Workflow and Analysis Tools for the Characterization of Fractured Reservoirs*

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Search and Discovery Article #40424 (2009)
Posted June 10, 2009

*Adapted from oral presentation at AAPG International Conference and Exhibition, Cape Town, South Africa, October 26-29, 2008

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Abstract

The workflow developed at IFP for characterizing fractured reservoirs is based on: (i) the construction of geologically-realistic models of the fracture network; (ii) the characterization of fracture properties from available field data; (iii) the up-scaling of the fracture properties; (iv) the selection of a suitable up-scaled model usable for field-scale simulations of multi-phase production methods. This fractured reservoir workflow is reviewed, and a software platform is presented, on which methodologies and tools were developed in order to perform each step of the workflow.

A geologically-realistic model is presented on which constrained modeling of the geological fracture network based on the analysis of fracture information acquired in wells and derived from seismic data has been performed. Then optimization algorithms and a 3D discrete fracture network flow simulator are used in order to automatically characterize fracture properties that are consistent with transmissivities data, flowmeters and/or well tests data. The characterized fracture properties are the mean length, mean conductivity, orientation dispersion factors, and facies-dependent properties such as the average spacing and the bed-crossing probability. The effectiveness of the optimization algorithms to characterize physically meaningful and data-consistent fracture properties is discussed. Finally, full-field upscaling of the fracture properties has been performed such that a single or dual-porosity simulation model can be used at field scale, taking into account the multi-scale fracture properties.

This consistent workflow allows flow simulation models to remain interpretable in geological terms, therefore facilitating subsequent model updating. Moreover, specialists in geosciences and reservoir engineers can cooperate in a very effective way to improve the management of fractured reservoirs.

Workflow and Analysis Tools for the Characterization of Fractured Reservoirs

AAPG International Conference & Exhibition
26-29th October 2008

A.Lange, A.Fourno, M.Delorme, N.Khvoenkova and C.Ponsot-Jacquin

Innovation Energy Environment

Objectives

- To identify & characterize the main geological drivers on multi-scale natural fractures based on:
  - Geological data (BHI, cores, logs)
  - 3D seismic (seismic facies analysis)
  - Dynamic data
- To compute the equivalent fracture properties (fracture porosity, permeability and block sizes):
  - Hydraulic fracture characterization

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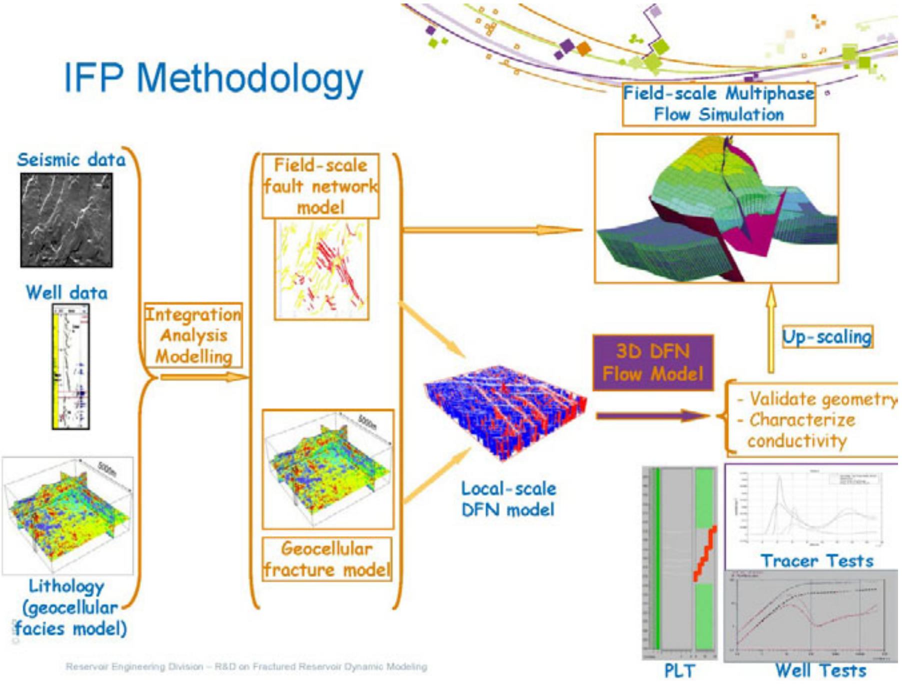


Notes by Presenter: The methodology developed at IFP in the past years consists in:
- First, integrating all available data about fracture properties - from seismic measurements, well data … the geocellular facies model,
- in order to build two models:
- a ***discrete model of large-scale*** fractures and faults, mainly derived from the analysis of seismic attributes,
- at a lower scale, a ***geocellular model of fracture properties*** that is consistent with the facies geomodel of the reservoir, giving the fracture density and orientation per fracture set per facies,

These models provide the necessary information for generating ***local discrete fracture network models*** anywhere in the reservoir**.**
These local models are then used for assessing the flow properties of the fracture network via our 3D DFN flow model.
Interference, well tests and PLT can be simulated and calibrated with available dynamic field data in order to:
- validate the geological DFN model geometry.
- characterize the fracture conductivity for each set.

Then the flow properties may be upscaled to an appropriate field-scale flow simulation model to optimise reservoir production.
Therefore this methodology allows the reservoir engineer to convert geological models into representative flow models.

IFP Methodology

- Advantages
  - Geologically-realistic models of fracture networks
  - 3D DFN flow simulator
  - Dual-medium approach, 1K and 2K
  - Fast image processing algorithm for matrix discretization
  - Reservoir model consistent with geological model
- Drawbacks
  - DFN (realizations of stochastic fracture model)
  - Single-phase (oil or gas)
  - Characterization not automatic → Automated calibration
  - Computer-intensive for dense DFN → Simplified DFN (A.Fourno)

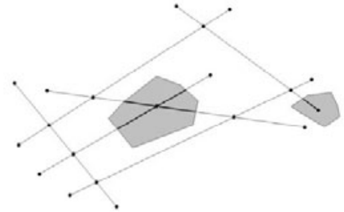
3D Dual-Porosity Flow Model

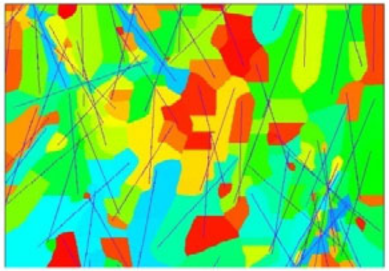
(SPE 88675, 94344)

Barenblatt and Zheltov (1960) :

$$
\begin{array}{ll}
\text{Fracture medium:} & \left\{ \begin{array}{l}
\nabla \cdot \left(k_f \nabla P_f\right) + \alpha_{mf}\left(P_m - P_f\right) = c_f \cdot \mu_o \cdot \phi_f \cdot \dfrac{\partial P_f}{\partial t} \ , \\[2ex]
\nabla \cdot \left(k_m \nabla P_m\right) - \alpha_{mf}\left(P_m - P_f\right) = c_m \cdot \mu_o \cdot \phi_m \cdot \dfrac{\partial P_m}{\partial t} \ ,
\end{array} \right. \\
\text{Matrix medium:} &
\end{array}
$$

- Originality: Finite Volume Solving on the discretized geological fracture model





Discretized middle plane of a stratum

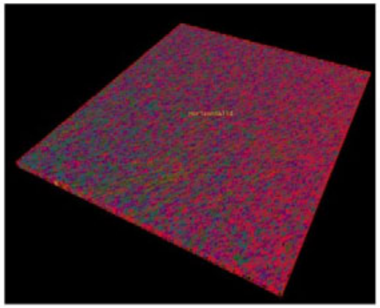
Notes by Presenter: It is generally agreed that a double-porosity, single-permeability model is suitable for a connected fracture network and a matrix medium that only acts as a source of fluids. Otherwise, as soon as the flow in the matrix has to be taken into account, the double-porosity, double-permeability model should be used. However, it may be difficult to estimate the connectivity property of a random fracture network, or whether the matrix/fracture permeability contrast does actually lead to non-negligible contributions from the matrix medium in terms of flow.

Moreover uncertainties in the geometrical properties of the fracture network, such as the fracture length distribution, may affect the connectivity of the network, particularly around the percolation threshold. As a result it is not always straightforward to identify which model should be used in practice.

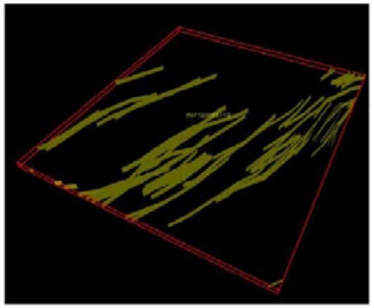
We illustrate this issue by performing a sensitivity analysis on a realistic case combining both small-scale fractures and major objects such as seismic and sub-seismic faults.

3D Dual-Porosity Flow Model

(SPE 88675, 94344)

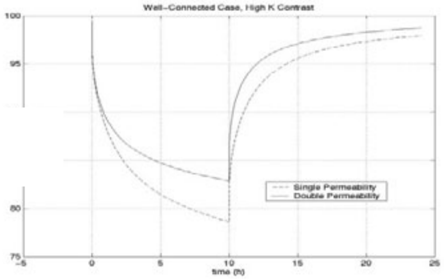


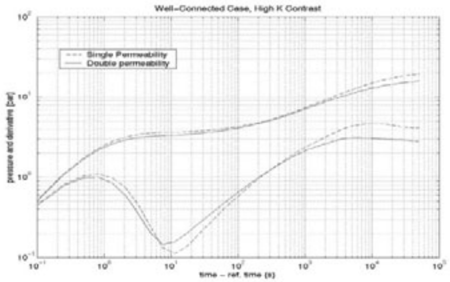
Full fracture network.



Fault network alone.

- **Domain Properties:**
  - Lx = 742 m,
  - Ly = 877 m,
  - Thickness: 10 m.





Notes by Presenter: It is generally agreed that a double-porosity, single-permeability model is suitable for a connected fracture network and a matrix medium that only acts as a source of fluids. Otherwise, as soon as the flow in the matrix has to be taken into account, the double-porosity, double-permeability model should be used. However, it may be difficult to estimate the connectivity property of a random fracture network, or whether the matrix/fracture permeability contrast does actually lead to non-negligible contributions from the matrix medium in terms of flow.

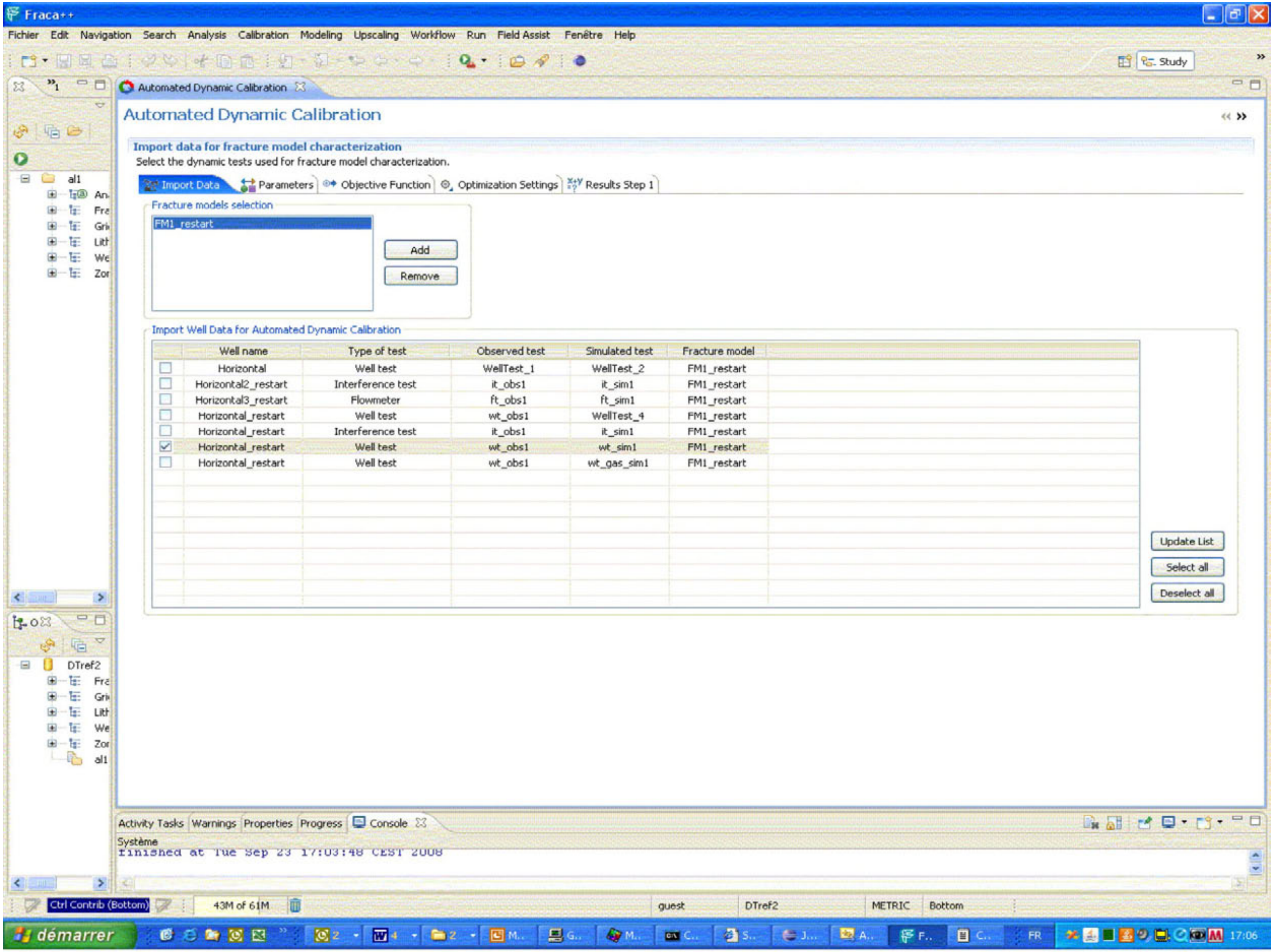
Moreover uncertainties in the geometrical properties of the fracture network, such as the fracture length distribution, may affect the connectivity of the network, particularly around the percolation threshold. As a result it is not always straightforward to identify which model should be used in practice.

