Earth and Planetary Science Letters 450 (2016) 292–305

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Origin and role of fluids involved in the seismic cycle of extensional faults in carbonate rocks

Luca Smeraglia [a,*], Fabrizio Berra [b], Andrea Billi [c], Chiara Boschi [d], Eugenio Carminati [a,c], Carlo Doglioni [a,c]

[a] *Dipartimento di Scienze della Terra, Sapienza Università di Roma, P.le Aldo Moro 5, 00185 Roma, Italy*
[b] *Università degli Studi di Milano, Dipartimento di Scienze della Terra, Via Mangiagalli 34, 20133 Milano, Italy*
[c] *Consiglio delle Nazionale Ricerche, IGAG, c.o. Dipartimento di Scienze della Terra, Sapienza Università di Roma, P.le Aldo Moro 5, 00185 Roma, Italy*
[d] *Istituto di Geoscienze e Georisorse, Consiglio Nazionale delle Ricerche, Via Moruzzi 1, 56124 Pisa, Italy*

ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 6 May 2016
Accepted 23 June 2016
Available online 11 July 2016
Editor: A. Yin

Keywords:
fluid circulation
seismic cycle
fluid pressure
stable isotopes
fault zone evolution
central Apennines

ABSTRACT

We examine the potentially-seismic right-lateral transtensional–extensional Tre Monti Fault (central Apennines, Italy) with structural and geochemical methods and develop a conceptual evolutionary model of extensional faulting with fluid involvement in shallow ($\leq$3 km depth) faults in carbonate rocks. In the analysed fault zone, multiscale fault rock structures include injection veins, fluidized ultracataclasite layers, and crackle breccias, suggesting that the fault slipped seismically. We reconstructed the relative chronology of these structures through cross-cutting relationship and cathodoluminescence analyses. We then used C- and O-isotope data from different generations of fault-related mineralizations to show a shift from connate (marine-derived) to meteoric fluid circulation during exhumation from 3 to $\leq$1 km depths and concurrent fluid cooling from $\sim$68 to $<$30 °C. Between $\sim$3 km and $\sim$1 km depths, impermeable barriers within the sedimentary sequence created a semi-closed hydrological system, where prevalently connate fluids circulated within the fault zone at temperatures between 60° and 75 °C. During fault zone exhumation, at depths $\leq$1 km and temperatures $<$30 °C, the hydrological circulation became open and meteoric-derived fluids progressively infiltrated and circulated within the fault zone. The role of these fluids during syn-exhumation seismic cycles of the Tre Monti Fault has been substantially passive along the whole fault zone, the fluids being passively redistributed at hydrostatic pressure following co-seismic dilatancy. Only the principal fault has been characterized, locally and transiently, by fluid overpressures. The presence of low-permeability clayey layers in the sedimentary sequence contributed to control the type of fluids infiltrating into the fault zone and possibly their transient overpressures. These results can foster the comprehension of seismic faulting at shallow depths in carbonate rocks of other fold-thrust belts involved in post-collisional seismogenic extensional tectonics.

1. Introduction

Fluid flow along faults has been widely explored for implications on various topics including hydrocarbon and ore exploration, CO_2 sequestration, groundwater and contaminant transport, and faulting (e.g., Cox, 1995; Williams et al., 2015). Faults and fault zones can be preferential conduits or barriers for the passage of geofluids. Moreover, fault slip behaviors and the seismic cycle are often controlled by the geofluids themselves (e.g., Hickman et al., 1995).

Fluids have been suggested to play either passive or active roles during the seismic cycle (e.g., Sibson, 2014; Fig. 1). For instance, the "fault-valve" model (Fig. 1a) involves an active role of overpressured fluids that can trigger earthquakes (e.g., Miller et al., 2004; Haney et al., 2005). After seismic failure, fluid discharge and sealing mineralizations are favored by hydrofracturing and decompression (stress drop), respectively (e.g., Cox, 1995). Complete fracture sealing allows fluid overpressure to build again and initiate a new seismic cycle. This mechanism can commonly act within fluid-overpressured crustal blocks (e.g., Di Luccio et al., 2010), especially along subduction interfaces, where fluid overpressure is more likely to develop and be sustained (Sibson, 2014). On the other hand, different scenarios involve a passive role of fluids that

---

* Corresponding author at: Dipartimento di Scienze della Terra, Sapienza Università di Roma, Piazzale Aldo Moro 5, 00185 Roma, Italy.

