Dynamic weakening along incipient low-angle normal faults in pelagic limestones (Southern Apennines, Italy)

Rocco Novellino1, Giacomo Prosser2, Richard Spiess3, Cecilia Viti1, Fabrizio Agosta2, Enrico Tavarnelli1 & Francesco Bucci4

1 Dipartimento di Scienze fisiche, della Terra e Ambientali, Università degli Studi di Siena, Via Laterina 8, 53100 Siena, Italy
2 Dipartimento di Scienze, Università della Basilicata, Via dell’Ateneo Lucano 10, 85100 Potenza, Italy
3 Dipartimento di Geoscienze, Università degli Studi di Padova, Via G. Gradenigo 6, 35131 Padova, Italy
4 CNR-IRPI, Via della Madonna Alta 126, 06128, Perugia, Italy
*Correspondence: roconovellinogeo@yahoo.it

Slip along low-angle normal faults is a mechanical paradox requiring activation of strain weakening mechanisms. Microstructures present in the slip zones of incipient low-angle normal faults cutting carbonates in the Southern Apennines of Italy show that slip was promoted by two weakening mechanisms producing a reduction of the friction coefficient: (1) high pore fluid pressures; (2) dynamic weakening related to thermal decomposition indicated by decarbonation microstructures and concomitant localized dynamic calcite recrystallization. Furthermore, as a consequence of thermal decomposition, nanoparticles occur as infilling of injection veins, suggesting that powder lubrication processes are active along the slip surface during seismic slip.

Supplementary materials: A geological sketch of the study area, detailed field photographs of the studied faults and detailed micrographs are available at http://www.geolsoc.org.uk/SUP18806.

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Low-angle normal faults are shallowly dipping (<30°) extensional structures whose origin remains an intensely debated mechanical paradox (Collettini 2011). Slip along these unfavourably oriented structures requires fault weakening mechanisms, which may occur during fault nucleation and growth: (1) presence of weak minerals with a low friction coefficient (<0.6) allowing slip along planes at high angles to the maximum principal stress (Smith & Faulkner 2010); (2) high pore fluid pressures, reducing the effective normal stress (Faulkner & Rutter 2001); (3) dynamic fault weakening during co-seismic rupture.

In case (3) above, at seismic slip rates, much of the mechanical work (i.e. the force required to overcome friction) during slip is converted into frictional heat within a narrow zone (less than a few millimetres thick) adjacent to the slip surface (Rice 2006). Heating triggers several phenomena, including thermal expansion of pore fluids in undrained slip zones with consequent increase of the pore fluid pressure (Pp) and reduction of both the effective normal stress (σn) and shear strength (τ) (Rice 2006). Other processes potentially leading to dynamic fault weakening include decarbonation reactions (Han et al. 2007), powder lubrication owing to ultrafine decomposition products (nanoparticles) in carbonate-bearing faults (Han et al. 2010; De Paola et al. 2011) and frictional melting in silicate rocks (Di Toro et al. 2006).

This dynamic fault weakening process, mainly inferred from high-slip-rate experiments, is thought to be responsible for a dramatic reduction of fault strength during seismic slip (Di Toro et al. 2011). Despite recent experimental advances, knowledge of the physico-chemical processes active along natural faults and their implications for dynamic fault weakening is still limited; therefore, careful examination of well-exposed low-angle faults is critical for enhanced understanding of fault zone weakening mechanisms.

We studied natural incipient (small-displacement) low-angle normal faults hosted within the Lagonegro basinal succession (Southern Apennines, Italy). Previous mapping and structural analysis of the low-angle normal faults (Bucci et al. 2014) provide sound constraints on their geometry, kinematics and role in the tectonic evolution of this area.

Unlike larger-displacement faults, which typically contain complex fault rock sequences and overprinting relationships (e.g. Zuccale low-angle normal fault; Collettini & Holdsworth 2004), incipient low-angle normal faults preserve evidence of the primary physico-chemical processes controlling fault initiation and the earliest stages of slip. In this sense, incipient low-angle normal faults are more easily compared with the results from high-velocity friction experiments, and our investigation provides original background information from natural, well-exposed examples. The microstructures preserved along the incipient low-angle normal faults suggest slow aseismic creep overprinted by short-lived seismic events, the latter controlled by two distinct weakening mechanisms.

Mesosstructural analysis. The study area is located about 20 km south of Potenza, in the axial sector of the Southern Apennine fold-and-thrust belt.

In a well-exposed section (Fig. 1a), folded limestones of the Upper Triassic Calcarei con Selce Formation belonging to the Lagonegro succession are cross-cut by a series of small-displacement NE-dipping low-angle normal faults (F1, F2, F3 and F4 in Fig. 1a), which in turn are truncated by younger southward dipping (55–70°) high-angle normal faults (HANF in Fig. 1a). In some cases, it is documented that a set of high-angle normal faults with throws of a few tens of centimetres branch off the main slip surfaces of the outcropping low-angle normal faults (hanging-wall normal faults in Fig. 1a), indicating a broadly synchronous slip along these structures.

