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Discussion

Lost in interpretation: Facts and misconceptions about the mantle of the Siberian craton. A comment on: “Composition of the lithospheric mantle in the northern part of Siberian craton: Constraints from peridotites in the Obnazhennaya kimberlite” by Sun et al. (2017)

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Sun et al. (2017) reported petrographic, chemical and Os isotope data on eleven mantle xenoliths from the Obnazhennaya kimberlite and claimed that their results enable them to establish “*the character of the lithospheric mantle beneath the northern Siberian craton*”.[1] Here we show that their results are neither novel nor pertinent, and that errors in data treatment and interpretations discredit many of their conclusions.

1. Petrography and chemical composition

One series of unfounded claims in the paper of Sun et al. (2017) serves to warrant the novelty of their petrographic and chemical data: “*…no full set of petrographic and chemical compositions were given for these samples* (referencing Obnazhennaya xenoliths studied in Ionov et al. (2015)). *Therefore, the character of the SCLM underneath the northern of craton is still unclear*” (*p. 384, Introduction*). The authors failed to note that Ionov et al. (2015) reported a summary of essential petrographic, e.g. modal abundances, chemical (Al, Ca, Cr and Mg# in whole-rocks; Mg#$_{Ol}$, Cr#$_{Spl}$), Re-Os and PGE data on 19 Obnazhennaya xenoliths and established that the mantle lithosphere was formed by melting of fertile mantle ~2.0 and 2.8 Gy ago, and later experienced metasomatism by silicate and carbonate-rich melts. Also surprisingly, considering that some authors are Russian-speaking, Sun et al. (2017) fail to give credit to data in the Russian literature, e.g. from compilations of Spetsius and Serenko (1990) and Ukhanov et al. (1988), which report petrographic descriptions and chemical compositions for whole-rocks (WR) and minerals for dozens of Obnazhennaya xenoliths.

Sun et al. (2017) do not report the processing protocol for their small samples, nor the methods of WR major element analyses and modal estimates (we presume that “*mineral model composition*” in the title of their Table 1 refers to modal abundances). In particular, the mass of rock taken to make WR powders could be important because a sufficiently large amount of uncontaminated material must be used to provide representative sampling for coarse-grained xenoliths (e.g. Boyd, 1989; Doucet et al., 2013).

Instead of reporting the method of their WR analyses Sun et al. (2017) state the following: “*Whole-rock major elements were analyzed at the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). The method has been described by Sun et al. (2012)*”. Yet, *section 3.1* on analytical methods in Sun et al. (2012) does not say anything about the method and quality of WR major element analyses at IGGCAS though it quotes precisions of 1–3% with no documentation of this precision or of values measured for rock standards.

Sun et al. (2017) report, plot and discuss raw major element data, with loss-on-ignition (LOI) as high as 3–11 wt% included in the totals. They also report all Fe as Fe_2O_3, whereas Fe in the peridotites occurs mainly as FeO. When using major element data uncorrected for this alteration, their plots reflect the combined effects of both variable alteration and mantle processes, such that comparisons with primitive mantle (PM) or melting trends based on anhydrous normalized data and all Fe as FeO make little sense. Sun et al. (2017) do not plot the MgO, Al_2O_3 and CaO in 19 Obnazhennaya xenoliths reported by Ionov et al. (2015). The data from Ionov et al. (2015) are shown in this comment in Fig. 1 to demonstrate that the Sun et al. (2017) data mainly fall into the range of published work.

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[1] Quotes from Sun et al. (2017) are given as published, without correcting language and other errors.

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Table 1
Model Re-depletion ages and rock names from Sun et al. (2017) and those calculated in this comment.

