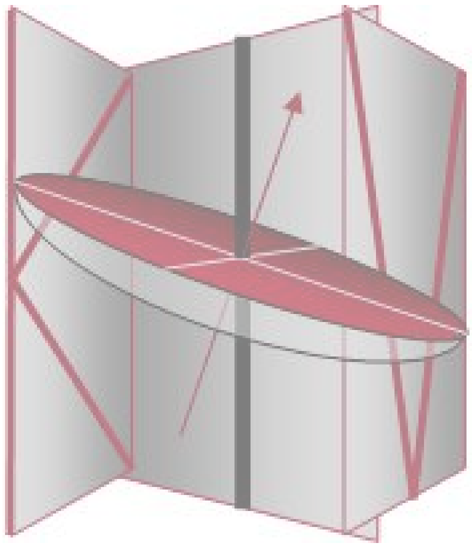
Calibration of NFR models with interpreted well-test k.h data



Michel Garcia

KIDOVA

Calibration with interpreted well-test k.h data

Intermediate step between

- Reservoir characterization
  - **Static model** conditioned by structural, core and fracture data
- History matching
  - **Dynamic model** conditioned by production data

Focusing on equivalent permeabilities

- Locally measured permeabilities of the fracture system

Step specific to NFR models

- Permeability fields **not directly modeled** but derived (calculated) from
  - Fracture densities
  - Fracture geometric and flow properties

Aim of the calibration

Relating

– NFR model parameters defined on a fracture-set basis

- Frature densities
- Geometric properties: orientation, length, height
- Flow properties: conductivity

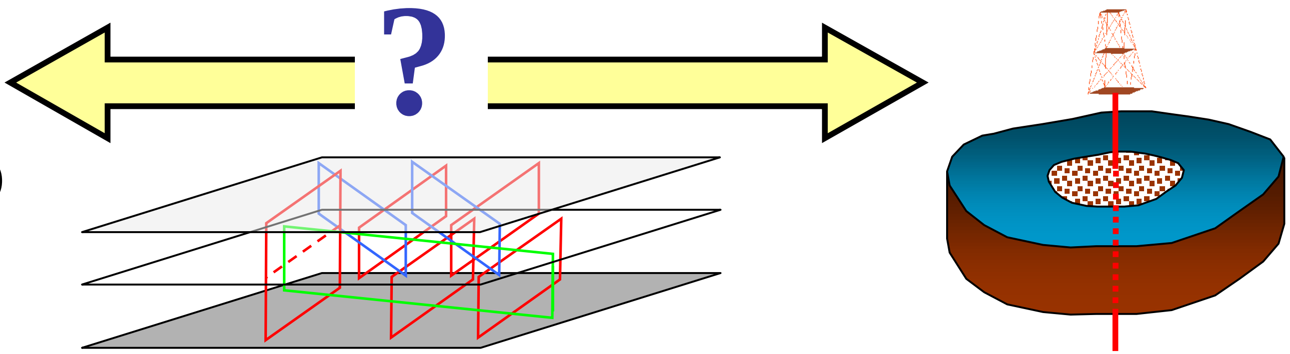
To

– Locally measured permeabilities of the fracture system

- Interpreted well-test k.h

One Fracture-set **Fracture system = all fracture-sets** **Interpreted well-test k.h**

FD = density (m^{-1})
L = length (m)
H = fracture height (m)
ke = conductivity (md.m)
n = orientation
...



Choice of a conceptual fracture system model

Discrete fracture network vs. continuous fracture model

- DFN and CFM
  - Same model parameters to characterize the fracture system
  - Equivalent flow properties are to be calculated in gridblocks or at gridblock interfaces as required for reservoir flow simulation
- Particularity of DFN
  - Realization of the fracture system is part of the model
    ð the realization should be part of the calibration
- Particularity of CFM
  - Equivalent flow properties locally derived from global or locally defined fracture parameters (local DFN, analytical solution)
  - If non-bijective relationship between fracture parameters and equivalent permeability tensor
    ð need for an additional connectivity-like parameter

Calibration issues

Evaluation of the (flow) well-test response of NFR models

- Requirements on the calculation method
  - Fast and automatic method for inversion purposes
  - **Grid support** for consistency with the reservoir flow simulator
  - Applicable to permeability **tensor** fields & anisotropic drainage areas
  - Distinction between fracture and matrix permeabilities

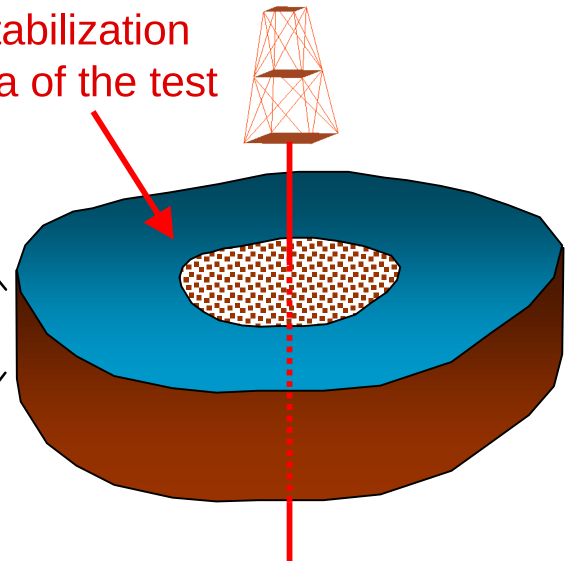
Optimization of model parameters

- Numerous model parameters
  - Several mechanical unit dependent directional fracture-sets
  - Each fracture-set characterized by ≥ 4 parameters
- Poorly known fracture parameters
  - Spatial vs. non-spatial parameters
  - Single (effective) value vs. probability distribution
- Connectivity of the fracture system = missing parameter

Evaluation of interpreted well-test k.h

Forward problem

- Interpreted k.h = average k.h corresponding to
  - Planar and radial-like flows around the well
  - Uniform homogenization of k (or more precisely k.h) within a drainage (stabilization) area around the well
  - Instantaneous pressure equilibrium in the matrix and the fracture system
  - Average (effective) $k = (k_{max}\ k_{min})^{1/2}$
    $\mathbf{k}(\mathbf{u}) \approx \mathbf{k}_f(\mathbf{u}) + \mathbf{k}_m(\mathbf{u})$



- Particularities of NFR

CFM
  - Upscaling of fracture densities
  - Permeability field = tensor field
  - Anisotropic drainage area (R_{max} / R_{min} up to 10 or more)

Evaluation of interpreted well-test k.h (cont.)

