Response letter to RC2

We appreciate the critical and constructive comments and suggestions made by anonymous referee 2, that increased the scientific quality of the manuscript. Below are our replies to anonymous referee 2 comments.

Comment 1
"Some terminology is not properly used and can be misleading. I know that it is a boring and common debate, but terms uplift, exhumation and erosion should be used properly. For instance metamorphic data are usually used to quantify exhumation, i.e. the vertical movement with respect to the earth surface. It sounds strange quantify uplift by metamorphic condition. Same approach should be used with thermochronological data."

Response from authors:
Thank you for pointing out the imprecise use of the terms "uplift, exhumation, and erosion". We have checked all of these terms for proper usage and revised the manuscript accordingly.

Comment 2
"One of the my main criticism is in using the metamorphic degree as a tools to quantify differential exhumation of crustal blocks. The authors should review the different mineral assemblages that characterize each domain and evaluate the pressure condition that in this case can be eventually used to evaluate the depth of metamorphic event. I think that metamorphic degree only is not enough to discriminate the depth of the metamorphic event, especially in this case where differences of exhumation are proposed between domain of high metamorphic degree, e.g. between diatectic gneisses and diatextites."

Response from authors:
Thank you very much for giving us the chance to clarify why we think using the metamorphic grade to reveal first-order differences in the relative amount of exhumation is appropriate. Below, we provide a brief summary of the metamorphic configuration of the study area. Subsequently, we discuss the different models that could explain this metamorphic configuration and why we think that a tectonically-driven model is the most plausible.

From the geological map, the study area can be divided into three first-order domains, each of which is characterized by a distinct pattern of metamorphic overprint (domains A, B, and C, Fig. 3 in manuscript). Identified domains are sharply separated by fault zones, such as the Pfahl and Runding shear zones. A general NNE to SSW increase in the metamorphic grade is observed in the study area. In the north (domain C), mica schists and mica gneisses occur close to the southeastern border of the Teplá-Barrandian unit (Fig. 3 in manuscript). Farther south, the onset of anatexis is indicated by metatectic cordierite-sillimanite-K-feldspar gneisses. An abrupt increase in the anatectic grade occurs along the Runding Shear Zone, as indicated by the presence of diatectic, garnet-bearing gneisses in between the Runding and Pfahl shear zones (domain B, Fig. 3 in manuscript). Another jump in the anatectic grade occurs along the Pfahl Shear Zone, as evidenced by vast complexes of diatexites in between the Pfahl and Danube shear zones (domain A, Fig. 3 in manuscript).

To explain the metamorphic zoning presented above, we postulate a tectonic model involving differential exhumation of distinct crustal blocks (domains A, B, and C), with progressively deeper crustal levels exposed towards the southwest. In fact, such a model of deeper crustal levels exposed to the southwest of the Pfahl Shear Zone is not novel and has been frequently assumed in previous work (e.g., Grauert et al., 1974; Beer, 1981; Finger and Clemens, 1995; Bader, 1996; Siebel et al., 2008; Finger and Rene, 2009) but the possible reason for such abrupt changes in metamorphic grades observed in the study area is presented for the first time in this study.

We agree that a detailed analysis of the mineral assemblages within the three outlined domains is required to evaluate the pressure conditions under which metamorphism occurred and ultimately to quantify the amount of differential exhumation. Table 1 summarizes the different mineral assemblages of the metamorphic rocks, including index minerals and textures. For details on the mineral assemblages and the inferred metamorphic grades, the reader is referred to the original publications referenced in Table 1.

Table 1 Sequence of predominant metamorphic rocks in the study area from NNE to SSW. Index minerals and textures are indicated (data from Blümel and Schreyer, 1977; Baburek, 1995; Bader, 1996; Mielke, 1996; Rohrmüller et al., 1996; Kalt et al., 1999; Teipel et al., 2008; Propach et al., 2008). Mineral abbreviations: *And* andalusite, *Bt* biotite, *Chl* chlorite, *Crd* cordierite, *Grt* garnet, *Hbl* hornblende, *Kfs* K-feldspar, *Opx* orthopyroxene, *Sil* sillimanite.