Sample	Sun et al. (2017)				This comment					
	Rock type	$^{187}Re/^{188}Os$	$^{187}Os/^{188}Os$	T_{RD} (1)	T_{RD} (2)	Rock type	T_{RD} (3)	$^{187}Os/^{188}Os$	T_{RD} (4)	ΔT_{RD}
								160 Ma	160 Ma	
Obn6-212	sp-hzb	0.05	0.11469	1.81	1.81	hzb	2.02	0.11456	***2.04***	*0.23*
Obn6-216	sp-hzb	0.17	0.11637	1.57	1.57	hzb	1.80	0.11592	***1.86***	*0.29*
Obn6-218	sp-hzb	0.05	0.11418	1.89	1.88	hzb	2.09	0.11405	***2.11***	*0.22*
Obn74-318	sp-hzb	0.16	0.11345	1.99	1.99	hzb	2.19	0.11302	***2.24***	*0.25*
Obn6-228	sp-lh	0.61	0.13278	−0.90	−0.87	lh	−0.44	0.13115	−0.21	
Obn7-297	sp-lh	0.16	0.11931	1.14	1.14	lh	1.40	0.11888	***1.46***	*0.32*
Obn7-330	sp-dun	0.07	0.11489	1.78	1.78	dun	1.99	0.11470	***2.02***	*0.24*
Obn7-343	sp-dun	0.23	0.11414	1.89	1.89	dun	2.09	0.11353	***2.18***	*0.29*
Obn7-329	sp-dun	0.01	0.11227	2.16	2.16	dun	2.34	0.11224	***2.35***	*0.19*
Obn7-362	sp-lh	0.97	0.17372	−7.40	−7.42	wehr	−6.41	0.17113	−6.02	
Obn7-341	sp-gar-lh	1.19	0.17627	−7.80	−7.85	wehr	−6.81	0.17309	−6.32	

Abbreviations: sp., spinel; gar, garnet; hzb, harzburgite; lhz, lherzolite; dun, dunite; wehr, wehrlite.
T_{RD} (1), Re-depletion model ages reported by Sun et al. (2017).
T_{RD} (2), Re-depletion model ages calculated using the chondritic model of Shirey and Walker (1998).
T_{RD} (3), Re depletion model age calculated using the primitive mantle model of Meisel et al. (2001).
$^{187}Os/^{188}Os$ at 160 Ma, Os isotope ratios corrected to the eruption age of the Obnazhennaya kimberlite (160 Ma).
T_{RD} (4) 160 Ma, T_{RD} (3) corrected using the eruption age of the Obnazhennaya kimberlite (160 Ma).
$\Delta T_{RD} = T_{RD}$ (4) 160 Ma − T_{RD} (1). The average ΔT_{RD} is ~0.25 Ga.

The way Sun et al. (2017) name rocks and discuss modal compositions can be misleading. They identify three rock types among their xenoliths: dunites, harzburgites and lherzolites (and group them in 3 suites following Ionov et al. (2015) using fertility indices). Based on the classification of Streckeisen (1976), however, two of the "lherzolites" are close to wehrlites because of high cpx and low opx, and thus are distinct from other lherzolites in their suite as we show in our Fig. 2. They should be named either wehrlites or cpx-rich lherzolites. Also taking into account pyroxene ratios and "accessory" minerals brings more surprises. One "dunite" has no opx, but >7% cpx and > 8% amphibole, another has more cpx than opx. These differences are not purely semantic, they matter because the rock names are meant to imply the origin of the xenoliths (melting residues vs. "re-fertilization") and assess Re-Os model ages, which make sense for pristine melting residues, but may be wrong for melt-reacted rocks rich in cpx and amphibole (see Table 1).

Most surprising in their modal data is the seeming "discovery" of lherzolites with the highest (to the best of our knowledge) modal abundances of spinel ever reported for mantle xenoliths: 11.1% and 12.5% ("lherzolites" 6–228 and 7–362), much higher than in Cr-rich Obnazhennaya peridotites (≤3–4% spinel) reported by Ionov et al. (2015). Yet, no spinel at all can be seen in the thin section image of 6–228 in Sun et al. (2017), though the image size is admittedly fairly small. This may suggest that the reported modal compositions are wrong, possibly because of combined problems with sampling, analyses or calculations.

