Sources of Platinum Group Elements in the Environment

Sebastien Rauch and Bernhard Peucker-Ehrenbrink

Abstract Platinum group elements (PGE, i.e. Pt, Pd, Rh, Ir, Ru, Os) are among the least abundant elements in the Earth's continental crust. PGE concentrations in urban and roadside environments are, however, increasing as a result of anthropogenic emissions. Automobile catalysts are generally considered the main PGE source into the urban and roadside environments. We argue that most studies to date have been carried out with a presumption of potential sources, and this bias may have masked additional, yet unidentified PGE sources. Comparison of environmental records at urban locations suggests that PGE emissions reflect contributions from several sources, including automobile catalysts, industry and medical treatment centers. Coal combustion may also contribute to urban PGE fluxes. Environmental records at remote locations support contributions from such diverse sources. Estimates of PGE emissions, however uncertain, indicate that these diverse sources contribute significantly to the global PGE budget at the Earth's surface.

1 Introduction

The highly siderophile properties of the platinum group elements (PGE, i.e. Pt, Pd, Rh, Ir, Os, Ru) has caused segregation of the vast majority of these elements' terrestrial inventories into the Earth's core (Goldschmidt 1922). Consequently, PGE are among the most depleted elements in the Earth's crust relative to bulk earth abundances (Noddack and Noddack 1931; Wedepohl 1995; Peucker-Ehrenbrink and Jahn 2001). The natural biogeochemical cycles of these elements at the Earth's

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S. Rauch (✉)
Department of Civil and Environmental Engineering, Chalmers University
of Technology, 412 96 Gothenburg, Sweden
e-mail: Sebastien.rauch@chalmers.se

B. Peucker-Ehrenbrink
Department of Marine Chemistry and Geochemistry, Woods Hole
Oceanographic Institution, Woods Hole, MA 02543, USA

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surface are dominated by erosion of the continental crust, volcanic eruptions and accretion of extraterrestrial matter. The low natural backgrounds facilitate the detection of even small anthropogenic additions to the natural PGE cycles in the Critical Zone. Increasing use of PGE in a range of applications is now resulting in the release of PGE into the environment to an extent that anthropogenic PGE fluxes are exceeding natural fluxes at the Earth's surface (Klee and Graedel 2004; Sen and Peucker-Ehrenbrink 2012).

Anthropogenic emissions have largely been attributed to automobile exhaust catalysts, which use Pt, Pd and Rh as main active component for the removal of harmful gases (i.e. CO, NOx and hydrocarbons) from automobile exhaust fumes. The introduction of automobile catalysts in the USA in the mid-1970s and in Europe in the 1980 s led to investigations on PGE emissions (e.g. König et al. 1992; Palacios et al. 2000; Moldovan et al. 2002) and their accumulation in urban and roadside environments (e.g. Ely et al. 2001; Gomez 2002; Rauch et al. 2004, 2006; Zereini et al. 2004). Other documented anthropogenic PGE sources are metal production (Niskavaara et al. 2004; Rodushkin et al. 2007; Rauch and Fatoki 2013) and medical applications (Esser and Turekian 1993; Kummerer et al. 1999). PGE also enter waste streams through their uses and emissions, making wastes and sewage additional PGE sources into the environment (Ravizza and Bothner 1996; Lashka and Nachtwey 2000). Recent studies performed in remote environments suggest that additional anthropogenic sources contribute to the PGE cycles in surface environments (Rauch et al. 2010; Sen et al. 2013).

This chapter critically reviews current knowledge of PGE sources and raises questions over the completeness of this knowledge. We argue that most studies to date have been carried out with a presumption of relevant, well-documented sources. This bias may have masked additional, yet unidentified PGE sources.

2 Automobile Catalysts as a Source of PGE

Automobile catalysts are devices placed in the exhaust system of vehicles to convert gaseous pollutants (i.e. carbon monoxide, nitrogen oxides and hydrocarbons) emitted from the engine into less hazardous forms. The catalysts use Pt, Pd and Rh as main active components and are the most potent PGE source owing to the amount of PGE used (37, 72 and 79 % of Pt, Pd and Rh demand, respectively) (Fig. 1) and the usage pattern (exhaust gas flowing through a PGE containing matrix).

