Dual Porosity, Dual Permeability Modeling of Carbonate Reservoir with Integration of Fracture Characterization*

Hugo Caetano[1], Reza Iskandar[1], Sahid Sutanto[1], Elena Niculescu[1], Magdy Hozayen[1], Umer Farooq[1], Vincent de Groen[2], Solenne Roosz[2], and Ghislain de Joussineau[2]

Search and Discovery Article #20366 (2016)**
Posted September 19, 2016

*Adapted from oral presentation given at AAPG GEO 2016, The 12th Middle East Geosciences Conference and Exhibition March 7-10, 2016, Manama, Bahrain

[1]SE, Abu Dhabi Company for Onshore Petroleum Operations, Abu Dhabi, United Arab Emirates (hcaetano@adco.ae)
[2]Beicip-Franlab, Paris, France

Abstract

Characterization of naturally fractured reservoirs is challenging due to its heterogeneous quality. An example is the complex fractured carbonate reservoir (Upper Cretaceous) in a field on-shore of Abu Dhabi. In order to control early water breakthrough problems caused by fracture connections to aquifer and resulting in reduced oil production and bypassed oil issues, a detailed dual porosity, dual permeability (DPDP) modeling study was conducted to accurately characterize and model both matrix and fracture properties occurrence.

Initially, the workflow involved an evaluation of Electrofacies (EF) for rock-typing definition, full integration of seismic and fracture characterization, sedimentology, sequence stratigraphy and diagenesis. Based on 43 wells, 11 EF have been defined (6 limestones, 3 calcitic dolomites, 1 shale, 1 dolomitized limestone) for the reservoir using DT, NPHI, RHOB and VCL logs. Poro-perm relations and capillary pressures have been defined for each EF. The seismic mapping conversion to depth insured proper horizontal wells placement in the model. Based on Impedance distributions of facies, most porous limestone (EF05) was discriminated from the rest. Therefore, a cube of predicted EF05 with attached probabilities was used in the geomodel.

Sedimentological and stratigraphical analysis assisted in defining 4th order sequences between main seismic horizons comprising of depositional, erosions and onlapping, helped to control facies distribution and created an exquisite framework.

Secondly, modeling of matrix properties with a nested approach where EF were simulated with pluri-gaussian methods provided a robust integration of seismic and diagenesis distribution. Petrophysical properties were simulated conditionally to the facies for Poro, Perm and Sw, based on the rock-types associations. Thirdly, the dynamically calibrated fracture model built previously, using seismic facies maps, fractures density map, rock facies and dynamic reservoir data measurements, has been used to define range of length, spacing and spatial distribution of the fracture system. Uncertainty analysis and upscaling was finally performed, where sensitivity analysis show a maximum 5% of variability from P50. Upscaling reduced 13M active cells to a dynamic case with 1.9M. The upscaled model will be dynamically modeled and historically matched in order to optimize location of new wells and trajectories for increased field production and delayed water breakthrough.

GEO 2016

12th Middle East Geosciences Conference and Exhibition

Conference: 7 – 10 March 2016

Exhibition: 8 – 10 March 2016

BAHRAIN INTERNATIONAL EXHIBITION AND CONVENTION CENTRE

شركة أبوظبي للعمليات البترولية البرية المحدودة (أدكـو)
Abu Dhabi Company for Onshore Petroleum Operations Ltd. (ADCO)

BeicipFranlab

"Dual Porosity, Dual Permeability Modeling of Carbonate Reservoir with Integration of Fracture Characterization"

Hugo Caetano, Reza Iskandar, Sahid Sutanto, Elena Niculescu, Magdy Hozayen, Umer Farooq - SE, ADCO, Abu Dhabi, UAE.
Vincent de Groen, Solenne Roosz, Ghislain de Joussineau - Beicip-Franlab, Paris, France.

AAPG

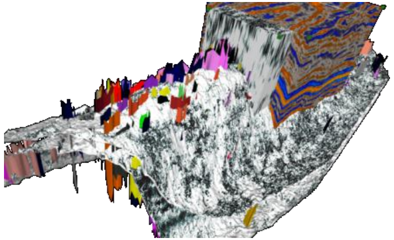
EAGE
EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS

SEG
Society of Exploration Geophysicists
The international society of applied geophysics

ادارة المعارض العربية
Arabian Exhibition Management

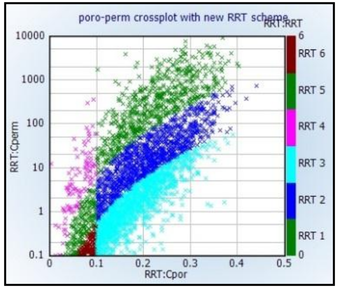
Workflow

- Studies Integration:



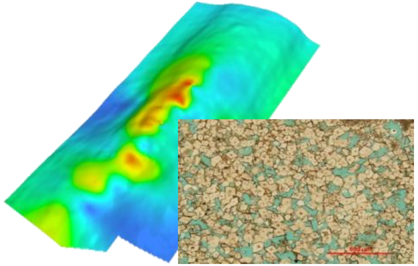
Seismic Studies

(Structure, Faults/Lineaments)



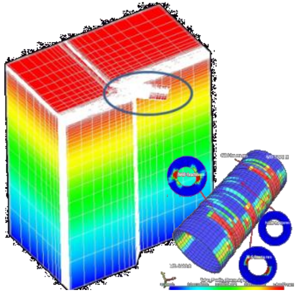
RRT Prediction Study

(Pc, Sw)



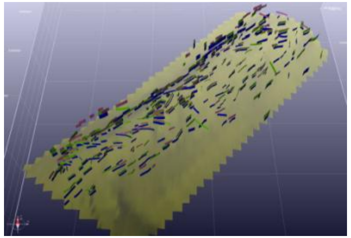
Diagenesis Study

(Alteration Processes, Dolomitization, Cementation)



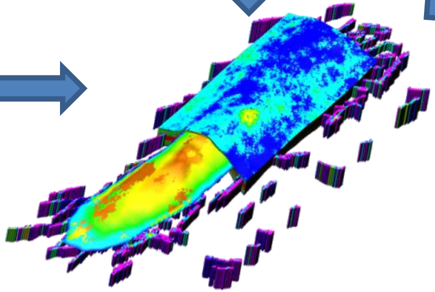
Geomechanic Study

(Wellbore Stability, K evolution, Well orientation)



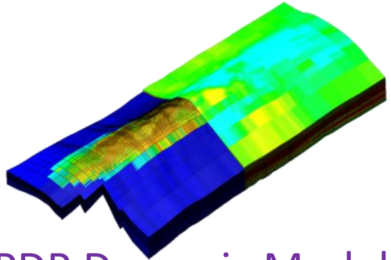
Fractures Characterization Study

(DFN Model)



DPDP Static Model

(Static properties in dual medium environment)



DPDP Dynamic Model

(FFDP Update, Development Scenarios)

Study Objectives

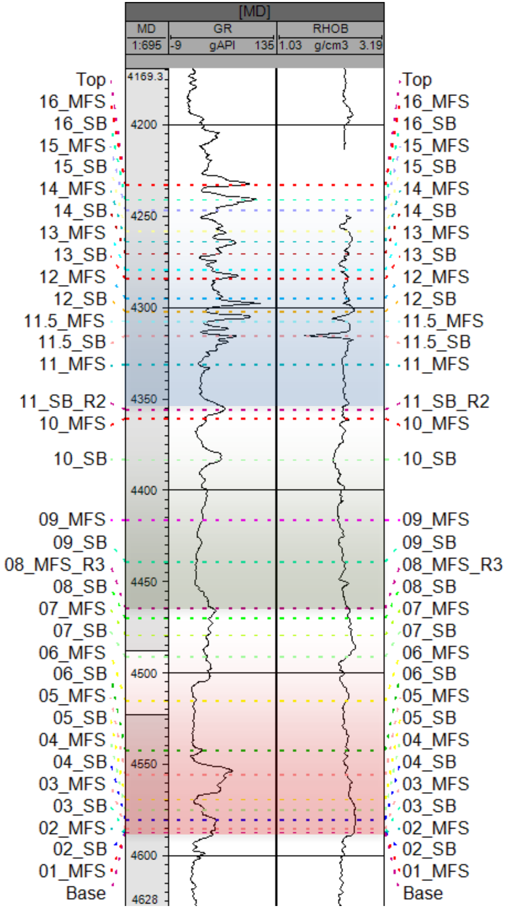
- Generate a Dual Porosity-Dual Permeability Static Model with natural fracture network integration based on Fracture Modeling Study done previously.
  (Caetano, H., Niculesco, E., Hozayen, M., Radwan, S., Farooq, U., Joussineau, G., Games, F., Haeck, T., Ibert, S., 2014, "Fracture Characterization of Carbonate Reservoir with Integration of Dynamic Data", SPE 171973, 2014 SPE/ADIPEC)
- Study Phases:
  - Geology analysis
  - Structure framework modeling
  - Property modeling incorporating fracture network
  - Uncertainty analysis
  - Upscaling assessment
- DPDP Static Model will be input for DPDP Dynamic Model to:
  - Optimize Development Plan
  - Increase Ultimate Recovery

Geology analysis

Paleo-environmental approach

- Results of seismic stratigraphic and sedimentological approaches allows us to define three main units and 32 parasequences based on paleo-environment:

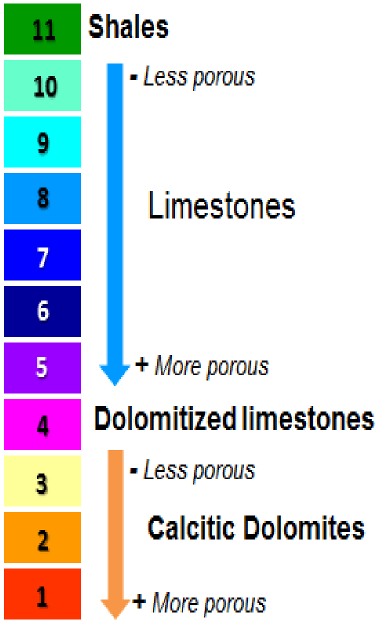
  - Lower Reservoir (Base Reservoir / Top Lower)
  - Middle Reservoir (Top Lower / Top Middle)
  - Upper Reservoir (Top Middle / Top Reservoir)

