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Interactive comment on "Experimental deformation and recrystallization of olivine – processes and time scales of damage healing during postseismic relaxation at mantle depths" *by* C. A. Trepmann et al.

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We thank the anonymous referee for the very thorough and constructive review. We appreciate all suggestions and comments and will carefully consider them when preparing a revised manuscript. In the following we respond to all raised points one by one, answer questions and indicate, how we intend to follow the suggestions and indicate corresponding modifications. Comments by the referee are in quotation marks.

1) "Suggestion to share the paper in two companion papers: a) experimental deforma-

tion and annealing of peridotites (kick-and-cook experiments) and b) implementation or extension of the Avrami-kinetic equation on recrystallization kinetics."

Experimental observations and their analysis are inseparable from our point of view. Avrami-kinetics is applied to analyze our experimental findings with the aim of providing a substantial basis for extrapolation to natural conditions. Presenting the experimental observations in an isolated manuscript without substantiating implications by a kinetics analysis would lead to the (in)famous "so what". The kinetics-analysis on its own would remain quite academic.

2) "Cataclasis - They describe intra- and inter-granular fractures, highly damaged zones and fragments, but never use the term of "cataclasis". However, all ingredients for cataclasis seem to be present ..."

The term "cataclasis" is not used because it does not include the coequal aspect of crystal-plastic deformation as observed in the "highly damaged zones". The brittle and the crystal-plastic deformation cannot be seen independently at the given deformation conditions, therefore we prefer addressing the deformation regime as "low-temperature plasticity" instead to account for the coeval occurrence of crystal-plastic and brittle mechanisms in the highly damaged zones. Low-temperature plasticity has been found by Druiventak et al. (2011) to be the strength-controlling process, especially at deformation temperatures of 600°C, characterized by an absence of pressure-dependence of strength.

"...and, in the highly damaged shear zones, we may expect some rigid rotation and high misorientation between small fragments which should survive after annealing. Papers by Druiventak et al. describe the CPO of new olivine grains after "kick-and-cook" experiments but not after "kick only" experiments. ". I think that this step is necessary to check if scattering of CPO in new grains is mainly due to "kick" (damage) or to "cook" (annealing-recrystallization). Moreover, as "comminution" is inferred as one of the two mechanisms of formation of the new recrystallized grains, it would be useful to characterize this comminution before the "cook" experiment by some observations with an SEM-FEG for example (shape and size of the comminuted grains and of the pores between them)."

After the “kick” stage, only fragments are present. Recrystallized grains were exclusively observed after annealing. The fragments and misorientation of fragments in highly damaged zones directly after the kick stage was described and displayed in FEG-SEM images and TEM micrographs by Druiventak et al. (2011, e.g. Fig. 6 and Fig. 8), a paper that focused on the "kick" stage of the experiments. In the current manuscript, we focus on the annealing stage and Fig. 4 shows that the misorientation of fragments inherited during kick experiences little modification during subsequent annealing at low temperature of 700°C. Fig. 4a shows an EBSD map (performed on a FEG-SEM) and Fig. 4b-d shows TEM-micrographs from highly damaged zones. We observe both, misorientation between the fragments but ALSO an increase in relative misorientation within individual fragments (cellular structures, high dislocation densities) due to crystal-plastic deformation.

To summarize the major point "cataclasis", we suggest for the revised text (Chapter 4): "The fragments in the highly damaged zones show a marked misorientation with misorientation angles of 30° to 50° (Druiventak et al., 2011, their Figs. 6 and 8). Little modification of misorientation characteristics arise during subsequent annealing (Fig. 4). As such, the fragments show both, a misorientation between each other due to rigid body rotation and at the same time substructures (i.e. patchy undulatory extinction in polarization microscope and cell-structures, high dislocation densities in TEM) due to crystal-plastic deformation."

3) "Terminology: the term "recrystallized host fragments" is confusing. As far as I know, recrystallization is defined as the creation of new grains from highly deformed parent grains either during deformation or during a post-deformation anneal (Nicolas and Poirier, 1976, p. 137). Recovery (re-organization of dislocation) occurred in these host fragments which are not new grains. In my point of view, the growth of the

host fragments during annealing ("cook") has not been demonstrated and migration of their grain boundaries neither. Why not "annealed host fragments" or solely "host fragments"? As a consequence, the term "recrystallized grains" used to designate the assemblage of "new grains" and "recrystallized host fragments" is also confusing. I strongly suggest to use "porphyroclasts" (as is in the paper) and "mosaic" where new strain-free grains and small porphyroclast fragments coexist. This is not only a problem of terminology, but concerns different mechanisms and makes the discussion unclear (page 479 lines 20-27 and page 481 lines 6-14, for example)."

