A Combined Re-Os and Pt-Os Isotope and HSE Abundance Study of Ru-Os-Ir Alloys from the Kunar and Unga Placer Deposits, the Taimyr Peninsula, Polar Siberia

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Abstract: In order to provide further insights into the origin of Ru-Os-Ir alloys, this study presents new highly siderophile element (HSE: Re, Os, Ir, Ru, Pt, and Pd) abundance and 187Re−186Os and 190Pt−186Os isotope data for detrital grains of native Ru-Os-Ir alloys in placer deposits of the Kunar and Unga Rivers, which display a close spatial association with the Kunar dunite–harzburgite complex in the northern part of the Taimyr Peninsula in the Polar Siberia. The study utilized electron microprobe analysis, negative thermal ionization mass-spectrometry (N-TIMS) and laser ablation multiple-collector inductively coupled plasma mass-spectrometry (LA-MC-ICP-MS). The primary nature of the Ru-Os-Ir alloys is supported by the occurrence of euhedral inclusions of high-Mg olivine (Fo92–93) that fall within the compositional range of mantle olivine. The LA-MC-ICP-MS data show similar average initial 187Os/188Os and γ187Os(740 Ma) values for PGM assemblages from the Kunar and Unga deposits of 0.1218 ± 0.0010, −0.18 ± 0.85, and 0.1222 ± 0.0025, +0.10 ± 2.1, respectively. These values are identical, within their respective uncertainties, to the initial 187Os/188Os value of the Ru-Os-Ir alloy grain measured by N-TIMS (0.1218463 ± 0.0000015, γ187Os(740 Ma) = −0.1500 ± 0.0012). The combined 187Re−187Os isotopic data for all studied grains (γ187Os(740 Ma) = −0.02 ± 1.6) indicate evolution of the Kunar and Unga mantle sources with a long-term chondritic 187Re/188Os ratio of 0.401 ± 0.030. In contrast to the 187Os/188Os data, the initial 186Os/188Os value of 0.1198409 ± 0.0000012 (µ186Os(740 Ma) = +34 ± 10) obtained for the same Ru-Os-Ir alloy grain by N-TIMS is suprachondritic and implies evolution of the Kunar and Unga mantle source(s) with a long-term suprachondritic 190Pt/188Os ratio of 0.00247 ± 0.00021. This value is ~40% higher than the average chondritic 190Pt/188Os ratio of 0.00180 and indicates long-term enrichment of the Kunar source in Pt over Os. Establishing the source of this enrichment requires further investigation.

Keywords: Ru-Os-Ir alloys; highly siderophile elements; Re-Os and Pt-Os isotopic systems; ophiolite; mantle; the Kunar and Unga placer deposits; the Taimyr Peninsula; Polar Siberia

1. Introduction

Abundances of the highly siderophile elements (HSE = Os, Ir, Ru, Rh, Pt, Pd, Re, and Au) and HSE-based isotopic systems (187Re−187Os and 190Pt−186Os) are important tools for geochemical investigations of the mantle. Because Re and Os have strongly contrasting partitioning behavior during mantle melting and magma differentiation, e.g., [1–4], the 187Re−187Os isotopic system is particularly useful in (i) distinguishing between crustal and mantle sources of the HSE, (ii) tracking melt extraction events, and (iii) studying long-term evolution of mantle sources. This tool can be applied at both the whole-rock and individual mineral (i.e., chromite, Ru-Os-Ir alloy, sulfide) scales.
Since the dawn of the Re-Os isotopic method [5], followed by the development of the Pt-Os method [6], numerous applications of these systems focused on platinum-group-element (PGE = Os, Ir, Ru, Rh, Pt, and Pd) mineralization in placer deposits derived mostly from dunite–harzburgite (e.g., Alpine- or ophiolite-type) and clinopyroxenite–dunite (e.g., zoned-, Uralian-, Alaskan or Aldan-type) massifs, e.g., [7–21]. These studies have shown that the platinum-group minerals (PGMs) are formed simultaneously with the host ultramafic rocks and are not related to secondary processes, as some authors proposed, e.g., [22–26].

Despite numerous publications on the mineral deposits of the Taimyr Peninsula, particularly well known for its gold placer deposits [27–30], only limited data are available for alluvial PGE mineralization [31,32]. The HSE abundance and Re-Os isotopic data for Ru-Os-Ir alloys from gold placer deposits were previously described only in the area of the Unga River [17,33] located in the northern extremity of the Taimyr Peninsula (Figure 1). The Ru-Os-Ir alloys (i.e., native osmium, iridium, and ruthenium) prevailing over Pt-Fe alloys and other PGM [17,33] of the Unga River deposit were considered to be sourced from the spatially associated ultramafic rocks of the Kunar dunite–harzburgite complex, which is part of the Chelyuskin ultramafic belt [34], although no conclusive evidence to that effect were presented by these authors.

To gain further insight into the origin of these detrital Ru-Os-Ir alloys, we obtained HSE abundance and $^{187}$Os/$^{188}$Os isotopic data for eight alluvial grains of Os-rich alloys from the Kunar River placer deposit, which is closely associated with the ultramafic rocks of the Kunar ultramafic complex, and for fourteen Ru-Os-Ir alloy grains from the Unga River placer deposit. This dataset is supplemented by a high-precision $^{186}$Os/$^{188}$Os isotopic
analysis of an Os-rich alloy sample from the Kunar deposit. These new data are compared with the published data for Ru-Os-Ir alloys of the Unga placer deposit [17] and other globally distributed placer deposits, e.g., [14,15]. We integrate an application of electron probe microanalysis (EPMA) of HSE, Fe, Ni, and Cu abundances in Ru-Os-Ir alloys and solid inclusions within these PGM, and $^{187}\text{Os}/^{188}\text{Os}$ LA MC-ICP-MS isotopic analysis of Ru-Os-Ir alloys supplemented by high-precision $^{186,187}\text{Os}/^{188}\text{Os}$ N-TIMS isotope analysis of native osmium. The objectives of the research were to (i) obtain HSE abundances in the PGM from both localities, and (ii) constrain the source(s) of the HSE in these PGM and HSE composition of that source. This study is part of a larger effort to elucidate the mantle versus crustal origin of HSE/PGM in oceanic and subcontinental mantle settings, e.g., [7,8,11,12,14–17,21,37–51].

