental differences



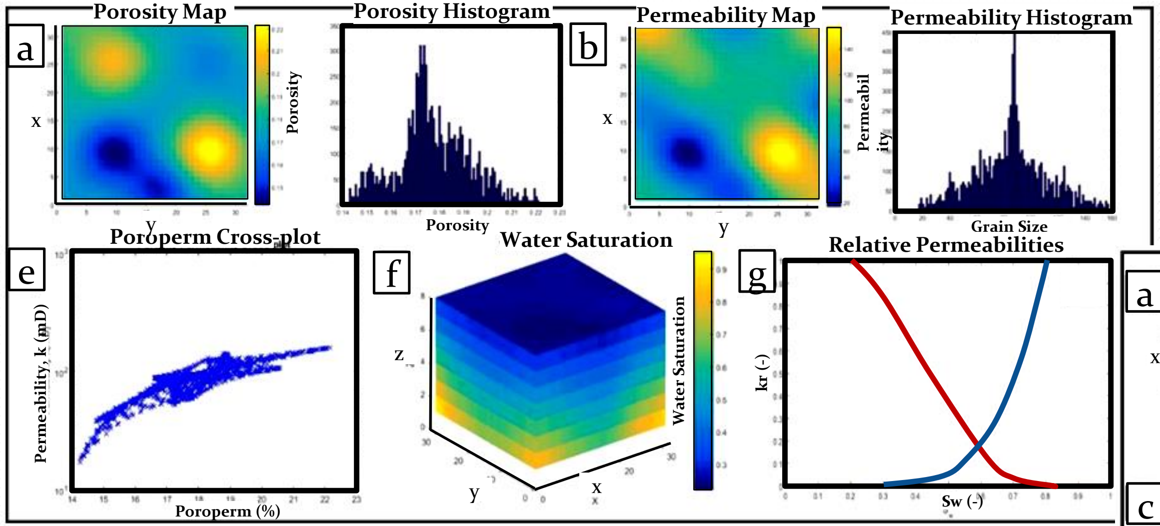
Fractal interpolation



Krigged interpolation

The fractal interpolation is not identical to the gold standard reference
But it contains information over the whole range of frequencies, whereas the conventional interpolation contains only long wavelength information.

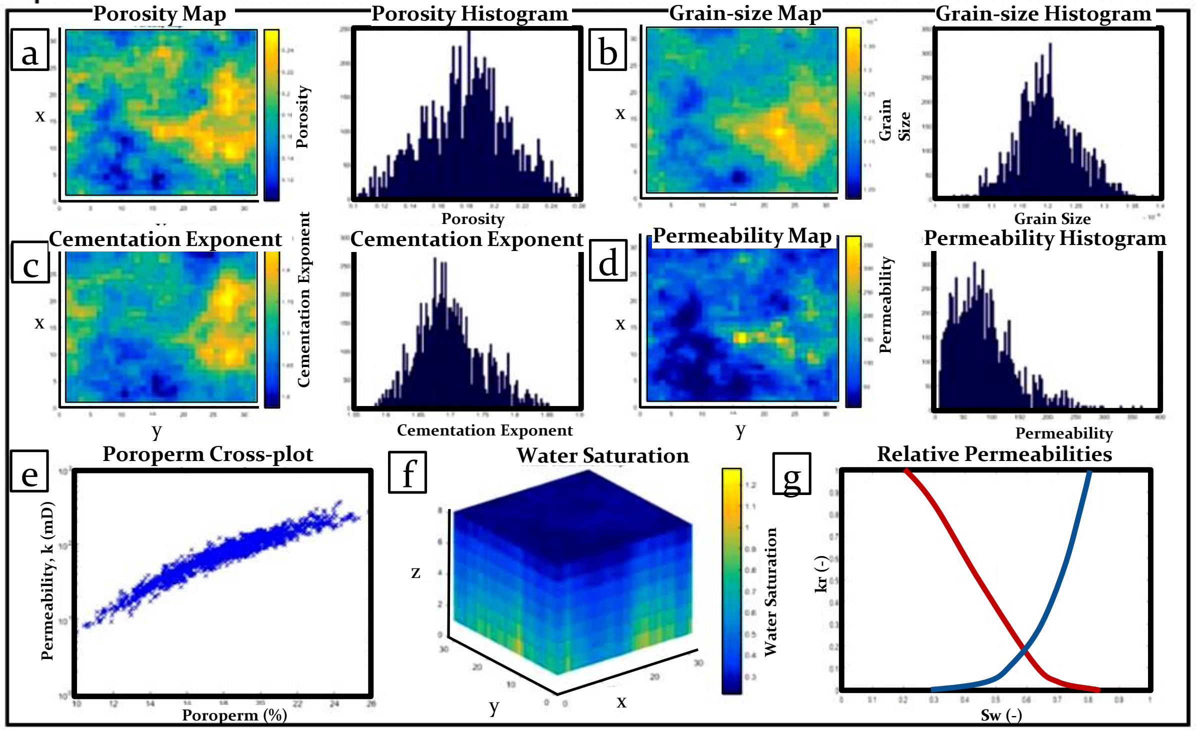
Fractal interpolation and scale conservation



