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The MPS-based fracture network simulation method: application to subsurface domain

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Summary

Natural fractures conduct fluids in subsurface reservoirs. Quick and realistic predictions of the fracture network organization and its fluid flow efficiency from limited amount of data is critical to optimize resources productivity. We recently developed a method based on multiple point statistics (MPS) technique to produce geologically-constrained fracture network simulations. The method allows to account for the intrinsic non-stationarity of these networks by considering a multivariate input data instead of averaged distribution of fracture parameters. In addition, the method considers probability maps reflecting the influence of fracture drivers in the network variability. Consequently, the simulated fracture networks derived from the innovative MPS approach are geologically better constrained than in classical discrete fracture network modelling approaches.

This paper proposes to apply this method in subsurface conditions where available data are sparsely distributed. We developed a workflow where data are gathered from wellbore and from additional sources (outcrops). These data are used to extrapolate a network around the borehole as training images and themselves are extrapolated at the reservoir scale following a geological probability map.

This work also presents innovations on the way how training images and probability maps that may integrate more geology constrain than relying almost entirely on available data.

Introduction

Fractures are one of the most common geological feature in the Earth's upper crust (Twiss and Moores, 1992). Natural fractures form networks and occur at scales ranging from nanometre to multi-kilometre scale. These objects could be open and connected and they may have a strong impact on fluid flow and eventually fluid storage in subsurface reservoirs (Nelson, 2001). Predicting their geometry and their efficiency (fluid flow) is timely to optimise resources exploitation (hydrocarbon, water or heat). However, the organisation of fracture is mostly unknown in the subsurface due to: i) the sub-seismic scale of a large proportion of these objects and ii) the scarcity of data (wellbores). In addition, while fractures present systematic attribute helping geologist to understand how and when they were generated, they also present an intrinsic geometric variability which is difficult to consider.

Initial methodology

Techniques already exist to predict fracture geometry and fluid flow efficiency in the subsurface. Discrete fracture models (DFM) are extensively used in applied geosciences. These models are useful to better constrain the estimation of equivalent fracture porosity and permeability in the reservoir. However, DFM are generally built from averaged distributions of fracture parameters (e.g. fracture density/intensity, fracture length distribution) that are considered constant over the entire simulation domain and results of these models are substantially far from the geologic reality.
Alternatively we developed a quick and flexible method to generate good-enough (geologically constrained) fracture network simulations in 2D. Our approach is based on multiple point statistics (MPS) and combines i) the use of multiple training images at time (accounting for the intrinsic geological variability of the fracture network) and ii) the use of a probability map constrained by geology at a larger scale (Bruna et al., 2018b; Bruna et al., in review, 2018). The MPS-based simulations provide a non-stationary model representing more accurately the complexity of fracture arrangement (variability of orientation, length, density and topology). Another strength of this approach is that the training images used for the simulation are synthetic and small, hence relatively easy to design.

Development of a workflow applied to subsurface reservoirs

In operational subsurface conditions the expected dataset available might be composed but not limited to: i) a 3D model representing the structural framework of the reservoir, and ii) a series of vertical and potentially deviated wells (cored or containing log data) with interpreted stratigraphic and structural (fracture) data.
Based on these possible inputs, we developed a complete workflow starting with the synthesis and the interpretation of fracture data available from wells (hard data). The key structural parameters not available from well and required to build a fracture network may be gathered from outcrop analogues, mechanical models or geological concepts (soft data).
These "hard" and "soft" data are used to extrapolate a fracture network at a size defined by the user around the borehole. This extrapolation is a sketch constituting the training image used in the MPS process. Multiple training images are generated honouring the information carried by each well specifically. Far from these data, synthetic training images coming from concepts (i.e. intensification of fracturing in a fault zone) were created.
At the same time the geological context of the area of interest is analysed in order to identify potential fracture drivers. Three main structural drivers can be identified: regional stress field, folding and faulting. Probability maps indicating the relevance of each training image over the entire considered domain are derived. These data are then used to generate non-stationary 2D DFN's at the reservoir scale.
Multiple realisations can be performed at the reservoir scale or in specific area of interest (minimodels – i.e. 500-1000m around the borehole).
The generated DFN models are then evaluated using a measure of connectivity, aperture and fluid flow. The 2D connectivity trough MPS-based network is assessed using an algorithm modified from Alghalandis et al., (2015). This algorithm identifies if two fractures are directly intersecting each other

(hence connected) or if two fractures are indirectly connected via a pathway of connected fractures. The connectivity is measured as an index (connectivity index - CI) in 2D or in 3D. Assuming that fractures are fluid pathways and are consequently connected, the connectivity field is a convenient visual way to evaluate the results of the MPS simulations.

