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Reply to Comment on "^{190}Pt-^{186}Os geochronometer reveals open system behaviour of ^{190}Pt-^{4}He isotope system" by Yakubovich *et al.* (2022)

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Reply

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Luguet *et al.* (2019) applied the Re-Os and Pt-Os chronometers to date the Pt mineralisation of the Kondyor Zoned Ultramafic Complex (ZUC) and suggested this to be ~250-240 Ma and related to the subduction of the Mongol-Okhotsk (MO) ocean seafloor under the Siberian craton. The discrepancy with the Early Cretaceous ^{190}Pt-^{4}He isochronal ages of Mochalov *et al.* (2016) led Luguet *et al.* (2019) to conclude that the ^{190}Pt-^{4}He chronometer was not robust due to the complex history of the Kondyor Pt mineralisation, thus not providing a meaningful insight into the mineralisation age. Yakubovich *et al.* (2022) challenge these interpretations. There is however little controversy when the current Pt-Os (Luguet *et al.*, 2019) and Pt-He (Mochalov *et al.*, 2016) isotopic systems are considered together with regional geological history.

(1) Nekrasov *et al.* (2005) identified, within the chromitites of the Kondyor ZUC dunitic core, an early high temperature (HT) Pt alloy suite associated with chromites containing up to 64 wt. % of Cr_2O_3, and a late suite of Pt alloys associated with chromites containing up to 54 wt. % Cr_2O_3. The chromites from the schlieren 1265 (Luguet *et al.*, 2019) yield 55.4 to 56.4 wt. % Cr_2O_3 (Pushkarev *et al.*, 2002), supporting the Pt mineralisation to be akin to the early HT Pt alloys. Furthermore, the $^{190}Pt/^{188}Os$ ratios of the Pt alloys range from 0.06 to 19.89 (Table S-2 of Luguet *et al.*, 2019), encompassing those of the Pt^-, Pt > Ir, Pt > Os and Pt > Pd Pt-alloys (0.24 to 9, Table S-2 of Yakubovich *et al.*, 2022). The claim of Yakubovich *et al.* (2022) that Luguet *et al.* (2019) analysed exclusively the latest generations of Pt alloys (*i.e.* Pt > Ir and Pt > Pd type grains) is thus flawed.

(2) Figure 1 of Yakubovich *et al.* (2022) only demonstrates that the $^{190}Pt/^{188}Os$ ratio does not show a normal distribution, defining compositional clusters between Os-poor Pt alloys and increasingly Os-rich Pt alloys. The subsequent "mineralogical classification" undertaken by Yakubovich *et al.* (2022) is erroneous and arbitrary. These authors argue that the Os-richest Pt alloys of Luguet *et al.* (2019) are native osmium. The Os-richest Pt alloy analysed by Luguet *et al.* (2019) has a $^{190}Pt/^{188}Os$ of 0.064, corresponding to Pt/Os ~60 - clearly not native osmium. It is also puzzling that two grains classified as "Os" by Yakubovich *et al.* (2022) have $^{190}Pt/^{188}Os$ overlapping with their own "Pt + Os" group. These "Os" grains appear to be classified as such to fortuitously yield a 116 Ma Pt-Os isochron, similar to the Pt-He age. In contrast, the internal isochrons of the $^{190}Pt/^{188}Os$ compositional clusters yield ages (see Fig. 1, this reply) in agreement with the model age of the Os-poorest Pt alloy and the isochronal age calculated on the whole dataset (Luguet *et al.*, 2019).

(3) According to Yakubovich *et al.* (2022), native osmium, which we did not analyse, formed prior to the Pt alloys, implying a primary heterogeneity in $^{186}Os/^{188}Os$ and systematic Pt/Os variations among the Pt alloys. The sole observation that native osmium occurs as nanometric exsolution lamellae *within* the Pt alloys (Fig. 1 of Luguet *et al.*, 2019) rules out native osmium being primary, and undeniably argues for a sub-solidus origin. Osmium exsolution lamellae observed in Pt alloys from the Uralian Alaskan-type ZUC (Garuti *et al.*, 2002; Zaccarini *et al.*, 2018) and from the Kondyor ZUC (Luguet *et al.*, 2019; Malitch *et al.*, 2020) likely reflect the low fS_2 of a given magmatic system, where Os partitions into the Pt alloy structure unable to form Os sulfides (Garuti *et al.*, 2002). The large range of Pt/Os of the Pt alloys reflect variable proportions of Os exsolution lamellae (Luguet *et al.*, 2019) and the "heterogeneous" $^{186}Os/^{188}Os$ is simply due to the ingrowth of ^{186}Os over *ca.* 250 Myr. This is the basic implication of an isochron and a model age!

