Dear Editor Mr. Rossetti!

I want to express my sincere appreciation for your detailed analysis of our manuscript and the reviewer's comments. Your input certainly helped us to further improve the manuscript.

Some of your statements are, however, difficult to apprehend in the light of the referees' comments and the information given in the MS.

Let me first address this difficulty in a general sense.

(Henceforth, your comments are given in black color, italic typeface. My/our response is given in blue color. Underlining of parts of your comments is mine).

Your comments §1a and §3 (first part):

1a - the Abstract, Introduction and Discussion sections are too focused to the specific geological case that, despite interesting, should be better introduced to the broad audience of the journal. Apart the local significance, what is the general geological problem that the manuscript aims to address and characterise? which the (expected) advancement of knowledge in the discipline (tectono-metamorphic evolution of high-grade basement terrains)?, etc.

(3) - Impact of the study (see also point 1a above). As it stands, despite providing interesting results, the manuscript appears as a regional study of local significance.

For the convenience of the reader following this discussion, let me copy/paste here the general comments of the referees (bold typeface is mine).

Hans-Joachim Massonne:

"I would like to see the manuscript published soon after minor revisions".

Martin Racek:

- *"The work is of a particular interest **from both the more regional point of view, but mainly for a broader audience due to its quite unconventional approach**, which seems to be quite appropriate for a study of such peculiar lithologies"…*
- *"The manuscript … contains large set of **new data** and **includes novel approach for estimates**" …*
- ***"The substantial part of the manuscript is new authors contribution"** …*
- *"Overall, it can be summarized as follows - **scientific significance - excellent**, **scientific quality - excellent**, presentation quality - good to excellent)".*

Finally, let me add the statement given by you prior to your comments:

Your revised version adequately addressed the reviewers' comments.

As they stand, the reviewer's comments and your comments diverge significantly. If the MS is "too focused to the specific geological case" and the "general geological problem" as well as the "advancement of knowledge" are missing, and the MS is of "local significance", then revising a manuscript designed as a case study with a regional link to one with a more general significance is a major task and certainly at odds with “minor revisions”, as given in your statement just at the beginning of your comments:

Topical Editor Decision: Publish subject to minor revisions (review by editor) (02 May 2018) by Federico Rossetti

Even if this communication is not necessarily conclusive in itself, we see the point you raise, especially in the last part of

your §3:

The Authors are thus encouraged to expand the implications of this study and extract results that can be of interest for a broader audience, i.e. broaden the impact of the presented results away from the study area. A specific sub-section of the Discussion dedicated to these broad implications would greatly increase the impact and relevance of the study.

In this sense, we have modified and extended accordingly the sections “Abstract”, “Introduction”, “Discussion” and “Conclusions”. Please, see these changes and extensions after our response to the specific points of your criticism.

Now let me turn specifically to your comments and questions.

The “general geological problem”: In fact, we address a petrological problem in the Introduction (the way PT-conditions are commonly calculated), which has major geodynamic implications. The “advancement of knowledge” has been implicitly or explicitly emphasized by the referees. Please, see also our response to your comment §1c.

Your §1b:

The Introduction, rather than focusing just on the specific case, should instead introduce the <u>general geological problem</u>, its significance, <u>gaps of knowledge</u> and <u>aims the manuscript pursues</u> with respect to the existing background information. On this regard, <u>Table 1</u> should be part of the geological background, rather than part of the Introduction section. In other words: <u>Why this study should be of interest for a broad audience?</u>

As mentioned above, the Introduction was/is setting up a petrologic problem with major geodynamic implications. Let me describe this problem shortly. The tectono-metamorphic evolution of the high-grade Moldanubian rocks is based almost solely on strongly divergent PT-estimates summarized in Table 1. These PT-estimates imply severe, contrasting, mostly speculative, geodynamic implications. The “gaps of knowledge” were/are stated too, namely calculating PT by using garnet, particularly the Ca- content and/or Ca-zoning, <u>which is supposed to be invariably robust against modifications other than those implied by changing PT</u>. The “aims the manuscript pursues” were/are given too, namely <u>that garnets treated in the MS and particularly their Ca contents are shown to be susceptible to change also by intracrystalline diffusion and metasomatic processes, calling thus into question the above assumption.</u> We offered/offer physically based criteria and methods for evaluating observed microstructures and composition patterns. These criteria are generally applicable and, we reckon, that they are of interest to a broad audience involved in evaluating petrographic data and in quantifying PT-conditions of rock metamorphism from metamorphic rocks themselves. It is rather boring to list here the numerous places of the MS, where implications beyond the regional/local context are addressed. A short list of outcomes interesting for a broad audience is given in our response to the last underlined part of your §1c.

