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Multiscale 3D prediction of fracture network geometry and fluid flow efficiency in folded carbonate reservoir analogues; Case study of the Island of Pag (Croatia).

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Abstract

Natural fractures are one of the most common geological features occurring on the upper crust (Pollard and Aydin, 1988). Fracture networks can act as fluid pathways or fluid barriers and may have an impact on reservoir properties at depth (Laubach and Ward, 2006). However, the distribution of fractures in the subsurface is largely unknown due to their sub-seismic size and to the scarcity of available qualitative and quantitative data.

This paper present a multiscale workflow used to populate 3D models with fracture network geometries and topologies and to quantify the degree of efficiency of these fractures under subsurface conditions. This workflow makes simultaneous use of small scale (order of 10 m) structural data acquired in the field, high resolution aerial photography acquired with a drone (order of 10^2 m), satellite imagery and other large scale datasets (order of $10^{3\text{-}4}$ m). The method we developed follow four main steps: 1) modelling the 3D architecture of the outcrop analogue, 2) modelling strain and stress in the 3D environment, 3) populating the 3D environment with fractures characterised at various scales and 4) modelling the permeability of the obtained network in the outcrop analogue. This method constitute the essential prerequisites for a more predictive approach where fractures are generated as a consequence of the stage of deformation experienced by the object of interest.

Introduction

Fractures in carbonate rocks strongly impact reservoir quality (Aydin, 2000; Laubach et al., 2004).Understanding their genesis mechanisms, their geometry, and their efficiency in regard to fluid flow and fluid storage is a major challenge for geoscientists and for the O&G industry. Outcrop analogues provide interesting natural laboratory where a substantial part of the present-day multiscale geological heterogeneity can be characterised.

This paper presents a multiscale and multidisciplinary workflow applied to a folded carbonate case study from southern Europe. The Island of Pag, Croatia, belongs to the External Dinarides region. In this area, a series of carbonate platforms including the main Adriatic-Dinaridic Carbonate Platform (ADCP) persisted from Triassic to Eocene (Tari, 2002). These platforms were folded during Paleocene-Miocene Dinaridic deformation phases (Zibret and Vrabec, 2016). The present-day geology of the Pag island exhibits a “box-type” anticlinal structure with up to 1 km thick Cenomanian to Senonian shallow-water rudists-bearing carbonates and about 650m thick Eocene-Oligocene Nummulitic carbonates successions.

Structural data acquisition process was completed locally in key areas of the fold and at several imbricated scales. The architecture of the Island of Pag was captured in 3D and represents the present-day framework where fracture network geometry and fluid flow behaviour can be modelled. The Pag’s 3D model was restored to its unfolded stage in order to compute strain maps and to calculate

regional stress directions and magnitudes. Locally observed pre-, syn- and post-folding fractures were sequentially and independently integrated into their corresponding stage of deformation in the 3D environment.
The local fracture networks were then simulated at the scale of the fold using Multiple Points Statics algorithm. The obtained fracture network was mechanically tested under subsurface conditions in order to calculate mechanical and hydraulic aperture using a Finite Element approach. Finally, the discrete fracture network was dynamically tested using multiphase fluid flow simulations in order to control the quality of our approach and eventually quantify uncertainties.

Our approach aims to establish a series of structural, mechanical and dynamic rules helping to define the fracture network geometry and its efficiency. These rules are used to constrain subsurface flow or mechanical models and to make quantitative and qualitative flow- and storage-efficient fractures predictions.

Methods
At small (station - order of 10 m) and intermediate (outcrop - order of 10^2 m) scales, fracture data were acquired in the field. Measurements stations were selected in both pavement and vertical sections to investigate the type of deformation and to reconstruct the fracturing history occurring pre- to post-folding. At the outcrop scale a drone was used for photogrammetry applications in order to extend the understanding of the fracture network between stations. The field-based fracture data acquisition was completed with satellite imagery (fig. 1), these images allowing to digitize and to interpret fractures that are larger than the outcrop scale and major fault structures.

