GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G47625.1

Manuscript received 24 February 2020
Revised manuscript received 4 June 2020
Manuscript accepted 5 June 2020

Published online 21 July 2020

Intermittent fracturing in the middle continental crust as evidence for transient switching of principal stress axes associated with the subduction zone earthquake cycle

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ABSTRACT

In the Neves area, eastern Alps, fractures that localized shear zones in middle continental crust above the Alpine megathrust are commonly oriented at a high angle to the inferred long-term shortening direction. Fractures show a segmentation geometry and, locally, a discernible offset, indicating movement opposite to the sense of subsequent ductile shear and implying a switch of principal stress axes σ_1 and σ_3 during fracturing. We propose that this repeated switch, demonstrated by overprinting relationships and different degrees of fracture reactivation, was due to sporadic co-seismic to early post-seismic rebound in the upper plate of the Alpine continental collision system. Fracturing occurred intermittently in the weak midcrustal rocks due to seismic stress release at high transient strain rates and pore-fluid pressures. Widespread transient fracturing in the hanging wall of the Alpine megathrust regionally controls the orientation of ductile shear zones in the middle crust, as well as the emplacement of magmatic dikes.

INTRODUCTION

Fractures can provide precursors for ductile shear zones in middle to lower continental crust. This is documented in isotropic rocks such as (meta-) granitoids, but also in foliated midcrustal rocks (Fusseis and Handy, 2008; Pennacchioni and Mancktelow, 2018). Precursor fractures in magmatic rocks may be inherited cooling joints (e.g., Segall and Pollard, 1983; Segall and Simpson, 1986), but others are new fractures that were coeval with ductile shearing, reflecting cycles of brittle failure and flow (Pennacchioni and Mancktelow, 2007, 2018; Hawemann et al., 2019; Leydier et al., 2019). In some cases, precursor fractures are oriented at a high angle (>70°) to the regional long-term shortening direction (ε_1; Pennacchioni and Mancktelow, 2007; Hawemann et al., 2019), which is surprising, since extensional fractures should develop at ~90° to the axis of minimum compressive stress (σ_3; Pollard and Aydin, 1988). This contradiction suggests that during fracturing, σ_3 has switched with ε_1. Such a switch could be due to the interplay between tectonic and gravitational forces (Molnar and Lyon-Caen, 1988). However, on a shorter time scale, reversal of stress axes is typical of co- to early postseismic rebound after earthquakes (e.g., Hasegawa et al., 2012; Wang et al., 2012; Becker et al., 2018; Govers et al., 2018). In this study, field structures in the Neves area (eastern Alps, Italy) are used to assess the mechanism of transient fracturing at midcrustal levels in the hanging wall of a continental subduction megathrust. We propose that fracturing occurred intermittently during aseismic creep in weak midcrustal rocks due to rapid, transient seismic stress release under high fluid pressures.

OBSERVATIONS

The Neves area (Fig. 1) exposes pre-Alpine granitoids that preserved kilometer-scale, low-strain domains during Alpine midcrustal deformation at ca. 30 Ma (Christensen et al., 1994) under high fluid pressure and amphibolite-facies conditions (~550 °C, 0.75 GPa; Cesare et al., 2001; Leydier et al., 2019). At this time, the Neves granitoids were in the immediate hanging wall of the Alpine continental megathrust (Fig. 1; Schmid et al., 2013, their figure 6). Several studies (Pennacchioni and Mancktelow, 2018, and references therein) have shown that, within the low-strain domains, small-scale (centimeters to decimeters thick) ductile shear zones were localized on tabular rheological discontinuities provided either by dikes or by mineralized fractures. For fractures, ductile shear and foliation development is either confined to the mineral filling and/or affects the altered host rock at the fracture selvages. The orientations of sinistral and dextral shear zones, extensional veins, solid-state foliation, and intersection zones between conjugate ductile shear zones constrain the axis of maximum shortening (ε_1) as subhorizontal at 345° and the axis of maximum extension (ε_3) as subhorizontal at 075°, i.e., approximately perpendicular and parallel to the Alpine chain, respectively (Fig. 1; Figs. S1 and S2 in the Supplemental Material[1]; Pennacchioni and Mancktelow, 2007). The direction of ε_1-ε_3 was maintained, with only slight rotation, during exhumation/cooling to ~300 °C (Fig. S2; Pennacchioni and Mancktelow, 2007). A similar ε_1-ε_3 orientation is reported on a regional scale from Oligocene to present time in the eastern Alps (e.g., Ratschbacher et al., 1991; Mancktelow et al., 2001; Scharf et al., 2013).

