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Predicting Multiscale Fracture Patterns in Buried Reservoirs: the Importance of Outcrop Data in a Coherent Workflow

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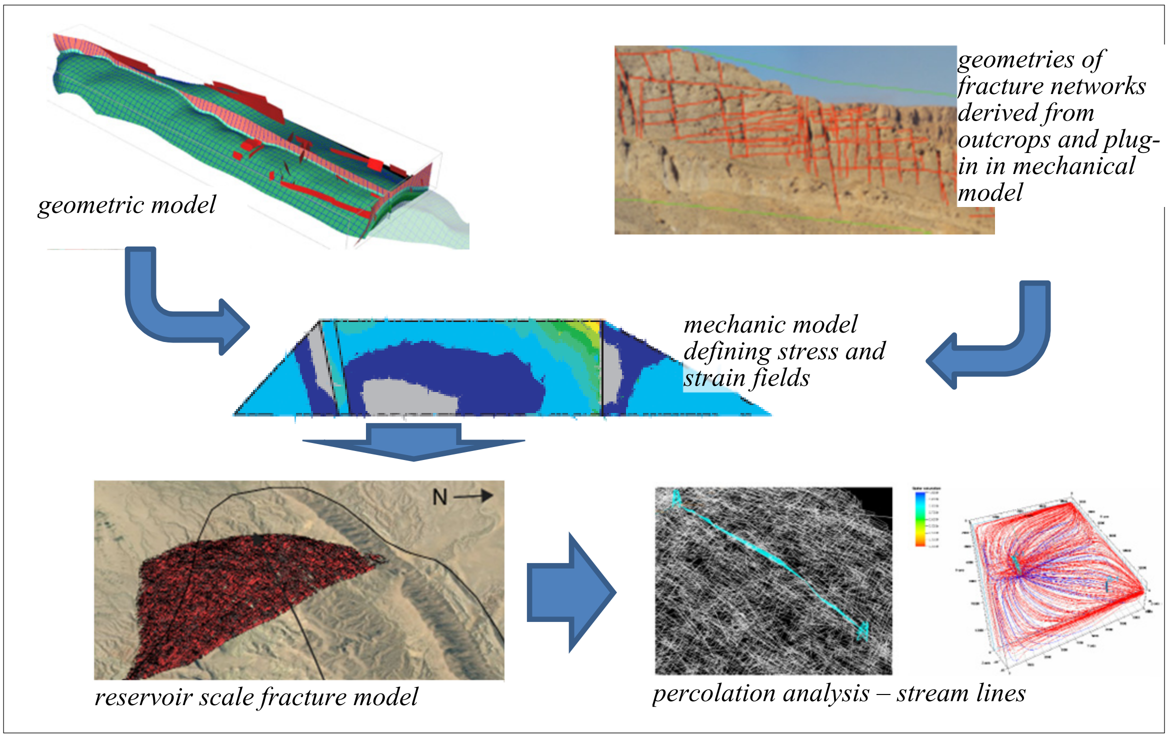
SUMMARY

Fracture data from outcropping analogs are often acquired but rarely used to improve permeability predictions in buried reservoirs.
To improve this we present a systematic workflow which includes i) the building of a geometric model of the investigated structure, ii) the execution of mechanical simulations to determine state of stress and strain field, iii) the use of outcrop data to populate the model and iv) develop a reservoir-scale permeability model
To make full use of outcrop data, we present new acquisition and processing tools allowing able to provide a full characterization of the fracture field even when fractures are not bed-confined.
A few case studies are presented to discuss this workflow in sedimentologically and structurally heterogeneous settings.

DigiFract: A software and data model implementation for flexible acquisition and processing of fracture data from outcrops Faced with the challenges posed by fractured (carbonate reservoirs) there is a widely spread need for improving knowledge and tools to predict fracture related porosity, permeability and, ultimately, of performance of buried hydrocarbon (and, to a less extent, water) reservoirs. For this purposes Industry and Academy alike invest significant amounts of resources in the acquisition of fracture data from outcrops. However, only a small portion of the gathered information is translated in real knowledge and eventually used for a better understanding of flow behaviors in the reservoir. Seemingly, it is often forgotten that outcrops are not the goal but are only as useful as they can be used to learn "lessons" useful for reservoir predictions. It follows from the above that outcrop studies are only one, though a crucial one, of the steps leading to more effective predictions.