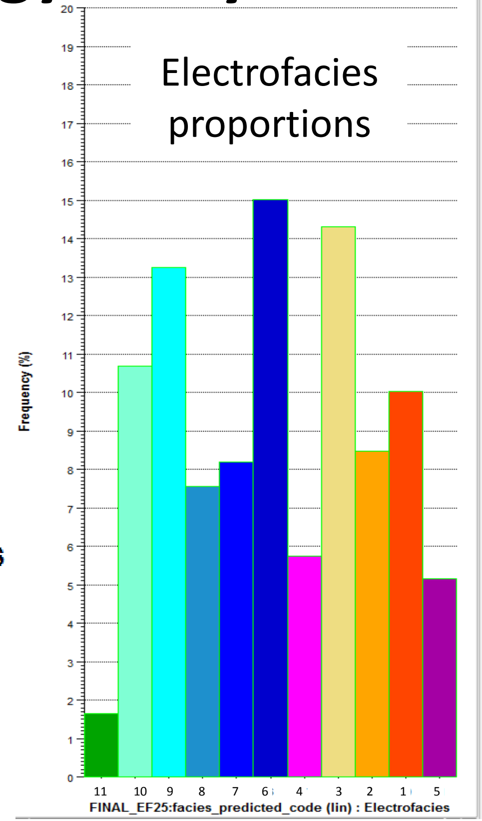


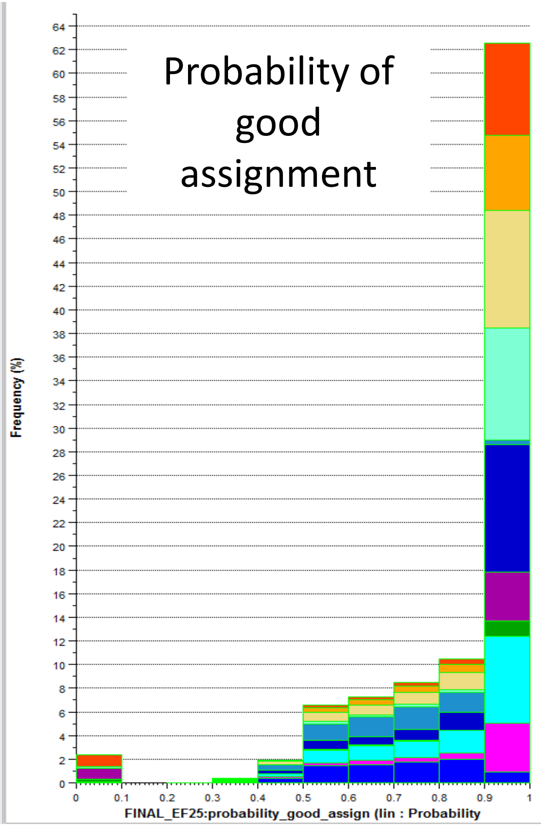
Geology analysis

Electrofacies Definition

- 11 Electrofacies defined based on:
  - Logs: DT, NPHI, RHOB and VCL.
  - Core plugs: Poro and K
  - Dynamic Data: k-phi / Pc



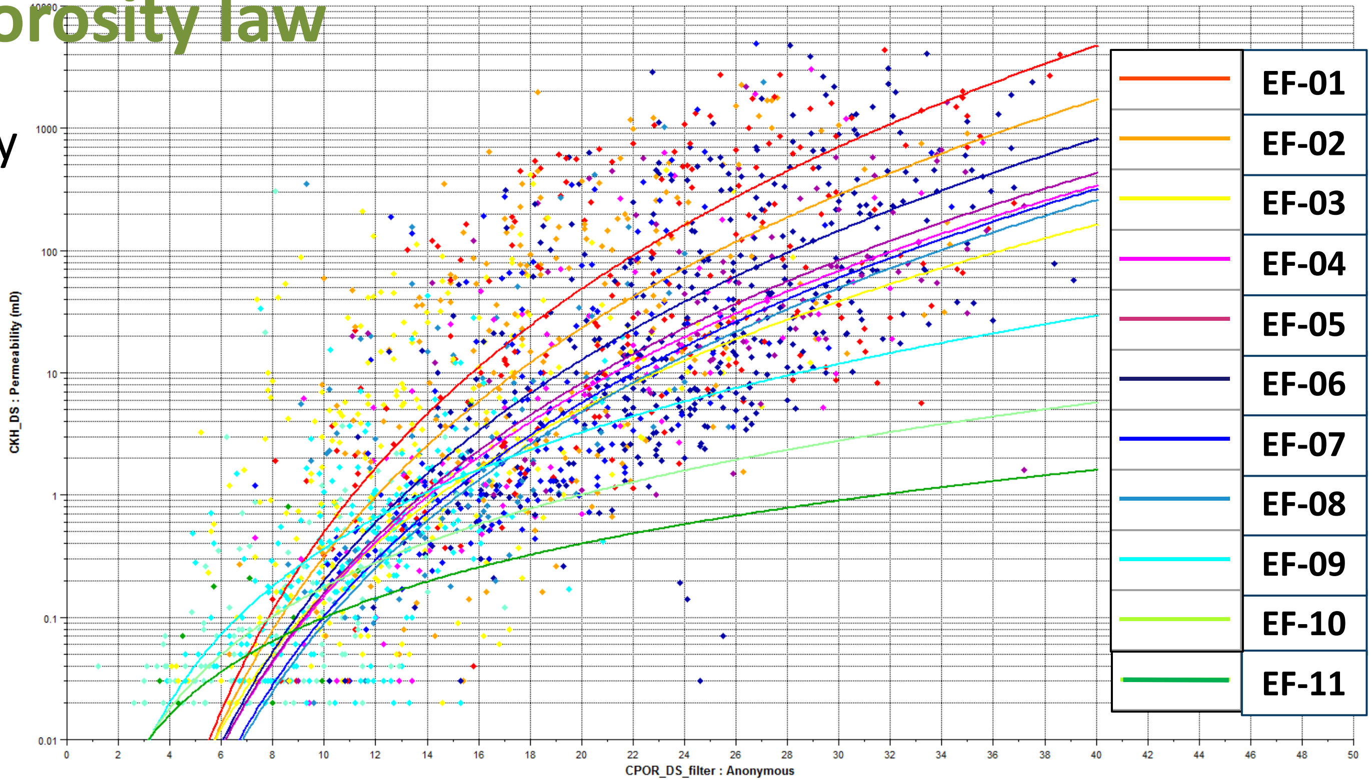




Geology analysis

Permeability – Porosity law

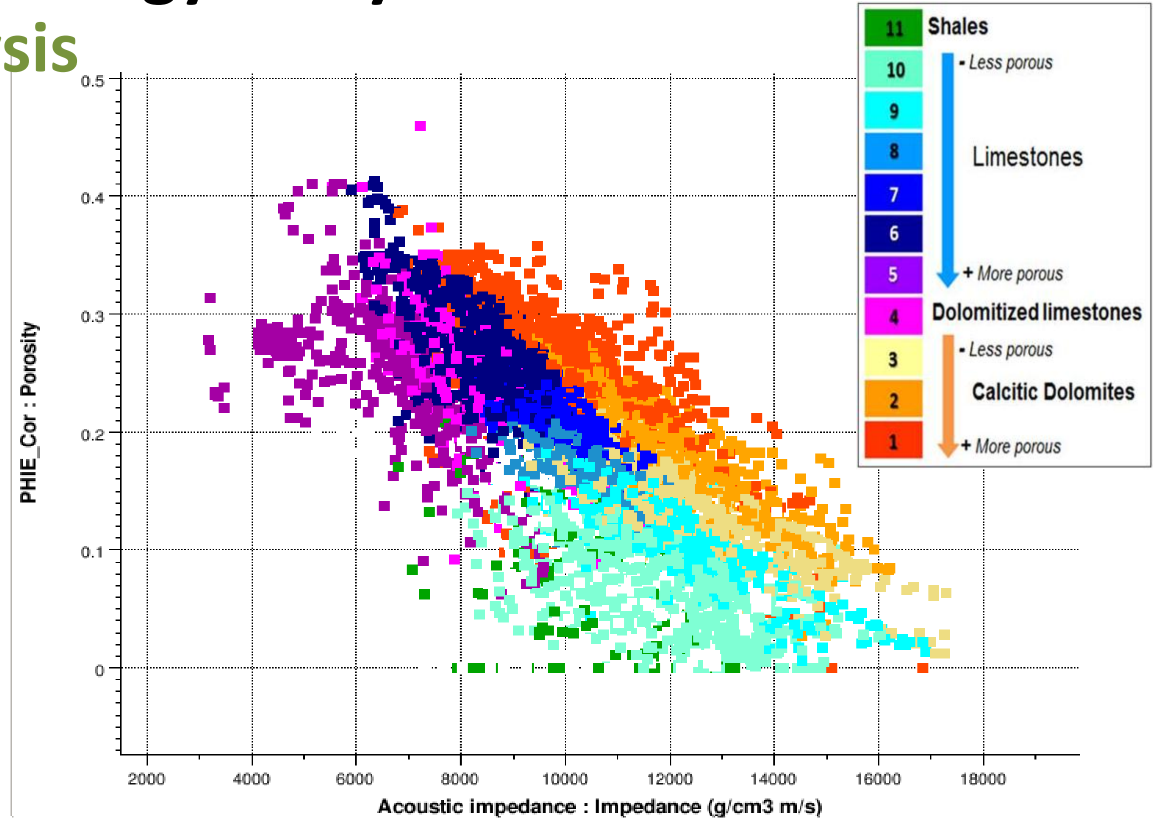
- Porosity-Permeability laws are being defined for each Electrofacies from cores.



