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Reply on RC1

Giulio Viola et al.

Author comment on "Structural characterization and K–Ar illite dating of reactivated, complex and heterogeneous fault zones: lessons from the Zuccale Fault, Northern Apennines" by Giulio Viola et al., EGU sphere,
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Bologna, July 23, 2022

We thank Reviewer 1 for the constructive inputs to our manuscript. We appreciate that our methodological approach, which builds on- and further develops the work by Tartaglia et al. (2020), is considered sound and useful when dealing with the time-constrained structural and mechanical evolution of architecturally complex fault zones. This is indeed our main goal and hope that the community may wish to adopt and further refine it in similar future studies.

The points raised by the Reviewer deal, instead, with the geological implications that our study (hence, the Brittle Structural Facies approach - BSF) bears on the understanding and on the possible revisiting of some aspects of the regional geological evolution of the Northern Apennines.

In the following we address these points individually and anticipate the changes that we will be implementing in the resubmitted text to improve it as per these useful inputs.

In *Italic font* are the original comments, while our replies/rebuttal are in normal font.

Authors suggest that the preservation of Aquitanian ages within the fault zone excludes significant thermal overprinting possibly associated with the intrusion of the Porto Azzurro Pluton. This is quite astonishing due to the location and geological evolution of the area, and I think it would need a more in-depth discussion (i. e. addressing what would be the P-T conditions that could eventually prevent a dating in the frame of the thermal evolution of the area, thus defining the thermal window that affected the area).

This is an interesting, yet rather complex, issue, the solution of which (if ever possible) requires considering elements of regional geology, structural considerations and analytical constraints on the K-Ar dating method applied to fine-grained clays.

Dating generally assumes that no- or little isotopic re-equilibration has occurred since the dated minerals formed. However, exposure to temperatures at or above the formation temperature of the dated clay in the studied gouge (for example, to the high-temperature

effects of the cooling Porto Azzurro pluton) for considerable time intervals may cause volume diffusion of radiogenic ^{40}Ar , leading to the partial or complete resetting of the system and, thus, to mixed ages that are devoid of geological meaning. It is, therefore, correct to wonder (as the Reviewer does) about the preservation of ages as old as Aquitanian within the complex patchwork of Brittle Structural Facies of the Zuccale Fault.

Finding such old ages, however, is perhaps, not at all incompatible with the idea of complex evolution of the internal architecture of long-lived fault zones.

When distancing ourselves from the static vision of a fault architecture as we see it in the field and when instead trying to integrate such architecture and its dynamic evolution over the time dimension of localization of faulting, then it becomes easier to understand and accept that (as the BSF approach predicts) different structural facies that are now side by side may have formed very far apart and at very different times.

In the specific case of the Aquitanian ages of the ZF, those ages may thus reflect the fact that the very specific BSF's preserving them made it to their current structural position only after the waning of the resetting effects of the thermal aureole of the Porto Azzurro pluton. Those BSF's, therefore, would reflect deformation and isotopic records acquired elsewhere more to the west, with their final translation to the current structural position occurring only after final cooling.

We actually had already commented on this in the original text, but we will certainly better stress this possibility in the amended version, highlighting even more clearly the implications that this possibility has upon the structuring of the ZF complex architecture.

A different (yet complementary) take on this point relates to the systematics of K-Ar of fine-grained clays. In more detail, one may wonder how, if the BSF's containing Aquitanian ages were not translated to their current location after final cooling of the pluton, those ages could "escape" thermal resetting by the Porto Azzurro. After all, the estimated pressure-temperature (P-T) conditions of its contact aureole are reported as ranging from 300 °C (biotite zone) to 650 °C (andalusite-K-feldspar zone and wollastonite zone), with $P_{\text{max}} < 0.18\text{--}0.2$ GPa (Duranti et al., 1992; Caggianelli et al., 2018; Papeschi et al., 2019). These P-T conditions are diagnostic of a low-pressure/high-temperature (LP/HT) contact metamorphism and indicate that the Porto Azzurro pluton was emplaced at a very shallow crustal level. These conditions would almost certainly suffice to reset the Aquitanian isotopic signature, if maintained over long-enough time spans.