Non-exhaustive list of methods for CFM

1 Numerical simulation of transient (well-test) flow responses

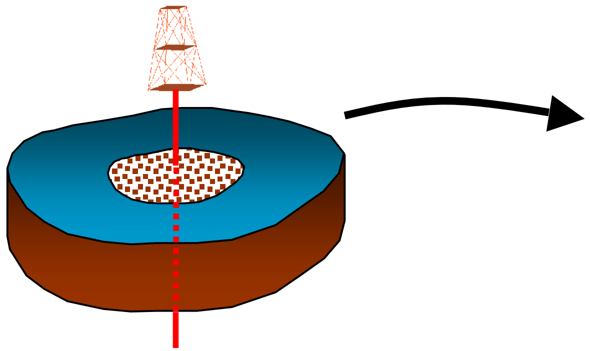
2 Power or other types of averaging based on calibrated data

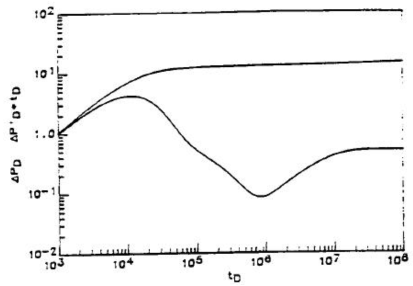
3 Annulus ring-based calculation of apparent test-permeability

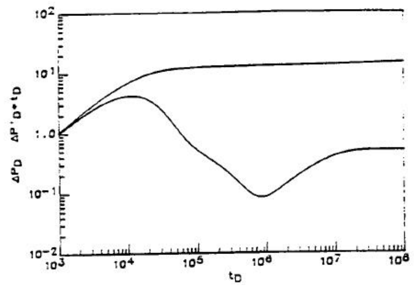
4 Steady-state flow based calculation of around-well average permeability (TOTAL/KIDOVA approach)

Evaluation of interpreted well-test k.h (cont.)

Numerical simulation of transient (well-test) flow responses







Simulated test *vs.* *Experimental test*

– Possible comparisons

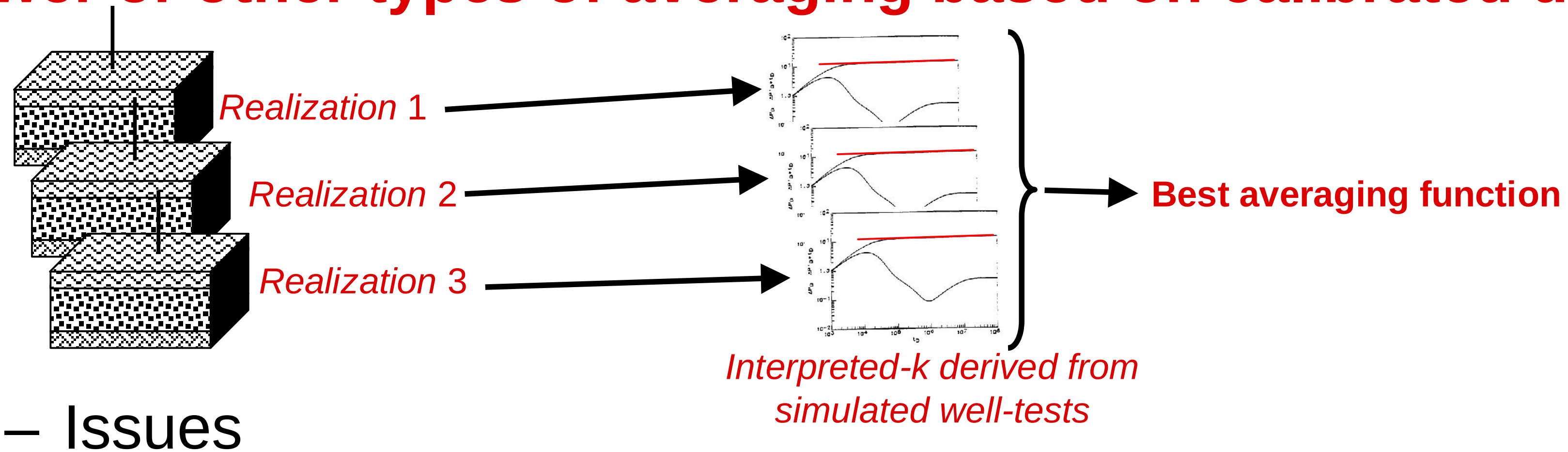
- Automatically interpreted simulated tests vs. interpreted well-test
- Simulated vs. experimental pressure (or pressure variation) curves
  ð relying on raw data instead of a reservoir engineer's interpretation

– Issues

- Complex numerical simulations: local grid refinement, well-model
- Transient flows = additional model parameters (e.g. fracture porosity, compressibility)
- What about fracture/matrix exchanges?

Evaluation of interpreted well-test k.h (cont.)

