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Reply

# Reply to comment by C. Collettini on "Structural controls on a carbon dioxide-driven mud volcano field in the Northern Apennines (Pieve Santo Stefano, Italy): Relations with pre-existing steep discontinuities and seismicity"

## 1. Introduction

Collettini (2009) comments on my recent paper (Bonini, 2009) and raises a number of questions about the reliability of the mechanical analysis of the normal faults and other brittle discontinuities that are responsible for the distribution of seismicity and that act as pathways for the discharge of $CO_2$-rich fluids accompanying the Sansepolcro seismic sequence (essentially November–December 2001), in the Upper Tiber Basin area (Northern Apennines, Italy). Collettini highlights three weak points, specifically: (1) the assumption of a fault dip angle of 50°, which, he suggests is not consistent with the structures that were active during the seismic sequence; (2) the mechanical analysis and the $P_f = \sigma_3$ condition; and (3) the isotropic stress state (i.e., $\sigma_2 = \sigma_3$). I welcome his stimulating comments and appreciate the opportunity to clarify my interpretations and starting points in the analysis. Each of these points is addressed below.

## 2. Discussion

### *2.1. The structures that were active during the 2001–2002 Sansepolcro seismic sequence, and the 50° fault dip angle*

The Upper Tiber Basin area, in the axial Northern Apennines, was struck by a seismic sequence that started on 26 November 2001 and lasted for some months afterwards, with the greatest activity during December 2001, with a few events continuing until September 2002 (data from Castello et al., 2006; Fig. 1a). The main seismic shock localised a few kilometres northwest of Sansepolcro, had Mw = 4.74 (focal depth 5.5. km) and produced a nearly pure extensional focal mechanism solution (CPTI Working Group, 2004; Castello et al., 2006; Ciaccio et al., 2006: Heinicke et al., 2006). The mainshock and a large part the November 2001 seismicity were most likely generated by the ENE-dipping low-angle Alto Tiberina normal fault, ATF (Heinicke et al., 2006), but in Bonini (2009) it is not stated that the 2D mechanical analysis was applied to the ATF, nor that the ATF is dipping at 50° (Collettini, 2009, his case 1). Instead, my analysis refers to the SW-dipping normal fault that bounds the northeastern margin of the Upper Tiber Basin and extends northwestward up to the pre-existing NE-trending discontinuities associated with the transverse Arbia-Val Marecchia Line, AVML (Fig. 1a). Such a SW-dipping normal fault has been interpreted as antithetic to the ATF basal detachment (Collettini and Barchi, 2002).

In my view, the SW-dipping fault – together with the AVML structures – acted as the preferential pathway for the post-seismic release of $CO_2$-rich fluids, which showed a marked increase in flow rate and mud extrusion at the Covivoli vent 18 months after the main seismic shock (Heinicke et al., 2006; Fig. 1a). As Collettini (2009, his case 2) acknowledges, my intention is illustrated in Fig. 5b in Bonini (2009). However, Collettini (2009) states that "*this fault was not reactivated during the 2001 seismic sequence, since all the earthquakes are located to the east of the surface expression of the fault and therefore the seismic activity cannot be related to a SW-dipping normal fault. Thus frictional fault reactivation cannot be applied to a SW-dipping normal fault, inclined at 50°, to explain the 2001 seismic sequence.*"

In contrast with this statement, the precise positioning of earthquakes (data from Castello et al., 2006), including events not shown in Fig. 5a of Bonini (2009), reveals that a number of the November 2001 epicentres and the great majority of the December 2001 seismicity occurred well to the west/southwest of the surface trace of the SW-dipping normal fault (Fig. 1a). Interestingly, (1) the December 2001 epicentres define a clear NW-SE-trending belt located ca. 3–4 km southwest of, and subparallel to such a SW-dipping fault (Fig. 1a), (2) the spatial distribution of the Sansepolcro hypocentres starts off around the intersection (at ca. 5 km depth) between the SW-dipping (antithetic) normal fault and the ATF, and (3) many of the aftershocks are approximately aligned along the SW-dipping fault plane (cf. Fig. 1a with 1b).

