Lessons for Subsurface Fractured Reservoir Studies from an Outcrop-based 3-D Model of Fluid Flow in a Fractured Carbonate Fold*

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Abstract

The characterization of heterogeneous fracture patterns in complex reservoirs, such as folds, is difficult, as multiple stages of fracturing and fracture reactivation take place pre-, syn- and post-folding. Outcrop studies help understand the behavior of fractures and subsequent fluid flow in folds, as outcrops provide both small-scale fracture patterns and the large-scale fold geometry. We aim at characterizing these patterns in terms of stresses, deriving from outcrop fracture data the stress conditions under which the fractures were formed, and linking this to large-scale development of the fold. From these relations, we construct 3D fracture networks, conditioned to outcrop data, which serve as the basis for upscaling and fluid flow simulations. Through these simulations, we quantify the relative fluid flow trends in different domains of a fold. We map the large-scale geometry of and fracture patterns in two formations, one Eocene and the other Upper Cretaceous, in different domains of a reservoir-scale outcropping fold in central Tunisia. Both formations are limestones with comparable bed thicknesses, but the Eocene formation has cm-thick shale layers in between the beds, while the Upper Cretaceous formation has no shale. During subsidence, regional fracturing resulted in a system of two bed-perpendicular conjugate orientation families. The bisection of the small angle of the conjugates corresponds to the tectonic stress direction. The angle between the two conjugate families is 40°, and the fractures have an opening and shear component, indicating that they are hybrids between Mode I and Mode II. During folding, the lack of shale in the Upper Cretaceous layer resulted in pure flexural slip, creating oblique-to-bedding stylolites and veins. In the Eocene layer, the presence of shale causes the maximum principle stress to remain parallel to the layers, creating bed-perpendicular fractures. These fractures are organized in two conjugate families which are perpendicular to the pre-folding conjugate system. Their spatial arrangement is determined by the pre-folding fractures, which created local weaknesses and stress heterogeneities in the rock. The small-scale stresses are correlated to large-scale stresses, using mechanical modelling, to construct a fold-scale fracture frequency model. The resulting model is upscaled to an equivalent fracture permeability model for fluid flow simulations, to analyze the behavior of flow through fractures in folds.

Introduction

The characterization of heterogeneous fracture patterns in complex reservoirs, such as folds, is difficult, as multiple stages of fracturing and fracture reactivation take place pre-, syn- and post-folding (e.g. Casini et al., 2011). Outcrop studies help understand the behavior of fractures and subsequent fluid flow in folds, as outcrops provide both small-scale fracture patterns and the large-scale fold geometry (e.g. Shackleton et al., 2005, 2011).

We aim at characterizing these multi-scale patterns in terms of stresses, deriving from outcrop fracture data the stress conditions under which the fractures were formed, and linking this to large-scale development of the fold. From these relations, we construct 2D and 3D fracture networks, conditioned to outcrop data, which serve as the basis for fluid flow simulations. Through these simulations, we quantify the relative fluid flow trends in different domains of a fold.

Fracture Data Analysis

We map the large-scale geometry of and fracture patterns in two formations, one Eocene and the other Upper Cretaceous, in different domains of a reservoir-scale outcropping fold in central Tunisia (Figure 1). Both formations are limestones with comparable bed thicknesses and similar rock properties (density, porosity, and elastic properties). In addition, the formations are apt analogs to several subsurface reservoirs in North Africa.

Fracture data, calibrated with outcrop observations, is acquired through digitizing of georeferenced photographs in 2D and 3D in 25 outcrops in different domains of the fold, resulting in a dataset of nearly 4,000 fractures and their corresponding orientation, size, and spacing distributions. Digitizing of the data is done directly in the field, using DigiFract (Hardebol and Bertotti, 2013). In addition, we sample approximately 40 veins from different domains, to study the composition and structure of the cement and to analyze the fluid inclusions. The veins observed in outcrops are parallel to large open fractures observed in the large-scale 3D outcrop models. The vein study provides additional information on the conditions and depths at which fractures were formed or reactivated.