Power or other types of averaging based on calibrated data



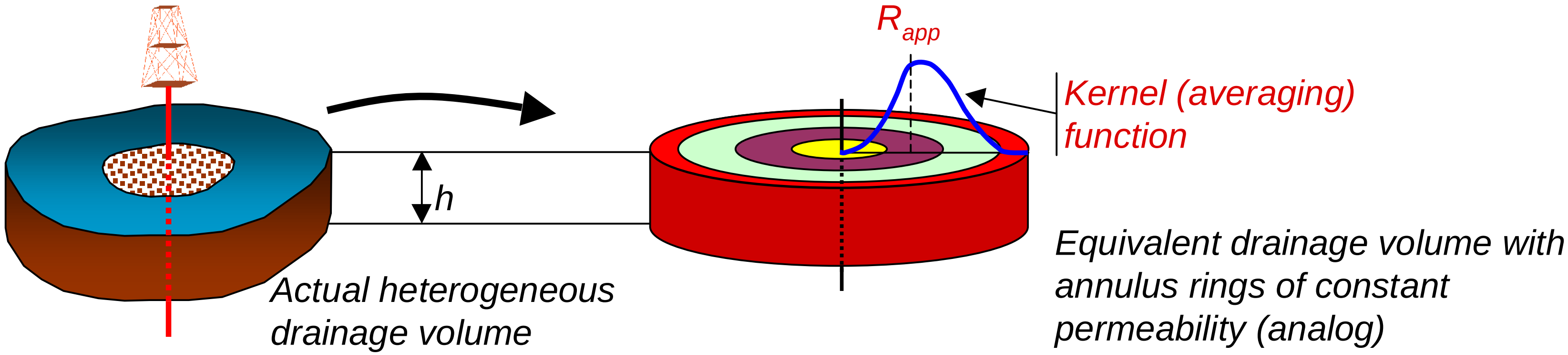
– Issues

- Applied to scalar permeability fields (not permeability tensor field)
- Defining drainage volumes (generally cylindrical)
- Relying and depending on (inferred) spatial statistics
- Same calibration function applying everywhere

Ref. Power averaging: Deutsch 1992. Multiple point proxy: Srinivasan & Caers 2000, Noetinger 1994

Evaluation of interpreted well-test k.h (cont.)

Annulus ring-based calculation of apparent test-permeability



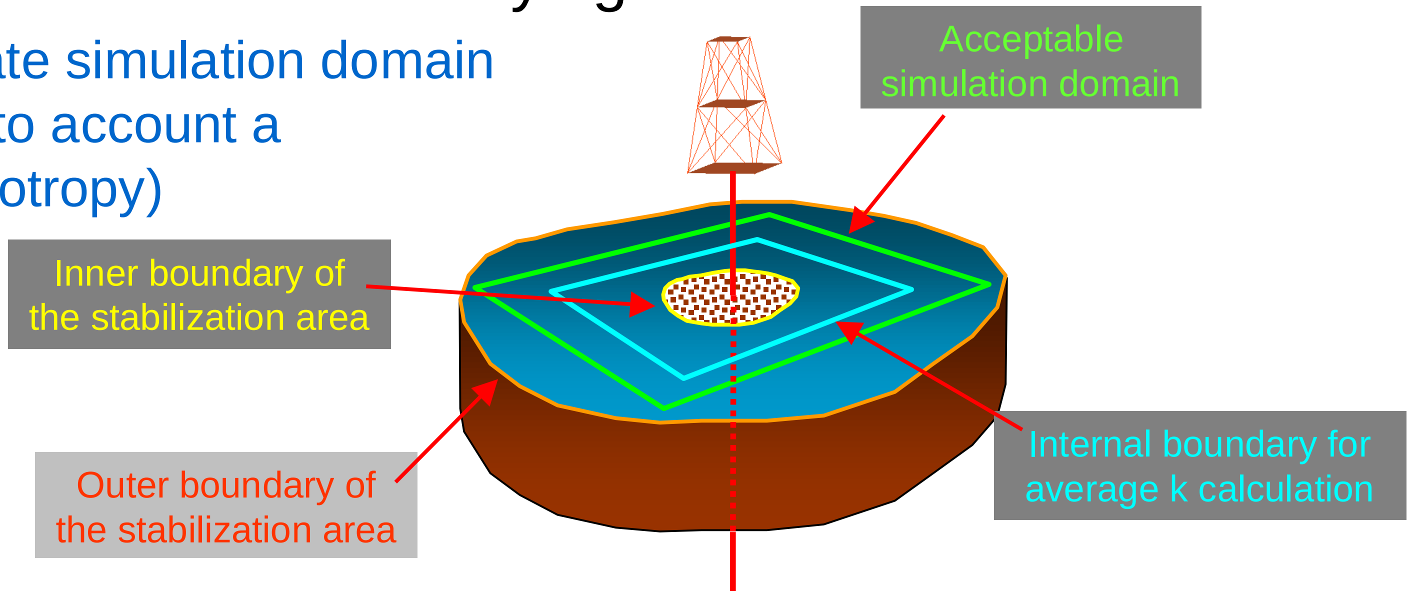
– Issues
  - Applied to scalar permeability fields (not permeability tensor field)
  - Defining equi-travel time rings (generally circular)
  - Calibration of the weighting function that should apply everywhere

Ref. Gautier & Noetinger 2004, Sagar 1993, Oliver 1989

Evaluation of interpreted well-test k.h (cont.)

Effective-gradient based averaging (TOTAL/KIDOVA method)

- Steady-state flow solution relying on:
  - Appropriate simulation domain (taking into account a local anisotropy)



  - Appropriate boundary conditions (notion of energy)
  - Appropriate calculation of average k.h vs. Rd (equivalent drainage radius) around the well (notion of effective gradient)

$$k_\Gamma = \frac{\int_\Gamma q(\gamma)\,d\gamma}{\int_\Gamma q(\gamma)\left\|\mathbf{K}(\gamma)^{-1}\mathbf{n}(\gamma)\right\|d\gamma}$$

- Ref. Garcia, Goult & Gosselin 2007 and 2006

Evaluation of interpreted well-test k.h (cont.)

Effective-gradient based averaging (TOTAL/KIDOVA method)

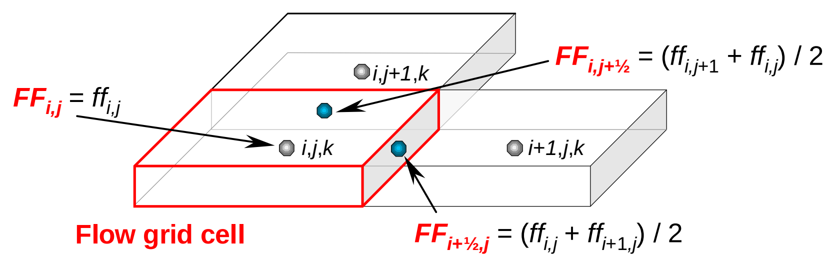
– Flow simulation

- Need for a flow simulator allowing full permeability-tensors

$$\begin{pmatrix} k_{xx} & k_{xy} & 0 \\ k_{yx} & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{pmatrix}_f + \begin{pmatrix} k_{xx} & k_{xy} & 0 \\ k_{yx} & k_{yy} & 0 \\ 0 & 0 & k_{zz} \end{pmatrix}_m$$

