A Procedure for Upscaling a Complex Fractured Reservoir using Near-Well Refinement
Manuel G. Correia, SPE, Celio Maschio, SPE, Denis J. Schiozer, SPE, State University of Campinas.

Abstract
Classical fracture upscaling techniques are usually based on numerical or analytical solutions which can present some problems to capture the near-well flow behavior, leading to wrong well productivity index. In addition, grid cell size must be chosen carefully to maintain both connectivity and permeability tensor of fracture network in a reasonable simulation computational time. This paper proposes a near-well refinement in conjunction with a classic fracture upscaling technique in order to improve the accuracy of well productivity. The matrix porous media is respected to a microbial carbonate reservoir where discrete fractured network is composed by diffuse fracture pattern (small-scale fractures) and sub-seismic conductive fractures that strongly affect fluid flow. Fracture network density was defined using lithology as control driver. In this work, a dual-porosity system with a block cell size smaller than diffuse fractures was used as reference model (fine grid) for the upscaling method due to its quality to reproduce properly the connectivity between diffuse and sub-seismic fractures. The fracture upscaling method based on Oda’s solution (Oda, 1985) was applied to a coarser model defined by near-well refinements, which capture the fine grid fracture properties near-well. Homogeneous petrophysical matrix is applied in order to isolate the matrix heterogeneity effects. It was possible to adjust the main reservoir parameters (field average pressure, oil recovery factor and water cut) and advanced water front. The fine grid simulation time was drastically reduced using the proposed procedure.

Introduction
Reservoir simulation is used for major reservoir development decisions over the last twenty years (Lemonnier and Bourbiaux, 2010). About half of the world’s proven oil reserves are trapped in fractured carbonate reservoirs (Bourbiaux, 2010). For flow simulation purposes, to develop a naturally fractured carbonate reservoir keeping its heterogeneous behavior and in a reasonable simulation consumption, time can be a challenge. Fracture scales could range from small scale diffuse fractures, intermediate scale sub-seismic faults to large scale seismic faults. The discrete fracture network (DFN) model cannot be included into field scale models because of the computational limitation to fix possibly billions of fractures in each cubic kilometer of reservoir rock. Upscaling is therefore a pre-requisite for flow simulation (Dershowitz et al, 2000). For such simulations, a dual-porosity reservoir simulator is typically used. The dual porosity system is an implicit representation of the geological model of fault/fracture network and matrix medium using large grid blocks. The translation of DFN models and/or implicit fracture models into dual porosity reservoir-simulation parameters is set by upscaling procedures. These parameters are the equivalent fracture permeability and equivalent matrix-block dimensions or shape factor. Either analytical or numerical methods can be used to upscale fracture permeability. Oda (1985) proposed an analytical equation to calculate fracture-permeability tensor, and Lough et al. (1997) presented an approach using the boundary-element method. The first method consists of a numerical integration without any DFN generation and uses as input statistical parameters of fracture sets. Equivalent permeabilities are supposed to be linearly proportional to the density variations. Oda’s solution has the advantage that it can be calculated without requiring flow simulation, resulting in a fast processing. However, this method is only valid for well-connected and high density DFN. The second method is numerical. It consists in solving a steady-state flow problem, under boundary conditions, on the discrete fractured network with application of Poiseuille’s formula for fracture flows. This method takes into account the full geometry of the system but requires a larger CPU simulation time. Because of the high computational effort, this method is normally applied to small density of fractures. Besides, the DP formulation considers perpendicular fractures oriented along grid axes.
which do not always occur, leading to an erroneous representation of the fully permeability tensor computed by upscaling techniques.

The dual porosity formulation is a simplified representation of DFN models to implicitly represent possible hundreds of fractures in a simulation grid and consequently decrease CPU simulation time. These simplifications make difficult the determination of equivalent parameters, especially in vicinity of wellbores. For high fractured systems the conventional structural grid can be applied with an analytical upscaling method without losing information. When fracture density decreases particularly near wells, the conventional structural grid in conjunction with Oda’s method cannot capture the real fracture behavior and induces to an erroneous well productivity index. Ding et al. (2006) combine a conventional upscaling technique with a complex well-modeling in order to take into account the near-well flow behavior. Productivity Index (IP) errors from 16 to 100% were reduced to 2 or 3%. There are two main areas where detailed discrete fracture models can be used: (1) Upscaling of fracture properties and (2) Optimization of well-design, completion and operation based on an understanding of the inter-well scale flows (Ouennes and Hartley, 2000).