Sun et al. (2017) argue that their harzburgites and dunites "*may represent refractory lithospheric mantle relicts*", but fail to provide any quantitative constraints of the origin of these rocks, which is commonly done using appropriate major oxides and their ratios (Al_2O_3, MgO, FeO, Mg#) in bulk rocks and Mg# in olivine based on experimental work on melting of fertile mantle (e.g., Herzberg, 2004; Walter, 2003). By contrast, Sun et al. (2017) claim that "*degrees of partial melting can be estimated by spinel Cr#, which is generally accepted as a sensitive indicator for the extent of melting* (Dick and Bullen, 1984; Hellebrand et al., 2001)". From our reading of the cited papers, they use Cr-spinel as a petrogenetic indicator exclusively for abyssal and alpine-type peridotites formed by low melting degrees and spatially associated lavas. We are not aware of any "*general*" use of $Cr\#_{Spl}$ to infer melting degrees for refractory cratonic peridotites.

Plots of $Cr\#_{Spl}$ vs. $Mg\#_{Ol}$ or other robust melt extraction indices reported by Ionov et al. (2015) show no trends and no means to infer or compare melting degrees (Ionov et al., 2018). We note that sample 7–362, described by Sun et al. (2017) as a "*fertile lherzolite*" (rather a wehrlite, see Fig. 2) has the highest $Mg\#_{WR}$ among their rocks (0.929), higher than the supposedly "*refractory*" dunites (≤0.919). Furthermore, Ionov et al. (2015) used major element and Os abundance data to argue that dunites from Obnazhennaya may have formed in melt migration channels rather than as residues of partial melt extraction, which is ignored by Sun et al. (2017) who claim that their dunites may yield robust Re-depletion ages.

Another "novel" and spectacular feature reported by Sun et al. (2017) is what they call "*Ca-melt*" in the sample reportedly containing 12.5% spinel. No definition of what they mean by "Ca-melt" is given in the paper. The "Ca-melt" is shown in plate (g) of their Fig. 2, entitled "*Photograph and microtexture of the Obnazhennaya mantle xenoliths*", but the image appears to be a back-scattered electron image, with light spots (labeled "Melt") in darker Cpx, presented as "*clinopyroxene surrounded by Ca-melt*". The composition and nature of this material are not disclosed and remain a mystery. Sun et al. (2017) seem to mean that the phase is rich in Ca, yet apparently linked to phlogopite (a Ca-free mineral). The only other thing reported about it (*pp. 385–386*) is that "*Ca-melts are randomely distributed the clinopyroxene grains*", which serves as a major argument in the *Discussion* for metasomatism by "*carbonatite melt*".

The discussion of metasomatism (*section 5.2*, pp. 391–392) is particularly confused, with statements that often contradict both each other and those in *section 5.1* on partial melting. In particular, the origin of lherzolites is attributed to three distinct processes in three consecutive paragraphs: different melting degrees, "melt refertilization", and metasomatism. *Section 5.1* states, based on the WR contents of major oxides including Al_2O_3 and CaO: "*These compositional features indicate that the harzburgites and dunites, have been subjected to higher degrees of partial melting than the lherzolites.*" *Section 5.2* on the same page attributes the higher Al_2O_3 and CaO in the lherzolites not to lower melting degrees, but to metasomatism: "*…lherzolites contain higher CaO and* Al_2O_3 *content than those in harzburgites and dunites (*Fig. 3a–b, d*), which suggest that these lherzolites have suffered metasomatic processes*". The next paragraph argues: "*…some lherzolites might have been transformed from dunite through melt refertilization processes".*

Sun et al. (2017) report no WR trace element analyses (only cpx and a single garnet were analyzed while the rocks also contain amphibole, silicate glass as well as "Ca-melt"), yet they claim: "*Peridotites in this study have complex contamination-free trace element compositions, which cannot be produced by a single process*" (the origin of this phrase is addressed at the end of this Comment).

