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How do normal faults grow above dykes?

Craig Magee (1) and Christopher Jackson (2)

(1) School of Earth and Environment, University of Leeds, Leeds, United Kingdom (c.magee@leeds.ac.uk), (2) Department of Earth Science and Engineering, Imperial College London, London, United Kingdom (c.jackson@imperial.ac.uk)

Dyke intrusions feed volcanic eruptions and drive crustal extension. Yet many dykes stall and thicken at depth, inducing formation of normal fault-bound graben in the overlying rock. Monitoring seismicity and ground deformation generated by these dyke-induced normal faults is used to track active dyke intrusion and estimate dyke properties (e.g. volume), which are critical to volcanic hazard assessment. Dyke-induced normal faults also control the geomorphology of volcanic rift zones, providing accessible surficial records of how magmatism shapes continental break-up, seafloor spreading, and the evolution of other planetary bodies. Whilst understanding how dyke-induced normal faults grow above dykes is thus fundamental to a wide-range of volcanic, tectonic, and surface processes, their geometrical and kinematic relationship remains unclear because we cannot view natural examples in 3D. Here we use seismic reflection data to map the 3D structure of graben-bounding, dyke-induced normal fault arrays developed above a dyke swarm offshore NW Australia. The dykes can be mapped over numerous 2D and 3D seismic surveys and extend for >250 km along-strike; dyke-induced normal faults are commonly observed above individual dykes and can be traced for >100 km along-strike. By mapping multiple areas of high displacement (up to $\sim$120 m) across the dyke-induced normal faults, we show nucleation occurred at various heights between, but not at, the dyke tip or contemporaneous free surface. Faults grew via linkage of discrete slip surfaces, likely in response to the incremental injection of a laterally propagating dyke. Our results highlight the surface expression of dyke-induced normal faults is controlled by where they nucleate, meaning fault properties at the surface cannot be easily related to underlying dyke properties. However, analysis of fault kinematics can be used to reconstruct dyke emplacement mechanics and flow direction. Furthermore, we show that the dyke-induced normal faults are much longer and have lower displacements than tectonic faults; i.e. on maximum displacement-length plots they occur outside the range of tectonic faults. Seismic reflection data can thus be used to distinguish dyke-induced normal faults from tectonic faults, thereby providing a method for mapping dyke swarms on other continental margins.