– Permeability tensors defined at gridblock interfaces

● = *ff simulation node*

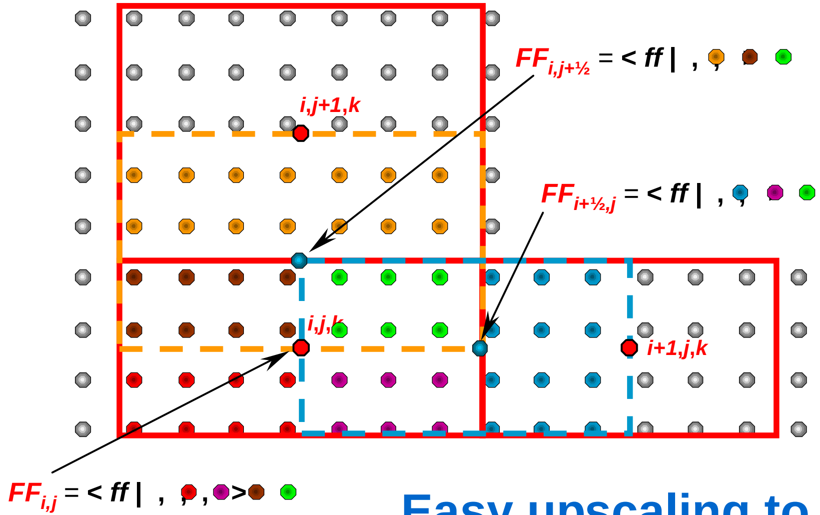


On the *FF* grid

$FF_{i,j} \rightarrow k_{zz_{i,j,k+1/2}}$

$FF_{i+½,j} \rightarrow \begin{pmatrix} k_{xx} & k_{xy} \\ k_{yx} & k_{yy} \end{pmatrix}_{i+1/2,j,k}$

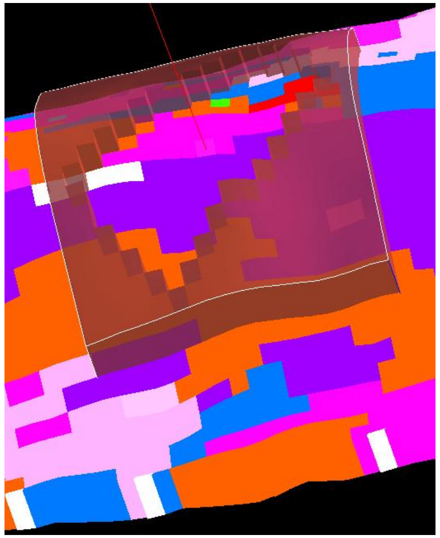
$FF_{i,j+½} \rightarrow \begin{pmatrix} k_{xx} & k_{xy} \\ k_{yx} & k_{yy} \end{pmatrix}_{i,j+1/2,k}$



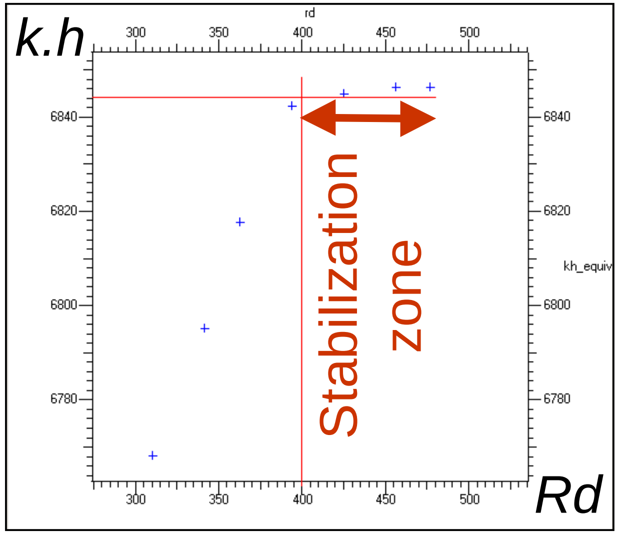
Easy upscaling to a coarser grid

Evaluation of interpreted well-test k.h (cont.)

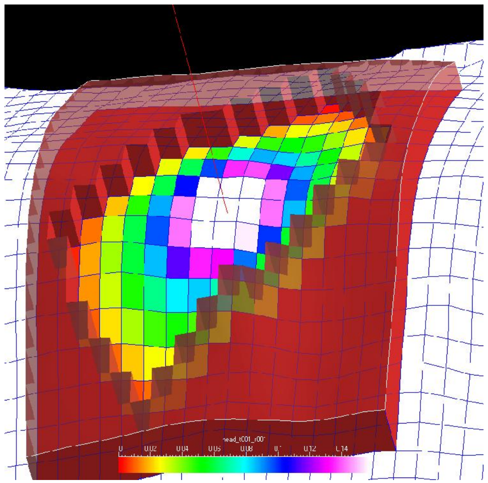
Illustration of the effective-gradient based averaging method



Appropriate simulation domain: based on local k anisotropy + drainage radius



Effective-gradient based calculation of k.h



Flow simulation: based on appropriate boundary conditions + full k-tensor simulator

Calibration of model parameters

Position of the problem

– N_d = nb of interpreted well-test (k.h) data

Well location + interpreted k.h + associated R_d

– N_p = nb of model parameters

= nb of fracture-sets x nb of fracture parameters

+ nb structural parameters

– Typically: N_p > if not >> N_d

ð “under determined” problem

ð multiple solutions

Calibration of model parameters (cont.)