We greatly appreciate this comment and admit that the currently used terminology may be confusing. We propose to change the terminology as follows: We will use the term “new grains” as the superordinate concept comprising âĂć “fragments” (small fragments from the original grains; formed in highly damaged zones with inherited defects; present already after low-temperature deformation; modified by recovery and grain-boundary migration during isostatic annealing) and âĂć “recrystallized grains” (evolving during annealing from small dislocation free crystalline volumes in highly damaged zones). “Porphyroclasts” are large remnants of the original grains in low-strain areas with inherited defects. The differentiation in types of grains is necessary but in parts quite subtle, also because their characteristics change during the experiments. Some fragments (in particular small ones for which the average distance for a dislocation to the surface is small) may indeed anneal early on and then evolve exactly like recrystallized grains. Furthermore, the distinction between recrystallized grains and fragments is straightforward when inspecting individual grains using TEM, small EBSD maps and polarization microscopy (given sufficient size) but rather impossible on the scale of an entire sample. In particular, the CPO and grain size analyses resting on large EBSD data sets comprise both, fragments and recrystallized grains. In our revision we will use this new terminology.

4) "CPO of recrystallized grains - The Fig. 10b shows new grains in an intragranular fracture. In this case (001) are less scattered than (100) and (010) which are sinis-

trally dispersed (no point on the right-hand side of the blue dot). It may tell us that the microfracture has moved sinistrally -which is consistent with a vertical shortening direction- and that the small grains issued from cataclasis have suffered a solid rotation around (001) which is within the shear plane and perpendicular to the shear direction (blue dots in Fig. 10b). In the larger agregates, the host fragments are larger and, therefore, do not rotate easily and are able to keep the memory of the crystallographic orientation of the host crystal as the authors point out (page 479, lines 26-27)."

The polefigures in Fig. 10b may indeed suggest that the [001] direction represents a rotation axis. However, to use the crystallographic orientation of new grains to infer a correlation between rotation of fragments and shear sense along the microfracture remains arguable in the light of the two different types of new grains: Some of the grains along the microfracture (red rectangle in Fig. 10b) are probably “recrystallized grains”, formed by nucleation and growth from highly damaged zones, where the high misorientation to the host crystal (indicated by the yellow and red colours in the EBSD map and pole figures of Fig. 10) is due to the highly strained volume from which they nucleated. "Fragments" with little rigid body rotation can show small misorientation angles to the orientation of the host (green-blue grains). Furthermore, in the polefigures in Fig. 10c, new grains from the whole area are displayed, where part of the new grains are derived from the neighbouring porphyroclasts. We will mention that the polefigures in Fig. 10b suggest that the [001] direction represents a rotation axis in the revised manuscript.

5) Other comments "As mentioned in the introduction, I did not check the maths. However, I was very perturbed by the absence of definition of the parameters used in the equations (page 481 and following)."

Indeed, the parameters in equation (1) and (2) were unfortunately not explicitly defined in the text. They are, however, explained in Table 3: ΔG denotes the difference in free energy, i.e. in our case, the driving force for growth of recrystallized grains; ΔG and $\Delta G\gamma$ denote the difference in free energy associated with dislocations and interfaces,

respectively; ddef and drec denote the grain diameter of deformed grains (including fragments) and recrystallized grains, respectively; def and rec are dislocation densities of deformed grains and recrystallized grains, respectively; γ is the grain boundary energy, μ the shear modulus and b the Burgers vector; and are the activation enthalpies of grain boundary mobility and dislocation recovery, respectively. The notation will be clearly stated in a revised text.

"References to related works: - Experiments of "kick-and-cook" have been performed with analogs (camphor, octachloropropane) that document the static recrystallization (see as one example the paper by Urai and Humphreys, 2000, http://virtualexplorer.com.au/special/meansvolume/contribs/urai/index.html; Piazzolo et al., Tectonophysics, 2006). I think that this literature has to be refered in the present paper as some similar experiments in ceramics."

We appreciate the additional references, which will be cited and accounted for in a revised text (Chapter 2.1.)

" In the discussion, a comparison of the results of these experiments with natural examples of "kick-and-cook" deformation in peridotites would be welcome I believe that the authors will have some examples in mind. Peridotite xenoliths in basalts or kimberlites are good examples because they have been deformed in the mantle and cooked in the lavas during their ascent. In some ultramafic massifs, pseudotachylytes or very high-strain shear zones have been described in peridotites. Is there some analogy in the host peridotites with the experiments presented here?"

