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The enigmatic botryoidal nuggets of platinum (Pt) and palladium (Pd) from Córrego Bom Sucesso in the southern Serra do Espinhaço, Minas Gerais, Brazil, are considered to have formed during supergene alteration of placer deposits. This is inconsistent with Pt–Os age of 180 Ma that entails formation at depth. Here we report the first mercury (Hg) and helium (He) isotopic determinations of Pt–Pd nuggets. Mercury isotopic compositions have a mass-independent fractionation (MIF) signature with an odd-mass deficit (Δ199Hg -0.22 ± 0.04; 1SD, n = 15), which requires aqueous photochemical reduction of Hg (II). Extremely low 3He/4He (< 0.001 Ra) and extremely high concentrations of He (up to 1.9 x 10^17 at/g) are indicative of nugget formation from He-enriched fluids within the quartzite sequence of the Espinhaço basin, not from meteoric surface water. The data are consistent with a nugget-forming setting in the deep biosphere, as a result of groundwater interaction with Pt–Pd–Hg minerals in Pan-African-Brasiliano post-orogenic veins. We propose that the negative Hg-MIF signature was inherited from the vein minerals that originally acquired their Hg from Earth’s surface during the intracratonic sedimentation of the Proterozoic Espinhaço basin.
Metal recycling tracked by mercury and helium isotopes in platinum–palladium nuggets
from Córrego Bom Sucesso, Brazil

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Abstract

The enigmatic botryoidal nuggets of platinum (Pt) and palladium (Pd) from Córrego Bom Sucesso in the southern Serra do Espinhaço, Minas Gerais, Brazil, are considered to have formed during supergene alteration of placer deposits. This is inconsistent with Pt–Os age of 180 Ma that entails formation at depth. Here we report the first mercury (Hg) and helium (He) isotopic determinations of Pt–Pd nuggets. Mercury isotopic compositions have a mass-independent fractionation (MIF) signature with an odd-mass deficit ($\Delta^{199}$Hg -0.22 ± 0.04; 1SD, n = 15), which requires aqueous photochemical reduction of Hg (II). Extremely low $^{3}$He/$^{4}$He
(< 0.001 R₃) and extremely high concentrations of He (up to 1.9 x 10¹⁷ at/g) are indicative of nugget formation from He-enriched fluids within the quartzite sequence of the Espinhaço basin, not from meteoric surface water. The data are consistent with a nugget-forming setting in the deep biosphere, as a result of groundwater interaction with Pt–Pd–Hg minerals in Pan-African-Brasiliano post-orogenic veins. **We propose that the negative Hg-MIF signature was inherited from the vein minerals that originally acquired their Hg from Earth’s surface during the intracratonic sedimentation of the Proterozoic Espinhaço basin.**

1. Introduction

Platinum was sourced from nuggets in placer deposits until the first quarter of the 20th century, prior to the discovery of lode deposits in South Africa and Siberia (e.g., Hattori and Cabri, 1992). The long-standing debate on the origin of Pt nuggets in regoliths and placer deposits show no sign of being convincingly resolved. The two prevailing mechanisms explain their origin either as residual grains inherited from a magmatic source (e.g., Hattori and Cabri, 1992; Oberthür et al., 2017) or authigenic aggregates formed at the surface (e.g., Cousins and Kinloch, 1976; Aiglsperger et al., 2017; Bowles and Suárez, 2021). The placer deposits of Córrego Bom Sucesso, southern Serra do Espinhaço, Minas Gerais, Brazil (Fig. 1), are historically important by providing the nuggets where Pd was first identified (Wollaston, 1809; Hussak, 1906; Cassedanne and Alves, 1992; Cabral et al., 2009). The delicate botryoidal habit and the chemical composition distinguish these nuggets from Pt-rich nuggets of magmatic origin based on the enrichment in Se, Pd and Hg, the virtual absence of Fe and low Ru, Rh, Os and Ir concentrations (Cabral et al., 2019).