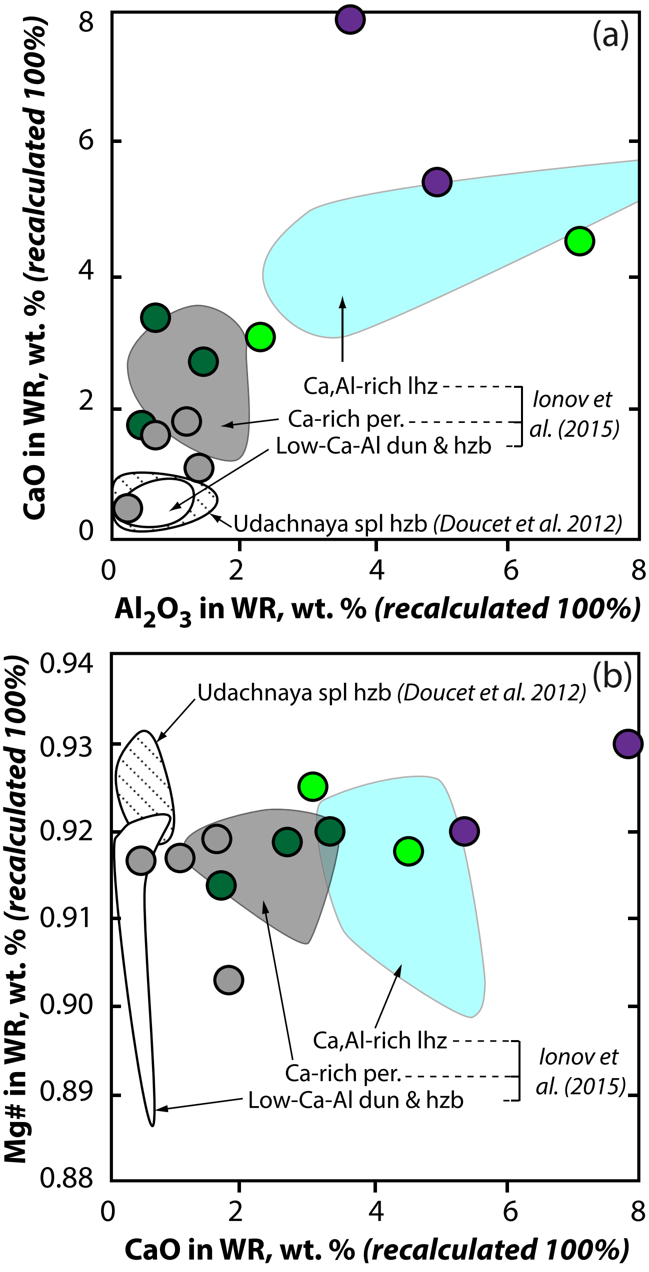

Fig. 1. Co-variation plots of (a) Al$_2$O$_3$ vs. CaO and (b) CaO vs. Mg# [Mg/(Mg/Fe)]$_{at}$ in whole-rock peridotites from Sun et al. (2017) recalculated to 100% anhydrous. Also shown are the fields of Udachnaya spinel harzburgites from Doucet et al. (2012) (diagonal lines) and Obnazhennaya peridotite groups from Ionov et al. (2015): low-Ca-Al dunites and harzburgites (white), Ca-rich peridotite with moderate Al (grey) and Ca, Al-rich lherzolites (blue).

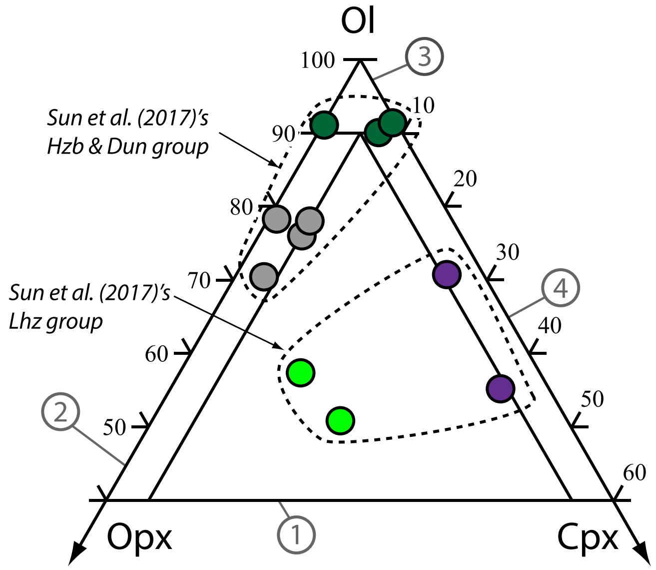

Fig. 2. Modal proportions of olivine and pyroxenes in peridotites from Sun et al. (2017) plotted in the triangular modal composition diagram for ultramafic rocks, with peridotite types after Streckeisen (1976): (1) lherzolite (green), (2) harzburgite (grey), (3) dunite (dark green), (4) wehrlite (blue).