PGE emissions from catalysts during vehicle operation have been documented in both bench tests and environmental studies. Emissions are thought to result from mechanical abrasion and chemical reactions at the catalyst surface (Moldovan et al. 2003). Emission rates measured in bench tests are in the ng km^{-1} range (König et al. 1992; Palacios et al. 2000; Moldovan et al. 2002). Emission rates are significantly higher for diesel catalysts than for three-way catalysts used with gasoline engines (Moldovan et al. 2002), and at higher speeds (König et al. 1992). Emission

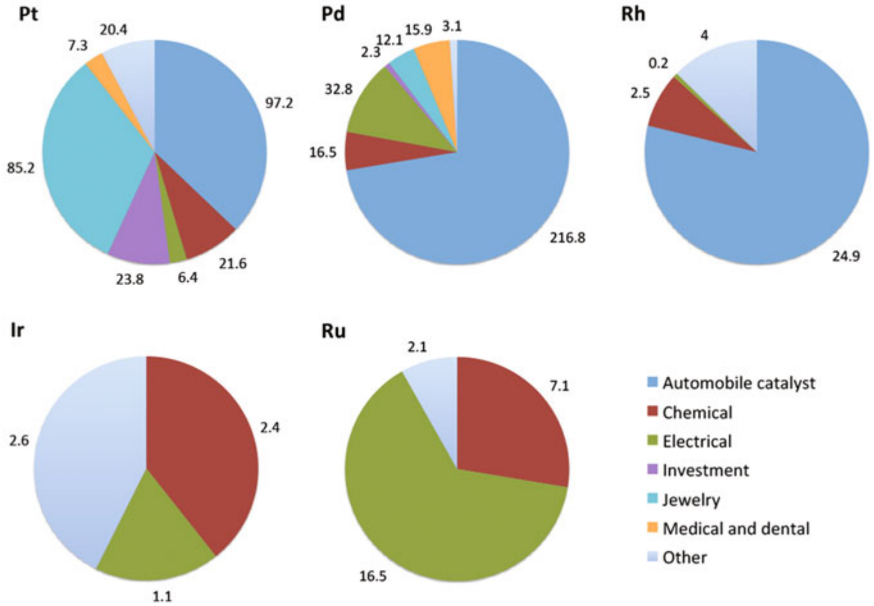


Fig. 1 Estimates of Pt, Pd, Rh, Ir and Ru demands in metric tons in different applications in 2013. Chemical applications include petrochemical and electrochemical uses. *Data source* Matthey (2013)

rates reported by Moldovan et al. (2002) and measured using a driving cycle representing both urban and non-urban driving conditions with speeds up to 120 km h^{-1} are summarized in Table 1. The emission rate inferred from Pt deposition at an urban site is similar to measured emission rates for gasoline catalysts (Lashka et al. 1996). The average relatively low speed (50 km h^{-1}) at this site may, however, have affected the results, and a higher emission rate can be expected for non-urban driving conditions (Helmers and Kummerer 1999). In addition, Helmers (1997) suggests that emissions might also be enhanced by engine malfunction (e.g. ignition problems), and estimates emission rates of the order of 0.5–0.8 µg Pt km^{-1}. Such high emission rates are supported by estimates of Pt losses during a vehicle's lifetime, putting an upper limit on emission rates at 10 µg km^{-1} (40 % Pt loss for a mileage of 100,000 km) (Helmers 1997). Using an emission rate of 0.1–0.8 µg Pt km^{-1}, Rauch et al. (2005b) estimated that 0.8–6.0 metric tons of Pt are emitted annually by automobile catalysts. Based on the emission range shown in Table 1, we extend the emission range to 0.01–6.0 tons Pt $year^{-1}$. As most vehicles equipped with a catalyst are operated in the Northern Hemisphere, this flux is expected to be representative of the global Pt emission. It is important to note that estimates of PGE emission from automobile catalysts remain quite uncertain despite nearly 30 years of research.

