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A Powerful and Practical Workflow for a Naturally Fractured Reservoir with Complex Fracture Geometries from Modeling to Simulation

Feng Xu*[1,2], Xianbing Li[1], Yiwen Gong[3], Cheng Lei[1], Xiangling Li[1], Wei Yu[4,5], Jijun Miao[4,6], Yutao Ding[2]; 1. RIPED, CNPC, 2. CNODC, 3. The Ohio State University, 4. The University of Texas at Austin, 5. Texas A&M University, 6. SimTech LLC.

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Abstract

Natural fractures are commonly observed in the unconventional reservoir. Production history indicates that natural fractures have been playing an important role in the oil and gas development progress by improving the permeability of the reservoir and increasing the well productivity. In addition, inappropriate development strategies result in the unreasonable single well oil rate, early water breakthrough, severe damages to the unconventional reservoir and overwhelming economic losses when the fracture properties and distributions are not well understood before the development. Hence, it is of great importance to propose a powerful and efficient workflow to describe the fracture distribution clearly, including building a 3D fracture model, performing history matching and forecasting productions of the unconventional reservoir. In this study, we present a powerful and practical workflow through using Fracflow software and EDFM (Embedded Discrete Fracture Model) to build the 3D DFN (Discrete Fracture Network) model. The main methodology used to perform the fracture modelling allows rigorously handling of both hydraulic fractures and natural fractures that can be identified in an unconventional reservoir. This modelling allows computing the real geometrical fracture attributes (mainly orientation and density) and the spatial distribution of fractures. Fracture conductivity values will be calibrated through a comparison of the *Kh*(permeability thickness) from the well test to the *Kh* model computed from the upscaling of the fracture model. The mentioned model above will be built by means of a stochastic simulation constrained by the results of the static and dynamic fracture characterization. In the reservoir simulation phase, EDFM processor combining commercial reservoir simulators is fully integrated to perform history matching and production performance forecast of the unconventional reservoir. With a new set of formulations used in EDFM, the non-neighboring connections (NNCs) in the EDFM are converted into regular connections in traditional reservoir simulators, and the NNCs factors are linked with gridblock permeabilities. EDFM provides three kinds of NNC pairs, transmissibility factors, and the connections between fractures and wells. With the aid of the EDFM processor, we can obtain the number of additional grids, the properties of fracture grids, and the NNCs as the simulation input. From the proposed workflow, complex dynamic behaviors of natural fractures can be captured. This will further ensure the accuracy of DFMs and the efficiency offered by structured gridding. The practical workflow for the unconventional reservoir from modelling to simulation highlights the model

constrained by the results of the static and dynamic fracture characterization, and the high efficiency to model discrete fractures through the revolutionary EDFM processor. Through this workflow, we can perform history matching effectively and simulate complex fractures including hydraulic fractures and naturally fractures. It potentially can be integrated into existing workflow for unconventional reservoirs for sensitivity analysis and production forecasting.

Introduction

Natural fractures can often be seen in unconventional reservoirs. Based on unconventional reservoir production, it is commonly accepted that natural fractures play an important role in the oil and gas development progress. Fractures can improve reservoir permeability and change the fluid flow rate in a tight reservoir (Nelson, 2001), but the effects of fractures are very easy to be incompetently understood and most underestimated. It is very important to establish a reasonable fracture model and make numerical simulation research in the oilfield development deployment. However, naturally fractured reservoirs are especially difficult to characterize, model and simulate because of its high static and dynamic heterogeneity (Nelson, 2001; Xu, 2015; Gong and El-Monier, 2018a, 2018b). Hence, it is of great importance to propose a powerful and practical workflow to describe the fracture distribution clearly, including building a 3D fracture model, performing history matching and forecasting productions of the unconventional reservoir.

At present, natural fractured reservoirs modeling methods and technologies have made great progress, but further development is needed (He et al., 2017). Conventional modeling cannot effectively characterize the internal complexity in the unconventional reservoirs because of various reservoirs types, irregular reservoirs shapes, different reservoirs scales, and discrete reservoir distributions (Hou et al., 2012; Hu et al., 2014). A large number of theoretical methods and new technologies have been researched in fracture modeling at home and abroad (Jenkins et al., 2009; Lang and Guo, 2013), and the equivalent continuum model has been used to establish fracture models and simulation studies (National Research Council, 1996). However, due to the influence of scale, the equivalent continuum model cannot characterize the heterogeneity. DFN model has been applied in some fractured reservoir modeling (Karimi-Fard et al., 2003). However, there are many factors affecting the spatial distribution of fractures. The key issue is how to determine the location of the fracture space in the study of discrete fracture models. In addition, there are few previous studies on the prediction of interwell fractures in fractured reservoir modeling (He et al., 2017).

It is very challenging to effectively simulate complex fractures in naturally fractured reservoirs. A lot of research has been conducted to model the fluid flow in naturally fractured reservoirs (Warren and Root, 1963; Cinco-ley and Samaniego-v, 1981; Karimi-Fard and Firoozabadi, 2003; Hoteit and Firoozabadi, 2006; Zhou et al., 2014; Hajibeygi et al., 2011). Analytical solutions and local grid refinement (LGR) have great limitations because of many simplifications and idealization, and they could not model complex fractures. Dual porosity and dual permeability (DPDK) method is still the most commonly used approach in commercial reservoir simulators (Warren and Root, 1963; Blaskovich et al., 1983), which is very fast and efficient in computation time and has been successfully used in many NFR (naturally fractured reservoir) studies. However, there are many simplifications in the models, they are not suitable for accurately simulating reservoirs with complex and large-scale fractures and fluids flowing along the fractures. To solve the problems above, unstructured grids are proposed and employed in most discrete fracture models (Karimi-Fard and Firoozabadi, 2003; Hoteit and Firoozabadi, 2006; Hui et al., 2013;) to vividly model the complex fracture geometry. It generates large quantities of small-scale grids around the fractures, so the models have great limitations in real field-scale reservoir simulation because of its complicated gridding and time-consuming computation. To balance between the accuracy and the computation time, EDFM is proposed and extended in 3D in-house reservoir simulator and other commercial simulators (Moinfar et al., 2014; Panfili and Cominelli, 2014; Cavalcante Filho et al., 2015; Zuloaga-Molero et al., 2016; Xu et al., 2017a, 2017b; Zhang et al., 2017; Dachanuwattana et al., 2018a, 2018b; Xu et al., 2018; Yu et al., 2018a, 2018b, 2018c), making the EDFM method more popular in the fractured reservoir simulation.