Mercury isotopes have been used to retrieve geochemical pathways of Hg in modern surface environments (Blum et al., 2014) and in the geological past, from the incorporation of atmospheric Hg into sediments and hydrated oceanic crust, through subduction and dehydration, to the formation of Hg-bearing mineral deposits in volcanic arcs (e.g., Deng et al.,
This relies on mass-independent-fractionation (MIF) signals that were generated at Earth’s surface and survived deep geological processes. Significant MIF of odd-mass-number isotopes of Hg (Δ\(^{199}\)Hg and Δ\(^{201}\)Hg) is commonly observed at Earth's surface – i.e., in soil/sediment, water, atmosphere and biological samples (Blum et al. 2014). Experiments have demonstrated that the signature results from the photoreduction of Hg(II) and photodegradation of methylmercury in aqueous solutions with dissolved organic matter (Bergquist and Blum, 2007). Other processes such as evaporation of Hg\(^0\) (Estrade et al., 2009) and dark abiotic reduction of Hg(II) by dissolved organic matter (Zheng and Hintelmann, 2010) can generate MIF of odd-mass Hg isotopes, but the fractionation is too small to explain the Hg-MIF of natural samples (Blum et al., 2014; Blum and Johnson, 2017).

Helium isotopes are a powerful tool for understanding the source of volatiles in hydrothermal minerals (e.g., Stuart et al., 1994), being particularly suitable for studies of Pt nuggets given the extreme retentivity for He (Shukolyukov et al., 2012a). A supergene origin for mineral aggregates requires the precipitation from meteoric solutions which would have a diagnostic isotopic fingerprint, in contrast to the \(^3\)He/\(^4\)He of crust- and mantle-derived fluids (e.g., Mamyrin and Tolstikhin, 1984). Further, the production of cosmogenic \(^3\)He at Earth’s surface provides a way to determine the residence time of Pt nuggets in the upper few metres (Yakubovich et al., 2019).

Here we report the Hg and He isotopic compositions of Pt–Pd nuggets from the placer deposit of Córrego Bom Sucesso that have a putative supergene origin (Cabral et al., 2019; Reith et al., 2019), representing the most spectacular case of Pt–Pd neoformations at the Earth’s surface. This view has recently been disputed on the basis of Pt–Os age of ca. 180 Ma and Se isotopes, which suggest nugget formation in the deep biosphere (Cabral et al., 2021). The Δ\(^{199}\)Hg and Δ\(^{201}\)Hg signals and reconnaissance He isotopic determinations provide new constraints on the geochemical processes responsible for the generation of the nuggets. Our
novel approach implies that precious-metal nuggets can be used as tracers of metal recycling and fluid interaction in the crust.

2. Samples and geological setting

Botryoidal Pt–Pd nuggets were recovered from a heavy-mineral concentrate from Córrego Bom Sucesso, southern Serra do Espinhaço, Minas Gerais, Brazil (Fig. 1, 2) Córrego Bom Sucesso is a stream, with associated placer deposit, in the platiniferous Au–Pd belt of Minas Gerais approximately 50 km SSE of Diamantina (Fig. 1; Cabral et al., 2009). The platiniferous alluvium was deposited on a bedrock of Mesoproterozoic quartzite in the interstices among quartzite boulders, and consists mostly of quartz sand with subordinate specular hematite, tourmaline, tourmalinite fragments, and minor palladiferous gold, Pt–Pd alloy, hongshiite (PtCu) and potarite (PdHg), among other minerals (Cassedanne et al., 1996; Cabral et al., 2017).

Platinum–osmium age determinations of 5 nuggets are indistinguishable within error (181 ± 6 Ma; Cabral et al., 2021). The age coincides with the final stage of rapid exhumation that brought basement granite-gneissic rocks to ~70°C until the Eocene–Oligocene (Amaral-Santos et al., 2019). The nugget Pt–Os age coincides with the emplacement of Transminas dolerite dykes that occur in the study area (Cabral et al., 2021) and in south-eastern Brazil, related to the South Atlantic opening (Chaves and Correia Neves, 2005).