Overall, these structural relationships suggest that the studied low-angle normal faults did not experience substantial tilting, proving that they are not rotated high-angle structures. Based on geological constraints, mainly inferred from the thickness of the Siclide Unit, which tectonically covers the Lagonegro succession, and on clay mineralogy data derived from the Calcarei con Selce Formation (Schiatterella et al. 2003), we suggest that these Pliocene faults (Bucci et al. 2014) were exhumed from about 2–3 km depth and <100°C.

Although determination of displacement across the low-angle normal faults is generally difficult to assess owing to fault-related damage, locally, correlation of bedding surfaces allowed us to estimate throws ranging from tens of centimetres (<30 cm along F4) to
Microstructural analysis. Oriented specimens were collected along the incipient low-angle normal faults from areas that included the slip zone and discrete slip surfaces (Fig. 1b). Polished thin sections were prepared perpendicular to the slip surface and parallel to the slickenlines. Following Smith et al. (2011) we use ‘slip surface’ to refer to the fault surface itself, and ‘slip zone’ to refer to the adjacent fault rock volume where shearing was localized.

Microstructural analysis was performed by scanning electron microscopy (SEM) and transmission electron microscopy (TEM) at the University of Siena. The crystallographic preferred orientation (CPO) of selected slip zone samples was measured at the University of Padova, using electron backscatter diffraction (EBSD).

Petrographic thin section analysis shows that limestone within the slip zones of the incipient low-angle normal faults mainly consists of a fine-grained calcite matrix (<2 µm) in which are embedded lens-shaped fossil fragments (up to hundreds of microns) consisting of relatively coarse and twinned calcite crystals (Fig. 1c). Ultra-thin sections (<10 µm thin) reveal that the fine-grained matrix consists of intensely twinned, elongated calcite crystals with no interposed residual material (i.e. phyllosilicates) along grain boundaries. Elongate crystals are preferentially oriented at a low angle with respect to the slip surface, defining a finely spaced foliation within a layer (layer A in Fig. 1d) whose thickness can vary between 1 and 10 cm.

In backscattered electron (BSE) SEM images, the foliated fault rock appears as a massive, extremely fine-grained, undeformed limestone containing euhedral quartz crystals varying in size from 10 to 50 µm (Fig. 1e). Within the slip zone the foliated limestone is affected by brittle fracturing that locally evolves from crush-microbreccia to protocataclasite as the slip surface is approached. Cataclasism causes formation of millimetre to sub-millimetre angular clasts that may contain intra-granular extensional fractures. The matrix of these breccias typically consists of fine-grained (<1 µm), dark brown calcite clasts.

Locally, a layer of newly formed calcite crystals, a few microns to millimetres in size, is present along the slip surface (layer B in Fig. 1d).

At least two generations of calcite veins oriented at high angles to the slip surface occur within the slip zone. The older vein generation (‘vein generation 1’, VG1 in Fig. 1c), folded and disrupted, was involved in ductile and brittle deformation processes. In contrast, the
younger vein generation (‘vein generation 2’, VG2 in Fig. 1c) is characterized by sharp and straight boundaries crossing the whole slip zone. The younger veins are filled with blocky calcite crystals. Other vein generations show features intermediate between these two end-members, suggesting continuous vein formation during slip.

Several black to dark grey ultra-cataclastic veins depart from the slip surface and transect the slip zones (Fig. 2a and b). These veins, aphanitic and resembling pseudotachylites, generally occur as single veins, from which minor single ultra-cataclastic veins emanate (Fig. 2a). They are generally funnel shaped, tens to hundreds of microns wide, with sharp and planar boundaries. The thickness of the ultra-cataclastic veins decreases progressively with increasing distance from the slip surfaces. Ultra-cataclastic veins are filled by at least two generations of fine to ultrafine calcite grains. The oldest, dark and ultrafine-grained infill is frequently disrupted and dispersed within the younger and coarser material (Fig. 2c). Host rock fragments may also be included. Locally, the grain size of the calcite fill varies gradually: close to the slip surface, where the ultra-cataclastic veins are wider, lighter coarse to fine material passes to ultrafine darker aphanitic materials farther from the slip surface, where the ultra-cataclastic vein decreases in thickness toward its termination (Fig. 2a).

TEM investigations in the slip zone, between the ultra-cataclastic vein boundaries and the wall-rock, outline contrasting microstructural features. The wall-rock calcite is dominated by polycrystalline twins characterized by lamellae of constant width between 100 and 200 nm, and regular and planar twin planes. Twinning relationships between nearby lamellae (Fig. 2d) are confirmed by selected area electron diffraction (SAED) patterns, which always show reflection splitting (Fig. 2d, inset). Locally, the lamellar twinned nanostructure becomes irregular (Fig. 2e) and progressively evolves to angular to sub-rounded calcite nanoparticles typically 100 nm in size (Fig. 2f and g), randomly oriented as suggested by ring-like SAED patterns (Fig. 2f, inset).