Geology analysis

Seismic Inversion Analysis

- Combined impact of porosity and facies on acoustic impedance

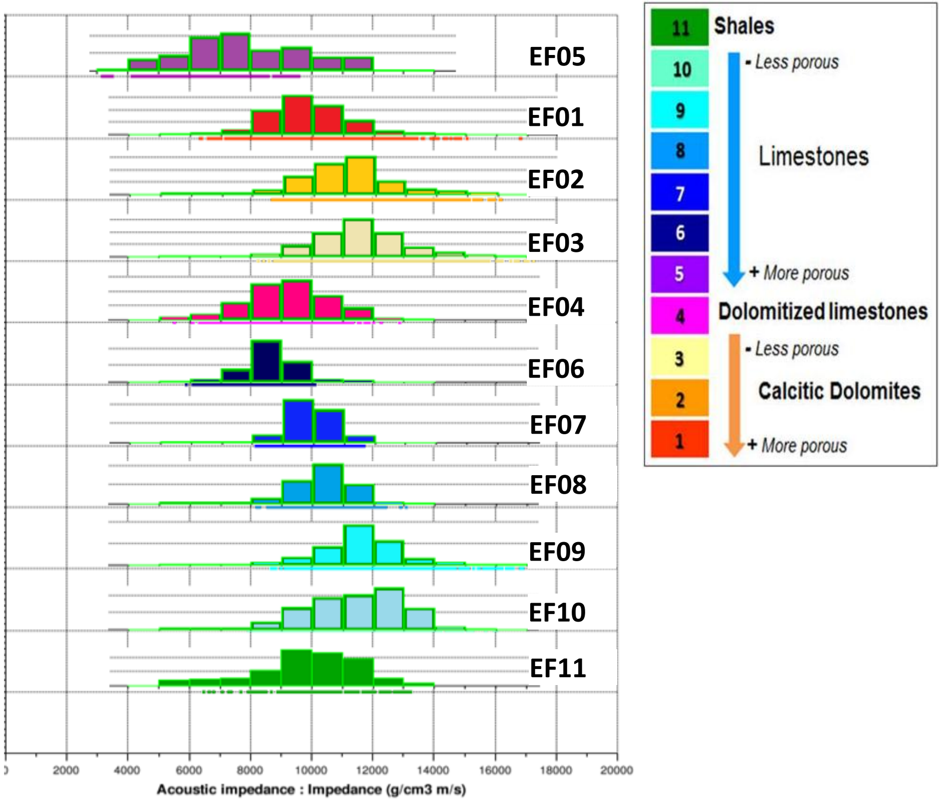


Geology analysis

Seismic Inversion Analysis

- Impedance distributions of facies are strongly overlapping

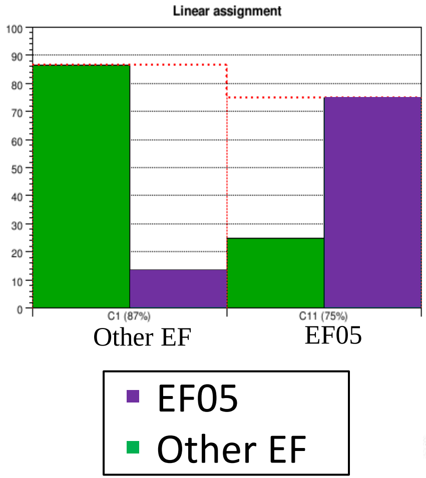
- This is partly due to the impact of heterogeneity and porosity variation on acoustic impedance, which is not simply related to facies

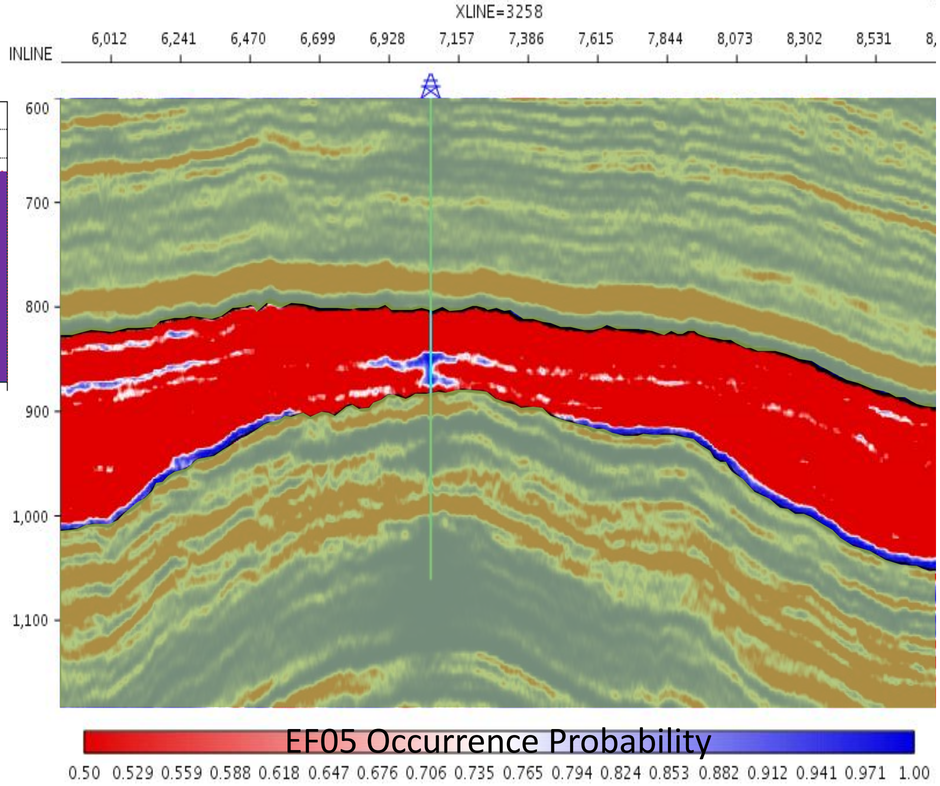


Geology analysis

Seismic Inversion Analysis

- EF05 (most porous limestone) can be predicted from acoustic impedance, when compared to others facies which have been grouped together.





- EF05 occurrence has been identified at seismic characterization interval where calibration has been done.

Structure framework modeling

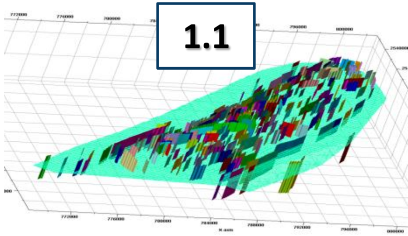
- Build a representative 3-D geological model grid that can be used for detailed reservoir modelling.

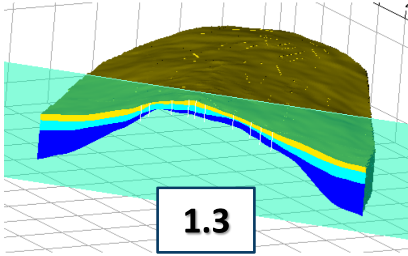
1- Structural Framework
  1.1- Fault network building
  1.2- Gridding
  1.3- Horizon gridding

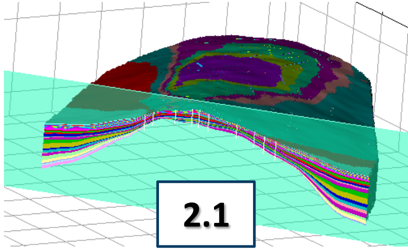
2- Stratigraphic Model
  2.1- Stratigraphic units
  2.2- Layering
  2.3- Logs discretization

3- Facies & Petrophysical Modeling

4- Volumetrics



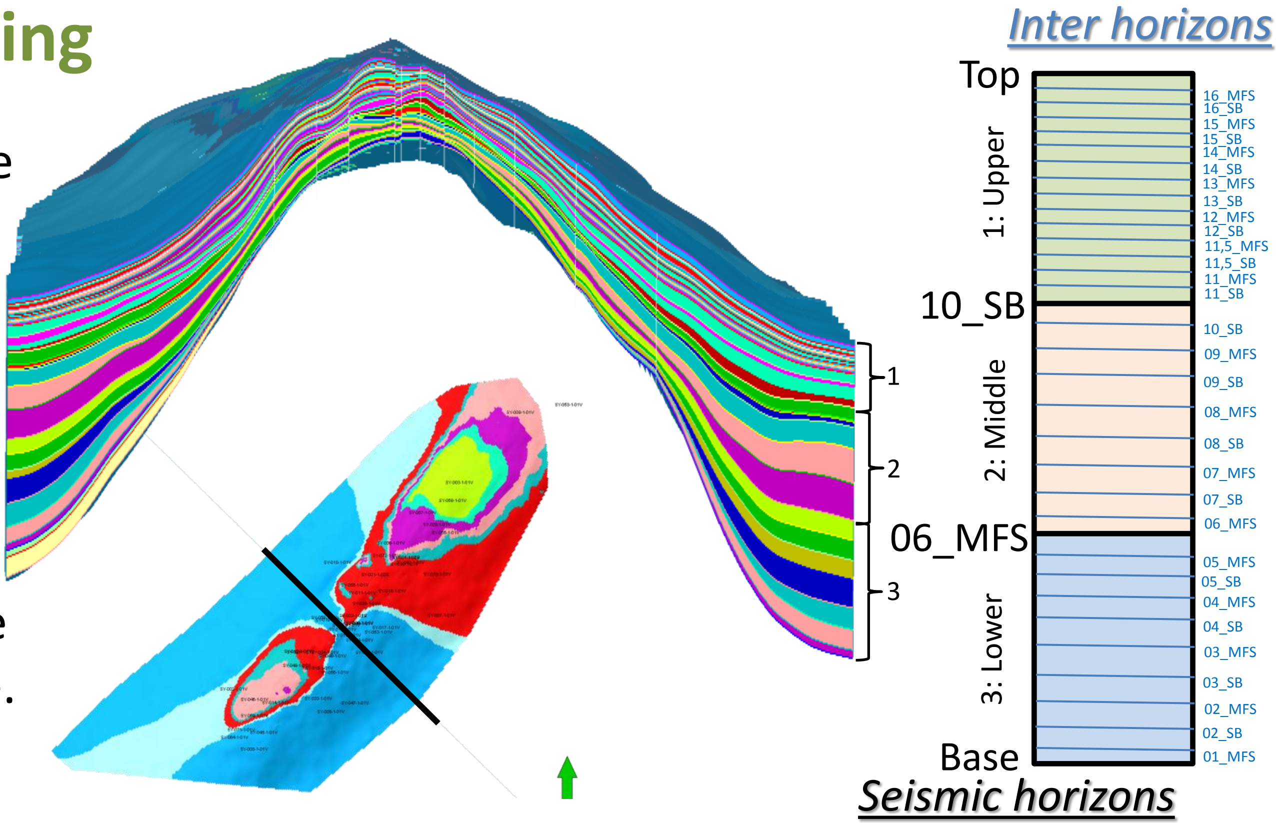




Structure framework modeling

Stratigraphic modeling

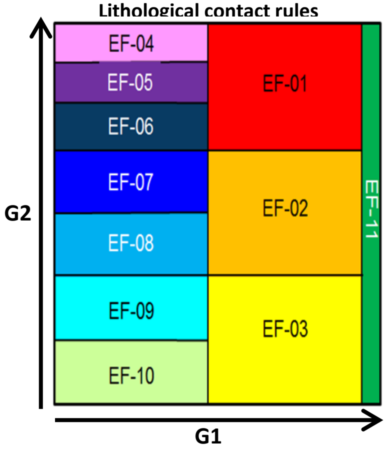
- This model integrates the geometry of 3D seismic interpretation and well tops data.
- The layering is based on the detailed sequence stratigraphy correlation scheme developed in the geological analyses stage.