The use of a hybrid grid with near well refinement shows improvement reservoir parameters for some cases without disregarding Oda’s method application. For a lower fracture density away from wells Oda’s method cannot be applied even using a hybrid grid. The solution can be the use of smaller grid blocks in order to capture the fracture connectivity, but under a higher CPU simulation time, or use the numerical method “Block K”. The problem in using a numerical method is related to high CPU upscaling time. This method is normally taken only for few blocks models.

Another issue in upscaling procedures is related to the multi-scale fractures length relative to grid block size. Lee et al. (2001) demonstrated that long fractures, whose scale is much larger than grid block, have more influence in flow than short or medium fractures. Any homogenization method will underestimate the real effect of these geological features. The conventional procedure is the explicit modeling by triangular grids or by applying a transmissibility multiplier between grid blocks. Sub-seismic faults at an intermediate scale remain a difficult issue at flow modeling simulators, as they can neither be treated as part of a fracture continuum (dual porosity) nor be defined as discrete objects. Occasionally, they can be too numerous and too large to be modeled as an equivalent medium at simulator cell size (Bourbiaux, 2010). Small scale fractures can be modeled as part of an equivalent medium using dual porosity simulators or implicitly in matrix component. Some works (Li and Lee, 2006) consider a numerical method to upscale medium discrete fractures and an analytical method to upscale small scale fractures. In addition to fracture length scale, flow properties of fractures and interaction with matrix medium can be important to determine a representative model (SP system, DP system or explicit fault modeling).

Summarizing, several criteria drive the choice of a conceptual model: (1) the fracture scale compared to block grid cell size; (2) the connectivity of the fracture network and matrix medium and (3) the time scale of flow interaction (sigma factor) between medium and the time scale of fluid transport within a given medium (Bourbiaux, 2010). Besides the difficult fracture modeling processes described before, uncertainty analysis in fractured reservoir could lead to a harder handwork. A detailed procedure needs to be applied in order to consider all the assumptions in DP simulators and conventional upscaling techniques mentioned before.

Figure 1 represents an example of upscaling fracture methods applied to a simplified DFN system. It is possible to assert that upscaling methods based on analytical procedures (Oda’s solution) are sensitive to grid cell size. Table 1 represents the computational simulation time. For higher block sizes Oda’s method becomes unreliable for this hypothetical case. Numerical methods are highly CPU demanding but takes into account the full DFN geometry for permeability tensor calculation, even for reservoir grid cell sizes. The motivation of this work is the study of a hybrid grid, in order to get a better match with DFN system, without disregarding the fastest method (Oda’s solution).

The purpose of this study is to compare the use of a conventional structural grid with a hybrid grid in order to improve the Oda’s method applicability without an algorithmic modification.

This work combines the two subject areas. A fully comprehension of inter-scale flows of discrete fracture models and a comparison between upscaling procedures under structural and hybrid grids are the main areas of this work.
Figure 1. Oil Recovery Factor for Numerical and Analytical fracture upscaling techniques

Table 1. Computational Simulation Time

<table>
<thead>
<tr>
<th>Computational Simulation Time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFN Model (Reference model)</td>
</tr>
<tr>
<td>Cell size 10 x 10 (Oda method)</td>
</tr>
<tr>
<td>Cell size 20 x 20 (Oda method)</td>
</tr>
<tr>
<td>Cell size 50 x 50 (Oda method)</td>
</tr>
<tr>
<td>Cell size 50 x 50 (Numerical method)</td>
</tr>
</tbody>
</table>

Methodology

The methodology (Figure 2) is divided into four steps: (1) Study of DFN behavior in a fine grid single porosity system; (2) DFN model conversion into a DP reference system for posterior upscaling matches; (3) fracture upscaling with a conventional grid and (4) fracture upscaling with a hybrid grid.

