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Predicting Multi-scale Deformation and Fluid Flow Patterns in Folds Using 3D Outcrop Models and Mechanical Modelling

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SUMMARY

Natural fracture patterns in folded carbonates are highly heterogeneous. The present-day fractures are often the result of pre-folding, syn-folding and post-folding related fractures. Furthermore, syn-folding fractures may differ in different domains of the fold. Although there are studies that characterize fracture patterns in outcropping folds, there is still a poor understanding of the relation between large-scale deformation (i.e. folding), and small-scale deformation (i.e. fractures), especially in terms of stresses and process-based predictions of fractures. Our overarching goal is to assess the sensitivity of reservoir-scale flow to different fracture patterns and different fracture properties. Therefore we build multi-scale models of 3D fracture networks in outcropping folds in the foothills of the Tunisian Atlas (central Tunisia). The fracture data is collected from outcrops using efficient methods that collect both fractures and the 3D geometry of the outcrops. We interpret small-scale deformation in terms of stresses and combine this with fold-scale mechanical models to predict the fracture patterns in 3D throughout the fold. The 3D model is used to model fracture fluid flow. This work presents a new approach to outcrop studies, that distinguishes different stages of fracturing and uses stresses to make predictions about fracture patterns in similar structures.

Introduction

Natural fracture patterns in folded carbonates are often highly heterogeneous. The present-day configuration of fracture networks in both subsurface reservoirs and outcrops is often the cumulative result of pre-folding, syn-folding and post-folding (exhumation) related fractures (Becker et al., 2010). Furthermore, syn-folding fracture patterns may differ strongly in different structural domains of the fold (Bergbauer & Pollard, 2004). Although there are studies that characterize fracture patterns in outcropping folds, there is still a poor understanding of the relation between large-scale deformation (i.e. folding), and the small-scale deformation (i.e. fractures) patterns (e.g. Smart, Ferrill, & Morris, 2009). We explicitly build our models in a process-based fashion which includes fracturing and reactivation at different stages. Little of this is visible in buried reservoirs, which is the reason for focussing on outcrops instead.

Understanding relations between multi-scale deformation is complicated by a number of factors. First, it is difficult to discern the pre-folding fractures from syn-folding fractures, as folding can also alter the pre-existing fractures by reactivating or extending them (Becker et al., 2010). Reversely, the pre-existing fractures may influence the syn-folding fracture patterns, as they cause local weaknesses in the rock. The third stage, post-folding, possibly results in more fracturing, for example due to exhumation, or it can lead to reactivation of existing fractures or dissolution and recirculation of cement, changing the properties of the fractures and veins.

In this paper, we present an integrated approach to modelling fractures in outcropping folds in central Tunisia, focussing on the stress patterns that link large-scale deformation to small-scale fracturing. Understanding the relation between multi-scale deformation in outcropping folds provides predictive rules that can be applied to predict fracture patterns in the subsurface.

Methodology

The fieldwork area of this study is located in central Tunisia, where we study the foothills of the Tunisian Atlas in the Gafsa basin (Figure 1a). This basin separates the Tunisian Atlas mountains in the north from the Saharan platform in the south. In the basin, we focus on the Alima anticline, which is an E-W striking cylindrical fault-propagation fold with a fold axis length of 20 km (Figure 1b). This fold contains excellent exposures of two outcropping formations of fractured carbonates: The Eocene Kef Eddour Fm. and the Upper Cretaceous Upper Berda Fm.

Figure 1 a) Setting of the Gafsa basin in between the Tunisian Atlas and the Saharan platform; b) Enlargement of the red boxed area in (a) with the Alima anticline in the centre. Seismic lines indicated in red. Green star indicates a well.

Our work is divided into three parts: i) capturing a statistically complete and georeferenced 2.5D fracture dataset in the field to define small-scale deformation, ii) building geometric, kinematic and mechanical models of the fold to capture large-scale deformation, and iii) studying fractures in outcropping horizontal layers away from the fold and fluid inclusions of veins to quantify pre-, syn- and post-folding fractures.

Field data acquisition

During two short fieldworks, we digitized thousands of fractures, veins and stylolites, using a tablet PC and DigiFract software (Hardebol & Bertotti, 2013). Fractures were digitized directly in the field using the software and georeferenced photographs (Figure 2). For each fracture, the orientation, infill and sense of movement was measured and stored. In addition, for each outcrop, bed surfaces were measured and digitized. The result is a comprehensive database of fractures and beddings that can be used to directly, in the field, produce orientation, size and density plots, in addition to quantifying the relations between fractures and bed surfaces. The database is extended with physical rock properties, such as rock strength, P- and S-wave velocities and porosities, measured in a companion project performed at the VU Amsterdam.

