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Facies Modelling in Fault Zones

A.R. Syversveen* (Norwegian Computing Center), A. Skorstad (Norwegian Computing Center), H.H. Soleng (Norwegian Computing Center), P. Røe (Norwegian Computing Center) & J. Tveranger (CIPR)

SUMMARY

Traditionally fault impact on fluid flow is included by assigning transmissibility multipliers to flow simulation grid cell faces co-located with the fault plane (Manzocchi et al. 1999). A new method, called Fault Facies modelling (Tveranger et al. 2004, 2005), captures fault impact by considering faults as deformed rock volumes rather than simple planes. Architectures and petrophysical properties of these deformed volumes (i.e. fault zones) are linked to a range of factors such as lithology, host rock petrophysical properties, tectonic regime, orientation, magnitude, and distribution of stress, as well as the burial depth at the time of faulting. By understanding these links and identifying bounding values for distributions and parameters, fault zone architectures and properties, as well as uncertainties attached to these, can be forecasted.

The fault facies approach allows 3D features such as anisotropic permeability fields, capillarity effects and tortuosity of flow paths inside the fault zone to be explicitly represented in the reservoir models. Furthermore, on the simulation grid scale, flow between cells on opposite sides of faults, as well as any uncertainty attached to this, can be estimated a priori rather than set deterministically a posteriori using history matching.

The paper compares fluid flow behaviour of conventional transmissibility multiplier-type fault property models and fault facies type models through a series of simple tests. The study demonstrates that the fault facies concept is a technically feasible methodology that represents an alternative or supplement to standard industrial fault modelling methods.

Introduction

Faults commonly act as barriers for fluid flow in petroleum reservoirs, but sometimes they may act as conduits. In order to get reliable forecasting of production performance and reservoir response, it is crucial to understand the causes for this contrasting behavior, and capture them properly in the reservoir models.

The traditional way of representing faults in reservoir models is as membrane-like surfaces. The impact of faults on fluid flow is emulated using transmissibility multipliers across these surfaces (Manzocchi et al. 1999, Yielding et al. 1999), augmented by non-neighbor connections to represent ducts along fault surfaces. The latter feature is derived in an ad-hoc, deterministic manner using dynamic well data.

However, most outcrop studies show that faults should be considered as volumetric elements, often exhibiting highly complex architectures on scales relevant for reservoir characterization. A fault should therefore rather be described in terms of displacement, petrophysical alteration of a volume of host rock surrounding this displacement, and internal architecture of the deformed host rock in the fault zone. Hence, it should be natural to represent faults as volumetric elements also in reservoir models. This will give a more physically correct representation of faults as seen in nature. It will allow frequency, distribution and petrophysical properties of the fault zone elements to be modeled stochastically using boundary conditions derived from field studies. In order to choose parameters for the probability distributions used, field observations of faults and fault zones in different lithologies, burial depths and tectonic settings need to be analyzed. Ideally this approach should enable us to forecast what kind of deformational products, properties and architectural elements can be expected to form from any given host rock as well as their spatial distribution, provided an estimate of strain distribution is supplied. This approach is termed the “Fault Facies” concept (Tveranger et al. 2004, 2005).

In the present study, a workflow for a Fault Facies type modeling procedure is demonstrated. Strain conditioning is applied and a qualitative comparison of streamline simulations is carried out on both the Fault Facies model and a corresponding model using traditional fault modeling techniques.

Fault Facies Workflow

The fault zone is defined as a certain volume around the fault, in which host rock properties are altered or affected by recurrent fault movements.

An illustration of the workflow is given in **Figure 1**. Model generation can be broken down into the following main steps:

1. Conventional grid modeling.
2. Facies modeling.
3. Petrophysical modeling.
4. Grid refinement in fault zone.
5. Fault Facies modeling.
6. Fault zone petrophysical modeling.
7. Merging of grids.

A strain model can be given as input to the facies modeling in the fine grid fault zone for honoring the intensities of the different facies. Strain modeling is described later.