Table 1 Estimates of PGE emission rates from automobile catalysts

Estimation	Catalyst	Emission rates (ng km^{-1})			References
		Pt	Pd	Rh	
Direct measurements, exhaust samples collected on bench test with driving cycle representing both urban and non-urban driving conditions, catalyst mileage 30,000 km	Pt-Pd-Rh (gasoline)	6.3	12.0	3.7	Moldovan et al. (2002)
	Pd-Rh (gasoline)	8.2	15.9	12.2	Moldovan et al. (2002)
	Pt (diesel)	152	46	26	Moldovan et al. (2002)
	Pt (diesel)	110	82	39	Moldovan et al. (2002)
Inferred from deposition at an urban site, speed 50 km h^{-1}	–	5	–	–	Lashka et al. (1996)
Inferred from emission estimates for different vehicle and driving conditions, and comparison with environmental samples	–	500–800	–	–	Helmers (1997)

Although Pt, Pd and Rh are the main active ingredients of automobile catalytic converters, Os has been reported to be present as an impurity in such catalysts (Poirier and Gariepy 2005). Environmental studies suggest that Ir and Ru are also present as impurities (Fritsche and Meisel 2004; Rauch et al. 2004). Automobile catalysts are therefore also considered to be sources of Os, Ir and Ru to the environment.

3 Are Automobile the Main Source of PGE in Urban Areas?

The introduction of automobile catalysts and initial reports of PGE emissions from such catalysts raised concern over the potential risks of this new contamination. Several studies aimed at assessing PGE levels in urban and roadside environments and have shown that PGE concentrations are elevated relative to expected natural concentrations or concentrations in remote environments. These studies have also attempted to confirm an automobile catalyst source through various strategies, including sampling at sites with varying traffic intensities (Gomez 2002; Rauch et al. 2006), sampling at increasing distances from automobile traffic (Helmers 1996; Zereini et al. 2000; Jarvis et al. 2001; Ely et al. 2001), estimation of temporal changes in PGE concentrations or accumulation rates (Rauch et al. 2004, 2006), the use of PGE ratios (Ely et al. 2001; Gomez 2002; Rauch et al. 2005a, 2006) as well as correlations with other elements presents in catalysts (Helmers 1996; Rauch et al. 2000). More recently, the isotopic composition of Os (^{187}Os/^{188}Os) has shown that elevated PGE concentrations in urban air are associated with unradiogenic (i.e. low ^{187}Os/^{188}Os values) PGE sources in urban environments (Rauch et al. 2005a, 2006) that are similar to the Os isotopic composition of catalysts (Poirier and Gariepy 2005).

While many studies support an automobile catalyst source, these studies also present discrepancies. For instance, relatively small differences have been reported between cities with different population sizes, vehicle numbers and catalyst introduction dates, as well as traffic patterns and intensities at specific sampling locations. Pt concentrations in airborne particles range from 3.9 to 15.6 pg m^{-3} in six cities in Western Europe (Gomez 2002). For comparison, Pt concentrations of 6.9 ± 1.9 and 9.6 ± 1.8 pg m^{-3} were reported for airborne particles in Boston, USA (Rauch et al. 2005a) and Mexico City, Mexico (Rauch et al. 2006), respectively. PGE concentrations do not necessarily correlated with traffic intensities. For instance, relatively high PGE concentrations at a site with low traffic intensity in Mexico City were attributed to an industrial source (Rauch et al. 2006). In addition, no significant difference was found between airborne PGE concentrations in samples collected on weekdays and weekends in Boston, USA, although traffic intensity is expected to be lower on weekends (Rauch et al. 2005a). PGE abundance ratios in environmental samples, which were used to confirm an automobile catalyst source in some studies, do not necessarily match expected catalyst compositions (Fig. 2). In addition, abundance ratios in catalysts are not always measured, and their use is therefore not necessarily valid. For instance, different PGE ratios between Hong Kong and Mainland China have been attributed to differences in automobile catalyst composition, although automobile catalyst compositions have not been documented (Qi et al. 2011).