In this study, seismic data, logging data, core data, casting and other data are fully used to model natural fractures at large fracture scale and small and medium fracture scales. Matrix model and discrete fracture network model are integrated into the same grid system to complete the modeling of fractured reservoirs with different scales in the Fracflow software. The mentioned model above is built by means of a stochastic simulation constrained by the results of the static and dynamic fracture characterization. The geological model provides a solid geological basis for numerical simulation of fractured reservoirs. When doing reservoir simulation, EDFM processor combining commercial reservoir simulators is fully integrated to perform history matching and production performance forecast of the unconventional reservoir. The practical workflow for the unconventional reservoir from modeling to simulation highlights the model constrained by the results of the static and dynamic fracture characterization, and the high efficiency to model discrete fractures.

The New Workflow

Usually logging, seismic, drilling data and dynamic production data are collected, and various geological studies are performed by different disciplines, but the uncertainties of the naturally fractured reservoir are beyond the current methodology. One major challenge is how to understand the natural fractures, which will decide if you could get a reasonable geological fracture model. What's more, the fractured reservoir simulation is an international hot topic. Traditional equivalent continuum simulation method could not capture the fluid flow behavior in the fractures. The presence of multi-scale natural fractures, low matrix porosity and permeability greatly increases the heterogeneity of naturally fractured reservoirs, adding significant complexity for reservoir modeling and simulation. Typical DFN models are commonly challenged for its representativity by reservoir engineers, and the DFN upscale simulation method is blamed for low accuracy representing the DFN model by geologists.

Based on the traditional workflow from BeicipFranlab (2018), we proposed an innovative workflow (Figure 1), which can bridge the gap between geological modeling and reservoir simulation with EDFM method. This method is very easy and efficient to model any complex fracture geometries using structured gridding. It can preserve the complexity of the DFN and avoid additional running time or steps into the conventional fluid flow simulation workflow. Unlike previous fracture modeling techniques, the EDFM method allows to integrate any complex fracture geometry into a reservoir grid model without compromising fracture resolution and with much higher computational efficiency, which makes the quick high-resolution fracture reservoir modeling feasible. This EDFM method is introduced into DFN calibration to calibrate the DFN model and implemented to conduct full field reservoir simulation and history matching with real production data. Therefore, a close-loop workflow from fracture modeling, calibration and simulation is developed for the first time. This powerful workflow mainly includes four steps, which are detailed below:

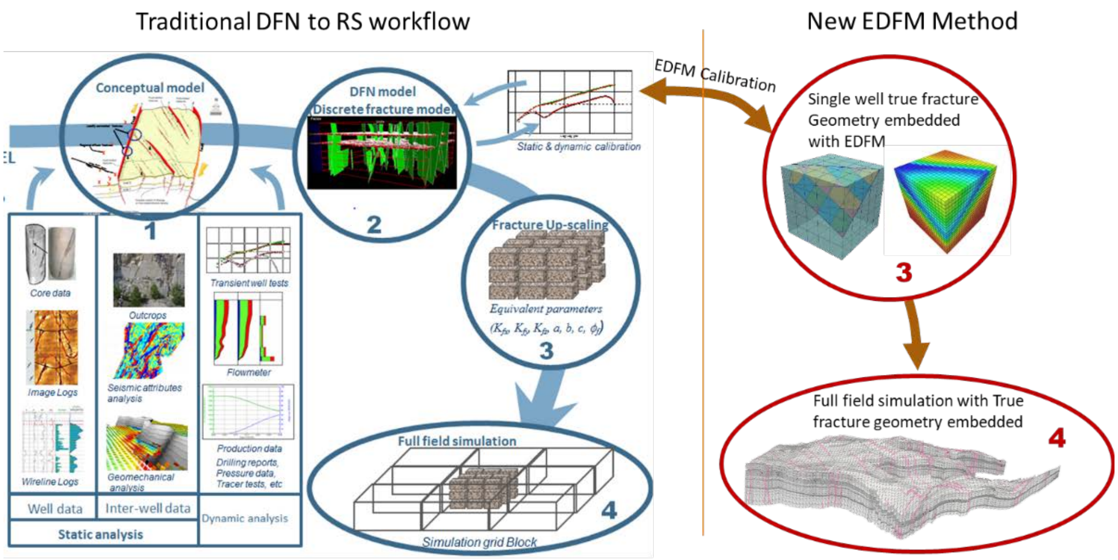


Figure 1—An EDFM workflow from modeling to simulation in fractured reservoir. Traditional fractured reservoir simulation workflow, the fracture was upscaled to dual porosity model; The new EDFM method to embedded real fracture geometry into regular reservoir grids to conduct high resolution fracture reservoir simulation.

(1) Building a single well DFN and geological model based on the detailed geological data, such as seismic interpretation, borehole image and core analysis of the fractured reservoir. The faults and natural fractures were identified, and their geometrical properties were vested. The fractures are characterized into three groups according to their size grades and their hydraulic impact on the fluid flow in the reservoir, which are those large-scale fractures representing highly conductive corridors and those small-medium scale fractures with lower overall conductivity and connectivity. L_m is the matrix gridblock length scale and L_f is the fracture length. We can define short fractures (L_f /L_m<<1), medium (grid-block scale) fractures (L_f /L_m~1), large fractures (L_f/L_m>>1), which are shown in the Figure 2. The red and blue lines are small-medium and large fractures. The green box has more than one fractures in one cell.