Table 1 is an integral part of the problem set up and "belongs" primarily to the Introduction. It emphasizes the divergence of PT-estimates calculated on the basis of the above assumption; it is complemented with geodynamic implications therefrom, which are mostly speculative. Of course, Table 1 serves also the Section "Geological background".

Your §1c:

Criteria for sample selection, sample location and constituent mineralogy are not provided. A table is needed. As far I have understood, your study is based just on one sample? How representative? How chosen? *This information would greatly help the reader to evaluate the scientific rationale followed in this study.*

There are many points "condensed" here. Let us start with the sample location and copy/paste page 5, lines 9 – 14 of the MS you have annotated, as well as Caption of Fig. 1 (the only change with regard to the version you have annotated, is the original word "inlay" replaced by "inset" according to your suggestions in the annotated pfd-file).

> "Seven samples of mafic granulites were collected from **loose boulders dispersed over the steep flanks of the Mitterbachgraben** (inset, Fig. 1). The local bedrock comprises serpentinites pertaining to the mantle-derived peridotite of the Dunkelsteiner Wald. The ultramafic rocks form several 100 m long lensoid bodies embedded in mylonitic felsic granulite. The collected samples are noticeable in the field, as they do not belong to the regionally widespread rock types in this area. They are dark gray, middle to fine-grained, mostly granofelsic mafic granulites containing abundant pyroxene and kelyphitic reddish-brown garnets of occasionally striking large size up to 1.5 cm."

> Figure 1. "Simplified geological map of the Austrian part of the Moldanubian Unit modified after Schnabel (2002), Krenmayr et al. (2006), Cháb et al. (2007) and Kalvoda et al. (2008). DW signifies the Drosendorf Window. **The inset is a sketch of the sampling area** of the mafic granulites (embedded within felsig granulites) at the **steep flanks of Mitterbachgraben**. **The land road Gansbach-–Kicking as well as the GPS-coordinates at the star are shown** (after Sheet 37, "Mautern", Geological Survey of Austria)."

So, we think that the sampling location is adequately given. It is not about outcrops to be listed with GPS coordinates in a Table, but loose boulders at the steep flanks of the Mitterbachgraben, indeed, a sampling location of restricted areal extent.

The sampling criteria are also given; please see the underlined part of the text above. Additionally, the information is given (page 5, lines 15 – 20) that the collected rocks are interesting objects by previous work done on them (Carswell et al., 1989).

The sample description is given too. The samples are described chemically by stating their normative contents (page 5, lines 21-32) and compared, due to their peculiar composition, with other similar or related rocks known from literature. The rock analyses are given in the Supplement. Here is the appropriate text, please, re-evaluate.

> XRF-analyses of the collected samples reveal K-poor, Mg-rich compositions with Xmg ranging within 0.70–0.82 (see Supplement). In terms of normative contents, they contain crn in the range 10 to 16 %. Three of them contain an in the range 9 to 19 %; the other four samples contain instead ol between 3 and 9 %. The di contents of all samples vary between 48 and 61% and the hy content between 3 and 19 %. The ab content varies between 9 and 19 %. Some of the samples (UM5, UM6, UM8) resemble the corundum-bearing garnet clinopyroxenites from the Beni Bousera ultramafic massif that have been considered as low pressure crystallization cumulates from plagioclase-rich gabbros of ophiolitic affinity that underwent subduction and re-equilibration at mantle conditions (Kornprobst et al., 1990). Svojtka et al. (2016) assigned the Dunkelsteiner Wald pyroxenites to LREE-enriched melts of the subcontinental lithospheric mantle. In comparison with Al2O3 contents of 15–24 wt.-% in the samples presented here, their pyroxenitic samples are characterized by significantly lower Al2O3 not exceeding 12.23 30 wt-% and higher Xmg = 0.87 – 0.90. Based on the pronounced peraluminous composition variability, we consider our samples as mantle-derived clinopyroxenitic melts that have assimilated variable amounts of Al-rich crustal material during ascent and tectonic emplacement to their current position.

To your question about <u>the one sample</u> and its representative power. Yes, the MS is dealing with one sample and more sections thereof. All collected samples are mineralogically similar (Grt+CPX+PL with minor HbL), but the one selected for intensive investigation contains exceptionally large garnets with an exceptionally high number of features described in the MS. Please, re-evaluate page 5, lines 32 – stating the following.