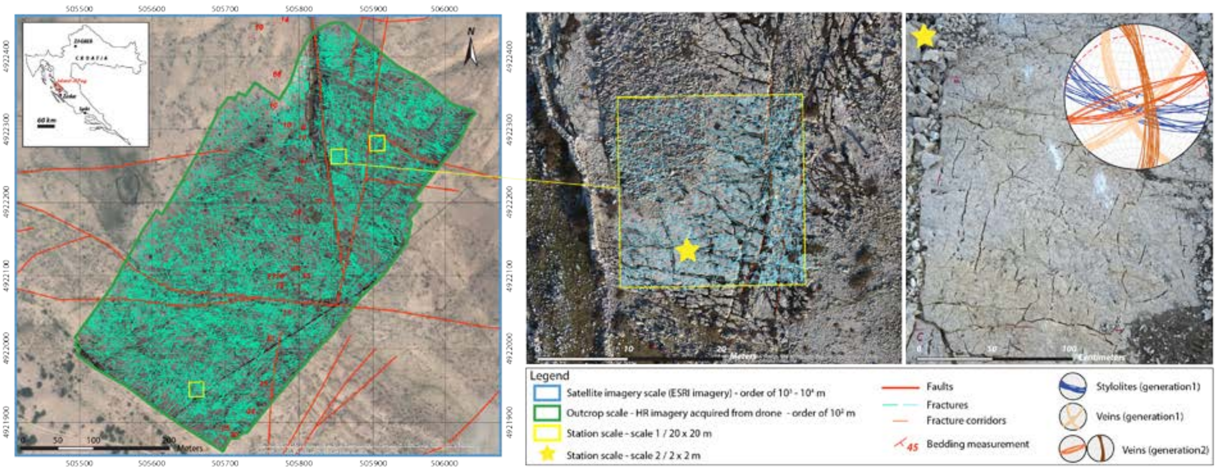

Figure 1: multiscale fracture data collected in the island of Pag.

The architecture of the Island of Pag was represented in 3D using an implicit modelling method (fig. 2). The structural modelling phase is fundamental to provide a 3D framework to represent objects or properties. The model of the occidental part of the island of Pag (9 x 2.5 x 1 km modelling box) is constrained by surface data and interpretations on the form of geological contacts, bedding measurements, cross sections and DEM.
The 3D model of the island of Pag was restored to its initial position to quantify the deformation and to be able to sequentially integrate the interpreted fracture network into the 3D environment. Strain maps were computed on the kinematic model (restored) and inverted to obtain principal stress directions and magnitude. The fracture history defined from field data acquisition was used to locally and sequentially populate the 3D model with fractures.

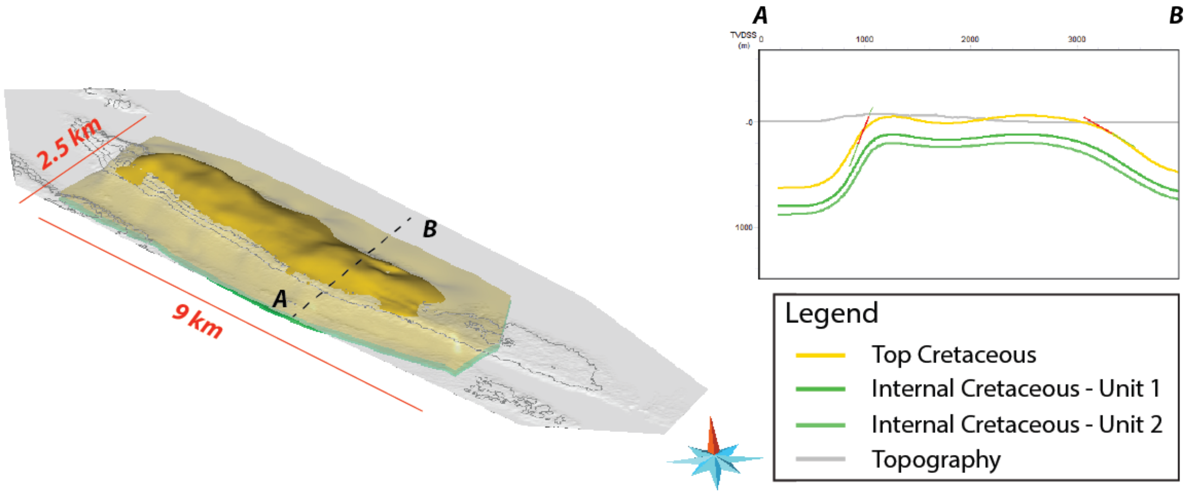

Figure 2: simplified 3D geometry of the island of Pag. The Cretaceous layer only are represented in this figure.

The variability of fracture type in the fold structure and in the different phases of deformation was taken into account using the multiple point statistic method (Bruna et al., 2017). At the reservoir scale, one or more representative training images per outcrop were created and simultaneously used during simulation runs (fig. 3). The obtained models forecast the 2D fracture distribution at the scale of the island of Pag.