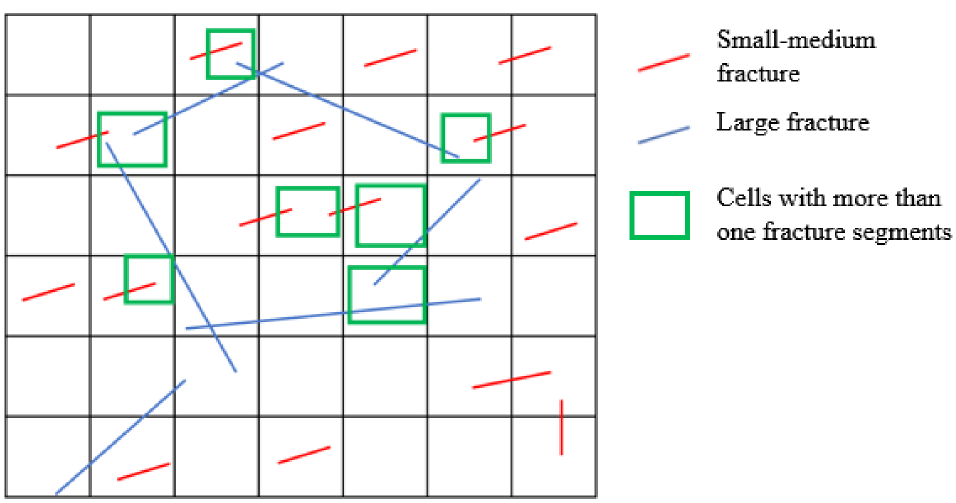
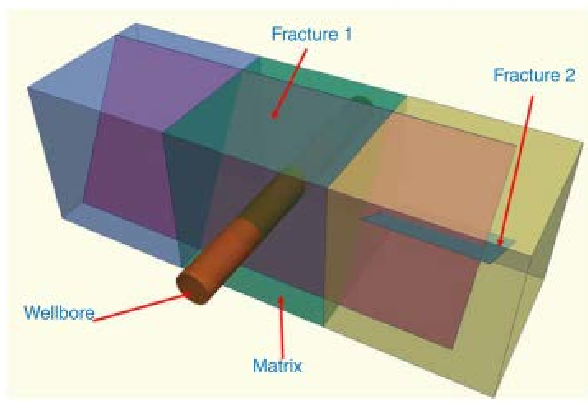


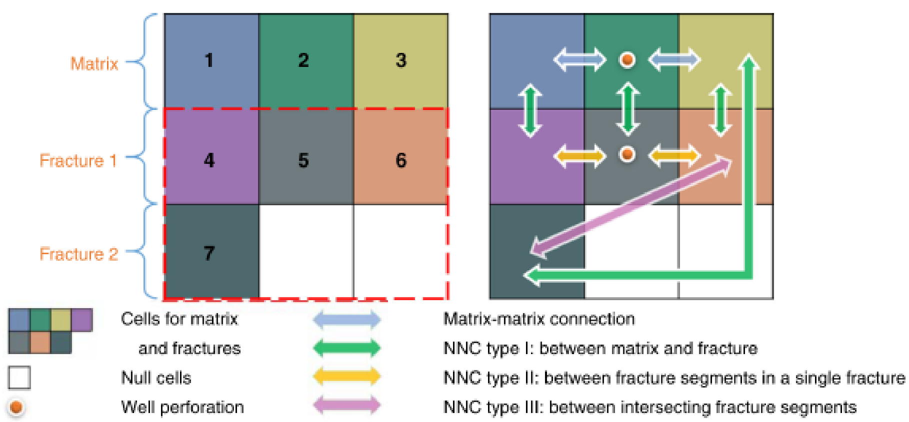
Figure 2—Schematic diagram of three different scale fractures.

(2) Calibrate the DFN through the pressure forward modeling to align with the well testing data, and the fracture number and size could be optimized.

(3) Calibrate the fracture properties. In this process, the single well DFN is integrated into the reservoir model through EDFM method. With a new set of formulations used in EDFM, the non-neighboring connections (NNCs) in the EDFM are converted into regular connections in traditional reservoir simulators, and the NNCs factors are linked with gridblock permeabilities. EDFM mehod provides three kinds of NNC pairs, transmissibility factors, and the connections between fractures and wells. EDFM processor is compiled to cope with the parameaters mentioned above. With the help of the EDFM processor, we can get the number of additional grids, the properties of fracture grids, and the NNCs as the simulation input. During the process of calculation, complex fractures will be discretized into some fracture segments based on the interaction between fracture geometry and structured matrix grid boundaries. So it brings some virtual cells to keep the properties of the fractures. The fluid flow between matrix, fractures, and well can be simulated inside commercial reservoir simulators by making use of on-neighboring connections (NNCs) and effective wellbore index (Figure 3).



(a) Physical domain



(b) Computational domain

Figure 3—Explanation of the EDFM method in conjunction with commercial reservoir simulator to handle complex fractures (Xu et al. 2017a)

After the griding, we can use the numerical model to perform history matching effectively and simulate complex fractures including hydraulic fractures and naturally fractures. The fracture properties are adjusted to agree with the production data.

(4) Define the DFN properties to a bigger scale for the block DFN model.

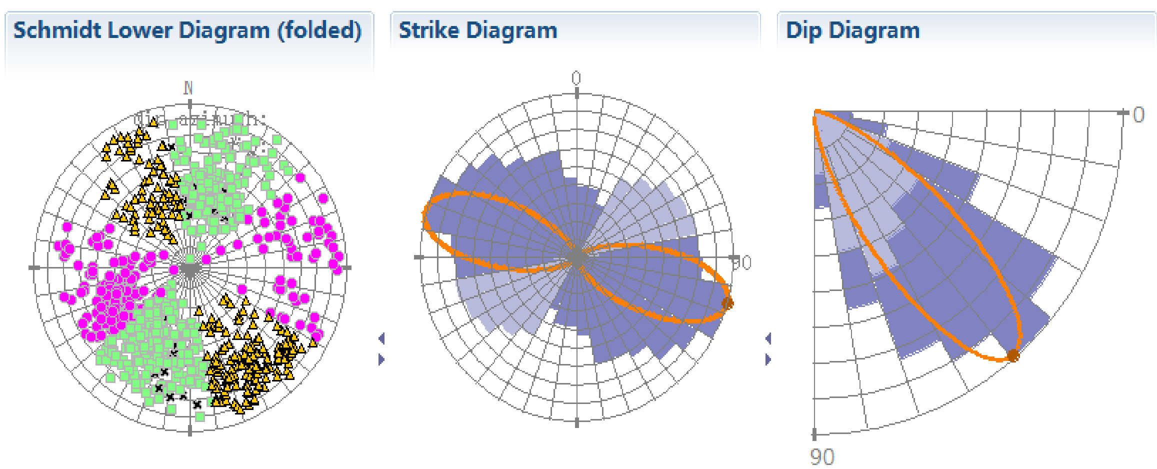
After that, we implemented EDFM method to conduct the full field-scale numerical simulation. We kept large-scale fractures by using EDFM, and upscaled the fractures in other scales into DPDK model to reduce the total number of cells to save computation time of performing history matching and production prediction.