Conventional interpolation Emphasises highs and lows with information lost in the mid-range.

- High frequency information lost.

D = 2.6



Fractal interpolation Depth of information in the mid-range retained but not at the expense of the highs and lows.

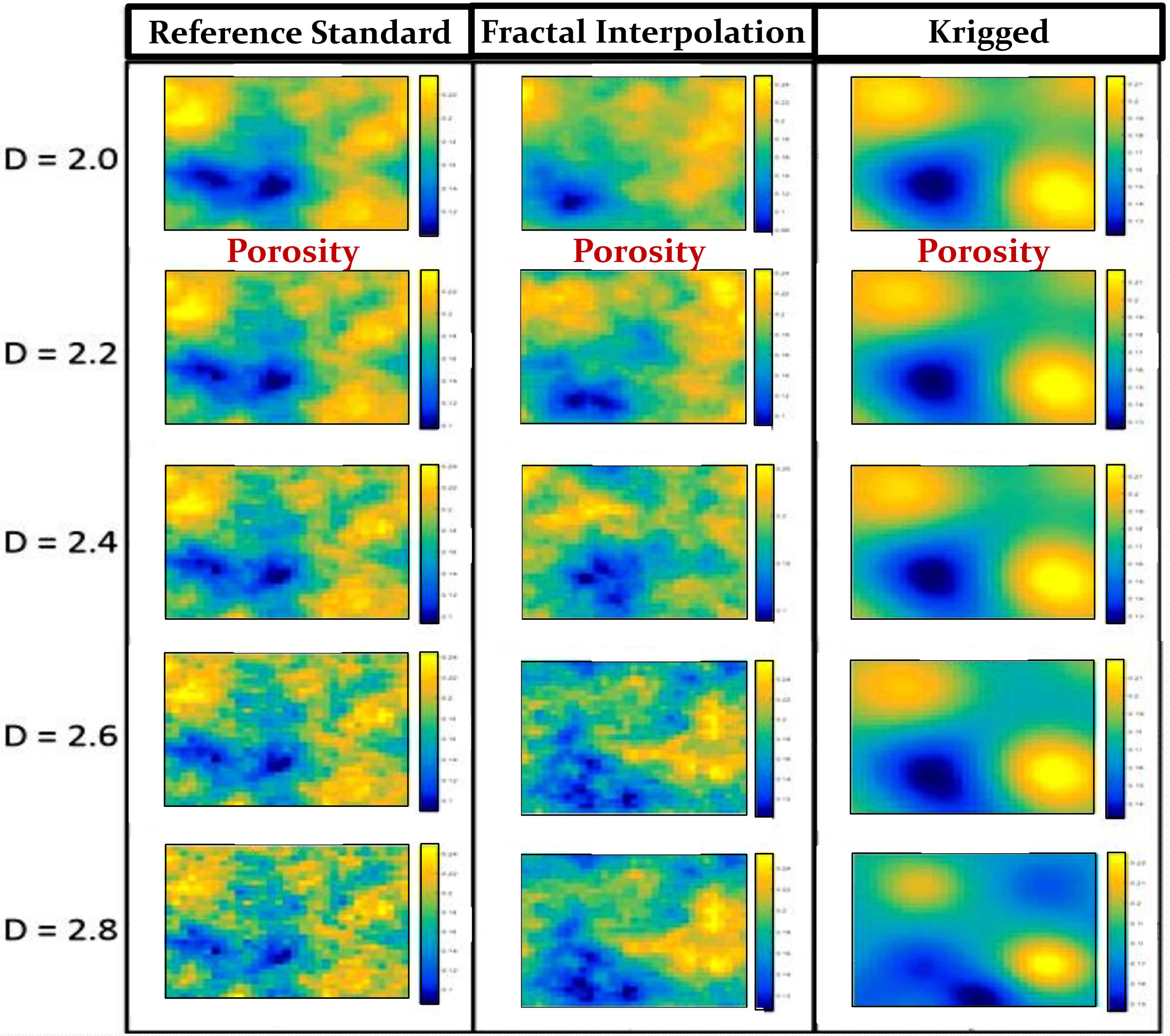
- Contains information at all frequencies.
- Poroperms are more realistic.