Property modeling incorporating fracture network

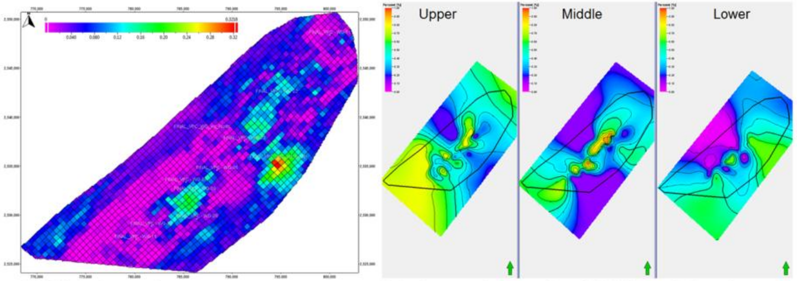
Electrofacies modeling

- Electrofacies have been propagated in the geological grid with the Pluri-Gaussian method based on:
  - Well log
  - Lithological contact rules
  - Two variograms (one per contact rule direction)
  - Facies proportion integrating the seismic characterization for the EF-05 and the Dolomite proportion (EF-01, EF-02 and EF-03)



Variogram G1:
X range : 1200 m
Y range : 600 m
Z range : 5 ft

Variogram G2:
X range : 600 m
Y range : 600 m
Z range : 5 ft



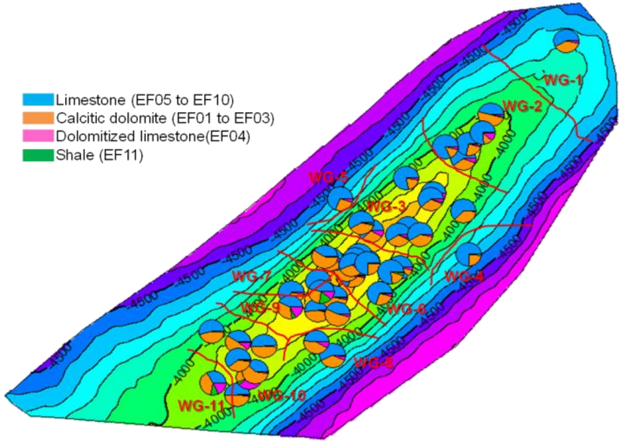
EF-05 Seismic proportion map

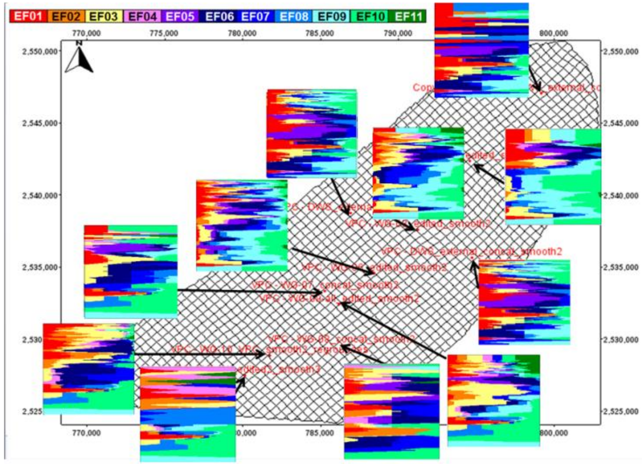
Dolomite proportion maps

Property modeling incorporating fracture network

Electrofacies modeling

- Electrofacies have been propagated in the geological grid with the Pluri-Gaussian method based on:
  - Electrofacies well group definition
  - VPC Matrix made from the Vertical Proportion Curves (VPC) per well set

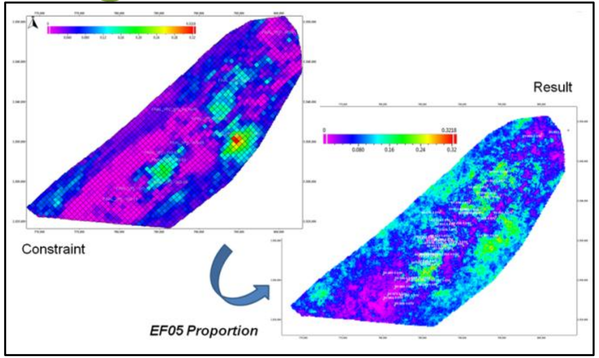




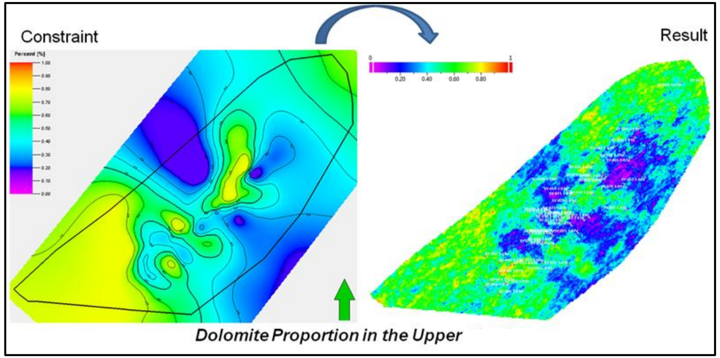
Property modeling incorporating fracture network

Electrofacies modeling

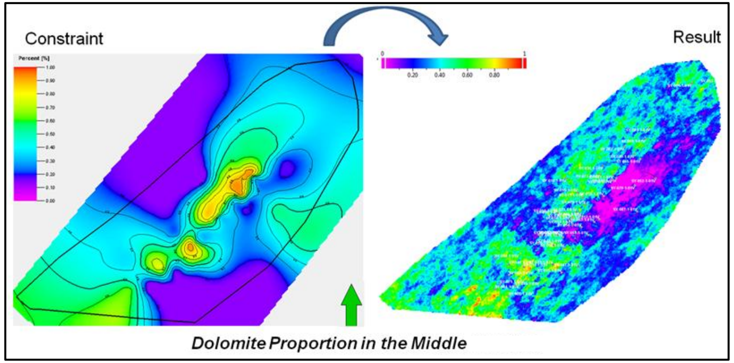
- Quality Control of Electrofacies modeling with constraints



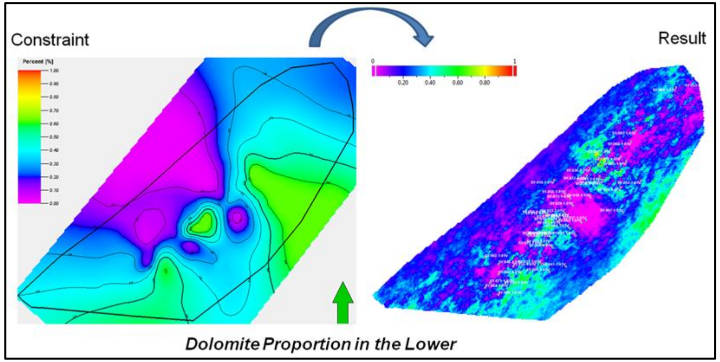
EF05 Proportion



Dolomite Proportion in the Upper



Dolomite Proportion in the Middle



Dolomite Proportion in the Lower

Property modeling incorporating fracture network

Porosity modeling

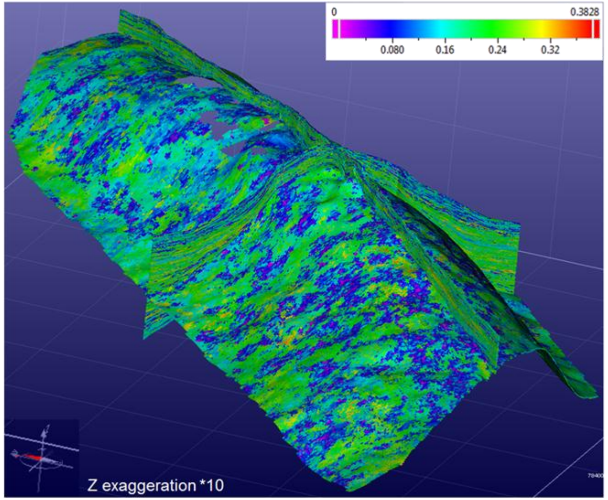
- Porosity has been modeled using the FFT-MA method (Fast Fourier Transform – Moving Average) based on:
  - Well upscaled porosity as conditioning data
  - Distribution histograms built from the well upscaled values
  - Variograms

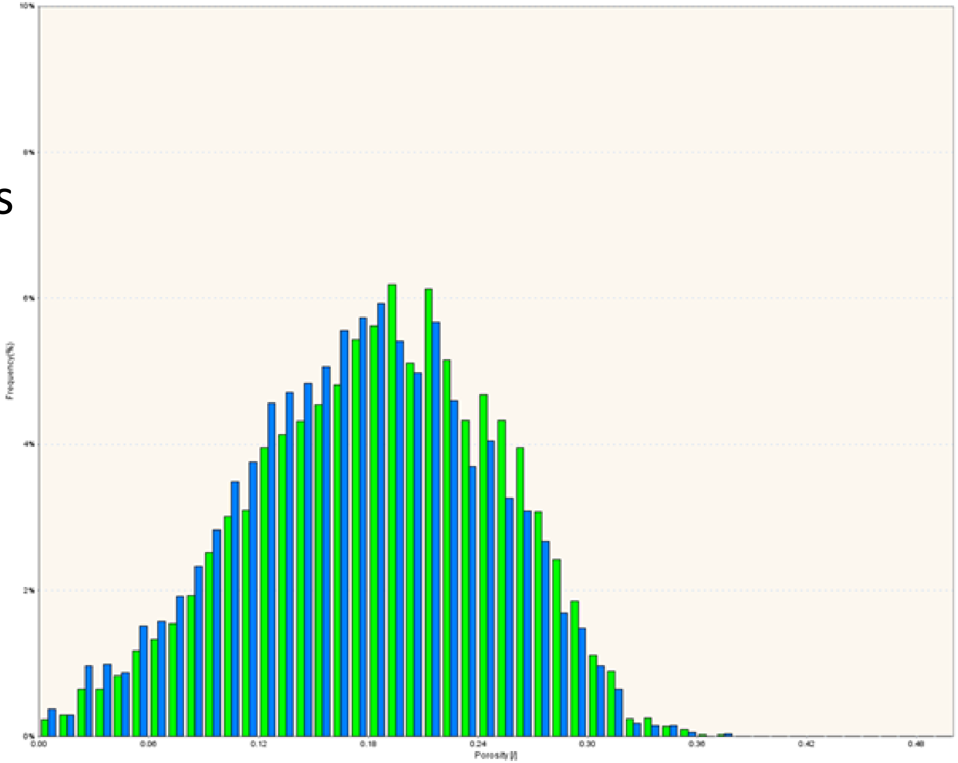
Electrofacies	Variogram Structure	Range X (m)	Range Y (m)	Range Z (m)	Azimuth (compared to the Grid J Direction)
EF-01	Spherical	2300	2300	1.9	90
EF-02	Spherical	1800	1800	1	90
EF-03	Spherical	3350	3350	1	90
EF-04	Spherical	3000	3000	0.8	90
EF-05	Spherical	700	700	1	90
EF-06	Spherical	3850	3850	1.7	90
EF-07	Spherical	1900	1900	0.85	90
EF-08	Spherical	2200	2200	1	90
EF-09	Spherical	800	800	1.39	90
EF-10	Spherical	125	125	0.82	90
EF-11	Spherical	2500	2500	1	90