We illustrate this issue by performing a sensitivity analysis on a realistic case combining both small-scale fractures and major objects such as seismic and sub-seismic faults.

Automated Characterization of Fractured Reservoirs from Dynamic Data

- Field data: flowmeters, well tests, interference tests...
- Knowledge model: 3D DFN flow simulator
- Fracture properties:
  - mean length
  - mean conductivity
  - orientation dispersion factors
  - density per facies
  - crossing probabilities per facies

- Inversion method: genetic algorithm...


Fraca++
Fichier Edit Navigation Search Analysis Calibration Modeling Upscaling Workflow Run Field Assist Fenêtre Help
Study
Automated Dynamic Calibration
Automated Dynamic Calibration
Import data for fracture model characterization
Select the dynamic tests used for fracture model characterization.
Import Data Parameters Objective Function Optimization Settings Results Step 1
Fracture models selection
FM1_restart
Add
Remove
Import Well Data for Automated Dynamic Calibration
Well name Type of test Observed test Simulated test Fracture model
Horizontal Well test WellTest_1 WellTest_2 FM1_restart
Horizontal2_restart Interference test it_obs1 it_sim1 FM1_restart
Horizontal3_restart Flowmeter ft_obs1 ft_sim1 FM1_restart
Horizontal_restart Well test wt_obs1 WellTest_4 FM1_restart
Horizontal_restart Interference test it_obs1 it_sim1 FM1_restart
Horizontal_restart Well test wt_obs1 wt_sim1 FM1_restart
Horizontal_restart Well test wt_obs1 wt_gas_sim1 FM1_restart
Update List
Select all
Deselect all
al1
DTref2
Activity Tasks Warnings Properties Progress Console
Système
finished at Tue Sep 23 17:03:48 CEST 2008
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43M of 61M
guest
DTref2
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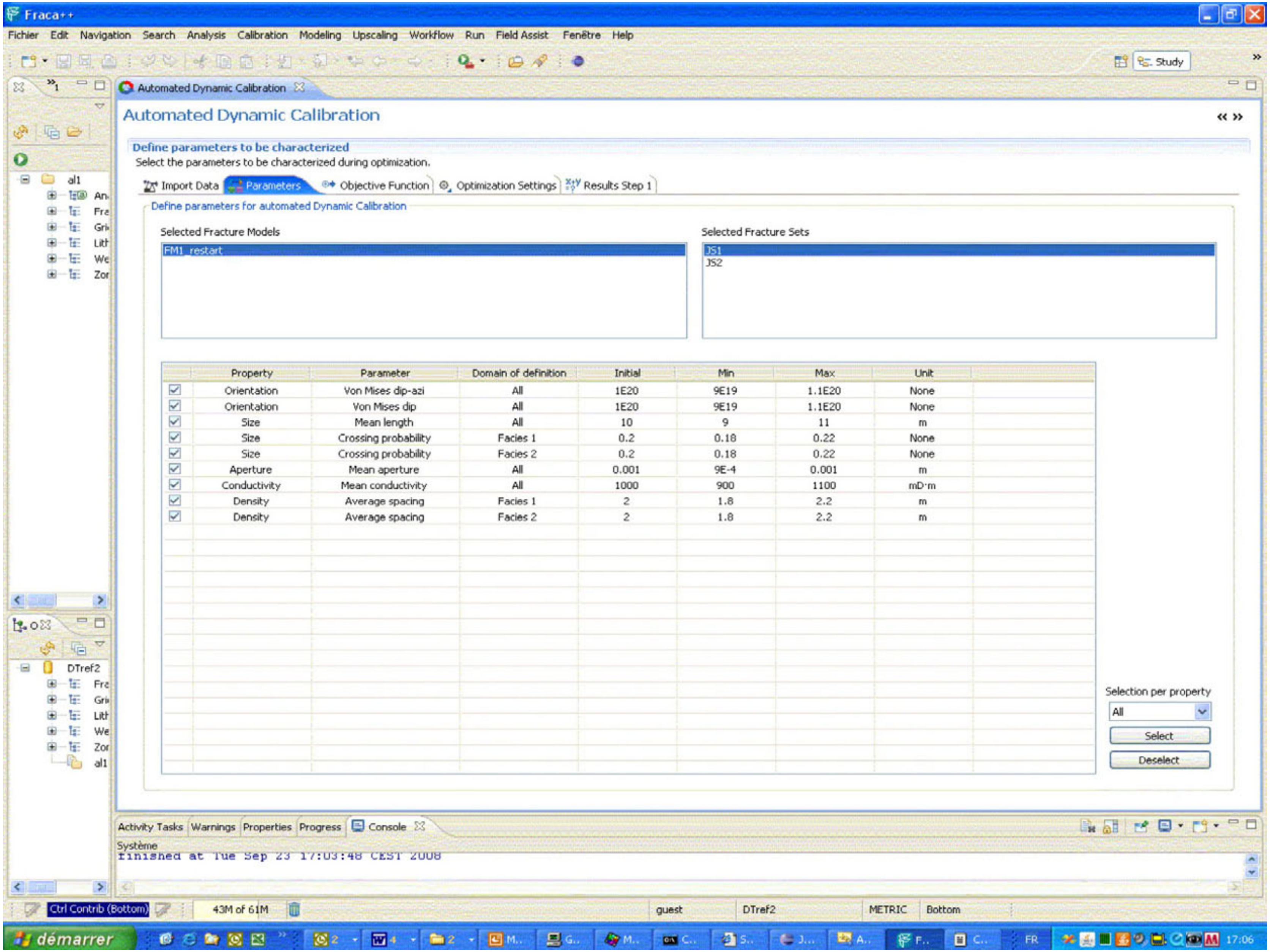
Fraca++
Fichier Edit Navigation Search Analysis Calibration Modeling Upscaling Workflow Run Field Assist Fenêtre Help
Study
Automated Dynamic Calibration
Automated Dynamic Calibration
Define parameters to be characterized
Select the parameters to be characterized during optimization.
Import Data
Parameters
Objective Function
Optimization Settings
Results Step 1
Define parameters for automated Dynamic Calibration
Selected Fracture Models
FM1_restart
Selected Fracture Sets
JS1
JS2
Property | Parameter | Domain of definition | Initial | Min | Max | Unit
Orientation | Von Mises dip-azi | All | 1E20 | 9E19 | 1.1E20 | None
Orientation | Von Mises dip | All | 1E20 | 9E19 | 1.1E20 | None
Size | Mean length | All | 10 | 9 | 11 | m
Size | Crossing probability | Facies 1 | 0.2 | 0.18 | 0.22 | None
Size | Crossing probability | Facies 2 | 0.2 | 0.18 | 0.22 | None
Aperture | Mean aperture | All | 0.001 | 9E-4 | 0.001 | m
Conductivity | Mean conductivity | All | 1000 | 900 | 1100 | mD·m
Density | Average spacing | Facies 1 | 2 | 1.8 | 2.2 | m
Density | Average spacing | Facies 2 | 2 | 1.8 | 2.2 | m
Selection per property
All
Select
Deselect
al1
DTref2
Activity Tasks Warnings Properties Progress Console
Système
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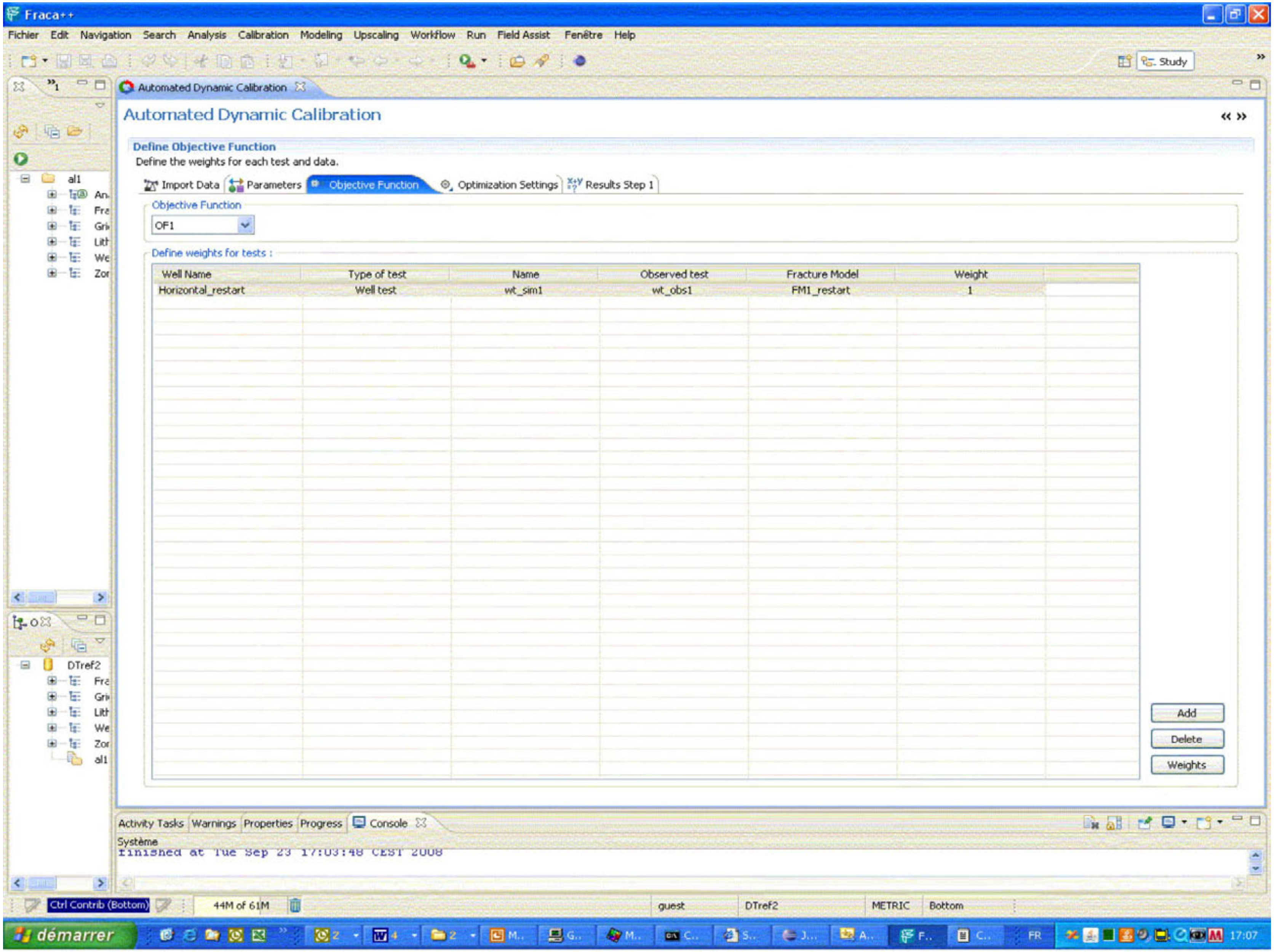
Fraca++
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Study
Automated Dynamic Calibration
Automated Dynamic Calibration
Define Objective Function
Define the weights for each test and data.
Import Data
Parameters
Objective Function
Optimization Settings
Results Step 1
Objective Function
OF1
Define weights for tests :
Well Name
Type of test
Name
Observed test
Fracture Model
Weight
Horizontal_restart
Well test
wt_sim1
wt_obs1
FM1_restart
1
Add
Delete
Weights
DTref2
Activity Tasks
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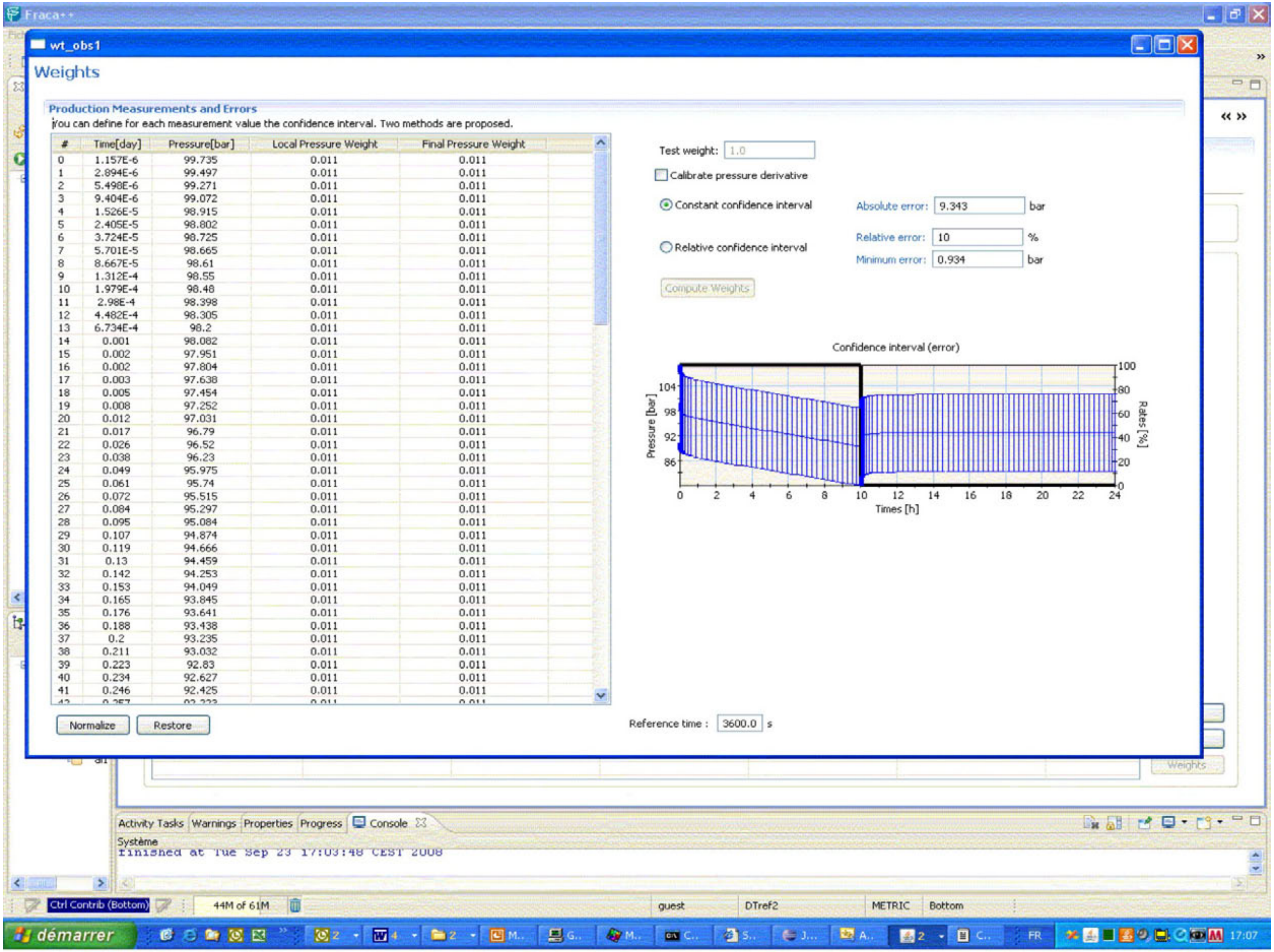
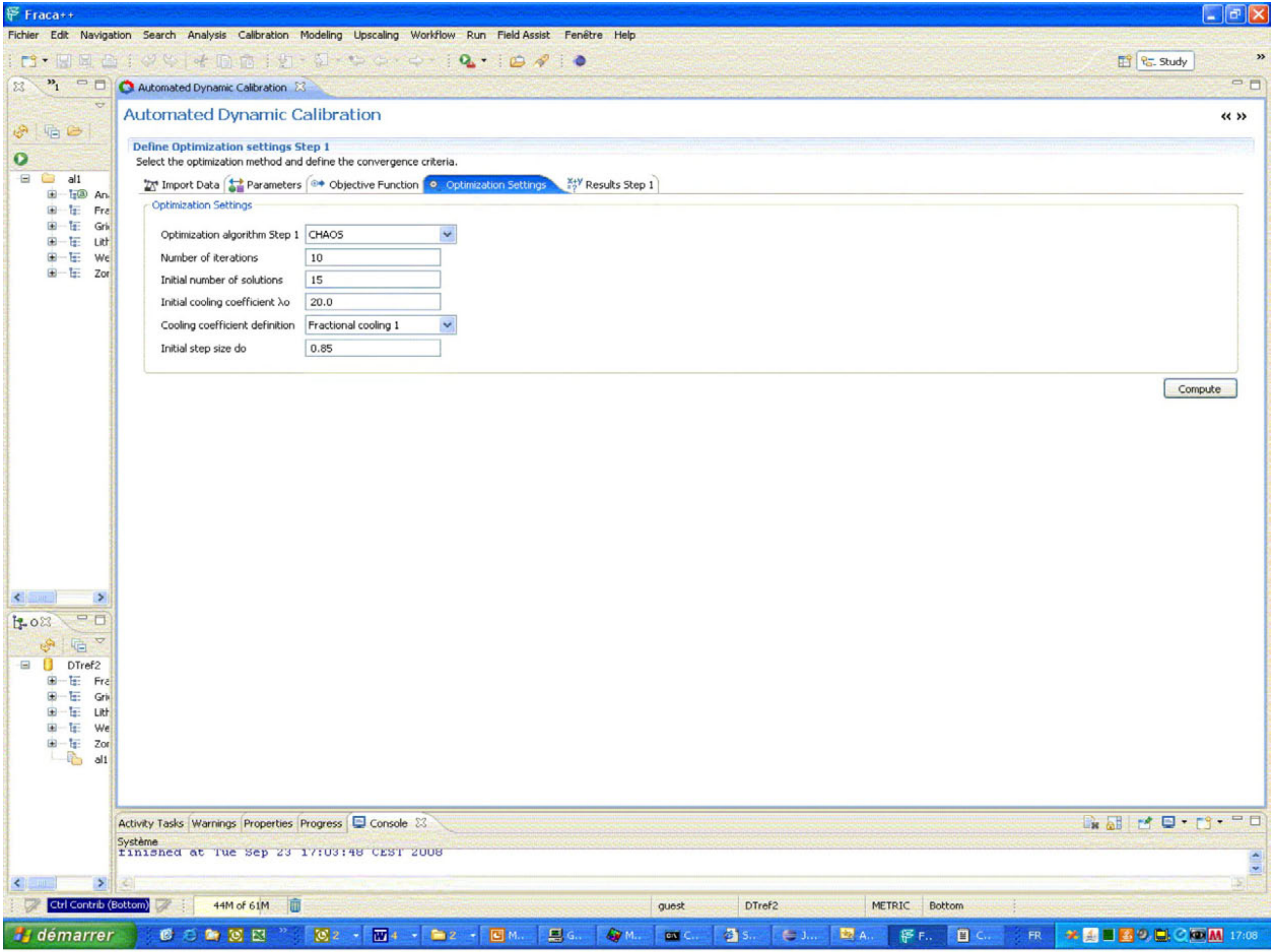