Sun et al. (2017) calculate REE concentrations of the hypothetical metasomatic liquids based on those in the cpx assuming that the cpx was equilibrated with such liquids. This assumption may not be correct. Metasomatic enrichments may be produced by reaction with metasomatic liquids (e.g. Ionov et al., 2018) or their entrapment followed by in situ crystallization; the liquids may not be primary, but end products of percolation and melt-rock reaction involving chromatographic fractionation (e.g. Ionov et al., 2002).

Regarding "*…the presence of carbonatite melt (*Fig. 2g*) also supports the carbonatite metasomatism*", if the "carbonatite melt" is indeed present in the sample, one does not need to calculate its composition, but simply analyze it. The meaning of several statements on inferred silicate melts is not clear, e.g.: "*Silicate metasomatic melts contain kimberlitic melt and basaltic melt. The calculated REE ranges in the melts (Fig. 11) suggest these peridotites are not metasomatism result of a single silicate melt.*"

Altogether, Sun et al. (2017) claim to discern in their samples essentially all known types of metasomatic enrichments, including "*carbonatite melts, basaltic melts from Siberian Trap and kimberlitic melts*", as well as "*infiltration of hydrous silicate melts*" - the latter based on the declared, but undocumented discovery of "*silicate melt inclusions that are distributed in parallel with the exsolution lamellae*" in clinopyroxene. Yet, they present no robust evidence for any of these metasomatic events or their mechanisms, sequence or sources. In particular, we see no reason to invoke metasomatic melts "*from Siberian Trap*", because the eruptive centers of the magmas are too far away, and because the Obnazhennaya kimberlite carries no zircons with ages close to the trap eruption (250 Ma), but abundant zircons with ages of 300–550 Ma (Fig. 3; Ionov et al., 2018). Further, Sun et al. (2017) infer (p. 392) that "*the sample Obn 7-343 which contains phlogopite, indicates that this sample are metasomatised by kimberlite fluid*". By contrast, the only phlogopite-bearing sample in their Tables 1 and 2 is Obn 7–362, which according to Sun et al. (2017) experienced "carbonatite" metasomatism.

2. Re-Os isotope data and age estimates

Another main theme in the paper by Sun et al. (2017) is the use of Re-Os isotope data to infer that (see the abstract): "*old cratonic mantle still existed beneath the Obnazhennaya*" and "*the cratonic mantle beneath the northern part of Siberian craton contain both ancient and reworked lithospheric mantle*". These findings repeat those from Ionov et al. (2015) who established the timing of lithospheric formation and evoked important reworking events for the mantle beneath Obnazhennaya.

Regarding the attempts of Sun et al. (2017) to date lithospheric events using model Re-Os ages, several aspects of their Table 4 make it impossible to reproduce their results. First, the Os isotopic composition in the table is denoted with the subscript "i", usually implying that this ratio has been corrected to the age of the host kimberlite. The text, however, does not make clear if this indeed is