Very similar microstructures with localized zones of new grains within or surrounding deformed porphyroclasts and a weak, unsystematic CPO, are reported from shear zone peridotites of the Ivrea zone (Druiventak et al., 2012; Matysiak and Trepmann, 2012). In peridotites from the Balmuccia complex of the Ivrea zone, these diagnostic microstructures occur in relation to pseudotachylytes, giving independent evidence of a high stress and strain-rate event (i.e. seismic activity in a nearby region). We will add a remark on this similarity in Chapter 5.5.2.

"page 467 -the initial material is a coarse-grained natural peridotite (Almklovdalen, Norway). Is it a chlorite-bearing peridotite or a Aheim dunite? In the first case, what happens with chlorite at high temperature (700-1100C)? -line 19: 2GPa? "

The initial material is a chlorite-bearing peridotite. Chromium chlorite is present in the peridotite and after annealing it is replaced by alteration products, a corresponding note will be added.

"Page 469 -lines 16 and following: As the grain size measurement is important in this paper, it could be useful to show an example. Why the expectation (expected?) value? Why not the mean value? -"

We used the weighted average (expectation value) rather than the arithmetic average (mean value) to account for the skewness of distributions of grain sizes (a high frequency of small grain sizes and low frequency of coarse grain sizes). Examples of grain size distributions will be displayed for the EBSD data shown in Figures 7 and 8 (see uploaded figures).

"Plots of EBSD data: precise if all the measurements are used in the plots or if only One Point Per Grain (OPPG) is used. Precise also if the orientation of the plots is always the same (shortening direction orientated NS)."

We use the complete data set, especially for new grains, as the OPPG data set would over-interpret artifacts that are present for small grains. Generally, there is no marked difference in the characteristics of the patterns for the complete data set or OPPG. We will specify in the respective figure captions that we used the complete data set.

"Page 471: - line 6: could you show the stress-strain curves for the "kick-and-creep" and the "kick-cook-kick" experiments?"

In “kick-and-creep” tests, changes in pressure and temperature conditions are imposed on the loaded sample. Changing conditions however hinder a sensible friction correc-

tion. Thus, classic stress strain curves cannot be provided but we have to refrain to the presented back-of-the-envelope calculations regarding stress and strain in the creep phases of the experiments. We can provide stress-strain curves for “kick-cook-kick” experiments though the added information is rather limited. These curves exhibit the same principal features as the presented curves but suffer from a somewhat increased uncertainty regarding the friction correction.

"Page 474: -line 5: The grain size in mosaic will increase with increasing "cook" temperature, but in detail, I guess that only the size of the new grains increases when the size of host fragments should decrease."

The reviewer correctly describes the subject: the average size of “new grains” increases, whereas the average size of porphyroclasts decreases, see page 475, lines 4-7 ” the grain size of porphyroclasts shrinks as they are replaced by the growing new grains (Fig. 8a).”

"-line 7-9: The variability slightly increases with increasing annealing temperature and annealing time (Fig. 5c and 5d) not only in absolute values but also relative to the expectation values (Table 1)."

We will change the reference to the Figures/Table, as suggested.

"Page 474: -line 19: LAGBs are visible in fragments of host grains when HAGBs are mostly visible in new grains. Could it be an artefact due to misindexation or to pseudosymetry in olivine?"

The observation of LAGBs in “fragments” is confirmed by a correlation between EBSD-data and TEM observations from site-specific FIB-cut TEM samples (Figs. 8, 9). Sutured grain boundaries and LAGBs are THE characteristics to distinguish them from “recrystallized grains”.

-line 26: "Even after isostatic annealing at 1100C for 69 h, the recrystallized host fragments (labelled “h” in Fig. 8a) show mostly concave and sutured boundaries whereas new grains exhibit isometric shape with curved convex boundaries."

We will relocate the reference to the Figure as suggested.

"Page 475: - line 26-28 (Fig. 11): in the B9028 sample, the new grains are completely different from the host grains but the host fragments have similar orientation than the host grains. Is there any difference in this case between all points plots and the OPPG plots?"

As mentioned above, there is generally no marked difference in the characteristics of density plots for the complete data set or OPPG. Especially for recrystallized grains we use the complete data set, as the OPPG data set would over-interpret artifacts that are present for small grains. Yet, we noticed a mistake of the CPO pattern of small grains in sample B9-28. Figure 11 is corrected accordingly.