Hematite-bearing quartz veins cross-cut quartzite of the 1.19-Ga Sopa-Brumadinho Formation of the Espinhaço Supergroup (Chemale et al., 2012) in the Córrego Bom Sucesso catchment. Such veins contain palladiferous gold and a variety of hydrothermal Pt, Pd and Hg minerals, e.g., potarite, hongshiite and jacutingaite (Pt₂HgSe₃) (Cabral et al., 2009, 2017). The veins likely formed after the compressional period of the Brasiliano orogeny (e.g., Cabral et al., 2017), which represents the assembly of West Gondwana (Alkmim et al., 2017, and references therein). Two geodynamic models have been proposed for the formation of Brasiliano orogenic
domain in the southern Serra do Espinhaço (the Araçuaí orogen): (i) a subduction–collision model in which subduction of oceanic crust occurred between 630 and 580 Ma (e.g., Alkmim et al., 2017); (ii) an intracontinental (ensialic) model (e.g., Fossen et al., 2020). The Brasiliano orogenic event occurred between 620 and 500 Ma in the southern part of the platiniferous Au–Pd belt (Cabral et al., 2020). Quartz veins, with and without Au–Pd–Pt mineralisation, are late in relation to the main orogenic compression, usually regarded as post-orogenic lodes (e.g., Cabral et al., 2017).

3. Methods

3.1. Mercury isotopes

Total Hg concentrations (THg) and Hg isotopic compositions were determined at the Institute of Geochemistry, Chinese Academy of Sciences. Fifteen Pt–Pd nuggets of 5–19 mg were digested in a water bath (95°C) using 5 mL of aqua regia (HCl:HNO₃=3:1). After digestion, THg was measured in solutions by cold vapour atomic absorption spectrometry (F732–S spectrophotometer, Huaguang Ltd, China). Measurements of reference material, GSS-4 (soil), yielded Hg recoveries of 93 and 113%, and coefficients of variation for triplicate analyses were < 9%. The digestion solutions were diluted to 1.0 ng/mL Hg with ~10% acid prior to isotopic analysis using a ThermoFisher Neptune Plus multi-collector inductively coupled plasma mass spectrometer (Yin et al., 2016). Mercury isotopic compositions are reported following convention (Blum and Bergquist, 2007), mass-dependent fractionation expressed in δ²⁰²Hg notation, in per mil, referenced to the NIST-3133 Hg standard analysed before and after each sample:

\[ \delta^{202}\text{Hg}(\%o) = \left( \frac{^{202}\text{Hg}^{198}\text{Hg}_{\text{sample}}}{^{202}\text{Hg}^{198}\text{Hg}_{\text{standard}}} \right) - 1 \times 1000 \]

Mass-independent fractionation is reported in \( \Delta \) notation, which describes the difference between the measured \( \delta^{xx}\text{Hg} \) and the theoretically predicted \( \delta^{xx}\text{Hg} \) value, in per mil:
\[ \Delta^{xxx}\text{Hg} \approx \delta^{xxx}\text{Hg} - \delta^{202}\text{Hg} \times \beta \]

\(\beta\) is equal to 0.2520 for \(^{199}\text{Hg}\), 0.5024 for \(^{200}\text{Hg}\), and 0.7520 for \(^{201}\text{Hg}\). The analytical uncertainty is estimated based on replication of the NIST-3177 standard solution, and full procedural analyses of GSS-4. The overall average and uncertainty of NIST-3177 and GSS-4 (Table 1) agree well with previous studies (Blum and Bergquist, 2007; Deng et al., 2021). The higher 2SD uncertainty for either GSS-4 or NIST-3177 are used in calculation of analytical uncertainties.