In a macro-scale, a fine single porosity model cannot always be used as reference due to the high CPU consumption time. The first step is to study the DFN flow behavior in a single porosity system. If the fracture system has very poor connectivity the consequent procedures could be unreliable since Oda’s method is only valid to high connected systems. The second step is to verify a DP reference model that could be an approximation of a DFN behavior for consequent upscaling matches. A single porosity fine grid model with a block size of 1 x 1 meter is used as representative of our DFN system. In this case, discrete fractures are projected in a single porosity system with a block size of 1 x 1 meter, in conjunction with matrix properties. This scale evaluation is taken under a bi-dimensional model size, in order to evaluate and compare reservoir parameters in a reasonable simulation time. This bi-dimensional model is a representative layer from the fine grid DP model used for consequent upscaling matches. The third and fourth step is the upscaling procedure from the transition meso to macro block scale. DP reference model is defined by a grid block size of 5 x 5 meters and defined by Oda’s solution applied to DFN model. The same DFN that characterizes the DP reference model is applied to a conventional simulator block scale of 60 x 60 meters. The applicability of a Hybrid Grid is then compared to a conventional grid. Oda’s method is used as an upscaling method.

Discrete fracture network models are described by fracture intensity, orientation, length, transmissibility and aperture. Table 1 represents DFN model characterization. Fracture aperture is given in meters. Fracture intensity (P_{zz}) is described by \( m^2/m^3 \) unit. Fracture orientation is specified along grid axis, in order to follow DP simulator assumptions. Sub-seismic fractures average dimension is assumed close to block grid size, defined as intermediate-scale. Small-scale diffuse fractures are defined as smaller than cell size.

The reservoir structure applied in this work follows a characterization of a thrombolite-stromatolite reef distribution in a carbonate ramp system presented by Adams et al, 2005. The carbonate ramp system consists of a shoaling-upward ramp associated with: grainstone, heterolitic facies and thrombolite-stromatolite reefs. Porosity and Permeability are considered homogeneous in order to isolate the matrix heterogeneities effects. Matrix permeability is defined as 1 milidarcy in order to disregard flow between matrix blocks, and avoid a high CPU intensive Dual-permeability model.
The hierarchy of scales (Figure 3) in fractures systems characterized by DFN models leads to the use of a representative model to upscale matches for flow simulation. The conventional representative model in fracture upscaling matches is the DFN flow behavior. Given the uncertainties set in these work, the use of several DFN models as representative model could be high CPU intensive. In this case we prove, through some 2D simulation examples, that a fine grid DP system can be representative to DFN models, thus reducing the CPU simulation time for consequent upscaling matches.

Application
The DP model used as reference has a dimension of 700 x 700 x 80 meters and a grid cell size of 5 x 5 x 5 meters. The Field Stratigraphic Architecture (figure 4) of thrombolite- stromatolite reef in a carbonate ramp was used to construct the synthetic background lithology (figure 5) for the DFN distribution.

For reference model validation, a fine single porosity grid was used to simulate the DFN model (figure 6). For conventional procedures, a triangular grid is normally adopted to simulated DFN behavior. In this case, discrete fractures are projected in a very fine grid with a grid cell size of 1 x 1 meter. One layer from the final 3D model was used to validate our DP reference model, given the high CPU simulation time to apply a flow simulation model with millions of cells. A hybrid grid (figure 7) with near well refinements and a conventional grid are used for simulation grid. The cell size near wells is equivalent to cell size DP reference model. Cell size outside wells are two times larger than conventional grid block size. It was impossible to use local refinements just around wells due to a software limitation in fracture upscaling approach to local grids.

Dozens of cases were tested, and the most representative three cases are represented in table 2. For both cases we show the effects of considering and disregarding vertical fracture permeability.

Table 2. Statistical data of representative Discrete Fracture Network models.