Choice of an uncertainty model for each parameter

– Single value vs. probability distribution function (pdf)

  • pdf ð 2 or more distribution parameters (central and dispersion statistics) for each (probabilistic) model parameter

– Spatial vs. non-spatial (global)

Usual practice

– Layer thickness (*T*): spatial + deterministic structural model

– Fracture parameters on a (directional) fracture-set basis

  • Fracture density (FD): stochastic spatial distribution (realization)

  • Orientation (*dir*, *dip*): pdf + possibly spatially varying mean direction

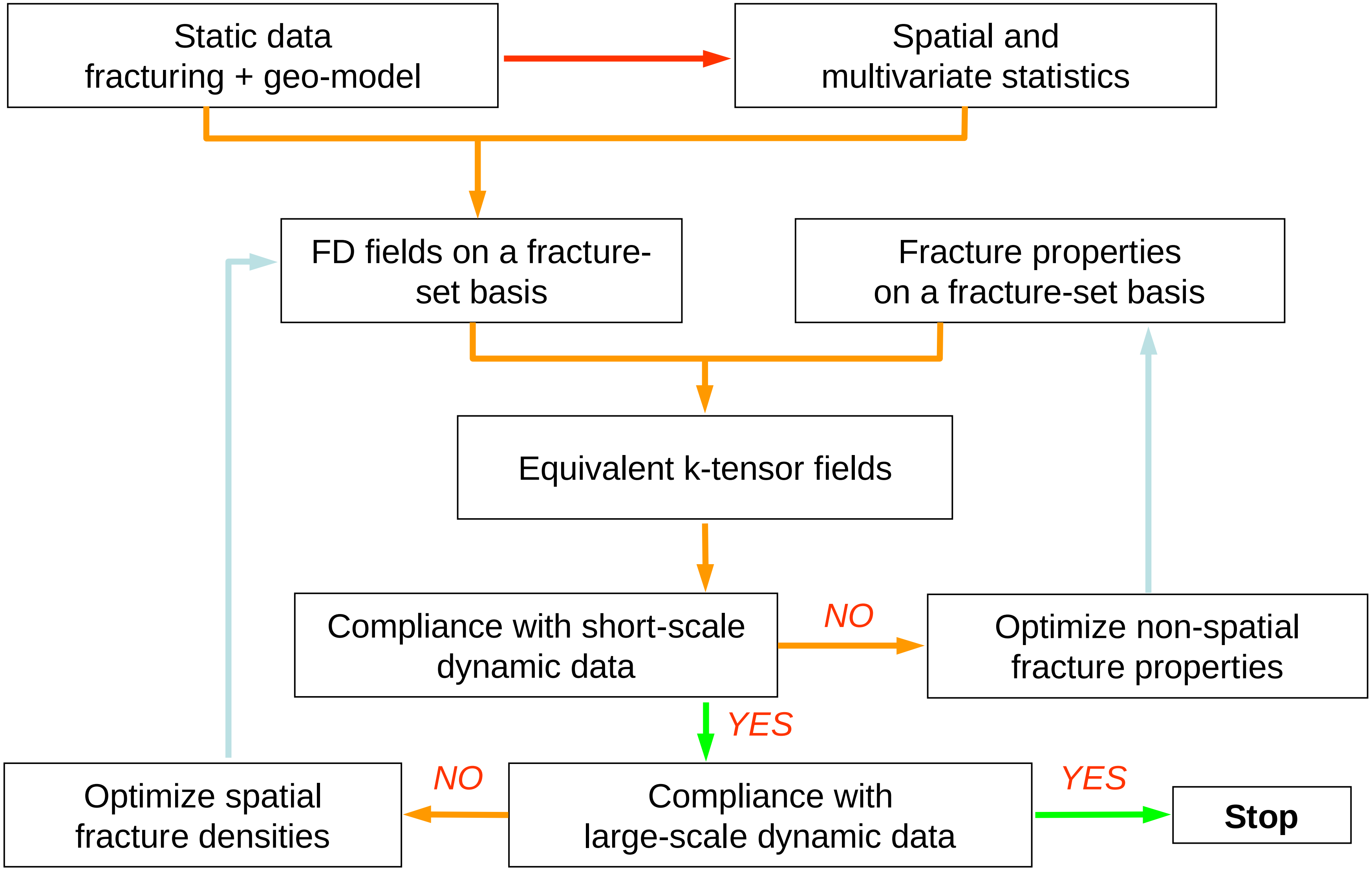
  • Other fracture properties (*L*, *ke*, *H* or *Pij*): different options

    Ø Single (effective) value often sufficient
    Ex. effective length (Masihi & King 2008)

    Ø Spatially defined: if correlated to a well-known spatial variable
    Ex. $ke \propto e^{-\lambda.FD}$ (Pollard & Segall 1987, Pollard & Gross 2000)

Calibration of model parameters (cont.)

Two-step approach for non-spatial and spatial parameters



Calibration of model parameters (cont.)

Assisted and automatic approach (TOTAL/KIDOVA)

- Sensitivity analysis
  - Charaterization of parameter uncertainty
- Inversion/optimization of non-spatial parameters
  - Experimental design (random starting points)
  - Gradient-based method (use of NPSOL)
  - Objective function

$$O(\mathbf{np}) = \left(\frac{1}{\sum_{r=1}^{N_r} 1/O_r^0(\mathbf{np}) \sum_{i=1}^{N_d} w_i} \sum_{r=1}^{N_r} \frac{1}{O_r^0(\mathbf{np})} \sum_{i=1}^{N_d} w_i \left| \frac{d_i - d_i^*\left(\mathbf{np} \middle| \mathbf{sp}^r(\mathbf{u})\right)}{\sigma_i} \right|^{\omega} \right)^{1/\omega}$$

Weighted FD realizations

Model response vs. Dynamic data

  - Aim
    - Ø Finding non-spatial parameter values matching at best dynamic data
    - Ø Identifying “best” fracture density realizations
    - Ø Managing local minima or non-unique solutions (multiple starting points)

Calibration of model parameters (cont.)