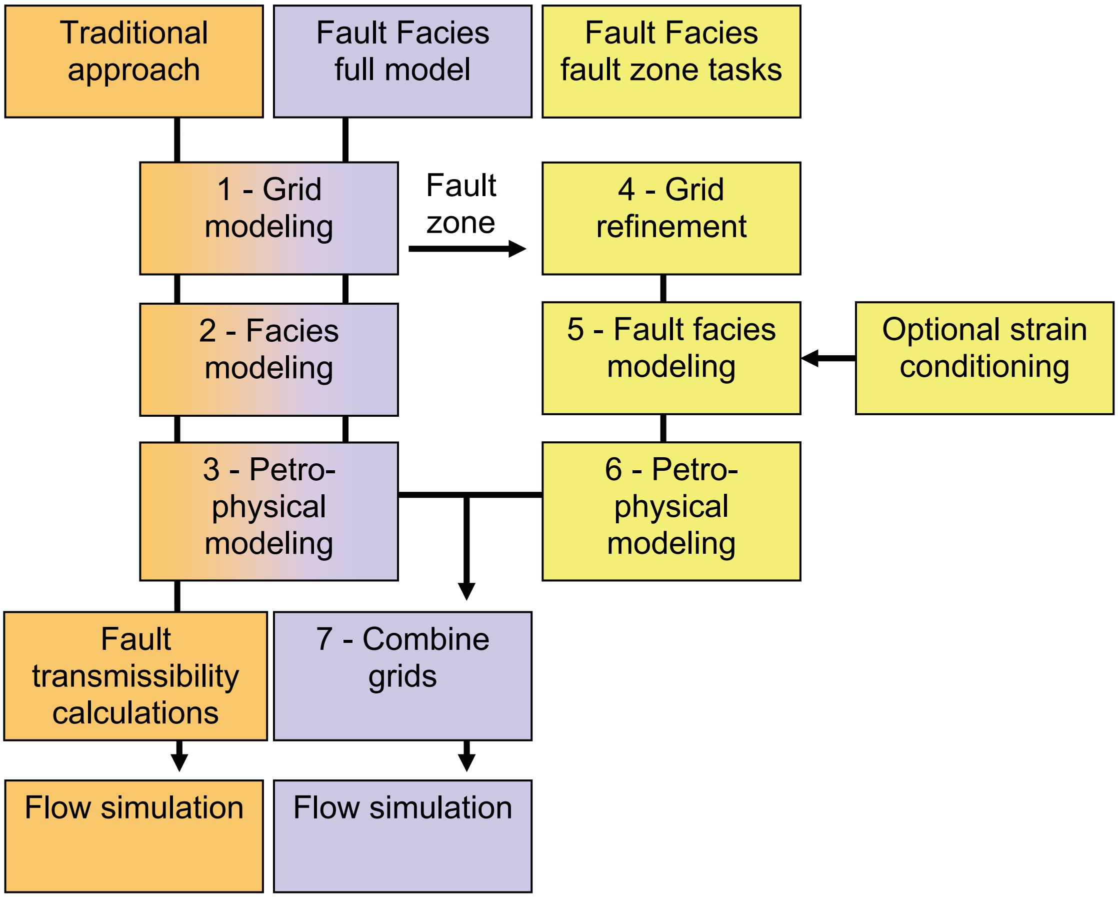


Figure 1: Schematic workflow for both a traditional and a Fault Facies approach. Upscaling prior to fluid flow simulation is not included here.

Grid modeling concept

The fault is initially defined in the grid in the traditional way, as a surface. In the Fault Facies concept, we will treat the fault zone as a volume. Because of a higher degree of heterogeneity in the fault zone compared to the undeformed host rock, the fault zone is extracted from the full model and handled separately using a finer grid resolution, see Figure 1. The fault zone local grid refinement will subsequently replace the coarse grid in the fault zone region, as illustrated in **Figure 2**. For the present purpose the fault zone is set to extend to a width of three cells into the footwall and three cells into the hanging wall of the fault. We construct the fine grid in the fault zone as follows: We start with the coarse grid cells belonging to the fault zone. Each grid cell is refined, for example by a factor of two in the x-, y-, and z-directions. Then each of these cells is stretched in z direction to ensure that the grid has the same height on both sides of the fault plane. This is shown in **Figure 3** where a single slip plane occurs to the leftmost edge of the fault zone. In this figure, the fault zone is three cells wide to the left and to the right of the fault plane. The marked cell in the left figure has become four cells in the right figure, and these are stretched in z-direction compared to its origin.