"Page 476: -line 7: "average" or "expected"?"

The average grain diameter is given as the expectation value of the associated grain size distribution (p. 469: line 18-19).

"p. 476-line 9: "the observed CPO patterns are variable with strong scatter in orientations and unsystematic correlation with the host orientation (Fig. 11)": control by the host orientation is stronger in B9037 and B9038 than in B9028 and B9036 which were described as a "marked imprint of the crystallographic orientation of the host crystal" (page 475, line 24-25)."

The sentence in p. 476, line 9 will be rephrased as: “the observed CPO patterns are variable with strong scatter in orientations, unsystematic correlation to the shortening direction, and instead, with a similar orientation pattern compared to the host orientation (Fig. 11).”

"Page 479: -line 1: "some thermal effects" -line 18: "has also been observed""

The mistakes will be corrected.

"Page 480: -line 16-20: This section is not very clear. Give reference for the positive correlation between d and T and precise that of the negative one between d and strain. "A positive correlation between the final grain size attained during static recrystallisation and annealing temperature as observed here (Fig. 5b, c, Table 1) has also previously been reported (references), as has a negative correlation between resulting grain size and accumulated bulk strain during the preceding deformation in metals (e.g. Fig. 4.16 in Nicolas and Poirier, 1976; Humphreys and Hatherly, 2004)."

Example references for studies that report a positive correlation between the final grain size attained during static recrystallisation and annealing temperatures are: Nicolas and Poirier, 1976; Humphreys and Hatherly, 2004.

"Page 481: This paragraph is not entirely clear because of the used terminology "recrystallized host fragments" (spelling is recrystallised in some places and recrystallized in others). Lines 6-7 are a good example: "In contrast, at some distance of the highly damaged zones fewer and larger recrystallised grains (up to 40 μm) occur (Fig. 10a), likely due to a lower nucleus density for new grains and/or predominant occurrence of recrystallized host fragments over new grains." Why not: "In contrast, at some distance of the highly damaged zones fewer and larger recrystallised new grains (up to 40 μm) occur (Fig. 10a), likely due to a lower nucleus density for new grains and/or predominant occurrence of host fragments or porphyroclasts over new grains"? -line 9-12: "Furthermore, for the new grains that are almost free of defects on the one hand and the recrystallized host fragments that inherit the deformed microstructure on the other, variations in the driving force for growth during isostatic annealing have to be considered".In my point of view, the growth of the host fragments has not been demonstrated and migration of their grain boundaries neither. There is apparently no difference on the dislocation densities or microstructures between the core and borders of host fragments. -line 19-21: here there is only two types of grains: the new grains (interfacial energy) and the deformed grains (strain energy). It is much clearer and much simpler, even if the distinction is not easy and if both types may be mixed together in the mantle zone of the core-and-mantle structures."

We will clarify the terminology (see above) and correct the spelling. Strain-induced grain boundary migration is indicated by sutured and characteristically curved boundaries especially between dislocation-free “recrystallized grains” and “fragments” (or porphyroclasts) with inherited dislocations and LAGBs, as shown in Figs. 7, 8, 9c, for example (see text e.g., Chapter 4.1.2, p. 474, line 19 – p. 475 line 18). The defect-free crystalline volume (“recrystallized grains”) grows on the expense of the deformed crystalline volume with inherited dislocation density (i.e., “fragments” and “porphyroclasts”).

"Page 482 - line 26 and following, plateau in the grain size: we may expect that migration of grain boundaries may be limited by the number of the grains during the first stages of annealing and that, after a sufficient duration, Ostwald ripening may occur. Then, the smallest grains will disappear and the average grain size will increase (analog see-through experiments, http://virtualexplorer.com.au/special/meansvolume/). Is the duration of experiments long enough to allow Ostwald ripening?"

Our experiments show parallels to Ostwald ripening in as much as nucleation ceases early on. However, the driving force for growth is constant for classical Ostwald ripening while here the driving force for growth of defect-poor grains diminishes with annealing time since their environment exhibits recovery (i.e., reduction in defect concentrations).

"Page 483: "Two alternative explanations deserve consideration. Firstly, ... Secondly, ...". The second consideration(continuation nucleation) is unlikely. A sentence of conclusion is waited there. If the resolution limit of the EBSD analysis is responsible for the initial stagnation of the grain size, it is important to well describe the method and to give an example (see remark above, page 469)."

