Comment on “\(^{190}\text{Pt}-^{186}\text{Os}\) geochronometer reveals open system behaviour of \(^{190}\text{Pt}-^{4}\text{He}\) isotope system” by Luguet et al. (2019)

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Supplementary Information

The Supplementary Information includes:

- 1. General Remarks on Retentivity of Radiogenic Helium in Pt-alloys
- 2. Summary of Previous Geochronology for the Kondyor Massif
- 3. General Remarks on Pt Mineralisation of the Kondyor Massif
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1. General Remarks on Retentivity of Radiogenic Helium in Pt-alloys

The thermal retentivity of \(^{4}\text{He}\) in Pt-alloys is high. Numerous studies have shown that helium has an extremely low solubility in metals and at temperatures below half of the melt temperature (0.5 \(T_m\)) it tends to be trapped by vacancies with the formation of He-V clusters (e.g., Trinkaus and Singh, 2003). Consequently, the diffusion of single helium atoms in metal cannot be significantly faster than self-diffusion (Sciani and Jung, 1983). The activation energy of self-diffusion of Pt metal is \(\sim 64\) kcal/mol (Cattaneo et al., 1962). This is comparable with the activation energy of hetero-diffusion of Pt in Fe-Pt alloys (\(\sim 70\) kcal/mol; Kučera and Million, 1975). The same range of values can be expected for hetero-diffusion of radiogenic Os in Pt-Fe alloys. The high retentivity of He in native metals has been empirically confirmed by extensive diffusion experiments (Shukolyukov et al., 2012a,b). Thus, the discrepancy between the \(^{190}\text{Pt}-^{4}\text{He}\) and \(^{190}\text{Pt}-^{186}\text{Os}\) ages cannot be explained by diffusive loss of \(^{4}\text{He}\). The \(^{190}\text{Pt}-^{4}\text{He}\) dating method has been successfully applied to platinum mineralisation from a wide variety of deposits (e.g., Yakubovich et al., 2015a). In all these studies the \(^{190}\text{Pt}-^{4}\text{He}\) age is consistent with independent geochronological age estimates and regional geology.

2. Summary of Previous Geochronology for the Kondyor Massif

A lot of work was done to understand the timeframes of the formation of alkaline ultramafic massif Kondyor (Table S-1). Sm-Nd, Rb-Sr, \(^{40}\text{Ar}-^{39}\text{Ar}\), baddeleyite U-Pb and Pt-He dating of the Kondyor ultramafic massif and the associated PGM mineralisation all yield essentially Early Cretaceous ages which are more or less consistent within measurement uncertainty.
Table S-1  Summary of previous geochronology for the Kondyor massif.

<table>
<thead>
<tr>
<th>Dated material</th>
<th>Age, Ma</th>
<th>Method</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyroxenite (isochron)</td>
<td>132 ± 8, 120 ± 1</td>
<td>Rb-Sr,</td>
<td>Pushkarev et al., 2002</td>
</tr>
<tr>
<td>Biotite in magnetite peridotite and from veins in dunites</td>
<td>128 ± 2</td>
<td>Rb-Sr,</td>
<td>Efimov et al., 2012</td>
</tr>
<tr>
<td>Apatite–phlogopite clinopyroxenites (isochron)</td>
<td>131 ± 35</td>
<td>Sm-Nd,</td>
<td>Efimov et al., 2012</td>
</tr>
<tr>
<td>Clinopyroxene from dunite (isochron)</td>
<td>128 ± 40</td>
<td>Sm-Nd,</td>
<td>Savatenkov and Mochalov, 2018</td>
</tr>
<tr>
<td>Detrital and lode isoferroplatinum</td>
<td>129 ± 6, 122 ± 6</td>
<td>Pt-He,</td>
<td>Mochalov et al., 2016</td>
</tr>
<tr>
<td>Baddeleyite in dunite</td>
<td>125 ± 2, 2477 ± 18</td>
<td>U-Pb,</td>
<td>Ronkin et al., 2013</td>
</tr>
<tr>
<td>Zircon from dunite</td>
<td>1895 ± 50, 1885± 52</td>
<td>U-Pb,</td>
<td>Malitch et al., 2012</td>
</tr>
<tr>
<td></td>
<td>1016 ± 22, 390 ± 12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>176 ± 1.2, 125.8 ± 3.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