> The following presentation and discussion is focused on sample UM8 that contains some large garnets with an unusual high number of features. This sample is the most magnesian and peraluminous of the whole collection (Xmg = 0.82 with normative crn = 14.07 % and an = 18.78 %).

In order to avoid further misunderstandings, the above text has been extended in the new version as follows (the essential part is underlined):

> <u>The collected samples are mineralogically similar containing slightly variable amounts of clinopyroxene, plagioclase and garnet accompanied by some hornblende.</u> The following presentation …..

Regarding the <u>last underlined part of your §1c</u>. I don't quite understand, what is meant here. I can only guess. Indeed, when collecting these samples, we could not anticipate that they will provoke questions about Ca-rich garnets, about their potential susceptibility to metasomatic modification and re-adjustment of composition by intracrystalline diffusion, about their almost isochemical break-down to symplectites under "Moldanubian" conditions, about the recognition of their state of equilibrium or non-equilibrium, about reliability by using them in PT-calculations, about intragranular deformation features, about poikiloblast-resembling growth, about a lot of other features reported in the MS. We think that all these aspects, though obvious to a specific study object, are of interest in the broadest context of petrology and assessment of the tectono-metamorphic history of high-grade rocks (cf. about "advancement of knowledge" in your comment §1a). In fact, we are very happy and very lucky to own these samples, especially the one treated in the MS.

Your §2a:

A figure dealing with the regional geology is not provided in the Introductio section, despite essential for people not familiar with the regional geology.

This is somewhat puzzling. The appropriate Fig. 1 showing a simplified geological map is on page 4 and is referring to the second section of the MS dealing, in our opinion, adequately with the regional geology. That a figure or whatever "dealing with the regional geology" is part of the introduction is very new to me. According to your comment §1b

> *"The Introduction, rather than focusing just on the specific case, <u>should instead introduce the general geological problem</u>, … "*

Your §2b:

a Materials and Method section is missing and this information is mixed up with the introduction statements (see the ending part of the Introduction section). This section should also provide analytical details.

This is half of the truth. Indeed, such information is missing in the MS, but, as stated in page 2, lines 26-27 it is present in the Supplement. Why in the Supplement? We have always been concerned about the length of the paper and decided to put it there, because it takes another three full pages including an additional Table and an additional additional figure (of course tables of rock and microprobe analyses are excluded). The claimed information is not missing, but placed into the supplement. Please, re-evaluate the Supplement and appreciate the volume of data, the transparent and exact description of methods as well as the volume of work done on this single sample. Further three pages about devices, device settings, recalculation methods etc. may be boring for the general reader that wishes first to get the essential outcomes of the MS. For the reader interested in these "technical" matters, the Supplement provides thorough information. But, on the other hand, pointing to the Methods by reference to the Supplement at the last paragraph of the Introduction, is, indeed, not elegant. So, we created a short new section called "Methods of data acquisition and recalculation" providing essentially the same information about the Supplement together with mineral abbreviation etc. Please, check the new version.

Your §3 (last part):

The Authors are thus encouraged to expand the implications of this study and extract results that can be of interest for a broader audience, i.e. broaden the impact of the presented results away from the study area. A specific sub-section of the Discussion dedicated to these broad implications would greatly increase the impact and relevance of the study.

Yes, this is indeed a straightforward constructive point. Things can always be done better. In this sense, we have partly reformulated and / or extended the Abstract, the Introduction, the Discussion and the Conclusions. The new versions are given in the next pages.

At the end of your comments:

I have provided an annotated version of the manuscript, where these and other points that need further consideration by the Authors are detailed.

Thank you very much, it was very useful.

Broader impact of this study is primarily depending on how this criticism will be addressed in the revised version. Critical on this regard is the re-organisation of the Introduction, Discussion and Conclusion sections

We have done our best.

With best regards.

K. Petrakakis in the name of all co-authors

New versions

The most essential changes/insertions/extensions relative to the version you have annotated are underlined.

Abstract

Mafic peraluminous granulites associated with the mantle-derived peridotites of the Dunkelsteiner Wald provide evidence of the tectono-metamorphic evolution of the Gföhl Nappe System, Austria. They contain the primary assemblage garnet + Al-rich-clinopyroxene + kyanite. Large Ca-and Mg-rich garnets are embedded in a granoblastic matrix of Al-rich-clinopyroxene, Ca-rich-plagioclase and minor hornblende. They have been partially replaced by different generations of symplectites: (a) corundum + sapphirine + spinel + plagioclase formed around kyanite inclusions, (b) orthopyroxene + spinel + plagioclase ± hornblende formed at their rims and (c) clinopyroxene + orthopyroxene + spinel + plagioclase ± hornblende formed within cracks.