Predominant rock type	***Index minerals***	***Textures***	***Domain***	
Mica schist	*And, Bt, Chl, Grt*	*Foliated*	*C*	NNE
Mica gneiss	*And, Bt, Crd, Sil*	*Foliated*		
Metatectic gneiss	*Bt, Crd, Grt, Kfs, Sil*	*Leucosome schlieren*		
Diatectic gneiss	*Bt, Crd, Grt, Kfs, Opx, Sil*	*Metablastesis*	*B*	***Runding S.Z.***
Diatexites	*Bt, Hbl, Kfs, Opx, Sil*	*Nebulitic / schlieren to homogeneous*	*A*	***Pfahl S.Z.*** SSW

From the arrangement of metamorphic rocks and their different mineral assemblages presented in Table 1, a NNE to SSW progressive Buchan-type metamorphic zoning from upper greenschist facies to anatexis under low to intermediate pressures becomes apparent (Read, 1952; Grauert et al., 1974; Winter, 2010). Kyanite has not yet been observed in the anatectic rocks of the study area, thus bracketing pressure conditions to the andalusite-sillimanite stability field. This is in line with estimates of pressure and temperature conditions, which, unfortunately, are largely restricted to the area north of the Pfahl Shear Zone. Here, early studies estimated metamorphic conditions of 2-4 kbar and 650-730 °C (Schreyer et al., 1964; Schreyer and Blümel, 1974; Blümel and Schreyer, 1976, 1977). Higher P/T conditions of up to 5-7 kbar and 800-850 °C are suggested for the cordierite-bearing migmatites in the central part of the study area (Kalt et al., 1999).

To precisely evaluate the different pressure conditions in each of the domains, however, a much greater dataset compared to the one presented in Table 1 is needed. Unfortunately, such a dataset does not yet exist for the study area. In fact, even with the availability of such a dataset, several problems would arise from its interpretation. First, due to the highly anatectic character of the entire study area, pressure differences among the identified domains are most likely in a very narrow range, probably even within the range of the statistical/methodological error. High-temperature metamorphic overprint is thought to has occurred in very shallow depths (<20 km, Kalt et al., 1999), which further complicates quantifying contrasts in pressure conditions. In addition, the problem arises that in the range of the inferred peak metamorphic conditions (>700 °C) further changes in the pressure-indicative mineralogy of the rocks are nearly absent, as significant partial melting is already taking place (Winter, 2010). Instead, progressive anatexis, e.g., due to the increased temperatures in the deeper crust, rather results in textural changes, such as the formation of schlieren and nebulitic structures, which are widely observed in the study area (Table 1; e.g., Brown, 1973; Wimmenauer and Bryhni, 2007; Chen and Grapes, 2007; Rohrmüller et al., 1996). From the presence of anatectic rock textures (e.g., schlieren and nebulitic structures) and the occurrence of orthopyroxenes, the highest anatectic conditions certainly occurred towards the south of the Pfahl Shear Zone. Four endmember scenarios could thereby explain the described metamorphic zoning in the study area:

- *(I) Lateral differences in protolith rocks with varying solidus*
- *(II) Lateral differences in temperature during metamorphism*
- *(III) Lateral differences in the amount of available fluids, e.g., due to different contents of OH-bearing minerals or the presence of fluid-pathways*
- *(IV) Post-metamorphic, tectonically-driven differential exhumation of crustal blocks leading to contrasting anatectic domains at the present level of erosion (this study)*

Below, we discuss the four different scenarios that could potentially explain the encountered metamorphic configuration in the study area and why we think that a tectonically-driven model (IV) is the most plausible.

The protoliths of the anatectic rocks in the Bavarian part of the southwestern Bohemian Massif are considered as a monotonous sequence of mainly pelitic greywackes ("Monotoneous Group", e.g., Rohrmüller et al., 1996). Only in the Passau Forest (southeastern part of domain A), a significant area is formed by amphibole-bearing diatexites, pointing to a greater abundance of igneous protoliths and to the existence of a former island arc (Propach et al., 2008). A sharp contrast in the protoliths of the three *outlined domains, similar to the tectonic boundary between the Austrian Ostrong unit (= Monotoneous Group) and Drosendorf unit (= Varied Group) (Fuchs, 1995), however, has not yet been identified in Bavaria (Propach et al., 2008). Therefore, a scenario of different protolith rocks in each of the three domains (Scenario I) most likely is not plausible.*

Regarding the mechanisms of heat supply during the Variscan metamorphic event, models range from magmatic underplating (Kalt et al., 1999; Kalt et al., 2000) to lithospheric delamination (Klein et al., 2008). Regardless of the true mechanism, however, a sharp lateral temperature boundary (Scenario II), which would be required to explain the observed anatectic segmentation, is very unlikely.