Discrepancies between expected and observed PGE concentrations or abundance ratios suggest that a number of sources contribute to PGE fluxes in urban areas. Contributions from other sources are supported by studies of PGE at water treatment plants, which collect water from urban areas and therefore integrate emissions from different sources. A Pt flux of 5.3 kg yr^{-1} has been estimated for a wastewater

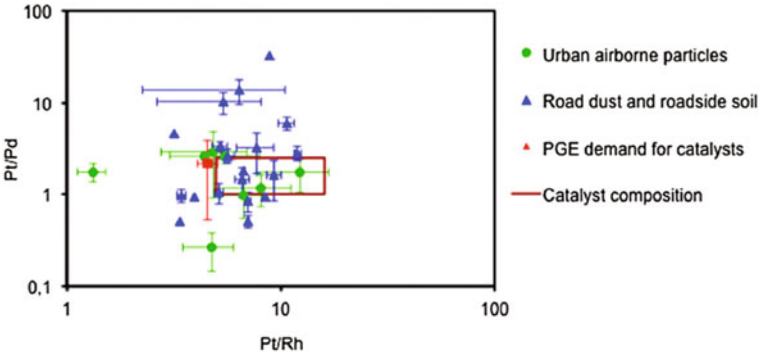


Fig. 2 Comparison of published PGE ratios (Pt/Pd vs. Pt/Rh) in road dust and roadside soils obtained in urban and roadside environments (data published in Rauch et al. 2005b) with automobile catalyst composition (Ely et al. 2001) and PGE demand for catalysts (Johnson Matthey)

treatment plant in Munich, Germany, that includes 0.9 kg yr^{-1} from automobile catalyst emissions (Lashka and Nachtwey 2000). In contrast, another study indicates that automobile catalysts are the main source of PGE in sewage sludge in the UK, although elevated Pd concentrations at three sites could not be attributed to an automobile catalyst source (Jackson et al. 2010). This difference supports the contention that there is no dominant PGE source that explains findings in all urban areas. The relative importance of different PGE sources therefore depends on specific characteristics of an urban area.

4 PGE Emissions from Non-automobile Sources

Studies of the occurrence of PGE in urban settings suggest that multiple sources contribute to anthropogenic PGE fluxes. In this section, we assess the relevance of documented non-automobile PGE sources that may contribute to both local and global PGE cycles, including PGE production activities, industry and medical applications.

4.1 PGE Uses as Indicator for PGE Sources

PGE are used in a range of applications besides automobile catalysts (Fig. 1). Jewelry is an important use for Pt (33 % of Pt demand), but very high recycling rates make this use an unlikely source of significant Pt emissions into the environment. Although other uses are more limited, they may contribute significantly to PGE releases into the environment. The use of Pt-based drugs in cancer treatment that accounts for about 5 % of total Pt demand may cause the emission of this metal into the environment through the excretion of administered drugs. Electrical applications, uses by the chemical industry, jewelry and dental applications are unlikely to be significant sources of PGE into the environment. Therefore, significant Ir and Ru emissions are unlikely. Osmium has a limited number of uses, the largest single use being as fixative and stain in the preparation of tissue thin sections for optical and electron microscopy (Esser and Turekian 1993). It should, however, be noted that PGE uses may contribute to elevated PGE loadings in waste and sewage streams despite active recycling of automobile catalysts and electronic components.

4.2 PGE Emissions from Mining and Production Activities

PGE mining and production activities in South Africa and Russia have been reported to cause emission of PGE into the environment. Elevated Pt concentrations were found near Pt mining and ore processing sites in the Bushveld Igneous

Complex, South Africa. The highest concentration in soils (i.e. 653 ng g^{-1}) was measured near a PGE smelter (Rauch and Fatoki 2013). Nickel, Cu and PGE production in Northern Europe has also been implicated in PGE emissions. Nickel smelters on the Kola Peninsula in NW Russia have been identified as important regional sources of Pt and Pd based on the spatial distribution of these metals in environmental samples (Niskavaara et al. 2004). In addition, chromium smelters in the Kemi district in Finland have been identified as a source of Os to the atmosphere (Rodushkin et al. 2007).

