# Fracture Networks, Apertures and Flow Patterns in Carbonates Rocks from the Surface to Reservoir Depths

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## ABSTRACT

Carbonate rocks often experience early diagenesis/lithification and are therefore prone to fracturing already at shallow depths. Further fracturing can occur during regional subsidence, folding and faulting and (partial) exhumation. During these stages, rocks are exposed to far-field stresses of variable direction and magnitude. Stress conditions inside the body are also modified by multiscale sedimentological and structural heterogeneities.

To improve predictions of fracture-related flow in carbonate rocks, we i) characterize fractures and fracture networks, ii) investigate apertures and iii) explore fluid flow behaviour during the geological evolution from deposition to present day setting.

We characterize fractures and fracture networks on the basis of exposed analogs. We use photogrammetry to extract digital models from images acquired by either hand-held or drone-borne cameras. Fractures are digitized manually on the back-drop of the digital model and integrated with observations (strike, dip, infill etc) acquired in the field.

We subject the field-derived fracture network to numerical mechanical experiments to predict the aperture of fractures as a function of different stress conditions, such as different far field stresses, rock property variations and (variations in) pore pressure. We also consider the impact of partial fracture closing under compression, as well as shearing along irregular fracture surfaces. The resulting fracture geometries, with their heterogeneous aperture distributions, are the basis for fluid flow modeling, where we consider both matrix and fracture flow. The impact of fractures on flow is quantified in terms of effective permeability of the entire fracture-matrix model.

Data relevant for deformation and flow during regional subsidence are derived from the Cretaceous Jandaira formation (Brazil). The first episode of fracturing occurred at depths of 500-1000m and caused the development of a set of sub-vertical hybrid veins organized in conjugate sets associated with sub-vertical stylolites. Isotope data from vein cements document wholesale flow of meteoric waters circulating through the underlying sands. Aperture and flow analysis of large outcrop-based fracture models indicate that fracture density is not a good indicator of fracture flow, unless it is combined with fracture orientation, to account for the impact of shearing on aperture.

We document the effect of folding analysing fracture patterns in Cretaceous and Tertiary carbonates in the Alima anticline (Tunisia). Fracturing occurred prior to and during folding. Pre-folding fractures are bed-perpendicular conjugates slightly oblique to the $\sigma1$ and have therefore a significant component of shear displacement resulting in large hydraulic apertures. Synfolding fractures are stylolites and faults associated with frictional flexural slip on the fold flanks and poorly understood sets of conjugate veins roughly parallel to the fold axis.

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We constrain the impact of (partial) exhumation on pre-fractured rocks in the Jandaira formation and Alima anticline comparing subsidence-related fractures with presently visible open fractures. During stress unloading, no new fractures are created, but older features are reactivated, resulting in fracture growth both in terms of length and aperture. However, reactivation is heterogeneous, especially in terms of aperture, resulting in strong aperture variations within single sets, as observed from vein measurements in outcrops. It is therefore important to model the aperture and flow distribution to capture these heterogeneities, rather than assigning constant apertures to each fracture orientation set, as the latter may overestimate fracture flow.