A conceivable mechanism that could trigger anatexis in spatially limited areas is the presence of fluids (Scenario III). Fluids could thereby be provided either internally by the breakdown of OH-bearing minerals (e.g., micas; Le Breton and Thompson, 1988) or externally via fluid-pathways ("fluid-enhanced", e.g., Prince et al., 2001). As discussed previously, no discernible differences in the protoliths among the three defined domains have been discovered yet. Therefore, a model of different amounts of OH-bearing minerals in the protoliths of the domains is less plausible. In contrast, varying amounts of externally derived fluids, for example, infiltrated through tectonic structures such as shear zones, appear to be a reasonable mechanism to explain sharp contrasts in the anatectic grade. Indications for such an influx of H_2O along tectonic structures triggering enhanced partial melting are provided by the presence of diatectic patches aligned with tectonic structures of the horsetail-splay in domain C (Figs. 3, 11, and 12 in the current manuscript). Nevertheless, although such a scenario could explain locally enhanced partial melting, it is unlikely to have evoked the formation of vast diatexite complexes as observed in the study area. Pervasive melting in the absence of an aqueous fluid (i.e., hydrate-breakdown melting) is also supported by geochemical analysis of cordierite-bearing migmatites in the central part of the study area (Kalt et al., 1999).

Therefore, after reviewing the mineral assemblages and P/T metamorphic conditions, we prefer post-metamorphic tectonic exhumation (Scenario IV) as the most plausible scenario to explain the observed juxtaposition of different anatectic grades along very sharp boundaries in the study area. To emphasize this conclusion, we extended the related discussion part in the manuscript by the above-mentioned points.

Comment 3

"I have also same remarks even about thermochronological ages interpretation. I find interesting the interpretation of regional pattern of fission track ages and I agree that different ages can reflect different post-cooling vertical movement. Nevertheless it is not obvious to ascribe a depth of closure to a zircon FT age especially when you are considering one sample only. Complex thermal histories made by long persistence on partial annealing zone can produce very different age also in close samples. For this reason more information on the discussed data (e.g. track length, thermal modeling), if available, could better support the thesis of the authors.

Following the data of Vamvaka et al. 2014, it seems that the major reason for different AFT ages is related to complex thermal histories. To be sure that regional pattern of AFT and ZFT ages reflects fault activity, a more precise discussion of thermochronological data is needed."

Response from authors:
Thank you for allowing us to clarify our interpretation of the Apatite and Zircon fission track record from the literature. First, we would like to emphasize that discussion on the low-temperature evolution of the study area in full detail is beyond the scope of our study. We used available FT data as an additional and supporting source of information confirming the presence of a km-scale yet unknown tectonic structure along the southwestern Bohemian Massif (Cham Fault), which complements our interpretations of the exposed granite inventory and topographic lineaments. In addition, FT data provide evidence for significant post-Variscan activity phases of the Cham Fault. Below, we outline the main points that indicate the presence of a significant tectonic structure that also influences the spatial distribution of low-temperature thermochronological ages.

We agree that complex thermal histories may result in very different apparent FT ages, even among samples located close to each other. Indeed, complex thermal histories are suggested for most of the analyzed AFT samples (Wagner et al., 1989; Vercoutere, 1994; Hejl et al., 1997; Siebel et al., 2010; Vamvaka et al., 2014). A generally enhanced paleo-geothermal gradient is thereby assumed for the study area during the Mesozoic (Vercoutere, 1994; Vamvaka et al., 2014).

From track length characteristics (mixed-bimodal to positively skewed), AFT data in the Naab Mountains to the west of the Cham Fault are interpreted as post-Variscan cooling ages (ca. 270 Ma) that were partially reset during late Permian to Mesozoic subsidence and burial (up to 1000 to 1400 m) followed by Late Cretaceous to Cenozoic uplift and exhumation (Vercoutere, 1994).

An even more complex thermotectonic record is suggested for the Bavarian Forest in the southeastern part of the study area (Vamvaka et al., 2014). Here, thermal models indicate a first reheating during mid- to late Jurassic times (ca. 160-140 Ma), which was followed by tectonically-driven exhumation and denudation during the Early Cretaceous (ca. 140-120 Ma). After a phase of stagnation, sedimentation recurred during the Late Cretaceous (ca. 95-85 Ma), which caused reheating of marginal parts of the Bavarian Forest. The latter phase is especially depicted by the "Grub" sample, which is the only sample in the study of Vamvaka et al. (2014) that is located to the west of the newly proposed Cham Fault (c.f., Figure 10 in the manuscript). Similar to the tectonic record of the Naab Mountains (Vercoutere, 1994), the final uplift phase of the Bavarian Forest was initiated in the Late Cretaceous, probably in the course of inversion tectonics related either to the Alpine collision (e.g., Ziegler, 1987; Ziegler et al., 1995) or Africa-Iberia-Europe convergence (Kley and Voigt, 2008).

