Dear Editor,

I am herewith submitting to your consideration the revised version of the manuscript "Structural characterization and K-Ar illite dating of reactivated, complex and heterogeneous fault zones: Lessons from the Zuccale Fault, Northern Apennines" by myself and coauthors.

We have greatly appreciated the reviews by the 2 anonymous reviewers and have gladly implemented all of their requests for inputs, amendments and improvements. The details of our changes are discussed in the open discussion, where we went at length addressing how we would be dealing with the received inputs.

The revised version, submitted to your attention, has been significantly improved by modifying the original text and figures so as to comply with requests of improvements.

For your convenience, here I report the text of the open rebuttal, with some other minor additions that came about during the actual revision of the text:

Reviewer 1

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 to the resubmitted text to try to improve it as per these useful inputs.

In red are the original comments, while our replies/rebuttal are in black.

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 Port 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 Pmax <0.18–0.2 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 have elaborated further on this important point in the revised version of the text (e.g., 725-730), by also clarifying the prevalent P-T conditions during the thermal anomaly associated with the Porto Azzurro pluton (161-165).

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 discussion, therefore, contains an add-on on this and Figure 9 has been 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 have inserted a short discussion on this (767-780), even though this aspect of the regional geological evolution is not central to the mostly methodological flavor 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.

All figures that were suggested to be in need of some improvements have been modified according to the specific requests by Reviewer 1. The one point that we did not comply with, however, is the request by the Reviewer (reported in the annotated file) to add an extra figure with more details on the structural framework of the study area. We sincerely think that this is unnecessary for two reasons: 1) This is not a regional study, although the new results have major implications on the evolutionary scheme for the Northern Apennines. Adding another geological map would shift the balance of the paper.

2) Additionally, all the structural elements that the Reviewer asks for are already in our figures and readers can easily find them. They are properly labelled. Also, we extensively refer to many other published papers that have all the necessary information, should readers be interested in further exploring the details of the local geology.

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

All the points made by the Reviewer have been attended to. In particular, we greatly appreciated the requests to be less speculative in a couple of places and to better address a couple of points (e.g., addition of some extra text to clarify the discussion on the seismic character of deformation and the details of the retrograde evolution of the BSFs en route to the surface).

Reviewer 2

We thank Reviewer 2 for the constructive inputs provided to our manuscript. We are pleased to see that the Reviewer appreciated the proposed methodological approach to the study of long-lived, complex fault systems. Also, we appreciate the fact that, although our data seem to confirm that alternative takes from those commonly reported by the majority of the community on the evolution of the Zuccale Fault (ZF) are partly necessary, the Reviewer thinks that our model is quite well supported by the new data. This is indeed an important point, in our opinion. To discriminate between existing models, it inevitably becomes necessary to produce and make available new results and data that can assist in stepping forward in a specific direction. The results presented here are analytically sound “hard numbers”, which require us to take them into account and use them while refining the understanding of this spectacular structure.

As in the case of Reviewer 1, Reviewer 2 only has minor comments and requests of improvements on the part of the study that deals with the regional framework of the ZF and on how this needs to be partly revisited in light of the new dates.

In red are the original comments, while our replies/rebuttal are in black. All minor editorial aspects have been attended to.

The data here provided suggest a different interpretation, following the one proposed by Musumeci et al. (2015), and consider the Zuccale Fault as a thrust fault active at different times from the Aquitanian to the Miocene-Pliocene boundary. The provided interpretation is quite well supported by presented data but I feel that it needs a more detailed description of the relationships among fault activity and the intrusion of the Porto Azzurro pluton. In figure 9, the one that summarizes the tectonic significance of the Zuccale Fault, the evolution step in which the granite intruded the already formed stack is missing and I strongly suggest the authors to consider it in the in the figure.

A similar comment has been proposed by Reviewer 1. Both Reviewers commenting on the same issue with basically the same suggestion and request for improvement has convinced us of the necessity to comply with their request. As already written in the reply to Reviewer 1, we originally abstained from elaborating in detail on the relationships between tectonics and plutonism 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 Vaselli and Musumeci (2012), Massa et al. (2017) and Papeschi et al. (2017) which we extensively quote in our work. This notwithstanding, the amended version of the text is shortly expanded to also contain an add-on on this aspect (lines 767-780) and Figure 9 has been amended accordingly.

Line 241: Is there any information related to the depth of emplacement of the Porto Azzurro pluton

The estimated pressure-temperature (P-T) conditions of the Porto Azzurro contact aureole are reported as ranging from 300 °C (biotite zone) to 650 °C (andalusite–K-feldspar zone and wollastonite zone), with Pmax <0.18–0.2 GPa (Duranti et al., 1992). Recently, fluid-inclusion studies (Caggianelli et al., 2018) and detailed investigations of the migmatitic layering of the hosting Calamita Schist unit (Papeschi et al., 2019) showed that these P-T conditions are diagnostic of low-pressure/high-temperature (LP/HT) contact metamorphism and indicate that the Porto Azzurro pluton was emplaced at a very shallow crustal level. The revised text now explicitly reports these constraints (lines 161-165)

Line 388: Please add a brief description of the Calanchiole Shear Zone

This has been done (lines 400-409).

Line 635-642: I feel this paragraph may be obscure to readers not accustomed to the Apennines geology. The extensional phase that affected the Northern Apennines and its timing need to be described in brief to better support the interpretation proposed by the authors.

We specifically addressed the Mid-Miocene evolution of the Northern Apennines orogenic prism in terms of the significant extensional phase that affected it (673-675; 756-762). We have also amend Figure 9 so as to introduce this further step of the complex local tectonic evolution (see also specific comment to Figure 9).

As to the other requested changes to the figures, all have been implemented.

We also improved all three tables from a content and aesthetic point of view.

We hope that you will find the revised version of the manuscript of sufficient quality to warrant its acceptance.

Thank you for your time.

Yours sincerely.

Giulio Viola