Shear zones localized on fractures can be assigned to two groups based on their orientation and composition of the mineral filling. The north-south– to NNW-SSE–striking fractures (hereafter referred to as the N-S set) are filled with thick (up to meters wide), coarse-grained, quartz-calcite ± biotite ± plagioclase veins. The veins, oriented at a high angle to ε_3, are either hybrid or purely extensional. Segmented veins with an extensional-sinistral sense are generally left-stepping features, developing pull-apart step-overs (Fig. 2A), whereas extensional-dextral veins are right-stepping features. The overprinting ductile deformation, mostly localized within the vein, shows the same shear sense as during vein opening (Fig. S2B).

[1]Supplemental Material. Study locations, stereoplots, detailed outcrop maps, and high resolution photographs. Please visit https://doi.org/10.1130/GEOL.S.12510383 to access the supplemental material, and contact editing@geosociety.org with any questions.

CITATION: Mancktelow, N., and Pennacchioni, G., 2020, Intermittent fracturing in the middle continental crust as evidence for transient switching of principal stress axes associated with the subduction zone earthquake cycle: Geology, v. 48, p. 1072–1076, https://doi.org/10.1130/G47625.1

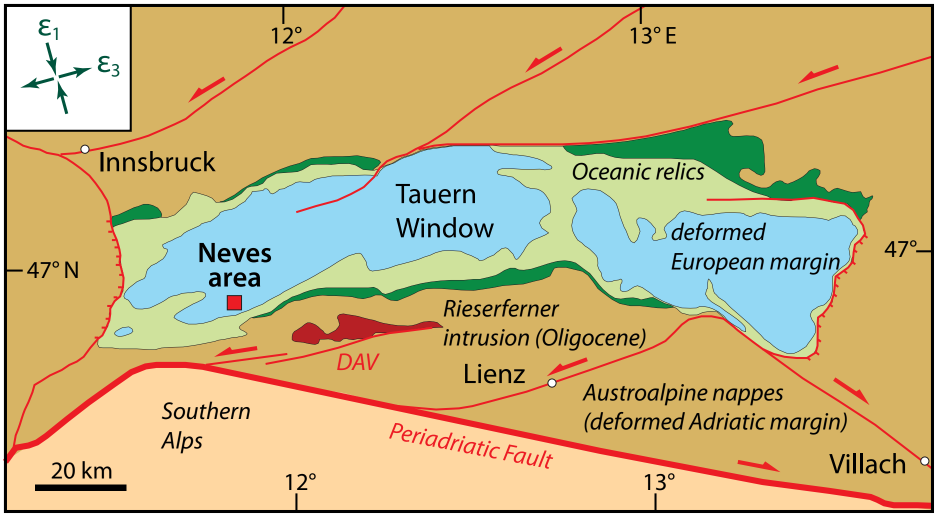

Figure 1. Simplified tectonic map of part of the eastern Alps, after Scharf et al. (2013), with the Neves area indicated. Oligocene–Miocene shortening (ε_1) and extension (ε_3) directions in the Neves area are shown (Pennacchioni and Mancktelow, 2007), which are consistent with the shear sense (red arrows) on regional strike-slip faults active at the same time. DAV—Defereggen-Antholz-Vals fault.

The shear zones exploiting fractures filled with thin mineral veins have an east-west to ESE-WNW strike (referred to as the E-W set), at a high angle to ε_1. These fractures are sealed cracks, in some cases without discernible offset (Fig. 2B). Fluid-rock interaction along fractures involved metasomatic replacement of the host-rock assemblage by biotite, garnet, epidote, and plagioclase (Leydier et al., 2019; Mancktelow and Pennacchioni, 2005). Segmented arrays of the E-W set are typically left-stepping features (Figs. 2C and 3A), with step-overs developing contractional domains during dextral ductile shear reactivation. The stepping geometry of the E-W set is therefore opposite to that of the N-S set, for the same sense of overprinting ductile shear. For the E-W set, the following features are locally observed:

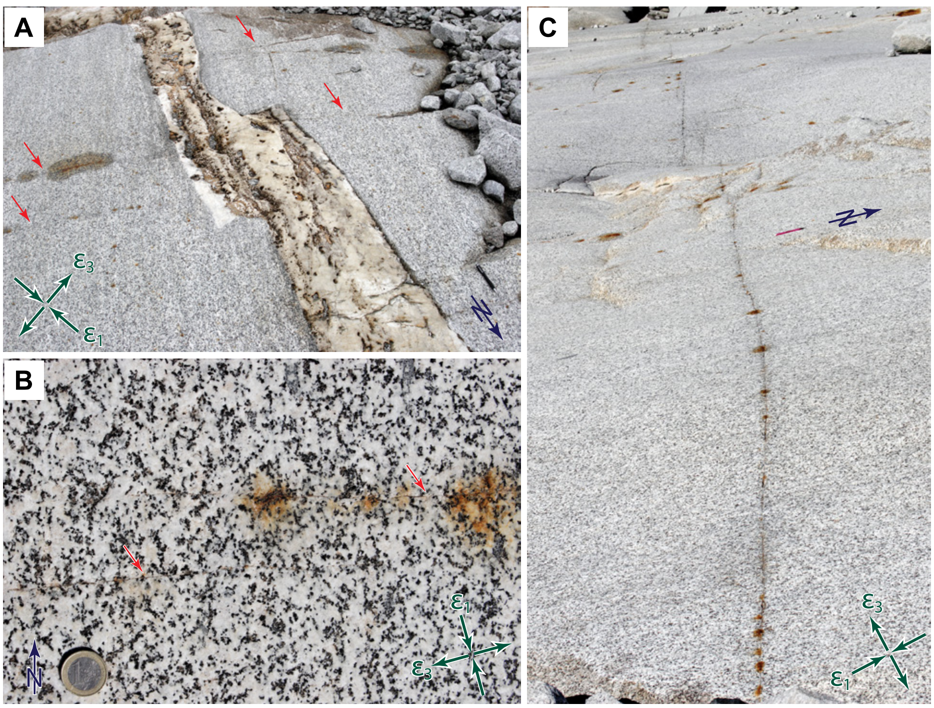

Figure 2. (A) North-south–striking, left-stepping, sinistral quartz-calcite-biotite-plagioclase vein and east-west–striking thin fractures (red arrows). Pen = 14 cm. (B) East-west–striking hairline fractures (red arrows) without discernible offset (joints), showing left-stepping segmentation. 1 Euro coin = 2.3 cm. (C) Overview of segmentation of east-west–striking thin fractures. Pen = 14 cm. Long-term shortening (ε_1) and extension (ε_3) directions are indicated.

(1) Segmented arrays, horsetail splays (Figs. 3A and 3B; Figs. S2–S6), and zones of fluid infiltration and localized fluid-rock interaction (Pennacchioni and Mancktelow, 2007, their figure 5d) suggest an extensional rather than a contractional step-over during fracturing.

(2) The initial fracture shows the opposite sense of displacement to that of the subsequent ductile shear zone (Figs. 3D and 3E).

Mutual overprinting between fractures and ductile shear zones is locally evident. Figure 3B shows a dextral shear zone exploiting a dike that is cut by discrete, segmented, parallel fractures. The fractures were the locus for fluid-rock interaction and subsequent localized ductile shear. Figure 3C shows an aplite dike that was sheared into parallelism with an east-west–striking lamprophyre dike. Discrete fractures in the axial plane of the drag fold became the loci for fluid-rock interaction and were exploited as shear zones (Figs. S7–S10).

DISCUSSION

The quartz-calcite–rich veins (Fig. 2A) and the associated ductile shearing are unequivocally of Alpine age, having developed under amphibolite-facies conditions (Cesare et al., 2001). The age of the more discrete fractures (Figs. 2B and 2C) is not self-evident. The origin of these fractures as pre-Alpine cooling joints, with associated fluid-rock interaction, would be consistent with their orientation parallel to the east-west–striking lamprophyre dikes (Fig. 3A). However, the study by Leydier et al. (2019) on garnet-enriched, east-west–striking sheared fractures concluded that fracturing and ductile shearing occurred during Alpine prograde metamorphism. Field evidence also establishes that the fractures developed intermittently during Alpine deformation (Figs. 3B and 3C), and the occurrence of subparallel fracture sets with different degrees of ductile overprinting suggests that fracturing occurred repeatedly during overall ductile deformation.