2. Geological Background and Sample Location

Dunite–harzburgite and dunite–peridotite massifs of the Taimyr Peninsula are represented by multiple elongated bodies confined to five ultramafic belts, i.e., Chelyuskin, Malinovsk, Zhdanininsk, Moskvichevsk, and Stanovoi [35,36,52–56]. The first four represent relicts of the supra-subduction zone ophiolite of the Late Riphean (ca. 740 Ma) suture located on the border of the North Kara microcontinent and the Siberian Craton. The dunite–peridotite massifs of the Stanovoi belt record an earlier event (ca. 960 Ma), manifested by the transformation of the regime of the passive continental margin into an active one that occurred in the Early Neoproterozoic.

Ultramafic rocks of the Kunar complex (Figure 2), together with the other NE-trending bodies that form the Chelyuskin ultramafic belt, are controlled by the zone of the Main Taimyr Fault [52]. The ultramafic bodies of the Kunar complex are composed of serpentinitized harzburgites, dunites, and associated chromitites; these trend northeast for about 70 km (Figure 2). These bodies usually have tectonic contacts with metavolcanics, zones of serpentinite melange, greenschists, and listvenites [36]. Other rocks in the Chelyuskin ophiolite belt are represented by tholeiitic basalts, dolerites of a dyke–sill complex, and sheeted plagiograniites [35]. The geology of the Chelyuskin ophiolite belt has been described in previous studies [36,52,57].

Despite the lack of direct geochronological information on the ultramafic rocks, the constraining nature of the ultramafic bodies, confinement to the Late Riphean formations, and findings of chromite in conglomerates of the Lower sub-formation of Laptevsk Suite ($R_3Lp_1$) allowed the emplacement of ultramafic bodies to be attributed to the pre-Laptev time.

U-Pb and Sm-Nd isotopic studies indicate that the plagiograniites of the Chelyuskin ophiolite formed between 720 and 740 Ma [35,56,58]. Taking into account the above structural, petrological, and geochronological constraints, we assume the minimum formation age of 740 Ma for the ultramafic rocks of the Kunar complex.

In this study, we analyzed (i) 12 grains of Ru-Os-Ir alloys ranging in size from 0.25 to 2 mm, obtained by panning the Quaternary deposits in the middle part of the Kunar River stream (Figure 2), and (ii) 33 grains of Ru-Os-Ir alloys that range in size between 0.25 and 0.5 mm, which were obtained from a gold production concentrate in the area of the Unga River located between Cape Chelyuskin and Cape Pronchishcheva (Figure 2). The Unga placer deposit area is characterized by polygenic and polychronous placers of gold, which are represented by Jurassic conglomerates of riverbed valleys, Paleogene weathering crusts, Paleogene-Neogene coastal-marine sediments, and Quaternary eluvial–deluvial formations [27,28]. The significant content of chromite (4.7–17.5 g/m$^3$ [28]) in the heavy fraction of the production concentrates and the spatial proximity of the Kunar complex imply that chromitites of the Kunar complex are the most probable source of the PGM studied.
3. Analytical Techniques

The analytical work was performed at the Institute of Geology and Geochemistry, Ural Branch of the Russian Academy of Sciences (IGG UB RAS), Ekaterinburg, Russia, Australian Research Council Centre of Excellence for Core to Crust Fluid Systems (ARC CoE CCFS)/ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents (GEMOC ARC National Key Centre) in the Department of Earth and Planetary Sciences at Macquarie University, Sydney, Australia, and the Isotope Geochemistry Laboratory (IGL) at the Department of Geology, University of Maryland College Park, USA.

Initially, the morphology of the PGM grains, represented by individual crystals and polymineral aggregates, was documented by the scanning electron microscopy (SEM). The grains were then mounted and polished, described, and analyzed by electron probe microanalysis (EPMA) using a CAMECA SX-100 equipped with five WDS spectrometers and a Bruker energy dispersive spectrometer system at Common Use Center “Geoanalyst” of the Institute of Geology and Geochemistry, Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia. Quantitative WDS analyses were performed at 25 kV accelerating voltage and 20 nA beam current, with a beam diameter of about 1 µm. The following X-ray lines and standards have been used: RuLα, RhLα, PdLβ, OsMα, IrLα, PtLα, NiKα (all native element standards), FeKα, CuKα, SKα (chalcopyrite), and AsLα.

Figure 2. Sketch geological map of the northern Taimyr Peninsula modified after [59] with locations of the PGM grains studied.
(sperrylite). Corrections were performed for the interferences involving Ru-Rh, Ru-Pd, and Ir-Cu. Only Os, Ir, Ru, Rh, Pt, Fe, and Ni were found to be above the detection limits of the EPMA analysis. A total of 128 EPMA analyses of Ru-Os-Ir alloys were performed. Additional details of the analytical protocols used are given in Badanina et al. [60].

Thirty one in situ Re-Os isotope analyses of Ru-Os-Ir alloys were carried out at the Geochemical Analysis Unit, CCFS/GEMOC laboratories, Macquarie University, Sydney, Australia, using analytical methods described in detail by Marchesi et al. [42], González-Jiménez et al. [61] and Malitch et al. [48]. These analyses employed a New Wave/Merchantek UP 213 laser ablation system attached to a Nu Plasma multi-collector ICP-MS instrument. Laser ablation was carried out with a frequency of 4 Hz, energies of 1–2 mJ/pulse and a spot size of 40 µm. A standard NiS bead (PGE-A) with 199 ppm Os [62] and $^{187}$Os/$^{188}$Os = 0.1064 [63], along with a native osmium (i.e., Os$_{1.0}$) from the Guli massif [64], were analyzed between the samples to monitor and correct for mass-fractionation. The isobaric interference of $^{187}$Re on $^{187}$Os was corrected by measuring the $^{185}$Re peak and using $^{187}$Re/$^{185}$Re = 1.6742. All analyzed grains have very low Re contents (typically, $^{185}$Re/$^{187}$Os < 0.0003), allowing for the isobaric interference of $^{187}$Re on $^{187}$Os to be accurately and precisely corrected for. The Os isotopic data were reduced using the Nu Plasma time-resolved software, which allows the selection of the most stable intervals of the signal for integration. The external reproducibility of $^{187}$Os/$^{188}$Os for the PGE-A standard during the period of data collection was 0.10652 ± 0.00013 (0.12% relative; 2SD; n = 15). Repeated analyses of a crystal of native osmium, which has been used to estimate the accuracy of the LA MC-ICP-MS measurements, yielded $^{187}$Os/$^{188}$Os = 0.12452 ± 0.00004 (2SD, n = 27).