Property modeling incorporating fracture network

Porosity modeling

- Quality Control of porosity modeling results





Well Upscaled Porosity

# of samples:	3438
Minimum:	0
Q1 quartile:	0.13
Median:	0.18
Q3 quartile:	0.22
Maximum:	0.37
Mean:	0.18
Std. deviation:	0.067
Variance:	0.0044

Simulated Porosity

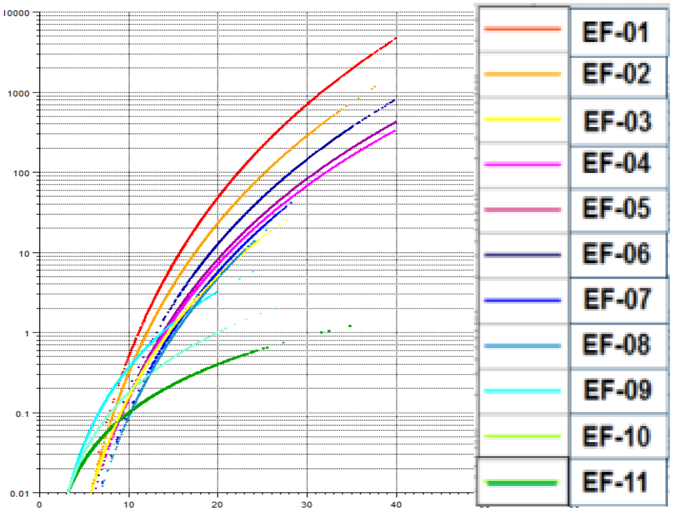
# of samples:	13217525
Minimum:	0
Q1 quartile:	0.14
Median:	0.19
Q3 quartile:	0.24
Maximum:	0.38
Mean:	0.19
Std. deviation:	0.067
Variance:	0.0044

Property modeling incorporating fracture network

Permeability modeling

- In order to represent the uncertainty and variation of permeability around the defined porosity-permeability relationships, permeability is computed in three steps:
  - Step 1: Permeability computation
  - Step 2: Permeability error simulation
  - Step 3: Generation of final permeability

- Step 1: Permeability computation
  - In each cell, permeability is computed by using the Permeability/Porosity relationship for each Electrofacies

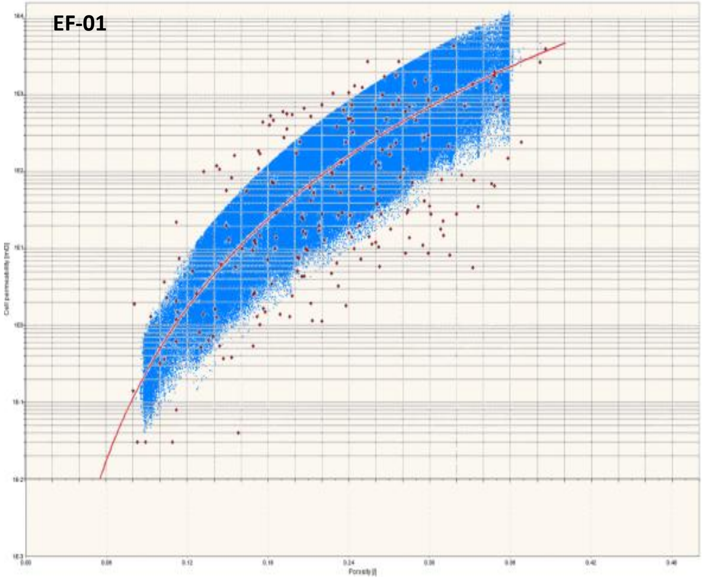


Property modeling incorporating fracture network

Permeability modeling

- Step 2: Permeability error simulation
  - A random error of normal distribution
  - Centered on 0 and from Log(0,05) to Log(5)
  - Standard deviation of 0,3
  - Error obtained from variation of core permeability variation
- Step 3: Generation of final permeability
  - Adding of error to Permeability computation based on:

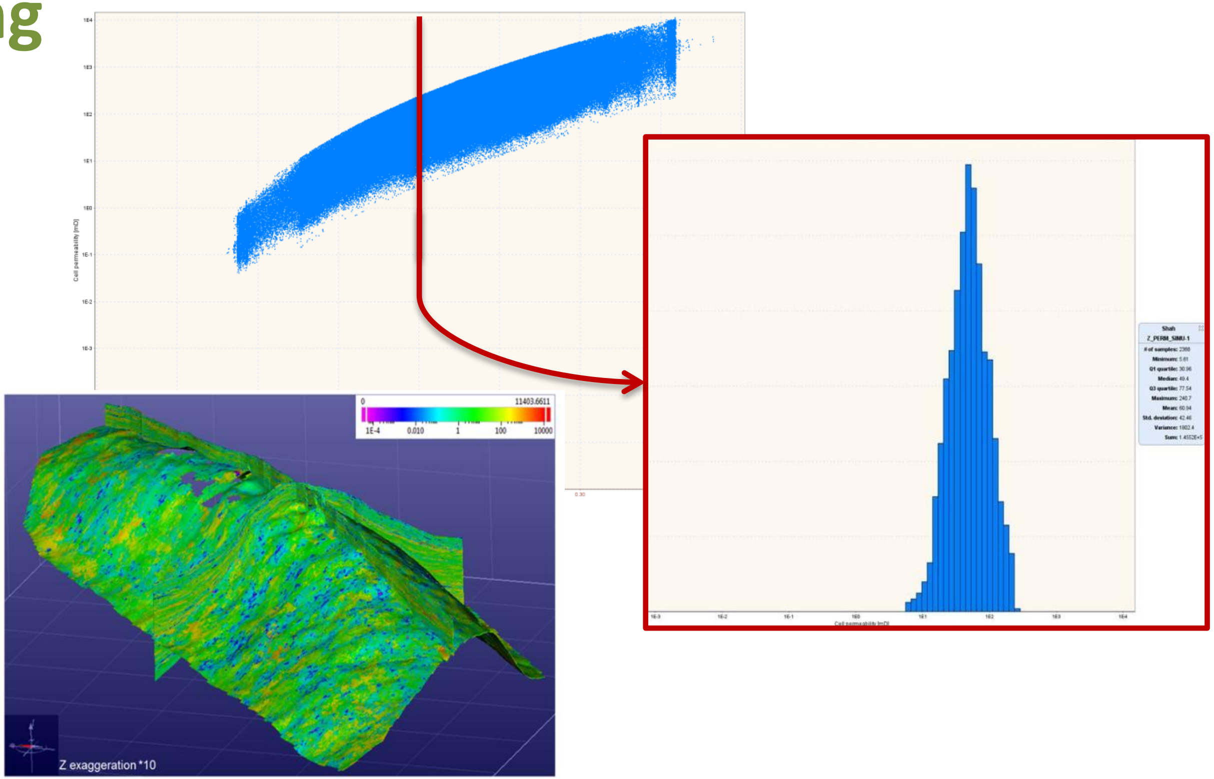
$$K_{final} = 10^{(\log(K)+K_{error})}$$



Property modeling incorporating fracture network

Permeability modeling

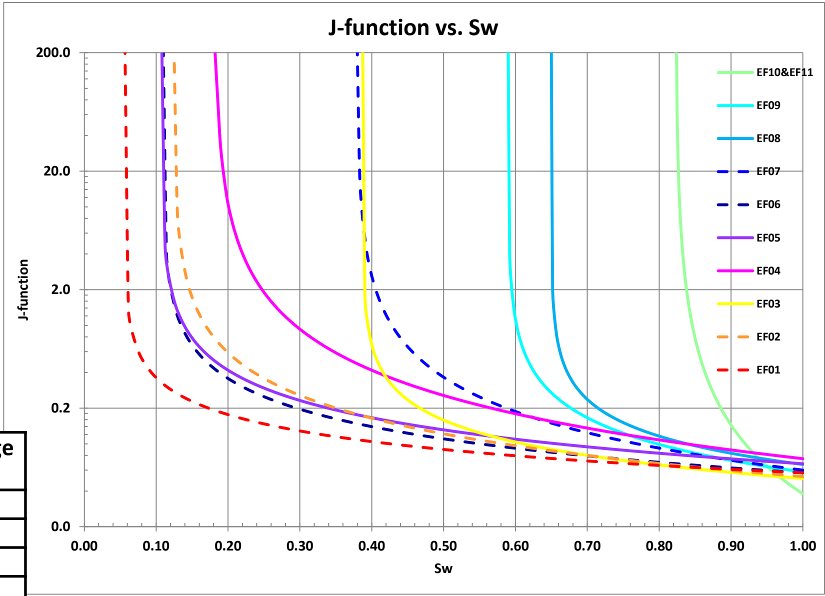
- Quality Control of Permeability modeling
- Example of permeability variability for a value of Porosity in EF01
- Histogram shows the computed permeability in model grid-cells for all porosity values at 0.20 v/v of EF-01 cells.