We present a consistent and integrated work flow, dedicating particular attention to the acquisition, processing and interpretation of field data.



Step 1. Geometric model
The first step of our workflow involves the construction of surface-based geological models of the reservoir and surrounding volume. A surface-based model is preferable to volume-based as it results, among others, in computationally lighter models which can be easily used for further modeling work. The model should include all "visible" sedimentological (different lithologies) and structural (folds and faults) heterogeneities.

Step 2. Mechanic model
During the 2nd step of our work-flow, the geometric model is used to predict orientation and magnitude of principal stresses and the distribution of the portion of the model experiencing fracturing (proximity to failure). For this purpose, mechanical properties are assigned to volumes (lithologies) and surfaces (mainly faults). Especially in the case of carbonates, mechanical properties of rocks change significantly during diagenesis (e.g. Laubach et al. 2010; Boro et al., 2013). In addition, decisions need to be taken on the stress conditions of the model during and following fracturing. This requires the often neglected determination of i) the timing of fracturing (not

necessarily at present burial depth) (e.g. Lamarche et al. 2012) and ii) the geological evolution of the relevant bodies (e.g. folding, episodes of exhumation).

Step 3. Fracture networks

Obviously, determining the distribution and intensity of fractured domains is insufficient to allow predictions on permeability as this crucially depends on the **fracture networks** which develop in the heterogeneous rock. We extract this information from outcropping analogs and build our strategy in two steps, i) outcrop-scale data acquisition and processing and ii) integration of outcrops sampling the different heterogeneities of the target volume.

3.1. Outcrop-scale data collection and processing is performed with DigiFract (Hardebol and Bertotti, 2013), a GIS-based tool which allows for efficient and objective full characterization of the fracturing network visible in the 2D outcropping surface inclusive of directional sets, height (length) distribution, position of fracture terminations, spatial relations with bedding and fracture stratigraphy across the layered succession. DigiFract is preferable to traditional scan-line methods which are typically unable to provide full geometric description of poorly bed-confined fracture sets and to LiDAR acquisition, often logistically and computationally heavier than DigiFract. DigiFract acquisition can also be extended to (polished and oriented) samples and to thin sections.

3.2. By acquiring data from multiple outcrops, we constrain fracture patterns in all sedimentological and heterogeneities characterizing the model (see Fig 2 as an example).

		structural			
		flank	hinge	corridor	fault
sediment	marls	# 1	# 2	# 3	# 4
	packst.	# 5	# 6	# 7	# 8
	slope	# 9	# 10	# 11	# 12
	margin	# 13	# 14	# 15	# 16

Step 4. Model-scale extrapolation

Integrating the strain maps derived in step 2 with the outcrops scale geometries of step 3, the entire model is populated with fracture-related physical properties. The first stage consists in the development of outcrop-scale Discrete Fracture Network models constructed by extruding measured fractured data to a representative volume. Tow paths can then be followed. One can derive parameters such as connectivity and then extrapolate these values to (structurally and sedimentologically) homogeneous domains. Alternatively, one can build a larger DFN of the entire homogeneous domain; this obviously requires simplifications of the fracture field.

Step 5. Quantification of flow

Once the permeability model has been built, simulations are performed to quantify flow properties. The priority lies in the assessment of the model uncertainties and their impact on the overall flow pattern. Simple and rapid tools are used including cluster analysis, pathway analysis and streamlines determinations.

Case studies

During the last years, we have analyzed a number of outcropping case studies covering different sedimentological and structural heterogeneities. The impact of the juxtaposition of sedimentologically different bodies typical for flat-topped carbonate platforms has been studied at Mt Latemar (Dolomites, N Italy). On km-scale anticlines exposed in Central Tunisia, we constrain the fracture networks developed during the different stages of fold growth and characterize their changes from one lithology to the other and from one structural position to the other.

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