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A geological explanation for intraplate earthquake clustering complexity: The zeolite-bearing fault/fracture networks in the Adamello Massif (Southern Italian Alps)

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Interconnected networks of faults and veins filled with hydrothermal minerals such as zeolite are widespread in many orogenic terrains. These fractures commonly form at relatively low temperatures (e.g. <200 °C) late in the tectonic history and represent significant phases of fluid flow and mineralisation during exhumation. Zeolite-bearing fractures spatially associated with the Gole Larghe Fault Zone in the Southern Italian Alps are preserved along an interconnected network of variably orientated pre-existing structures. They show evidence of repeated episodes of hydraulic tensile fracturing and small magnitude (total offsets <5 m) shear displacements. We use geological observations and Coulomb stress modelling to propose that repeated seismogenic rupturing of larger offset faults led to local stress transfer and reactivation of widely distributed smaller pre-existing structures in the wall rocks. The differing orientations of the pre-existing features within what is assumed to have been a single regional stress field led to the simultaneous development of reverse, strike-slip and extensional faults. The kinematic diversity and cyclic nature of the hydraulically-assisted deformation suggest that the mineralised fracture systems represent a geological manifestation of intraplate micro-earthquake clusters associated with fluid migration episodes in the upper crust. Our observations highlight the role of crustal fluids and structural reactivation during earthquakes.

1. Introduction

It is well-known that some lower magnitude earthquake clusters are spatially and temporally associated with larger mainshock events along faults: these are referred to as *fore-* and *after-shock sequences* (e.g. Scholz, 2002 and references therein). In other instances multiple lower magnitude seismic events may be closely spaced in time and space, but no main shock is observed: these are known as *swarms* (Sykes, 1978; Mogi, 1963). The latter are often – but by no means always – associated with volcanic or geothermal activity, whilst some may be artificially induced by fluid injection (e.g. see Fischer et al., 2013 and references therein).

The origins of the frequently observed kinematic and spatial complexity associated with low magnitude earthquakes – as illustrated, respectively, by their complex focal mechanism solutions and diffuse, cloud-like distributions (e.g. Shearer et al., 2003; Godano et al., 2013, Kassaras et al., 2014) – are matters of speculation and debate. In general, clustering activity seems to be strongly associated with fluid ingression: the stress perturbation induced by each event results in stress and fluid redistribution and, as a consequence, in the complex spatial evolution of the sequence (Kisslinger, 1975; Main, 1996). A number of authors have already tried use geological observations to make inferences about past seismogenic clustering behaviour along fault and fracture systems exposed at the surface (e.g. Sibson, 1985a; Micklethwaite and Cox, 2004, 2006; Kirkpatrick et al., 2008). Others have used theoretical approaches such as the use of slip tendency analyses to address this issue (e.g. Collettini and Trippetta, 2007). Key questions for structural geologists studying ancient brittle structures are: what might such foreshock-aftershock/earthquake sequences or swarms look

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like in rocks, why are they diffuse in their distribution and why might they sometimes be kinematically complex?

In this paper, we discuss this problem from a geological perspective, documenting well-exposed examples of zeolite-mineralised factures associated with a linked, distributed system of reverse, strike-slip and extensional faults developed close to the well-known Gole Larghe Fault Zone cutting the Adamello Massif in the Italian Alps. The spatial and geometric diversity of these fractures is shown to result from the hydraulically-assisted reactivation of pre-existing structures occupying at least 0.5 cubic kilometres of the granitic host rocks. We investigate whether, on the reasonable assumption that the fracture sets formed seismogenically, the observed geometric and kinematic relationships represent the geological manifestation of foreshock-aftershock sequences and/or earthquake swarms in an intraplate setting.

2. Regional setting

The Adamello Massif lies in the South Alpine Domain of the Italian Alps and is a tonalitic batholith located near to the intersection of the Giudicarie and Tonale segments of the Periadriatic fault system (Fig. 1a; Bianchi and Dal Piaz, 1937; Bianchi et al., 1970). According to Callegari (1985) and Callegari and Brack (2002), there are four distinct tonalitic–granodioritic intrusions: 1) Re di Castello–Corno Alto; 2) Adamello; 3) Val d'Avio-Val di Genova; 4) Presanella. Geochronological data (Del Moro et al., 1983; Hansmann and Oberli, 1991; Viola et al., 2001; Mayer et al., 2003; Stipp et al., 2004) indicate a progressive decrease in the age of these intrusive units from S to N (Re di Castello: 42–38 Ma; Presanella: 32–30 Ma; Pennacchioni et al., 2006). Mineral assemblages preserved in the aureole of the batholith suggest syn-emplacement pressures in the region of 0.25–0.35 GPa, which corresponds to depths in the region of 9–11 km assuming typical rock densities (Stipp et al., 2004).

