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Evolution of near surface structures at normal faults in columnar basalts – insights from discrete element method simulations

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Normal faults in basaltic rocks are common in volcanic provinces and rift zones worldwide, such as Hawaii, Iceland, the East African Rift, the Rio Grande Rift and along mid ocean ridges. These basalts have layer thicknesses from several cm to meters and are frequently affected by columnar jointing. Layer boundaries and joints introduce regular weak zones into the otherwise strong basalt, leading to mechanically anisotropic (orthotropic) properties of the rock mass. While the rock mass is strong in compression (e.g. vertical stress), it shows little resistance to horizontal or vertical extension. We suggest that this property influences fault geometry and dilatancy in the damage zone more than currently understood. Outcrop studies provide insights into the surface geometry, but deep structures are rarely accessible. Analogue models have successfully been used in the past to determine the evolution of structures at dilatant faults but analogue materials do not allow reproducing the required joint sets and most of all not to change the inter-joint strength.

We overcome these problems by using 2D numerical discrete element method simulations (DEM). This method allows for randomization of column width and length and independent adjustment of strengths between columns, both, vertically and horizontally. These two parameters and the basement fault dip define a parameter space that we systematically explore in a number of simulations.

On a larger scale of observation, the resulting structures are similar to those from models with homogeneous materials. We observe dilatant faults at the surface, tilted blocks forming ramps, overturned precursor faults and antithetic graben faults. On closer scale of observation, faults and fractures localize exclusively at the pre-existing columnar joints, thus forming a stair-stepping structure when a fault propagates through the rock mass. This results in a more complex fault structure and a higher surface-to-volume ratio of the open fractures as compared to faults in a homogeneous material. Faults in orthotropic media also show a wider damage zone with different appearance in hanging- and footwall. In the footwall, the damage zone mostly consists of vertical extension fractures with lengths exceeding multiple layers. In the hanging wall, horizontal fractures make up a distinct portion of the damage zone, connected by vertical fractures. These form the aforementioned stair-stepping with step heights often equaling layer thickness. This observation has important influence on the localization of mineralization, which will be much more prominent in the hanging wall. It may also indicate that young magma intrusions in the footwall preferentially form dikes, while they form sills in the hanging-wall.