Property modeling incorporating fracture network

Saturation modeling

- Water saturation was estimated by using Leverett J type equation established from capillary pressures data
- J-function parameters (a & b) are defined from mercury injection sample measurement analysis



EF	J-Function parameters			Swirr Range (%)
	a	b	Swirr	
11	0.12	-1.6	82.33%	75-85%
10	0.11	-1.6	72%	75-85%
9	0.15	-1.19	53.2%	60-70%
8	0.14	-0.79	57.5%	50-65%
7	0.15	-1.21	40%	30-40%
6	0.16	-1.01	20%	10-20%
5	0.15	-0.91	17%	10-17%
4	0.13	-1.29	21.2%	12-22%
3	0.12	-0.89	54.4%	30-40%
2	0.15	-1.21	13%	10-20%
1	0.14	-0.81	8%	5-10%

Property modeling incorporating fracture network

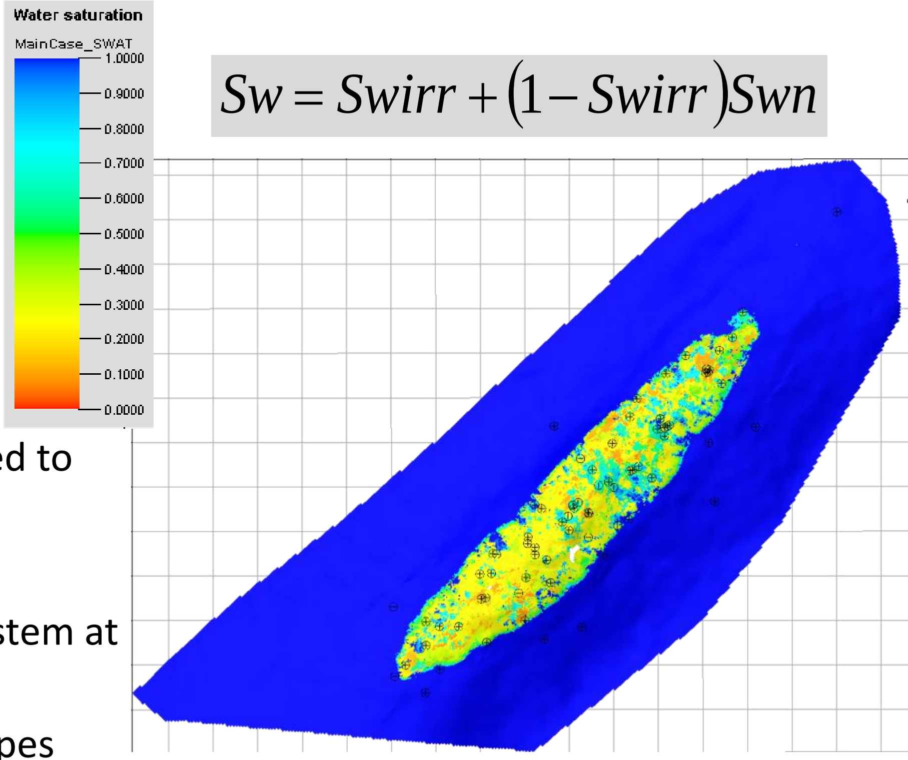
Saturation modeling

- Saturation-Height law per rock-type

$$Swn = \left(\frac{0.216601}{a} \frac{(\rho_w - \rho_o)_{res} H}{144(\sigma \cos\theta)_{res}} \sqrt{\frac{K}{\Phi}} \right)^{\frac{1}{b}}$$

  - Δρ (lb/ft3) from oil and water densities associated to the reservoir
  - H (ft) height above the free water level
  - With (σcos(θ))res (dynes/cm) for the oil-brine system at reservoir conditions
  - a and b exponents are dependent on the rock types
  - K and ϕ from models

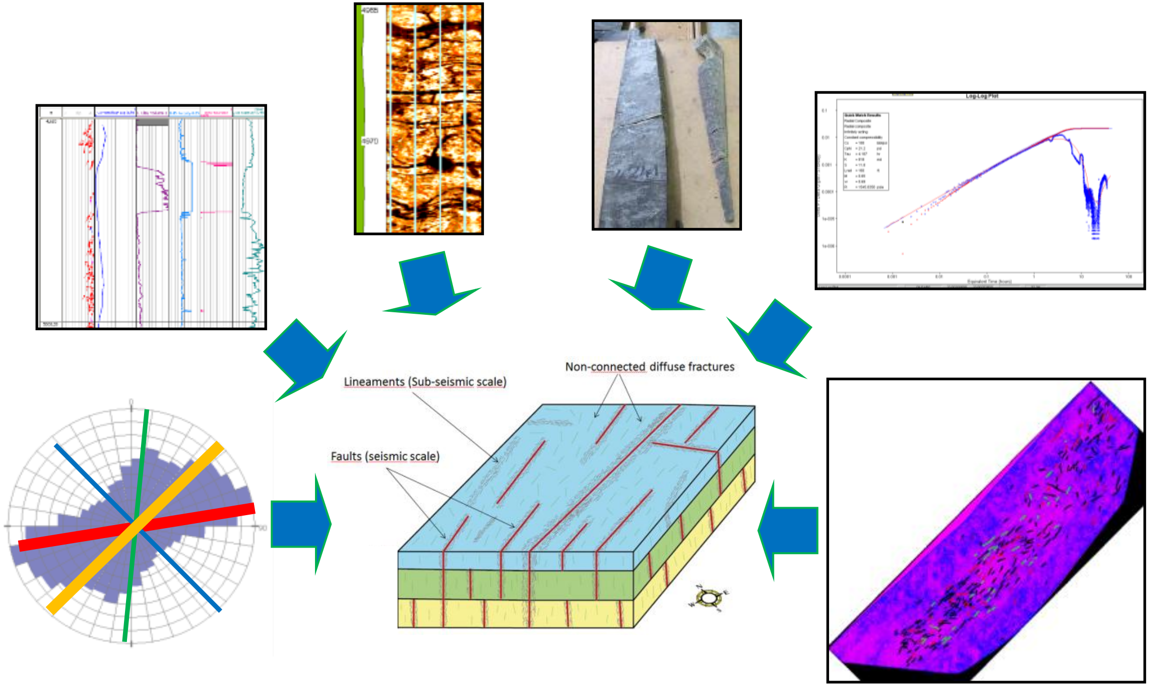
$$Sw = Swirr + (1 - Swirr)Swn$$



Property modeling incorporating fracture network

Fractures modeling

- Data integration:
  - Components of fracturing in the Reservoir (source: core, BHI and seismic data)
  - Statistical properties of the diffuse fractures and corridors (source: BHI data)
  - Fractures distribution drivers (source: properties in wells and grid-based approaches)
  - Possible hydraulic behavior of fractures (source: dynamic data)



Property modeling incorporating fracture network

Fractures modeling

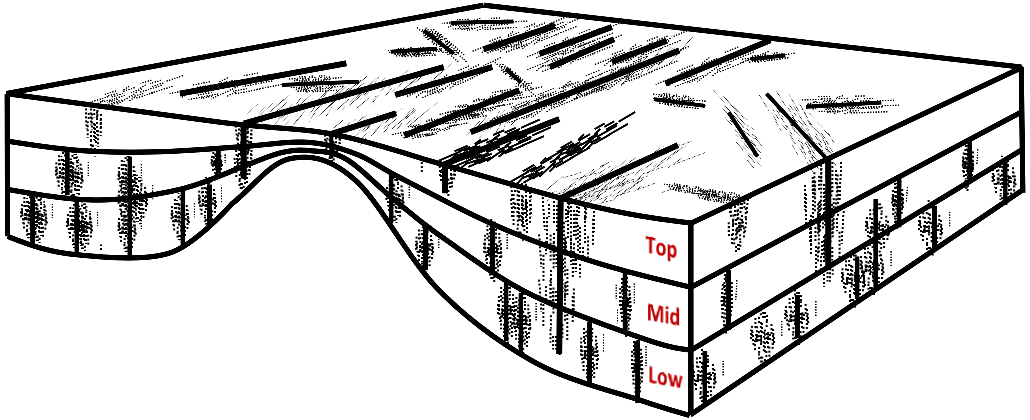
- Discontinuity Analysis and Seismic Lineament classification:

  Seismic faults

  High confidence lineaments

  Low confidence lineaments

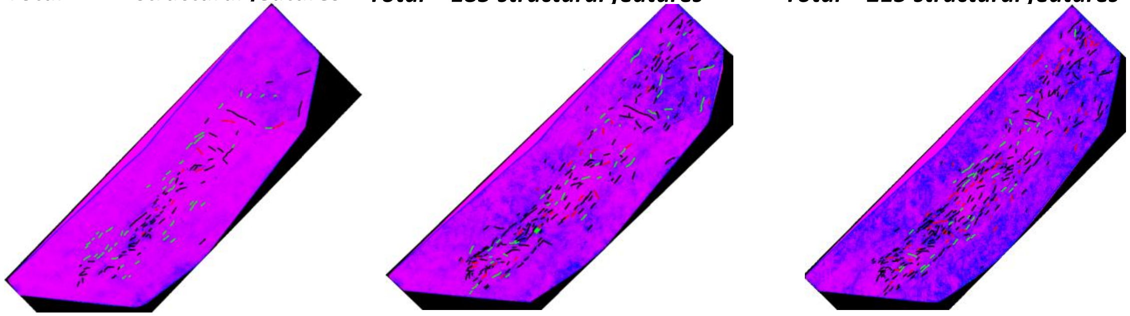
- Fracture intensity increases with depth:
  Lower on Top Reservoir
  Higher on Lower Reservoir



<u>Top:</u> 50 faults + 62 lineaments
Total = 112 structural features

<u>Middle:</u> 105 faults + 80 lineaments
Total = 185 structural features

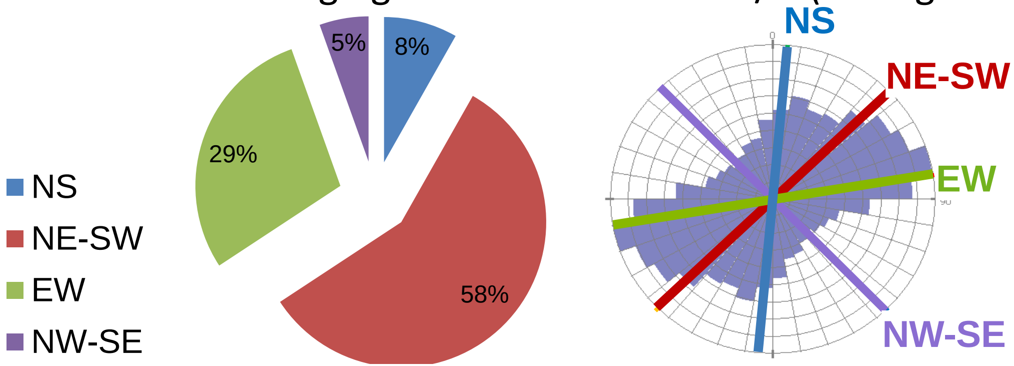
<u>Lower:</u> 99 faults + 116 lineaments
Total = 215 structural features



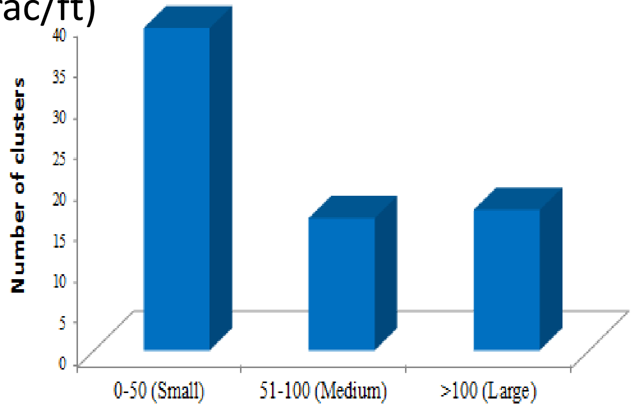
Property modeling incorporating fracture network