The country rocks along the northern border of the Adamello massif were sheared during dextral strike-slip movement of the Tonale Fault (30–32 Ma; Stipp et al. 2004; Pennacchioni et al. 2006). Post-magmatic, solid-state deformation structures are widely documented in the Val d'Avio-Val di Genova and Presanella plutons and record a progressive down-temperature history of deformation during exhumation of the pluton (Di Toro and Pennacchioni, 2004; Pennacchioni et al., 2006; Mittempergher et al., 2009). These structures include: cooling joints and aplite dykes formed at elevated temperatures (>600 °C); conjugate dextral and sinistral ductile shear zones (550-450 °C); mainly dextral epidote-chlorite-bearing cataclasites and pseudotachylytes (300-250 °C); and late stage zeolite-bearing faults and veins (<200 °C) (Pennacchioni et al., 2006). Larger-scale dextral faults and shear zones associated with the development of the main brittle deformation stage (epidote-chlorite-bearing cataclasites and pseudotachylytes) include the NW–SE Passo Cercen Fault Zone in the north together with the E–W to ESE–WNW-trending Gole Larghe Fault Zone (GLFZ) and Lares Fault Zone in the south (Fig 1a). On a regional scale, these structures are viewed as offshoots of the Tonale Fault. The Tonale Fault is also thought by some authors to be cross cut and offset by up to 20 km in a sinistral sense by the younger (<17Ma) Giudicarie Line, the southern part of which forms the eastern boundary of the Adamello plutons (Fig. 1; see Viola et al., 2001).

The rocks of the Adamello pluton arewell exposed in the scoured rock platform where the GLFZ crosses the valley at the toe of the Lobbia Glacier (Fig. 1b–c). The host rocks of the Val d'Avio-Val di Genova pluton are typically fine-to medium grained tonalites with a bulk mineralogy: 45–50% plagioclase, 25–30% quartz, 15–20% biotite and 1–5% K-feldspar (Di Toro and Pennacchioni, 2004). Many previous studies (e.g. Di Toro and Pennacchioni,

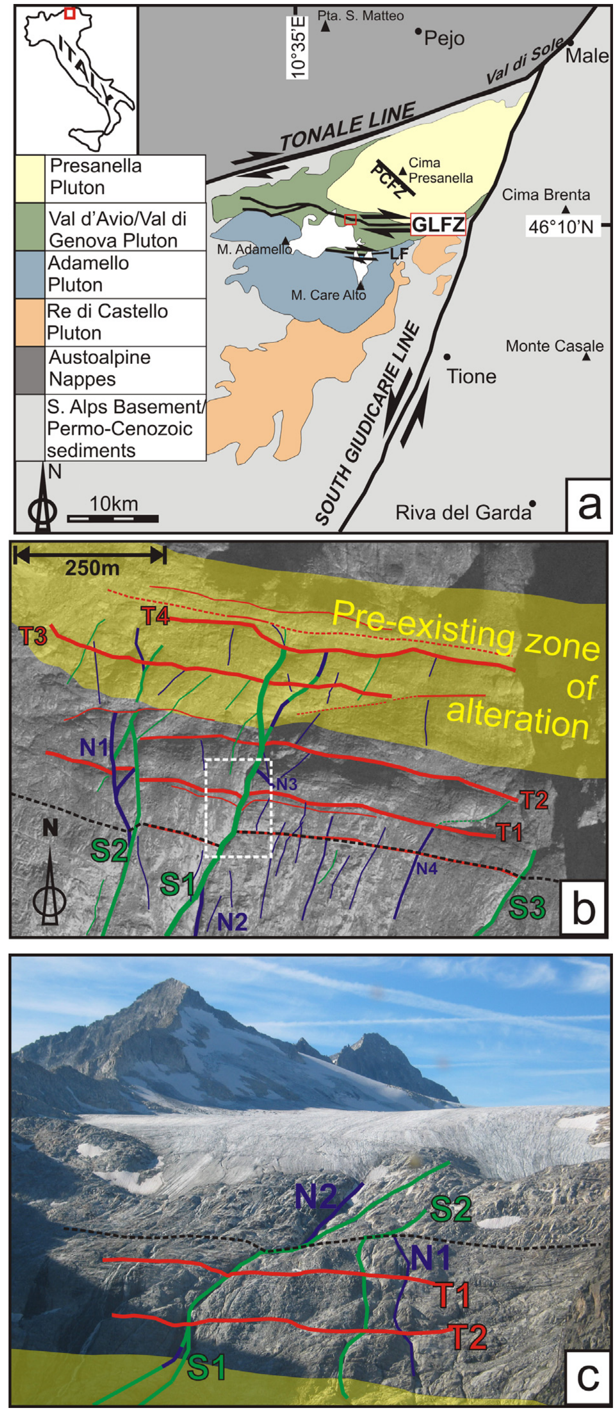

Fig. 1. (a) Schematic geological map of the Adamello region. GLFZ = Gole Larghe Fault Zone; PCFZ = Passo Cercen Fault Zone; LF = Lares Fault. Red box shows location of study area. (b) Aerial photograph of the study area with numbered faults (NNE–SSW sinistral = green (S); E–W sinistral-reverse = red (T); N–S normal = blue (N)). Black dashed contact and yellow shaded zone are, respectively, the southern margin of the GLFZ and central zone of K-feldspar-epidote-chlorite alteration according to Smith et al. (2013). Box shows location of Fig. 4. (c) An oblique aerial view looking S showing the typical appearance of the fractured tonalities in the glacier valley. The largest fault, S1, lies in the centre of the valley. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2004, 2005; Pennacchioni et al., 2006; Bestmann et al., 2012; Smith et al., 2013; Mittempergher et al., 2014) have focussed on post-magmatic deformation structures related to the development of the E–W-trending GLFZ. This structure is made up of a series of