Fracture Modeling of Fractured Reservoir

The fracture modeling method is different from the traditional methods. This research uses a real case study from a fractured reservoir, by employing the new complex fracture simulation technique (EDFM method) that can accurately and efficiently simulate the complex fracture network for both natural and hydraulic fractures in 3D model. Then a novel DFN calibrating workflow will be introduced. A feasible solution is figured out to implement the fracture true properties into full field scale to predict full-scale production. The following naturally fractured granite reservoir workflow from geomodelling to simulation is used in this research. There are the detailed steps:

(1) Building a single well DFN.

In this target oilfield, we have15 wells, but only 6 wells have reliable well logging data and other dynamic data. The image logging data is the best candidate preserving the subsurface fracture information. This feature relates to the regional structure and stress fields. Other dynamic data could be used to confirm the fracture parameters. We obtained fracture basic properties, including orientation, fracture densities and apertures. Figure 4 shows the stereo plot of 807 fractures interpreted in the fractured reservoir units from the wells considered for the analysis. Fracture orientations are organized into three sets. Three sets of fractures are clearly recognizable: WNW-ESE (main trend), ENE-WSW (secondary trend) and NS (minor trend). Table 1 details the number of fractures, the mean orientation and the mean dip of each subset.



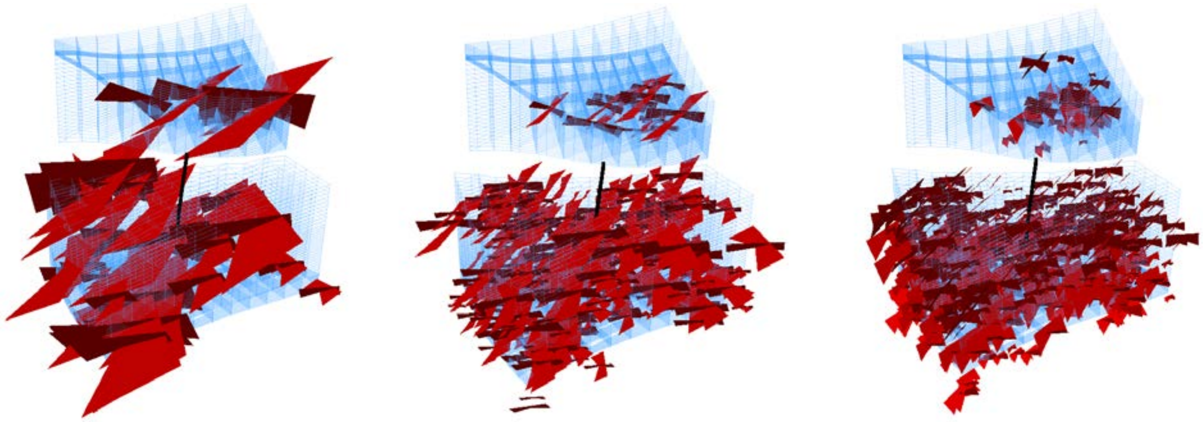
(a) (b) (c)

Figure 4—Global fracture analysis results. The fracture set are divided in three subsets based on their orientations shown in (a).

Table 1— Global fracture statistics.

Set Orientation	Fracture Number	Mean Orientation (°)	Mean Dip(°)	Fracture Density(frac/m)
WNW-ESE	412	114	43	0.3
ENE-WSW	216	58	73	0.19
NS	179	165	51	0.155

With these single well fracture inputs, we can then generate the single well fracture model now. The fracture size and number are unknown out of the wellbore. Thus, we must estimate and validate the fracture sizes and fracture numbers. Multiple DFN models are generated for this purpose. Figure 5 are three examples of the possible representations. Their fracture sizes and numbers can be tuned accordingly. To calibrate these models, the fracture conductivity will be tuned along with the fracture sizes and numbers.



(a) Fracture size 200-500 m and No.69 (b) Fracture size 50-300 m and No.467 (c) Fracture size 20-200 m and No.934

Figure 5—Single well DFN models with different fracture size and number.

(2) Calibration of the DFN to reduce uncertainty.

In the tradition calibration workflow, DFN model is matched with well testing parameter *Kh*, which is a very rough estimation. Many DFN models could be matched. However, those matched parameters have large uncertainties for the future reservoir simulation. The new calibration workflow is an improved calibration workflow avoiding stated issues (Figure 6). Here, we conduct a single well history matching before the well testing calibration. We use EDFM method to do the single well reservoir simulation to make sure the accuracy. If a DFN model passes the two-step calibrations, the model will be considered as a representative model. Otherwise, we need to go back to change the DFN model parameters or even reevaluate geological fracture characterization. This is a unique workflow to recalibrate geological parameters and optimize DFN inputs.