Reimann and Niskavaara (2006) estimated that 2.2 metric tons Pd (1.1 % of global annual production) and 0.8 metric tons Pt (0.5 % of global annual production) were emitted annually by the Monchegorsk smelter in the mid 1990s. Based on these estimates, global smelter emissions could exceed 5 % of the annual Pt and Pd productions, equivalent to 9 metric tons Pt and 10 metric tons Pd. In contrast, Pt and Pd emissions estimated using Cu emissions rates from Cu-Ni production (Pacyna 1984) amount to only 0.3–0.7 metric tons per year.

4.3 Industrial PGE Emissions

An increase in Os accumulation rates in a peat record in NW Spain has been observed at the onset of the industrial revolution, indicating that industrial activities are associated with PGE emissions (Rauch et al. 2010). Helmers and Kummerer (1999) note that although industrial emissions are likely, they are difficult to quantify because few data are available for industrial PGE emissions. Elevated PGE concentrations at a site with relatively low traffic in an industrial area in Mexico City were attributed to industrial PGE emissions (Rauch et al. 2006). Sewage from a microelectronics factory in Germany contained 11–33 ng Pt L^{-1} (Laschka and Nachtwey 2000). High PGE concentrations were found in soil near a PGE processing plant in Germany (Zereini et al. 1998). Comparison of PGE distribution patterns near the plant and aside roads shows that industrial and automobile PGE emissions are characterized by different relative PGE abundances. PGE abundance ratios could therefore be used to differentiate between these sources. However, the abundance ratios for industrial sources depend on the type of industrial activity and would need to be determined.

4.4 PGE Emissions from Medical Treatment Centers

Platinum-based drugs, including cisplatin (cis-diammine-dichloro-platinum[II]) and carboplatin (diamine[1,1-cyclobutanedicarboxylato] platinum[II]), are used in the treatment of several forms of cancer. Platinum is excreted by the patients after treatment with Pt-based drugs and is found in hospital effluents at concentrations ranging from <10 ng L^{-1} to 3.5 μg L^{-1}. Pt is subsequently diluted in the municipal wastewater system to concentrations 10 ng L^{-1} in sewage effluents (Kummerer et al. 1999; Lashka and Nachtwey 2000). Emissions are expected to be in form of soluble compounds, including administered drugs and their derivatives (Kummerer et al. 1999). In addition, patients that have undergone treatment with Pt drugs are expected to excrete Pt for a period of over 8 years, indicating that Pt is also released outside of medical facilities (Schierl et al. 1995). Evidence based on the unique isotope signature of industrial Os led Esser and Turekia (1993) to argue that this element is released from biomedical facilities where it is used as a stain fixative in electron microscopy applications.

4.5 PGE in Urban Sewage and Waste

Elevated PGE concentrations have been reported in sewage and waste (Esser and Turekian 1993; Lashka and Nachtwey 2000; Jackson et al. 2010). Sewage and waste potentially become secondary PGE sources, leading to PGE emissions during treatment, reuse or disposal. Depending on characteristics of the sewage network, sewage discharges can result in the release of PGE into the aquatic environment. Wastewater treatment plants in Munich, Germany released 1.3 kg Pt yr^{-1} into local rivers (Lashka and Nachtwey 2000). The use of sewage sludge in agriculture has been identified as a source of PGE in soils (Helmers and Kummerer 1999). PGE enrichments have also been found in incinerator ash, reflecting the occurrence of PGE in municipal waste (Jackson et al. 2010). Elevated Os concentrations in coastal marine sediments have been attributed to sewage discharges into Massachusetts and Cape Cod bays, USA, based on the good correlation of Os concentrations with Ag concentrations and co-variations in Os isotopic composition that point to an anthropogenic source of the Os (Ravizza and Bothner 1996). However, a later study performed in Boston Harbor, USA, reported a large discrepancy between Pt and Pd fluxes estimated from sediment concentrations and fluxes associated with sludge and effluent release, suggesting that sewage discharges are not the main source of these elements to Massachusetts Bay (Tuit et al. 2000).

