PS Methodology to Integrate Multiscale Fracture Analyses in Fractured Systems Modeling: Application to Reservoirs of Southeastern Mexico*

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Search and Discovery Article #41393 (2014)**
Posted July 24, 2014

*Adapted from poster presentation given at 2014 AAPG Annual Convention and Exhibition, Houston, Texas, April 6-9, 2014

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Abstract

Naturally fractured reservoirs (NFR) are the main producers of hydrocarbon in the southeastern part of Mexico, and the need to be modeled is a challenge, since these models serve as guide for the locations of exploratory and development wells. The main objective of this work is to show a methodology to develop a 3D model that represents the orientation and distribution of conductive fractures in the reservoirs. This task requires analysis of fracture attributes and integration of data from different scales: thin sections, cores, images logs and seismic. We applied the SDPS (Structural-Diagenetic-Petrographic-Study) methodology to calibrate and to extrapolate the attributes of conductive aperture and fracture density. A 3D geological model, built from structural seismic interpretation and geomechanical data, was created to compute structural attributes. The final products were a Discrete Fracture Network that simulates each fracture set, and a flow model for each conductive set. Six wells, eleven cores, nineteen structurally oriented thin sections, six-hundred thin sections from cutting samples, five images logs, and one triaxial test from two oil and gas fields were analyzed. The two fields, located in the southeast of Mexico, consist of two main reservoirs: carbonate basinal facies, with less than 2% of matrix porosity, and an internal ramp facies with porosities of 4 to 6%. Based on their structural-diagenetic origin, five fractures sets were identified. Two are conductive: Set 4 (NE-SW) and Set 5 (N-S), and three sets are sealed: Set 1 (N-S), Set 2 (NW-SE), and Set 3 (E-W). The SDPS indicates that deformation degree, porosity and diagenetic processes (recrystallization) were the main geological controls of fracturing. Geomechanical data was used to analyze the deformation of the rock and to compute structural attributes, which were integrated with the SDPS results to model the conductive sets and to predict their distribution. With the result of this modeling has been verified that the

trajectory of the wells T-1, 3, 11, and 23 intercepted the main conductive fractures sets favorably, but it was not the case for T-12 and 1 DL wells. The well N-1 cut just a little favorably the main fracture sets. The wells productivity confirms the quality of fracture sets identified. Therefore, this work demonstrates that the results of this methodology can be used as a guide to propose new exploratory and development well locations.

ABSTRACT

Naturally fractured reservoirs (NFR) are the main producers of hydrocarbon in the southeastern part of Mexico, and the need to be modeled is a challenge, since these models serve as guide for locations of exploratory and development wells. This task requires analysis of fracture attributes and integration of data from different scales: thin sections, cores, images logs and seismic. In this work, we applied the SDPS (Structural-Diagenetic-Petrografic-Study) methodology, to calibrate and to extrapolate the attributes of conductive apertures in a carbonated reservoir, located in one of the most important oil and gas production region in Mexico. A 3D geological model built from structural seismic interpretation and geomechanical data, was created to compute structural attributes. The final product is a discrete fracture network (DFN) that simulates each fractures sets, and a flow model for each conductive set.

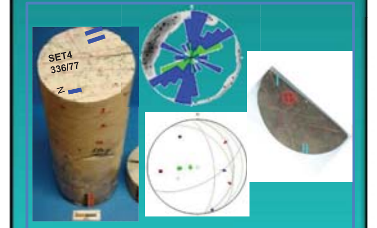
OBJECTIVE

The main objective of this work is to show an integrated methodology to develop a 3D model that represents the properties of conductive fracture sets in carbonated naturally fractured reservoirs. This study was focused on characterization of fractures at different scales and their integration in a model that represents how these fractures interact in the flow of fluids in the subsurface.

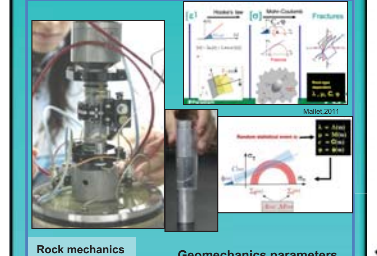
METHODOLOGY

The methodology includes the analysis of fracture sets in well cores and in oriented thin sections. The SDPS consists in establishing the reservoir paragenesis sequence, including the fracturing as an additional diagenetic process (Monroy, 2001). Once the paragenesis is established, it is possible to differentiate sets of fractures of different origin by their attributes and cross-cutting relationships. From this, the SDPS permits to determine the orientation, density and quality of conductive fractures sets in the reservoir, these are hard data for fracture modeling that can be calibrated with dynamic data, such as production tests, traces, PLT´s, normalized cumulative productions, and interference tests (Monroy, 2009). The calibrated fracture model guides the development of the fields, and is also used to design the best drilling trajectories of wells.

Core scale analysis



Acquisition of structural and sedimentary information.
Orientated samples for a SDPS.

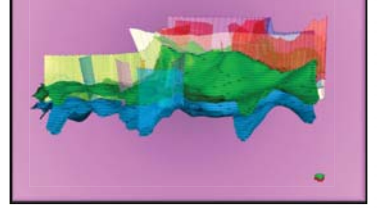


Rock mechanics analysis
Elastic modules, and Mohr-Coulomb criteria

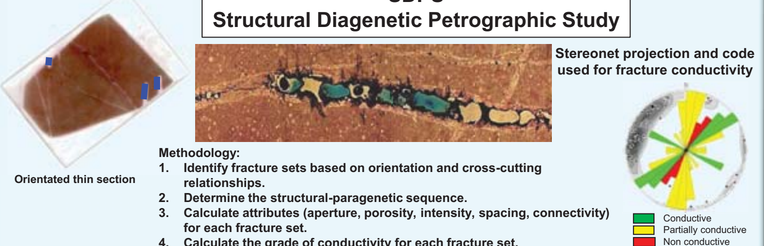
Geomechanics parameters

Mohr-Coulomb cohesion range (C)(GPa)	Mohr-Coulomb friction angle (phi)(deg)	Poisson ratio range	Young modulus range (GPa)
0.018 0.02	15 40	0.29 0.35	59.6 81.14

Seismic scale analysis



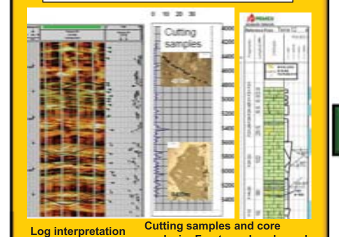
SDPS
Structural Diagenetic Petrographic Study



Orientated thin section

Methodology:
1. Identify fracture sets based on orientation and cross-cutting relationships.
2. Determine the structural-paragenetic sequence.
3. Calculate attributes (aperture, porosity, intensity, spacing, connectivity) for each fracture set.
4. Calculate the grade of conductivity for each fracture set.