The fracture data analysis shows that prior to folding, very limited shortening resulted in a system of bed-perpendicular conjugate veins. The veins are relatively small, up to several meters, and are homogeneously spaced. The bisection of the small angle of the conjugates corresponds to the tectonic stress direction. The veins have an opening and shear component, indicating that they are hybrids between Mode I and Mode II.

Exhumation led to reactivation of many of the original veins, resulting in large open fractures with orientations similar to the original veins. These open fractures are several tens of meters and often extend the dimensions of the outcrops. The combination of exhumation and folding also resulted in additional deformation features, including shear fractures striking parallel to the fold axis and oblique-to-bedding stylolites. The combination of shortening-related features and deformation related to folding and exhumation resulted in the present-day fracture patterns shown in the conceptual model in Figure 2.

Aperture and Flow Modeling

To better understand the impact of the studied fracture systems on fluid flow in subsurface analogs, we build detailed fracture flow models in both 2D and 3D. The basis for the flow models is the deterministic fracture data digitized from outcrops. Rather than trying to create an upscaled reservoir-scale flow model, we focus on the near-wellbore behavior of fracture flow, using high-resolution fracture models of 65x65 meters, containing up to a hundred deterministic fractures with varying orientations (Figure 3). The flow models are constructed using the simulator code CSMP++ (Matthai et al., 2007). Differently from other codes, CSMP++ takes into account both fracture and matrix flow, which is of crucial importance especially where no fully interconnected fracture network is present (Paluszny and Matthai, 2010; Geiger et al., 2013).

In these models, we focus on the impact on flow of fracture aperture. The fracture aperture is modeled mechanically in 2D, using the commercial FEM solution ABAQUS. The fracture models are constructed from digitized outcrops, so fractures are deterministic features rather than stochastically generated. This way, we aim at better capturing the natural variability found in fracture networks. For a range of different boundary conditions, such as the direction and magnitude of shortening, the fracture opening is modeled and used as input for flow models. The range of likely material properties and boundary conditions is derived from kinematic reconstructions and rock sample measurements from rocks collected during the fieldwork. Through these models, we quantify the impact of the uncertainties for different boundary conditions on aperture, as well as provide a database of scenarios for boundary conditions and the subsequent aperture distributions.

Next, flow is quantified through the aperture models by solving for the pressure distribution and effective permeability in the outcrop-based deterministic fracture networks, using CSMP++. We use pressure as a quantification for flow as it is faster than calculating detailed two-phase flow. Furthermore, we do not have any fluid properties or PVT data for this outcropping analog. Through this workflow, aperture and subsequent flow is quantified as a function of different mechanical boundary conditions. Effective permeability is also calculated for these models, which is defined as the impact of matrix flow and fracture flow combined. The layers in the model are horizontal, corresponding to the simplistic scenario where fracturing preceded folding.

Results

The resulting models show that even small variations in the amount of shortening can have a large impact on aperture. Furthermore, fracture opening is very sensitive to the orientation with respect to the shortening direction. The outcrop-based flow models can be used to better quantify the uncertainties and sensitivities in subsurface fracture modeling and upscaling exercises. The models will be further extended by studying the behavior of fractures in 3D and by quantifying the impact of well placement on fracture flow.