#	Time[day]	Pressure[bar]	Local Pressure Weight	Final Pressure Weight
0	1.157E-6	99.735	0.011	0.011
1	2.894E-6	99.497	0.011	0.011
2	5.498E-6	99.271	0.011	0.011
3	9.404E-6	99.072	0.011	0.011
4	1.526E-5	98.915	0.011	0.011
5	2.405E-5	98.802	0.011	0.011
6	3.724E-5	98.725	0.011	0.011
7	5.701E-5	98.665	0.011	0.011
8	8.667E-5	98.61	0.011	0.011
9	1.312E-4	98.55	0.011	0.011
10	1.979E-4	98.48	0.011	0.011
11	2.98E-4	98.398	0.011	0.011
12	4.482E-4	98.305	0.011	0.011
13	6.734E-4	98.2	0.011	0.011
14	0.001	98.082	0.011	0.011
15	0.002	97.951	0.011	0.011
16	0.002	97.804	0.011	0.011
17	0.003	97.638	0.011	0.011
18	0.005	97.454	0.011	0.011
19	0.008	97.252	0.011	0.011
20	0.012	97.031	0.011	0.011
21	0.017	96.79	0.011	0.011
22	0.026	96.52	0.011	0.011
23	0.038	96.23	0.011	0.011
24	0.049	95.975	0.011	0.011
25	0.061	95.74	0.011	0.011
26	0.072	95.515	0.011	0.011
27	0.084	95.297	0.011	0.011
28	0.095	95.084	0.011	0.011
29	0.107	94.874	0.011	0.011
30	0.119	94.666	0.011	0.011
31	0.13	94.459	0.011	0.011
32	0.142	94.253	0.011	0.011
33	0.153	94.049	0.011	0.011
34	0.165	93.845	0.011	0.011
35	0.176	93.641	0.011	0.011
36	0.188	93.438	0.011	0.011
37	0.2	93.235	0.011	0.011
38	0.211	93.032	0.011	0.011
39	0.223	92.83	0.011	0.011
40	0.234	92.627	0.011	0.011
41	0.246	92.425	0.011	0.011