For one grain of Ru-Os-Ir alloy (sample T-2), the osmium isotopic composition was determined via negative thermal ionization mass-spectrometry (N-TIMS; [65]) at the IGL, following the analytical procedures detailed in Puchtel et al. [66,67]. To obtain the Os isotopic data, a ~1 mg piece of the Ru-Os-Ir alloy, 6 mL of Os-purged, triple-distilled concentrated HNO$_3$, and 3 mL triple-distilled concentrated HCl were sealed in a chilled 25 mL Pyrex™ borosilicate Carius Tube and heated to 270 °C for 96 h. Osmium was extracted from the aqua regia acid solution by CCl$_4$ solvent extraction [68], back-extracted into HBr, and purified via microdistillation [69].

The high-precision measurements of the $^{186}$Os/$^{188}$Os and $^{187}$Os/$^{188}$Os ratios were performed in static mode on the Faraday cups of a ThermoFisher Triton® mass spectrometer. The sample load was run twice; during each run, 1800 ratios were collected, and the results from the two runs were averaged; the resultant in-run uncertainty on the measured $^{186}$Os/$^{188}$Os and $^{187}$Os/$^{188}$Os was 4.0 ppm for both ratios (2SE). The possible isobaric interference of $^{186}$W$^{16}$O$_3^-$ on $^{186}$Os$^{16}$O$_3^-$ was monitored and corrected for by measuring masses $^{184}$Os$^{16}$O$_3^-$ and $^{183}$W$^{16}$O$_3^-$ using the secondary electron multiplier.

The mean of the Johnson-Matthey Os standard runs during the period of data collection was 0.001302 ± 2 for $^{184}$Os/$^{188}$Os, 0.1198433 ± 17 (±14 ppm) for $^{186}$Os/$^{188}$Os, and 0.1137952 ± 21 (18 ppm) for $^{187}$Os/$^{188}$Os (2SD, N = 14); this long-term reproducibility was used to assess the true uncertainty on the measured $^{186}$Os/$^{188}$Os and $^{187}$Os/$^{188}$Os ratios for the Ru-Os-Ir alloy sample analyzed, also accounting for the fact that the sample was run twice. Since the high-precision $^{186}$Os/$^{188}$Os ratios obtained at IGL were previously instrumental bias-corrected to a common Johnson-Matthey Os standard $^{186}$Os/$^{188}$Os value of 0.1198475 [66,67,70,71], the $^{186}$Os/$^{188}$Os ratio measured in this study was also bias-corrected to the same value using correction coefficient of 1.0000354.

The initial $\gamma^{187}$Os values for the alloy grains measured by LA ICP-MS were calculated as the per cent (%) deviation of the isotopic composition at the time of the formation of the Ru-Os-Ir alloy grains at 740 Ma relative to the chondritic reference of Shirey and Walker [72] at that time and using the $^{187}$Re/$^{188}$Os ratios obtained from the LA ICP-MS analysis of the respective alloy grains. To calculate the initial $\gamma^{187}$Os value for the alloy grain analyzed by N-TIMS, we used the average $^{187}$Re/$^{188}$Os ratio obtained for all alloy grains from the Kunar placer deposit in this study. The average chondritic Os isotopic composition at the time of the alloy formation was calculated using the $^{187}$Re decay constant.
\[ \lambda = 1.666 \times 10^{-11} \text{ year}^{-1} \], an early Solar System initial \({ }^{187}\text{Os}/^{188}\text{Os} = 0.09531\) at \(T = 4558\) Ma, and \({ }^{187}\text{Re}/^{188}\text{Os} = 0.40186\) \([72,73]\). To calculate the initial \({ }^{186}\text{Os}/^{188}\text{Os}\) ratio for the Ru-Os-Ir alloy grain analyzed by N-TIMS, the average \({ }^{190}\text{Pt}/^{188}\text{Os}\) ratio obtained from the LA ICP-MS analysis of all alloy grains from the Kunar placer deposit and the \(\lambda = 1.477 \times 10^{-12} \text{ year}^{-1}\) \([74]\) were used. The initial \(\mu^{186}\text{Os}\) value was calculated as the part per million (ppm) deviation of the \({ }^{186}\text{Os}/^{188}\text{Os}\) ratio of the alloy sample at 740 Ma relative to the chondritic reference of Brandon et al. \([15]\) at that time. The latter was calculated using an early Solar System initial \({ }^{186}\text{Os}/^{188}\text{Os} = 0.1198269\) at \(T = 4567\) Ma and \(\lambda = 1.666 \times 10^{-11} \text{ year}^{-1}\).

It should be noted that, due to the very low \({ }^{187}\text{Re}/^{188}\text{Os}\) and \({ }^{190}\text{Pt}/^{188}\text{Os}\) ratios in all alloy grains analyzed, age corrections of measured \({ }^{186}\text{Os}/^{188}\text{Os}\) and \({ }^{187}\text{Os}/^{188}\text{Os}\) for radioactive decay of \({ }^{190}\text{Pt}\) and \({ }^{187}\text{Re}\) were minimal and usually below the in-run uncertainty of individual analyses.

4. Results

Investigation of the PGM grains at the Kunar and Unga placer deposits revealed their significant diversity (Figure 3). Both localities are characterized by dominance of solitary grains of osmium (9 and 18 grains at Kunar and Unga, respectively) and iridium (6 and 5 grains, respectively), which prevail over those of ruthenium (5 grains) and rutheniridosmine (3 grains). Only one polymineralic grain composed of dominant osmian iridium intergrown with rutheniridosmine was detected at Kunar (Figure 3a). Abundant solitary inclusions (i.e., Pt-Fe alloy and high-Mg olivine) and rare polyphase PGM inclusions (i.e., Pt-Fe alloy, Ni-Fe-Ir sulfide and pentlandite) hosted by IPGE alloys have been also observed. Typical internal features of the Ru-Os-Ir alloys and associated minerals are illustrated in Figures 3 and 4. Representative results of 10 electron microprobe WDS analyses of Ru-Os-Ir and Pt-Fe alloys (out of a total of 138 analyses) and 5 electron microprobe WDS analyses of high-Mg olivine are presented in Tables 1 and 2 and Figures 3–5.