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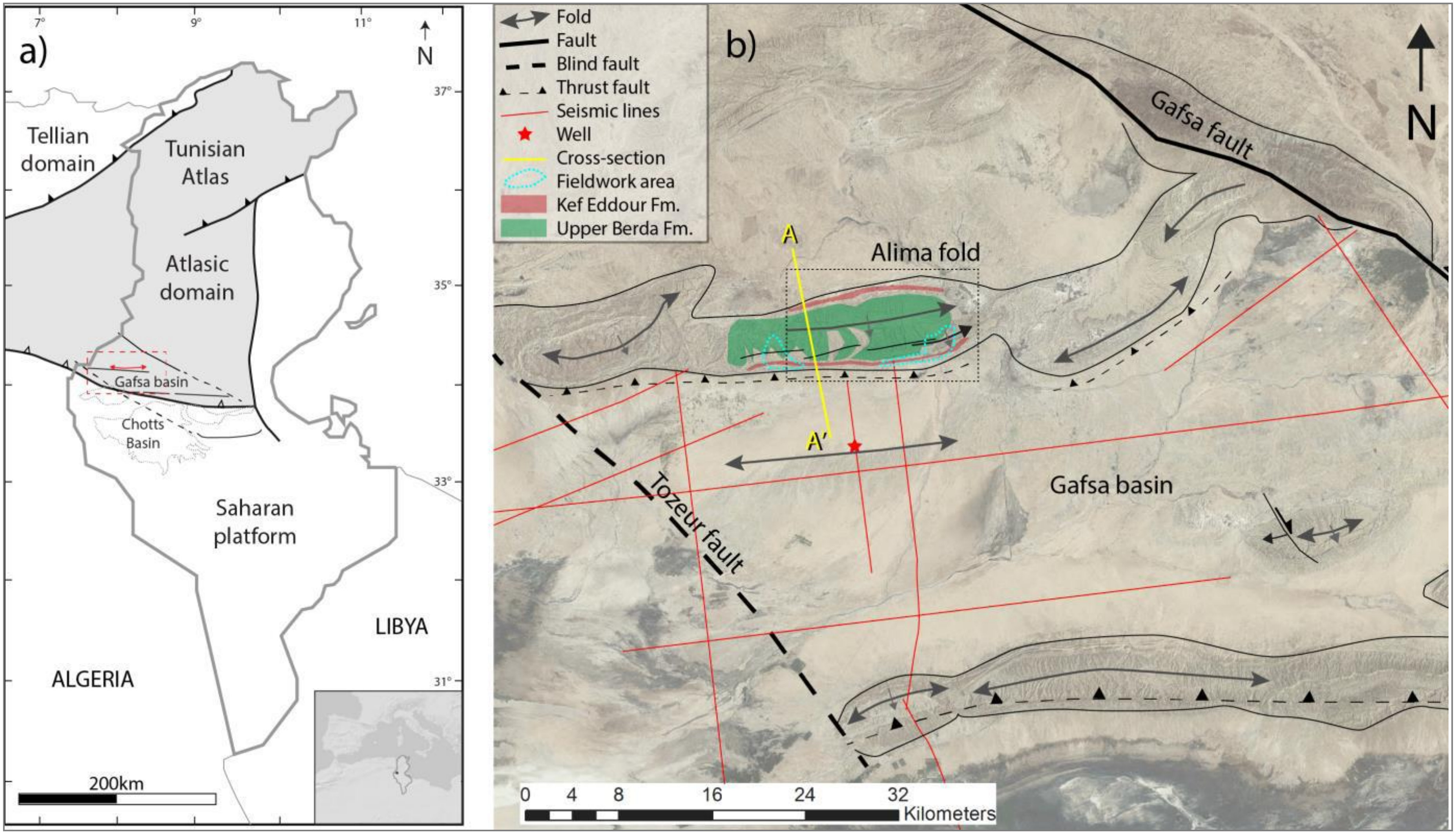

Figure 1. a) Outline of the Atlasic domain in Tunisia with the fieldwork area located at the southern border of this domain. b) Detail of the Gafsa Basin, with the outcropping structure of interest: the Alima fold. Upper Cretaceous and Eocene carbonates are outcropping along the crest and flanks of this fold (green and red areas). Red lines and the red star indicate 2D seismic lines and a well respectively, which allow for constraining the geometry of the Alima fold in the deeper subsurface. Fracture data is mostly collected along the southern slope of the fold.