The garnet show a complex compositional structure comprising several repeatedly occurring garnet types, which are characterized by specific compositions. The areal extend and the cross-cutting relations observed in element distribution maps allowed for the derivation of the relative timing of the formation of the different garnet types. The compositional features of the garnets indicate post-formational modification by intracrystalline diffusion and metasomatic agents.

The garnet composition isopleths in equilibrium assemblage diagrams are in line with compositions modification as indicated by the element distribution maps. They confirm the deviation of composition from equilibrium for all garnet types. Furthermore, the latest garnet types show evidence of metasomatic (Fe+Mg)-loss affecting their Ca-content. <u>PT-estimates are based on equilibrium assemblage diagrams that reproduce satisfactorily the observed mineral assemblages and measured mineral compositions. Criteria for checking the existence of preserved equilibrium compositions are suggested. The results call in question the invariability of the assumption that the Ca-content and/or zoning in garnet preserves primary PT-information from garnet growth in every case.</u>

Recrystallization and compositional readjustment of the reactive garnet volume during symplectite formation has led to the development of pronounced, secondary diffusion-induced zoning profiles overprinting the different garnet types and post-dating the complex garnet compositional structure. The primary assemblage is stable between 760 and 880° C and pressures >11 kbar. The bulk

composition of the crack- symplectites is almost isochemical to the oldest, breaking-down garnet type. These symplectites have been formed above 730° C and pressures between 7.5 and 5 kbar. The studied rocks have undergone a more or less isothermal decompression from pressures above 11 kbar to ~6 kbar at temperatures of about 800° C. Crack- and rim symplectites have been formed after decompression during approximately isobaric cooling under conditions of low differential stress. Due to limited availability of fluids promoting symplectite formation, the time-scale of symplectite formation calculated from secondary diffusion profiles associated with crack- symplectites is shown to be geologically very short (< 0.5 ka).

Section Introduction

Reconstruction of the PT-conditions attained by metamorphic rocks during their evolution provides key information for the assessment of geodynamics of orogenic belts. Reconstructions of the PT-history of metamorphic rocks are based on the thermodynamic analysis of equilibrium phase relations. Thereby, preservation of equilibrium is often difficult to assess and often is tacitly assumed rather than rigorously tested. Especially in rocks metamorphosed under granulite facies conditions, the equilibrium phase relations attained at peak metamorphic conditions may be modified in the course of slow cooling, or due to recrystallization, repeated deformation and retrogression.

Due to its refractory nature, garnet is considered as one of the most reliable mineral in preserving its original composition. Based on its low inter-diffusion coefficient, Ca in garnet is supposed to be particularly robust and hardly affected by late recrystallization and retrogression. With this study, we challenge this proposition by analyzing granulite-facies rocks from the eastern-most part of the Moldanubian Zone of the Variscan Orogen exposed in the Czech Republic and in Austria (cf. Fig. 1).

Over about the last three decades, the assessment of the PT- evolution of granulites and associated rocks within the Moldanubian high-grade Gföhl Nappe System has been addressed by several tens of papers. The high number alone points to a poor agreement of the estimated PT and PT-path interpretations. Table 1 is a representative selection of the most recent PT-estimates complemented with obvious geodynamic implications resulting therefrom.

The PT-estimates in Table 1 are based on three approaches. The first approach used conventional continuous-reaction thermo-barometry involving integral ternary feldspar compositions from perthite and antiperthite, Na-bearing clinopyroxene and the Ca-content in garnet (O'Brien, 2008; Vrána et al., 2013, and references therein). The calculated PT- conditions are about 1000° C and 15–20, occasionally more, kbar. The second approach claims additionally the derivation of the prograde path of the rocks with the aid of equilibrium assemblage diagrams (pseudosections) mostly combined with results of conventional geothermobarometry relying again on garnet Ca-content (Štípská and Powell, 2005a; Racek et al., 2008; Štípská et al., 2014a; Jedliˇcka et al., 2015, 2017). This approach implies the most complex geodynamic evolution of the rocks (cf. Table 1). The third approach aims similarly at the derivation of PT-conditions, but points also to anatectic and open- system processes that have affected rocks and minerals under the specific "Moldanubian" conditions (Hasalová et al., 2008b; Štípská et al., 2014a).