Fractal Interpolation

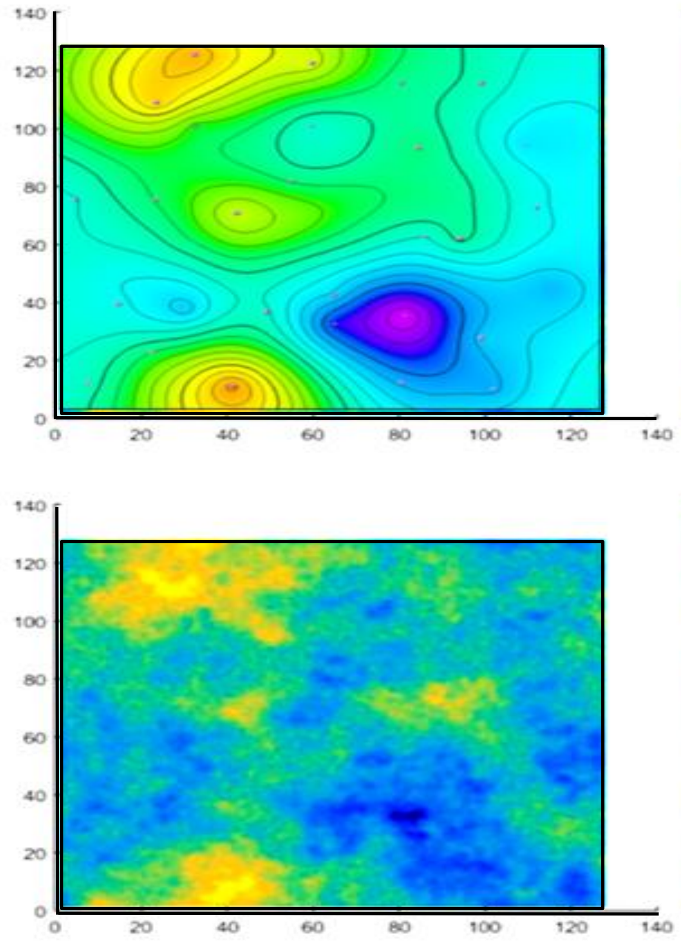
The FRACTAL INTERPOLATION mimics the reference model very well. It contains information over all wavelength scales.