Figure 3. Back-scattered electron images of the PGM grains from Kunar (a–c) and Unga (d–f). Numbers 1–7 denote locations of electron microprobe analyses corresponding to the same numbers in Table 1. Circles denote locations of laser ablation MC-ICP-MS analyses listed in Table 3; numbers in numerator and denominator correspond to the \(187\text{Os}/188\text{Os}\) composition and the measurement error, respectively. (Ir, Os, Ru)—native iridium, RIO—rutheniridosmine, (Ru, Os, Ir)—native ruthenium, (Os, Ir, Ru)—native osmium, Ol—high-Mg olivine. Blue square shows an area detailed in Figure 4.
at.%), Ni (<2.0 at.%), Rh (< 1.5 at.%), and Os (< 0.2 at.%). Calculated formula of Pt-Fe alloy deviate from ideal isoferroplatinum, Pt 3Fe (BM/PGE = 0.33), being more base metal rich (BM/PGE = 0.40 – 0.46). This corresponds to an average formula of PGE 2.8±2.9BM1.1–1.2, or PGE3−хBM1+x, with х = 0.13–0.26, and an average of 70 at.% PGE. We suggest the presence of ferroan platinum (disordered face centered cubic structure Fm3m) instead of isoferroplatinum (ordered primitive cubic structure Pm3m), although we did not confirm this by X-ray crystallography data [76].

Figure 3. Back-scattered electron images of the PGM grains from Kunar (a–c) and Unga (d–f). Numbers 1–7 denote locations of electron microprobe analyses corresponding to the same numbers in Table 1. Circles denote locations of laser ablation MC-ICP-MS analyses listed in Table 3; numbers in numerator and denominator correspond to the 187Os/188Os composition and the measurement error, respectively. (Ir, Os, Ru)—native iridium, RIO—rutheniridosmine, (Ru, Os, Ir)—native ruthenium, (Os, Ir, Ru)—native osmium, Ol—high-Mg olivine. Blue square shows an area detailed in Figure 4.

Figure 4. Back-scattered electron image (a) and single element scans for Mg (b), Si (c), Fe (d), Pt (e) and Ir (f) of high-Mg olivine and ferroan platinum inclusions in native iridium (sample 231) at Kunar. Numbers 1 and 8–10 denote areas of EMP analyses corresponding to the same numbers in Tables 1 and 2, respectively. (Ir, Os, Ru)—native iridium, (Pt, Fe)—ferroan platinum, Ol—high-Mg olivine.

Table 1. Representative electron probe microanalyses (WDS) of Ru-Os-Ir and Pt-Fe alloys from the Kunar and Unga placer deposits.

| Analysis# | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|-----------|----|----|----|----|----|----|----|----|----|----|
| Sample#   | 231| 231| 233| 235| 241| 246| 250| 231| 231| 231|
| PGM *     | Ir | RIO| Ru | Os | Os | Os | Ru | Ir | (Pt, Fe) | (Pt, Fe) |
| Figure    | 3a | 3a | 3b | 3c | 3d | 3e | 3f | 4a | 4a | 4a |
| Wt.%      |    |    |    |    |    |    |    |    |    |    |
| Fe        | 0.84| 0.48|    | 0.20| 0.32| 0.61| 0.26| 0.78| 9.71| 9.61|
| Ni        | 0.17|    | 0.02|    | 0.02| 0.02| 0.02| 0.02| 0.02| 0.02|
| Cu        |    |    |    |    |    |    |    |    | 0.81| 0.71|
| Ru        | 9.22| 12.02| 29.49| 17.49| 13.48| 18.28| 22.62| 9.74| 9.74| 9.74|
| Rh        |    |    |    |    |    |    |    |    | 0.70| 0.97|
| Pd        |    |    |    |    |    |    |    |    | 0.70| 0.97|
| Os        | 25.25| 42.87| 53.85| 42.96| 44.29| 41.66| 38.49| 23.81| 0.34| 0.25|
| Ir        | 56.29| 43.08| 12.49| 35.19| 39.64| 36.64| 35.13| 57.10| 1.81| 2.06|
| Pt        | 7.51| 0.97| 3.82| 3.68| 1.71| 2.37| 2.03| 7.77| 86.33| 86.28|
| Total     | 99.28| 99.42| 99.65| 99.52| 99.56| 98.53| 99.39| 99.70| 99.70| 99.88|
| Ar.%      |    |    |    |    |    |    |    |    |    |    |
| Fe        | 2.62| 1.48|    | 0.99| 0.98| 1.78| 0.74| 2.43| 26.87| 26.60|
| Ni        | 0.51|    |    |    |    |    |    | 0.56|    |    |
| Cu        | 15.91| 20.43| 44.25| 28.63| 22.72| 29.48| 35.87| 16.74|    |    |
| Ru        |    |    |    |    |    |    |    | 1.97| 1.73|    |
| Rh        |    |    |    |    |    |    |    |    |    |    |
| Pd        |    |    |    |    |    |    |    |    |    |    |
| Os        | 23.16| 38.73| 42.93| 37.37| 39.67| 35.70| 32.43| 21.75| 0.28| 0.20|
| Ir        | 51.08| 38.51| 9.85| 30.29| 35.14| 31.06| 29.29| 51.60| 1.45| 1.65|
| Pt        | 6.72| 0.85| 2.97| 3.12| 1.49| 1.98| 1.67| 6.92| 68.38| 68.36|