U-Pb ages of zircon from dunites sometimes reflect the age of magmatic event, although zircon cannot crystallise from ultramafic melts (Heaman, 2009; Borisov and Aranovich, 2019). Typically, zircon grains are xenocrysts (Bea et al., 2001) or crystallised during later metasomatic processes (e.g. Rudnick and Walker, 2009). Crystallisation event with the age of 240–250 Ma is not observed in the zircon U-Pb population (Table S-1). However, the youngest zircon U-Pb age is fully consistent with the Early Cretaceous formation of the Kondyor ultramafic complex suggested by other methods.

To explain the discrepancy between $^{190}$Pt-$^{186}$Os and $^{190}$Pt-$^4$He ages Luguet et al. (2019) proposed that Kondyor massif represents the root of an Early Triassic volcano that was exhumed in the Early Cretaceous. According to Luguet et al. (2019) the rapid exhumation of Kondyor massif occurred in response to extension followed by the exhumation of deep-seated structures, such as metamorphic core complexes. This requires a cooling rate for Kondyor massif of ~ 160 °C/Myr. For metamorphic core complexes cooling of 80 °C/Myr is considered to be rapid (e.g., Kargaranbafghi et al. 2015). There are no metamorphic core complexes so far documented within the Aldan shield. The nearest metamorphic core complexes are located approximately 1,000 km to the south-west of Kondyor (Wang et al., 2011).

3. General Remarks on Pt Mineralisation of the Kondyor Massif

The prevailing view of the sequence of platinum group element (PGE) ore formation in the Kondyor massif has been developed from studies of the ontogeny of PGM aggregates with silicates, oxides and sulfides (Mochalov, 2019). The massif is composed of alkaline mafic-ultramafic rocks: dunites, wherlites, pyroxenites, kosvites, hornblendites, gabbros, alkaline pegmatites, alkaline syenites, monzodiorites, and sub-alkaline granites. It was intruded into basement composed...
of Archean crystalline rocks and Proterozoic meta-sediments (Nekrasov et al., 2005; Mochalov, 2019). Cumulate dunites, the earliest rocks of the massif, underwent syn-magmatic recrystallisation and metasomatic transformation under the influence of ultramafic, mafic, alkaline, and granitoid intrusions. Five genetically-distinct types of PGMs can be distinguished on the basis of mineralogy and geochemistry: (1) Magmatogenic platinum grains in cumulates of alkaline ultramafic (picritic) magma; (2) Magmatogenic-fluid-metasomatic Pt grains in metasomatic dunites that underwent high-temperature recrystallisation under the influence of picritic magmas; (3) Magmatogenic-fluid-metasomatic osmium-platinum grains (Pt>Os) in veins and schlieren of clinopyroxenites; (4) Fluid- metamorphic iridium-platinum grains (Pt>Ir) that formed as a result of syn-magmatic recrystallisation of dunite cumulates and the conversion of PGMs from the Pt- to Pt>Ir-type and is developed in dunites and chromitites; (5) Magmatogenic-fluid-metasomatic palladium-platinum grains (Pt>Pd) that formed due to remobilisation of all early types of PGMs and is present in a series of metasomatites within dunites, chromitites, clinopyroxenites and amphibolites. Currently 91 PGM species have been identified in the Kondyor massif and the related alluvial deposits. Native minerals of platinum (NMP), mainly isoferroplatinum, are the main type of PGM within the massif. Based on the \(^{187}\text{Os}/^{188}\text{Os}\) ratios and sample description (Luguet et al., 2019) we can conclude that PGM from sample 1265 are Pt>Ir or Pt>Pd type grains of chromitites (Table S-2). The general discernment of sample 1265 provided by Pushkarev et al. (2015) is consistent with this conclusion.