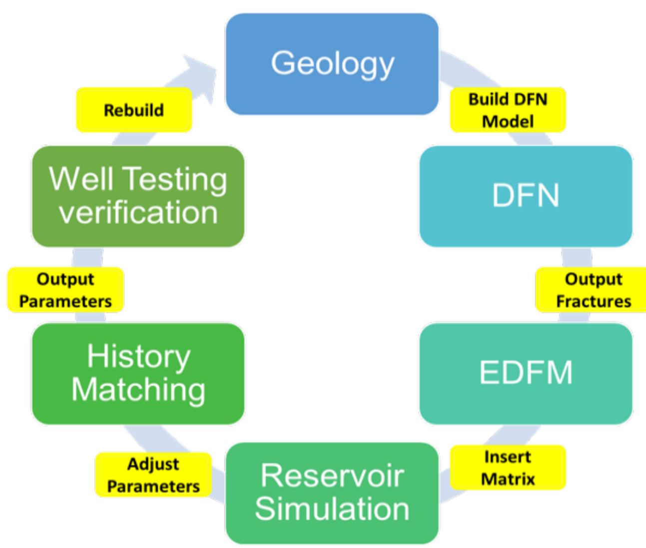
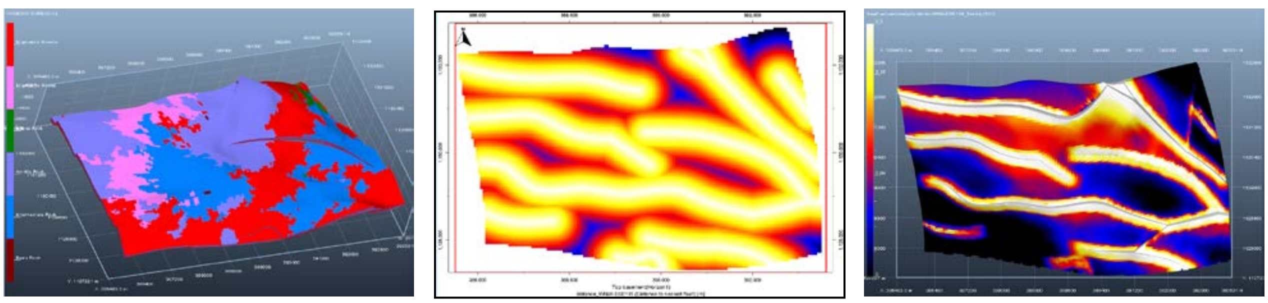


Figure 6—The proposed workflow of single well DFN calibration with EDFM.

(3) Definite the DFN properties to bigger range for block DFN model.

After the single well fracture characterization, the fracture conceptual model of these wells is built. However, apart from the wellbore, the fracture distribution is controlled by geological factors while more space control factors are needed to constrain the DFN population. So far, we have calibrated 6 wells with 6 control points in this field to generate a regional DFN model. More control factors will be analyzed, such as regional structures, the stress state, lithology and others. In here, we showed a lithofacies example as one of the additional control factors. The rock type has a strong correlation with the fracture density so that the lithofacies are reclassified, according to the previously defined fracture sets, to confine the fracture density. Then, all the control factors are merged together to get the fracture density and orientation maps for each subset (Figure 7). From Figure 7c, ESE set fracture is the dominate fracture set, which has a major impact on well production.



(a) Lithofacies distribution (b) Distance to the nearest fault (WNW -ESE) (c) Fracture density of ESE

Figure 7—Control factors used in the block DFN model.

Based on the above-stated workflow, we obtained the full field-scale DFN model, which includes two groups fractures. One group is a large fracture group while another group consists of fractures smaller than the grid size (Figure 8 and Figure 9). The effect of the small fracture group on the overall conductivity is comparatively minimal while the large fracture group has much the greater effect on the fluid flow.

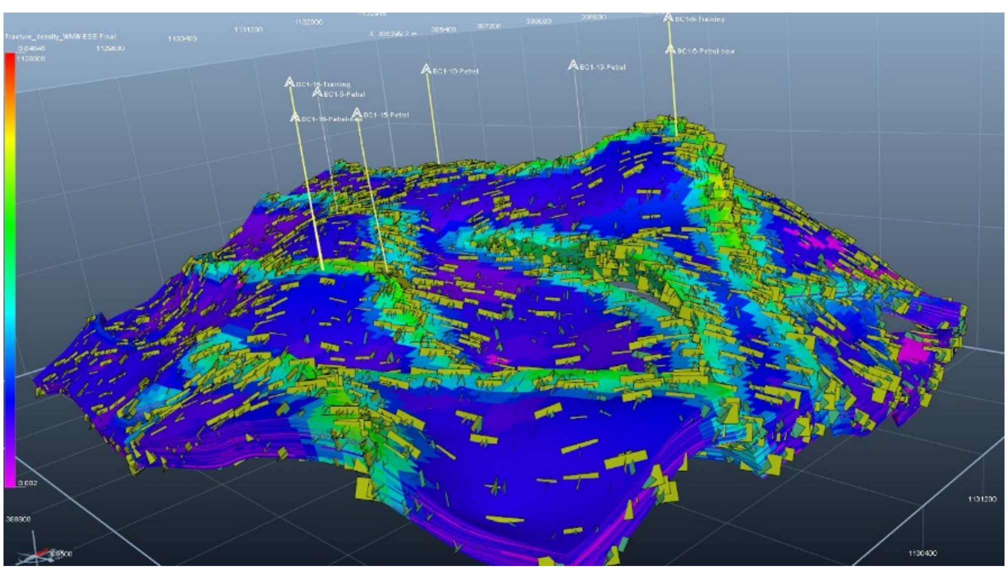


Figure 8—Large scale fractures(L_f/L_m>>1) in the full field-scale DFN model.

