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Failure modes and normal faulting in Miocene carbonate rocks, Granada Basin, Spain: implications for fluid flow units

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Along the southeastern termination of the Padul normal fault zone, southern Spain, a potentially active tectonic structure as long ∼15 km with throw of ∼800 m, there are several small normal faults with lengths up to ∼2km and throws up to ∼100m. These small faults are vertically segmented, and crosscut lithologically heterogeneous Miocene carbonates of the Lecrin Basin. Within the carbonate multilayer, we recognized three fundamental structural elements: joints, pressure solutions and deformation bands., Joints are present preferentially within calcarenitic beds (Uniaxial Compressive Strength, UCS= ∼70 N/mm2; 2D porosity, [U+F066]= ∼5%), whereas pressure solution seams localized in marl-rich microconglomeratic beds (UCS= ∼21 N/mm2 ; [U+F066]= ∼7%). On the contrary, in a clay-rich conglomeratic unit (UCS= ∼40 N/mm2; [U+F066]= ∼10%) underneath the carbonate multilayer, deformation banding was predominant. According to their abutting relationship, first generation structures consist of two orthogonal sets of bed-perpendicular joints and one set of bed parallel solution seams, both probably formed in response to overburden loading. One additional generation of high-angle to bedding joints developed thanks to shearing across the pre-existing bed-perpendicular joints sets. Similarly, low-angle to bedding pressure solution seams formed at the extensional quadrants of normally sheared, pre-existing bed parallel pressure solution seams due bed tilting and contemporaneous uplift an exhumation.

Within the individual carbonate beds, normal faulting initiated by shearing across all the aforementioned generations of joints and pressure solution seams, with formation of new sets of high-angle joints and low-angle pressure solution seams along the sheared parental discontinuities. Continued slip caused the linkage among structures present in neighboring beds, forming and discontinuous slip surfaces surrounded by pods of fragmented rocks. With further deformation, the isolated slip surfaces coalesced together forming through-going, segmented slip surfaces along which brecciation and cataclasis took place.

In the conglomerate unit, normal faulting initiated by mean of two conjugate sets of compressive shear bands, which formed due to clast rotation and translation within the clay-rich matrix. Ongoing deformation was accompanied by smearing of the clay-rich matrix within the proto-faults (offsets up to several cm), jointing and dilational of the pre-existing discontinuities present within the individual clasts. Discontinuous slip surfaces formed along the sheared fractures and, often, on the hanging wall side of the deformation bands. Further deformation was solved by linkage of adjacent slips surfaces, diffuse jointing, and cataclastic deformation which localized along the evolving slips surfaces.

The original fluid flow properties of the individual carbonate beds were alterated by the different structural elements: joints, sheared joints and sheared pressure solution seams enhanced the fluid flow in a direction parallel to these structures, whereas pressure solution seams and deformation bands inhibited the fluid flow in a direction orthogonal to them. Within the fault-bounded blocks, the fluid flow properties varied according to the structural elements they contained. Along the major faults, the fluid flow was compartimentalized along the through-going slip surfaces and fault breccia of the core, and in the fault damage zones. Conversely, the matrix-supported cataclasites formed seals for cross-fault fluid flow. The results of this work point out to the importance of a detailed structural analysis in the assessment of underground fluid pathways within carbonate rocks.