Analyses 1–4, 8–10—PGM from Kunar, analyses 5–7—PGM from Unga; * Abbreviations of PGM: Ir—native iridium, RIO—rutheniridosmine, Ru—native ruthenium, Os—native osmium, (Pt, Fe)—ferroan platinum. “—below detection limit; detection limit for concentrations in Ru-Os-Ir and Pt-Fe alloys were as follows, wt.%: Os—0.18, Ir—0.85, Ru—0.27, Rh—0.11, Pt—0.99, Pd—0.30, Fe—0.16, Ni—0.18, Cu—0.15.
Table 2. Electron probe microanalyses of high-Mg olivine inclusions in native iridium at Kunar.

| Analysis Sample# | 1  | 2  | 3  | 4  | 5  |
|------------------|----|----|----|----|----|
|                  |    |    |    |    |    |
| SiO₂             | 41.26 | 41.23 | 40.96 | 40.86 | 41.01 |
| MgO              | 51.74 | 51.60 | 50.03 | 50.36 | 50.08 |
| Fe₂O₃            | 6.50  | 6.53  | 8.08  | 7.80  | 8.13  |
| NiO              | 0.44  | 0.57  | 0.65  | 0.63  | 0.67  |
| Total            | 99.94 | 99.93 | 99.72 | 99.65 | 99.89 |
| Fo #             | 93   | 92   | 92   | 92   | 92    |

Apfu Cations on the basis of 4 atoms

\[ \text{SiO}_2, \text{CaO}, \text{TiO}_2, \text{MnO} \text{ were below the detection limit, Fo = 100} \times \text{Mg/(Mg + Fe)}. \]

Table 3. Os-isotope LA MC-ICP-MS data and calculated \( \gamma^{187}\text{Os} \) values of Ru-Os-Ir minerals from the Kunar and Unga placer deposits.

| Sample#, Mineral *, Figure | Atomic Proportions | \( \gamma^{187}\text{Os} \) values |
|----------------------------|--------------------|-------------------------|
|                            |                    | \( \text{Re/188Os} \)  | \( \text{187Os/188Os} \)  | \( \text{187Os/188Os(T)} \)  | \( \gamma^{187}\text{Os(T)} \)  |
| 236, Os                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00206 ± 2            | 0.12194 ± 3              | 0.12194 ± 0.05             | −0.07 ± 0.13               |
| 237-1, Ru                  | (R₂₂.₄₂Os₀.₅₁Ru₀.₂₆Pt₀.₀₂) | 0.00105 ± 4            | 0.12367 ± 3              | 0.12366 ± 0.05             | +1.3 ± 0.13               |
| 237-2, Ru                  | (R₂₂.₄₂Os₀.₅₁Ru₀.₂₆Pt₀.₀₂) | 0.00105 ± 4            | 0.12395 ± 3              | 0.12394 ± 0.05             | +1.6 ± 0.13               |
| 239-1, Os                  | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00189 ± 2            | 0.12183 ± 3              | 0.12183 ± 0.05             | +0.8 ± 0.13               |
| 240, Ir                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00060 ± 1            | 0.12193 ± 2              | 0.12193 ± 0.05             | +0.8 ± 0.13               |
| 241, Os, Figure 3d         | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00560 ± 4            | 0.12143 ± 2              | 0.12143 ± 0.05             | +0.5 ± 0.13               |
| 242, Ir                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00054 ± 2            | 0.12370 ± 4              | 0.12369 ± 0.05             | +1.4 ± 0.13               |
| 243, Os                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00037 ± 1            | 0.12154 ± 3              | 0.12153 ± 0.05             | −0.4 ± 0.13               |
| 244-1, Os, Figure 3e       | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00028 ± 2            | 0.12213 ± 2              | 0.12213 ± 0.05             | +0.8 ± 0.13               |
| 245-2, Os, Figure 3e       | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00018 ± 2            | 0.12213 ± 2              | 0.12213 ± 0.05             | +0.8 ± 0.13               |
| 246-3, Os, Figure 3e       | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00018 ± 2            | 0.12213 ± 2              | 0.12213 ± 0.05             | +0.8 ± 0.13               |
| 247, Os                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00201 ± 2            | 0.12389 ± 3              | 0.12389 ± 0.05             | +1.5 ± 0.13               |
| 248, Os                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.000005 ± 15          | 0.11848 ± 3              | 0.11848 ± 0.05             | −2.9 ± 0.13               |
| 249, Os                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00023 ± 1            | 0.12237 ± 2              | 0.12237 ± 0.05             | +0.8 ± 0.13               |
| 250, Ru, Figure 3f         | (R₂₂.₄₂Os₀.₅₁Ru₀.₂₆Pt₀.₀₂) | 0.00029 ± 1            | 0.12220 ± 3              | 0.12220 ± 0.05             | −0.3 ± 0.13               |
| 251, Os                    | (O₉₀.₃₉Ir₀.₃₉Ru₀.₂₆Pt₀.₀₂) | 0.00056 ± 1            | 0.12200 ± 2              | 0.12200 ± 0.05             | −0.3 ± 0.13               |