### Helium isotopes

Analysis of the Córrego Bom Sucesso nuggets was similar to detrital grains reported previously (Yakubovich et al. 2019). Grains were weighed then placed into 3-mm holes in a previously degassed copper pan, and covered with a degassed sapphire disk and baked for \(~36\) hours at \(~150^\circ\text{C}\) in ultra-high vacuum. Helium was extracted by directly heating each nugget with a focused beam of an 808-nm diode laser (Stuart et al., 1999). Quantitative release of He from metals requires melting (Shukolyukov et al., 2012a). This was achieved by slowly increasing laser power (maximum 75W) until melting, then holding for 5 minutes. Active gases were purified by exposure to two SAES GP50 getters and the heavy noble gases were removed by exposure to the liquid-nitrogen-cooled charcoal. The He isotopic composition was determined in a modified ThermoFisher Helix-SFT mass spectrometer (Carracedo et al., 2019). Sensitivity and mass fractionation were obtained by repeated measurements of aliquots of He from a tank of the HESJ standard (Matsuda et al., 2002). The reproducibility of \(^3\text{He}\) and \(^3\text{He}/^4\text{He}\) measurements was better than 5 per mil over the period of analysis. A Pt foil was melted in order to determine a representative hot blank level to correct the He concentrations released by heating the Pt–Pd nugget. The averages of \(^3\text{He}\) and \(^4\text{He}\) blanks were \(1.5 \times 10^8\) atoms and \(7 \times 10^8\) atoms, respectively.
Palladium alloys are excellent gas capacitors (Lewis, 1967), suggesting that natural Pd-rich alloys might host significant volumes of trapped gases. To determine He concentrations and the release temperature, Pt–Pd grains were step-heated and measured for He using the MSU-G-01 mass-spectrometric system at IPGG RAS, following the method described in Yakubovich et al. (2010).

The decay of $^{238}\text{U}$, $^{235}\text{U}$ and $^{232}\text{Th}$ can be sources of radiogenic He in Pt minerals in addition to the decay of $^{190}\text{Pt}$ (Shukolyukov et al., 2012b). The degassed Pt–Pd nugget was dissolved in aqua regia at a hot plate for 24 hours. Uranium and Th concentrations were measured in the resulting solutions using a ThermoFisher ELEMENT XR ICP–MS (GEOKHI RAS). Fresh mono-elemental solutions of U and Th (Inorganic Ventures) were used for calibrating the mass spectrometer. The full chemistry blank did not exceed 0.7 ppt both for $^{238}\text{U}$ and $^{232}\text{Th}$.

4. Results

4.1. Mercury isotopes

Total Hg concentrations and Hg isotopic ratios for Pt–Pd nuggets from Córrego Bom Sucesso are presented in Table 1. Each value refers to a whole-nugget analysis. Value ranges are as follows: $1.05 \leq \text{THg} \leq 8.33\%$; $-0.28 \leq \delta^{199}\text{Hg} \leq -0.09\%$; $-0.14 \leq \delta^{200}\text{Hg} \leq +0.35\%$; $-0.35 \leq \delta^{201}\text{Hg} \leq +0.25\%$; $-0.25 \leq \delta^{202}\text{Hg} \leq +0.52\%$. The ranges show consistently negative odd-MIF signals, with $\Delta^{199}\text{Hg}$ and $\Delta^{201}\text{Hg}$ between $-0.29$ and $-0.15\%$, and between $-0.28$ and $-0.12\%$, respectively. For comparison, plots of $\delta^{202}\text{Hg}$ vs. $\Delta^{199}\text{Hg}$ (Fig. 3A) and $\Delta^{201}\text{Hg}$ vs. $\Delta^{199}\text{Hg}$ (Fig. 3B) for the Bom Sucesso Pt–Pd nuggets are shown together with data for sulfide and sulfosalt minerals from sediment-hosted Pb–Zn deposits in south-western China (Xu et al., 2018). Those minerals display trends that marginally overlap with the Pt–Pd nuggets, which have a more restricted distribution without any trend (Fig. 3).
4.2. Helium isotopes

Helium concentrations in Pt–Pd nuggets differ by nearly an order of magnitude, from 3 to 19 x 10^{16} at/g (Table 2). Step-heating experiments showed that most of the \(^{4}\text{He}\) release occurred above 1000°C with distinct peaks at 1200, 1300 and 1400°C (Fig. 4). The \(^{3}\text{He}/^{4}\text{He}\) of 1.9 ± 0.8 x 10\(^{-9}\) (0.0014 ± 0.0005 R\(_{a}\) using the standard air normalisation) is indicative of a purely radiogenic He origin. This nugget has U and Th contents that are below the detection limit, corresponding to less than 45 ppb U and 25 ppb Th.