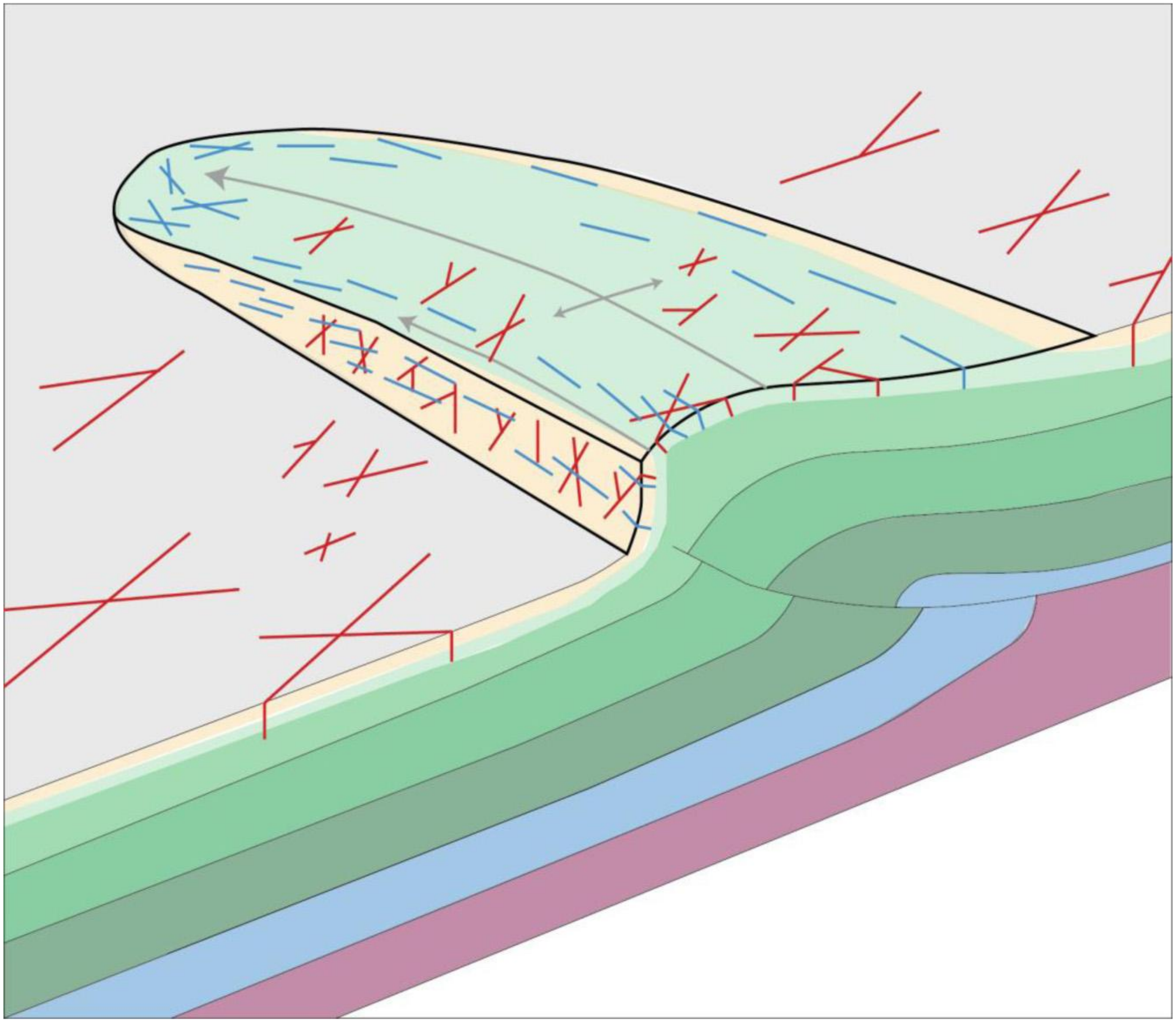

Figure 2. Conceptual sketch of the geometry of the Alima fold and the main fracture systems indicated in red (pre-folding) and blue (syn-folding). Green colors are Cretaceous formations, blue is Jurassic, and purple is Triassic evaporates. North is towards the right. The steeply dipping domain of the Upper Cretaceous formation also contains small (~20 cm) oblique-to-bedding stylolites (not shown).