In my interpretation, this setting indicates that the NE-directed slip along the ATF detachment stretched the hangingwall block and reactivated at depth the SW-dipping normal fault through a process assisted by the seismically-triggered fluid pressure pulse (see the following Section 2.2). The mechanical scenario illustrated in Fig. 1b for the Sansepolcro seismic sequence is thus essentially equivalent to that commonly assumed for this sector of the Northern Apennines, in which seismicity derives basically from the interplay between the SW-dipping antithetic normal faults and its ATF detachment (e.g., Boncio and Lavecchia, 2000; Collettini and Barchi, 2002; Lavecchia et al., 2002; Ciaccio et al., 2006).


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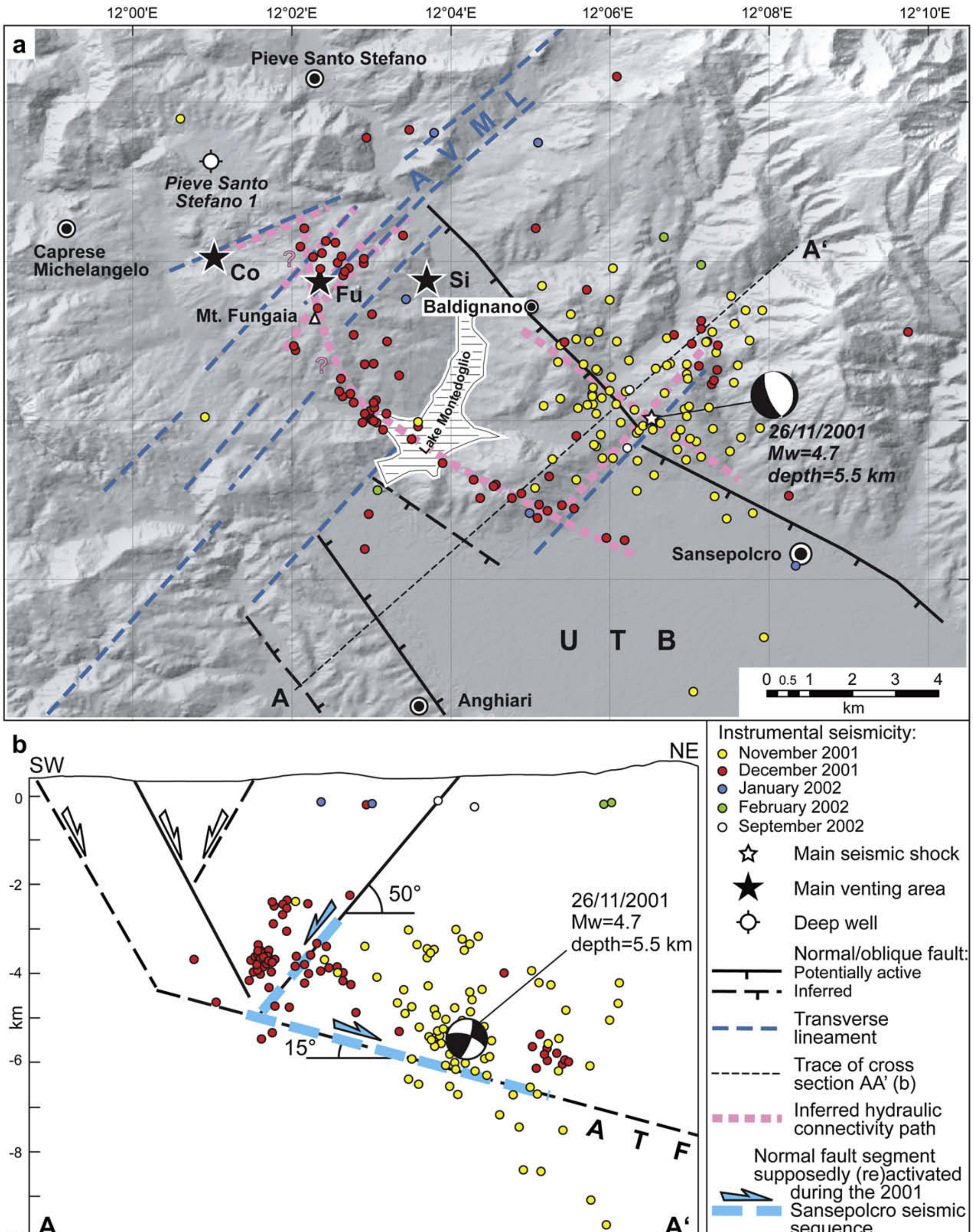