Uncertainty characterization and sensitivity analysis

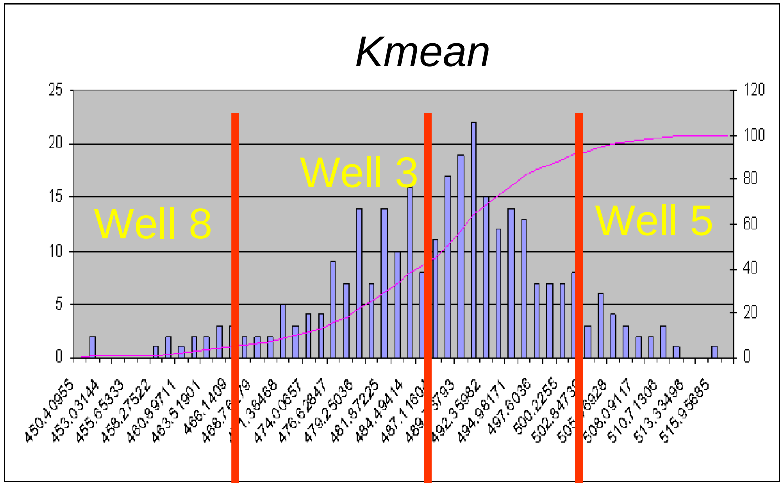
- Objectives
  - Identifying the most consequential uncertain model parameters
  - Fine-tuning their possible range
  - Eliminating parameters without or with limited effects on matching

- Tools
  - Latin hyper-cube Monte Carlo sampling
  - Uni and multivariate statistical analyses of results

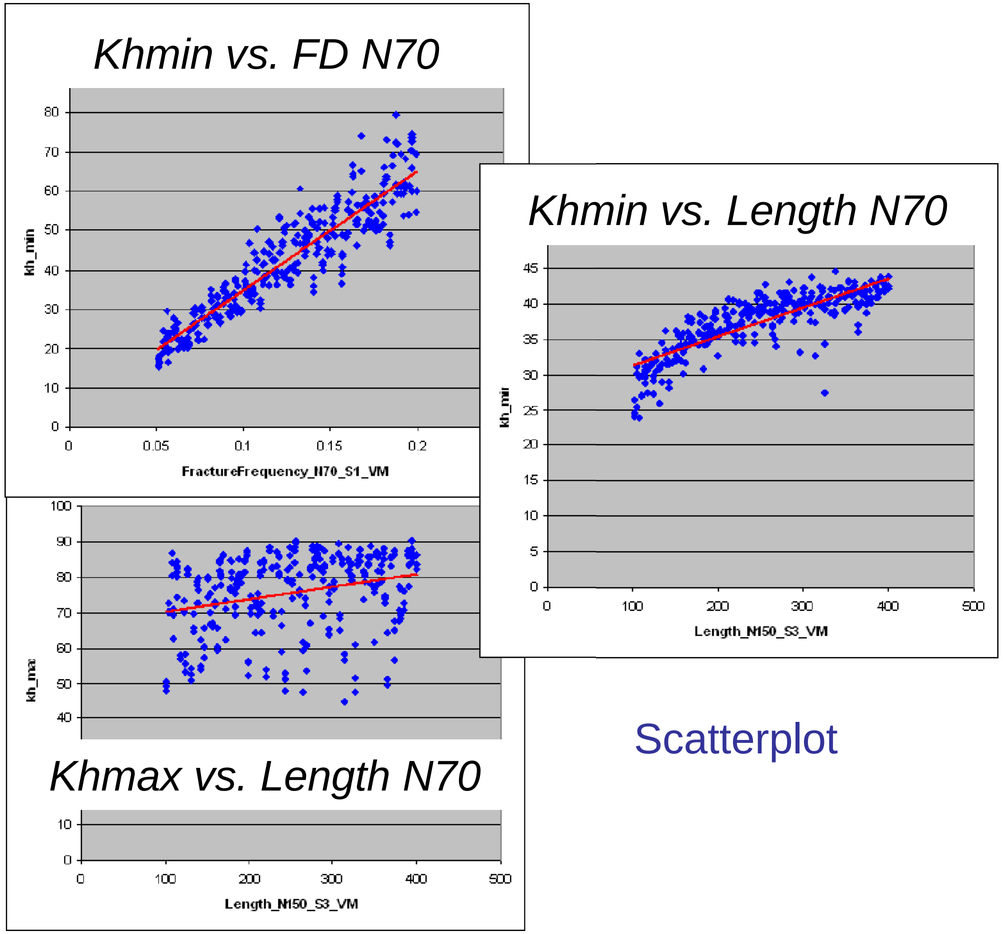
Calibration of model parameters (cont.)

Uncertainty characterization and sensitivity analysis

– Typical results



Histogram



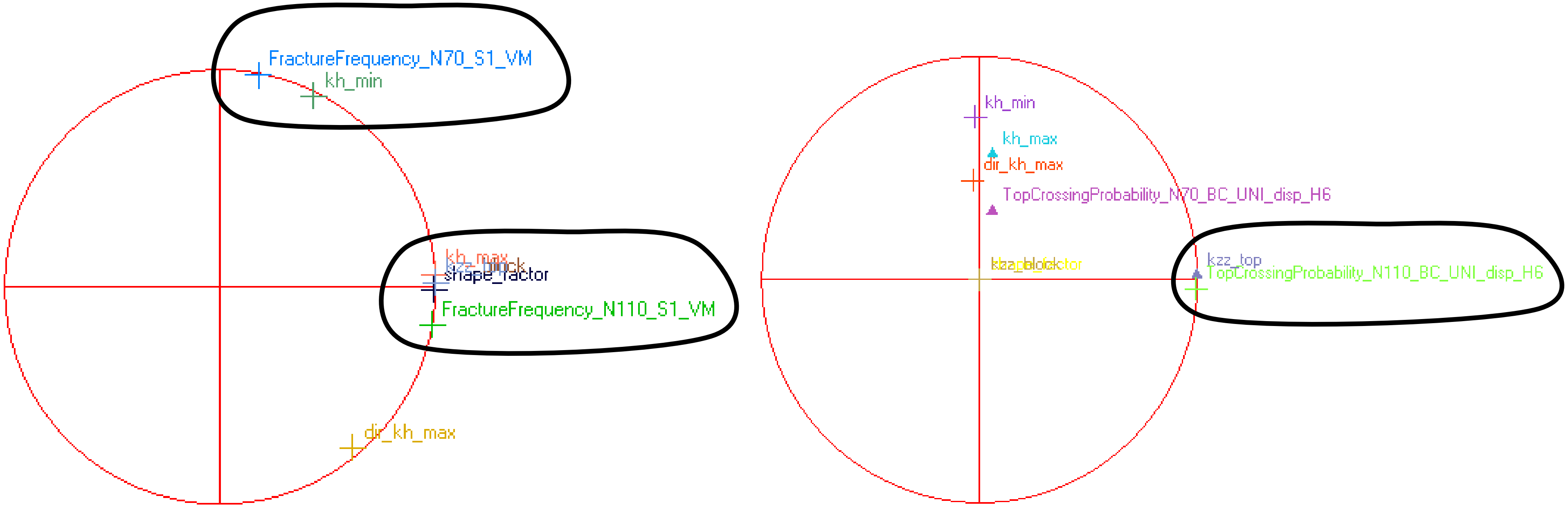
Scatterplot

– Ref. M.E. Luna Orosco Garcia, MSc. Reservoir Geosciences and Engineering, IFP School, 2007

Calibration of model parameters (cont.)