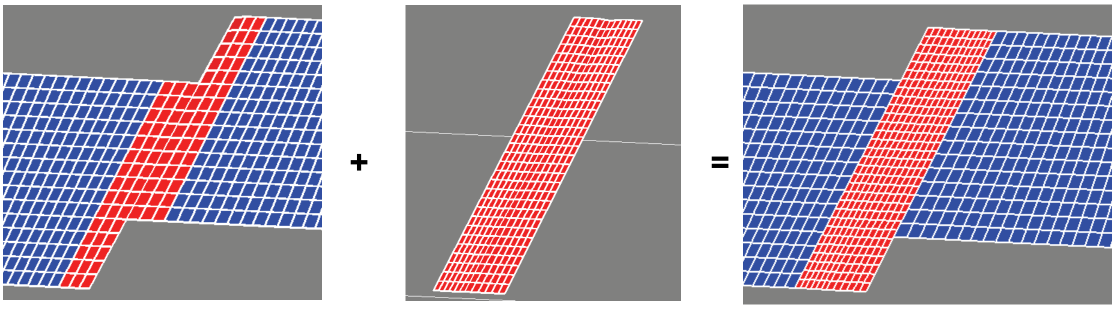


Figure 2: Merging of coarse and fine grid by replacing the coarse fault zone cells (red in the left picture) with the Fault Facies representation.

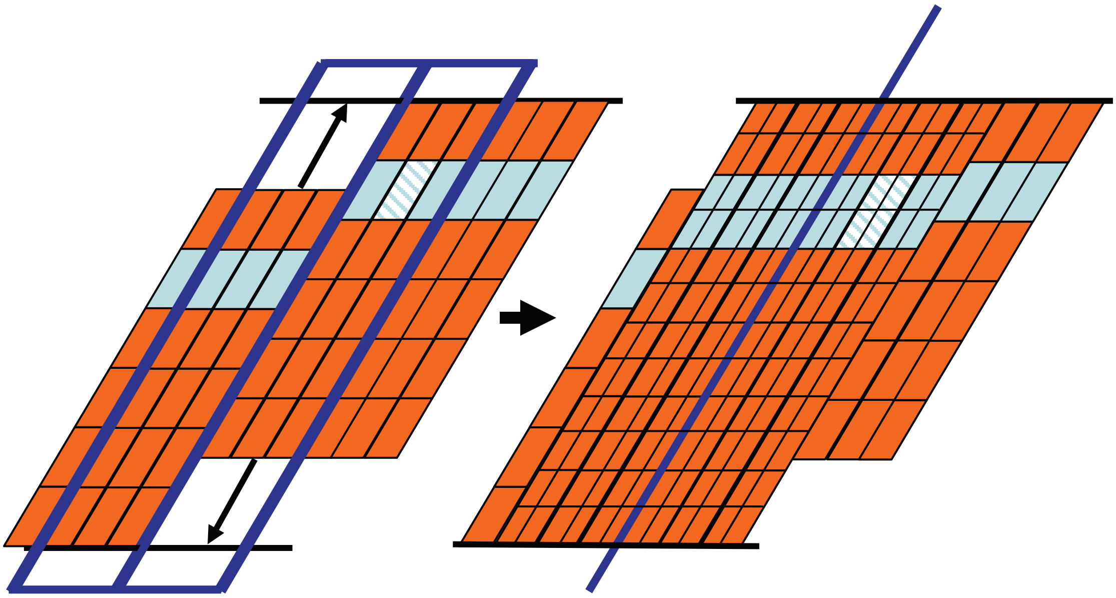


Figure 3: Stretching of cells in the fault zone grid.

Strain modeling

Plate tectonics, meteor impacts, volcanoes, salt domes, and loading and unloading of ice sheets among other things contribute with forces responsible for geological deformation. Often the stress is large enough to cause plastic behaviour and permanent (or non-recoverable) strain. In the fault zone one gets a complex rheological process and depending on the rock type and chemical and physical conditions such as the temperature, various new fault rock types (Fault Facies) may be created. A detailed physical description of the rheological processes during faulting is far beyond present-day computational power. Hence, we have to apply a simplified stochastic modeling method where strain is used as a conditioning factor for the occurrence of fault rocks.

Strain distribution is calculated on the basis of the fault model. The fault model defines a displacement going from the unfaulted to the faulted grid for each point in the volume deformed by the faults. By inverting this displacement we obtain the inverse displacement operator **x'**. This operator defines a restoration from the faulted grid back to an unfaulted representation.

From the inverse displacement operator we compute the spatial deformation gradient tensor by taking the gradient of the inverse displacement operator:

$$\mathbf{F}^{-1} = \nabla \mathbf{x}'.$$

Or on component form:

$$F_{ij}^{-1} = \delta_{ij} + \frac{\partial}{\partial x_j} u_i ,$$

where δ_{ij} is the Kronecker delta

$$\delta_{ij} = \begin{cases} 1, i = j \\ 0, i \neq j \end{cases} .$$

The spatial deformation gradient tensor can then be used to calculate the strain.