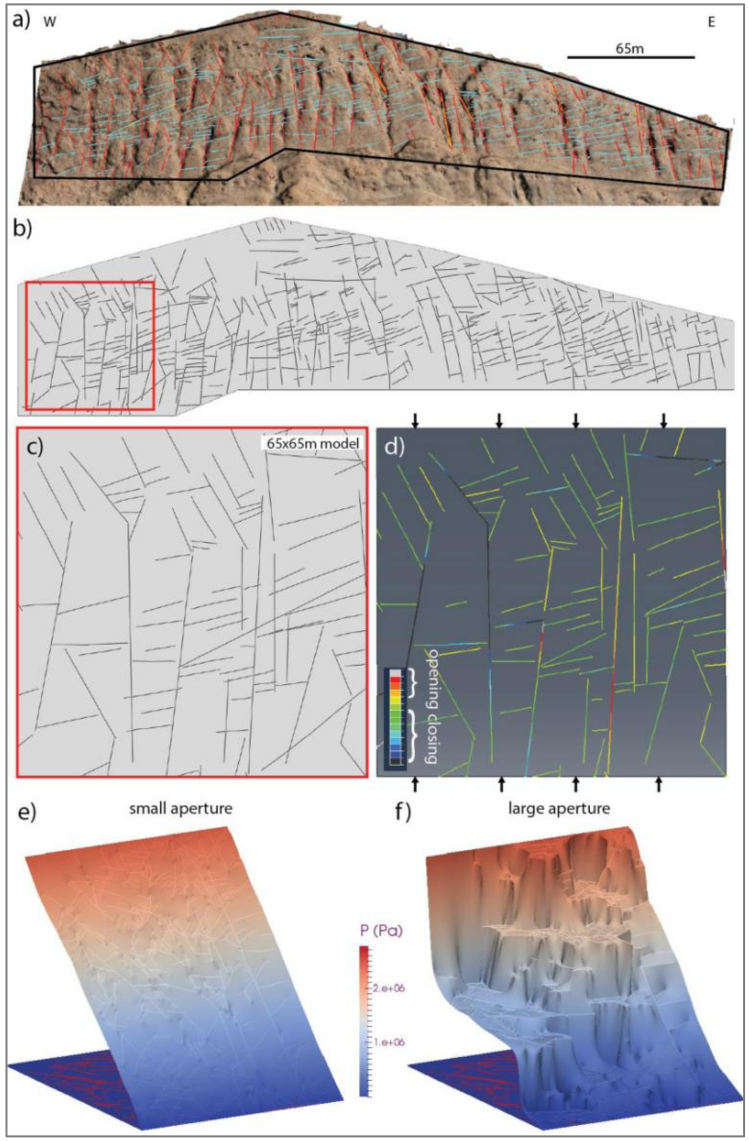

Figure 3. Workflow from outcrops to fractured flow models: a) outcrop model of a steeply dipping pavement from the southern slope of the Alima fold containing nearly 500 fractures (red and blue lines); b) mechanical model of the pavement with its fractures; c) 65x65 meter detail of the mechanical model with the fractures; d) mechanical fracture aperture distribution after shortening; e) 2D fracture model (dark blue with fractures in red) with a homogeneous pressure distribution (red to blue gradient) for low fracture aperture; and f) heterogeneous pressure distribution for the same model, but with a large average fracture aperture.