Fraca++
Fichier Edit Navigation Search Analysis Calibration Modeling Upscaling Workflow Run Field Assist Fenêtre Help
Study
Automated Dynamic Calibration
Automated Dynamic Calibration
Define Optimization settings Step 1
Select the optimization method and define the convergence criteria.
Import Data
Parameters
Objective Function
Optimization Settings
Results Step 1
Optimization Settings
Optimization algorithm Step 1
CHAOS
Number of iterations
10
Initial number of solutions
15
Initial cooling coefficient λo
20.0
Cooling coefficient definition
Fractional cooling 1
Initial step size do
0.85
Compute
al1
DTref2
Activity Tasks
Warnings
Properties
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Système
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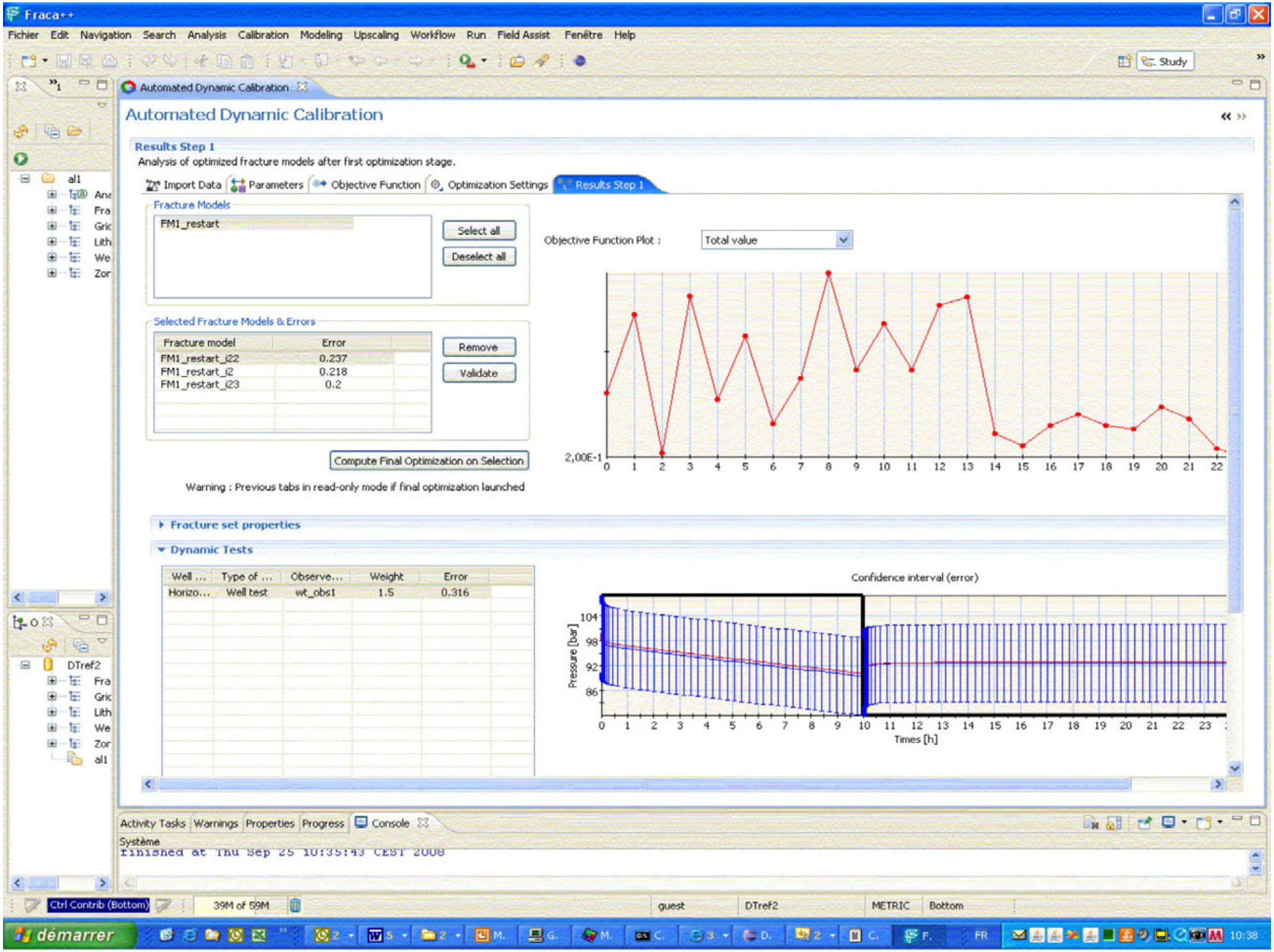

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Fichier Edit Navigation Search Analysis Calibration Modeling Upscaling Workflow Run Field Assist Fenêtre Help
Study
Automated Dynamic Calibration
Automated Dynamic Calibration
Results Step 1
Analysis of optimized fracture models after first optimization stage.
Import Data Parameters Objective Function Optimization Settings Results Step 1
Fracture Models
FM1_restart
Select all
Deselect all
Objective Function Plot :
Total value
Selected Fracture Models & Errors
Fracture model Error
FM1_restart_i22 0.237
FM1_restart_i2 0.218
FM1_restart_i23 0.2
Remove
Validate
2,00E-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22
Compute Final Optimization on Selection
Warning : Previous tabs in read-only mode if final optimization launched
Fracture set properties
Dynamic Tests
Well ... Type of ... Observe... Weight Error
Horizo... Well test wt_obs1 1.5 0.316
Confidence interval (error)
Pressure [bar]
104 98 92 86
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Times [h]
al1
DTref2
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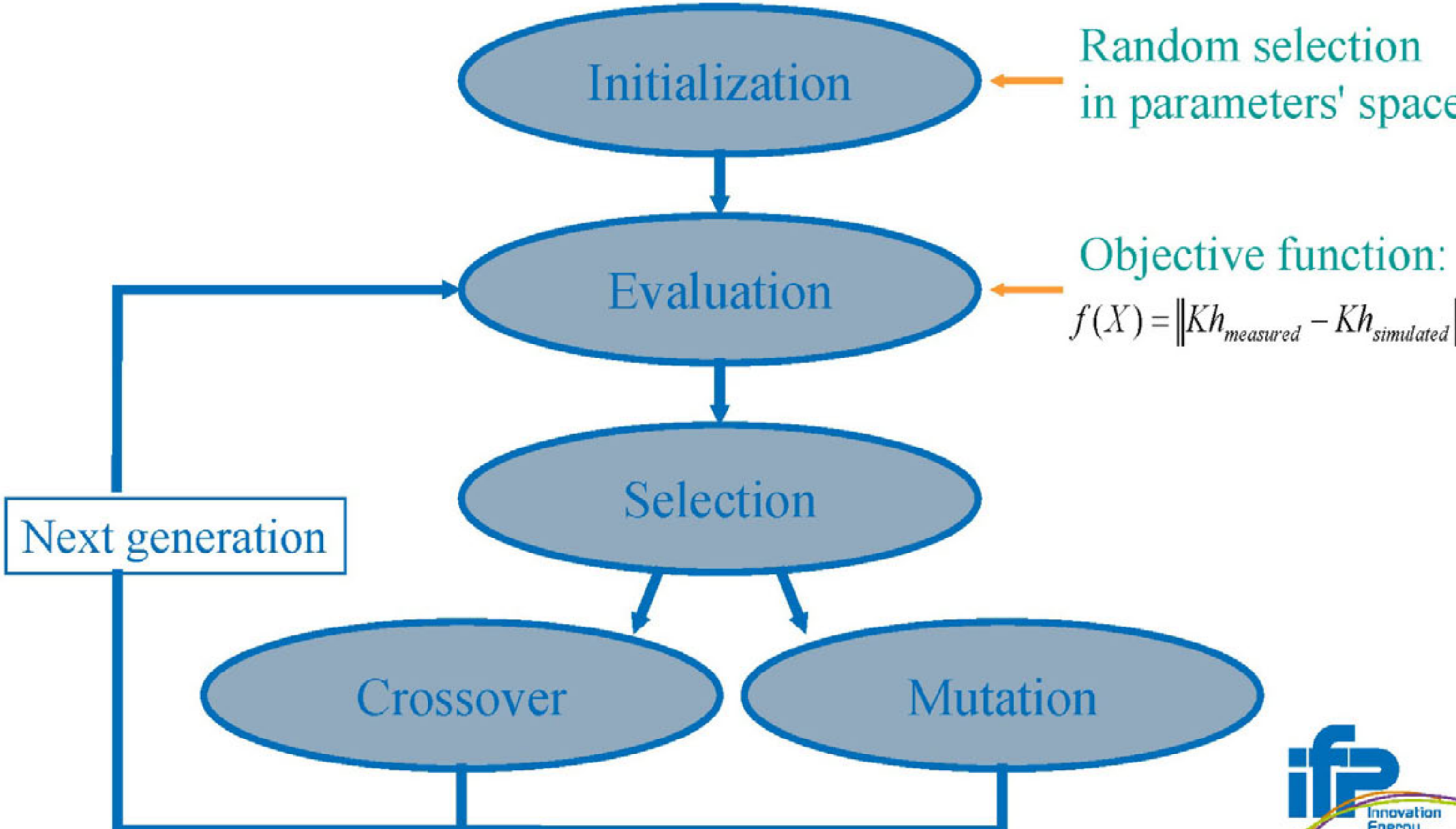
Genetic-based Characterization of Fractured Reservoirs from Interpreted Well Tests



Genetic-based characterization of fractured reservoirs from interpreted well tests

→ **Selection process:** selecting best solutions according to objective function value

$$f(X) = \frac{1}{2} \sum_{i=1}^{wells\_nb} w_i \left| Kh_{measured,i} - Kh_{simulated,i} \right|^2$$

Estimate the quality of a solution from a probability inversely proportional to the objective fct value *e.g.*

$$p(X_i) = \frac{\sum_{j \neq i} f(X_j)}{\sum_{j} f(X_j)}$$

Genetic-based characterization of fractured reservoirs from interpreted well tests

Crossover process:

- Select a proportion *Pc* of the population according to their probabilities *p(X)*.
- From two given parents, two offsprings are defined according to:

$$\begin{cases} (O_1)_i & = & \alpha_i (P_1)_i + (1-\alpha_i)(P_2)_i \\ (O_2)_i & = & (1-\alpha_i)(P_1)_i + \alpha_i (P_2)_i \end{cases}$$

where $(O_1)_i$ is the *i*-th property of the offspring 1, and α_i is a random number between 0 and 1.

Genetic-based characterization of fractured reservoirs from interpreted well tests

Mutation process:

- Select a proportion *Pm* of the population according to their probabilities *p(X)*.
- For each solution, a new solution is defined by modifying randomly a property as:

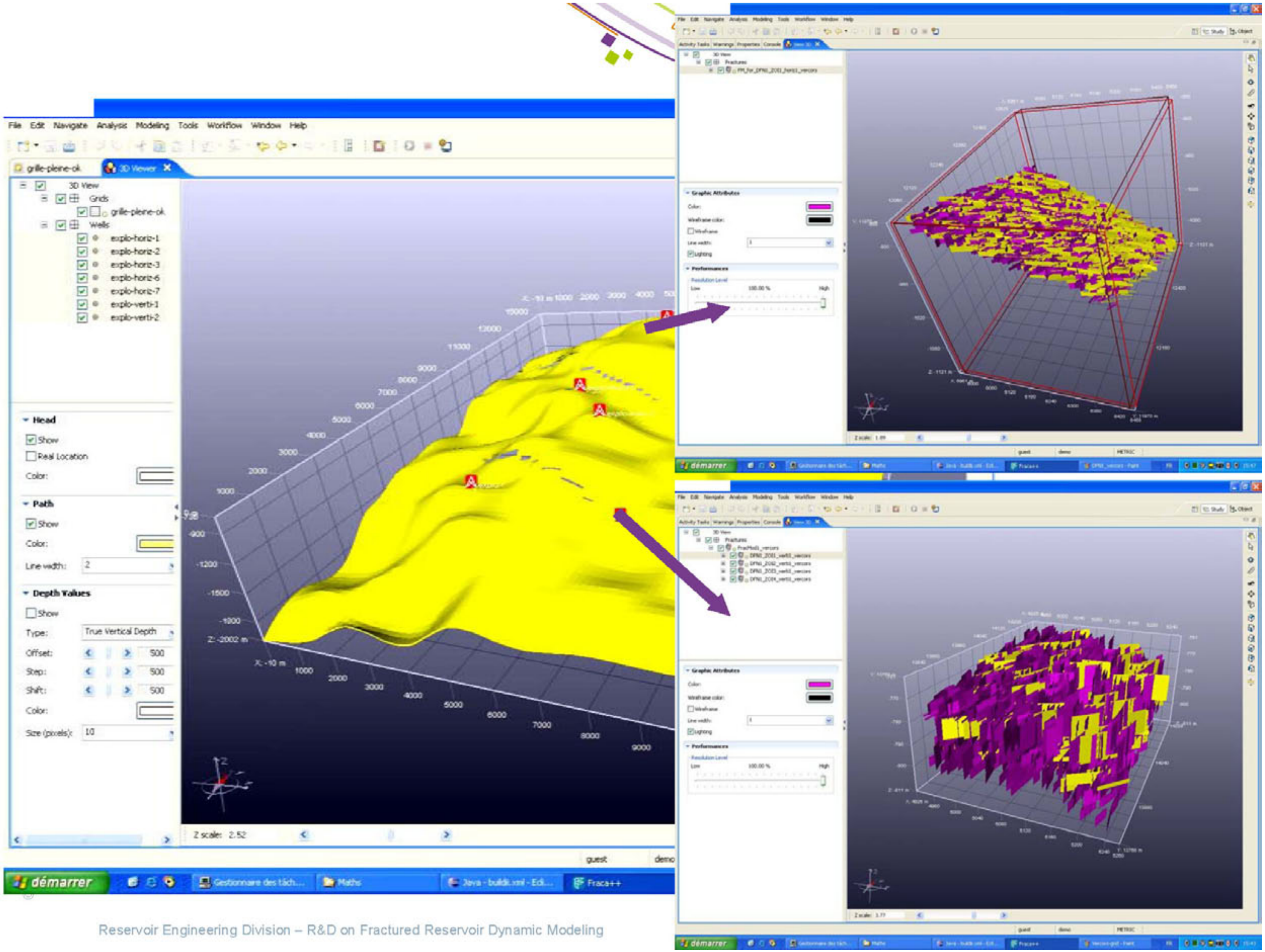
$$X_i^{'} = X_{i,Min} + \alpha(X_{i,Max} - X_{i,Min})$$