### Table S-2

Average chemical composition of the different isoferroplatinum grains types from Kondyor deposit and placer deposit of the Kondyor-Uorgalan rivers.

<table>
<thead>
<tr>
<th>Type</th>
<th>n</th>
<th>Pt</th>
<th>Ir</th>
<th>Os</th>
<th>Ru</th>
<th>Rh</th>
<th>Pd</th>
<th>Fe</th>
<th>Ni</th>
<th>Cu</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt&gt;Os</td>
<td>16</td>
<td>87.75</td>
<td>0.37</td>
<td>0.24</td>
<td>0.04</td>
<td>1.08</td>
<td>0.70</td>
<td>8.43</td>
<td>0.07</td>
<td>0.74</td>
<td>99.42</td>
</tr>
<tr>
<td>Pt&gt;Ir</td>
<td>37</td>
<td>86.66</td>
<td>2.25</td>
<td>0.29</td>
<td>0.05</td>
<td>0.48</td>
<td>0.22</td>
<td>8.89</td>
<td>0.16</td>
<td>0.70</td>
<td>99.70</td>
</tr>
<tr>
<td>Pt&gt;Os</td>
<td>47</td>
<td>89.47</td>
<td>0.00</td>
<td>0.01</td>
<td>0.03</td>
<td>0.60</td>
<td>0.76</td>
<td>8.38</td>
<td>0.01</td>
<td>0.74</td>
<td>100.00</td>
</tr>
<tr>
<td>Pt&gt;Pd</td>
<td>27</td>
<td>88.89</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.63</td>
<td>1.13</td>
<td>8.59</td>
<td>0.09</td>
<td>0.62</td>
<td>99.98</td>
</tr>
<tr>
<td>Pt&gt;Pd</td>
<td>12</td>
<td>88.07</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
<td>0.67</td>
<td>0.90</td>
<td>9.14</td>
<td>0.49</td>
<td>0.69</td>
<td>99.99</td>
</tr>
<tr>
<td>Placer</td>
<td>765</td>
<td>87.03</td>
<td>1.84</td>
<td>0.24</td>
<td>0.08</td>
<td>0.54</td>
<td>0.40</td>
<td>9.02</td>
<td>0.14</td>
<td>0.71</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Comment: For Pt>Pd type grains: 1 - crystals, 2 – twin crystals, 3 – chromitites; n is the number of the chemical analyses; element concentrations in weight %.

The structural state of the NMP corresponds to the relatively low-temperature region of the phase diagram of the Pt-Fe system. Formation of PGM occurred during crystallisation of picrite, monzonite, alkaline and granitoid melts and metasomatic transformations of dunites in shallow areas of the Aldan shield (Simonov et al., 2011 Mochalov, 2019). Oxygen fugacity in NMP of the Pt>Ir-, Pt>Os, Pt>Pd-types and in syngenetic clinopyroxene, chromespinelide and olivine are between the buffer equilibria of quartz-fayalite-magnetite and wustite-magnetite. At temperatures in excess of 1000 °C this indicator is similar to the oxygen fugacity of the redox state of the mafic magmas in near-surface environments in which Pt and Pt>Os PGMs are formed. At temperatures below 800–850 °C, the volatility of all these minerals is close to or below the buffer equilibrium of iron-wustite, which corresponds to the release of iron from silicates and indicates the conditions for the formation of NMP of Pt>Ir and Pt>Pd types (Kadik et al., 1998). The oxygen isotopic composition (δ\(^{18}\text{O} = 3.1–5.2 \text{‰}\)) of chromium spinels, clinopyroxenes, olivine in intergrowths with NMP of Pt>Ir, Pt>Pd PGM indicates that the formation of the minerals occurred in subsurface conditions from magmatic fluid in association with a water vapour that was ultimately of meteoric origin (Ukhanov et al., 1997).
Supplementary Information References


