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Topological fracture network characterization of damage zones in sandstone: A case study from the footwall of the regional-scale Compione extensional fault, Northern Apennines, Italy

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Understanding damage zone fracture network attribute evolution is of main importance for making reliable predictions of fluid flow and storage in aquifers and hydrocarbon reservoirs. Regional-scale fault zones represent important barrier, conduits or mixed barrier-conduit systems to fluid flow, depending on their complex structural and permeability architectures. The corresponding damage zones are constituted by intensely fractured rock volumes that developed from multiple deformation stages associated with fault propagation and linkage. We studied the Compione extensional fault zone, which accommodates about 1.5 km displacement and is the main segment of the about 30 km long Northern Lunigiana Extensional Fault System, located in the Northern Apennines of Italy. Here, up to 6 m thick sandstone strata preserve the deformation signatures of the entire evolutionary pathway, from early blind faulting and tip damage zone development, to late-stage wall damage zone fracture reworking and localization. Thick strata are commonly characterized by complex fracture networks, which can be better studied by areal methods instead of traditional linear scanline methods. Adding topological analysis to areal methods provides an effective tool for quick and unbiased fracture network characterization and connectivity assessment. Fracture network attributes were studied in cross-sectional exposures by acquiring circular scan windows moving away from the fault core, up to the host rock outside the damage zone. Thirty-five circular scan windows located on fault-perpendicular, vertical exposures of meter-thick Macigno Fm. sandstone strata, were performed at increasing distance between 80 and 1030 m from the Compione fault core, to analyze fracture apparent dip, density, intensity and connectivity of the footwall damage zone. A scan window diameter of 0.5 m was selected as the best compromise between the size of clean exposures and the need of including at least 30 nodes per window. Our preliminary results indicate that fault-related damaging evolved from initial formation of an about 900 m wide footwall tip damage zone ahead of the upward propagating blind fault tip, then overprinted later on only for 400 m away from the fault core, by fracturing produced by slip after fault breakthrough. Topological analysis shows a progressive and almost linear increase of X and Y nodes towards the fault core, which was mostly imprinted from the onset of the tip damage zone formation. Moreover, Y nodes are more abundant than X nodes because shearing conjugate pairs of shear fractures without visible displacement (X node) systematically produces a double number of Y nodes. Connectivity is above the percolation threshold value in the tip damage zone and this indicates efficient fault-controlled fluid circulation in the very early evolutionary stages of the Compione Fault. Later on, it was dramatically reduced by progressive cementation of the tip damage zone fracture network. After fault breakthrough and localization of deformation in the wall damage zone, the Compione fault zone assumed a typical conduit-barrier hydraulic behavior.