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Geometrical comparison of outcrop data and discrete element models of extensional fault zones in layered carbonates

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In the course of hydrocarbon or geothermal exploration the characterisation of fault zone architectures is of interest for fluid flow modelling and geomechanical studies. Seismic data normally offer the best information for the identification of fault zone geometries in sedimentary basins. However, the internal structure or the damage zone of a fault can be hardly resolved with seismic data as displacements along single fault strands or fractures are by far too small. Thus, it is not possible to directly map small scale faults with seismic methods, though these structures might significantly influence fluid flow. We try to examine the architecture of extensional fault zones in carbonate rocks at subseismic scales by using discrete element method (DEM) techniques to numerically simulate the evolution of fault zones including their associated damage zones.

As a case study we have analysed the geometry, displacement and fault width of normal faults in fine grained jurassic limestones in a quarry in Franconia, Germany. The quarry shows a rather simple set of conjugated 60deg dipping normal faults. Displacement is rather small and varies between c. 5cm up to c. 2m, some faults show almost no offset. The fault thickness varies between 2cm and c. 1m. A closer investigation of the fault geometries reveals, next to planar parts, sometimes complex fault zone structures including restraining and releasing bends, multiple fault strands as well as lenses and associated riedel shears. Analysis of high resolution photogrammetric data revealed a high number of small scale fractures between neighbouring discrete fault surfaces which are interpreted as highly fractured damage zones. Some faults with rather small displacement suggest that the overall inclination of the fault is a result of small subvertical sections which are connected in a staircase like appearance.

The DEM models simulate normal faulting in a layered marl-limestone sequence driven by the displacement of an underlying basement fault. Different layer geometries and effective vertical stresses in the range of 15-45 MPa, equivalent to an overburden thickness of c. 1000-3000m, have been used in the models. The stress range covers the maximum burial depth of the carbonates, which is assumed to be c. 1500m. Material properties used in the DEM were calibrated based on laboratory data, i.e. results of triaxial deformation tests on the studied limestones.

Results of the models show fault geometries which resemble those observed in the studied outcrop. In particularly under low stress, small offsets and with strongly decoupled layers we observe steeply dipping faults (>70deg) which also show staircase structures composed of subvertical fractures within each of the layers and horizontal offsets along the layer interfaces. We also observe the development of multiple fault strands and associated damage zones.

Our study shows that the DEM models are capable to reproduce observed fault geometries and damage zones. The results help to understand fault zone architectures and depict highly fractured areas in a sub-seismic scale.