Solid Earth Discuss., author comment AC5
https://doi.org/10.5194/se-2021-11-AC5, 2021

Reply on RC2

Laurent Jolivet et al.

Author comment on "Interactions of plutons and detachments: a comparison of Aegean and Tyrrhenian granitoids" by Laurent Jolivet et al., Solid Earth Discuss., https://doi.org/10.5194/se-2021-11-AC5, 2021

Comments by Referee #2 (Andrea Brogi):

The manuscript entitled "Interactions of plutons and detachments, comparison of Aegean and Tyrrhenian granitoids" by Jolivet et al. deals with the Neogene-Quaternary evolution of two areas in the Mediterranean that have been affected by magmatism strictly controlled by extensional tectonics. Authors mainly refer on the mechanism of emplacement and exhumation in relation with the Miocene – Pliocene tectonic evolution. Although the relationship between tectonics and magmatism is a "classical" topic, and several papers have focused on this precisely in the Tyrrhenian and Aegean areas, the authors offer a best opportunity to tackle a hot topic that in the last decade has been taking place overall on the evolution of the northern Tyrrhenian Sea and the Northern Apennines. In this view, Elba Island play a key role in the debate and has been object of different interpretations.

Thanks a lot for the kind general appreciation of our paper. We also thank you for the numerous suggestions of improvements that we have implemented in the revised version.

The manuscript sounds like a review paper as it has been constructed mostly integrating literature data apart from the last part which is dedicated to modeling.

This is not entirely true as the description of the detailed structure on the Monte Capanne pluton near San't Andrea is our own work also. The Aegean part is shorter and indeed corresponds to a summary of our recent findings in the Aegean plutons

In this view, the manuscript is well organized and symmetrically divided for illustrating both northern Tyrrhenian (i.e. Elba) and Aegean areas. The last part illustrates and discuss the model designed for reconstructing mechanism of emplacement and exhumation of the magmatic bodies. Figures are clear, well done and well represent all data needed for the discussion.

Thanks !

Nevertheless, in my opinion, a first figure comprehending both the northern Tyrrhenian Sea and the Aegean Sea, illustrating the tectonic scenario of the Mediterranean area is missed. A new figure in that line could be very useful for all readers not so familiar with this part of our Planet.

Yes, this is an excellent suggestion. We thus added a series of 3 maps taken and modified from our recent paper Romagny et al. (2020) reconstructing the Mediterranean region with a special look on magmatic events. The position of Elba Island and the Cyclades are shown with their plutons at the time of intrusion. The geodynamic context of both regions is thus better illustrated and the two can be compared.

See new figure 1

Some text was added to introduce this new figure and explain the geodynamic situation in more detail.

"Figure 3 shows the present-day situation as well as two stages at 5 and 15 Ma when the Tyrrhenian and Aegean plutons were forming adapted the detailed reconstructions of from Romagny et al. (2020). Magmatic events are shown with grey triangles (volcanism) and black squares (plutons). The detailed tectonic evolution, the reconstruction method and the link between magmatism and tectonics are described in discussed in Romagny et al. (2020) and Menant et al. (2016). The progressive retreat of subduction zones and foreland fold-and-thrust belts and/or accretionary wedges is shown coeval with crustal thinning and exhumation of metamorphic core complexes."

General conclusions of the paper are in line with what the authors are presenting and most of data presented in literature. However, a more accurate discussion should be dedicated to better highlight additional points as specified here below.

I agree with the authors that the Tyrrhenian Sea and Tuscany were affected by extensional tectonics since Ealy Miocene and this can explain all the geological evidences that we can see and measure on the surface. However, the tectonic evolution of the Tyrrhenian Sea is object of an increasingly noisy debate on the geodynamic scenario that should be mentioned in the text. As authors probably known, some authors have recently published papers that are framing all the geological issues of the northern Tyrrhenian Sea and inner Apennines in an alternative view with respect to the extensional tectonics. Also, the emplacement and exhumation of magmatic bodies are framed in a compressional setting instead of related to extension (see for example Montanari et al., 2010, Tectonophysics). I agree that the alternative conclusions are difficult to share, but just for this reason authors should face the problem and at least mention the existence of the improbable conclusions of these papers. Discussion has been addressed in several papers that could be useful for the authors; I mention here the most representative ones that may help authors to get useful idea: Brogi et al., 2005 (JVGR); Brogi 2008 (Int.J.Earth.Sciences); Brogi and Liotta 2008 (Tectonics); Brogi 2011 (Tectonophysics); Liotta et al., 2015 (Tectonophysics); Brogi 2020 (J.Struct.Geol.); Brogi et al. 2021 (Geosciences Switzerland). In particular, I recommend the last paper for focusing on the different views on the emplacement and exhumation of the magmatic bodies in the Tyrrhenian area (i.e. views from the office-desk vs fieldwork and data collection).

Yes. This is in line with the comment posted by Papeschi et al. on the discussion website. We have thus added in the geodynamic setting a paragraph devoted to this debate with associated references. We are in complete disagreement with this alternative interpretation, which is not new actually, but we mention the debate as suggested.