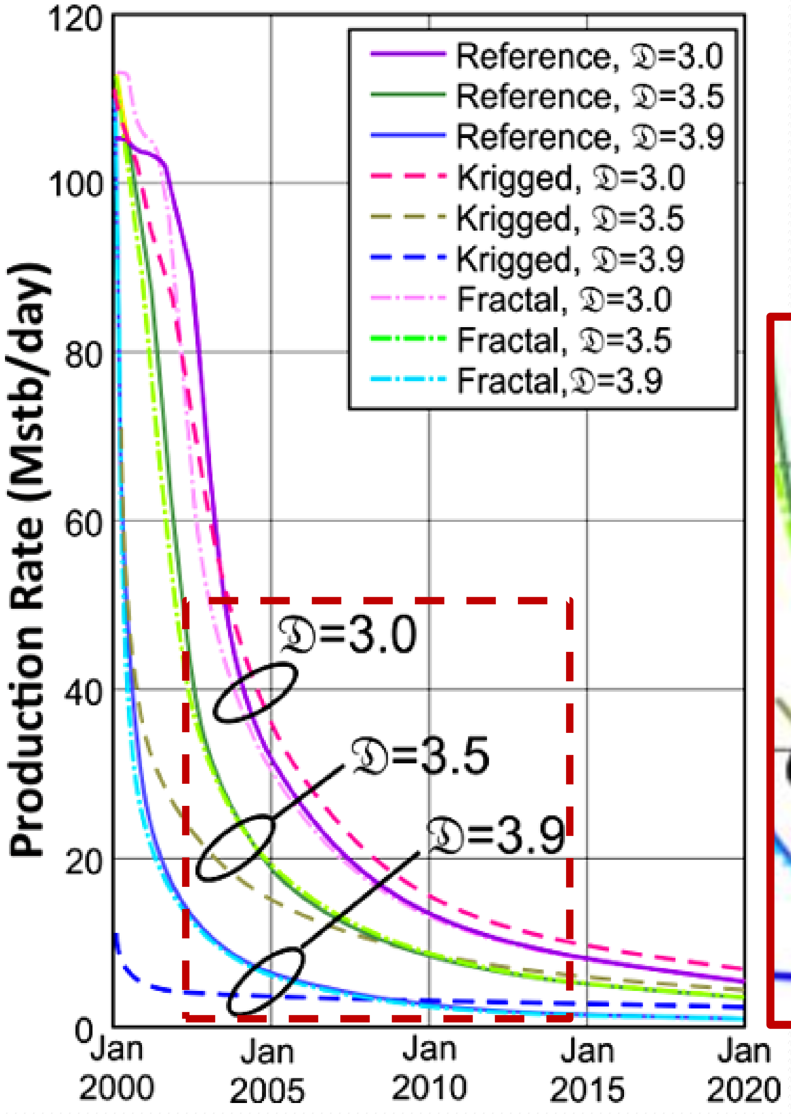
The conventional KRIGGED INTERPOLATION contains only long wavelength information

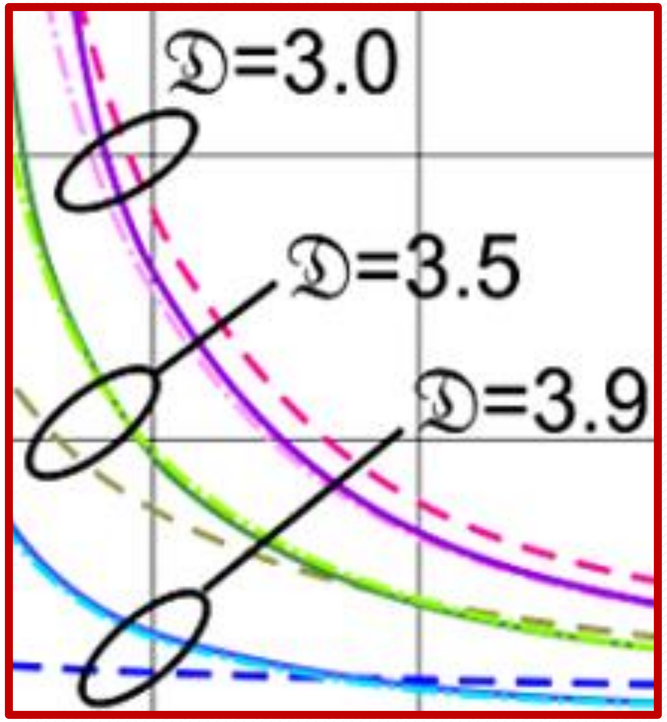
Consequently, production data is simulated from a fractal model of the reservoir