We measured fractures in pavements and outcrops cutting the stratigraphy, to capture both fracture length and height, in different structural domains of the fold. In addition, we also digitized fractures in outcrops in other areas of the basin, away from the folds, to capture and identify the regional pre-folding fractures. Furthermore, we collected vein samples to analyse fluid inclusions in the cement, to determine the origin of the fluids and when fractures were cemented.

DigiFract assists in accurately capturing fractures on relatively flat 2D outcrop surfaces, but results become inaccurate on 3D outcrop surfaces or pavements. Therefore, we use a small UAV (Unmanned Aerial Vehicle or 'drone') to create orthophotos and Digital Elevation Maps of the 3D fold geometry and the deformation features. Using photogrammetry, the drone images are quickly and accurately processed into a 3D model with draped orthophotos.

Figure 2 Example of a digitized sub-vertical pavement with fractures in red. The stereonet shows the fracture greatcircles (red) and bedding (blue) after rotating the bed back to the original horizontal position.

Multi-scale deformation patterns and stresses

Using the abundant fracture dataset, we interpret the small-scale deformation patterns and relate them to local stress patterns throughout the fold. In addition, we identify different stages of fracturing, both before and during folding. By linking small-scale deformation to stresses, rather than just defining fracture set statistics, we are able to create a predictive model for fracturing based on large-scale stress patterns.

The large-scale 3D geometry and mechanical development of the fold is constructed using geological maps, Digital Elevation Models, 2D seismic data and wells. Kinematic reconstructions of 2D cross-sections provides boundary conditions for the mechanical models, including exact depths and the amount of shortening. The mechanical models are forward models of 2D cross-sections, showing the stress distribution through time, during shortening and during folding. The resulting large-scale stress distribution is used to extrapolate fracture patterns digitized in the field to a 3D multi-scale fracture network in the fold.

To link large-scale stress models to small-scale deformations, we quantify the correlation between variations in the large-scale models with fracture density patterns measured in the outcrops. In case of a good correlation, the large-scale model is used to populate a 3D grid with stress-based fracture orientation, density and aperture properties.

Results & Conclusions

The datasets of the fieldworks are combined with the large-scale models of the fold geometry to construct a multi-scale 3D model of the outcropping fold that can be used to study the multi-scale deformation patterns and to quantify their impact on fluid flow patterns. The outcrop data indicates that the Kef Eddour Fm. and the Upper Berda Fm. have different dominant deformation patterns, even though they experienced the same amount of deformation during folding (Figure 3).

Figure 3 Interpretation of deformation stages and stress distributions in the Kef Eddour and Upper Berda Fms before folding (left) and during folding (right).

Fractures in the Kef Eddour Fm. are organized in two systems of perpendicular-to-bedding conjugate systems, each containing two orientation families separated by a $<40^\circ$ small angle. The conjugates are

hybrids between Mode I and Mode II fractures as they have both an opening and shear component. The bisection of the small angle of one system of conjugates is parallel to the tectonic stress and hence this system formed under a maximum principle stress parallel to the tectonic stress, during shortening, with a vertical σ_2 . The other conjugate system strikes perpendicular to the first one, and is the result of local stress perturbations during folding, caused by the pre-existing pre-folding conjugates.

The Upper Berda Fm. also contains some fractures belonging to the conjugate system that formed before folding, but, in contrast with the Kef Eddour Fm., displays mostly deformation features that are oblique-to-bedding veins or stylolites, indicating that the principle stresses were oblique-to-bedding as a result of flexural slip during folding. The difference in deformation features between the two formations is caused by a difference in mechanical units, as carbonate beds in the Kef Eddour Fm. are separated by a few cm's of shale, whereas there is no shale in the Upper Berda Fm.

Both outcrop observations and large-scale mechanical models indicate that the most intensive deformation is concentrated in steeply dipping layers in the fold, whereas more gently dipping layers have a lower fracture intensity and less fracture orientation sets. Through correlating the large-scale model with the small-scale fracture density trends measured in the field, we are able to construct a 3D fold-scale fracture density model. This model is the basis for upscaling and fluid flow simulations, to quantify fluid flow patterns and the sensitivity of different input parameters on the resulting fluid flow performance.

This combined approach of using efficient fieldwork tools and multi-scale stress models to collect and interpret large multi-scale deformation datasets proves useful for making predictions on the 3D fracture network distribution in folds, especially compared to the conventional approach of characterizing fractures in terms of statistics rather than stress patterns.

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