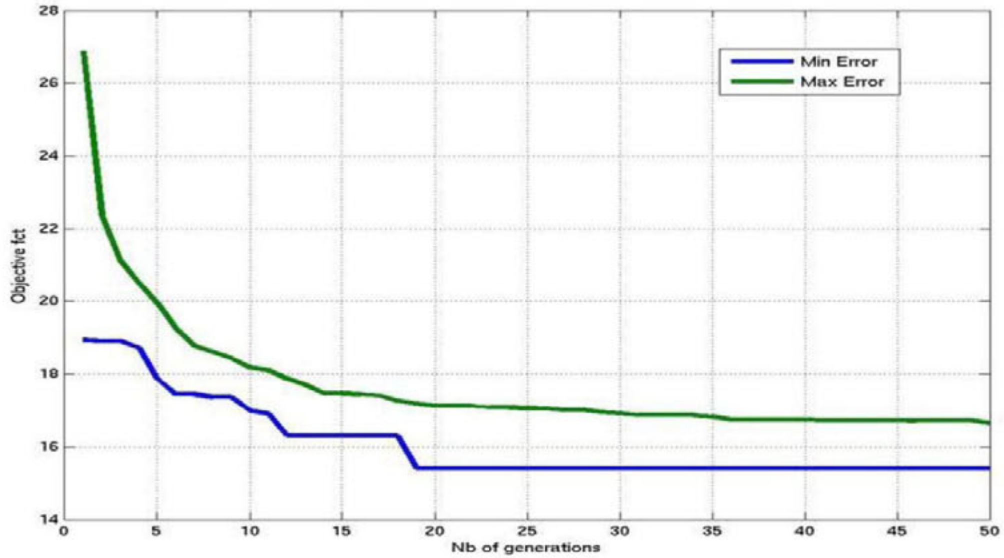
where $X_{i,Min}$ is the min. value of the *i*-th property of solution *X*, and α is a random number between 0 and 1.

Algorithm complexity: proportional to

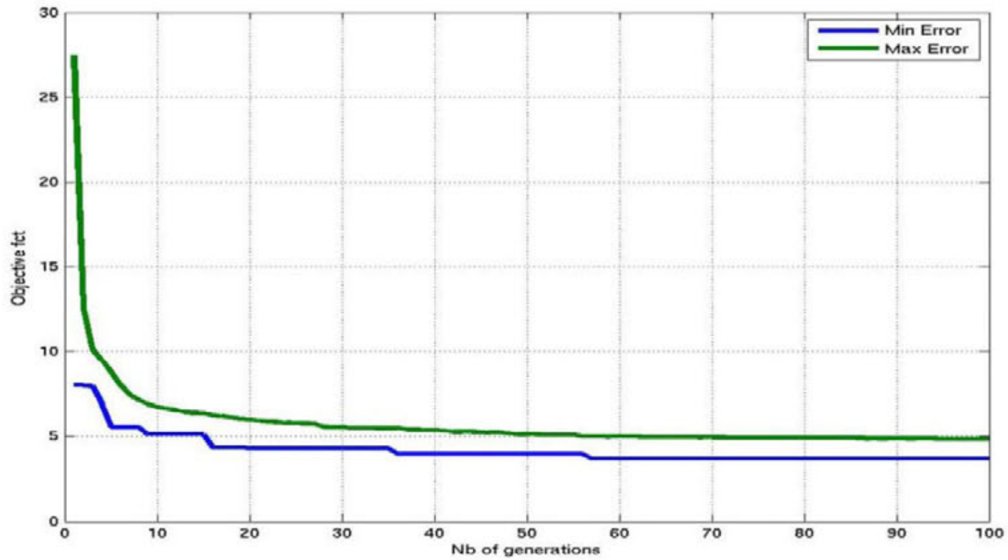
$$\Sigma wells\_nb*(2*Pc+Pm)*nb\_sol(k)*C_{km}$$

where C_{km} is the complexity of the knowledge model, Σ is the sum over the generations.


File Edit Navigate Analysis Modeling Tools Workflow Window Help
grille-pleine-ok
3D Viewer
3D View
Grids
grille-pleine-ok
Wells
explo-horiz-1
explo-horiz-2
explo-horiz-3
explo-horiz-6
explo-horiz-7
explo-verti-1
explo-verti-2
Head
Show
Real Location
Color:
Path
Show
Color:
Line width:
2
Depth Values
Show
Type:
True Vertical Depth
Offset:
500
Step:
500
Shift:
500
Color:
Size (pixels):
10
Z scale: 2.52
guest
demo
démarrer
Gestionnaire des tâch...
Maths
Java - build.xml - Edi...
Fraca++



Pc=85%
Nb_Gen=50
Nb_init=10
Nb_max=20



Pc=85%
Nb_Gen=100
Nb_init=10
Nb_max=30

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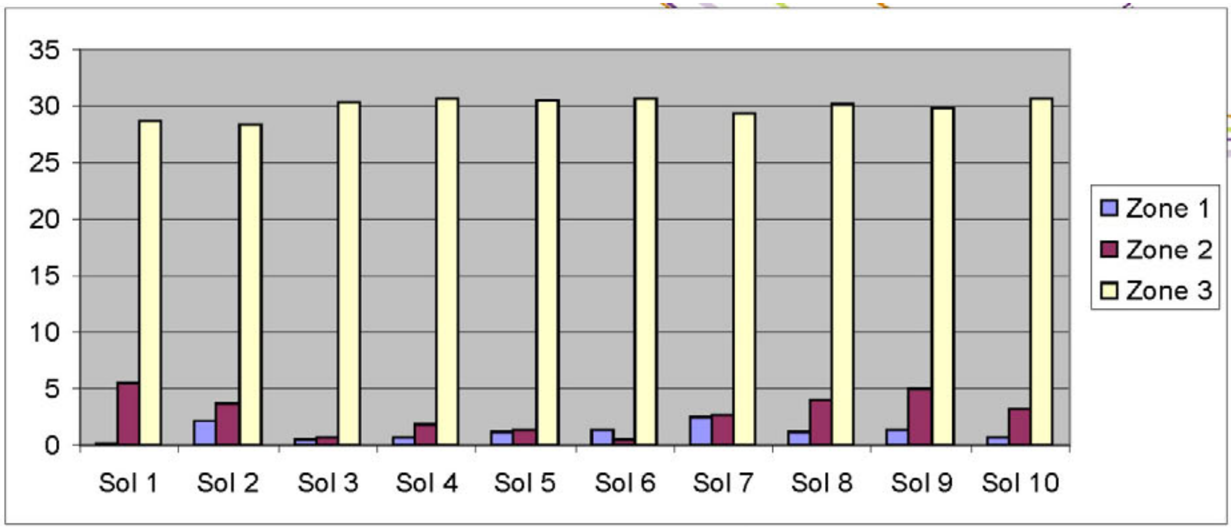
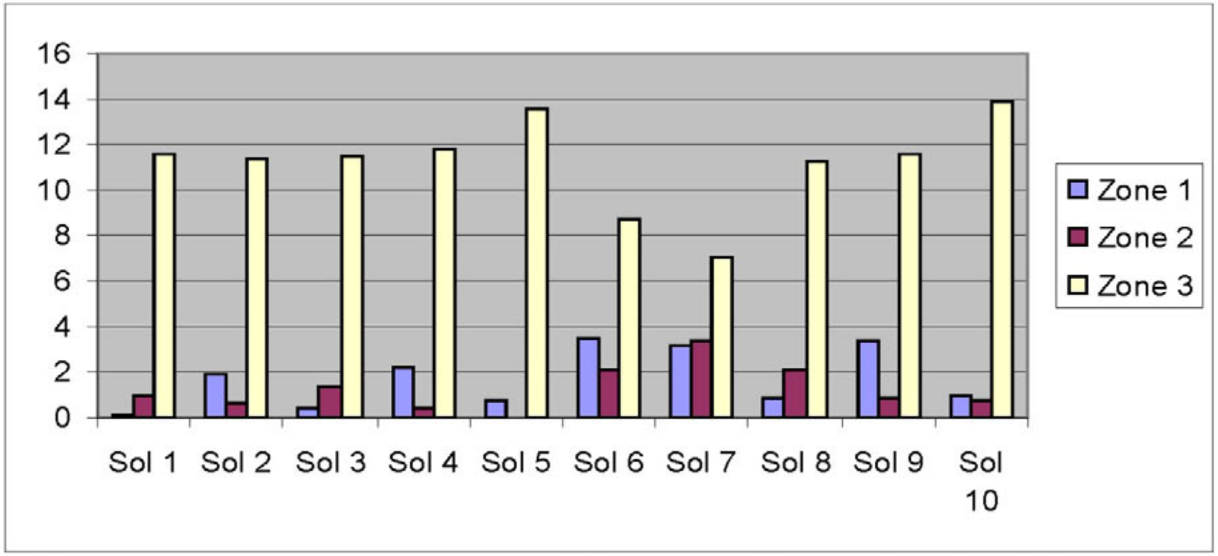


Measured data:
K1=1255 mD
K2=1775 mD
K3=425 mD

Relative error on Kh per zone for the 10 best solutions for Case 1



Relative error on Kh per zone for the 10 best solutions for Case 2

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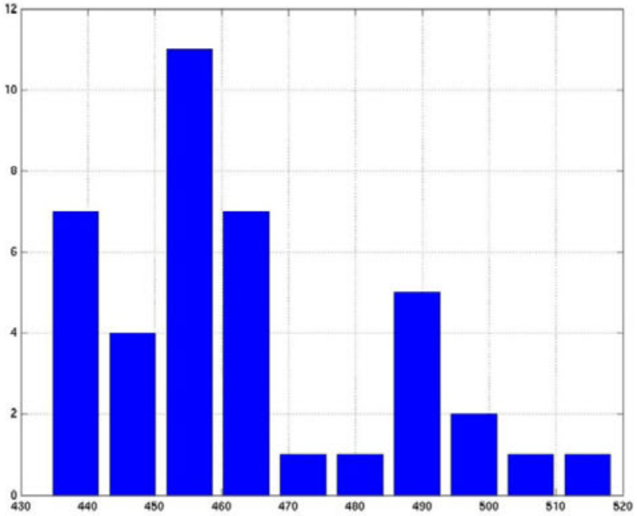
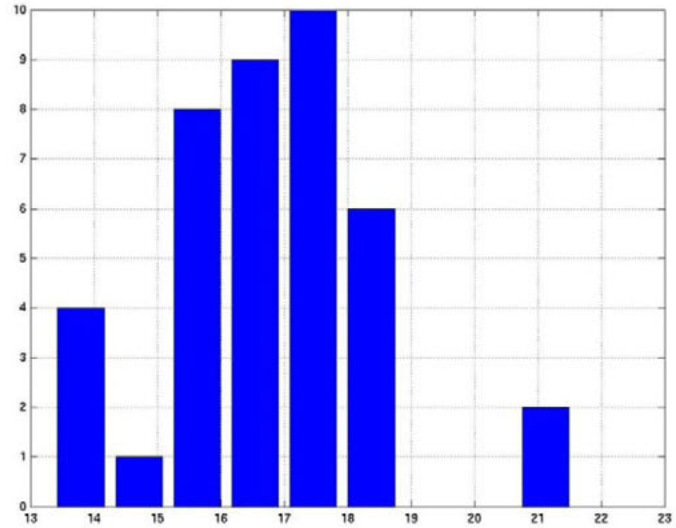
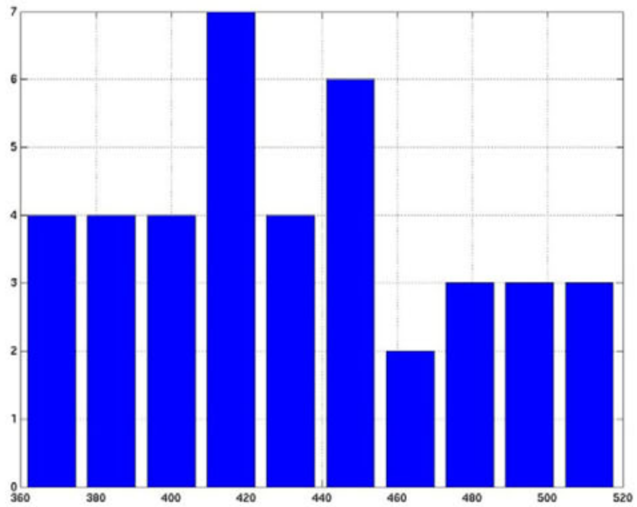