Fractal interpolation versus krigging



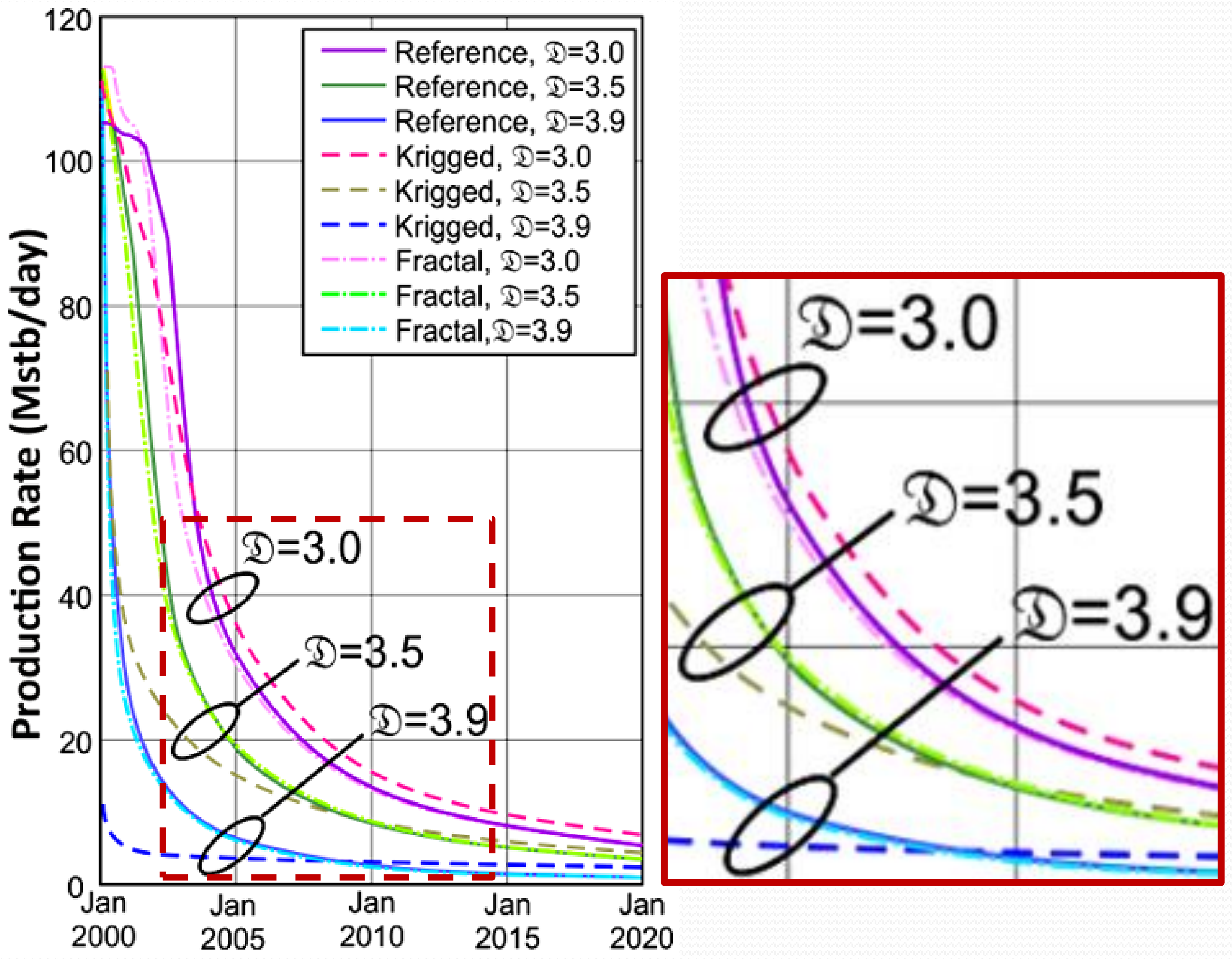




Fractal interpolation versus kriging

Homogeneous Reservoir (D=3.0) – Both krigged and fractal interpolations match the reference well.

Heterogeneous Reservoirs (*D*=3.5 and 3.9) – Krigged interpolations badly underestimate production rates, while fractal interpolation matches the gold standard reference well.



The Future

…Putting it all together.