SEM investigation of the slip zone revealed the occurrence of a very thin area (<0.5 mm) close to the slip surface (Fig. 3a) where calcite grains show irregular boundaries, voids and vesicles (Fig. 3b and c). In this area, calcite grains are lenticular to elongate and vary in size from a few microns to about 40 µm. Their long axes are slightly oblique to the slip surface, resulting in a well-defined shape preferred orientation (SPO, Fig. 3d) consistent with the top-to-the-NE sense of shear. Two hundred calcite grains (one point per grain) from the zone with SPO were manually indexed using EBSD. The pole figures (Fig. 3e) show a CPO, primarily defined by the distribution of c-axes in a broad maximum about the foliation normal, showing a c-axis splitting into two sub-maxima, separated from each other by about 45°.

Discussion and conclusions

Microstructures preserved within the slip zones of the incipient low-angle normal faults are consistent with a switch from ductile to brittle deformation during slip. Most of the fault rocks consist of pure calcite without any clay material along grain boundaries, and show a well-defined foliation formed by the alignment of polycrystically twinned calcite grains. This fabric, distributed within thick portions of the slip zones (up to 10 cm; layer A, Fig. 1d), is associated with ductile deformation that took place at sub-seismic strain rates (Power & Tullis 1989; Smith et al. 2011; Verberne et al. 2013). Relatively low-temperature ductile deformation is suggested by the twin morphology (Ferrill et al. 2004). TEM images show that twin lamellae are extremely thin (100-200 nm). We assume that the foliation formed during aseismic creep at T <100°C, where twinning is the dominant deformation mechanism (De Bresser & Spiers 1997).

We were unable to collect EBSD data from the twinned matrix calcite, because twin lamellae are narrower than the spatial resolution of our EBSD system. The CPO we obtained from tightly folded VG1 veins shows a weak c-axis alignment subparallel to the foliation trace (Fig. 3f).

Subsequent cataclasis partially erased the foliated microstructure and records the onset of brittle deformation and stick-slip instabilities. The initial formation of ductile structures owing to aseismic creep was overprinted by brittle structures partly formed during short-lived seismic events.

Two main mechanisms are supported by the observed microstructures, as follows.

1. High pore fluid pressure. The fault rocks pertaining to the studied low-angle normal faults are cross-cut by several vein generations and show occasional evidence for hydrofracturing. These features together with newly formed calcite layers (i.e. Layer[æq uc] A, Fig. 1d) are consistent with a (semi)-continuous fluid circulation within the slip zones during deformation and the potential for periodic build-ups of fluid overpressure along the fault surface (Collettini & Holdsworth 2004). In addition, fault-parallel pervasive foliation within the high-strain domain might have further facilitated fluid entrainment within the fault zone (Rossetti et al. 2007).

2. Dynamic weakening related to thermal decomposition. Temperature rise owing to frictional heating during seismic slip triggered local calcite decarbonation, indicated by the voids and vesicles observed in an area close to the slip surface (Fig. 3). These microstructures, together with the SPO and CPO of the calcite aggregates, are strikingly similar to those reported in high-velocity calcite gouge experiments by Smith et al. (2013) during which dynamic weakening occurred. The CPO we measured (Fig. 3e) is
more complex than that measured by Smith et al. (2013). The position of the c-axis maxima has striking similarities to the CPO measured and simulated by Barber et al. (2007) for calcite deformed during high-temperature torsion experiments, when dominant c slip is assumed. The switch from low-temperature deformation, with dominant c-twinning plus r-gliding (Verberne et al. 2013), to high-temperature deformation with slip along r ≈ 2c−1, and c occurs at about 400°C, whereas c−a slip dominates above 600°C (De Bresser & Spiers 1997). The temperature threshold for the onset of thermal decomposition in calcite-bearing rock is c = 700–900°C (Rodriguez-Navarro et al. 2009), suggesting that a thin layer next to the slip surface, with a maximum thickness of 300 µm, experienced a temperature increase of up to 700°C, triggering thermal processes such as decarbonation, dynamic recrystallization and grain growth of the host calcite. On the basis of these microstructures compared with those observed by Smith et al. (2013), we suggest that the low-angle normal faults have developed a low dynamic friction coefficient (µ ≤ 0.3) during seismic slip.

Moreover, TEM investigation reveals the presence of nanoparticles within ultra-cataclastic veins. In carbonate-bearing rocks, nanoparticles (<1 µm) form primarily by calcite decomposition during shear heating (Han et al. 2010; De Paola et al. 2011). It is thought that ultrafine decarbonation products such as lime (CaO) and portlandite (Ca(OH)2), together with CO2 pressurization of the contact aureole of the late Miocene Monte Capanne pluton (Elba Island, Italy). This research was supported by the RIL Funds of the Basilicata University and the CPDA 122324/12 grant ‘Progetto di Ateneo’ of the Padova University.

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