Mean (n = 18) 0.1218 ± 0.01 0.85 2SD (n = 18) 0.0025 2.1

* Abbreviations of PGCM: Os—native osmium, Ir—native iridium, RIO—rutheniridiosmine, Ru—native ruthenium. The initial \( \text{187Os/188Os} \) and \( \gamma^{187}\text{Os} \) values were calculated for the time of formation of the Os-rich alloys at 740 Ma using the parameters specified in the text. The uncertainty on the measured \( \text{187Re/188Os} \) and \( \text{187Os/188Os} \) is 2SE of the mean in the last decimal place; SD—standard deviation.
The Ru-Os-Ir alloys were classified according to the nomenclature of Harris and Cabri [75]. In descending order, they are represented by native osmium, iridium, ruthenium, and rutheniridosmine, with considerable variation in Os, Ir, and Ru abundances from one grain to another (Figure 5, Table 1, an. 1–8). The sum of Os + Ir + Ru + Pt in an alloy is usually >99 wt.\% (Table 1). Minor elements, systematically detected in some grains, include Fe (up to 0.84 wt.\%) and Ni (up to 0.19 wt.\%). It is noteworthy that the investigated Ru-Os-Ir alloys from the Kunar and Unga localities show similar compositional features (Figure 5a). However, solitary inclusions represented by minute high-Mg olivine and Pt-Fe alloy were only observed in Ir-rich alloys at Kunar. Grain sizes of individual high-Mg olivine inclusions can be as large as 35\,\mu m across, whereas Pt-Fe alloys range from 1 to 20\,\mu m but are usually below 10\,\mu m (Figure 4). High-Mg olivine (Fo\textsubscript{93-94}) contains NiO in the range of 0.44–0.67 wt.\% (Table 2). Chemically, the Pt-Fe alloy inclusions are dominated by Pt (64–69 at.\%) and Fe (26–28 at.\%) (Table 1, an. 9, 10), with notable concentrations of Ir (up to 5.9 wt.\% = 4.1 at.\%), rhodium (Rh <1.5 at.\%), and Os <2.0 at.\%). Calculated formula of Pt-Fe alloy deviate from ideal isoferroplatinum, Pt\textsubscript{2} Fe (BM/PGE = 0.33), being more base metal rich (BM/PGE = 0.40–0.46). This corresponds to an average formula of PGE\textsubscript{2.8±0.2}BM\textsubscript{1.1–1.2} or PGE\textsubscript{3–x}BM\textsubscript{1+x}, with x = 0.13–0.26, and an average of 70 at.\% PGE. We suggest the presence of ferroan platinum (disordered face centered cubic structure Fm\textsubscript{3}m) instead of isoferroplatinum (ordered primitive cubic structure Pm\textsubscript{3}m), although we did not confirm this by X-ray crystallography data [76].

4.2. Osmium Isotope Data

The Os-isotope data for the Ru-Os-Ir alloys from the Kunar and Unga placer deposits are listed in Table 2. The in situ Os-isotope data for 13 Os-rich alloy grains from Kunar show a narrow range of measured 187\textsuperscript{Os}/188\textsuperscript{Os} values between 0.12033 ± 0.00004 and 0.12244 ± 0.00003, 187\textsuperscript{Re}/188\textsuperscript{Os} mainly lower than 0.0003, with a mean initial 187\textsuperscript{Os}/188\textsuperscript{Os} value of 0.1218 ± 0.0010 (2SD, n = 13) and the calculated average γ\textsuperscript{187}Os(740 Ma) = −0.018 ± 0.085 (2SD, Table 3). These LA ICP-MS data are indistinguishable, within their respective uncertainties, from the N-TIMS data for the Ru-Os-Ir alloy sample T-2 at Kunar (initial 187\textsuperscript{Os}/188\textsuperscript{Os} = 0.1218463 ± 0.0000015 with γ\textsuperscript{187}Os(740 Ma) = −0.1500 ± 0.0012, Table 4).
The PGM assemblage at Unga is characterized by a larger degree of Os-isotope variations ($^{187}\text{Os}/^{188}\text{Os}$ values range from 0.11848 to 0.12395), with a mean value of $0.1222 \pm 0.0025$, $\gamma^{187}\text{Os}(740 \text{ Ma}) = +0.10 \pm 2.1 \text{ (2SD, } n = 18, \text{ Table 3)}$.

Table 4. Re-Os and Pt-Os isotopic N-TIMS data for a Ru-Os-Ir alloy grain from the Kunar placer deposit.

| Sample# | $^{187}\text{Re}/^{188}\text{Os}$ | $^{190}\text{Pt}/^{188}\text{Os}$ | $^{186}\text{Os}/^{188}\text{Os}$ | $^{187}\text{Os}/^{188}\text{Os}$ | $\mu^{186}\text{Os}(T)$ | $\gamma^{187}\text{Os}(T)$ | TRD, Ga |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| T-2     | $0.00024 \pm 0.10$ | $0.000152 \pm 0.26$ | $0.1198411 \pm 0.12$ | $0.1218493 \pm 0.15$ | $+34 \pm 10$ | $-0.1500 \pm 12$ | $0.760$ |

The uncertainties on the isotopic ratios and the initial Os isotopic composition are quoted at 2SD based on the long-term reproducibility of the Johnson-Matthey Os standard at IGL [67]. The initial $\mu^{186}\text{Os}$ and $\gamma^{187}\text{Os}$ values were calculated for the time of formation of the Ru-Os-Ir alloys at 740 Ma using the parameters specified in the text. The $^{187}\text{Re}/^{188}\text{Os}$ and $^{190}\text{Pt}/^{188}\text{Os}$ ratios used to calculate the initial $^{186,187}\text{Os}/^{188}\text{Os}$ isotopic compositions are the average values for all the Kunar Ru-Os-Ir grains obtained by the LA ICP-MS analysis.

Overall, the $^{187}\text{Os}$ isotope results identify a restricted range of broadly similar $^{187}\text{Os}/^{188}\text{Os}$ values for PGM assemblages at both Kunar and Unga (Figures 6 and 7, Table 3). Similarly, the average $\gamma^{187}\text{Os}(T = 740 \text{ Ma})$ values of PGM assemblages at Kunar and Unga are indistinguishable within uncertainty from each other ($-0.18 \pm 0.85$ and $+0.10 \pm 2.1$, respectively, Table 3). The combined average initial $^{187}\text{Os}/^{188}\text{Os}$ ratio for all grains analyzed in this study is $0.1220 \pm 0.0020 \text{ (}$\gamma^{187}\text{Os(740 Ma)} = -0.02 \pm 1.6 \text{ (2SD)\text{), which is indistinguishable from the chondritic reference value at that time (Figure 6).}$

**Figure 6.** Os-isotopic composition of Ru-Os-Ir alloys from the Kunar and Unga placer deposits.
Figure 7. Histogram of Os isotopic compositions of the Ru-Os-Ir alloys from (a) Kunar and Unga (this study, n = 32), (b) Unga (LA MC-ICP-MS data from this study and N-TIMS data from [17], n = 46), and (c) Kunar and Unga (data from this and [17] studies, n = 60).