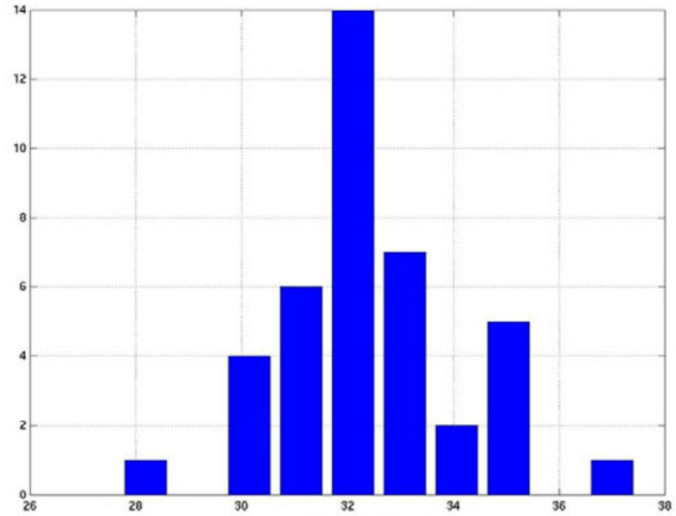
Conductivity 1



Length 1

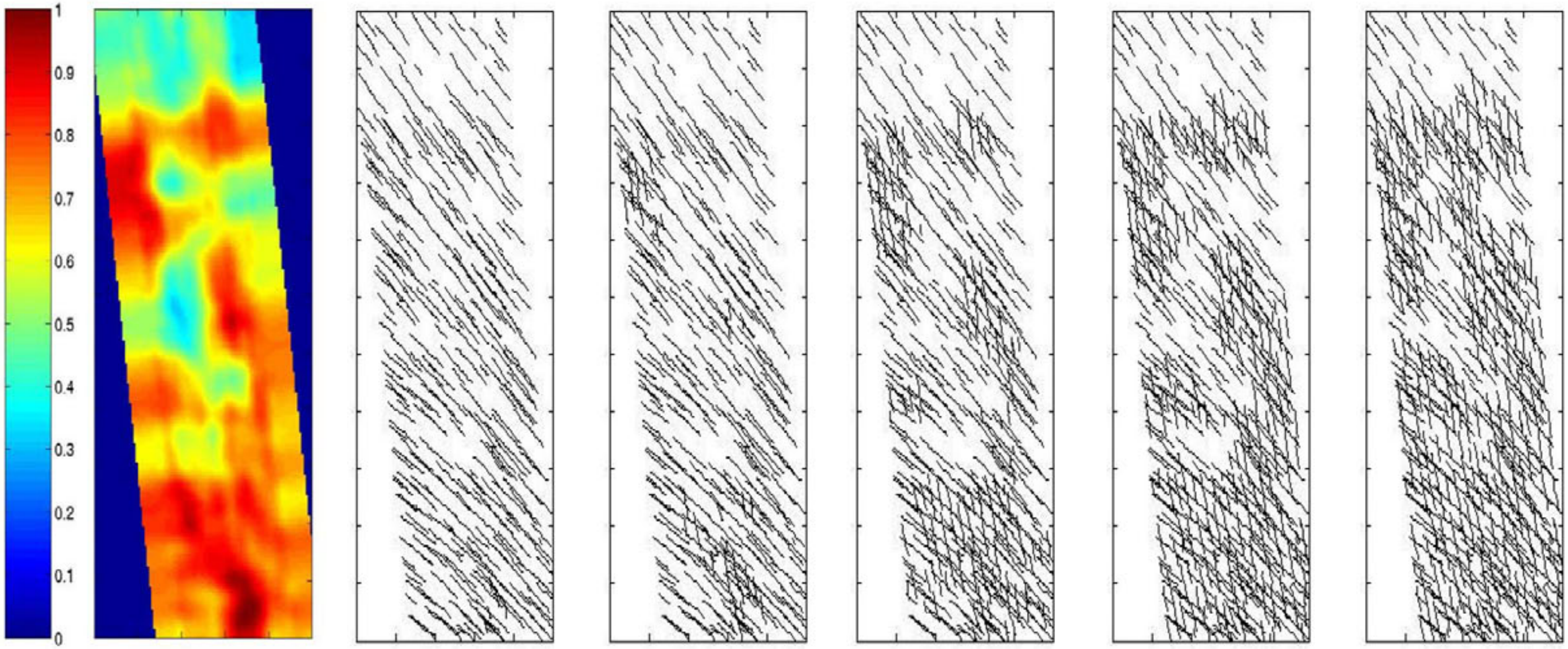


Density 1 Facies 2



Density 1 Facies 3

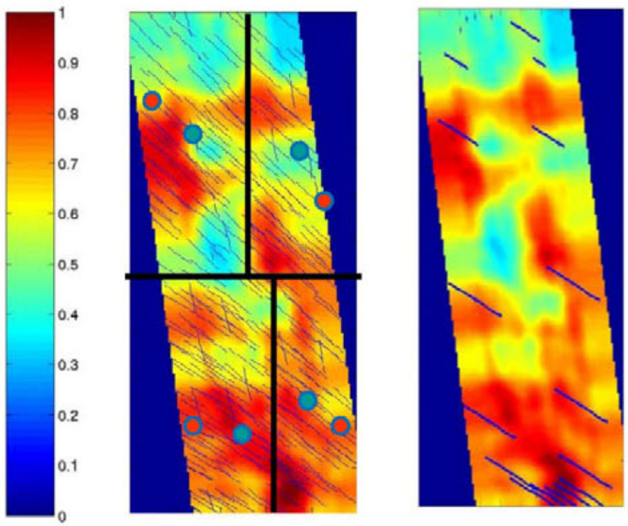
Calfrac Project:
History Matching of the Geometry of Fracture Networks

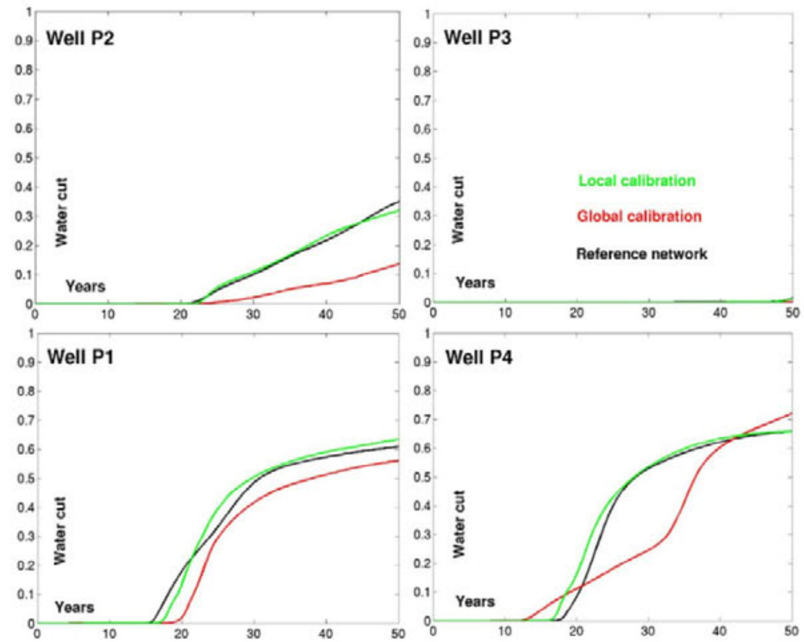


Geological Model of Large-Scale Fractures

Calfrac Project:

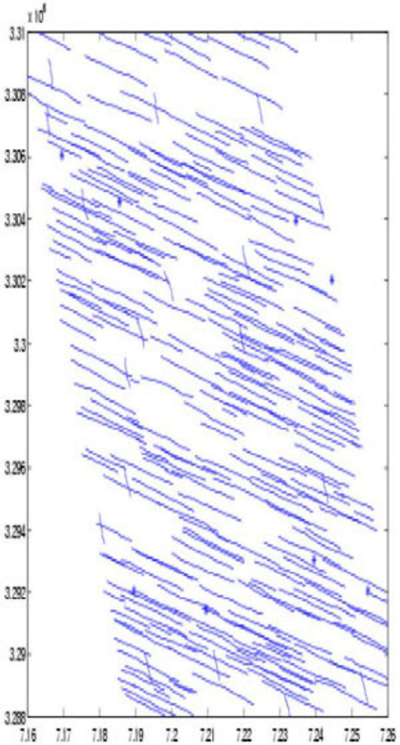
History Matching of the Geometry of Fracture Networks



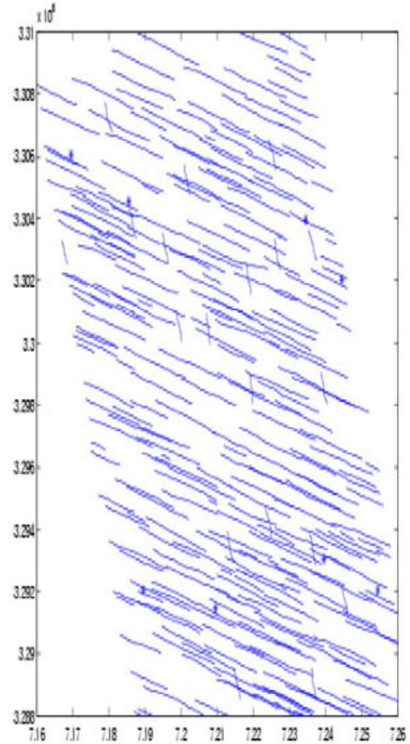


Calfrac Project:

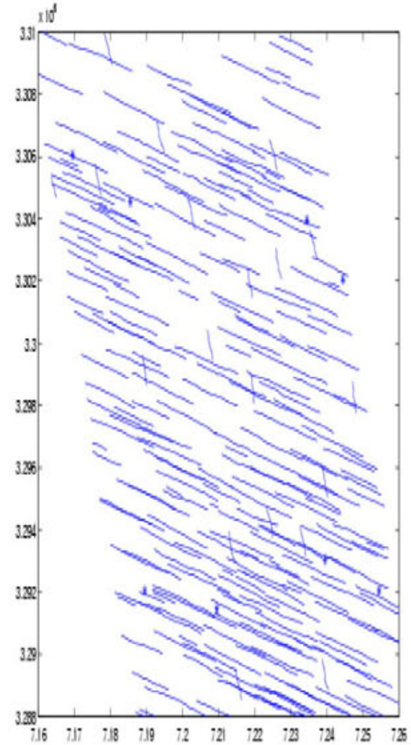
History Matching of the Geometry of Fracture Networks



Initial network



Global calibration



Local calibration

Comparison between stochastic fracture networks

Future perspectives

- Multiphase flow simulation on DFN at realistic scales:
  IOR/EOR on DFN, pseudo-kr/Pc, high P-T conditions

- Geomechanics

- Computational cost issue: adapted method for simplifying DFN ?

- Automated calibration of production data
  (parametrization, optimization techniques, classification...)