5. Discussion

5.1. Constraints on the origin of the Bom Sucesso Pt–Pd nuggets

A local magmatic source of Pt and Pd has been advanced by Reith et al. (2019). Negligible Hg-MIF signals – i.e., \(\Delta^{199}\text{Hg}\) and \(\Delta^{201}\text{Hg}\) of ~0‰ – have been observed in mantle materials in the Guaymas Basin sea-floor rift (Shermen et al., 2009). The significantly negative \(\Delta^{199}\text{Hg}\) and \(\Delta^{201}\text{Hg}\) of our samples (Table 1) rules out a mantle-derived source for the Hg, either directly transferred from a silicate magma or leached from mafic rocks. By extension, the nugget-forming precious metals Pt and Pd are unlikely to have been sourced from a mantle-derived magma, such as Mesozoic dolerite intrusions in the Espinhaco Supergroup. This is confirmed by the He isotopic data, which provide no indication of a contribution of mantle-derived \(^{3}\text{He}\), which is found in modern and ancient hydrothermal mineralisation associated with magmatism (e.g., Stuart et al. 1994, 1995).

Further constraints can be placed on the Bom Sucesso Pt–Pd nuggets by the ratio \(\Delta^{199}\text{Hg}/\Delta^{201}\text{Hg}\), which has been used to identify pathways of Hg isotopic fractionation. For example, sulfide and sulfosalt minerals from hydrothermal deposits display \(\Delta^{199}\text{Hg}/\Delta^{201}\text{Hg}\) ~1.0 (Xu et al., 2018; Deng et al., 2021), which is close to that reported from experimental photoreduction of aqueous Hg(II) (Bergquist and Blum, 2007). The Pt–Pd nuggets have odd-MIF signals that are distributed along the \(\Delta^{199}\text{Hg}/\Delta^{201}\text{Hg}\) line of 1.0 (Fig. 3B), suggesting that
the MIF was driven by aqueous Hg(II) photoreduction. On the other hand, the Pt–Pd nuggets appear to have been formed by microbial mediation (Reith et al., 2019; Cabral et al., 2021). Microbial reduction of aqueous Hg(II) has experimentally induced mass-dependent fractionation only, leading to isotopically lighter Hg(0) (Kritee et al., 2007). The data dispersion in Figure 3A likely reflects nugget-forming microbial reduction of aqueous Hg(II) with odd-MIF signals, mostly from photochemical reduction.

The negative odd-MIF signal of photochemical reduction requires that the Hg in the Pt–Pd nuggets was exposed to sunlight. Two pathways are possible: (i) supergene solutions carried Hg from the surface to the site of nugget formation within the placer deposit; or (ii) Hg-bearing hydrothermal minerals with the odd-MIF signal were dissolved to release Hg and also Pt and Pd to form nuggets at depth. The reconnaissance He isotopic data rule out the first possibility, according to the following lines of evidence: (i) the $^3\text{He}/^4\text{He}$ in the Pt–Pd nugget is three orders of magnitude lower than the atmospheric ratio; (ii) the high He content of the nugget would require the incorporation of $\sim3\text{ g}$ of air-equilibrated water into the 2.3-mg nugget; (iii) if all the nugget $^4\text{He}$ originated from the in situ decay of $^{190}\text{Pt}$, the nugget would have unrealistic Pt–He ages (60–340 Ga).