Images log interpretation

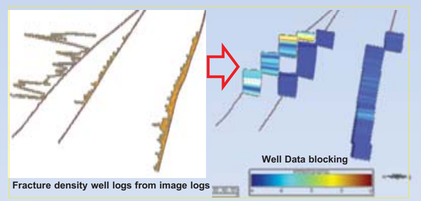


Log interpretation

Cutting samples and core analysis. Fracture abundance log

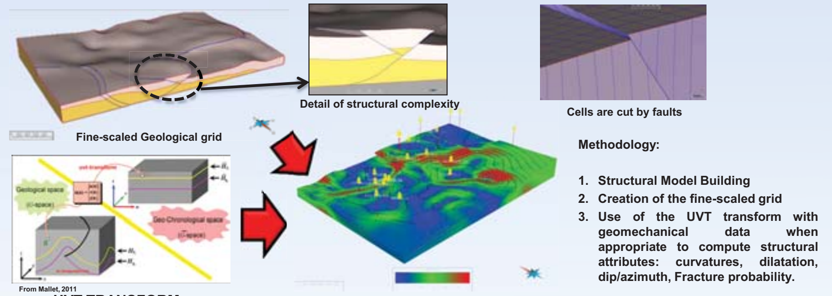
Note: Fracture sets are filtered according to the quality conductivity determined in the SDPS.

Well data analysis/blocking



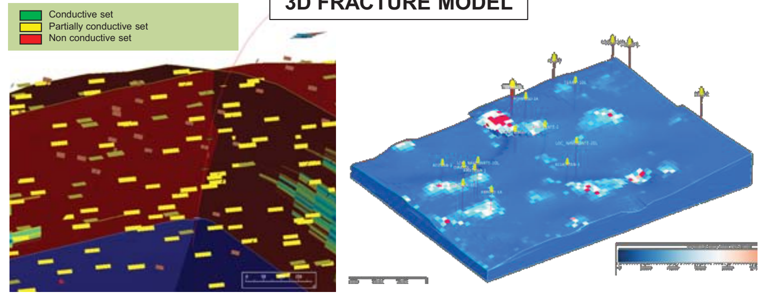
Integration of core data, fracture attributes and images logs analysis by fracture set. Well data blocking: Data scale change from scale of well logs to scale of fine-scaled grid.

Fine-scaled grid / Structural attributes



Methodology:
1. Structural Model Building
2. Creation of the fine-scaled grid
3. Use of the UVT transform with geomechanical data when appropriate to compute structural attributes: curvatures, dilatation, dip/azimuth, Fracture probability.

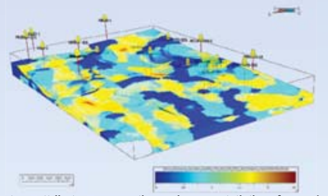
3D FRACTURE MODEL



Simulated DFN fracture sets with corresponding conductivity property displayed along with fracture probability attribute on fine-scaled grid

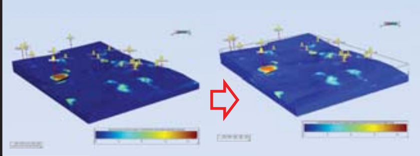
Upscaling of fracture properties from DFN to the coarse-scaled Flow Simulation Grid - flow simulation fracture model

Reservoir properties



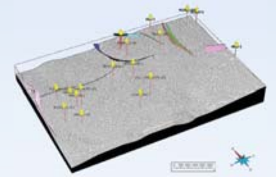
Fracture attributes propagation using geostatistics, for each fracture set, in the fine-scaled geological grid.

Upscaling



Fracture density rescaled from the fine-scaled grid to the coarse-scaled grid

Flow simulation grid



Building coarse-scaled Flow Simulation Grid from structural model

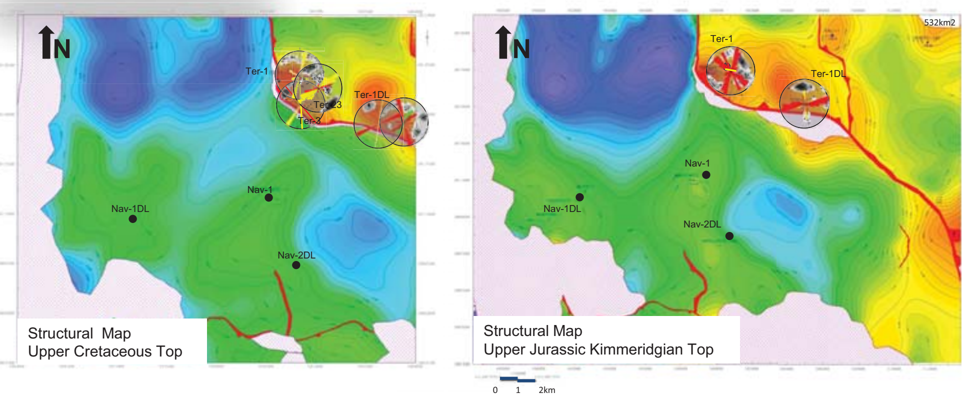
GEOLOGY

STUDY AREA

The methodology was applied in two oil and gas fields, located in the southeast of Mexico. Two reservoirs are present in each field:

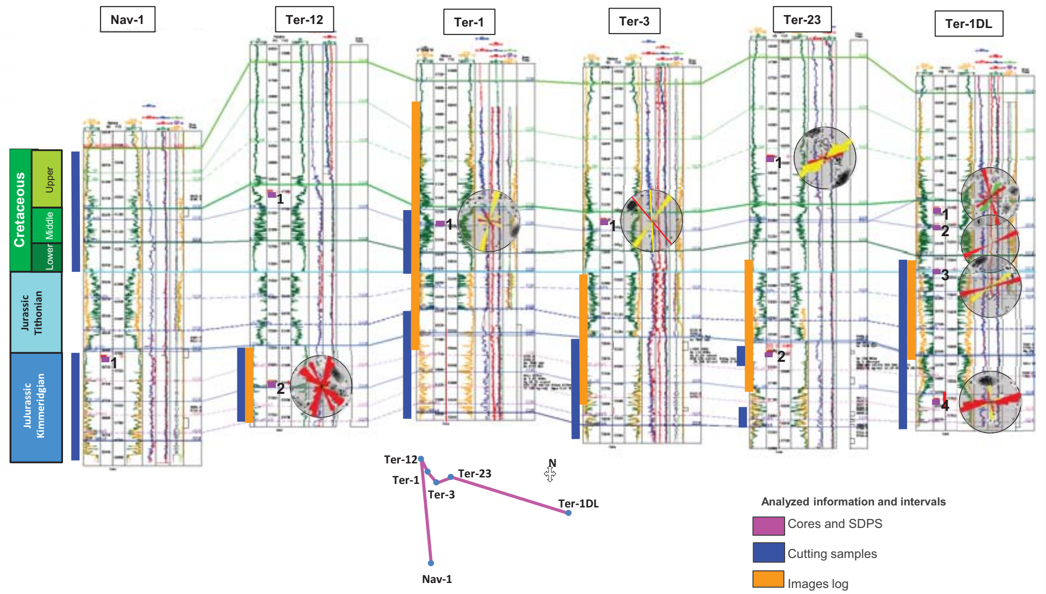
A) Cretaceous carbonates on basinal facies, with lower than 2% of matrix porosity. Natural factures provide the main permeability.