To be able to calculate the spatial deformation gradient tensor numerically, a regular grid encompassing the faulted grid is created and the inverse displacement values for each point in this regular grid is calculated. The spatial deformation gradient tensor is then calculated in each point in the regular grid by numerical derivation using a centered difference formula.

Since strain is a continuous concept, whereas displacement is discrete across the fault plane, backward or forward difference formula is used at points adjoining the fault planes.

Finally, the calculated strain is interpolated back into the original faulted grid. **Figure 4** shows an example on the calculated strain in a grid with three faults. We see that the strain has the highest values close to the faults, and decreases as we move away from the fault.

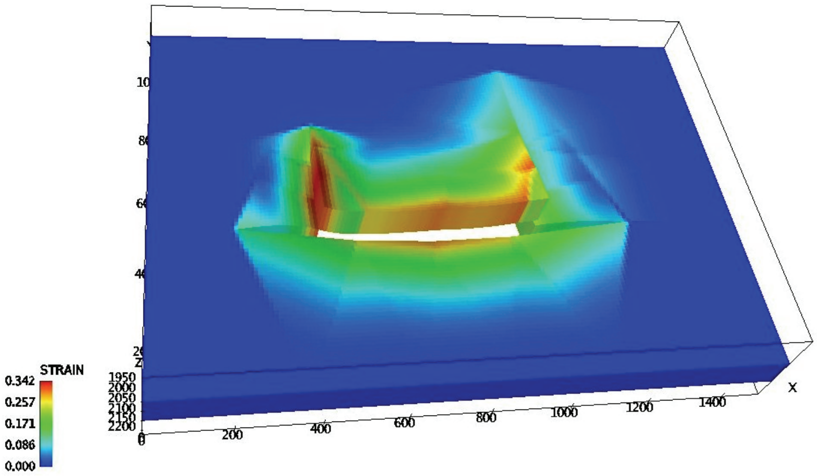


Figure 4: Calculated strain in a synthetic grid with three faults.

Property modeling

The Fault Facies concept means facies and petrophysical modeling on both the original coarse scale grid and the fine scale grid in the fault zone, before merging the two grids together. This allows incorporation of geostatistical methods for both facies and petrophysical modeling also in the fault zone.

Facies modeling

In the fault zone, there are typically many different fault facies types representing various deformational products of the sedimentary facies originally present in the position of the fault zone. The degree of deformation is expressed by strain, and the distribution of the Fault Facies, generated by various amounts of deformation, will conform to this. The center of the fault zone normally contains the most pervasively deformed facies. The strain can be used to define intensity fields for these facies. In addition, facies originating from the footwall and hanging wall blocks above and below the stratigraphic interval represented in the present model should be accounted for as these can interact with the facies in the fault zone.

Simulation Example

The concept is demonstrated on a test example with only one fault, see Figure 5. In the coarse grid, only two facies are present; high permeable sand objects, in a background of shale. The volume fraction of background and foreground facies objects is taken from the conventional grid realization in the fault zone. During faulting, the background is transformed to four new background facies, and the sand objects are transformed to four new foreground facies, each representing different degrees of deformation of the original facies. In addition, there are “upper” and “lower” elements inside the fault zone originating from overlying and underlying formations. This yields 10 different fault facies in the fault zone. One of the background facies and one of the object facies are modeled as ellipsoids with an object based model, and represent lenses in the fault zone. The other facies are modeled with Indicator Simulation, which is a grid based facies model. The two facies models are then merged, see Figure 5b. Due to different degrees of deformation, the fault facies are located at different places in the fault zone relative to the strain distribution. The intensities for the different facies are shown in Figure 6, where red color indicates high intensity, and blue indicates low intensity. The intensity shown in Figure 6a is proportional to the strain, which is calculated as described above, and has the highest value in the center of the fault zone. The intensity in Figure 6b is a function of the strain, whose maximum value is between the center and edge of the fault zone. This intensity is used for the medium deformed facies. Lenses are located at the edges of the fault zone, and are distributed according to the intensity function shown in Figure 6c. This intensity function is opposite proportional to the strain. The intensity in **Figure 6**d shows the intensity for the “upper” facies. A similar intensity, but with high values in the lower right corner, is used for the “lower” facies.