Hence, from this record, a complex regional thermotectonic evolution of the study area is proposed based on AFT data. Nevertheless, a significant difference in the thermal evolution between the sector to the west of the Cham Fault compared to the eastern sector is undoubtedly present, as evidenced by two pronounced age clusters at either side of the fault (Jurassic vs. Late Cretaceous, c.f., Figure 10 in the manuscript). Vamvaka et al. (2014) attributed this change to the presence of a fault zone in between the sample of Grub and the remaining samples to the east (i.e., the Cham Fault), accommodating a vertical displacement of at least 1 km. This interpretation is in line with Gebauer (1984), who proposes the presence of a significant tectonic structure close to the village of Winklarn between domains C1 and C2, based on two ZFT data points located only 2 km apart that record an apparent age gap of ca. 45 Myrs (ca. 260 Ma and 215 Ma, respectively), which is again in accordance with the newly proposed Cham Fault.

A possible cause for the apparent differences in timing between the western sector (ZFT: Upper Permian, AFT: Jurassic) and the eastern sector (ZFT: Lower Triassic, AFT: Upper Cretaceous) might be attributed to the northwest-southeast prograding Upper Permian to Mesozoic depositional system (e.g., Meyer, 1989; Peterek et al., 1997; Schröder et al., 1997). Based on the above-mentioned gap of ca. 45 Myrs between two ZFT data points close to the village of Winklarn, Meyer (1989) placed the basin margin during the Triassic close to this locality. From this interpretation, we conclude that the eastern margin of the Mesozoic basin most likely has been controlled by the Cham Fault, which, in turn, resulted in a larger sedimentary cover and the partial resetting especially of AFT ages towards the west of the Cham Fault. This interpretation is in accordance with the AFT data towards the east of the Cham Fault, where most sample sites are thought to have been covered only with an insignificant or, in parts, even completely absent sedimentary cover (Vamvaka et al., 2014). In fact, even the formation of syn-tectonic Permian basins along the northwestern segments of the Pfahl and Danube shear zones (Schröder, 1988; Peterek et al., 1996) might have been guided by the Cham Fault.

In summary, although the present FT ages are complex in their nature, the very distinct spatial distribution of both ZFT and AFT ages in combination with the close proximity between the two clusters suggests that the low-temperature thermal history of the study area is essentially controlled by block motion along the Cham Fault. However, it must be noted that this block motion most likely did not contribute to the differential exposure of granite bodies at the Earth's surface during the "Cham Phase", which has probably already been completed in the Permian (Siebel et al., 2010; Hejl et al., 1997; Mielke, 1993; Galadí-Enríquez et al., 2009). To clarify this interpretation of the FT data, we significantly extended the related discussion part in the updated manuscript version.

Comment 4

"The pattern of AFT ages suggests that ages get younger moving to the eastern region. It seems to suggest a correspondence between younger AFT ages and higher topography. This can suggest a process of isostatic response to the long-lasting erosion. It might be the case?"

Response from authors:
From Figure 10 in the manuscript, it becomes clear that no discernible (and statistically reliable) correlation between altitude and age can be observed. Towards the east of the Cham Fault, samples with consistent Cretaceous AFT ages show 250–650 m differences in the present-day elevation (Vamvaka et

al., 2014). This is rather a result of post-Cretaceous vertical displacements (Vamvaka et al., 2014), than of a regional isostatic response of the entire area, which should result in a much better correlation between ages and elevation.

Comment 5

"Why the authors speak about apparent age?"

Response from authors:

We use the term "apparent age" to emphasize the fact that thermochronological ages may be complex in their interpretation and do not necessarily represent cooling ages. In our opinion, the term "apparent age" helps to avoid misinterpretation of FT ages, and, therefore, we would prefer to retain this term in our manuscript.

Comment 6

"The authors do not touch one of the main problem regarding all the remnant Variscan massifs in Europe, and that is the persistence of high topography versus topographic rejuvenation. It could be worthy to discuss your results in the light of this debate."

Response from authors:

Thank you very much for highlighting this special and very interesting problem. In our view, the main reason for the persistence of high topography is the repeated tectonic reactivation of tectonic structures along the nowadays exposed Variscan massifs in Europe. A major reactivation event thereby occurred during the Late Cretaceous to early Paleogene, which initiated new reverse faults and reactivated inherited tectonic structures in Central Europe and also within the study area (e.g., Meyer, 1989; Kley and Voigt, 2008). In fact, we currently prepare another manuscript on this topic. However, due to the very different mechanisms, timing, and methodological approaches necessary for investigating this younger tectonic history of the southwestern Bohemian Massif, we decided not to include this discussion point in the present manuscript. Nevertheless, the fact that the Cham Fault also forms tectonic boundaries of Cretaceous to Cenozoic geological features implies that it also played a significant role in the tectonic evolution of the southwestern Bohemian Massif during Cretaceous to Cenozoic times.

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