B) Jurassic internal carbonated ramp facies, with porosities from 4 to 6%. Main porosities are dissolution and intercrystalline.

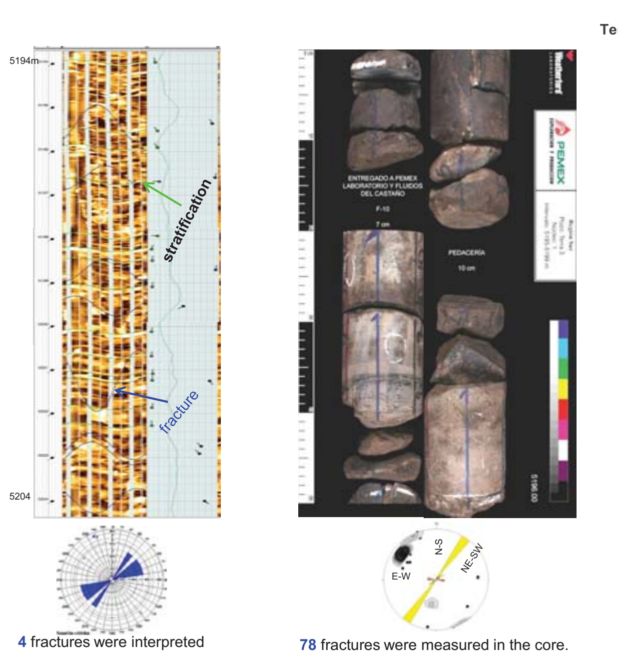


DATA

Six wells, eleven cores, nineteen structurally oriented thin sections, six-hundred thin sections from cutting samples, five images logs, and one triaxial test from two oil and gas fields were analyzed.



CORE-IMAGES LOG vs SDPS ANALYSIS

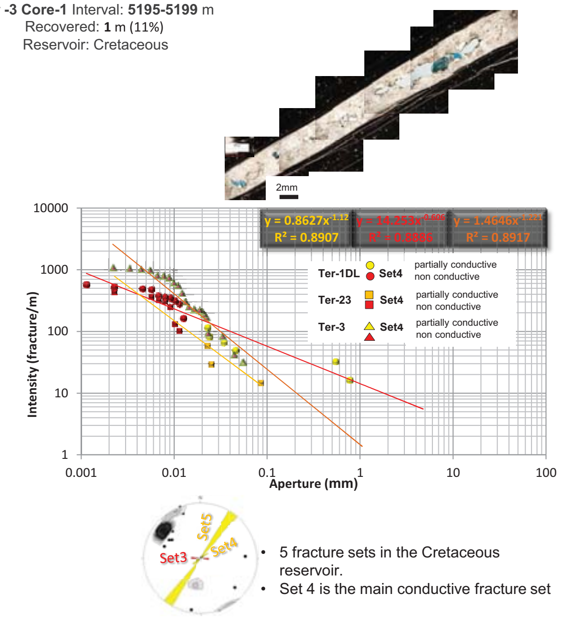


4 fractures were interpreted of the same cored interval.

78 fractures were measured in the core.

Conductive quality of set
- Conductive
- Partially conductive
- Non conductive
- Non characterized

Ter -3 Core-1 Interval: 5195-5199 m
Recovered: 1 m (11%)
Reservoir: Cretaceous



- 5 fracture sets in the Cretaceous reservoir.
- Set 4 is the main conductive fracture set

Set 4 has a minimum conductive aperture of **0.012mm.**
Fracture density: 180 conductive fractures of **0.012 mm of aperture or greater by meter.**

SDPS

Based on their structural-diagenetic origin, five fractures sets were identified. Two are conductive: Set 4 (NE-SW) and Set 5 (N-S); three are sealed: Set 1 (N-S), Set 2 (NW-SE), and Set 3 (E-W). The SDPS indicates that deformation degree, porosity and diagenetic processes (recrystallization) were the main geological controls of fracturing.

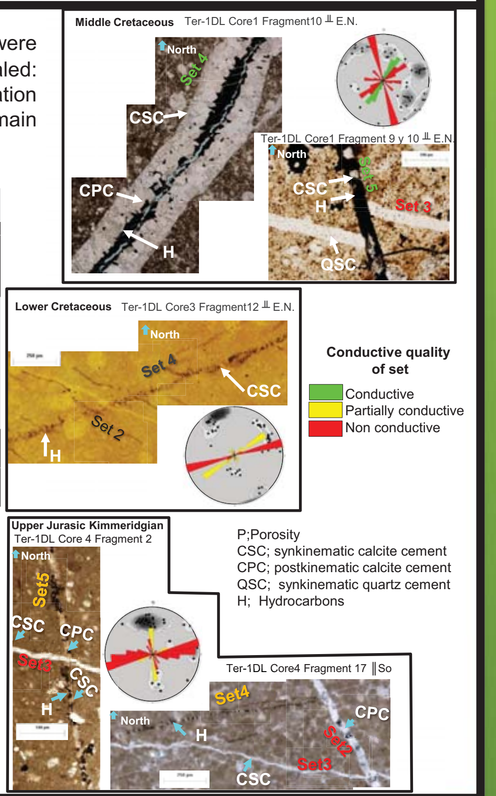
SDPS DATA

Cretaceous Fracture attributes

Well/Cores	Set	Orientation	Direction	Conductivity grade	Minimum conductive aperture (mm)	Average conductive aperture (mm)	Rank order (aperture conductive in one meter) mm	Fracture intensity (frac/m)	Remaining porosity set (%)
T-1DL/3,4	Set 1	05°/74°	NS	Non conductive	not present	not computed	not computed	not computed	0
T-1DL/3,4; T-3/1; T-23/1; T-1/1; T-12/1	Set 2	122°/72°- 125°/65°	NW	Non conductive	not present	1mm	0.001-2mm	60 fractures of 0.001-10mm in one meter	0
T-1DL/1,3,4; T-3/1; T-23/1; T-1/1	Set 3	71°/80°- 109°	EW	Non conductive	not present	0.03mm	0.01-0.062	40 fractures of 0.001-0.062 in one meter	0
T-1DL/1,2,3; T3/1; T-23/1; T1/1;	Se t4	21°- 67°/78°	NE	Conductive	0.02	8	0.02-16	75 fractures/m (0.02mm of aperture or higher)	9.26
T-1DL/1,2,4; T-3/1;T23/1; T12/1	Set 5	04°/43° - 09°	NS	Partially conductive	0.0058	0.54	0.0058-1.1	750 fractures/m (0.0058mm of aperture or higher)	20.4

Upper Jurassic (Kimmeridgian) Fracture Attributes

Well/Cores	Set	Orientation	Direction	Conductivity grade	Minimum conductive aperture (mm)	Average conductive aperture (mm)	Rank order (aperture conductive in one meter) mm	Fracture intensity (frac/m)	Remaining porosity set (%)
T-1DL N4	Set 1	05°/74°	NS	Non conductive				not computed	0
T-1DL N4	Set 2	340°/86°	NW	Non conductive	not present	0.5mm	0.001mm-1mm	28 fractures of 0.001-1mm of aperture in one meter	0
T-1DL/4	Set 3	275/86°-280°/86°	EW	Partially conductive	0.009	0.5	0.008-1	150 fractures/m (of 0.009mm of aperture or higher)	9
	Set 4	Absent	NE	Absent					
T-1DL/4; T-12/2	Set 5	176°/65°	NS	Partially conductive	not present	1.3	0.027-2.8	not computed	0



Conductive quality of set
- Conductive
- Partially conductive
- Non conductive

P;Porosity
CSC; synkinematic calcite cement
CPC; postkinematic calcite cement
QSC; synkinematic quartz cement
H; Hydrocarbons

Methodology to integrate multiscale fracture analyses in fractured systems modeling: application to reservoirs of southeastern Mexico.