As outlined above, fractures of the N-S set, at a high angle to ε_3, and fractures of the E-W set, at a high angle to ε_1, are distinctly different. N-S set fractures were originally dilatant and continued to dilate during development, with extensional step-overs formed during interplay between fracture and ductile shear (left-stepping for sinistral and right-stepping for dextral veins). This resulted in the growth of coarse quartz, calcite, plagioclase, and biotite. In contrast, the E-W set was not markedly dilatant, and the typical dextral shearing of left-stepping sets produced contractional step-overs and replacement veining, with growth of biotite, garnet, and epidote. If the N-S set is taken as a model, the E-W set could also represent extensional to mixed-mode fractures but without the continued opening of the north-south–striking quartz-rich veins. The problem is that their

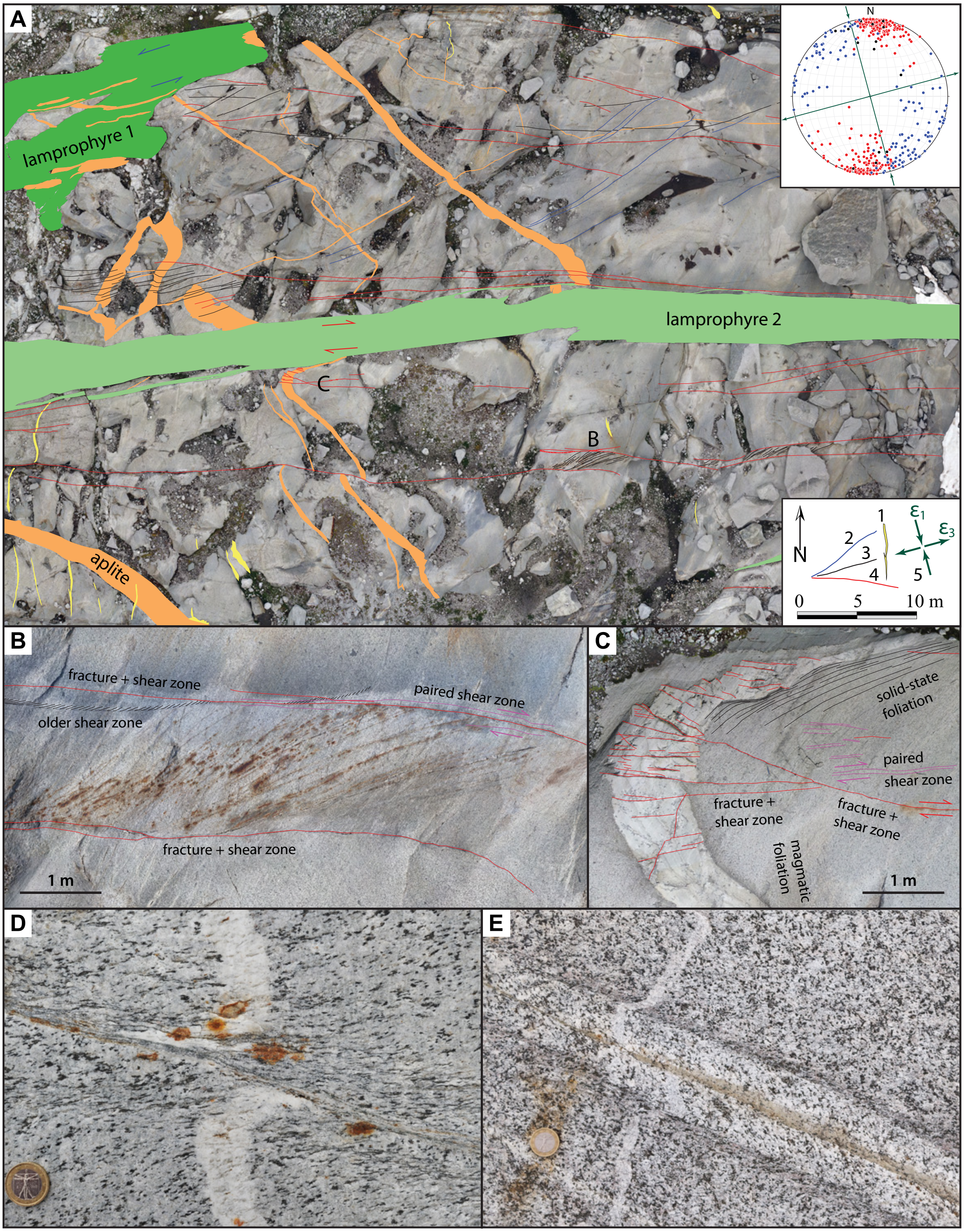

Figure 3. (A) Outcrop overview photo-mosaic. Upper-right corner: lower-hemisphere stereoplot of poles to shear zones and fractures from the Neves area; legend as in cartoon. Lower-right corner: cartoon of structures from mosaic, with same color scheme as stereoplot. 1—quartz-calcite ± biotite ± plagioclase veins; 2—sinistrally sheared fractures; 3—joints; 4—dextrally sheared fractures; 5—ε_1 and ε_3 directions, from change in shear sense of shear zones (see stereoplot and Figs. S1 and S2 [see footnote 1]). (B–C) Enlargements of areas located on the mosaic A. In B, note set of extensional wing cracks between overstepping east-west fracture segments, consistent with sinistral slip (opposite to overprinting ductile shear sense). (D–E) Dextral ESE-striking shear zones, showing discrete sinistral offset of aplite dike on central fracture, transitional from single to paired shear zone (D) and paired shear zone (E). 1 Euro coin = 2.3 cm.

orientation relative to ε_1 is not consistent with the development of extensional fractures. Observations from the E-W set are more consistent with a sporadic inversion of the stress field, with σ_3 and σ_1 interchanging with the ε_1 and ε_3 directions (Fig. 4). This could not be a durable reversal, since there is no significant dilation on the E-W fracture set. A long-term inversion would also result in reversal of the movement on the north-south quartz-rich veins, which is not observed. Figure 4 shows a summary, based on field observations, of the structure development related to fracturing during transient stress inversion and long-term viscous flow.