Fractures modeling

- BHI fracture analysis: 73 fracture corridors were detected in the 24 wells studied
  - With dominant NE-SW trend, secondary EW trend and minor NW-SE and NS trends
  - With a width ranging from 4 to 764 ft (average = 96 ft)
  - With densities ranging from 0.2 to 11.5 frac/ft (average = 1.8 frac/ft)



Clusters orientation



Clusters width

Property modeling incorporating fracture network

Fractures modeling

- Results of DFN calibration
  - The KH value to reach is 298000 mD.ft from dynamic analysis.
  - The value KH obtained is 310266 mD.ft in DFN model.
  - KH calibration: good match for the KH calibration with a relative error of less than 3%

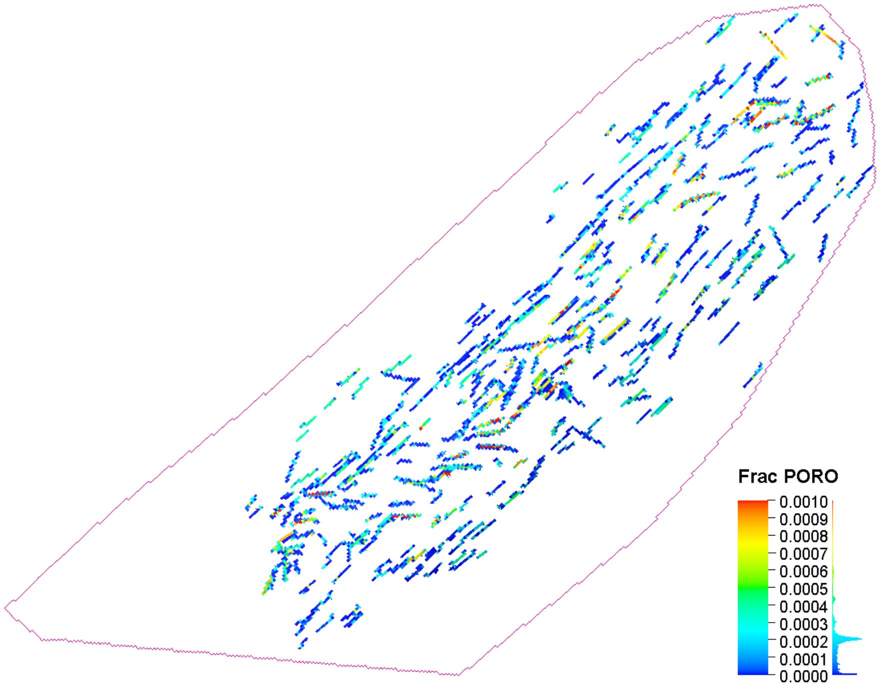
- Match obtained with a hydraulic conductivity of corridors that decreases from Upper to the Lower Reservoir: 26.5E+5 to 2.95E+5 mD.ft

Network	Conductivity (Cf, mD.ft)	Aperture (ft)
Corridors of Upper	26.50E+05	0.1526
Corridors of Middle	08.84E+05	0.1049
Corridors of Lower	02.95E+05	0.0721

Property modeling incorporating fracture network

Fractures modeling

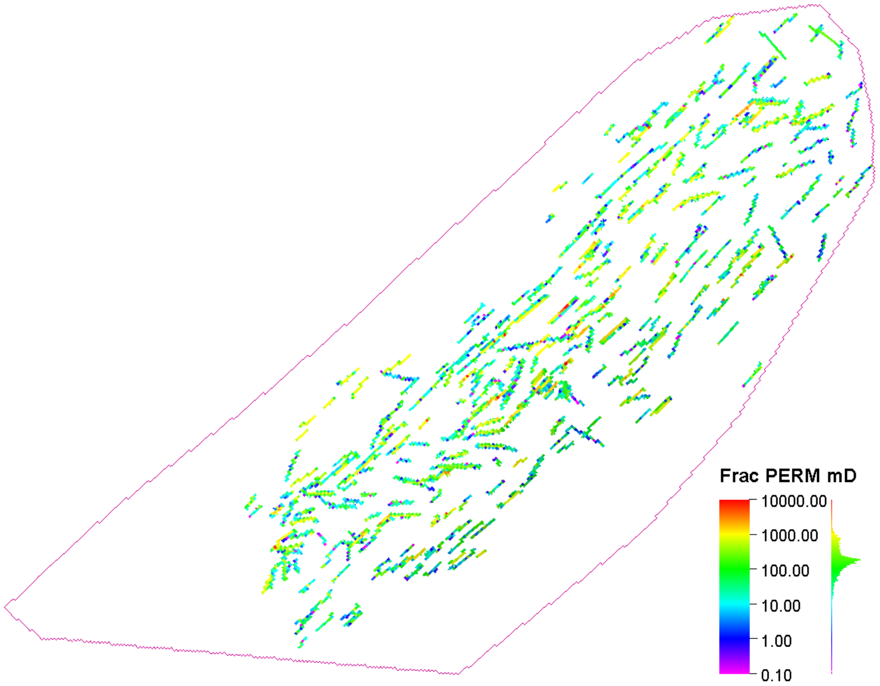
- Results of fracture upscaling: Porosity
  - The fracture porosity ranges between 0.00004 and 0.00103 p.u. (typical range).
  - The fracture porosity is higher in the Top unit than in the Middle and Lower units.
  - Because the Poiseuille's law gives a minimum value for fracture aperture, fracture porosity might be increased in dynamic modeling.



Property modeling incorporating fracture network

Fractures modeling

- Results of fracture upscaling: Permeability
  - Expected consistency between the fracture corridor occurrence and the highest values of permeability.
  - The permeability ranges between 0.2 and 40000 mD. This range is totally in agreement with the permeability values derived from well test.



Uncertainty Analysis

Multi Realizations Analysis

- For Porosity, a separate uncertain analysis was conduct with 10 multi-realizations with 11 iterations (1 for each EF). Impact is below ±1% on the STOIIP volume
- Structure was not considered for the uncertainty.
- Uncertain parameters are studied for 12 properties:
- A total of 190 iterations have been run to build a Response Surface.

Parameters	Initial	Minimum	Maximum	Distribution
Facies seed	456852	1	900000	Uniform
Permeability error seed	789	1	900000	Uniform
Bo	1.09	1.07	1.11	Normal
Rs	0.09	0.088	0.092	Normal
FWL	-4070	-4080	-4060	Normal
Swi_01	0.0567	0.03	0.08	Normal
Swi_02	0.125	0.12	0.13	Normal
Swi_03	0.388	0.25	0.55	Normal
Swi_04	0.182	0.12	0.22	Normal
Swi_05	0.108	0.05	0.17	Normal
Swi_09	0.59	0.4	0.78	Normal
Swi_10	0.823	0.72	0.93	Normal

Uncertainty Analysis

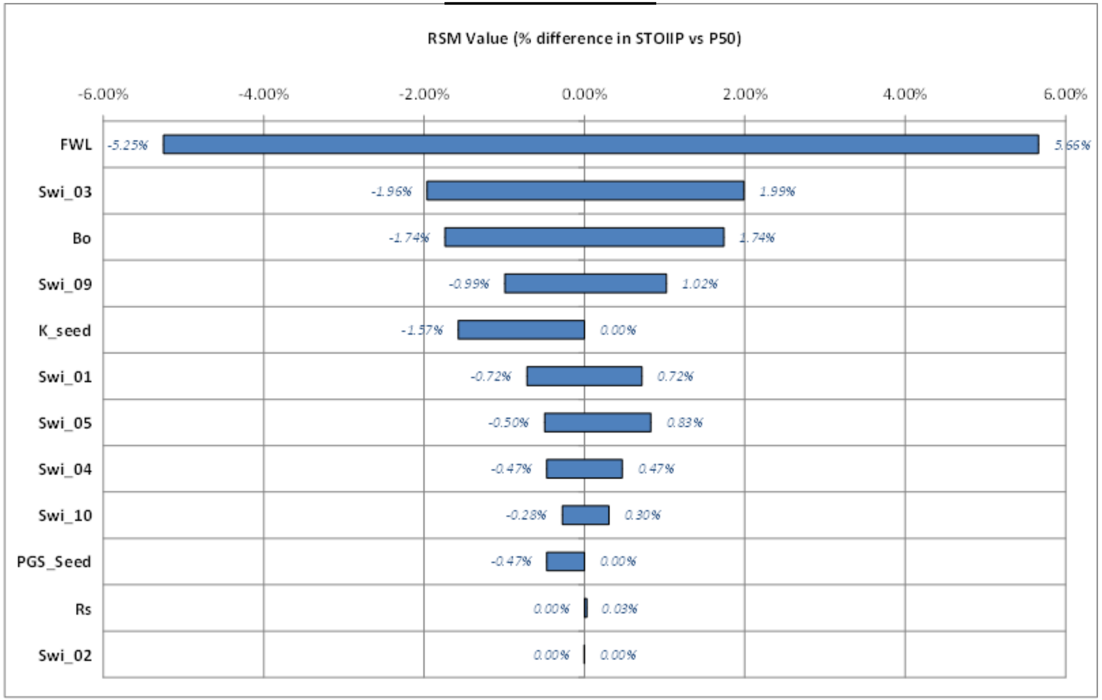
Multi Realizations Analysis

- Based on multi-realization, a response surface was build and shown a predictive of 95,9%.

- Tornado chart was defined:

- FWL are the parameter that induces the biggest variation.