- Impact of uncertainties (from measurements, model...)
  on fracture properties estimates

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Acknowledgements

Industry sponsors:

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Main contributors:

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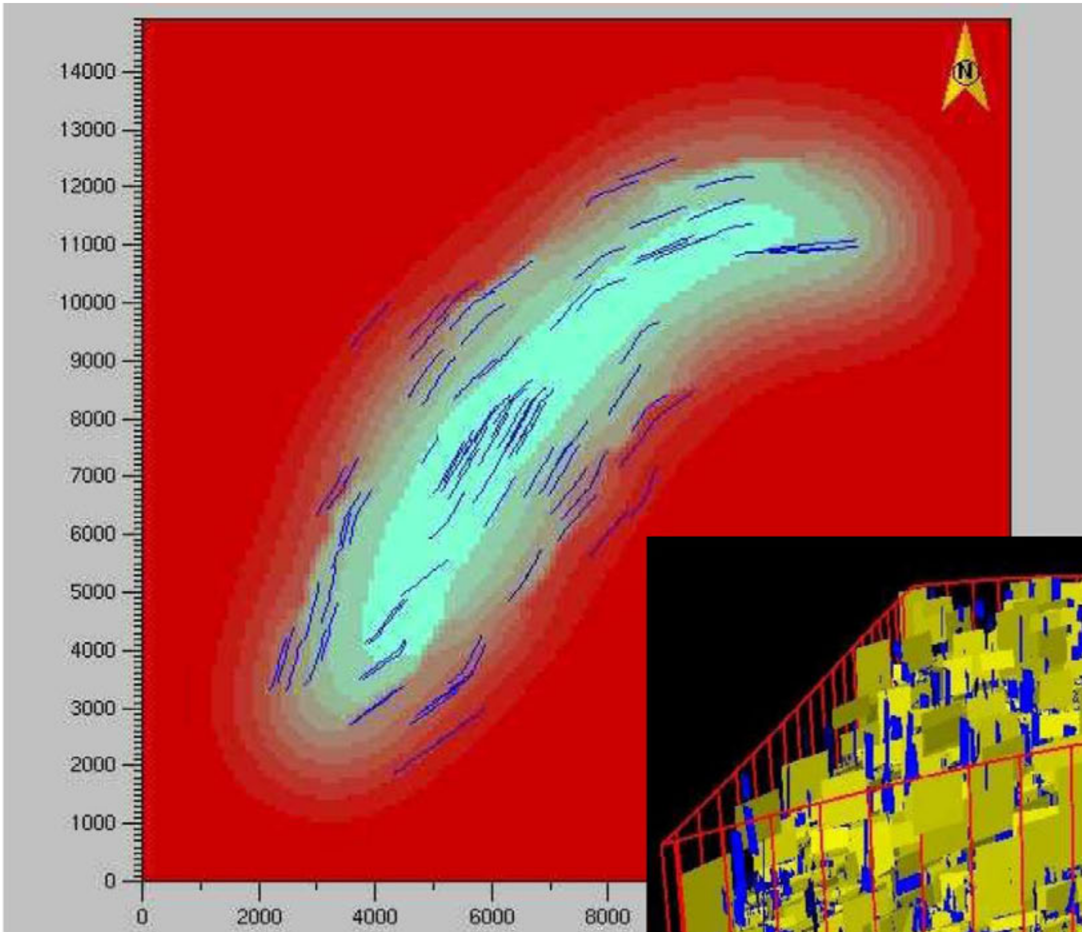
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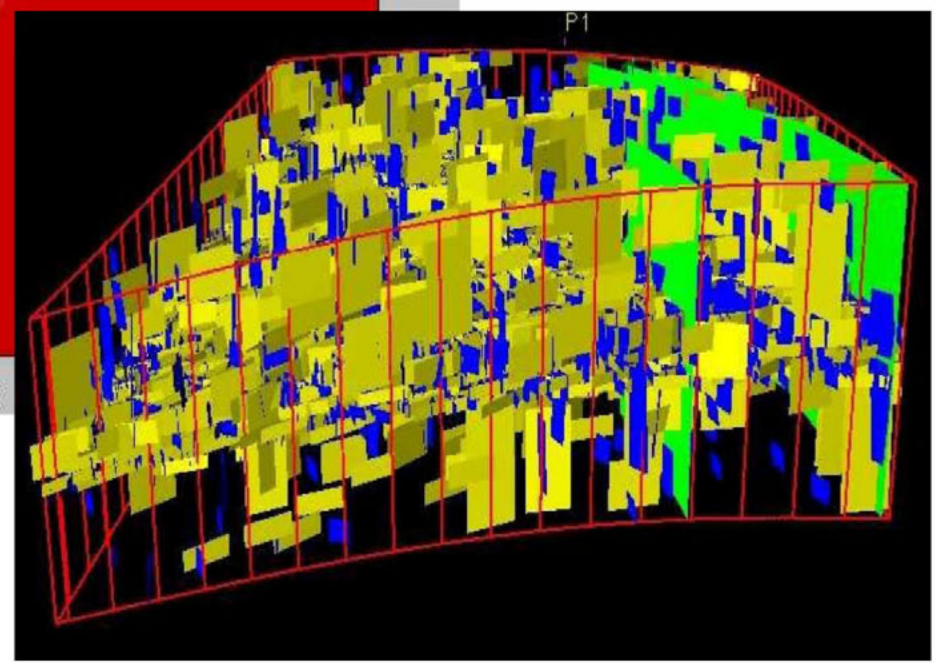
P1

References on Transport Simulation

1. Berkowitz B. and Zhou J.: "Reactive solute transport in a single fracture", *Water Resour. Res.*, **32**(4), pp. 901-913 (1996).

2. Gerke H.H. and Van Genuchten M.T.: "Evaluation of a First Order Water Transfer Term for Variably Saturated Dual-Porosity Flow Models", *Water Resources Res.*, **29**, April 1993.

3. Bodin J., Delay F. and De Marsily G.: "Solute transport in fissured aquifers: 2.Mathematical formalism", *Hydrogeology J.*, **11**(4), pp. 434-454 (2003).

4. Viallon M.C.: "Etude des schémas double-amont et éléments finis discontinus P0P1 pour la résolution numérique des lois de conservation scalaires", Thèse Univ. St-Etienne, June 1989.

5. Goldberg D.E., "Genetic algorithms in search, optimization and machine learning", Reading (Pa.): Addison-Wesley Ed., 1989.

Publications

1. Lange A., Bouzian J. and Bourbiaux B.: "Tracer-Test Simulation on Discrete Fracture Network Models for the Characterization of Fractured Reservoirs", SPE 94344 (2005). EAGE/SPE Europec 2005.

2. Basquet R., Cohen C.E. and Bourbiaux B.: "Fracture Flow Property Identification: an Optimized Implementation of Discrete Fracture Network Models", SPE 93748 (2005). 14th SPE MEOS 2005.

3. Lange A., Basquet R. and Bourbiaux B.: "Hydraulic Characterization of Faults and Fractures Using a Dual Medium Discrete Fracture Network Simulator", SPE 88675 (2004). 11th ADIPEC 2004.

4. Basquet R., Jeannin L., Lange A., Bourbiaux B and Sarda S.: "Gas Flow Simulation in Discrete Fracture Network Models", *SPE Res. Eval. & Eng.*, pp.378-384, Oct. 2004.

5. Jenni S., Lin Y.H., Basquet R., De Marsily G. and Bourbiaux B.: "History matching of stochastic models of field-scale fractures: methodology and case study", SPE 90020 (2004). SPE ATCE 2004.

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3D Dual-Porosity Flow Model on DFN

Numerical scheme :

$$\begin{cases} \nabla \cdot \left(k_f \nabla P_f\right) + \alpha_{mf}\left(P_m - P_f\right) = c_f \cdot \mu_o \cdot \phi_f \cdot \dfrac{\partial P_f}{\partial t} \ , \\ \nabla \cdot \left(k_m \nabla P_m\right) - \alpha_{mf}\left(P_m - P_f\right) = c_m \cdot \mu_o \cdot \phi_m \cdot \dfrac{\partial P_m}{\partial t} \ , \end{cases}$$

$$\begin{cases} \left[\dfrac{c_f V_{f,i}\phi_{f,i}}{\Delta t} + \dfrac{T_{mf,i}}{\mu_o} + \sum\limits_k \dfrac{T_{ff,ik}}{\mu_o}\right] P_{f,i}^{n+1} - \sum\limits_k \dfrac{T_{ff,ik}}{\mu_o} P_{f,k}^{n+1} - \dfrac{T_{mf,i}}{\mu_o} P_{m,i}^{n+1} = Q_{f,i} + \dfrac{c_f V_{f,i}\phi_{f,i}}{\Delta t} P_{f,i}^{n} \\ \left[\dfrac{c_m V_{m,i}\phi_{m,i}}{\Delta t} + \dfrac{T_{mf,i}}{\mu_o} + \sum\limits_k \dfrac{T_{mm,ik}}{\mu_o}\right] P_{m,i}^{n+1} - \sum\limits_k \dfrac{T_{mm,ik}}{\mu_o} P_{m,k}^{n+1} - \dfrac{T_{mf,i}}{\mu_o} P_{f,i}^{n+1} = Q_{m,i} + \dfrac{c_m V_{m,i}\phi_{m,i}}{\Delta t} P_{m,i}^{n} \end{cases}$$

Notes by Presenter: A 2-pt scheme in space and the Euler scheme in time are applied to the system of diffusion equations. K and J are the neighbours indexes of the fracture cell I and its associated matrix block, respectively.

3D Dual-Porosity Flow Model on DFN

Numerical scheme :

$$\begin{cases} \left[\dfrac{c_f V_{f,i}\phi_{f,i}}{\Delta t} + \dfrac{T_{mf,i}}{\mu_o} + \sum_k \dfrac{T_{ff,ik}}{\mu_o}\right] P_{f,i}^{n+1} - \sum_k \dfrac{T_{ff,ik}}{\mu_o} P_{f,k}^{n+1} - \dfrac{T_{mf,i}}{\mu_o} P_{m,i}^{n+1} = Q_{f,i} + \dfrac{c_f V_{f,i}\phi_{f,i}}{\Delta t} P_{f,i}^{n} \\ \left[\dfrac{c_m V_{m,i}\phi_{m,i}}{\Delta t} + \dfrac{T_{mf,i}}{\mu_o} + \sum_k \dfrac{T_{mm,ik}}{\mu_o}\right] P_{m,i}^{n+1} - \sum_k \dfrac{T_{mm,ik}}{\mu_o} P_{m,k}^{n+1} - \dfrac{T_{mf,i}}{\mu_o} P_{f,i}^{n+1} = Q_{m,i} + \dfrac{c_m V_{m,i}\phi_{m,i}}{\Delta t} P_{m,i}^{n} \end{cases}$$

- Fracture-to-fracture transmissivity: $T_{ff} = \sum_i \dfrac{C_i \cdot l_i}{L}$,
- Matrix-to-fracture transmissivity:

$$T_{mf} = \frac{2 \cdot l_f \cdot H \cdot k_m}{D}, \quad D = \frac{1}{N}\sum_{i=1}^{N} d_i \ ,$$

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Notes by Presenter : The fracture-to-fracture transmissivity is simply computed from the fracture conductivity, the length of the borderline between the fracture cells, and the distance between the fracture nodes.

The matrix-to-fracture transmissivity is computed from the matrix permeability, the matrix-to-fracture exchange surface and the average distance between the fracture cell and its matrix block horizontal area.

Therefore the matrix-to-fracture transmissivity is dependent on the local network geometry, it is not homogenized.

3D Dual-Porosity Flow Model on DFN

Single-Permeability Model : $T_{mm} = 0$

$$\left[A_{f,i} + \frac{A_{m,i} \cdot U_{m,i}}{A_{m,i} + U_{m,i}} + \sum_k \frac{T_{ff,ik}}{\mu_o}\right] P_{f,i}^{n+1} - \sum_k \frac{T_{ff,ik}}{\mu_o} P_{f,k}^{n+1} = Q_{f,i} + A_{f,i} \cdot P_{f,i}^{n} + \frac{A_{m,i} \cdot U_{m,i}}{A_{m,i} + U_{m,i}} P_{m,i}^{n}$$

with: $A_{f,i} = \dfrac{c_f \cdot \phi_{f,i} \cdot V_{f,i}}{\Delta t}$, $A_{m,i} = \dfrac{c_m \cdot \phi_{m,i} \cdot V_{m,i}}{\Delta t}$, $U_{m,i} = \dfrac{T_{mf,i}}{\mu_o}$.

- Twice less unknowns to be computed
- For dense and well connected fracture networks
- Matrix medium acts as a source of fluids only

Notes by Presenter : Both single and dual permeability models were developed so that the single-phase flow response of any type of fractured reservoir, whatever the scale, density and connectivity of fractures can be computed.
In the single-permeability model, the matrix-to-matrix flow is neglected, leading to an explicit relation between matrix and fracture pressures.
Therefore only one equation needs to be solved for determining the full pressure field.
This model is usually valid for a dense and well connected fracture network only, where the matrix medium only acts as a source of fluids.

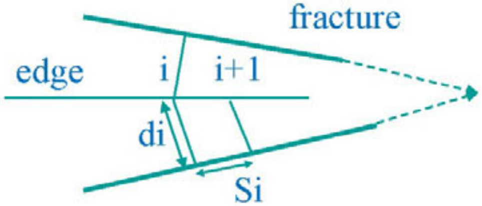
3D Dual-Porosity Flow Model on DFN

Double-Permeability Model : $T_{mm} \neq 0$

- **Horizontal transmissivities:**

Case 1 : edge not crossed by a fracture :

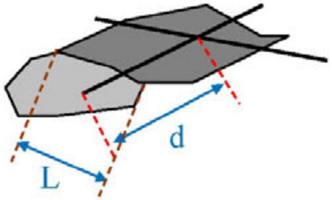
$$T_{mm} = K_m H \int_L dl/2d(l)$$



dl : elementary edge length,
d(l) : fracture-edge distance at l

Case 2 : edge crossed by a fracture :

$$T_{mm} = K_m H\, L/d$$



K_m : matrix permeability, H : stratum thickness,
L : edge length, d : computational nodes interdistance.