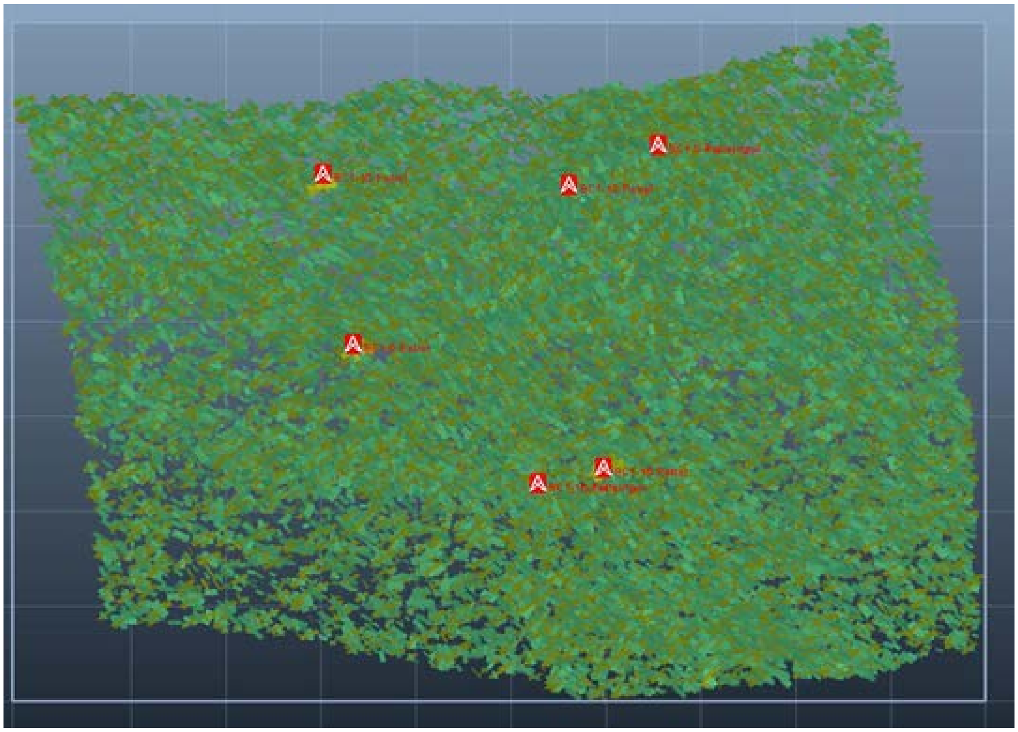


Figure 9—Small-medium (L_f/L_m<<1 and L_f/L_m~1)scale fractures in the full field-scale DFN model.

Fractured Reservoir Simulation by EDFM

Once we get the fractured reservoir model, we can then move forward to the reservoir simulation stage. Usually, we upscale the complex fracture model into the equivalent continuum model in the traditional workflow in order to get the equivalent parameters for full-field simulation by flow-based upscaling or analytical upscaling. In our proposed workflow, we keep the large fracture group by using EDFM mehtod while upscale the smaller fractures into DPDK model to reduce the total number of cells and to save computation time. With the aid of EDFM processor, commercial reservoir simulators are capable to perform history matching and production performance forecast of the unconventional reservoir. With the new set of non-neighboring connections (NNCs) formulations in the EDFM, the NNCs are converted into regular connections in regular reservoir simulators. These NNCs factors are linked with gridblock permeabilities. EDFM provides three kinds of NNC pairs, transmissibility factors, and the connections between fractures and wells (Figure 3). Based on the transport between the fracture and the matrix, additional grids are introduced to decompose into multiple NNC pairs as the simulation input. The detailed technical description is listed in the published paper (Xu et al., 2017a, 2017b; Xu et al., 2018; Yu et al., 2018a).

We succeed to run the workflow of DPDK+EDFM model with about 700,000 matrix cells. DPDK+EDFM model is then used to perform the history matching in the whole block, including 15 wells (Figure 10). Based on the geological study, we get the full field DFN model, which includes two groups fractures (Figure 8 and Figure 9). One group is large fractures, and their size is larger than grid size, ranging from 60 m to 200 m. The number of large fractures is 12,958. Another group is fractures smaller than grid size, ranging from 10 m to 50 m. The number of small fractures is 267,000. The two groups fractures are treated differently. For larger fractures, which have a bigger impact on production, will be integrated through EDFM. Those smaller scale fractures are upscaled to DPDK model. EDFM has very complex connections, which could cause the computational efficiency compromising. In order to take advantage of the accurate fracture flow behavior simulation capability of EDFM, the total fracture number must be constrained to a reasonable level.

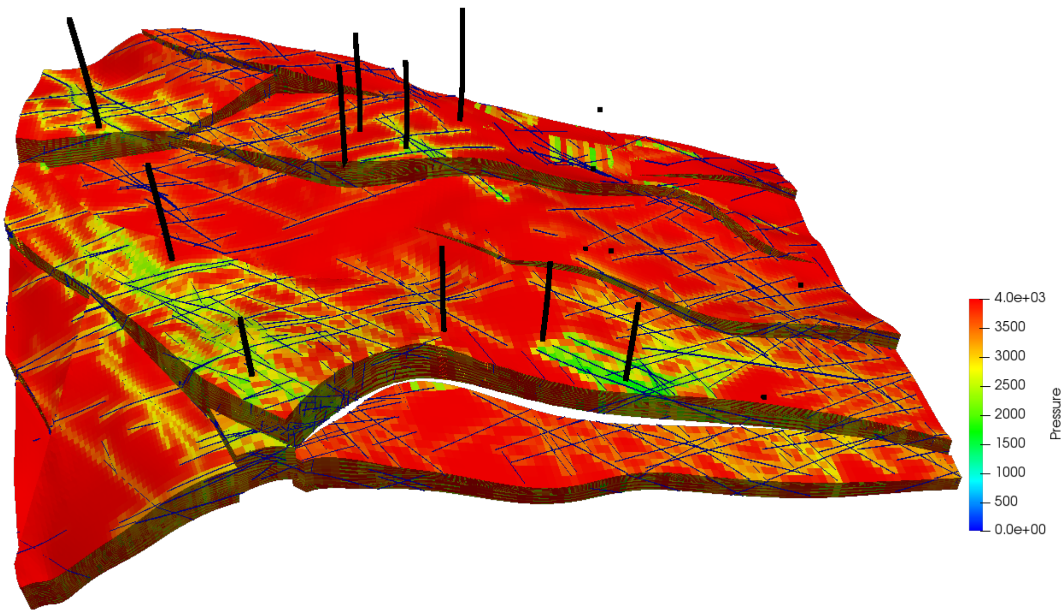
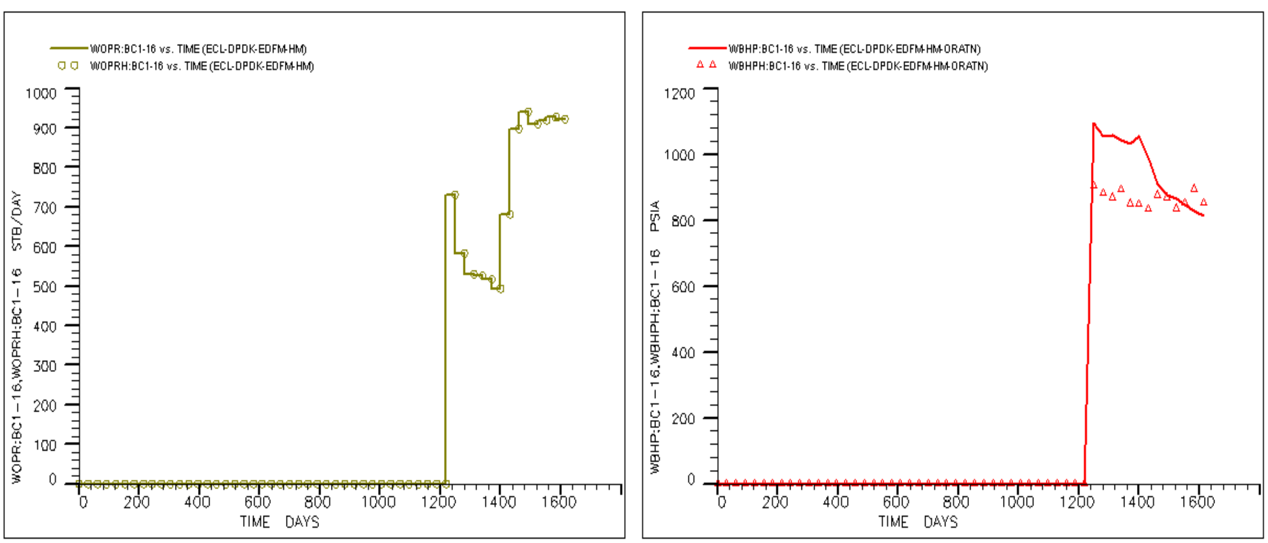