AAPG 2014 Annual Convention & Exhibition

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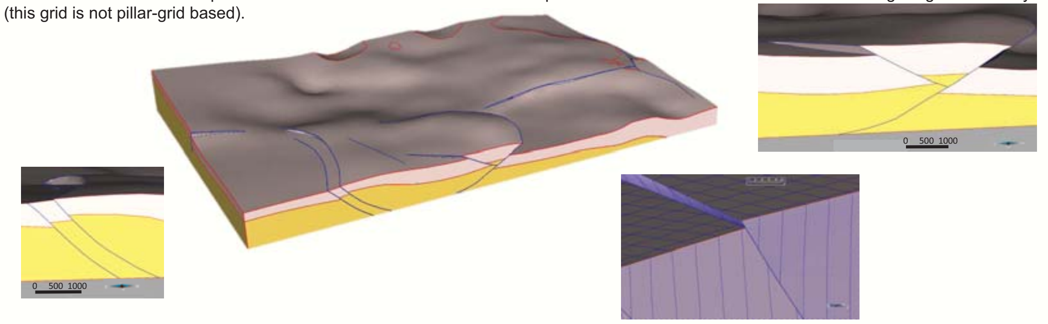
STRUCTURAL ATTRIBUTES

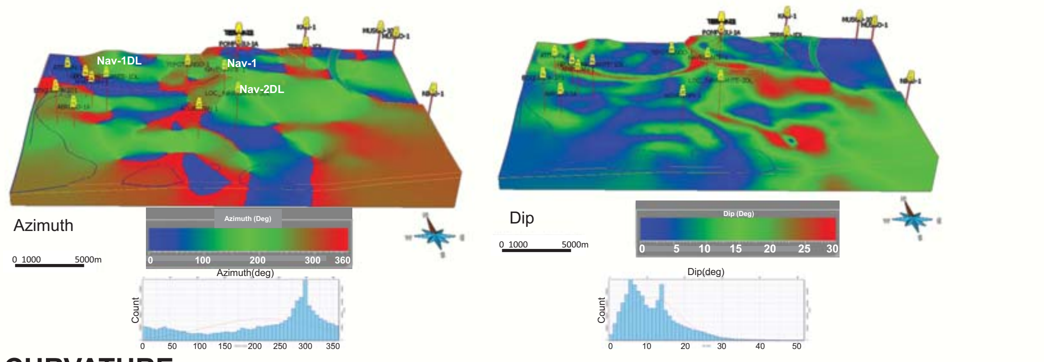
STRUCTURAL MODEL AND GEOLOGICAL GRID

Creation of the structural model and building the fine-scaled Geological grid. Please note that the fine-scaled grid respects the structural model without simplification of the faults or the horizons as interpreted with the seismic. The cells of the Geological grid are cut by faults (this grid is not pillar-grid based).



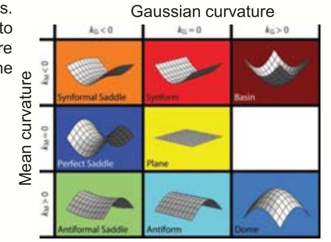
AZIMUTH AND DIP

Computation of azimuth and dip of each grid cell of the Geological grid.

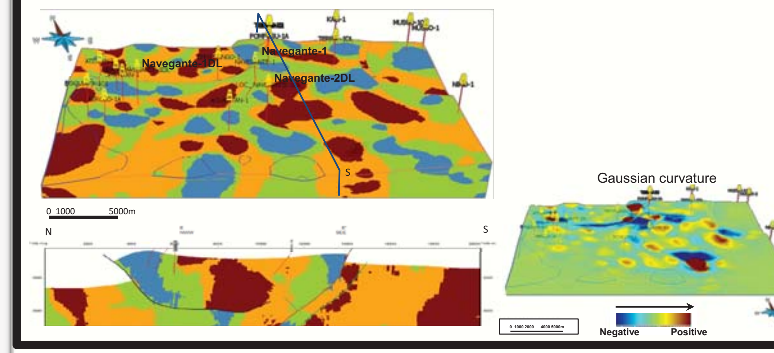


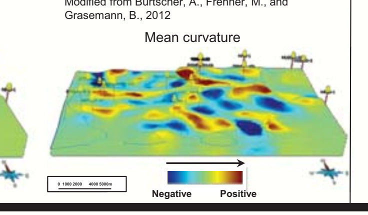
CURVATURE

The mean and Gaussian curvatures are computed onto each of the Geological grid cells. The combination of the information from the mean curvature and the Gaussian curvature allows to perform a qualitative description of the shape of the structures by computing the geologic curvature (Burtscher, A., Frehner, M., and Grasemann, B., 2012). The geologic curvature attribute separates the shape of the geological surfaces into eight areas of similar structural aspect.



Modified from Burtscher, A., Frehner, M., and Grasemann, B., 2012





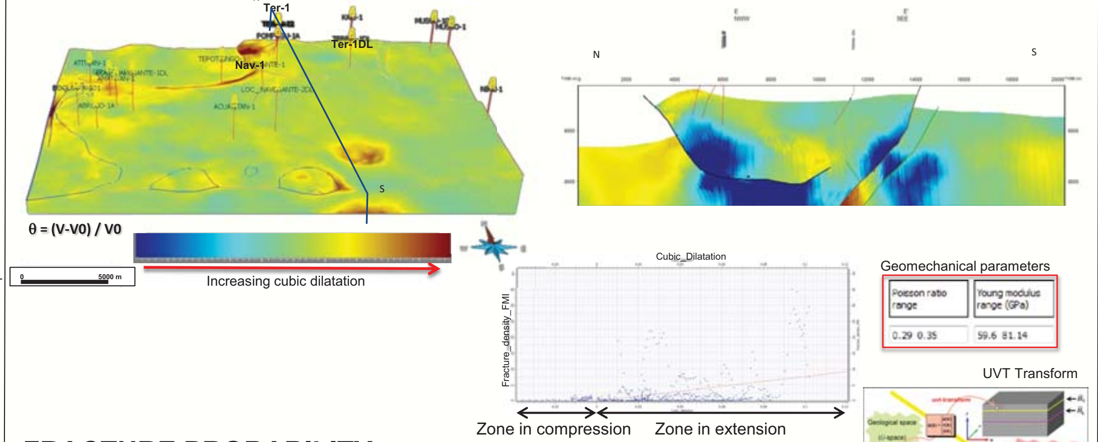
DILATATION

The Geological grid, built using the faults and horizons as interpreted onto the seismic, corresponds to the model at the state which has registered the sum of all the deformations undergone by the field. The UVT-transform allows the computation of the Geological grid at the time of deposition of the sediments, before the deformation. The dilatation is defined by (volume of the actual time - volume at time of deposition)/(volume at time of deposition).