Notes by Presenter: In the dual-permeability model, the matrix-to-matrix flow is considered. Thus matrix-to-matrix transmissivities have to be computed.
The horizontal transmissivities are computed according to the following formula (explain).
However a simplification occurs if the matrix edge is crossed by a fracture.
In this case, as the fracture-to-fracture transmissivity is usually much larger than the matrix-to-matrix one, the expression is simplified according to this formula, using the nodes interdistance.

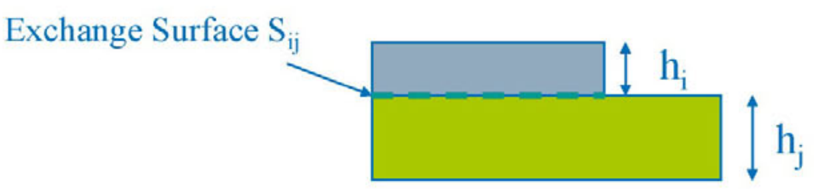
3D Dual-Porosity Flow Model on DFN

Double-Permeability Model : $T_{mm} \neq 0$

- **Vertical transmissivities:**

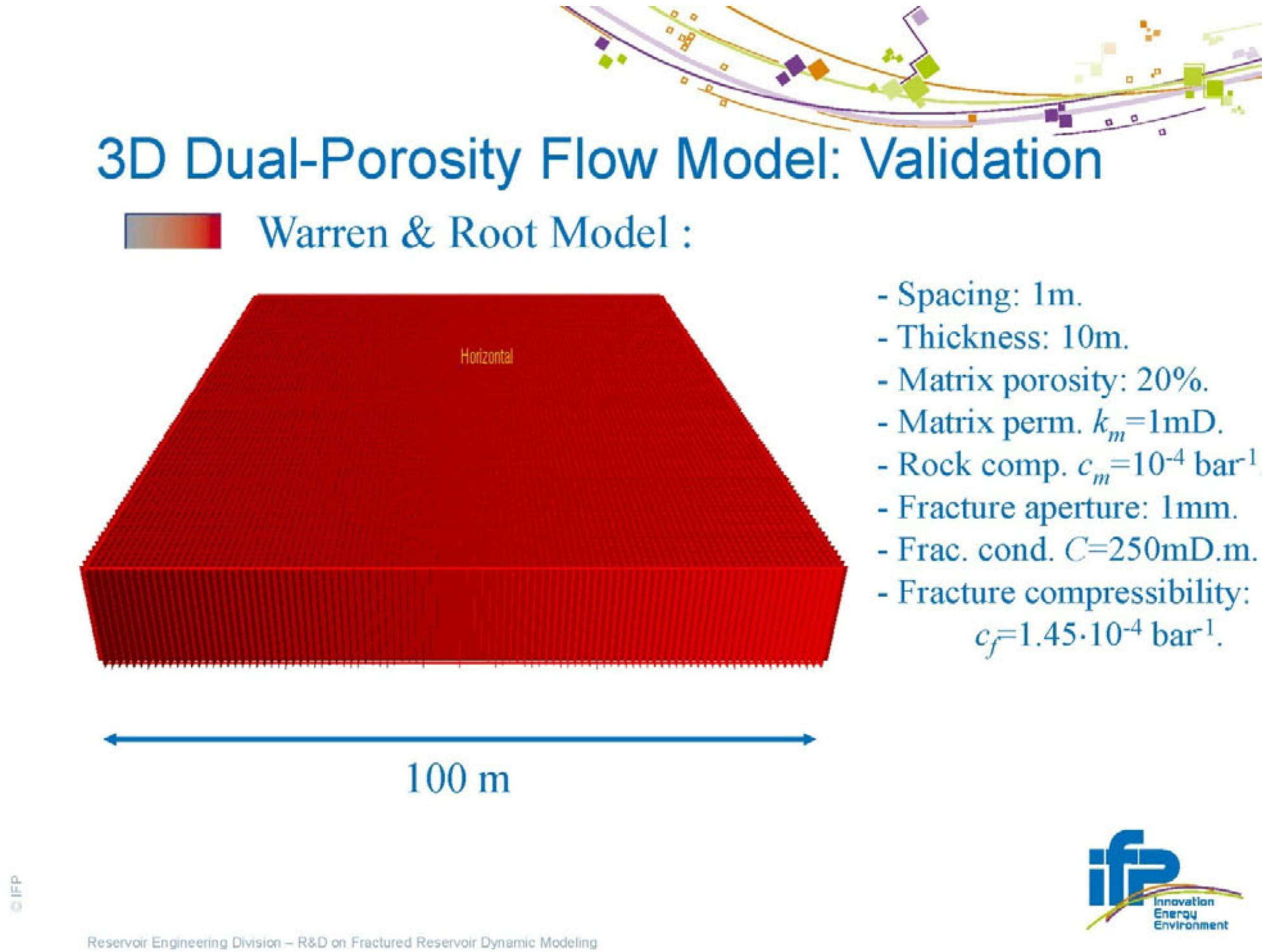
$$T_{ij}^{V} = \frac{2S_{ij}K_{V,i}K_{V,j}}{h_i K_{V,j} + h_j K_{V,i}}$$

Kv : vertical permeability, h : stratum thickness



Notes by Presenter: The vertical matrix-to-matrix transmissivity is computed according to a geometrical average of the vertical matrix permeabilities weighted by the layers thickness and the horizontal exchange surface.

The dual-permeability model is valid for any type of fractured reservoir, however its computational cost is at least twice larger than the single-permeability model. Indeed both pressures in the matrix and fracture network are unknowns, and the matrix-to-matrix transmissivities have to be computed on a large number of complex matrix blocks.

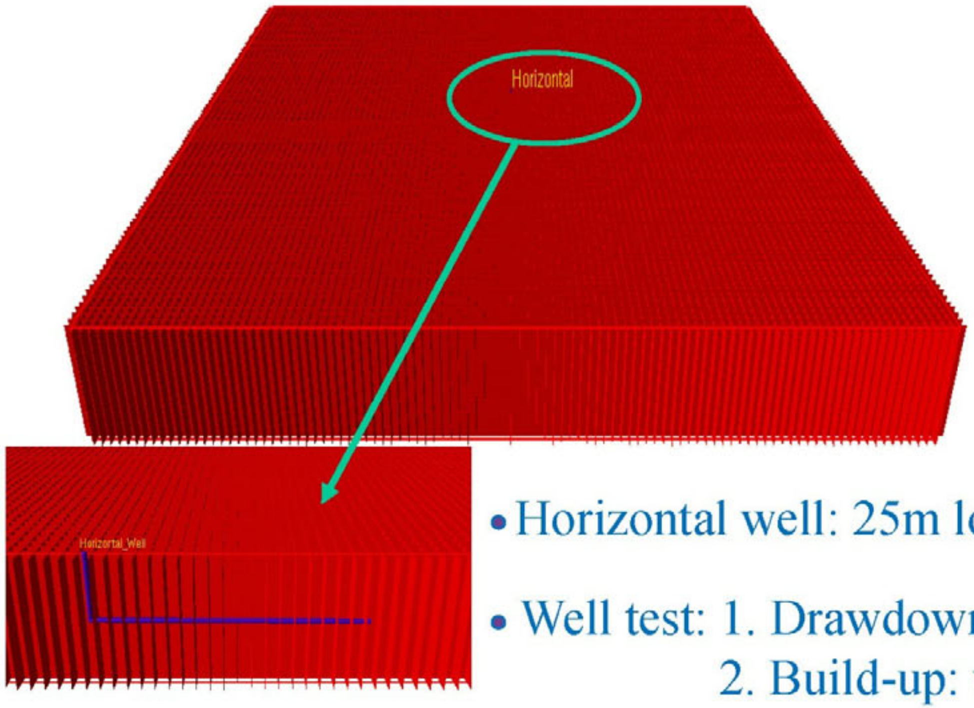


Notes by Presenter: A dense Warren & Root model is first considered for validating the dual-porosity, single-permeability model against existing analytical solutions, and verifying that the dual-permeability model does provide the same solutions.

A regular Cartesian fracture network composed of 100 vertical fractures with a spacing of 1m in each horizontal direction is constructed. This 2D fractured medium has the following characteristics...

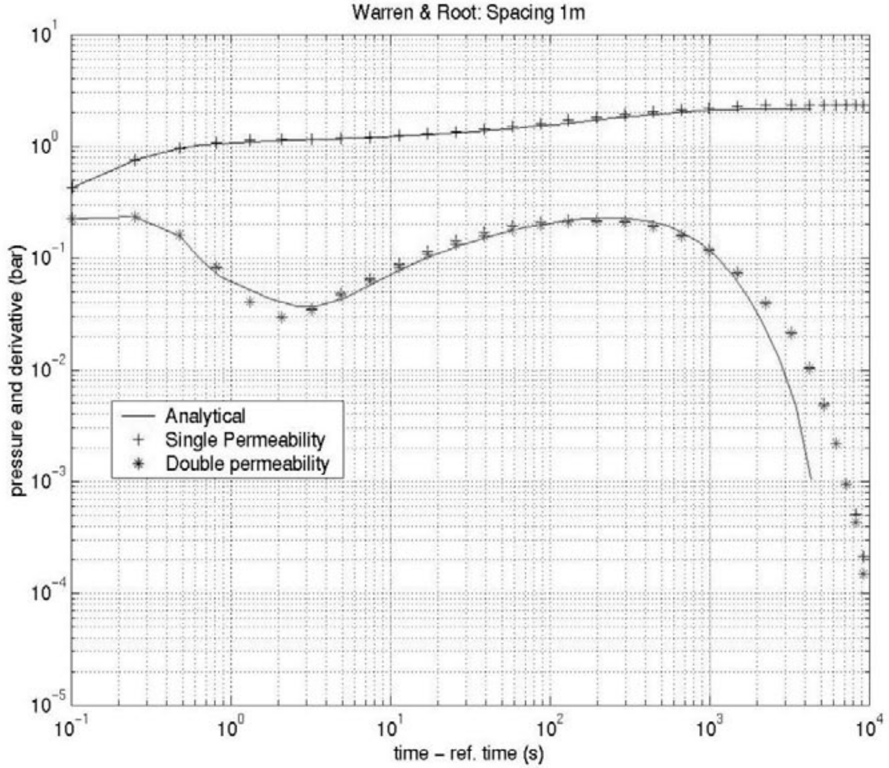
3D Dual-Porosity Flow Model: Validation

Warren & Root Model : Dense Fracture Network



- Horizontal well: 25m long
- Well test: 1. Drawdown: 100m^3/d during 10h.
  2. Build-up: well closed during 14h.

Notes by Presenter: A 25m long horizontal well is defined at the centre of the fracture network. A well test is performed with the following flow rate history...



Validation of the single- and dual-permeability models via an analytical solution for a dense fracture network.

Notes by Presenter: Pressure buildup and derivative curves are plotted, together with an analytical solution combining Gringarten's double porosity method and a horizontal well treatment.

The behaviour of the numerical and analytical solutions are very close, thus validating the single-permeability model, as well as the dual-permeability model in the case of a dense connected fracture network.

3D Dual-Porosity Flow Model: Application

- **Matrix Properties:**

- Porosity =20%,
- Permeability k_m=1mD,
- Rock compressibility $c_m=10^{-4}$ bar^{-1}.

- Fracture compressibility**:** $c_f=1.45\cdot10^{-4}$ bar^{-1}.
  - **Systematic Joint Sets Properties:**

	Set 1	Set 2	Set 3	Set 4
Mean Length	25m	12m	16m	6m
Aperture	1e-3 m	1e-3 m	1e-3 m	1e-3 m
Fisher dip & strike	1e20	60 & 30	60 & 30	1e20
Average Spacing	10 m	5 m	7 m	4 m
Mean conductivity	1000 mD.m	1000 mD.m	1000 mD.m	1000 mD.m
Azimuth & dip	110° & 90°	110° & 90°	130° & 90°	180° & 90°

- **Faults Properties:**

- Mean length: 200m,
- Aperture: $5\cdot10^{-3}$ m,
- Fisher dip and strike: 50,
- Fractal dimension: 1.6,
- Mean conductivity: 10^4 mD.m.

Notes by Presenter: The domain contains one set of faults and 4 sets of systematic joints with the following properties. All fracture lengths and conductivity distributions satisfy a log-normal law.