The Zuccale Low-Angle Normal Fault: A Case Study of Post-Collisional Extension in the Northern Apennines of Italy

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In the northern Apennines of Italy, an early pulse of Cretaceous-Pliocene collision was closely followed by a later phase of Miocene to recent post-collisional extension. Extension has largely been accommodated along a series of shallowly east-dipping Low-Angle Normal Faults (LANF) which are thought to have developed during eastward-migrating of extension associated with slab roll-back of the underlying Tyrrhenian subduction zone. Active LANF are present beneath the central belt of the northern Apennines, whilst older exhumed examples are found in western Tuscany and on the Tyrrhenian islands. LANF have been investigated over the past 10 years in this area using seismic reflection profiles, high-resolution microseismic surveys, borehole analysis, and detailed field investigations. Integration of these multi-scale datasets has resulted in the northern Apennines becoming a world-class area to study the initiation and evolution of these enigmatic structures.

The present contribution focuses on detailed field-based reconstructions of the evolution of the Zuccale LANF, a crustal-scale structure active between ~13 and 4Ma which is spectacularly exposed on the Island of Elba. The Zuccale LANF has a top-to-the-east displacement of 6-9km and is responsible for exhuming Palaeozoic crystalline schists in its footwall. Deformation within the footwall and hangingwall is entirely brittle, and the fault zone itself is dominated by a striking sequence of phyllonites, foliated cataclasites and fault gouges which can be used to reconstruct the geometric and kinematic history.

Deformation along the Zuccale Fault initially occurred through the development of brittle cataclasites. The formation of these cataclasites increased fault zone permeability and allowed the influx of chemically active fluids, triggering reaction softening and the development of a weak ($\mu < 0.2$) and pervasively foliated fault core. The sequence of fault rocks preserved within the fault core is highly heterogeneous, but the distribution of fault rocks is strongly controlled by the interaction between the Zuccale Fault and a suite of higher-angle faults in its footwall. We have used detailed structural analysis to show that the present-day geometry of the footwall structures can be used to place constraints on the evolution, and in particular the dip history, of the main detachment. Our results indicate that the Zuccale Fault could not originally have dipped at angles >20°E, and that it therefore represents a primary LANF.

Subsequent to the development of a foliated fault core, the Zuccale Fault behaved as an efficient structural seal to fluids migrating from depth within the footwall. Build-ups of fluid overpressure at the base of the fault zone resulted in widespread fluidization of pre-existing brittle cataclasites, a newly recognized phenomenon which has important implications for evaluating fault-valve behaviour along LANF. We use a diverse array of outcrop- and grain-scale observations to show that fluid flow leading to fluidization was strongly focussed along high-angle fault and fracture networks in the footwall of the Zuccale Fault. As fluid overpressure increased and reached a critical value, hydrofracturing of the overlying fault core increased permeability and allowed fluids to drain from the footwall to the hangingwall. We relate the fluidized cataclasites to the interseismic period along the Zuccale LANF, whereas the discrete hydrofractures represent co-seismic events and may partially explain the abundant microseismicity observed along active LANF in central Italy.