The geodynamic setting of the Northern Tyrrhenian Sea and Tuscany is debated. Since the late 90's two opposite interpretations have been discussed. One school of thought considers a continuum of extension from the Oligocene to the present with an eastward migration of extension in the back-arc region of the retreating Apennine subduction (Keller *and Pialli, 1990; Jolivet et al., 1994; Jolivet et al., 1998; Faccenna et al., 2001a; Faccenna et al., 2001b; Brogi et al., 2003; Brogi et al., 2005; Brogi, 2008; Brogi and Liotta, 2008; Brogi, 2020). Extension starts in the early Oligocene between Corsica and Provence and reaches the highest part of the Apennines in the recent period. Extensional basins, controlled by low-angle east-dipping normal faults migrate eastward following the migration of the magmatic arc. The Zuccale low-angle normal fault or an east-dipping ductile extensional shear zone bounding the Monte Capanne pluton, both observed in Elba Island, are part of this continuum of extension in the late Miocene and the Pliocene (Keller and Pialli, 1990; Daniel and Jolivet, 1995; Collettini and Holdsworth, 2004). This type of model is challenged by an alternative view where extension is only very recent, not before the Late Miocene or even later in the Tyrrhenian Sea and where several basins on the mainland of Italy are instead interpreted as compressional (Finetti et al., 2001; Bonini and Sani, 2002; Ryan et al., 2021). One of the main data set which is at the root of this debate is the CROP seismic profile crossing the Tyrrhenian, Tuscany and the Apennines (Finetti et al., 2001). Discussions of this alternative can be found more developed in several papers (Brogi et al., 2005; Brogi, 2008; Brogi and Liotta, 2008; Brogi, 2020). We consider that the compressional model cannot account for the first-order features off the northern Tyrrhenian Sea such as the crustal and lithospheric thickness and the geological evolution of Corsica, Elba, Giglio islands and we deliberately place our research in the framework of the migrating extension models."*

At the same time, Authors refer the development of the Tyrrhenian Sea to a back-arc basin related to the roll-back and slab-pull, but it is not a common view; see for example the papers by Mantovani et al. 2001 (J. Virtual Explor), Viti et al. 2004 (Tectoncis); Mantovani et al., 2019 (Journal of the Geological Society) and others, which highlight a more complex geodynamic scenario compared to the classic model. Authors probably should add some lines also for highlighting these different points of view.

Yes, we are also aware of this debate. We now mention it in the revised version:

"This evolution of the Northern Tyrrhenian region as a back-arc basin within the overriding plate of the retreating Apennine subduction is not however entirely consensual and alternative models exist, which involve different mechanisms, including escape tectonics. The reader is referred to the papers of Mantovani et al. (2020) and Romagny et al. (2020) for alternative views."

Magmatism (e.g. magma formation, emplacement and exhumation) has been modeled through numerical experiments and the results have been discussed in last part of the paper. In my opinion this is the most critical part of the manuscript. Authors set the model on parameters that I cannot understand: for example, the temperature, the depth and the volume of bodies seem to be not consistent with what it is known for the magmatic bodies described at least for the northern Tyrrhenian area. I suggest to better show in a table which are the parameters authors used for the numerical simulation.

There is a wide literature from which authors should constrain the parameters to be fixed for the modelling (Caggianelli et al. 2014, Geol.Soc.Spec.Publ; Rochira et al. 2018, Geodynamica Acta; Spiess et al., 2021, J.Struct.Geol.). Evolution of the magmatic systems can be found in Dini et al., 2002, Dini et al. 2008; Westerman et al., 2004...

Additional information for the age of the Porto Azzurro pluton are in Gagnevin et al. (2011, EPSL) and Spiess et al. (2021, J.Struct.Geol).

Our study is not so much about the specific case of Elba and the Monte Capanne, but more on the geometry and kinematics of plutons intruding the crust in an extensional *context where low-angle detachment form. Our observations in the Aegean have revealed a common scheme for all the plutons we examined and we find some striking similarities in the case of Elba, in terms of geometry of the internal organization of the pluton and its sheared border near the detachment. This is what we want to model and which has never been done before.*

The modelling procedure we use is entirely different from that adopted in the various papers you cite. Instead of pure thermal and rheological models we have here a thermo-mechanical model where we do not prescribe the position of the detachment and we accommodate large strain during the imposed extension, which is not achieved in other models. This detachment instead forms in a self-consistent way with the density contrasts and imposed rheology of the host rock and magma. The magma is a bit resistant probably compared to a true pluton, but its resistance is negligible compared to that of the host rock like we expect for a magma and changing this rheology a little would not change the main outcome of the model, as long as a significant rheological contrast is preserved. In our models, we also take into account the lateral thermal diffusion, which is not the case in most of the cited models. All parameters use for the modelling are in a table in the supplementary materials.

These models are shown for comparison with the conceptual model we derived previously from the field observations of the Aegean plutons and the overall geometry and kinematics are very similar, suggesting that our model is viable. The emplacement of granites in the model is controlled by structures that form in a way consistent with the rheology, dictated to the first order by the thermal evolution and the rheological contrasts introduced in the stratification of the initial setup. The fact that the plutons start as balloons is similar to the models you cite but the cause for melting is different. Melting is not caused by decompression but by heating from below because the upper lithospheric mantle thins and is boudinaged because of extension.