5. Discussion

5.1. Provenance of the Ru-Os-Ir Alloys

The provenance of the investigated Ru-Os-Ir alloy grains can be constrained by the close spatial association of the PGM placer deposits with the Kunar dunite–harzburgite complex (Figure 2). The Ru-Os-Ir alloys at Kunar and Unga show similar compositional signatures dominated by osmium and iridium over ruthenium and rutheniridosmine, which is a feature typical of ophiolite-type complexes [77,78]. The primary nature of Ru-Os-Ir alloys is supported by the occurrence of euhedral inclusions of high-Mg olivine (Fo$_{92–93}$) that fall within the compositional range of mantle olivine (Fo$_{88–93}$), as represented by the composition of olivine (with a pronounced peak between Fo$_{93}$ and Fo$_{94}$) in mantle peridotite xenoliths on Archean cratons [79–81]. The common occurrence of euhedral inclusions of Pt-Fe alloys in Os-Ir-(Ru) alloys is interpreted in light of the large miscibility gaps in the binary systems of Os-Ir, Ir-Os, and Ir-Pt [82–84] indicative of their high-temperature origin. Finally, the presence of a ruthenium trend in the mineral compositions of Ru-Os-Ir alloys (Figure 5) is indicative of high temperature and pressure values that can only be reached under mantle conditions [85]. These data present solid evidence that the Ru-Os-Ir alloys formed under the high P-T conditions and that the observed chemical variations represent primary features of the grains. Thus, the Ru-Os-Ir alloys at Kunar and Unga are considered
to be representative of the mantle material derived from the mantle section of the Kunar ophiolitic complex.

5.2. Os Isotopic Composition of the Mantle as Evidenced by the Ru-Os-Ir Alloys

The primary nature of the Ru-Os-Ir alloys and their formation at high temperatures implies that the Os-isotopic composition of these PGMs reflects that of their source region at the time of their formation. The LA MC-ICP-MS data from this study show similar average initial $^{187}$Os/$^{188}$Os values for both PGM assemblages at Kunar and Unga ($0.1218 \pm 0.0010$, $^{\gamma}$Os(740 Ma) = $-0.18 \pm 0.84$, and $0.1222 \pm 0.0025$, $^{\gamma}$Os(740 Ma) = $+0.10 \pm 2.1$, respectively, Table 3, Figure 7a). These values are identical, within uncertainty, to the initial $^{187}$Os/$^{188}$Os value for the Ru-Os-Ir alloy obtained by N-TIMS ($0.1218463 \pm 0.0000015$, $^{\gamma}$Os(740 Ma) = $-0.1500 \pm 0.0012$, Table 4). The combined average initial $^{187}$Os/$^{188}$Os ratio for all grains analyzed in this study is $0.1220 \pm 0.0020$ ($^{\gamma}$Os(740 Ma) = $-0.02 \pm 1.6$, 2SD), which is identical to that for Ru-Os-Ir alloys from the Unga deposit studied previously ($0.1220 \pm 0.0054$, $n = 28$, Figure 7b). No correlation between the chemical and Os isotopic composition of the PGM was found. This is also evidenced by the restricted range of $^{187}$Os/$^{188}$Os values for intimately intergrown native iridium and rutheniumdioxide pair that forms part of the primary PGM assemblage at Kunar ($0.12205$–$0.12213$, Figure 3a).

The average initial $^{187}$Os/$^{188}$Os value of the Ru-Os-Ir alloys at Kunar and Unga are indicative of derivation from a source that evolved with a long-term chondritic Re/Os ratio. This conclusion is in good agreement with the previous Re-Os studies of PGM associated with dunite–harzburgite and clinopyroxenite–dunite massifs [7,8,10,12,14,34,38,40–46,48,49,59,86–90], indicating that PGM were formed in and derived from the ultramafic rocks of the massifs.

For the Ru-Os-Ir alloy sample T-2 analyzed to the highest precision, and which is also representative of the entire population of alloy grains from the Kunar and Unga placer deposits, a Re-Os model age can be calculated. Since the studied alloy grain has a very low estimated Re content ($^{187}$Re/$^{188}$Os = $0.00024 \pm 10$), we estimated the $T_{RD}$ model age, which is calculated assuming that a melt-depletion event removed all Re from the sample at the time of its formation, and, hence, growth of $^{187}$Os was completely terminated at that time [72]. This calculated $T_{RD}$ model age is 764 $\pm 2$ Ma, which is consistent with the estimate for the age of the Kunar dunite–harzburgite complex at 740 Ma [56,58].

Using the accepted emplacement age of 740 Ma, the long-term $^{187}$Re/$^{188}$Os ratio, with which the mantle source of the Kunar dunite–harzburgite complex evolved, can be estimated. In order to model the time-integrated evolution of Re/Os in the Kunar mantle source, the average initial $^{187}$Os/$^{188}$Os ratio of the studied Ru-Os-Ir alloy grain samples of $0.1220 \pm 20$ has been used to calculate the minimum $^{187}$Re/$^{188}$Os ratio required to evolve to this Os isotopic composition by 740 Ma, and assuming formation of this mantle domain shortly after the start of the Solar System. Evolution of the Kunar mantle source from an early Solar System $^{187}$Os/$^{188}$Os = 0.09531 at 4558 Ma [72,73] to the initial $^{187}$Os/$^{188}$Os ratio of $0.1220 \pm 20$ at 740 Ma requires $^{187}$Re/$^{188}$Os ratio of 0.401 $\pm$ 0.030. This time-integrated $^{187}$Re/$^{188}$Os ratio for the Kunar mantle source is within the range of that for chondritic meteorites (a bulk chondrite average $^{187}$Re/$^{188}$Os = $0.410 \pm 0.051$ ($\pm$2SD), as compiled from the data of Walker et al. [91] and Fischer-Gödde et al. [92]).

We note that Os-isotope data at Kunar and Unga are consistent with a Neoproterozoic age for the formation of the Chelyuskin ophiolite, which is correlated with coeval ophiolites of other Arctic regions that mark the opening of the Paleo-Pacific Ocean and the breakup of the Neoproterozoic supercontinent Rodinia between 900 and 700 Ma [93].