Positive dilatation = extension (increase in volume); Negative dilatation = compression (loss in volume)

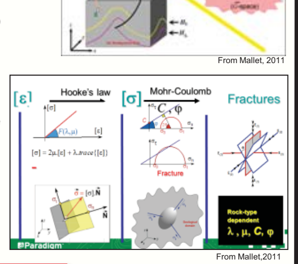
The dilatation is computed on all the grid cells of the Geological grid, using the UVT transform and the geomechanical parameters of the rock.

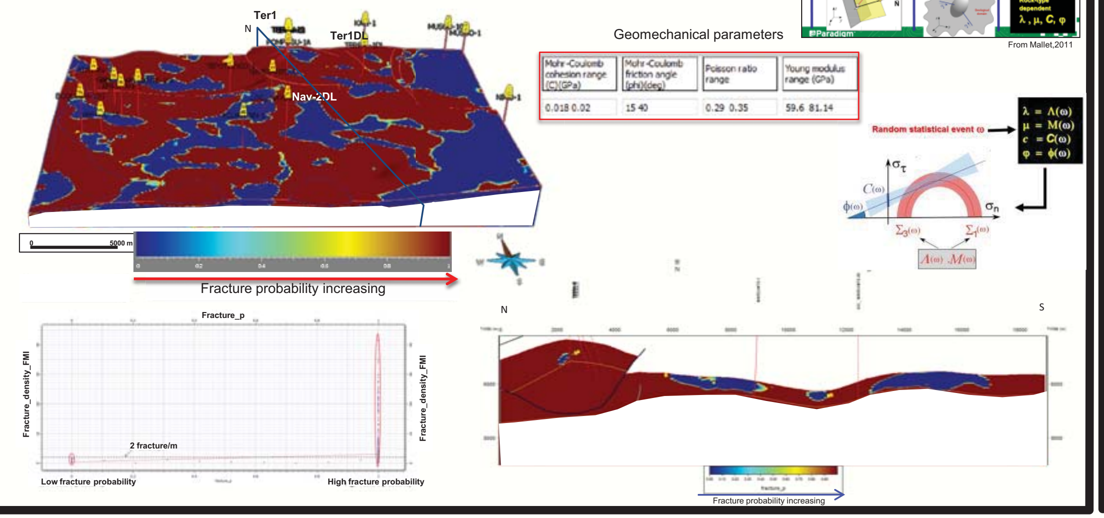
We have access to the very detailed information stating if the local part of the structure has undergone mainly compression or extension with the sum of deformations of the field.



FRACTURE PROBABILITY

The UVT transform links both the Geological grid at time of deposition (geochronological space) and the Geological grid at present state (geological space) which has undergone the sum of all deformations which have affected the field. Consequently, we know the vector of displacement for each grid cell between the moment of deposition and present, allowing a computation of a strain tensor. Using Hooke's law, it is possible from the strain tensor to compute the stress tensor using Poisson ratio and Young Modulus. The sensitivity of the rock material to the fractures can be assessed through a failure criterion, like the Mohr-Coulomb criterion (using Mohr-Coulomb cohesion and friction angle parameters). Ranges of geomechanical parameters values are used in order to take into account their uncertainties, allowing the computation of a fracture probability (Mace, 2004).

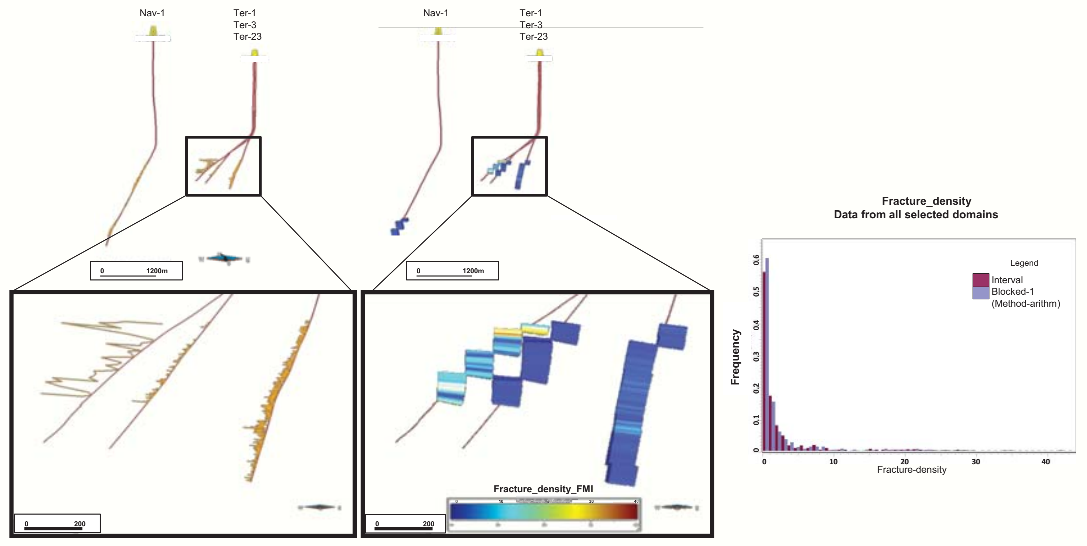




WELL DATA ANALYSIS

UPSCALING

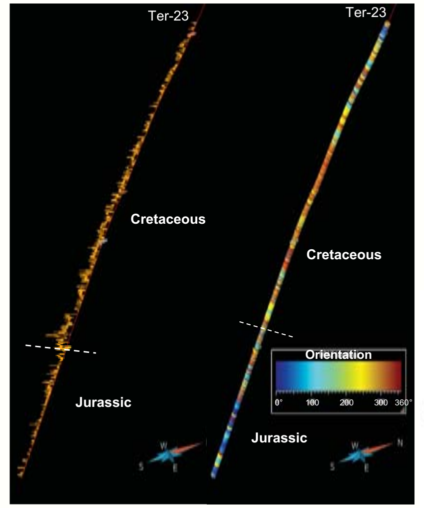
Upscaling of the fracture density calculated from images well logs to the scale of the fine-scaled Geological grid → Well data blocking. The arithmetic mean upscaling method was chosen, as it was the one which best preserved the statistics of distribution of the data from the images well logs and its heterogeneity. The fracture density data at the scale of the fine-scaled Geological grid was crossplotted against the structural attributes computed previously onto the Geological Grid to find correlations.