**Fig. 1.** a. Structures and seismicity (November 2001–September 2002) around the northwestern sector of the Upper Tiber Basin. The faults are modified from Bonini (2009), and the seismicity is positioned from Castello et al. (2006) and Ciaccio et al. (2006). Note the NW-SE-trending alignment of the December 2001 epicentres parallel to the strike (and on the hangingwall) of the SW-dipping normal fault. b. Vertical distribution of hypocentres projected on profile AA′, and interpretative sketch showing the structures activated during the 2001–2002 Sansepolcro seismic sequence. UTB, Upper Tiber Basin; ATF, Alto Tiberina normal fault; AVML, Arbia-Val Marecchia Line; Main venting areas: Co, Covivoli; Fu, Mt. Fungaia; Si, Sigliano.

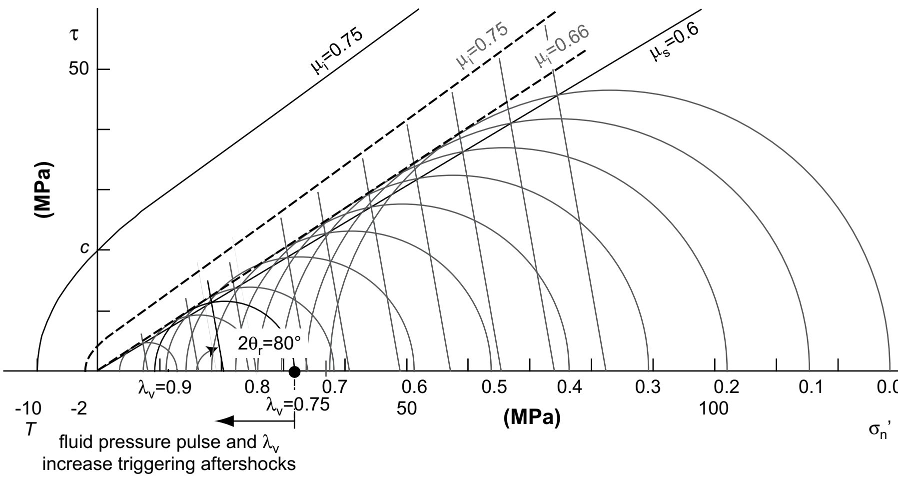


**Fig. 2.** Composite Griffith-Coulomb failure envelope for intact rock ($\mu_i = 0.75$), and fault reactivation conditions in anisotropic rocks ($\mu_s = 0.6$). Differential stress required for frictional reactivation ($z = 5000$ m; $\mu_s = 0.6$; $\rho = 2600$ kg m$^{-3}$; $T = 10$ MPa) of a normal fault plane dipping 50° ($2\theta_r = 80°$) in relation to fluid pressure $P_f$. The black dot indicates the fluid pressure conditions ($\lambda_v = 0.75$) predating the November 2001 seismic sequence in the area of the SW-dipping normal fault bounding the Upper Tiber Basin to the northeast. This value has been obtained from the extrapolation of the $P_f$ conditions measured in the near "Pieve Santo Stefano 1" well (70 MPa at a depth of 3700 m; Heinicke et al., 2006). The black arrow indicates the increase in $P_f$ along-strike of the SW-dipping fault following the fluid pressure pulse propagating from the earthquake damage zone, and the consequent effective normal stress decrease triggering aftershocks. The 50°-dipping fault plane is optimally oriented for frictional reactivation for a large variety of $P_f$ conditions and differential stresses, supporting this mechanism as being the causative process of the seismicity originating along the SW-dipping fault.