Uncertainty characterization and sensitivity analysis

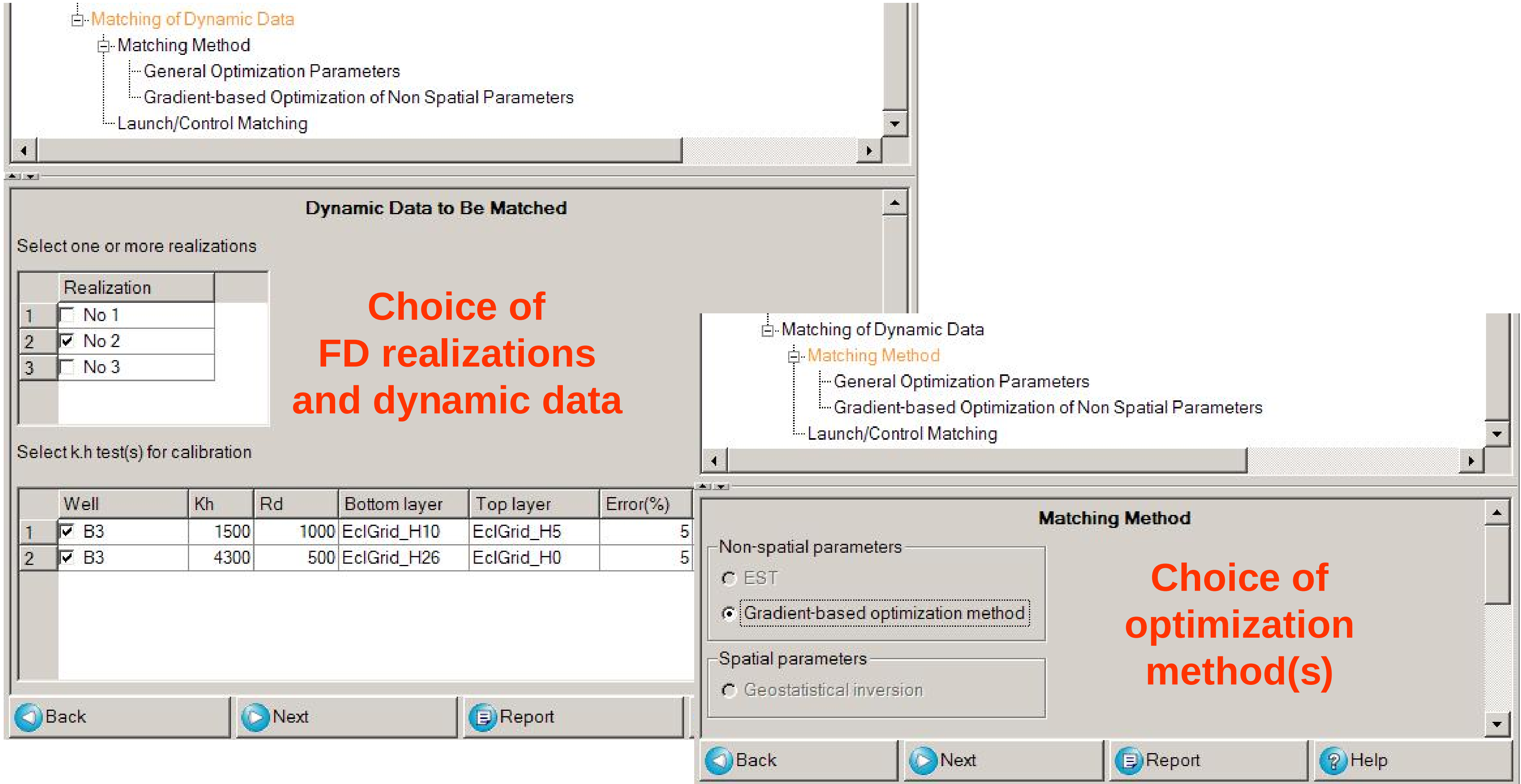
– Typical results



– Ref. M.E. Luna Orosco Garcia, MSc. Reservoir Geosciences and Engineering, IFP School, 2007

Calibration of model parameters (cont.)

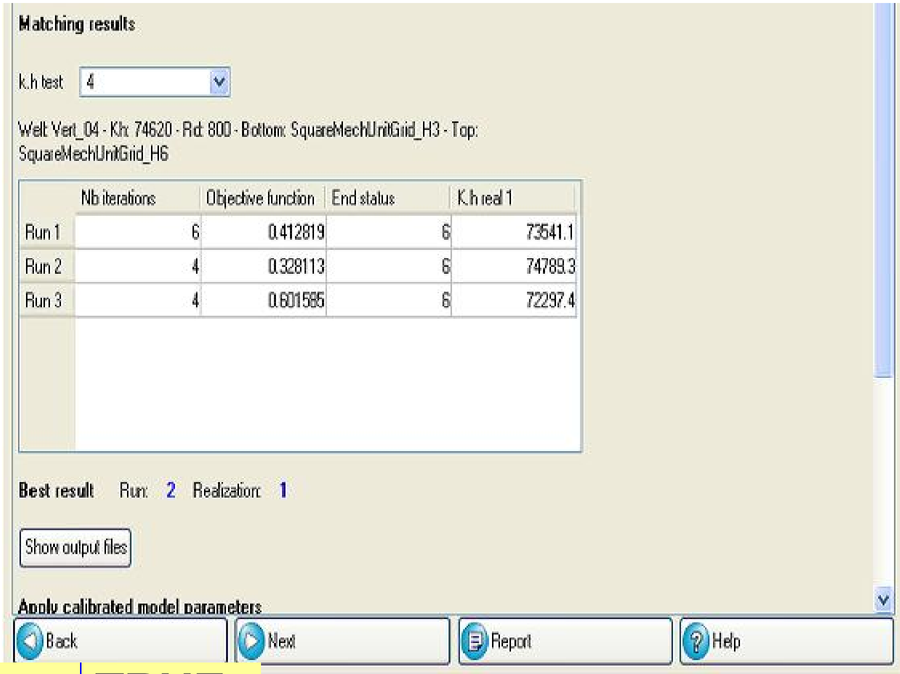
Automatic calibration of non-spatial parameters



Calibration of model parameters (cont.)