A longer-term, but still transient, reversal could reflect switches in stress axes due to the interplay between tectonic and gravitational forces (Molnar and Lyon-Caen, 1988). Indentation models for progressive late Oligocene–Miocene exhumation of the Tauern Window involve an interplay among NNW-directed convergence, upright folding, and normal faulting (e.g., Rosenberg et al., 2004; Scharf et al., 2013; Favaro et al., 2017). However, in these models, the potential switch is between principal stress axes that were either perpendicular to the Alpine chain (σ_1) or vertical (σ_2), but not a switch between σ_1 and σ_3 perpendicular and parallel to the chain, as documented here.

Reversal in the stress axes on a much shorter time scale is inferred in studies of elastic rebound after major earthquakes (Hyndman and Wang, 1993; Ozawa et al., 2011, 2012; Hasegawa et al., 2012; Wang et al., 2012; Avouac, 2015; Klein et al., 2016; Becker et al., 2018; Govers et al., 2018). Viscoelastic relaxation of the reversal from extension back to compression is

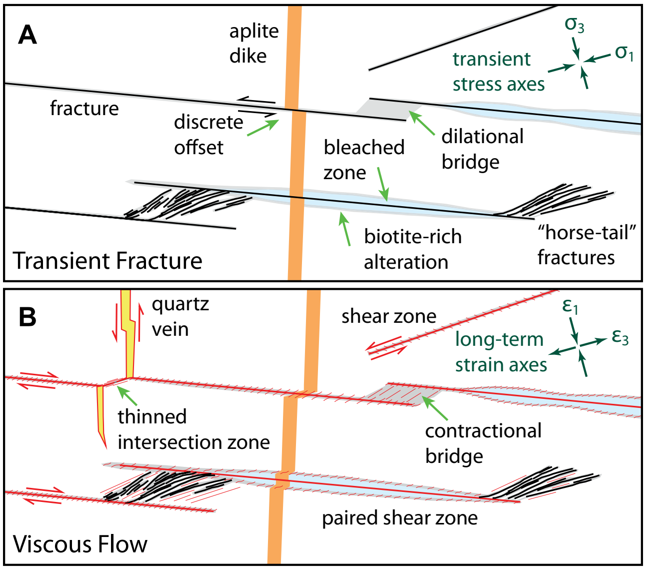

Figure 4. (A–B) Cartoons of structures developed and inferred stress and strain axes during transient fracture (A) and longer-term viscous flow (B). Line color codes: black—transient; red—longer term.

modeled to take years to decades (Klein et al., 2016; Becker et al., 2018). For subduction megathrust earthquakes, reversal is limited to the overriding upper plate (Hyndman and Wang, 1993; Wang et al., 2012). This corresponds to the tectonic position of the Neves block during the Oligocene to Miocene period considered here. At this stage of Alpine collision, units of the Neves area were already detached from the subducting plate and accreted to the immediate hanging wall of the main intracontinental megathrust (Schmid et al., 2013, their figure 6). However, there is no evidence for major earthquakes in the Neves area. Leydier et al. (2019) suggested that the Neves area fulfills the conditions to have hosted slow earthquakes during Alpine continental collision, namely, coupled frictional and viscous deformation under high fluid pressures, but their model does not account for the observed switch of stress axes described here.