E-mail addresses: luca.smeraglia@uniroma1.it (L. Smeraglia), fabrizio.berra@unimi.it (F. Berra), andrea.billi@cnr.it (A. Billi), c.boschi@igg.cnr.it (C. Boschi), eugenio.carminati@uniroma1.it (E. Carminati), carlo.doglioni@uniroma1.it (C. Doglioni).

http://dx.doi.org/10.1016/j.epsl.2016.06.042

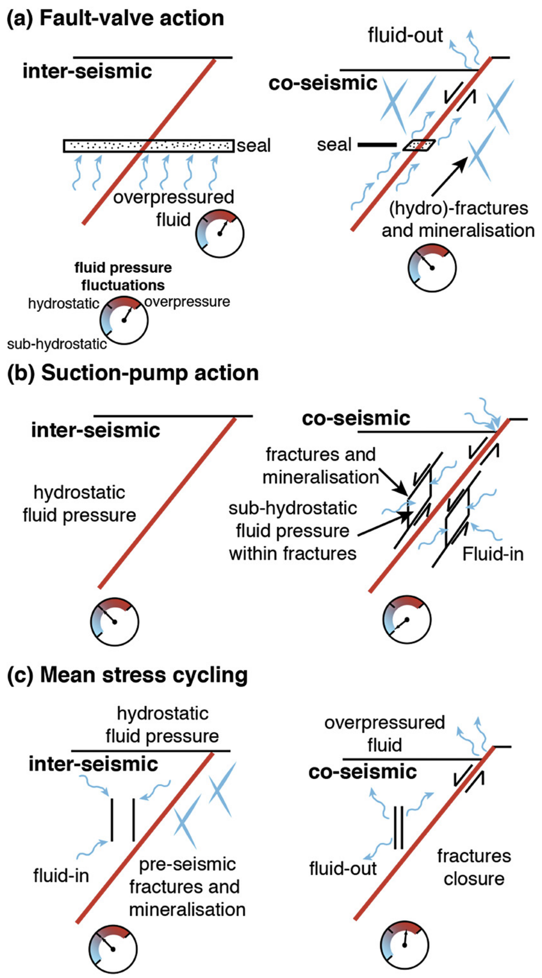

Fig. 1. Different models of interaction between fluids and seismic cycles (modified after Sibson, 2000). (a) Fault-valve action. (b) Suction-pump action. (c) Mean stress cycling.

are redistributed following an earthquake (e.g., Sibson, 2000). Fluid redistribution can be favored by rapid co-seismic dilation and creation of high-permeability fracture networks characterized by sub-hydrostatic pressure (Fig. 1b, "suction-pump" model) or by crack closure favored by post-seismic stress recovery (Fig. 1c, "mean stress cycling" model). If low-permeability barriers are not created, fluids conserve hydrostatic pressure. These mechanisms can easily act within extensional/transtensional regimes (e.g., Doglioni et al., 2014; Sibson, 2014) in the shallow crust (<5 km), where hydrostatic fluid pressure and high permeability zones have been documented (Townend and Zoback, 2000). These processes can be understood and validated by studying the evidence of seismic-related mineralization and rock-related fluid structures and textures (e.g., Uysal et al., 2009; Rowe and Griffith, 2015). Therefore, the study of the geological record of fluid–fault interactions is a fundamental pre-requisite for general models concerning the origin and role of fluids involved in the seismic cycle. Single case histories are fundamental to build comprehensive conceptual models of seismic-related fluid circulation.

