DGMK/ÖGEW-Frühjahrstagung, Fachbereich Aufsuchung und Gewinnung
Celle, 25./26. April 2019

Faults and Fracture Networks in Upper Muschelkalk Outcrop Analogues Detected by Photogrammetry, Upper Rhine Graben (URG), Germany

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Abstract

Fracture distribution is of prime importance in URG carbonate reservoirs and reflects the orientation of stress during deformation. Since subsurface data are limited, numerous studies derive data from field analogs. They include fault-fracture scaling relationships (e.g. Meier et al., 2015), fold-fracture relationships (e.g. Lamarche et al., 2012), fracture-bedding relationships (e.g. Ladeira and Prince, 1981) and connectivity of fracture networks (e.g. Sanderson et al., 2018). We studied outcrops on the eastern shoulder of the URG with drone-based photogrammetry in order to conduct fracture geometries of a reservoir analogue and evaluate the data with an automated workflow.

W-E opening of the URG commenced in the late Eocene, with sinistral strike slip caused by N-S alpine compression and continued with W-E extension (Schuhmacher 2002). However, in-situ stress variations from the generally described regional stress were observed in the URG, e.g. depending on lithology (Meixner 2016; Valley and Evans, 2009) and structures. Additionally, fracture geometry depends on the rock mechanical properties, which determine clustering of fractures (Olson et al., 1993). Outcrop analogs themselves might influence bulk fracture orientation as they are over-consolidated due to their uplift to the surface where they reached zero horizontal stress (Laubach and Gale, 2018). By applying the graph theory based on distinction of I-, X-, and Y-nodes (Sanderson et al., 2018) on a quarry floor we quantify the connectivity of the fracture network for later flow simulation.

Comparison of LiDAR and UAV data shows similar quality of both datasets, and we can underline the value of UAV based photogrammetry in outcrop characterization. From our digital outcrop analogue data on a hundred-meter-scale we can deduce that distribution, orientation and persistency of fracturing is related to: (1) decameter-scale buckling as kink-band-mechanism, (2) faulting in tri-shear-mechanism, with veins in fault-bend folds rather than a significant fractured damage zone, (3) bedding thickness and (4) uplift. We observe fracture clusters on a 30 m scale. Additionally, fracture networks show a high connectivity with a high ratio of Y- and X-nodes. Our results implicate compression tectonics and inversion on the URG shoulders manifested by ten- to hundred-meter-scale kinking and tri-shear zones with faulting and fracturing. This may be related to late Cretaceous, pre-alpine compression tectonics as described by Kley and Voigt (2008) and coincides with abutting relationships revealing NNE-SSW fracture sets to be the oldest.

We conclude that the Muschelkalk in southwestern Germany was subject to compression, resulting in kink-folds, tri-shear zones, reverse faults and associated fractures. Valuable outcrop analog data can be derived by UAV photogrammetry and digital processing. Combination with quantified connectivity of the fracture network allows for construction of a 3D fracture model and fluid flow simulation. Absolute timing of faulting and vein formation will further constrain our understanding of fracture history to reservoir charging.