Mancktelow and Pennacchioni (2010) established that the differential stress during ductile flow in the Neves area was low (<10 MPa). This, together with the high pore-fluid pressure (Cesare et al., 2001; Leydier et al., 2019), implies that the Mohr circle representation of the effective stress was close to the extensional (mode I) or hybrid (mixed mode I + II) failure envelope. A small perturbation in the stress field would have been sufficient to (intermittently) induce failure, causing extensional or hybrid failure, as recorded by both the north-south quartz-rich veins and the east-west thin fractures. A source for the intermittent stress inversion could have been distant earthquakes along the Defereggen-Antholz-Vals (DAV) and Periadriatic fault systems (e.g., Mancktelow et al., 2001), located ~15 km south of the Neves area (Fig. 1). In these faults, pseudotachylytes, which are reliable indicators of seismicity (Sibson, 1977), have an age range that includes the Oligocene–Miocene deformation of the Neves area (Müller et al., 2001). Both the range in ages and crosscutting relationships indicate that seismicity on these faults was repetitive, as was fracturing in the Neves area. At the regional scale of the Alps, widespread Oligocene dikes are commonly oriented at a high angle to the long-term NNW-SSE shortening direction (Guastoni et al., 2014; Mancktelow et al., 2001). This dike orientation suggests a regional transient switch in stress axes during magmatic emplacement, similar to that producing the E-W set of discrete fractures in the Neves area.

The Neves area is a well-exposed example of "wet" midcrustal deformation. Other examples of intermittent seismic deformation in the generally ductile middle to lower continental crust have been reported. Boullier and Robert (1992) documented repetitive paleoseismic events recorded in Archean gold-quartz vein networks (Quebec Province, Canada) emplaced after the peak of greenschist-facies metamorphism. Similar to Neves, the veins are oriented at a high angle to the long-term horizontal shortening direction. The authors ascribed the intermittent switch of ε_1 and σ_3, producing extensional vein opening, to shear stress release along neighboring shear veins after seismic rupturing. Similar to Neves, fluid pressures were high, and the perturbation in fluid pressure and stress during intermittent seismicity did not have to be large to cause fracturing. Hawemann et al. (2019) described a field example with similarities to Neves, though from a quite different environment—the exhumed dry lower continental crustal rocks of the Musgrave Ranges (central Australia), deformed under sub-eclogite-facies conditions. Also in this case, the precursor fractures, commonly decorated by pseudotachylyte and therefore coseismic, are oriented at a high angle to the regional ε_1 direction (Hawemann et al., 2019, their figure 3). Fractures and pseudotachylytes were exploited by shear zones, with evidence of repeated cycles of seismic fracturing and shearing. In this case, the absence of fluids and the presence of fractured garnet and pseudotachylyte suggest that the transient stress perturbation was large.

CONCLUSIONS

Long, thin fractures that localized fluid infiltration, fluid-rock interaction, and subsequent ductile shear are commonly oriented at a high angle to ε_1 in the Neves area. In many cases, these are effectively joints, without discernible offset, and would usually be interpreted as extensional fractures oriented perpendicular to σ_3 during initiation. Where the initial offset is discernible, it is not uncommonly opposite in sense to that of later ductile shear localized on these precursor structures. This implies a transient switch between σ_1 and σ_3 during fracturing relative to their orientation during long-term, aseismic, ductile deformation. Such short-term reversal has been observed and numerically modeled for co- to early postseismic rebound in the hanging wall of subduction zone megathrusts, with the postseismic rebound decaying viscoelastically over a period of decades. In the Neves area, this process of transient fracturing and stress reversal was repeated in an overall regime of fluid-rich, weak, aseismic viscous flow at middle continental crust levels, within units that, at the time, were in the immediate hanging wall of the Alpine intracontinental megathrust.

ACKNOWLEDGMENTS

This study was supported by ETH Zurich and the University of Padova (Padua, Italy) (project BIRD175145/17). Helpful reviews by R. Bürgmann, M. Handy, and G. Dresen and editorial comments by D. Brown are gratefully acknowledged.

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