Permeability and porosity are modeled for all facies, using transformed Gaussian random fields. Trends and variograms are specified for each facies based on geological knowledge. The permeability in the lenses is given an intra-body trend, see **Figure 5**c. The facies located in the center of the fault zone has the lowest permeability. **Figure 5**d shows the permeability for the final, merged grid.

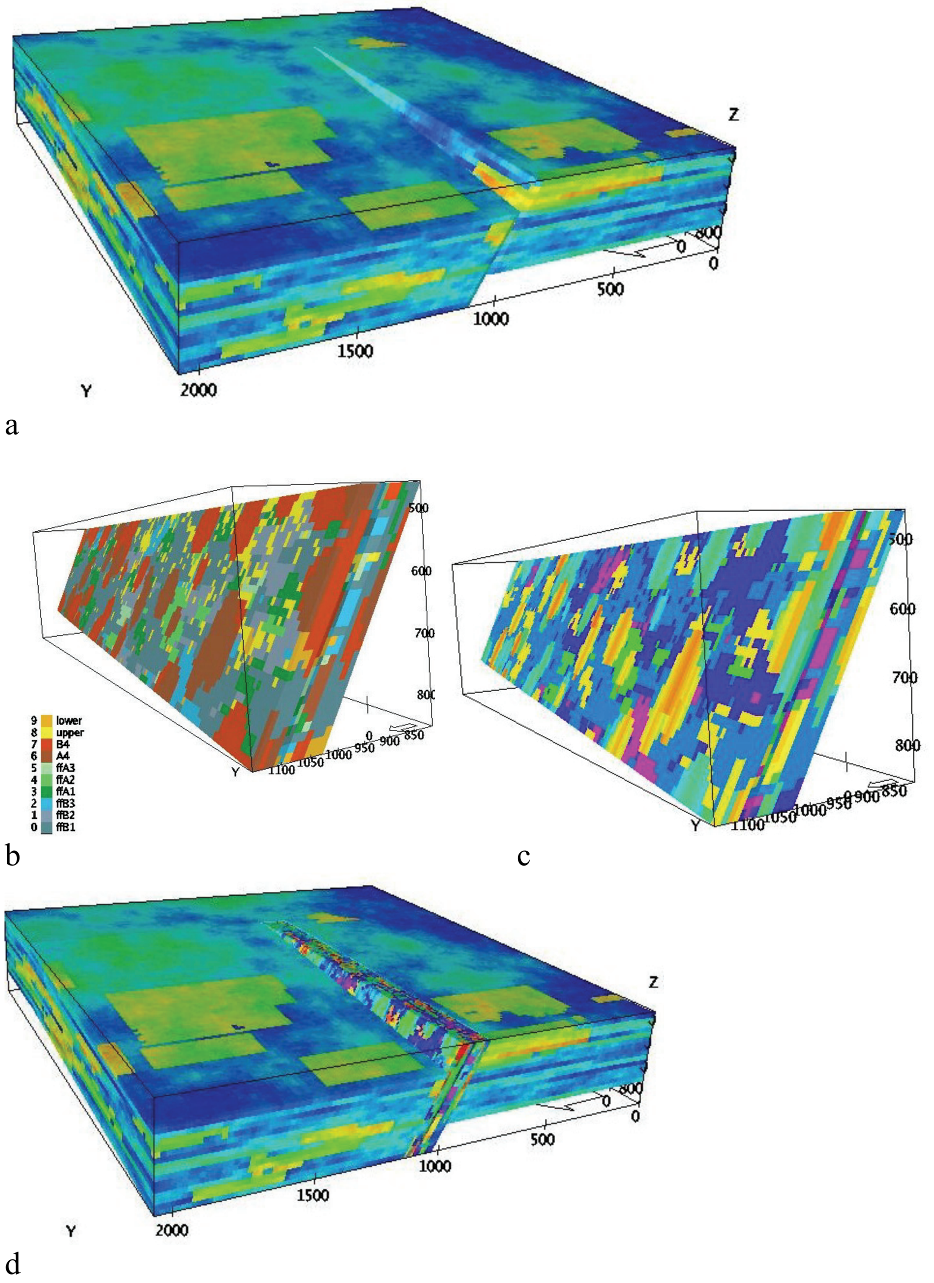
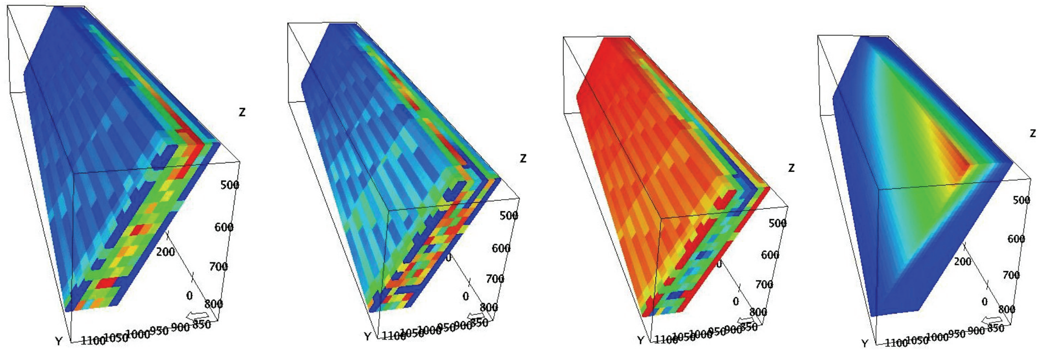