Fracture abundance from images log

Fracture density data blocked at the Geological grid scale

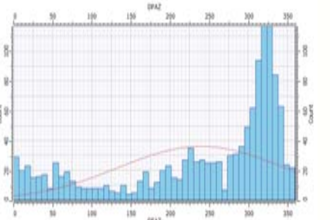
Data	Min	Max	Mean	Median	Std. Dev	Nb. Samples
1 Interval	0	43.8	2.35	0.483	5.3	3897
2 Blocked-1 Method_Arithmetic_mean Intersercted	0	41.5	2.49	0.500	5.5	542

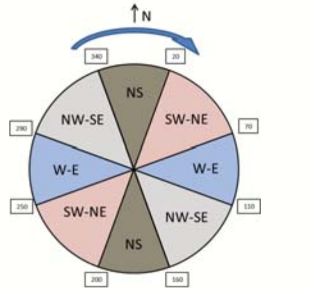


Total fracture density and main orientations from images logs.

The fracture density well log obtained from images logs does not make the distinction between the various fracture sets. The main FMI observed fracture orientation (azimuth) well log was used to split the fracture density well log into seven different fracture density well logs (one for each fracture set) taking into account the fracture sets orientation known from the detailed core analysis and the geological region (JSK / KS).

Analysis of the well log data for each fracture set density (histogram). Changing the scale of the fracture density well logs to the scale of the fine-scaled grid and creation of vertical trend curves.

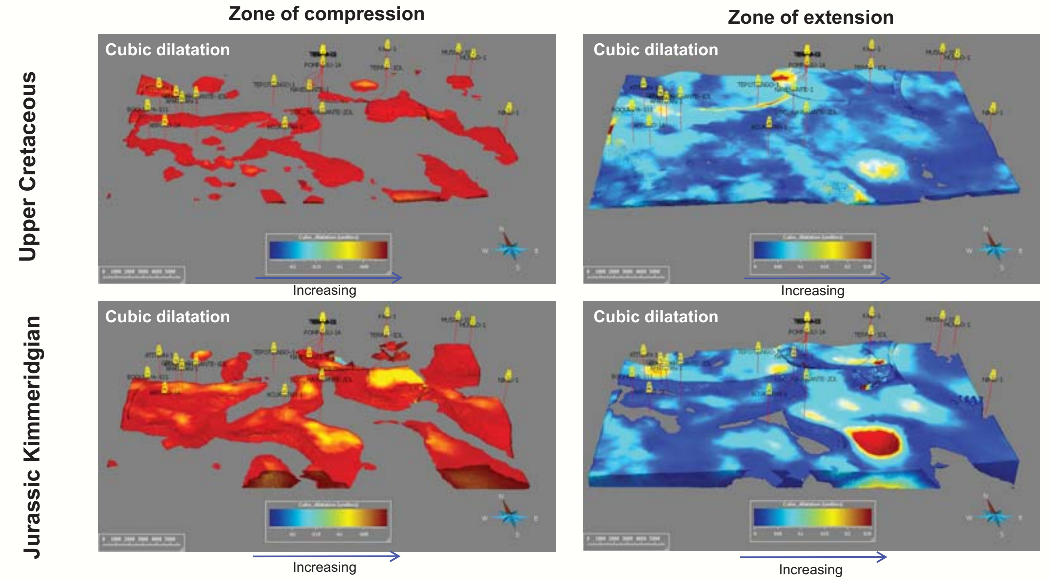




convention for fracture orientation

RESERVOIR PROPERTIES

Example of separation extension/compression zones for both Jurassic Kimmeridgian and Upper Cretaceous in a reservoir. The geostatistics simulations are done separately inside the four regions: Compression- Jurassic Kimmeridgian / Extension- Jurassic Kimmeridgian / Compression- Upper Cretaceous / Extension- Upper Cretaceous.

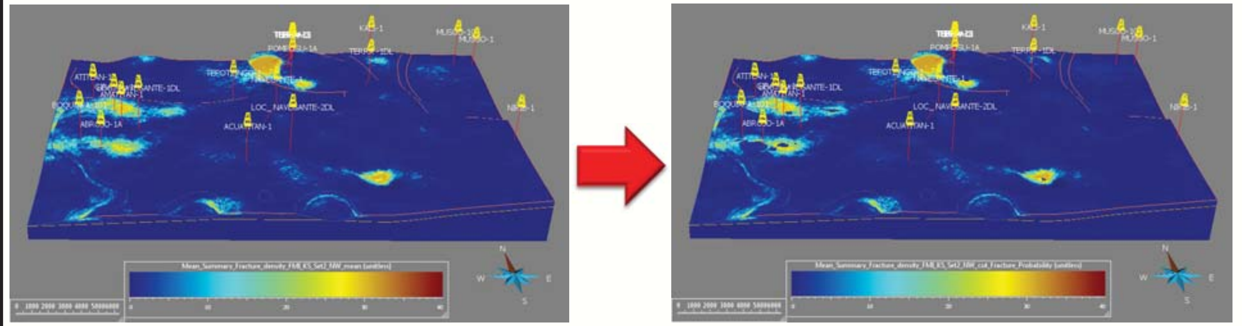


UPSCALING

FRACTURE DENSITIES PROPAGATION INSIDE THE GEOLOGICAL GRID

The fracture density property for each fracture set is simulated onto the whole Geological grid using a Sequential Gaussian Simulation, collocated coKriging (Multi) algorithm with the blocked fracture density data as the first data and the structural attributes as secondary data. In order to obtain a fracture density representative of the heterogeneity of the repartition of the fractures within the reservoir, several equiprobable simulations for each fracture set are performed and the mean of the simulations is computed.

Use of the fracture probability structural attribute to filter the results of the geostatistics.