Assuming a $^{190}\text{Pt}–^{186}\text{Os}$ age of 181 Ma (Cabral et al., 2021), less than 2% of the $^4\text{He}$ released from the Pt–Pd nuggets could be derived from in situ radiogenic decay of U and Th, implying that the nugget-trapped He comes from an external source. Low $^3\text{He}/^4\text{He}$ ratios are typical of aquifers in Li-poor (<15 µg/g Li) crustal rocks (e.g., Castro, 2004). The He isotopic data are compatible with Pt–Pd nuggets at least having interacted with old fluids that had previously equilibrated with U- and Th-rich, Li-poor bedrock. Possible source rocks include the quartzite-dominated metasedimentary sequence of the southern Serra do Espinhaço. In the cratonic region west of the southern Serra do Espinhaço, faults that cut the Archaean and Palaeoproterozoic basement and supracrustal rocks are thought to drain deep-seated hydrogen and He (Donzé et al., 2020).
Cosmogenic \(^{3}\text{He}\) can be used to estimate the residence time of nuggets in alluvial systems. Assuming that all \(^{3}\text{He}\) in the Pt–Pd nugget is cosmogenic in origin \((7 \times 10^7 \text{ at/g})\), and using a previously determined cosmogenic \(^{3}\text{He}\) production rate \((\text{Yakubovich et al., 2019})\), it is inferred that the Pt–Pd nuggets from Córrego Bom Sucesso resided in the placer deposit for less than 2.5 Ma. This rough estimate is close to the residence of detrital Pt grains in the Uorgalan-Kondyor and Is-Turinsk placer deposits \((5–28 \text{ Ma, Yakubovich et al., 2021})\).

The significant discrepancy between the nugget Pt–Os age of ca. 180 Ma and the \(^{3}\text{He}-\) exposure estimate of <2.5 Myr excludes the possibility of nugget formation in the surface environment – i.e., in the Bom Sucesso placer deposit. The depth at which the Pt–Pd nuggets formed can be estimated from the mean denudation rate, determined by cosmogenic \(^{10}\text{Be}\) produced in alluvial sediments on the quartzite substratum of the Diamantina region. The mean denudation rate of 4.4 m/Ma \((\text{Barreto et al., 2013})\), combined with the nugget Pt–Os age, suggests that they formed at approximately 800 m below the surface. This is in line with thermochronological modeling using apatite-fission-track (AFT) data from basement granitic-gneissic rocks \((\text{Amaral-Santo et al., 2019})\). The AFT thermal modeling indicates that the temperature at about 800 m below the surface 180 Ma ago was approximately 70°C. It is likely that at this depth the groundwater reached quartzite-hosted hydrothermal veins with high concentrations of Pt–Pd–Hg-bearing minerals, having replaced them in situ. The replacement would have involved removal of more soluble metals, such as As, Sb and Se, and relative enrichment of Pt, Pd and Hg. Alternatively, the groundwater could have obtained its metal load from the dissolution of Pt–Pd–Hg-bearing minerals in nearby hematite–quartz veins. In both scenarios, the estimated groundwater depth is within the conditions under which microbial life would have existed to account for the presence of iodine and organic matter remains in the Bom Sucesso Pt–Pd nuggets, and their Se isotopic values \((\text{Cabral et al., 2021})\).

5.2. Mercury recycling and geotectonic implication
These new constraints on the origin of the Bom Sucesso Pt–Pd nuggets indicate that the Hg isotopic signature was inherited from earlier vein minerals that contained recycled Hg from the continental crust. The negative $\Delta^{199}\text{Hg}$ values for the Pt–Pd nuggets are typical of terrestrial Hg (Blum et al., 2014). Photoreduction of Hg(II) generates negative $\Delta^{199}\text{Hg}$ in the product gaseous Hg(0), and positive $\Delta^{199}\text{Hg}$ in the residual Hg(II) phase (Bergquist and Blum, 2007). For this reason, terrestrial pools – e.g., soil and vegetation – mainly show negative $\Delta^{199}\text{Hg}$ due to the primary accumulation of Hg(0), whereas the ocean pools – e.g., marine sediments and seawater – mainly show positive $\Delta^{199}\text{Hg}$ because of wet deposition of Hg(II) (Blum et al., 2014).