Tornado chart

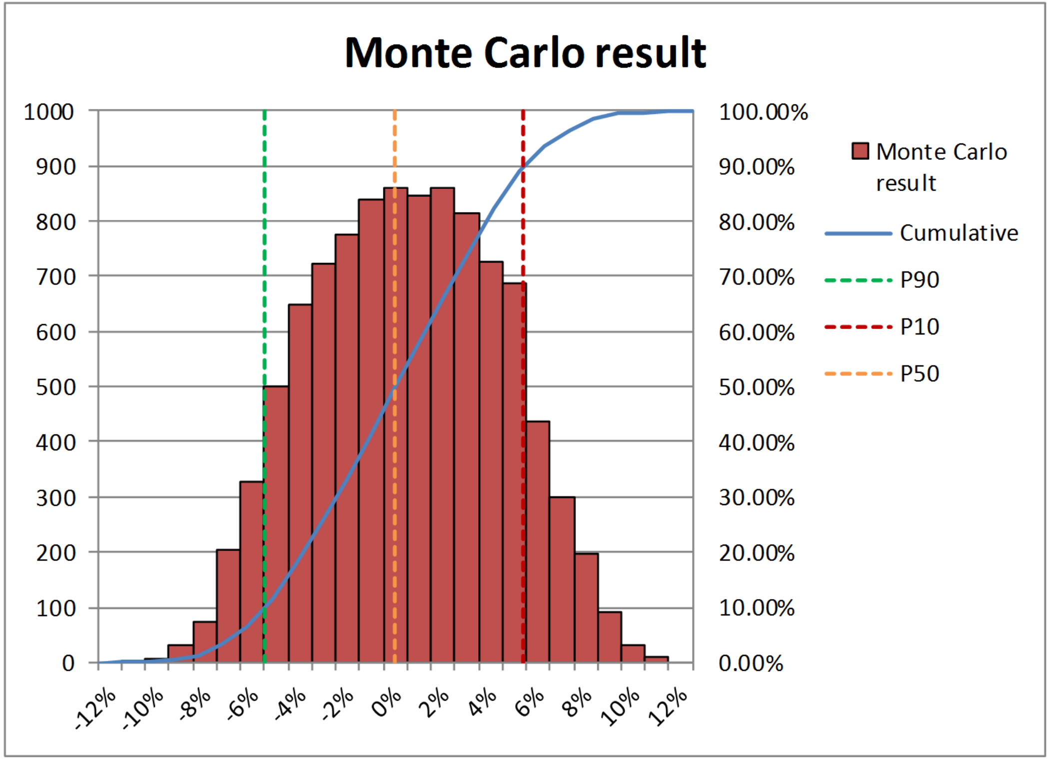


Uncertainty Analysis

Monte Carlo Analysis

- Propagation with 10 000 Monte Carlo iterations based on the response surface.

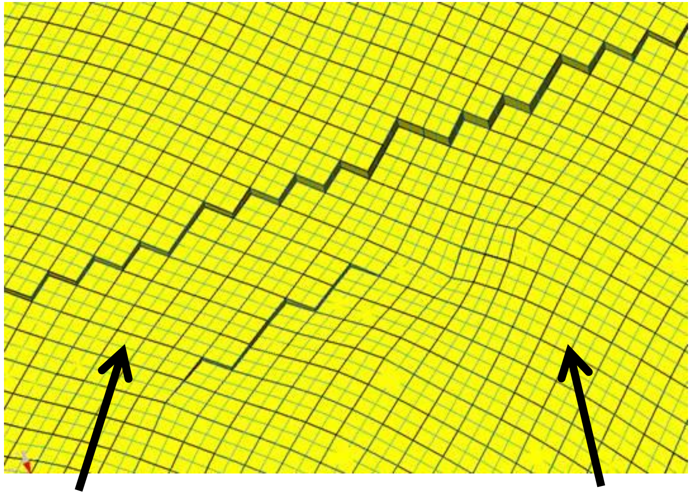
- Based on the uncertainty analysis performed the STOIIP variation between P90 and P10 are ±5% of P50.



Upscaling Analysis

Horizontal Upscaling

- Cells of the fine grid are grouped 2 by 2 horizontally in both I and J directions.
  - From: 800*302 cells in XY direction
    241 600 in total
    172 308 active 2D cells
  - To: 400*151 cells in XY direction
    60 400 in total
    43 077 active 2D cells



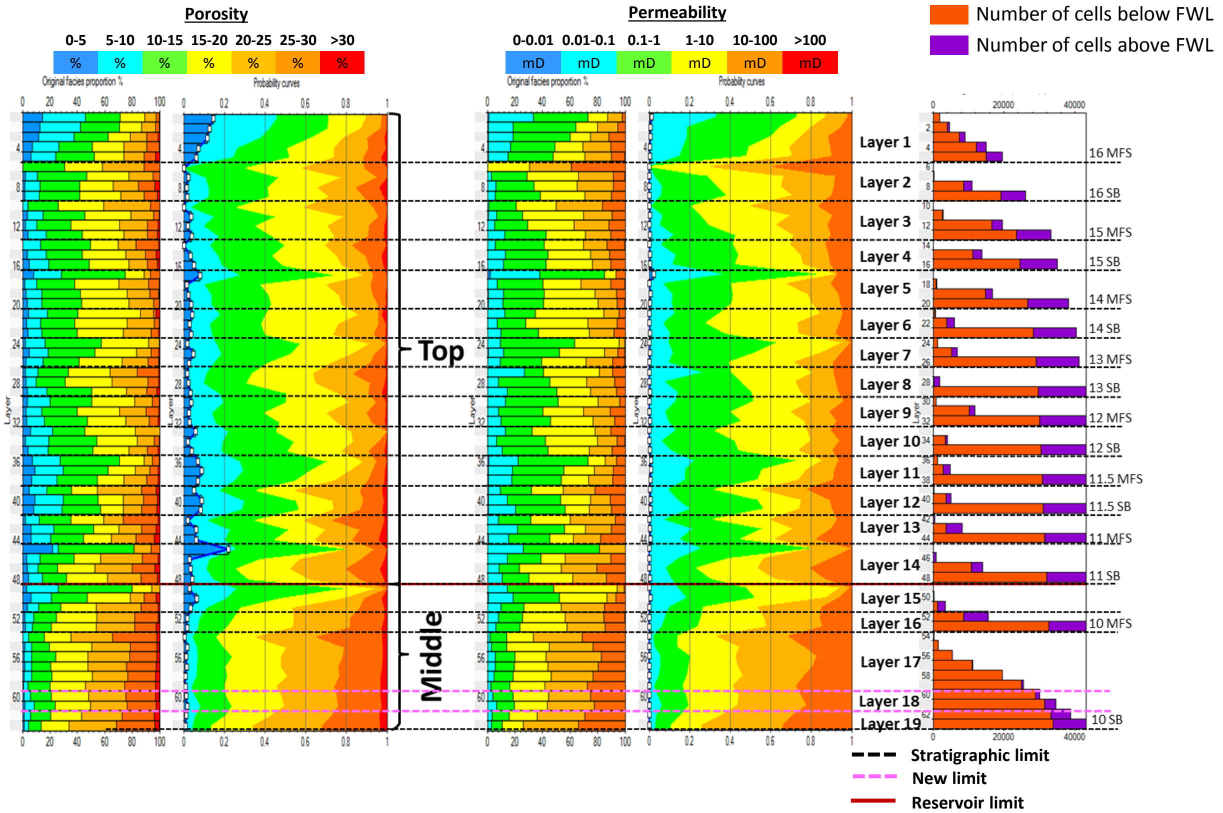
Green: 50m*50m gridding

Black: 100m*100m gridding

Upscaling Analysis

Vertical Upscaling

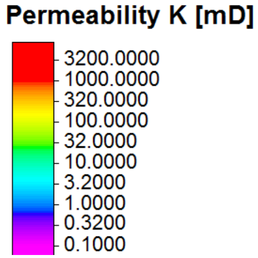
- For vertical upscaling property, trends have been investigated based on geological and stratigraphic layering:
  - From: 258 layers
    62 332 800 3D cells in total
    13 392 131 active 3D cells
  - To: 61 layers
    3 284 400 3D cells in total
    1 968 719 active 3D cells



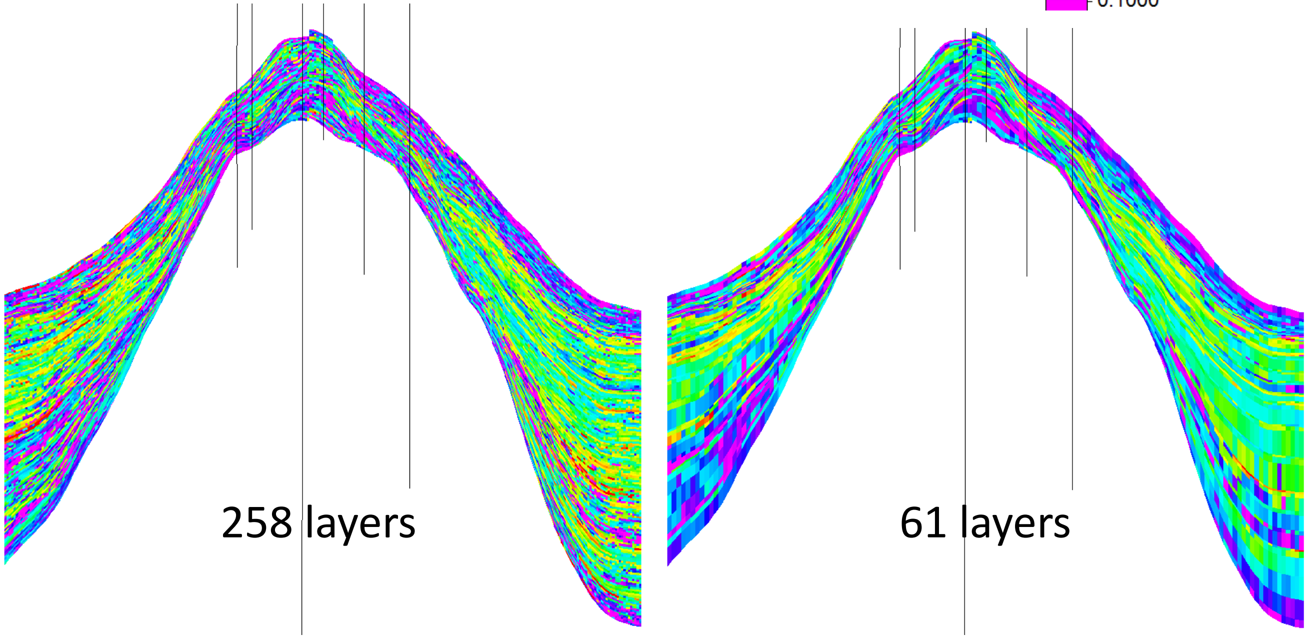
Upscaling Analysis

Vertical Upscaling

- Rock-Types
  - “Most of” averaging method weighted by the rock volume
- Porosity
  - Arithmetic average
- Permeability: Horizontal (Kx,Ky) and Vertical (Kz)
  - Lemouzy method: generalization of Cardwell & Parsons
- Water saturation
  - Arithmetic average weighted by the Pore Volume



- Upscaled Vertical Permeability



Conclusions & Way Forward

- DPDP Property modeling incorporating fracture network
  - Facies modeling has been performed based on seismic, sedimentological and diagenesis study
  - Petrophysical (matrix porosity and permeability) modeling has been constrained by modeled facies
  - Fracture network modeling has been incorporated in the resulting model
  - Static fracture properties have been calibrated to the well data and yield fracture properties (fracture porosity and permeability)
  - Uncertainties evaluated and Geological model has been upscaled

- DPDP Static Model will be input for DPDP Dynamic Model to:
  - Optimize Development Plan avoiding fracture network and early water break through.