Fracture Density KS SET 2 NW_Mean of the simulations

Filter with the fracture probability structural attribute

Fracture Density KS SET 2 NW_cut_Fracture Probability

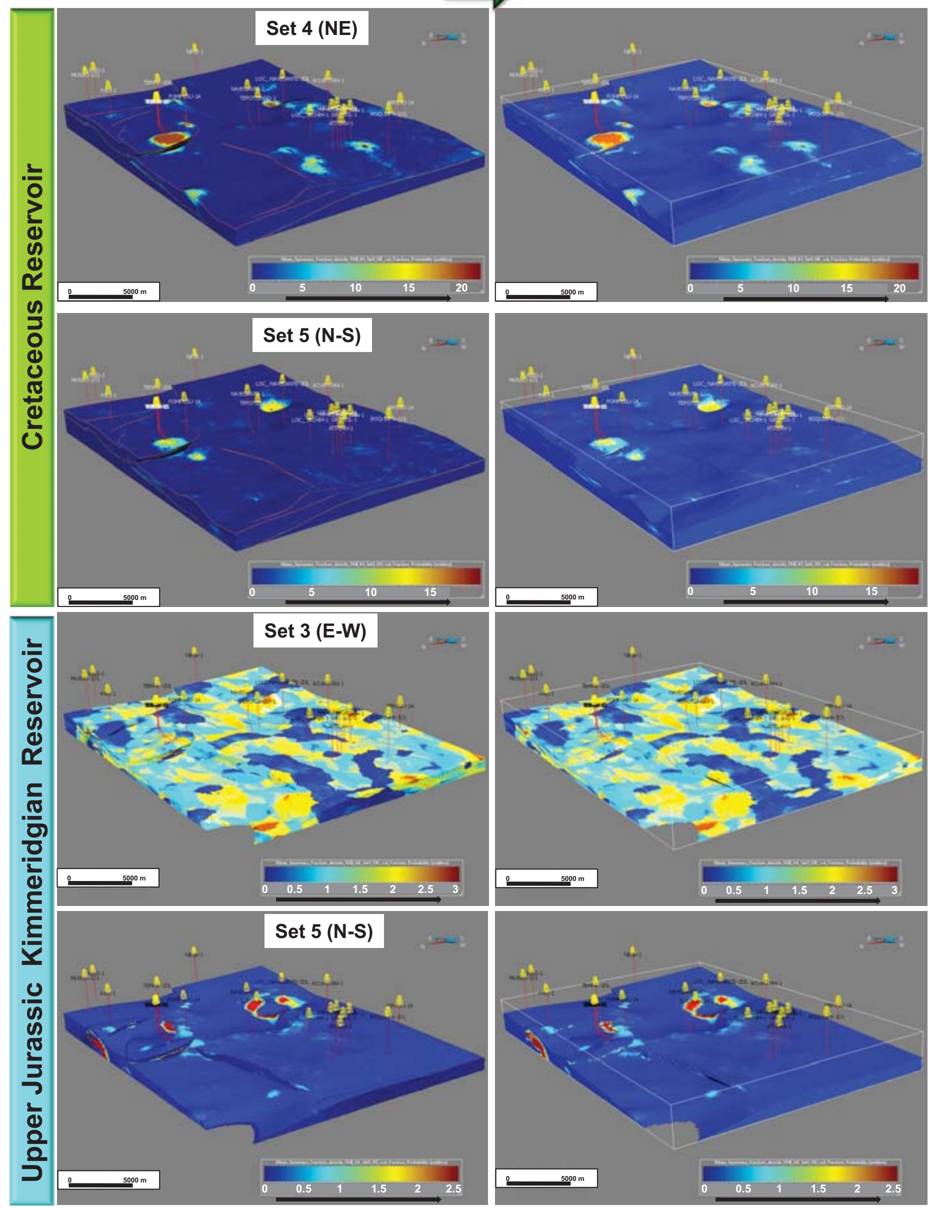
RESULTS

UPSCALING

The Flow Simulation Grid is a structured grid with faults stair-stepped in 3D and cells as orthogonal as possible in order to conserve mathematical consistency during fluid flow simulations. It is optimized for fluid flow simulations and DFN simulations.

Upscaling of the fracture densities from the fine-scaled Geological grid to the coarse-scaled Flow Simulation Grid.

The Discrete Fracture Network (DFN) simulation is performed on the Flow Simulation Grid.

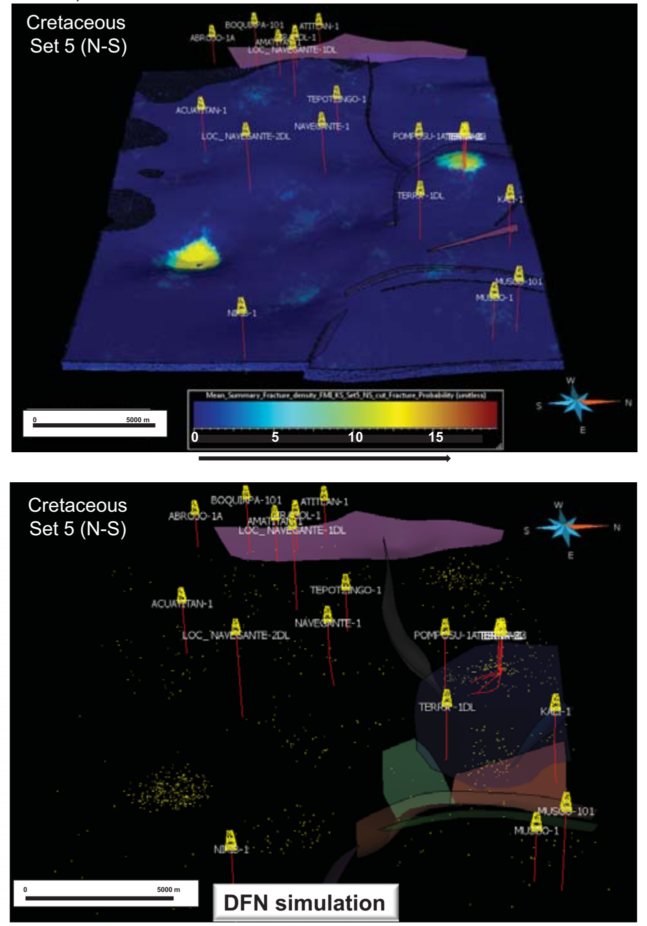


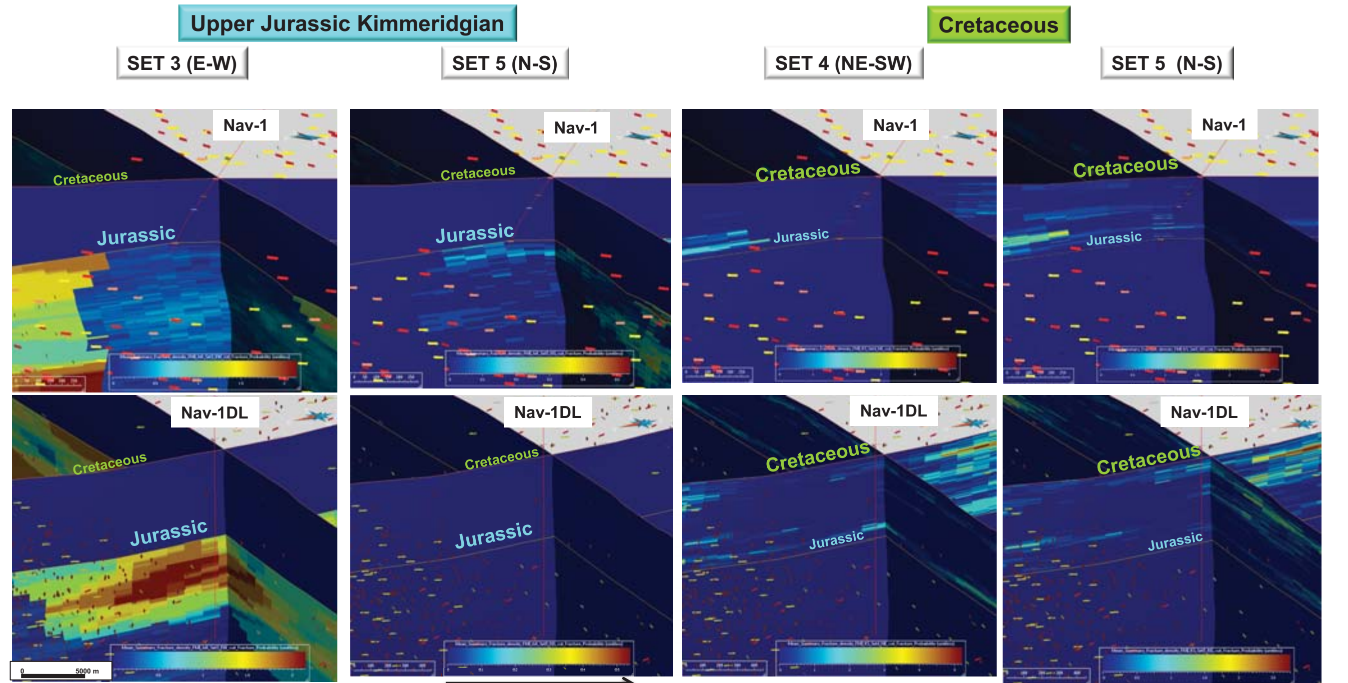
Left: Geological grid. Fracture densities propagation performed inside the Geological grid optimized for structural attributes computation and geostatistics.