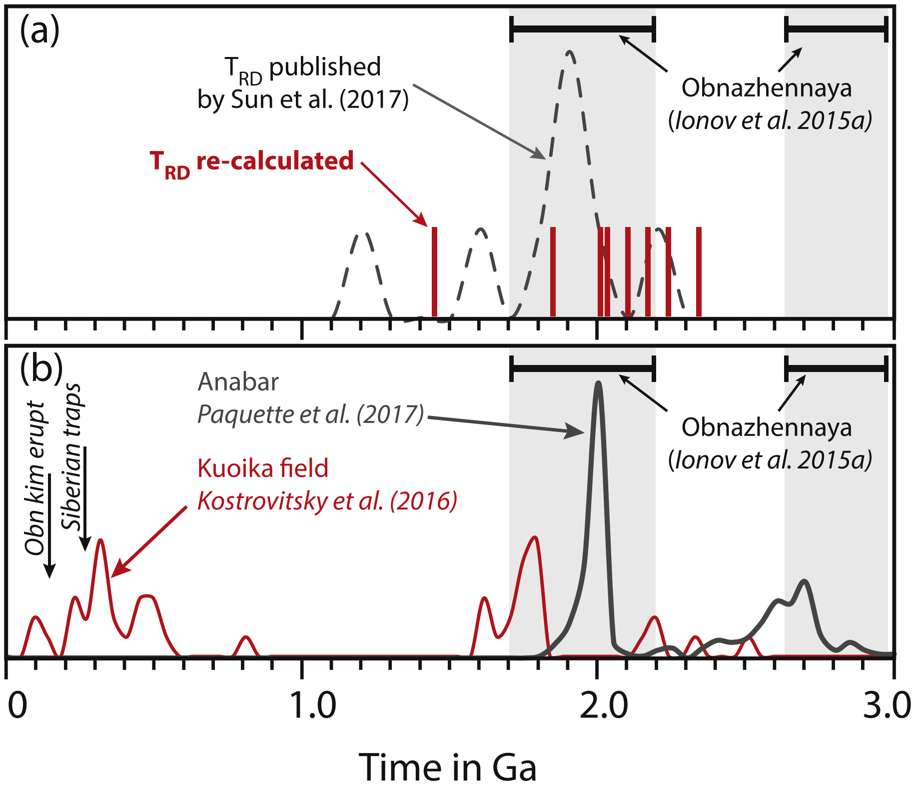

Fig. 3. (a) Relative probability density plot for T_{RD} of Obnazhennaya peridotites as reported by Sun et al. (2017) (dashed grey line) and a histogram for T_{RD} recalculated from their data in this comment (red bars) in comparison with T_{RD} for refractory ($Al_2O_3 < 2\%$; Mg# > 0.90) Obnazhennaya peridotites from Ionov et al. (2015) shown as age ranges. (b) Relative probability density plot of U/Pb ages for zircons from the Anabar shield (Paquette et al., 2017) (grey line) and the Kuoika field (Kostrovitsky et al., 2016) (red line). Vertical arrows show the U-Pb ages of zircons from Obnazhennaya kimberlite and the age (250 Ma) of the Siberian trap magmatic event.

an initial isotopic composition, and if it is, what age was used for the correction. Second, the model ages reported in their Table 4 state that they are calculated relative to the primitive upper mantle (PUM) values after Meisel et al. (2001), with $(^{187}Re/^{188}Os)_{PUM} = 0.4236$ and $(^{187}Os/^{188}Os)_{PUM} = 0.1296$. To reconcile this value for modern PUM Os isotopic composition with the likely initial $^{187}Os/^{188}Os$ of the Earth as estimated by, for example, the initial $^{187}Os/^{188}Os$ determined for iron meteorites, e.g. Smoliar et al. (1996), requires a $^{187}Re/^{188}Os > 0.43$, so the origin of the value (0.4236) quoted by Sun et al. (2017) is unclear and likely incorrect. More importantly, the T_{MA} and T_{RD} given in Table 4 cannot be obtained from the PUM values they quote. Instead, the model ages appear to be calculated relative to the average for ordinary and enstatite chondritic meteorites, with $^{187}Re/^{188}Os = 0.40186$ and $^{187}Os/^{188}Os = 0.1270$ (Shirey and Walker, 1998).

For clarity, we reproduce the T_{RD} values from Sun et al. (2017) in Table 1 of this comment in comparison with our T_{MA} and T_{RD} estimates after Meisel et al. (2001) and Shirey and Walker (1998). Table 1 demonstrates that the T_{RD} values given by Sun et al. (2017) are 0.2–0.3 Ga too low (Fig. 3) compared to those calculated using the model mantle parameters of Meisel et al. (2001). When calculated correctly for the Meisel et al. (2001) mantle parameters, the eight samples with valid (positive) T_{RD} values have model ages very similar to those for the Paleoproterozoic Obnazhennaya xenoliths in Ionov et al. (2015).

