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Permeability structure of a >40 m-throw normal fault crosscutting a carbonate multilayer (SE Granada Basin, Betic Cordilleras, Spain)

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Recent road cuts expose the internal structure of normal faults crosscutting sandy/clay-rich conglomerates and thin-beddedgrainstones. The detailed documentation of the deformation mechanisms associated to the processes of normal faulting, carried out by mean of field structural analysis and laboratory investigations of representative fault rock and host rock samples, is key to evaluate, at different scales, fault-related permeability structure of a carbonate multilayer. In particular, we consider the role played by the different structural elements present within the damage zone of a normal fault characterized by minor components of lateral slip and more than 40 meters of throw.
The study area is located on the southeastern edge of the Granada Basin, named Tablate area, which consists of an intramontane basin infilled by marine and continental deposits of Mio-Plio-Quaternary age. The whole basin infilling is as thick as about 180 m and cover a Paleozoic-Triassic basement. Based upon their age, content and texture, the siliciclastic/carbonate Miocene deposits are subdivided into four different members. The studied fault is made up of an inner fault core flanked by faulted conglomerates (footwall) and thin-bedded conglomerates (hanging wall), and crosscut basinal sediments gently dipping to the SW.
This study focuses on the fault-related structural elements present within the two lowest members, here named #1 and #2, respectively. Member #1 consists of brown-gray, clast-supported conglomerates arranged into 20 cm to 1 m-thick tabular beds with cm's-sized schist and quartzite pebbles and a quite abundant sandy/clay gray-yellowish matrix. The Uniaxial Compressive Strength (UCS), computed after Schmidt hammer testing, of the sandy portion of the matrix is ∼21 N/mm2, whereas its 2D porosity ([U+F066]), calculated by image analysis of representative thin-sections, is ∼10%. Member #2 consists of cemented grainstones(UCS= ∼70 N/mm2 ; [U+F066]= ∼5%) as thick as 40 meters. In the lowermost portion of this member, the grainstones are made up of rounded bioclastic fragments and interbedded with cm-thick, greyish, clay-rich micro-conglomerates (UCS= ∼40 N/mm2 ; [U+F066]= ∼7%).
Focusing on the main failure modes present within the damage zone of a normal fault active during the Tortonian-Messinian age, which is characterized by more than 40m of throw and minor components of lateral slip, we document contrasting deformation mechanisms. In the footwall damage zone that exposes the lowest member (#1), we recognize pervasive shear banding and clay smearing along incipient and more evolved small faults with throws up to 3m. On the contrary, in the hanging wall damage zone exposing member #2, joints and sheared joints are present only in the carbonate beds, whereas stylolites and sheared stylolites localize in the clay-rich, thin micro-conglomeratic interbeds. We infer that all these different structural elements formed, at the same time, during the faulting of the carbonate multilayer. Specifically, we propose the following conceptual model for fault nucleation and development:
- (member #1) in the conglomerate unit, normal faulting initiated by mean of two conjugate sets of shear bands that formed thanks to grain rotation and translation. Ongoing deformation was accompanied by pronounced smearing of the clay-rich portion of the matrix within the proto-faults, as well as by jointing of the individual pebbles. Discontinuous slip surfaces formed at the hanging wall side of the tabular bands, which eventually linked together forming through-going faults with m's of throw and low-[U+F066] fault cores surrounded by almost intact conglomerates.
- (member #2) on the contrary, in the carbonate member incipient faulting occurred due to shearing across the pre-existing, overburden related, bed-perpendicular joint sets and formation of high-angle joints at their extensional quadrants. In the micro-conglomeratic beds, when present, fault nucleation formed low-angle to bedding stylolites at the contractional quadrants of the sheared bed-perpendicular joints. Continued slip caused the linkage among structures present in neighboring beds, forming discontinuous slip surfaces surrounded by pods of fragmented

rocks which, with further deformation, coalesced together determining through-going, segmented slip surfaces surrounded by breccias and cataclastic fault rocks.
Thanks to the aforementioned deformation mechanisms, the original fluid flow properties of the individual members have been modified by the faulting processes: joints, sheared joints and sheared stylolites enhance the fluid flow in a direction parallel to these structures; conversely, stylolites, shear bands and small faults affected by clay-smearing processes inhibit the fluid flow in a direction orthogonal to them. At a larger scale, considering that the fault core is continuous all along the investigated section and consists of comminuted cataclastic fault rocks characterized by very low-values of porosity, we assess an asymmetric permeability structure of the 40m-throw normal fault. In fact, we observe that in the fault hanging wall, small faults and fractures forms localized fluid pathways within a low-porosity carbonate matrix, whereas in the footwall small faults and bands inhibit the cross-fault fluid flow within a porous sandy matrix. The two fault damage zones, characterized respectively by predominant secondary and primary porosity, respectively, are separated by a continuous impermeable fault core. At depth, the normal fault juxtaposes the conglomerates against each other and, as a whole, it behaves as a single fluid barrier for fault-orthogonal fluid flow. On the contrary, in the eroded section above the study outcrops, the fault juxtaposed the thin-bedded grainstones against each other. In that case, the fault formed a combined barrier-conduit structure in which the small faults and fractures enhanced the fault-parallel fluid flow within the two damage zones separated by the impermeable fault core. In the lowermost portion of the two fault damage zones, the stylolites at low-angle to bedding present within the micro-conglomerates interbeds form local barriers for fluid flow.