Once acquired in surface reservoirs, MIF signals of Hg isotopes remain even after Hg recycling through subduction zones to form volcanic-arc-related, Hg-bearing epithermal deposits, where inherited positive $\Delta^{199}\text{Hg}$ values of marine sediments and seawater have been found (Deng et al., 2021). As the seawater $\Delta^{199}\text{Hg}$ signal is missing in the Pt–Pd nuggets, it seems that Hg was recycled into the hematite–quartz veins from continental sedimentary material. Because the veins are late in relation to the Araçuaí orogen, they likely captured post-orogenic fluids from continental sedimentary rocks. It is interesting to note that the Pt–Pd minerals of hematite–quartz veins have a Hg–As–Sb metal association that is characteristic of low-temperature hydrothermal deposits in a continental setting, such as the Au–Sb deposits of South China with negative Hg-MIF signals (Yin et al., 2019; Fu et al., 2020). If continental sedimentary rocks provided metals for late-orogenic fluids, the veins that resulted from them would have carried $\Delta^{199}\text{Hg}$ signals of terrestrial surface reservoirs. Our Hg isotopic data support an ensialic setting for Hg cycling, without any traceable contribution of Hg from marine sediments or hydrated oceanic crust, the positive seawater $\Delta^{199}\text{Hg}$ signal of which can be retrieved from epithermal veins (Deng et al., 2021).

6. Conclusion
The Bom Sucesso Pt–Pd nuggets have been taken as examples of supergene accumulation of precious metals within alluvial sediments. This model is too simple. Our Hg and He isotopic data indicate that the nuggets formed in the subsurface, in an environment dominated by ancient groundwater. The nuggets symbolise precious-metal recycling, which is tracked by the odd-MIF signal of Hg isotopes, captured at Earth’s surface and kept through diagenesis, metamorphism, orogenesis and fluid overprint.

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Caption to Figures

Fig. 1. The platiniferous gold–palladium belt of Minas Gerais (Cabral et al., 2009, and references therein). The belt is defined by the distribution of lode and platiniferous placer deposits, which are located along the roughly north–south-trending trace of the Brasiliano thrust faults – i.e., the Araçuai orogen. Data source for ages are given in Cabral et al. (2017). Abbreviations: C. = Córrego (stream); Faz. = Fazenda (farm); Fm. = Formation; Gr. = Group; Sg. = Supergroup

Fig. 2. Backscattered-electron images of Pt–Pd nuggets from Córrego Bom Sucesso. A. Botryoidal, arborescent aggregate. B. Concentric Pt–Pd layers on a hollow core of botryoidal moulds.

Fig. 3. Plots of $\delta^{202}$Hg vs. $\Delta^{199}$Hg (A) and $\Delta^{201}$Hg vs. $\Delta^{199}$Hg (B) for the Bom Sucesso Pt–Pd nuggets. For comparison, sulfide and sulfosalt minerals from sediment-hosted lead–zinc deposits in south-western China are also plotted (Xu et al., 2018). Those hydrothermal minerals likely incorporated the Hg-isotope MIF from the metamorphic country rocks, which preserved surface MIF signals from terrestrial environments (negative odd-MIF values). Crosses refer to analytical uncertainties – i.e., 2SD values in reference materials, Table 1).

Figure 4. Kinetics of thermodesorption of $^4$He from a fragment of Pt–Pd nugget (0.183 mg). Duration of each step of heating was 280 seconds.
Figure 1
Figure 4

This figure shows the relationship between temperature (°C) and the fraction of $^4$He. The graph indicates a significant increase in the fraction of $^4$He at temperatures around 1200 °C, with a notable peak. The x-axis represents temperature, ranging from 0 to 1600 °C, while the y-axis represents the fraction of $^4$He, ranging from 0.0 to 0.8.
Table 1. Results of measurements for Hg isotopes in Pt–Pd nuggets from Córrego Bom Sucesso, Minas Gerais, and in reference materials

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<th>δ^{200}Hg (‰)</th>
<th>δ^{201}Hg (‰)</th>
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*Total Hg
Table 2. Results of measurements for He isotopes in Pt–Pd nuggets from Córrego Bom Sucesso, Minas Gerais

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* Measurement performed at SUERC; all others at IPGG RAS