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Fluid- and thermally-enhanced weakening mechanisms associated with the development of low angle normal faults

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Anderson-Byerlee frictional fault models ($0.6< \mu s<0.85$) predict that normal faults should initiate at dips of ~60° and then rotate down to frictional lockup angles of 30° - 40°. However, natural examples of low-angle normal faults (LANF; dips <30°) are widely recognised in both ancient and modern settings. Some of the best documented examples occur at depth in the Northern Apennines of Italy, where recent exhumation has exposed ancient examples at the surface, notably the Zuccale LANF on Elba. The Zuccale Fault has a displacement of 6-8km and was active between *c*.13-4Ma, dipping 15-20° east on a regional scale. At *c*.5.9Ma, the Porto Azzurro monzogranite pluton was intruded into the shallow footwall of the Zuccale Fault. We present field and microstructural data to show that: 1) fluid flow and 2) thermal weakening are central to the initiation and enhancement of low-angle slip over long- and short-timescales.

1) The Zuccale LANF comprises a foliated, phyllosilicate-rich fault core composed of a sequence of fault rocks which have been exhumed from 3-6km depth. Initial cataclasis along the fault zone promoted the influx of chemically active fluids, ultimately leading to the development of a weak, phyllosilicate-rich fault core. Comparison with laboratory experiments suggests that the phyllosilicate-rich fault rocks may have deformed by frictional-viscous creep at sub-Byerlee friction values ($\mu <0.3$). Subsequent to the development of the strong foliation, migrating crustal fluids were trapped beneath the sealing fault core. In the immediate footwall of the Zuccale LANF,

we have identified a hitherto unrecognized suite of cataclasites which were fluidized over large areas (10^{-2}-10^{-3} km^2) during the interseismic period, most likely due to short-timescale, periodic build-ups in fluid overpressure. Once a critical fluid overpressure was reached in the footwall, hydrofracturing and the formation of low-angle extensional detachments were promoted within the foliated core, leading to transient increases in permeability and draining of fluids from the footwall into the hangingwall.

2) Basement schists in the footwall of the Zuccale LANF are cross-cut by a dense, linked array of subsidiary extensional faults, which formed contemporaneously with slip along the overlying Zuccale LANF. These footwall faults can be divided into 2 sets: early low-angle normal faults which formed sub-parallel to the Zuccale LANF; and later high-angle (40˚-60˚) normal faults. The former are the only extension-related structures that cause high-temperature deformation within granitic sheets belonging to the Porto Azzurro pluton. Later, high angle footwall faults deform entirely by brittle mechanisms. We propose that the formation of the early low-angle footwall faults was driven by a thermal weakening pulse associated with intrusion of the Porto Azzurro pluton. It is conceivable that the overlying Zuccale LANF acted as a structural seal to the ascent of granitic melts, in a manner analogous to the processes observed with the fluidized cataclasites.