Figure 5: a: Permeability in original grid prior to fault zone modeling. b: Facies model in fault zone. c: Permeability trend in fault zone. d: Permeability in merged grid.



a b c d

Figure 6: Intensity functions. a: Strain. Intensity function for the most deformed facies. b: Intensity function for medium deformed facies. c: Intensity function for least deformed facies. d: “Upper” facies intensity.

Flow simulations

For comparison, a streamline simulation was run on a model using the traditional fault modeling method, Figure 5a, and the same model using Fault Facies type modeling approach (Figure 5d). The fault transmissibility multipliers for the traditional approach were computed with the Manzocchi (Manzocchi et al., 1999) approach with shale smear factor 7. The oblique slip angle was set to 0, and the displacement, brittle and cementation factors to 70, 100, and 0.35 respectively. Both reservoirs had two vertical wells; an injector close to the footwall side of the fault, and a producer close to the hanging wall side. They were set identically with respect to rate capacities, as were all reservoir conditions except permeabilities and porosities in the fault zone. The streamlines are shown in Figure 7.

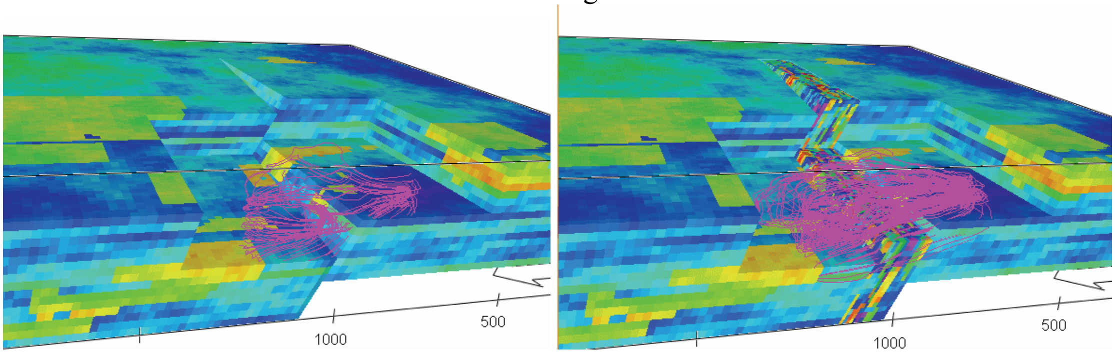


Figure 7: Streamlines from traditional (left) and Fault Facies approach (right). A part of the reservoir is not shown, to better visualize the streamlines around the wells.

The pictures show that the flow through the fault is higher for the Fault Facies approach reservoir. This is partly a consequence of the chosen fault transmissibility multiplier calculation method, and also the choice of Fault Facies petrophysical properties. The intention of this test is not to perform a detailed comparative evaluation of the two methods. That would require a far more comprehensive test scheme. However, what is interesting to note is that the Fault Facies approach gives a more spread-out flow through the fault than does the traditional approach, whose streamlines are more inclined to run through holes in the fault originating from high permeable facies on both sides of the fault surface. In the Fault Facies approach, the high permeable cells are more distributed. This is defined in the Fault Facies model. The vertical flow in the Fault Facies approach is not controlled by the non-neighboring connections, but on the facies distributions within the fault zone. This in strong contrast to the traditional methods which do not accommodate a vertical permeability description based on geological input data.

Conclusions

A new fault zone modeling approach has been demonstrated to be feasible to include in a reservoir characterization workflow. The flow within the fault zone can be determined, not through non-physical non-neighboring connections, but on the change in petrophysical properties within the fault resulting from the stress subjected on those rocks during the faulting process.

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