<table>
<thead>
<tr>
<th>Fracture Type</th>
<th>Orientation</th>
<th>Dip</th>
<th>Length (m)</th>
<th>Aperture (m)</th>
<th>Intensity (Pf)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>Sub-seismic</td>
<td>0/90</td>
<td>90/90</td>
<td>150/150</td>
<td>0.0004/0.0004</td>
<td>0.2/0.2</td>
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<tr>
<td></td>
<td>Diffuse</td>
<td>0/90</td>
<td>90/90</td>
<td>10/10</td>
<td>0.0004/0.0004</td>
<td>0.2/0.2</td>
</tr>
<tr>
<td>Case B</td>
<td>Sub-seismic</td>
<td>0/90</td>
<td>90/90</td>
<td>100/100</td>
<td>0.00003/0.00003</td>
<td>0.45/0.45</td>
</tr>
<tr>
<td></td>
<td>Diffuse</td>
<td>0/90</td>
<td>90/90</td>
<td>30/30</td>
<td>0.00003/0.00003</td>
<td>0.45/0.45</td>
</tr>
<tr>
<td>Case C</td>
<td>Sub-seismic</td>
<td>0/90</td>
<td>60/60</td>
<td>150/150</td>
<td>0.0004/0.0004</td>
<td>0.2/0.2</td>
</tr>
<tr>
<td></td>
<td>Diffuse</td>
<td>0/90</td>
<td>60/60</td>
<td>10/10</td>
<td>0.0001/0.0001</td>
<td>0.2/0.2</td>
</tr>
</tbody>
</table>
Results
The first step of this work is validating the use of a fine grid DP model as reference for consequent upscaling matches by comparing its reservoir parameters and water front with a DFN system. In this work we have shown this match in a 2D layer, as an example, due to the high CPU time for DFN model simulation. Figures 8, 10 and 12 represent the water front of a DFN system in a very fine single porosity grid for different time steps. Figures 9, 11, and 13 represent a match for the matrix component in the DP fine grid system used as reference for subsequent coarser models upscaling. Figures 14 to 16 represent a match in reservoir parameters for DFN and DP systems.

After applying this methodology for the other representative cases, we assume that a DP fine grid system can represent the DFN models behavior studied in this work, and consequently be used as reference for a full 3D model.
Figure 8. Injected Water Front for DFN model after 30 days

Figure 9. Injected Water Front for DP fine grid model after 30 days

Figure 10. Injected Water Front for DFN model after 1 year

Figure 11. Injected Water Front for DP fine grid model after 1 year

Figure 12. Injected Water Front for DFN model after 3 years

Figure 13. Injected Water Front for DP fine grid model after 3 years
The hybrid grid used in this work shows the importance of near-well refinement and consequently well index productivity preservation. For all the studied cases, the effect of disregard vertical fractured permeability is presented. The disregard of vertical fracture permeability shows the importance of near-wells refinements grid. The horizontal flow takes position in reservoir behavior.

For lower fracture intensity, case A, the hybrid grid shows a better match with reference model than the conventional grid (Figure 17, 18 and 19). For conventional grid, the block 60 x 60 meters takes into account several fractures for permeability tensor calculation that could lead to an erroneous well index productivity if the real system does not have any fracture intercepting well bore in that layer. This behavior could occur if any region near the wells has few fractures intercepting well bore.

For high density fracture systems, case B, hybrid grid shows equal reservoir behavior (Figure 20, 21 and 22) with conventional grid simulation. For high density systems but heterogeneous fracture permeabilities (fracture apertures), case C, the hybrid grid shows a better match with reference model than the conventional grid (Figure 23, 24 and 25).

Figure 26, 27 and 28 show an example (Case A) of the fracture water front for the reference model, conventional grid and hybrid grid, respectively. Unlike the reference model and the hybrid grid, the conventional grid shows advanced water front toward one producer well. In this layer, the conventional grid has erroneous well index productivity for one well producer since the reference model does not have any fracture intercepting well producers. Refined cells between wells could also allow a preferential water path that better matches the flow behavior with reference model.

The numerical method is applied for all the three representative cases. Using the conventional grid, the numerical method has good matches with reference model. These approach shows that our reference model and the numerical method are a good representation of our DFN system. The numerical upscaling methods take the full fracture geometry into account but its high CPU consumption can set the method unreliable if several DFN systems are taken as uncertainty cases.

