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Cyclical variations of fluid sources and stress state in a shallow megathrust-zone mélange

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Abstract: Differences in REE patterns of calcite from extensional and shear veins of the Sestola Vidiciatico Tectonic Unit in the Northern Apennines suggest variations in fluid source during the seismic cycle in an ancient analogue of a shallow megathrust (T_{max} *c.* 100–150°C). In shear veins, a positive Eu anomaly suggests an exotic fluid source, probably hotter than the fault environment. Small-scale extensional veins were derived instead from a local fluid in equilibrium with the fault rocks. Mutually crosscutting relations between two extensional vein sets, parallel and perpendicular to the megathrust, suggest repeated shifting of the σ_1 and σ_3 stresses during the seismic cycle. This is consistent with: (1) a seismic phase, with brittle failure along the thrust, crystallization of shear veins from an exotic fluid, stress drop and stress rotation; (2) a post-seismic phase, with fault-normal compaction and formation of fault-normal extensional veins fed by local fluids; (3) a reloading phase, where shear stress and pore pressure are gradually restored and fault-parallel extensional veins form, until the thrust fails again. The combination of geochemical and structural analyses in veins from exhumed megathrust analogues represents a promising tool to better understand the interplay between stress state and fluids in modern subduction zones.

Supplementary material: Cathodoluminescence microphotographs, methodological details of the microstructural analysis, microphotographs of the location of analysed spots and a geochemical data table are available at https://doi.org/10.6084/m9.figshare.c.4842165

Thematic collection: This article is part of the Polygenetic mélanges collection available at: https://www.lyellcollection.org/cc/polygenetic-melanges

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Subduction megathrusts have been recognized for a long time as weak interplate faults that localize deformation under low shear stresses (<20 MPa; Bird 1978; Lamb 2006; Wang and Hu 2006; Seno 2009; Duarte *et al.* 2015; Wang *et al.* 2019) and active circulation of fluids (for a review see Saffer and Tobin 2011). The weakness of megathrusts is ascribed to low-friction minerals and fluid overpressures (pore fluid factors $\lambda_v = P_f/\sigma_v > 0.9$, where P_f is the fluid pressure and σ_v is the vertical stress; Sibson 2013, and references therein), which significantly lower the effective friction coefficient of megathrust faults.

The widespread occurrence of fracture sets filled with mineral veins in fossil megathrust-related tectonic mélanges testifies to an active fluid circuit, cyclically subjected to pressure rises and drops and permeability changes related to fracturing and fracture healing by precipitation of hydrothermal minerals (e.g. Sibson 1992, 2013, 2017; Fagereng *et al.* 2010). Tectonic veins thus represent a valuable archive of information on both the orientations of the palaeostresses and the physicochemical characteristics of fluids circulating in the fault zone through time.

Several studies have investigated tectonic veins; for example, reconstructing stress changes and inversions during deformation history from the meso- and microstructural description of the structures (Fisher *et al.* 1995; Meneghini and Moore 2007; Fagereng *et al.* 2010; Ujiie *et al.* 2018), or inferring the characteristics of fluid source and circulation patterns from trace element abundances and isotope signatures retained in vein crystals (Yamaguchi *et al.* 2011, 2012; Lacroix *et al.* 2014; Dielforder *et al.* 2015). Structural and microstructural investigations on megathrust-related tectonic veins have led to the identification of tectonic mélanges deforming at a high angle to the maximum principal stress (e.g. Fagereng *et al.* 2010) or at a low angle to it (Meneghini and Moore 2007; Ujiie *et al.* 2018). Understanding the stress state of shallow megathrust faults is of particular interest, as it is known that large megathrust earthquakes might cause (near) complete stress drop and a switch from a compressive to a tensile stress regime in the forearc, as happened for instance after the 2011 M_w 9 Tohoku-Oki earthquake (Hasegawa *et al.* 2011, 2012; Ide *et al.* 2011; Hardebeck 2012; Lin *et al.* 2013; Brodsky *et al.* 2016, 2020).

With this work, we aim to unravel the relationships between structurally controlled fluid pathways and tectonic loading during the seismic cycle by combining petrostructural and geochemical analyses in tectonic veins sampled from an exhumed thrust surface inside the Sestola Vidiciatico Tectonic Unit in the Northern Apennines (Italy). This unit is a subduction megathrust-zone mélange representing a