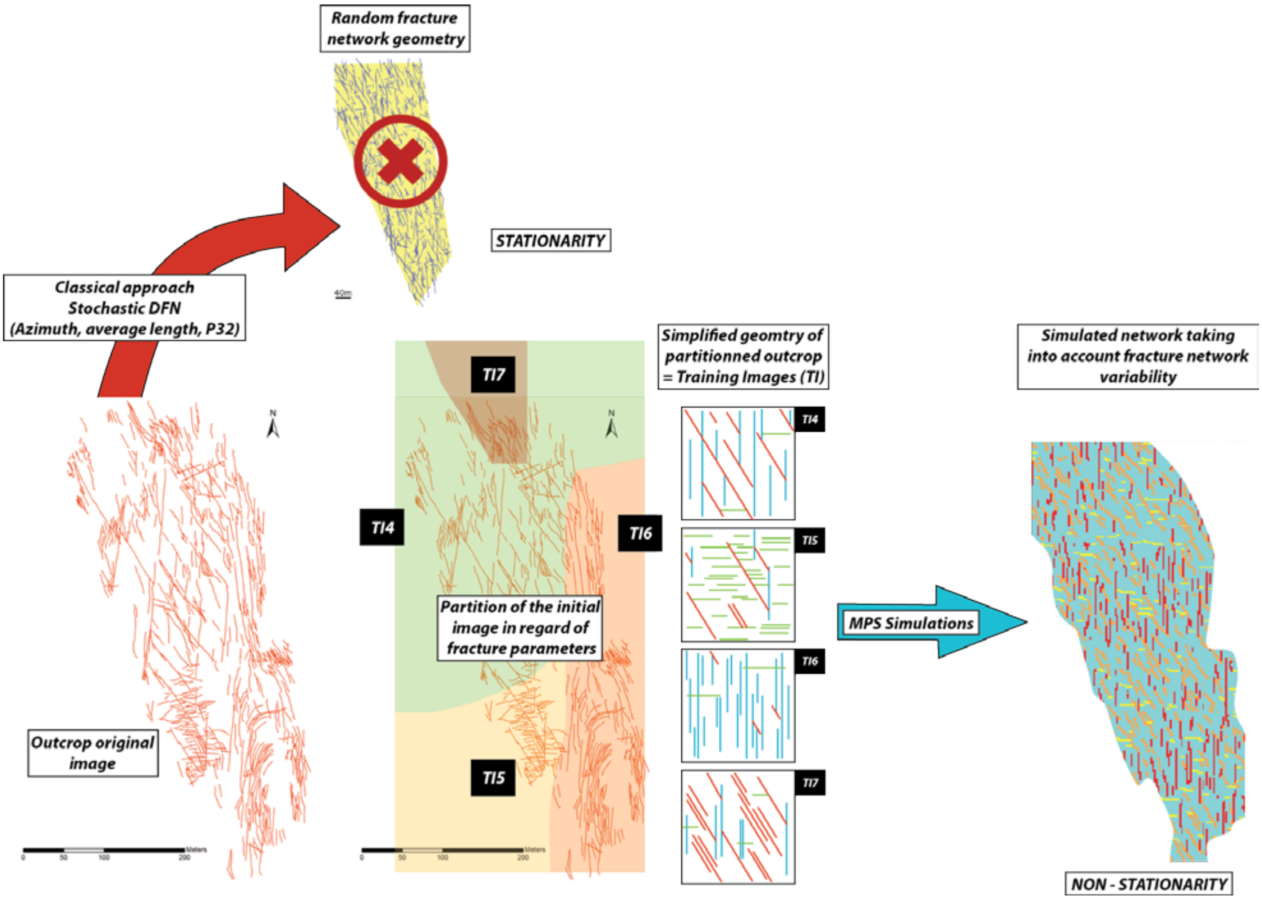

Figure 3: fracture network simulation workflow using multiple point statistics method.

In the obtained statistical network, mechanical and hydraulic aperture were calculated using the Barton-Bandis empirical model. This model quantifies the remaining aperture when irregular mismatching fracture wall are partially closed under in-situ stress (Bisdom, 2016). The fracture will be reactivated under local stresses - inverted from strain calculation obtained from the restored model - and will eventually remain open if the shear stress is sufficient.

Results of aperture model were used to calculate equivalent permeability by integrating the fluid flux across the model boundaries using multiphase fluid flow simulations.

Conclusions

The present paper proposes a multiscale and multidisciplinary approach to populate a 3D outcrop structural model with fractures observed at different scale in the field. Our mechanical modelling workflow allows estimating the efficiency of the fracture (aperture and equivalent permeability) both locally and at the scale of the island of Pag. Developments are ongoing to now predict the type and the intensity of fracture during folding process using a structural forward modelling approach coupled with mechanical testing.

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