We agree that continuous nucleation is unlikely, as stated on page 483, lines 11-14: “Yet, we consider a significant continuous nucleation rate during annealing unlikely, because the “nuclei” in this type of recrystallization phenomena are actually formed

during the deformation stage.” Examples of the grain size distribution are integrated into Figure 7 and 8 (see uploaded Fig. 7 and 8).

"Page 493: -line 24: "control recrystallization, the effective activation energy""

The mistake will be corrected.

"Page 494: -line 2-5: the sentence is too long and not understandable."

We will rephrase the sentence to: “The extended model predicts, however, a dominance of the thermal activation of grain boundary migration (i.e. again a single activation enthalpy) controlling the recrystallization progress at temperatures of 600°C or lower, rather than a time and temperature dependent effective activation energy."

"Page 494-495: - Diagnostic microstructures: this is a very important point and a major contribution of this paper. As the grain size distribution in recrystallized areas may be one recognition criteria, it should be better explained and described by at least one example in this paper."

Examples of grain size distributions will be displayed for the EBSD data shown in Figures 7 and 8 (see uploaded figures).

" -Reloading: "kick-cook-kick" experiments and localization of the second strain in porphyroclasts. Intuitively, I would expect that a fine grained aggregate would be more difficult to deform than a coarse grained aggregate at low temperature by dislocation gliding because dislocations glide will very quickly pile-up at the grain boundaries. Therefore, strain will be shortly limited in the fine grained aggregate by work hardening."

Strain appears to be accumulated preferentially in the larger grains that can be more easily deformed than fine-grained aggregates during low-temperature plasticity (inverse relation of strength to grain size, i.e., Hall-Petch effect).

"Figure 5: Labels a, b, c and d are missing."

We will add the labels in Fig. 5.

"Figure 7b: LAGBs are visible in fragments of host grains when HAGBs are mostly visible in new grains. Could it be an artefact due to misindexation or to pseudosymetry in olivine?"

The observation of LAGBs exclusively in “fragments” is confirmed by a correlation of EBSD-data and TEM observations from site-specific FIB-cut TEM samples (Figs. 8, 9).

"Figure 10a: FIB Locations of Fig. 7b-d and Fig. 7e, f are shown in yellow on this EBSD map. But there is no corresponding figure in the paper. I guess that these should be Fig. 9b-d and Fig. 9e, f."

The mistake will be corrected.

"Figure 13: the distinction between the different patterns is not as clear on the on-line version as on the printed version."

We will change the grey scale of the patterns in Fig. 13.

Interactive comment on Solid Earth Discuss., 5, 463, 2013.

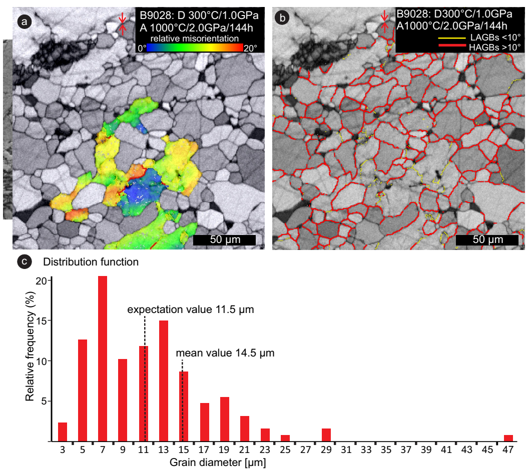

Fig. 1. New Figure 7. EBSD map of sample B9028 with grain size distribution added.

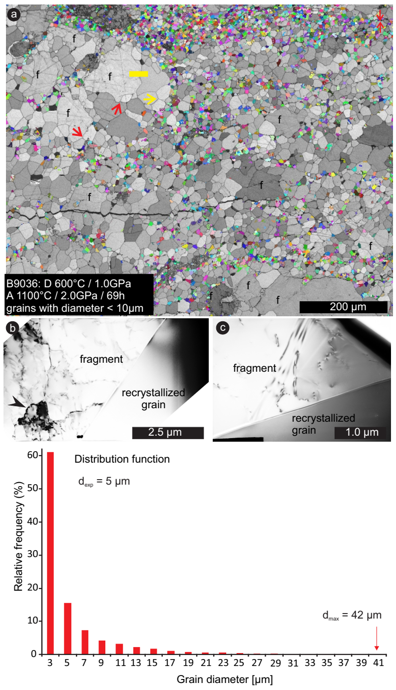

Fig. 2. New Figure 8. EBSD map of sample B9036 with grain size distribution added.