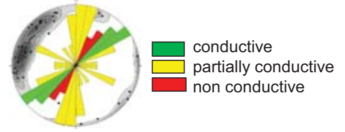
Right: Flow Simulation Grid optimized for flow simulation and DFN simulation. Upscaling for all the fracture densities from the Geological grid to the Flow Simulation Grid, using an arithmetic average method with weighting by the cell volume.

GEOMODELING FRACTURES (DFN SIMULATION)

Results of simulation of the fracture planes (Discrete Fracture Networks), for each fracture set.







A DFN simulation was performed for each of the fracture set using the following parameters:

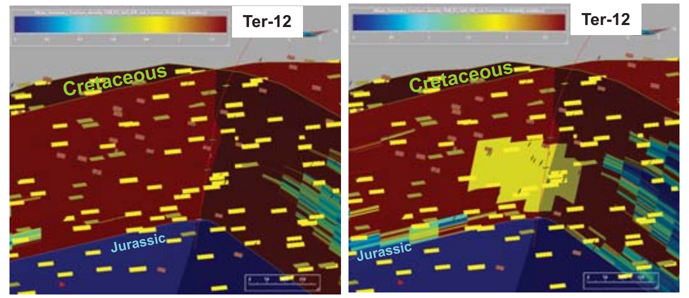
Fracture density: the one upscaled at the previous step

Fracture length: 1-5m (SDPS)

Fracture height: fracture height/length=0.5 (length=2*height)

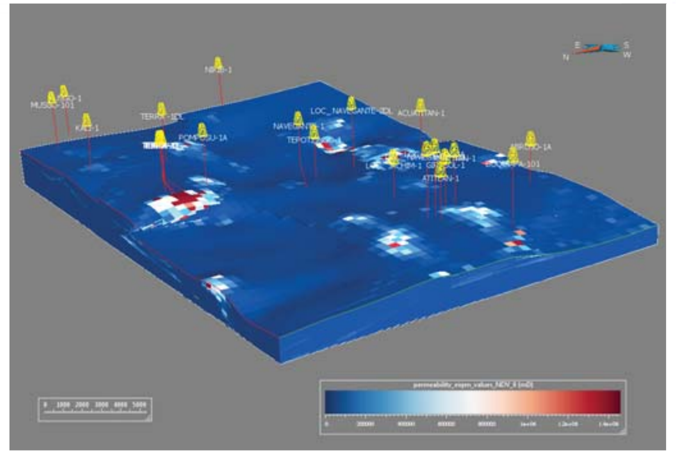
Fracture set orientation (SDPS): Dip and dip azimuth

Aperture: (SDPS)

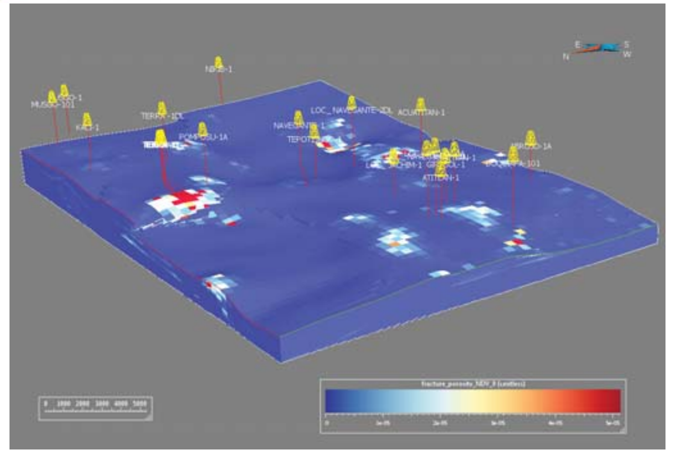


Fracture density for each fracture set and DFN simulations

UPSCALING FRACTURE PROPERTIES



Fracture permeability distribution



Fracture porosity distribution

The fracture properties are upscaled from the simulated fracture planes to the Flow Simulation Grid in order to get a double porosity-double permeability grid which can be exported to fluid flow simulators.

CONCLUSIONS

The work presented here is an example of integration of fracture data characterized at different scales (thin sections, cores, well logs) along with a geomechanical model in order to create a 3D model predicting the distribution of the fracture sets into a carbonate naturally fractured reservoir.

The results of the study are:

(1) A detailed fracture characterization study which allowed to identify the number of fracture sets and their attributes,
(2) A 3D structural model representing faults and horizons as interpreted at the seismic scale along with a geomechanical model,
(3) A fracture density model representing the heterogeneity of repartition of the fracture sets,
(4) DFN simulations allowing to represent explicitly the fracture planes of the various fracture sets, taking into account the distribution model computed before and the fracture attributes as determined by the SDPS methodology,
(5) A double porosity-double permeability model which can be sent to a fluid flow simulator.
(6) Reduction of uncertainties and risks in the exploration and development of oil and gas fields, optimizing the investment of a project.

With the result of this modeling has been verified that the trajectory of the wells T-1, T-3, T-11, and T-23 intercepted the main conductive fractures sets favorably, but it was not the case for T-12 and T-1DL wells.

The Nav-1 well cut just a little favorably the main conductive fracture sets.

The well productivities of these wells confirmed the quality of fracture sets identified. Therefore, this work demonstrates that the results of this methodology can be used as a guide to propose new exploratory and development well locations.

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ACKNOWLEDGMENTS

To Pemex Exploration and Production, particularly to the Exploration Department and the Cuencas del Sureste Terrestre Asset, to allow us to present the information and, for the financial support of this work. Also, we want to thank Paradigm to work together with Pemex applying the software to get better results in the fracture characterization of these oil and gas fields.

To AAPG for the opportunity to participate in the 2014 Annual Convention & Exhibition.