Figure 10—Simulation model of the full filed.

With this model, we run a 3-year production history matching for 15 wells. By using sensitivity analysis, natural fracture properties such as densities and permeabilities are modified to increase fracture connectivity and improve history matching results. After modification, the single well oil rate and the bottom hole pressure (BHP) obtained good matches (Figure 11). Now we have more options to adjust parameters by using EDFM, and this gives us more flexibilities to better match with field data.



(a) Oil rate matching (b) BHP matching

Figure 11—History matching result for a single well.

Conclusions

From the research above, we can make the following conclusions:

(1) The proposed practical workflow for the naturally fractured reservoir from modeling to simulation incorporates with the static and dynamic fracture characterization model result, shows the outstanding the efficiency to model discrete fractures through the innovative EDFM method.

(2) Different scale of natural fractures can be divided into two groups based on their size. Large scale fractures can be directly modeled by the EDFM method and small-medium scale fractures can be upscaled to the DPDK method, which enables the EDFM+DPDK approach to model the heavily fractured reservoir.

(3) Through this new workflow, a full field reservoir simulation with EDFM+DPDK can be conducted successfully. We achieved promising history matching results efficiently for naturally fractured reservoirs.

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References

BeicipFranlab. 2018. http://www.beicip.com/our-international-presence/beicip-inc (accessed 25 April 2019).

Blaskovich, F.T., Cain, G.M., Sonier, F. et al. 1983. A Multicomponent Isothermal System for Efficient Reservoir Simulation. Presented at the Middle East Oil Technical Conference and Exhibition, Manama, Bahrain, 14-17 March. SPE-11480-MS. https://doi.org/10.2118/11480-MS

Cavalcante Filho, J.S.A., Shakiba, M., Moinfar, A., and Sepehrnoori, K. 2015. Implementation of a Preprocessor for Embedded Discrete Fracture Modeling in an IMPEC Compositional Reservoir Simulator. Presented at the SPE Reservoir Simulation Symposium, Houston, Texas, 23-25 February. SPE-173289-MS. https://doi.org/10.2118/173289-MS

Cinco-Ley, H., and Samaniego-V, F. 1981. Transient Pressure Analysis for Fractured Wells. *Journal of Petroleum Technology* 33 (9): 1749-1766.

Dachanuwattana, S., Jin, J., Zuloaga-Molero, P., Li, X., Xu, Y., Sepehrnoori, K., Yu, W., and Miao, J. 2018a. Application of Proxy-based MCMC and EDFM to History Match a Vaca Muerta Shale Oil Well. *Fuel* 220: 490-502.

Dachanuwattana, S., Xia, Z., Yu, W., et al. 2018b. Application of Proxy-based MCMC and EDFM to History Match a Shale Gas Condensate Well. *Journal of Petroleum Science and Engineering* 167: 486-497. https://doi.org/10.1016/j.petrol.2018.04.025

Gong, Y., and El-Monier, I. 2018a. Quantification of Fracture Surface Roughness and Its Insights to Mechanical Rock Properties Determination Using Image Analysis Techniques. Presented at the SPE/AAPG Eastern Regional Meeting, Pittsburgh, Pennsylvania, 7-11 October. SPE-191824-18ERM-MS. https://doi.org/10.2118/191824-18ERM-MS

Gong, Y., and El-Monier, I. 2018b. Quantification of Fracture Roughness and its Effects on the Grain and Pore Size Distribution of the Fractured Rock Using Image Analysis Technique. Presented at the Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE, 12-15 November. SPE-193134-MS. https://doi.org/10.2118/193134-MS

Hajibeygi, H., Karvounis, D., and Jenny, P. 2011. A Hierarchical Fracture Model for the Iterative Multiscale Finite Volume Method. *Journal of Computational Physics* 230 (24): 8729-8743.

He, W., Ma, S. , Yuan, J., Ran, Q., Yuan, D., Li, D., Niu, D., Wang, H. 2017. Modeling Method of the Multi-Scale and Multiple Medium Unconventional Tight Oil-Reservoir: A Case Study of the Reservoir in Lucaogou Formation of Junggar Basin. *Progeress in Geophysics(in Chinese)* 32 (2): 0618-0625.

Hoteit, H., and Firoozabadi, A. 2006. Compositional Modeling of Discrete-Fractured Media Without Transfer Functions by the Discontinuous Galerkin and Mixed Methods. *SPE Journal* 11 (3): 341-352.

Hou, J., Ma, X., Liu, Y., Zhao, B. 2012. Modeling of carbonate fracturevuggy reservoir: A case study of Ordovician reservoir of 4th block in Tahe Oilfield. *Earth Science Frontiers* 19(2), 59-66.