The initial $^{186}$Os/$^{188}$Os value of 0.1198409 $\pm$ 0.0000012 obtained for the Ru-Os-Ir alloy sample T-2 at Kunar is 34 $\pm$ 10 ppm higher than this value in the chondritic reference of Brandon et al. [15] at that time. This indicates evolution of the mantle source with time-integrated suprachondritic Pt/Os ratio. Using the early Solar System $^{186}$Os/$^{188}$Os = 0.1198269 at 4567 Ma [15] requires a source with a $^{190}$Pt/$^{188}$Os = 0.00247 $\pm$ 21 to have evolved to its $^{186}$Os/$^{188}$Os = 0.1198409 $\pm$ 12 at 740 Ma. Thus, in contrast to the calculated Re/Os ratio, the required minimum $^{190}$Pt/$^{188}$Os ratio is $\sim$40% higher than the average $^{190}$Pt/$^{188}$Os = 0.00180 $\pm$ 17
(2SD) in bulk chondritic meteorites, as compiled from the data of Horan et al. [94], Brandon et al. [15,95], Fischer-Gödde et al. [92], and van Acken et al. [96].

The calculated initial $\gamma_{187}$Os (740 Ma) = $-0.02 \pm 1.6$ (2SD) of the Kunar mantle source is within the range of those for the majority of komatiite and abyssal peridotite sources and chondritic meteorites (Figure 8). The $^{186}$Os/$^{188}$Os isotope data available for Archean and Paleoproterozoic komatiite sources indicate that mantle sources of the 2.7 Ga Abitibi (Canada), 2.7 Ga Belingwe (South Africa), and 2.4 Ga Yeteny (Fennoscandia) komatiite systems evolved with time-integrated Pt/Os within the chondritic range (Figure 8), whereas the coupled high initial $^{186,187}$Os/$^{188}$Os of the 2.8 Ga Kostomuksha komatiite system (Fennoscandia) require long-term suprachondritic Pt/Os and Re/Os [97]. By contrast, the 3.5 Ga Komati, 3.3 Ga Weltevreden, and 2.05 Ga Lapland komatiite systems evolved with non-chondritic Pt/Os, but chondritic Re/Os ratios [67,98], displaying decoupling of the Re-Os and Pt-Os isotopic systems. The majority of abyssal peridotite sources evolved with long-term subchondritic Pt/Os ratios. The calculated suprachondritic initial $\mu_{186}$Os = $+34 \pm 10$ in the Kunar mantle source obtained in this study is similar to $\mu_{186}$Os = $+29 \pm 2$ in the source of the Lapland komatiite system [67]. The reason for such long-term Pt/Os enrichment in the Kunar mantle source is not yet clear and would require further investigation.

![Figure 8](image-url)  
Figure 8. (a) Initial $^{187}$Os/$^{188}$Os isotopic compositions, expressed as $\gamma_{187}$Os, of mafic–ultramafic rocks plotted as a function of age. The data for the Archean-Proterozoic komatiites are from Puchtel et al. [66,67,70,71,97–104]. The Kunar data are from this study and represent an average of all analyses (2SD). The data for chondritic meteorites are compiled from Walker et al. [91] and Fischer-Gödde et al. [92]. The Bulk Silicate Earth (BSE) value is from Meisel et al. [105] and Day et al. [106]. The abyssal peridotite (AP) data are from Snow and Reisberg [107], Brandon et al. [108], and Day et al. [106]. (b) Initial $^{186}$Os/$^{188}$Os isotopic compositions, expressed as $\mu_{186}$Os, of mafic–ultramafic rocks, plotted as a function of age. The data for Archean and Proterozoic komatiites are from Puchtel et al. [66,67,70,71,97,101]. The Kunar data are from this study. The data for chondritic meteorites, AP, and BSE are compiled from Brandon et al. [15,95], Fischer-Gödde et al. [92], and Day et al. [106]. See text for more details.
6. Conclusions

1. A multi-technique approach, including the use of electron microprobe analysis, negative thermal ionization mass-spectrometry (N-TIMS) and laser ablation multiple-collector inductively coupled plasma mass-spectrometry (LA MC-ICP-MS), provided a set of HSE abundance and Re-Os and Pt-Os isotope constraints on the origin of detrital Ru-Os-Ir alloys from placer deposits of the Kunar and Unga Rivers in the northern part of the Taimyr Peninsula in the Polar Siberia.

2. The Ru-Os-Ir alloys from both localities show similar compositional signatures dominated by osmium and iridium over ruthenium and rutheniridosmine. The common occurrence of euhedral inclusions of ferroan platinum in Os-Ir-(Ru) alloys is indicative of their high-temperature origin. The primary nature of PGM studied is further supported by the presence of a ruthenium trend in the mineral compositions of Ru-Os-Ir alloys and the occurrence of euhedral inclusions of high-Mg olivine (Fo$_{92-93}$) that fall within the compositional range of mantle (primitive) olivine (Fo$_{88-93}$).

3. The LA MC-ICP-MS data from this study show similar average initial $^{187}\text{Os}/^{188}\text{Os}$ values for both PGM assemblages at Kunar and Unga (0.1218 ± 0.0010, $\gamma_{\text{Os}}$(740 Ma) = −0.18 ± 0.84, and 0.1222 ± 0.0025, $\gamma_{\text{Os}}$(740 Ma) = +0.10 ± 2.1, respectively). These values are identical, within uncertainty, to the initial $^{187}\text{Os}/^{188}\text{Os}$ value for the Ru-Os-Ir alloy obtained by N-TIMS (0.1218±0.000015, $\gamma_{\text{Os}}$(740 Ma) = −0.1500 ± 0.0012). The average initial $^{187}\text{Os}/^{188}\text{Os}$ value of the Ru-Os-Ir alloys at Kunar and Unga are indicative of derivation from a source that evolved with a long-term chondritic Re/Os ratio; this source is within the range of those for the majority of komatiite and abyssal peridotite sources and chondritic meteorites.

4. In contrast to the $^{187}\text{Os}/^{188}\text{Os}$ data, the initial $^{186}\text{Os}/^{188}\text{Os}$ value of 0.1198409 ± 0.0000012 obtained by N-TIMS for the same Ru-Os-Ir alloy sample T-2 at Kunar is 34 ± 10 ppm higher than this value in the chondritic reference of Brandon et al. [15] at that time, but is similar to the $\mu^{186}\text{Os}$ value of +29 ± 2 in the source of the 2.05 Ga Lapland komatiite system [65]. This implies evolution of the Kunar mantle source with time-integrated suprachondritic Pt/Os ratio. The reason for such long-term Pt/Os enrichment in the Kunar mantle source is not yet clear and would require further investigation.

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