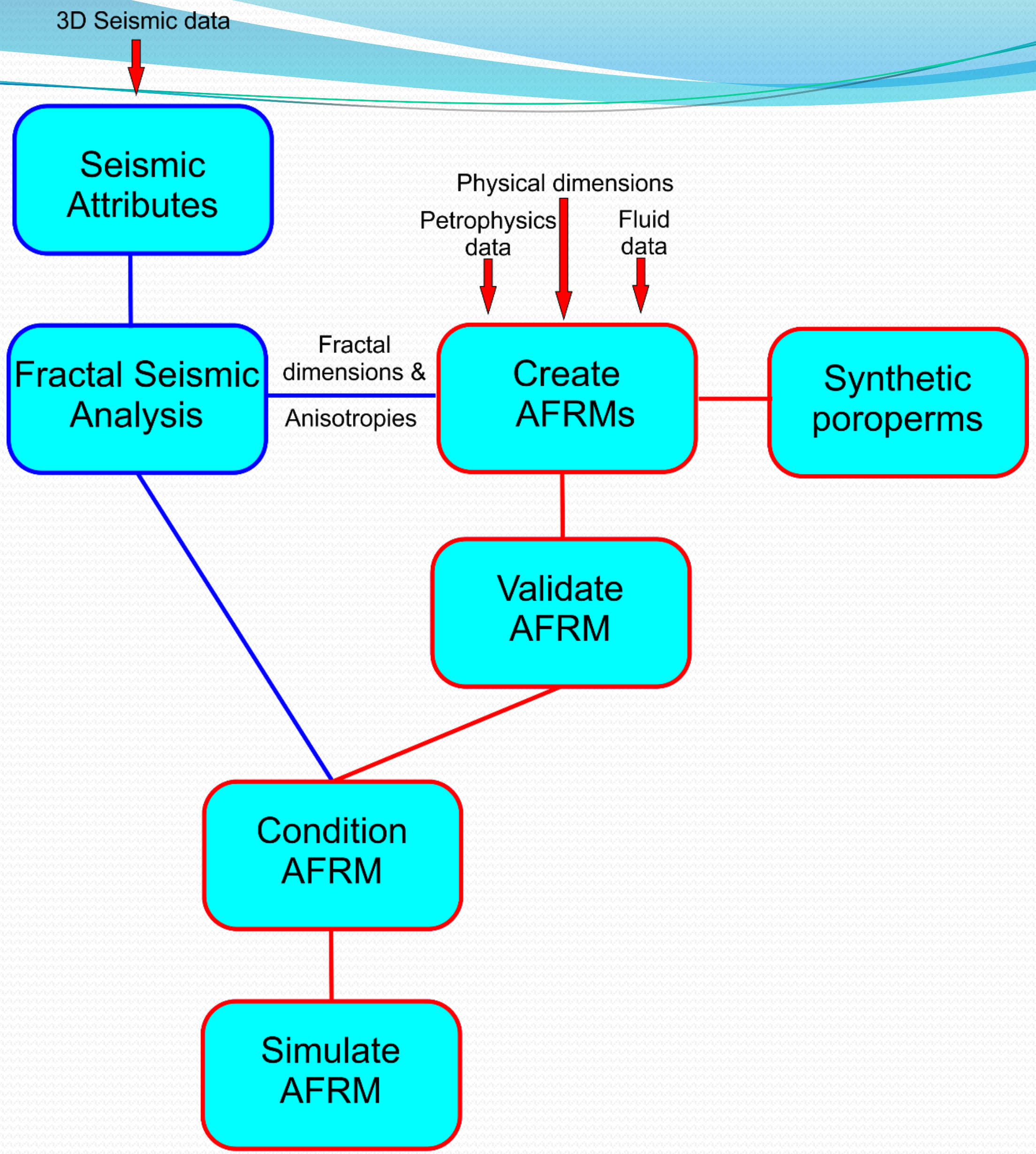
The AFRM advantage

- AFRMs can depict and control heterogeneity
- AFRMs can depict and control *xy*, *yz* and *zx* anisotropy
- AFRM accuracy can be verified
- AFRM allows generic sensitivity tests for heterogeneity, anisotropy, well placement and orientation
- AFRM is more accurate than conventional models in simulations
- AFRM contains information at all scales larger than cell size
- **AFRMs can be fully reservoir-conditioned**

The Future

To do:

- Create methods for deriving fractal dimensions and anisotropies from seismic attribute data
- Synthesise all methodologies and code into a professional UOI
- Run a number of case study scenarios in clastic, carbonate and unconventional reservoirs



Final Message

AFRMs are a powerful new approach to creating realistic 3D geological models of reservoirs for simulation…

…giving insight into how heterogeneity and anisotropy affect reservoir production at all scales and capable of being conditioned to represent real reservoirs.

Leeds University Petrophysics