Hu, X., Xiangchun, Yuan, X., Hou, J. 2014. Modeling method of carbonate fractured-cavity reservoirs using multiscale karst facies-controlling. *Acta Petrolei Sinica* 35(2), 340-346.

Hui, M.H., Mallison, B.T., Fyrozjaee, M.H. et al. 2013. The Upscaling of Discrete Fracture Models for Faster, Coarse-Scale Simulations of IOR and EOR Processes for Fractured Reservoirs. Presented at the SPE Annual Technical Conference and Exhibition New Orleans, Louisiana, 30 September-2 October. SPE-166075-MS. https://doi.org/10.2118/166075-MS.

Jenkins, C., Ouenes, A., Zellou, A., Wingard, J. 2009. Quantifying and predicting naturally fractured reservoir behavior with continuous fracture models. AAPG bulletin 93(11), 1597-1608.

Karimi-Fard, M., Durlofsky, L. J., and Aziz, K. 2003. An efficient discrete fracture model applicable for general purpose reservoir simulators. Presented at SPE Reservoir Simulation Symposium, Houston, Texas, 3-5 February. SPE-79699-MS. https://doi.org/10.2118/79699-MS

Karimi-Fard, M., and Firoozabadi, A. 2003. Numerical Simulation of Water Injection in Fractured Media using the Discrete-Fractured Model and the Galerkin Method. *SPE Reservoir Evaluation & Engineering* 6 (2): 117-126.

Lang, X., and Guo, S. 2013. Fractured reservoir modeling method based on discrete fracture network model. *Acta Scientiarum Naturalium Universitatis Pekinensis* 49(6), 964-972.

Moinfar, A., Varavei, A., Sepehrnoori, K. et al. 2014. Development of an Efficient Embedded Discrete Fracture Model for 3D Compositional Reservoir Simulation in Fractured Reservoirs. *SPE Journal* 19 (2): 289-303.

National Research Council. 1996. Rock fractures and fluid flow: contemporary understanding and applications. National Academies Press.

Nelson, R. 2001. Geologic Analysis of Naturally Fractured Reservoirs. Gulf Professional Publishing, 2nd Edition. BP Amoco Houston, TX: Elsevier Inc.

Panfili, P., and Cominelli, A. 2014. Simulation of Miscible Gas Injection in a Fractured Carbonate Reservoir using an Embedded Discrete Fracture Model. Presented at the Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, UAE, 10-13 November. SPE-171830-MS. https://doi.org/10.2118/171830-MS

Ray, D. S., Al-Shammeli, A., Verma, N. K., et al. 2012. Characterizing and modeling natural fracture networks in a tight carbonate reservoir in the Middle East: A methodology. *Bulletin of the Geological Society of Malaysia*, 58: 29-35.

Warren, J.E., and Root, P.J. 1963. The Behavior of Naturally Fractured Reservoirs. *SPE Journal* 3 (3): 245-255. https://doi.org/10.2118/426-PA

Xu, F., Yu, W., Li, X., et al. 2018, A Fast EDFM Method for Production Simulation of Complex Fractures in Naturally Fractured Reservoirs. Presented at the SPE/AAPG Eastern Regional Meeting, Pittsburgh, Pennsylvania, 7-11 October. SPE-191800-18ERM-MS. https://doi.org/10.2118/191800-18ERM-MS

Xu, Y. 2015. Implementation and Application of the Embedded Discrete Fracture Model (EDFM) for Reservoir Simulation in Fractured Reservoirs. Master Thesis, The University of Texas at Austin, Austin, Texas (December 2015).

Xu, Y., Cavalcante Filho, J.S.A., Yu, W., and Sepehrnoori, K. 2017a. Discrete-Fracture Modeling of Complex Hydraulic-Fracture Geometries in Reservoir Simulators. *SPE Reservoir Evaluation & Engineering*, 20 (2): 403-422.

Xu, Y., Yu, W., and Sepehrnoori, K. 2017b. Modeling Dynamic Behaviors of Complex Fractures in Conventional Reservoir Simulators. Presented at the SPE/AAPG/SEG Unconventional Resources

Technology Conference, Austin, Texas, 24-26 July. URTEC-2670513-MS. https://doi.org/10.15530/URTEC-2017-2670513

Yu, W., Xu, Y., Weijermars, R., Wu, K., and Sepehrnoori, K. 2018a. A Numerical Model for Simulating Pressure Response of Well Interference and Well Performance in Tight Oil Reservoirs With Complex-Fracture Geometries Using the Fast Embedded-Discrete-Fracture-Model Method. *SPE Reservoir Evaluation & Engineering* 21 (2): 489-502.

Yu, W., Xu, Y., Liu, M., Wu, K., and Sepehrnoori, K. 2018b. Simulation of Shale Gas Transport and Production with Complex Fractures using Embedded Discrete Fracture Model. *AIChE Journal* 64 (6): 2251-2264.

Yu, W., Zhang, Y., Varavei, A., et al. 2018c. Compositional Simulation of CO2 Huff-n-Puff in Eagle Ford Tight Oil Reservoirs with CO2 Molecular Diffusion, Nanopore Confinement, and Complex Natural Fractures. Presented at the SPE Improved Oil Recovery Conference, Tulsa, Oklahoma, 14-18 April. SPE-190325-MS. https://doi.org/10.2118/190325-MS

Zhang, Y., Di, Y., Yu, W., and Sepehrnoori, K. 2017. A Comprehensive Model for Investigation of CO2-EOR with Nanopore Confinement in the Bakken Tight Oil Reservoir. Presented at the SPE Annual Technical Conference and Exhibition, San Antonio, Texas, 9-11 October. SPE-187211-MS. https://doi.org/10.2118/187211-MS

Zhou, W., Banerjee, R., Poe, B. et al. 2014. Semianalytical Production Simulation of Complex Hydraulic-Fracture Networks. *SPE Journal* 19 (1): 6-18.

Zuloaga-Molero, P., Yu, W., Xu, Y., Sepehrnoori, K., and Li, B. 2016. Simulation Study of CO2-EOR in Tight Oil Reservoirs with Complex Fracture Geometries. *Scientific Reports*, 6: 33445.