Secondly, the stress-induced mechanical and hydraulic apertures of the fractures using the Barton-Bandis approach was used to evaluate the results of MPS simulations (Bisdom, 2016). Aperture is a key parameter that is directly linked with the fluid flow efficiency of the fracture network. Contrarily to the common aperture estimations from power-law distributions or from sub-linear length-aperture distributions, the Barton-Bandis approach integrates mechanical calculations and is sensitive to the geometry of the network.

The last method to evaluate the DFN realisations uses the aperture calculations for single phase fluid flow simulations. To perform this test, we represented explicitly the fractures in an unstructured conformal mesh. The depletion behaviour of the simulation is monitored and presents how fluid movements can be impacted by the geometry of the fracture network. This may emphasize where drain and/or barrier zones are located and what is their impact among a certain timescale.

As fractures are 3D objects and because their volumetric organisation is likely to play a role in fluid flow, we developed a simple method to extrude fracture surfaces from a 2D realisation. This method assumes that a fracture plane has a finite vertical dimension which is explicitly defined by the user. This vertical dimension is materialised by the use of equiprobable DFN simulations (different networks) shifted in the Z direction. The method produces vertical or oriented fractures. The validity of the 3D DFN was assessed using the well blind test method.

Figure 1*: workflow used to generate and assess 2D and 3D discrete fracture network using MPS-based method. The workflow is optimised for a subsurface case study.*

Generating geologically constrained training images

A fracture network simulation using the MPS-based workflow is critically dependant of the representativeness of the training images (TI). The presented method is almost exclusively based on: data collected in the field, interpretation from satellite or drone imagery, geological concepts, wellbore data or on a combination of these different source of data. All of these data are intrinsically local and thus difficult to interpret and to extrapolate a larger scale. In wellbore for instance, fracture

data are generally scattered and their classification (as sets of fracture) may be challenging and subjective. Scattered fracture data may lead geologists to split them into a large amount of sets (i.e. > 4) that are not necessarily related with a clearly identified tectonic event.
To tackle this issue, we proposed to use the mechanically-based stress inversion developed by Maerten et al (2014) and Maerten et al., (2016) to analyse the fracture data interpreted from wells. The Andersonian stress space solution is explored and a global fit between observed and predicted fractures along wells is calculated for each model (i.e.: a total of 25 000 models are tested). This method makes possible to identify the percentage of fractures that are likely to be related in a certain tectonic regime (normal, strike slip or reverse), accounting for faulting. As a result, this analysis will reduce the bias of the direct interpretation conducted by the geologist and allows to define relevant tectonic event responsible of the observed fracturing.
In combination with the use of this method, it appeared from fieldwork investigations that the geometry of fracture network can be simplified to a limited amount of end members. In general networks can be: i) parallel, ii) orthogonal, iii) purely conjugate (bimodal) or iv) polymodal (Boersma et al., 2018; Healy et al., 2015). In addition, stylolites (tectonic or sedimentary) can be considered or not as they can play an important role in fluid flow (Bruna et al., 2018a). The paleostress analysis and the data available from wells will be used to constrain a number of possible scenarios helping to choose which of the end member model is appropriate in the studied situation. Scenario can be defined as one tectonic regime from inversion and its associated forwarded stress field, which, in turn, will provide fracture orientation (dip azimuth and dip angle) and a proxy for fracture intensity, thus providing attributes to analysis deformation distribution.
The best scenario will be used to define the most likely fracture network to be observed around a borehole but also away from it. In turn, it will be used to create a geologically constrained.