The most probable reason for the observed divergence of PT- estimates is that in such rocks partial or complete re-adjustment of rock microstructures, mineral abundances and compositions during their multi-stage tectono-metamorphic evolution may hinder the calculation of consistent PT-estimates. Critical discussions about the deviation of minerals from equilibrium composition are, indeed, found in most of the papers given in Table 1. The discussions deal with (i) the diffusion-aided Na-loss in clinopyroxene during the granulite facies overprint, (ii) the effects of decompression and rock recrystallization, and (iii) the available thermodynamic properties of minerals and their validity for thermobarometric calculations. However and irrespective of thermodynamic method used, all PT-estimates listed in Table 1 are based explicitly or implicitly on the assumption that garnets and especially their Ca- contents have been hardly affected by processes other than changes of PT and that, therefore, any observed Ca-zoning has preserved past PT information.

In this paper, we address Ca-rich garnets (cf. Table 2) and associated symplectites in mafic, garnet-clinopyroxene-kyanite granulites that call into question the invariability of the above assumption. Extensive microprobe analysis and element mapping showed that the garnet composition, in particular the Ca-content, has been modified by intracrystalline diffusion and metasomatizing agents. Extending the possibilities currently offered by the calculation of equilibrium assemblage diagrams, we present criteria for the evaluation of preserved equilibrium compositions by checking the behavior of phase component isopleths. We emphasize the reliability of PT-estimates derived from equilibrium assemblage diagrams in case they reproduce satisfactorily the observed assemblages and mineral compositions. We have resolved the late evolution of the Moldanubian samples at hand with particular reference to garnet behavior. Garnet composition modification has predated a largely isothermal decompression that started above 11 kbar at a temperature of c. 800° C. This decompression induced garnet break-down and local compositional re-adjustment and recrystallization of garnet associated with the formation of different, locally controlled symplectites within a very short time interval during early, post-decompression, H_2O-undersaturated conditions that were characterized by strain-free, almost isobaric cooling at c. 6 kbar.

Section Discussion

Subsection added on page 27, Line 35: **Towards more reliable PT-estimates**

Apart from emphasizing the inherent uncertainty in the PT estimates of the mafic granulites of the Gföhl Nappe System a more general implication of our analysis needs to be addressed. Despite of the refractory nature of garnet, its composition may be strongly modified during high-grade metamorphism. The primary composition zoning attained during growth may be partially or completely obliterated by intracrystalline diffusion during prolonged high-temperature metamorphism and/or during successive stages of recrystallization, partial replacement or diffusion-mediated metasomatic alteration. Chemical alteration of garnet can be directly identified from secondary chemical zoning that is directly related to late-stage features such as cracks, veins or resorption features. More cryptic alteration such as homogenization during thermal annealing may be difficult to identify by petrographic means. In such case, the comparison of observed garnet compositions and calculated garnet-composition isopleths in equilibrium assemblage diagrams (pseudosections) is the method of choice for testing, whether an equilibrium composition was preserved or the garnet composition is due to post formational modification. When reconstructing the PT conditions of high-grade metamorphic rocks, such a test is mandatory. Even at conditions, where mafic granulites are well below their solidus temperature, anatectic melt derived from nearby felsic granulites may serve as a metasomatic agent that facilitates chemical mass transport and, at the same time, speeds up mineral reactions. Typically, in case of Gföhl Nappe System within the Moldanubian Zone, mafic granulites are comparatively small rock bodies immersed in more voluminous felsis granulites. Interaction between felsic and mafic lithologies at granulite faices conditions is an efficient and widespread process leading to partial loss of the "petrogenetic memory" of otherwise refractory minerals and rock types.

Section Conclusions

a) Last item deleted.
b) The following two items added after the item "Calculated equilibrium assemblage diagrams and analysis of the measured garnet component isopleths …."
    - Calculation of equilibrium assemblage diagrams (pseudosections) allows for the evaluation of the equilibrium or non-equilibrium state of minerals, particularly of garnet that is commonly included in calculations of PT-estimates. With these techniques the observed mineral assemblages and measured mineral compositions may be reproduced adding to the reliability and confidence of PT-estimates and PT-paths derived therefrom.
    - At least for metamorphic conditions pertaining to high-grade Moldanubian rocks, the commonly made assumption that measured Ca-contents and Ca-zoning in garnet invariably preserves past PT-information is called into question.

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