We stress in here, however, the nature of complex fault zones such as the ZF, whose *transient* behavior (both mechanical and thermal) represents a significant difference to the "static" environments that are generally used when conceptualizing Ar diffusion in coarse mica grains, and, thus, partial or total resetting. To explore possible resetting scenarios of the Ar signature within clays, we can refer to the study by Torgersen et al. (2014), who tried to evaluate the impact of thermal pulses of different duration upon different grain-size clay fractions. Their calculations assumed a cylindrical grain geometry and modeling was repeated for a range of grain-sizes (10, 2 and 0.1 μm), peak temperatures (190-370° C) and duration of thermal episodes (5 and 10 Ma). They concluded that during heating-cooling pulses of 5 and 10 Ma (that is, very long compared to the duration of contact metamorphism by the Porto Azzurro of only a couple of Myrs) to temperatures of 230-240° C (quite lower than those of contact metamorphism), even very fine-grained illites (< 0.1 μm) would not experience more than a 10% resetting of their initial K/Ar age. At 300-310°C, on the other hand, the Ar isotopic system of the < 0.1 and 2 μm grains would be completely reset. In summary, although Ar diffusion should not be completely ruled out, we feel confident that our internally consistent data do not reflect a significant influence of radiogenic ^{40}Ar diffusion and this is well supported by diffusion modelling done with the most recent and relevant diffusion parameters for clays. These

results, therefore, indicate that the Aquitanian ages did escape thermal resetting and are thus geologically meaningful, pointing to a discrete faulting event (recorded by two samples in different portions of the fault zone) that is well preserved in both the measured isotopic signature and the structural framework.

Only a BSF approach can unravel these complexities.

We will elaborate further on this important point in the revised version of the text, by also clarifying the prevalent P-T conditions during the thermal anomaly associated with the Porto Azzurro pluton.

It would be useful to try to insert in the discussion, as well as in the cartoon of Figure 9, the effects of the middle Miocene extensional phase. A brief discussion of how this LANF phase may have (or not) reactivated the pre-existing thrusts (negative inversion tectonics) as well as the subsequent OOSTs (including the ZF) may also have (or not) reactivated the previous LANFs (negative inversion). Definitely, it would be pretty useful to briefly discuss these possible scenarios.

We agree and thank Reviewer 1 for pointing this out. We originally abstained from doing it because we thought it could excessively complicate both the discussion and the figure. After all, that part of the story is studied and thoroughly discussed in Massa et al. (2017), which we extensively quote in our work. The comment by the Reviewer, however, has convinced us to explicitly address this important step of the local evolution in our work and the amended version of the text will, therefore, contain an add-on on this and Figure 9 will be amended accordingly.

The proposed reconstruction once again brings attention to the possible emplacement of magmatic bodies during shortening in southern Tuscany. This seems to confirm what has already been proposed for the Gavorrano area (Mazzarini et al., 2004), but also for the Larderello-Travale geothermal field (Sani et al., 2016). This is consistent with the argument that the Island of Elba could be considered an exhumed analogue of the deep roots of the Larderello geothermal system, with huge implications for the evolution of the well-known Tuscan geothermal systems. I believe that a brief discussion focused on these issues would be useful in the frame of the ongoing debate, also for the important associated implications.

We agree with this suggestion and will insert a short discussion on this, even though this aspect of the regional geological evolution is not central to the mostly methodological flavour of our contribution. Already here we point out that several scenarios contemplating different emplacement mechanisms have been proposed in the last few decades for the Porto Azzurro pluton. Pluton emplacement was initially attributed to extensional structures accommodating local gravitational instabilities (Trevisan, 1950; Pertusati et al., 1993). Subsequently, The Porto Azzurro Pluton emplacement has been interpreted as being coeval with extensional faulting of the Northern Apennines upper crust (e.g., Smith et al., 2010) or with- and driven by oblique, transtensional tectonics (Liotta et al., 2015). Recently, according to Spiess et al (2021), the Porto Azzurro Pluton has been interpreted as a syn-kinematic intrusion emplaced in the footwall of the active Zuccale Fault. The results of the geological mapping of the entire Calamita Peninsula by some of our research group, along with meso- and micro-structural analysis of the host rock fabrics, however, suggest to us that the Porto Azzurro pluton was emplaced into the Ortano and Calamita units during overall crustal shortening (Mazzarini et al., 2011; Musumeci and Vaselli, 2012; Papeschi et al; 2017; Papeschi et al; 2021; Papeschi et al., 2022), and certainly

before the last recorded early Pliocene activity of the ZF (Musumeci et al., 2015; Viola et al., 2018).

Some figures need to be implemented, see comments in the annotated version of the ms.

Please also note the supplement to this comment with detailed minor points to be addressed

We will attend to all this in the next version of the manuscript.

Giulio Viola