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High-resolution UAV structural mapping of dike-induced faults in Harrat Lunayyir, Saudi Arabia.

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Dike intrusions along divergent plate boundaries usually produce brittle deformation at the surface. We focus on the Harrat Lunayyir volcanic area in north-western Saudi Arabia, where in April-June 2009, a two-metre-thick dike intrusion formed a 2-5 km wide and over 10 km long NNW-striking graben bordered by normal faults. In order to determine the near-field deformation pattern and the kinematics of the graben faults, we have been testing a novel approach for high resolution structural mapping by using data acquired with fixed wing Unmanned Aircraft Vehicles (UAV). We inspected a total area of $\sim$9 km^2, including 10 out of the 14 km of the main western graben fault and 3 km of the less-continuous eastern graben fault system. We acquired $\sim$2000 images flying at an altitude of 90 m from the ground. For georeferencing the images, ground control points were systematically measured with differential GPS. By means of structure from motion technique, we obtained DEMs and ortho-photos with a 3-4 cm ground pixel resolution.

High-resolution structural mapping reveals that the main graben faults are formed by smaller segments consisting of several normal faults, extension fractures and secondary narrow grabens, tens to hundreds of meters long. The segments are parallel (N330° $\pm$ 10°) or oblique (N300° $\pm$ 10°) to the estimated dike strike (N343°). Some oblique segments show a left stepping en-echelon fracture pattern, possibly indicating a minor lateral component of the strain or suggesting that they may represent linking structures between dike parallel segments. From the high resolution DEM we measured vertical throws of normal faults at 98 sites along the western graben border. The throws are highly variable (from a few centimetres up to three meters) and related to topographic and lithological variations. They are in agreement with the few available field observations and their overall mean ($\sim$0.60 m) is comparable with that obtained by InSAR after the 2009 intrusion. However, when directly comparing our measured fault throws with those obtained by InSAR at each site, only 11% of the comparisons exhibit <10 cm difference. This mismatch may be due to the fact that while InSAR observations are limited to the intrusion event and show a regularly distributed vertical displacement on a single fault line, our structural mapping highlights a discontinued fault pattern where the effect of pre-existing fault throws may also be included.

We suggest that UAV based volcano-tectonics structural analysis may fill the gap between InSAR displacement mapping and field surveys. InSAR is useful for revealing the overall surface displacement related to an event/episode and can provide displacement maps covering a large area with ground pixel resolutions in the range of meters. Field surveys allow detailed inspection of structure kinematics, both in recent events and long term. However, this information is usually collected at a limited number of locations. Therefore, UAV based structural analysis significantly improves the resolution compared to InSAR, allowing mapping brittle deformation at a cm-scale, and moreover, it uniformly and efficiently covers much wider areas than those investigated by classical field surveys.