We examine a case study of a major right-lateral transtensional–extensional fault (Tre Monti Fault, TMF, central Apennines, Italy) from a carbonate domain in the central Apennines, Italy (Fig. 2a). The study of this fault is relevant as, at shallow crustal levels (<10 km depth), fault zones in carbonate rocks represent favorable structures for migration and entrapment of geofluids (e.g., Ghisetti et al., 2001). Moreover, in many seismically active regions worldwide (including our study area), shallow crustal earthquakes and seismic sequences (e.g., hypocenters at <10 km depth) nucleate in and propagate upward through carbonate rocks with fluids involvement in the seismic cycle (e.g., Macedonia, Greece, 1995, M_W 6.6 earthquake, Stiros, 1995; Wenchuan, China, 2008, M_W 8.0 earthquake, Chen et al., 2013; L'Aquila, Italy, 2009, M_W 6.3 earthquake, Chiaraluce, 2012).

The TMF has been exhumed from depths ≤ 3 km since about the Pliocene (Galadini et al., 2003) and exhibits excellent exposures allowing geoscientists to study the relationships between fault zone architecture, fluid circulation, and seismic cycle within a tectonically active extensional setting (Smith et al., 2011). As many normal fault earthquakes frequently cause surface ruptures and associated damage and fatalities (Stiros, 1995; Galli et al., 2008), the study of such a shallow fault is relevant for the understanding of the fault zone architecture and fluid circulation at shallow depths (≤ 3 km).

We synthesize the spatio-temporal tectonic evolution and fluid circulation of the TMF into a conceptual model of seismic-related fluid circulation within shallow (≤ 3 km) extensional fault zones. We combine structural, microstructural, mineralogical, and geochemical (cathodoluminescence, stable isotopes, and whole rock geochemistry) methods. The main novelty of this model concerns the origin of geofluids involved in the seismic cycle of exhuming extensional fault zones and their specific role, which is substantially passive along most part of the fault zone except along the principal fault, where fluid overpressures can locally arise during co-seismic phases.

2. Geological setting

2.1. Apennines evolution and seismotectonic setting

The Central Apennines is a late Oligocene-to-Present fold-and-thrust belt related to the west directed subduction and eastward rollback of the Adriatic plate under the European plate (Doglioni, 1991). Shortening was characterized by the northeastward migration of thrust fronts in a classical forelandward piggy-back sequence of thrust sheets (Cosentino et al., 2010). These tectonic processes juxtaposed carbonates onto syn-orogenic deposits along NW-SE-oriented thrust faults (Fig. 2a; Cosentino et al., 2010). The thrust sheets consist of ∼4–5 km thick Late Triassic–Middle Miocene shallow-water carbonate rocks, whereas the syn-orogenic deposits consist of up to ∼3 km thick Late Miocene hemipelagic marls and deep-marine siliciclastic sandstones with intercalated clayey layers (Cosentino et al., 2010).

Since Late Miocene time, while the compressional deformation was still active along the eastern fronts (Adriatic domain), the Apennines belt experienced extension and exhumation in its western and axial parts. This process has been associated with exhumation at rates of ca. 0.3 mm/a in the last 3–5 Ma (e.g., Thomson et al., 2010 for the Northern Apennines). Normal faulting led to crustal thinning related to the development of the Tyrrhenian backarc basin (Doglioni, 1991). This process is still active and has generated a system of NW-SE-oriented basin-bounding active extensional faults and perpendicular strike- to oblique-slip transfer faults (Fig. 2a). Both sets of faults produced large historical and instrumental earthquakes up to M_W 7 (Fig. 2a; e.g., Avezzano, 1915, M_W 7.0 earthquake; L'Aquila, 2009, M_W 6.3 earthquake; Galli et al., 2008; Chiaraluce, 2012). The TMF represents an active or recently-active transfer fault between two NW-SE-oriented extensional faults (Morewood and Roberts, 2000; Benedetti et al., 2013).

In the Apennines, the imbricated carbonates and syn-orogenic sequences can be traced from the surface to depths of ca. 8–10 km (Patacca et al., 2008). Although some mainshocks probably nucle-