### 2.2. Mechanical analysis and the $P_f = \sigma_3$ condition

Collettini (2009) is correct in stating that the attainment of $P_f = \sigma_3$ (or $\sigma'_3 = \sigma_3 - P_f = 0$) condition is difficult to reach on well-oriented cohesionless faults, but I re-iterate that the mechanical analysis was not applied to the ATF (as presented in Collettini and Barchi, 2002), but to the SW-dipping normal fault bounding the northeastern margin of the Upper Tiber Basin (see the previous Section 2.1). Unfortunately, Fig. 6 in Bonini (2009) presents an obvious and regrettable bias derived from a systematic mistake in the Matlab script I used for equations 1 and 2 reported in Bonini (2009). The correct figure is presented in Fig. 2. Frictional reactivation of the 50°-dipping fault plane can occur for a very large range of fluid pressure and differential stress conditions (Sibson, 2000). Instead, the creation of a new Andersonian fault may occur only under very restricted states, such as cohesion ($c$) and tensile strength ($T$) equal to zero, $\mu_i < 0.66$, and low pore fluid pressure, say $\lambda_v < 0.3$ (Fig. 2), a status that might arise from a sudden and strong fluid pressure loss (for instance, following the coseismic breakage of a hydraulic seal in karstic environments). Therefore, regardless of the aforementioned inaccuracy, I restate the concept that, as invoked in Bonini (2009), seismicity along such an SW-dipping normal fault can be related to a fault reactivation failure mechanism driven by a fluid pressure pulse propagating from the earthquake damage zone (Fig. 2). This mechanical model accords with the localization and migration of December 2001 aftershocks along the belt, subparallel to the SW-dipping normal fault (as well as along the AVML) described in Section 2.1 (see Fig. 1a). Particularly, such a process was likely controlled by the strong subhorizontal $\sigma_2$–parallel permeability that characterises normal fault settings (e.g., Sibson, 2000), and that this has presumably channelled the fluid pressure wave. In agreement with this hypothesis, a preferential fault strike ($\sigma_2$) – parallel hydraulic communication is consistent with the geological conditions of this region (Collettini, 2002).

### 2.3. The condition $\sigma_2 = \sigma_3$

The occurrence of an isotropic stress state (i.e., $\sigma_2 = \sigma_3$) was intended only as one of the possible conditions invoked to explain fluid transport, venting and seismicity along the NE-trending AVML. Almost certainly, the $\sigma_2$ and $\sigma_3$ are likely to be not equal at a regional scale (note the stress field reported in Fig. 5a of Bonini, 2009), but the case I was discussing referred to the theoretical possibility that a roughly isotropic stress state could arise ensuing the local stress variations (reorientation and redistribution) around pre-exiting AVML transverse structures (e.g., Homberg et al., 1997). Besides, I have hypothetically attributed (Bonini, 2009) the aftershocks along these transverse faults to the explosion of pressurised fluid pockets, trapped in the damage zones of faults, upon being reached by the fluid pressure pulse.

Following the experience of the Colfiorito 1997–1998 seismic sequence, Collettini (2009) offers an alternative explanation for seismicity, and suggests that "*the earthquakes along the AVML can be interpreted as fluid-driven, fault reactivation processes along a pre-existing steeply dipping NE-SW trending structure*". Like the Upper Tiber Basin, the Colfiorito sequence occurred on NW-trending normal faults and the two main ruptures are segmented by a NNE-trending, right-lateral strike-slip fault inherited from the compressional phase (Collettini et al., 2005). "*Late in the Colfiorito seismic sequence, this strike slip fault nucleated a left-lateral strike-slip mainshock and an associated aftershock sequence with left-lateral strike-slip focal mechanisms*" (Collettini, 2009). Collettini (2009) also mentions that the left-lateral kinematics of the NNE-trending fault is compatible with both static stress change analysis and the orientation of the fault with respect to the NE-SW trending regional extension direction.

The mechanism Collettini (2009) is proposing is certainly interesting, and may represent an additional process for explaining such seismicity. On the other hand, it should be noted that, unlike Colfiorito, the orientation of the NE-directed regional extension is essentially parallel to the steeply dipping NE-trending AVML fault planes, thus representing a condition unfavourable for the oblique-slip reactivation of these pre-existing transverse structures (see Fig. 5a in Bonini, 2009).

## 3. Conclusion

I consider the comments raised by Collettini (2009) as pertinent and helpful for improving and clarifying some of the concepts expressed in Bonini (2009). Nevertheless, I have found no reason to alter my original interpretation, since: (1) the 2D mechanical analysis was not applied to the ATF, but to an antithetic SW-dipping normal fault that in my interpretation was partly reactivated during the Sansepolcro seismic sequence; (2) the failure conditions generating the seismicity along the same SW-dipping fault can be still related to a fluid-driven fault reactivation process; (3) the isotropic stress condition was intended as a theoretically-possible local stress state condition around the pre-existing transverse AVML faults, and not to represent the regional stress.

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