Apart from the problematic age estimates, the discussion of Re-Os data suffers from erratic literature referencing. The reference to Griffin et al. (2002) is not appropriate with regard to "*studies on xenoliths from the Udachnaya pipe*" (p. 383) because those authors studied not xenoliths, but olivine grains ("macrocrysts") from mineral concentrates. The same reference is also used to argue that "*The Re-Os T_{RD} ages of most Udachnaya peridotites and sulfides… are close to 2 Ga*". In reality the great majority of sulfides in Udachnaya olivine "macrocrysts" reported in Table 3 of Griffin et al. (2002) have T_{RD} ages >2 Ga, and these authors argue that the mantle lithosphere beneath Udachnaya formed between 3.5 and 3.0 Ga and stabilized at ca 2.9 Ga.

The paper of Sun et al. (2017) also contains several inaccurate statements. Five examples include:

- *Introduction* (p. 383): "*…the kimberlites erupted on 160 Ma occurred in the northern of the Siberian craton are non-diamondiferous.*" Obnazhennaya is located in the northeastern corner of the Siberian craton; the northern part of the craton hosts the Anabar shield as well as kimberlites with ages of 170–220 Ma (eastern Anabar) and 400–410 Ma ("northern fields") (Kostrovitsky et al., 2016). At least one of the Kuoika field kimberlites is diamondiferous.
- *Introduction* (p. 384): The Siberian craton does not extend to "*the Sea of Okhotsk in the east*", as is evident from the inset in Fig. 1 of Sun et al. (2017).
- *Introduction* (p. 383): "*It is not clear whether this thinning process is the reason leading to the craton destruction and asthenospheric mantle upwelling as North China Craton*". First, Sun et al. (2017) provide no evidence that the lithosphere of the NE Siberian craton has been thinned, and was not thinner at the craton edge initially. Second, to the best of our knowledge, the Siberian cratonic lithospheric mantle keel still exists and so has not suffered the type of removal documented for the North China Craton.
- (p. 388) Contrary to what is stated in *section 4.1*, Ionov et al. (2010) and Agashev et al. (2013) did not report data on garnets from Obnazhennaya, but on garnets from Udachnaya.
- (p. 394) "*The temporal coupling between crust* (Kostrovitsky et al., 2016) *and mantle formation* (Ionov et al., 2015*a and this study*) *suggest that the Paleoproterozoic event created new lithosphere underneath Obnazhennaya rather than added new materials to the existing*

> *lithospheric domain*". This statement is self-contradictory. We refer to the paper of Ionov et al. (2015) who reported numerous Archean T_{RD} ages for Obnazhennaya peridotites (see Fig. 3 in this comment) and clearly showed that the lithospheric mantle in the region was initially created in the Archean, with new materials added in the Paleoproterozoic.

From our reading of the paper by Sun et al. (2017) they copy-pasted several phrases from our previous work. One of them, given above in this comment, as well as the next one from *section 5.2*: "*We have shown that the cpx compositions in the Obnazhennaya garnet peridotites are most likely linked to metasomatism*" (with 'Udachnaya' changed to 'Obnazhennaya') are from the section on metasomatism on page 1238 in the paper by Doucet et al. (2013). Other examples are the first phrase of *section 5.3* taken from Doucet et al. (2015), and the first phrase of their abstract, which closely follows the first phrase in the abstract of the paper by Ionov et al. (2015) on the same topic. Copying passages from the literature requires explicit referencing.

To sum up, the study of Sun et al. (2017) could be a useful complement to the knowledge of the composition and history of the lithospheric mantle beneath the Siberian craton. Unfortunately, poorly documented data quality and errors in the interpretation of these data and discussion of the current knowledge of the cratonic mantle in general, and for the Siberian craton in particular, make much of their paper misleading rather than beneficial.

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