(4) Magmatic *ca.* 250 Ma ages are reported all along the MO suture, from Mongolia to the Okhotsk Ocean, resulting from the bivergent subduction of the MO ocean under Siberia in the north and Amuria in the south. Of particular interest are those obtained in plutonic and volcanic rocks from the northern side of the MO suture (Sotnikov *et al.*, 2005; Gladkochub *et al.*, 2010; Donskaya *et al.*, 2013), especially from the Dzhugdzhur-Stanovoi magmatic belt (Sal'nikova *et al.*, 2006) and the Dzhagdy Transect (Sorokin *et al.*, 2020), located on the far east of the MO suture, regionally close to the Kondyor ZUC.

(5) Contrary to the proposal of Yakubovich *et al.* (2022), it is impossible to disturb and age the Pt-Os ages during or consequent to a younger event having overprinted the Kondyor ZUC, due to the very low abundance of ^{190}Pt (0.0136 %; Böhlke *et al.*, 2001) and the long half-life of the ^{190}Pt decay (~469 Gyr; Begemann *et al.*, 2001). We maintain that the Pt-He ages record a younger event than the Pt-Os ages, possibly

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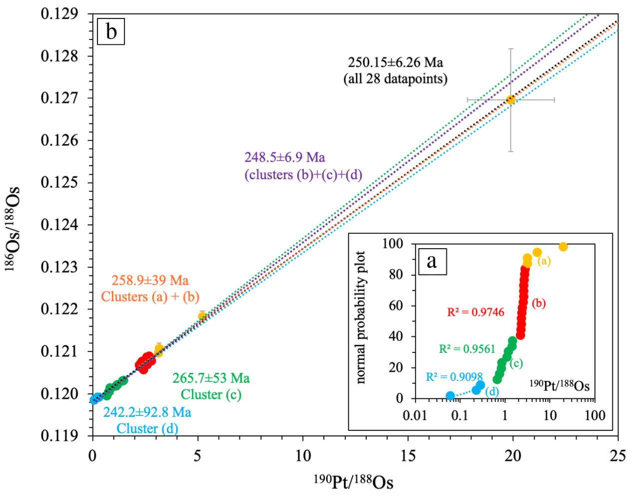

Figure 1 **(a)** Normal probability plot of the ^{190}Pt/^{188}Os composition of the Kondyor Pt alloys analysed by Luguet *et al.* (2019) and revealing compositional clusters/groups (a to d). **(b)** ^{190}Pt-^{188}Os isochrons of the Kondyor Pt alloys (global and compositional clusters) determined using IsoplotR. Isochronal ages (±1 sigma uncertainty) obtained on the compositional clusters overlap with each other as well as with the isochron calculated on the 28 analyses of Luguet *et al.* (2019).

reflecting poor He retention in Kondyor Pt alloys. Shukolyukov *et al.* (2012a,b) estimated in short (30 min) heating experiments the He loss in native Au (n = 10) and Pt (n = 1) alloys. To understand the He behaviour in native alloys, possibly stored at T > 600 °C in the mantle for millions of years, proper tests would have been to expose alloys to given temperature (600 to 1200 °C) for weeks or months and measure their Pt-He isotopic signatures before and after the experiments. Still, Au alloys clearly show He loss as low as 600 °C, while they are expected to efficiently retain He due to their high crystal lattice packing density (higher than Pt alloys; Shukolyukov *et al.,* 2012a). Alternatively, as highlighted by Malitch *et al.* (2020), the Pt-He ages are concomitant to the Mesozoic lamproitic magmatism, which affected the south margin of the Siberia craton and is suggested to have overprinted part of the Kondyor ZUC (Burg *et al.,* 2009). The age discrepancy points to open system behaviour of Pt-He system, making it unreliable for dating the timing of mineralisation in complex igneous systems.

(6) Finally, we highlight the conclusion of Yakubovich *et al.* (2022) [*"^{190}Pt-^{4}He age reflects the mineralisation itself, while the ^{190}Pt-^{186}Os isotopic system fingerprints an earlier redistribution of PGE"*], which ultimately asserts that the Pt-Os records an earlier event (*i.e.* the Pt mineralisation of Kondyor ZUC) than the Pt-He isotopic system. By agreeing with Luguet *et al.* (2019), Yakubovich *et al.* (2022) signal that they do not understand the implication of their own assertion, rendering their comment to Luguet *et al.* (2019) obsolete.

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Additional Information

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