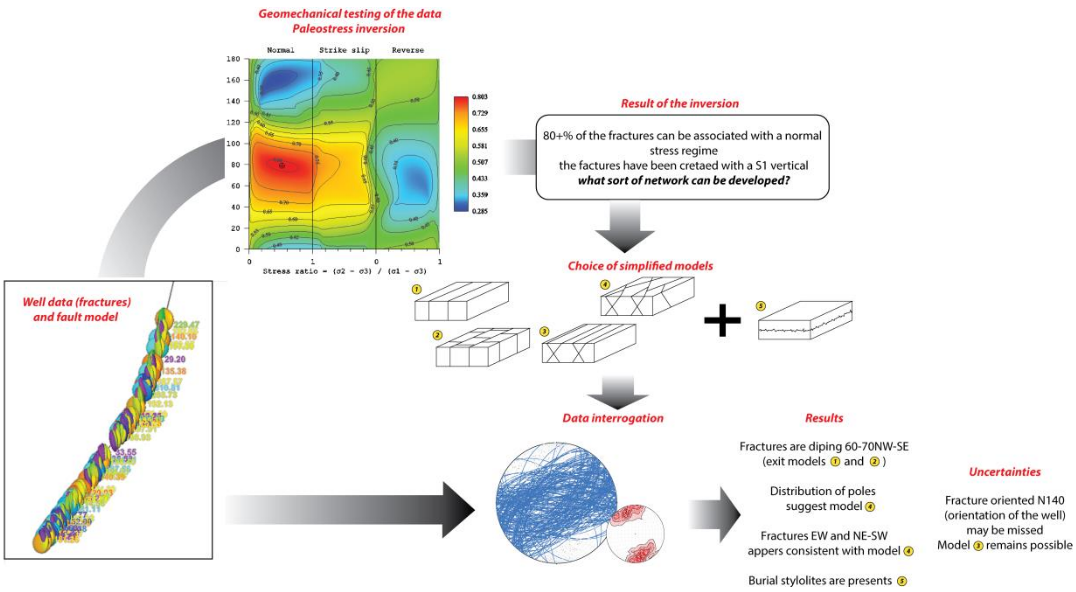

Figure 2*: method of interpretation and simplification of fracture data coming from wellbore data. This workflow is intended to be used to produce geologically constrained training images to be integrated in the MPS-based workflow*

How to build a probability map in a folded domain?

Folded structures are of primary importance in subsurface domain. The distribution of strain and stress on an anticline drives the distribution of fractures. Accurately mapping zones of strain variation in folded domain is a key to generate a suitable probability map. Restoration (combined geometric/geomechanical or purely geomechanical) methods are suited to generate these maps but must be evaluated. Dynel 3D is a geomechanical (elastic) restoration tool that firstly unfold 3-D volumetric model and re-fold it by simulating mechanical rock behaviour using continuum of rock mechanics (forward folding model, Plateaux et al, 2018). This tool is suited for folds formed under

tangential longitudinal strain. Fracture orientation (e.g.: joints) and intensity is then derived from the computed stress-field related to the folding. This method was applied to the Alima fold in Tunisia and showed a substantial correspondence between predicted fracture and structural measurement collected in the outcrop.
To compare the Dynel 3D method, Lamem plug-in was used. Lamem is a numerical geodynamic code that solves the creeping flow Stokes equations. In essence, the rock deformation on geological timescales is approximated as extremely slow flow of a viscoelastic fluid. The advantages of Lamem is that it can create (re-create) complex folding geometries with due consideration of rock visco-elastic behaviour and the effects of temperature (or burial depth) on folding behaviour of rock. The output of the Lamem simulations deliver stress maps of folded layers which may be used as probability maps for input to MPS.

Conclusions

The MPS-based technique presented in this paper is a quick and flexible method that takes into account multivariate input data (training images and probability map) to produce non-stationary simulations predicting the sub-seismic fracture network organisation (2D-3D) at an order of 10^3m scale in the subsurface. The workflow evaluates the results of the simulations using connectivity, apertures and fluid flow calculations. Developments are ongoing to input more geology during the generation of the training images and probability maps.

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