Our models do not consider a two-phase flow with a magma percolating in a permeable medium. Such models do not exist yet, at least for long-term models running on geological time scales, unfortunately. Tectonics involved in our models lasts for millions of years while porosity waves would last only a few hundred years, which correspond to only one time step of our model. We thus cannot consider the successive batches of magmas involved in the formation of plutons. The balloons that form at the beginning of extension are a good approximation of several successive episodes of magma extraction along the channels formed in the imposed stress field. This is the best we can do at the moment.

We have added a short paragraph citing some of the proposed papers (several ones were already cited):

"Quantitative data on the depth of intrusion of the Monte Capanne pluton can be obtained through the analysis of the metamorphic parageneses in the contact aureole and also assessed by comparison with the nearby Porto Azzurro pluton or the active geothermal field of Larderello. The Porto Azzurro pluton, more recent, induced the formation of a high-temperature contact metamorphism in the Calamiti Schists cropping out underneath the Zuccale Fault. Estimations of the P-T conditions of this metamorphism suggest that the pluton was emplaced at a similar depth of about 6.5 km and the maximum temperature recorded in the schists is about 650°C fringing the muscovite breakdown reaction (Caggianelli et al., 2018). Analysis of the metamorphic aureole also reveals multiple hydrofracturing episode by boron-rich fluids which can be compared to the present-day fluid circulation at depth in the Larderello geothermal field (Dini et al., 2008). Thermal modelling of an intrusion rising in the upper crust (Rochira et al., 2018) allows constraining the size of the pluton to produce the observed thermal anomaly beneath Larderello but such model does not allow testing the interactions between the detachment and the rising and cooling pluton. Although evidence of the involvement of transfer faults

have been described in the case of the Porto Azzurro pluton (Spiess et al., 2021) we do not address these in our modelling procedure as our model is kept 2-D for the moment."

and

"Magmatism is recorded in the Tuscan archipelago (Capraia, Elba, Giglio islands) from 8 to 5 Ma with plutons in Elba and Giglio and volcanism in Capraia and the mantle source of the magma appears highly contaminated by subduction-related and crustal-derived metasomatic fluids (Gagnevin et al., 2011)."

Concerning the structural control on the magma emplacement, authors should also discuss the role of the transfer zones that accommodated the extensional tectonics since Early Miocene and which contributed to channel the magmatic intrusion (see Dini et al., 2008 – Terra Nova; Liotta et al., 2015 - Tectonophysics; Gola et al., 2017 – Energy Procedia; Liotta and Brogi, 2020 - Geothermics; Brogi et al., 2021 – Geosciences Switzerland). This part should be better introduced as authors, in their models, figure out the emplacement of the magmatic bodies "like balloons" without any explicit connection with crustal structures.

These papers mostly deal with geothermal reservoirs in Tuscany (Larderello) and Iceland. It is most certainly true that transfer faults play an important role in the formation of geothermal reservoirs because they contribute to enhanced permeability at the junction with extensional detachments in this sort of context. This has been shown also in the Basin and Range and the Menderes Massif (Faulds et al., Roche et al.). This is not at all the main focus of our paper but we acknowledge this point and added the following text because there are connections between granite emplacement/cooling and geothermal reservoirs:

"The emplacement of plutons underneath extensional detachments may also be influenced by transfer faults accommodating along-strike variations of the rate of extension. This has been mainly discussed for geothermal reservoirs associated with plutons as the intersection of a detachment and a transfer fault leads to enhanced permeability and more efficient advection of fluids toward the Earth surface (Dini et al., 2008; Faulds et al., 2009; Liotta et al., 2015; Gola et al., 2017; Roche et al., 2018a; 2018b; Brogi et al., 2021; Liotta et al., 2021). In the case of the Tuscan Archipelago and Tuscany, this possibility has been documented by field studies in eastern Elba and the Gavorrano pluton (Liotta et al., 2015; 2021). The present paper is however mainly focused on the extension component of deformation and the interactions between low-angle detachments et the emplacement of plutons."

Of course, their geometry at melt and solid-state was modified by the activity of unroofing faults continuing to thin the tectonic pile, as clearly understandable from the surface analysis, but no indications are from the permeability development triggering the melt rise toward the upper crustal levels.

We focus on the interactions between plutons and detachments, based on field observations and numerical modelling and we show that the emplacement of a pluton in an extension context can be associated with the formation of detachments with a recurrent formation scheme with migrating detachments and a precise organization of structures within the pluton during emplacement and cooling that we find both the in the Aegean and Elba. So it is not only that the pluton is deformed by the detachment, it is a general emplacement mechanism that we propose here.

So in my opinion, this manuscript provides important inputs but additional work is necessary for refining at least the numerical modelling. The aim of the manuscript, addressed to resume and compare the tectonic setting which provided to the development of this part of Mediterranean as well as emplacement and exhumation of the magmatic bodies, is perfectly achieved.

Thanks a lot. We hope that the modifications we implemented will be satisfactory