Permeability tensor calculation by Oda’s solution is sensible to grid cell size. Connectivity and consequently permeability tensor calculation is proper for smaller grid blocks, especially for high density fracture models. Near-well refinements could enhance Oda’s solution applicability for petrophysical heterogeneous models given the closeness fracture permeability value.
calculated with DFN model. With the same cell size and permeability values, well productivity index is identical, under the same reservoir production parameters.

Fracture intensity and fracture aperture parameters can influence between a conventional or a hybrid grid choice. The hybrid grid provides better results for high fracture aperture variability or lower fractured intensity systems.

### Figure 17. Oil Recovery Factor for Case A

### Figure 18. Water Cut for Case A

### Figure 19. Reservoir Pressure for Case A

### Figure 20. Oil Recovery Factor for Case B

### Figure 21. Water Cut for Case B

### Figure 22. Reservoir Pressure for Case B
Table 3. Computational Simulation Time

<table>
<thead>
<tr>
<th>Case</th>
<th>Computational Simulation Time (minutes)</th>
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<tbody>
<tr>
<td>A</td>
<td>DP Reference Model: 1024</td>
</tr>
<tr>
<td></td>
<td>Conventional Grid: 1</td>
</tr>
<tr>
<td></td>
<td>Hybrid Grid: 5</td>
</tr>
<tr>
<td>B</td>
<td>DP Reference Model: 1159</td>
</tr>
<tr>
<td></td>
<td>Conventional Grid: 5</td>
</tr>
<tr>
<td></td>
<td>Hybrid Grid: 5</td>
</tr>
<tr>
<td>C</td>
<td>DP Reference Model: 995</td>
</tr>
<tr>
<td></td>
<td>Conventional Grid: 1</td>
</tr>
<tr>
<td></td>
<td>Hybrid Grid: 3</td>
</tr>
</tbody>
</table>

Figure 23. Oil Recovery Factor for Case C

Figure 24. Water Cut for Case C

Figure 25. Reservoir Pressure for Case C

Figure 26. Water Front for reference model (Case A)

Figure 27. Water Front for Conventional Grid (Case A)

Figure 28. Water Front for Hybrid Grid (Case A)
Conclusions
The analytical Oda’s method is only recommended for high connected systems because it can yield inaccurate results if different fracture intensity models are applied as uncertainty in a fractured reservoir. Numerical methods can be applied, but the higher CPU time for DFN upscaling procedures can hinder its application especially for uncertainty analysis approaches, where several cases need to be studied.

A near-well refinement grid is applied for fracture upscaling. From several tested cases, two hypothetical discrete fracture network cases with different intensity fracture networks were defined as representative for the proposed work. For higher connected fractures systems the use of near-well refinements is not recommended because of the high CPU simulation time. For lower connected fracture systems, but still under Oda’s solution principle, near well refinement shows a positive effect in reservoir match with DFN model, as a result of its proper permeability tensor calculation that lead to a better match of well index productivity.

The conventional grid can yield erroneous well index values in case of non-fracture well bore interception, because coarser cell sizes capture all fractures that are near and away from well bore. On the other way, hybrid grid with near-well refinements could be CPU expensive for an uncertainty workflow and the higher difference in size between larger and refined cells could lead to numerical convergence issues.

In order to solve possible erroneous well index productivity values, a cut off in critical parameters like fracture intensity can be applied in an uncertainty workflow and consequently alternate between a hybrid grid and a conventional grid.

The grid with near-well refinements studied in this work can be useful for DFN systems with high fracture aperture variability or lower fractured intensity and shows that near-well grid cell size is more relevant than grid cell size outside wells.

Nomenclature
DFN = Discrete Fracture Network
DP = Dual Porosity
SP = Single Porosity

Acknowledgments
The authors are grateful to the support of the Center of Petroleum Studies (Cepetro-unicamp/Brazil), PETROBRAS S/A, and special thanks to UNISIM and Petroleum Engineering Department (DEP-FEM-unicamp/Brazil). The authors are also grateful to Schlumberger Information Solution for the use of Petrel®.

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