Automatic calibration of non-spatial parameters

- **Grid – 200*200*6 cells**
- **Four zones with FD of 0.3, 1.5, 3 & 7 m^{-1}**
- **Two fracture sets N70 & N150**
  - N70: *L*=10 m, *ke* = 400 mD.m
  - N150: *L*=15 m, *ke* = 250 mD.m



Fracture set	Parameter	Run 1	Run 2	Run 3	**TRUE**
N70	*L*	170.1	348.0	871.8	**400**
N70	*ke*	19.5	11.8	11.5	**10**
N150	*L*	125.6	909.1	136.2	**250**
N150	*ke*	13.8	22.3	28.7	**15**

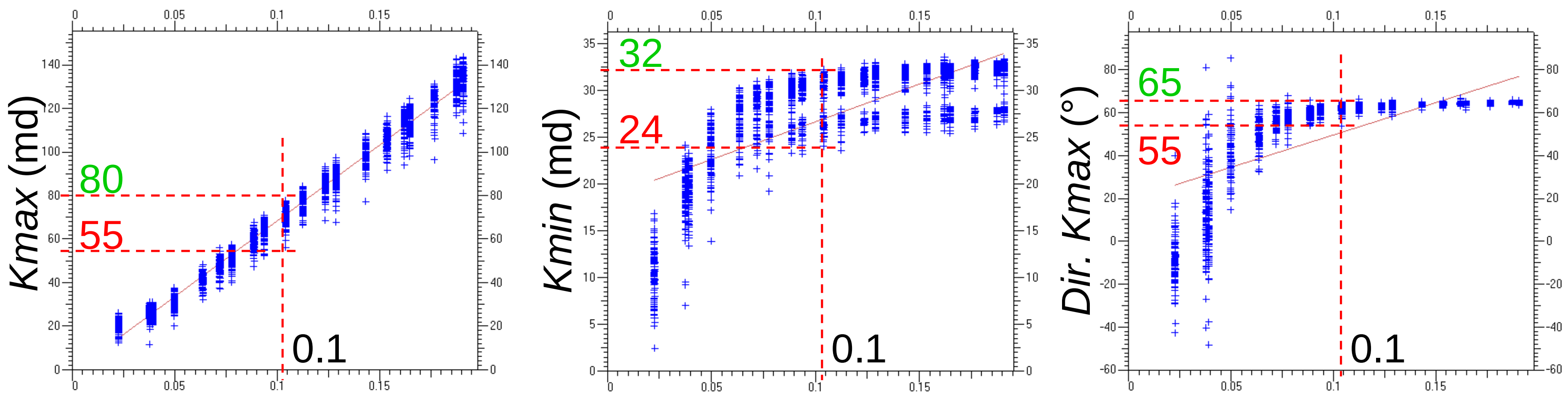
– Ref. Egor Mikhaylenko, MSc. Reservoir Geosciences and Engineering, IFP School, 2008

Calibration of model parameters (cont.)

About the need for a connectivity parameter

– Calculation uncertainty between fracture-set parameters and equivalent permeability tensor

Non-bijective relation = sensitivity to some DFN realizations



FD-N70 (m^{-1}) = only non-constant parameter

– Connectivity parameter = additional (locally or globally) defined model parameter to discard calculation uncertainty

Acknowledgements:

for its support and permission to publish results

Discussion

- **Evaluation of interpreted k.h test data on NFR models**
  - Easy forward problem, complex evaluation task
- **Automated vs. assisted model parameter calibration**
  - Practice of sensitivity analysis and optimization
- **Which support for calibration: DFN vs. CFM?**
  - Consistency of model calibration with history matching
- **Multisolution of NFR model parameters**
  - Trade-off between model complexity and available data

References

Conditioning to well-test data

- Deutsch, B. (2004), Conditioning reservoir models to well test information, *in* A. Soares, ed., *Geostatistics Troia Volume 1*, Kluwer Academic Publishers, Dordrecht, pp 506-518.
- Garcia M., Gouth F & Gosselin O (2007). Fast and efficient modeling and conditioning of naturally fractured reservoir models using static and dynamic data, in *SPE Europec/EAGE Annual Conf. & Exhibit., London*, SPE 107525.
- Garcia M., Gouth F. & Gosselin O (2006). New developments in GoFraK to condition naturally fractured reservoir models on dynamic data, in *26th gOcad Meeting, Nancy*.
- Gautier, Y. & Noetinger, B. (2004), Geostatistical Parameters Estimation Using Well Test Data, *Oil & Gas Science and Technology*, Rev. IFP, Vol. 59, No. 2, 167-183.
- Oliver, D.S. (1989). The averaging process in permeability estimation from well test data, in *SPE conference, San Antonio*, SPE 19845, pages 813-833.
- Sagar, R.K. (1993). *Reservoir description by integration of well test data and spatial statistics*, Ph.D. Thesis, University of Tulsa.
- Srinivasan, S. & Caers, J. (2000). Conditioning reservoir models to dynamic data - a forward modeling perspective, in *SPE Annual Conference and Technical Exhibition, Dallas*, SPE 62941.

Effective properties

- Masihi, M. and King, P.R. (2008). Connectivity Prediction in Fractured Reservoirs With Variable Fracture Size: Analysis and Validation. SPE J.13 (1): 88-98. SPE-100229-PA