5 Occurrence of PGE in Remote Environments and Implication for PGE Sources

Elevated PGE concentrations in remote environments have provided evidence for a widespread environmental contamination by anthropogenic activities, as well as information on the contribution of PGE sources to the global biogeochemical cycle of PGE (Barbante et al. 2001, 2004; Moldovan et al. 2007; Rauch et al. 2010; Sen et al. 2013).

5.1 Atmospheric PGE Dispersion

The extent of PGE dispersion from various sources is uncertain. Automobile emissions are expected to have a relatively limited dispersion because PGE are bound to fine particulates. A sharp decrease in PGE concentrations has been observed within a few meters from automobile traffic (Jarvis et al. 2001; Ely et al. 2001; Helmers 1996). However, PGE concentrations remain elevated 100 m away from roads (Jarvis et al. 2001; Ely et al. 2001; Helmers 1996). Industrial emissions from a PGE processing plant in Germany could be tracked for longer distances than automobile catalyst emissions, possibly due to smaller particle sizes and emissions through smoke stacks at greater height (Zereini et al. 1998). Regional dispersion of PGE from mining and ore processing plants has been demonstrated in both South Africa (Rauch and Fatoki 2010) and Russia (Reimann and Niskavaara 2006). Background concentrations were reached within 200 km of Russian smelters (Reimann and Niskavaara 2006). However, the emission of fine PGE-containing particles support the notion of more widespread dispersion (Rauch et al. 2005b), and it has been suggested that both metal production activities and automobile catalysts contribute to the global PGE cycle through long-range atmospheric transport (Barbante et al. 2001; Moldovan et al. 2007; Rauch et al. 2005b).

5.2 Sources of PGE in Rural Aerosols

PGE concentrations and Os isotopic composition ($^{187}Os/^{188}Os$) in airborne particles in Woods Hole, USA, reveal complex anthropogenic sources (Sen et al. 2013). Woods Hole is located more than 100 km away from the nearest urban center and more than 30 km from any industrial complex. PGE concentrations in Woods Hole aerosols are an order of magnitude below urban concentrations and vary by an order of magnitude. The $^{187}Os/^{188}Os$ range from 0.132 to 1.074, indicating contributions from different sources. Erosion of the earth's continental crust for instance is characterized by a radiogenic Os signature with an average $^{187}Os/^{188}Os$ of 1.4 (Peucker-Ehrenbrink and Jahn 2001). In contrast, commercial Os has an unradiogenic isotopic composition because it is mined from ore deposits that are genetically linked to sources in the Earth's mantle, a reservoir with 2–3 orders of magnitude higher PGE concentrations than the continental curst. The Earth's mantle is characterized by a low $^{187}Os/^{188}Os$ of $\sim$0.1–0.2 (Meisel et al. 1996) that reflects the small time-integrated ratio of the partent isotope (^{187}Re), a moderately incompatible element during mantle melting, to Os. For this reason automobile catalysts are characterised by unradiogenic Os isotopic compositions (Poirier and Gariepy 2005). Pt/Rh and $^{187}Os/^{188}Os$ indicate that ore smelting is the primary PGE source in airborne particles in Woods Hole, with possible minor contributions from automobile catalyst emissions and fossil fuel combustion (Sen et al. 2013).

5.3 Sources of Os in a Peat Record of Atmospheric Deposition

Evidence for unidentified Os sources has been obtained from a ca. 7000-year long peat record of atmospheric Os accumulation and isotopic composition from an ombrotrophic peat bog in NW Spain (Fig. 3a) (Rauch et al. 2010).

The Os record shows that human influence on Os accumulation in the environment started with early metal mining (ca. 4,700–2,500 years before present [BP]), possibly linked to mining and smelting of copper ores. Osmium accumulation remained elevated thereafter with a maximum during the Roman occupation of the Iberian Peninsula. A further increase is observed starting with the industrial revolution in ca. 1750 AD. While the Os isotopic composition is consistent with a two-component mixing between a radiogenic Os source (erosion) and an unradiogenic Os source (metal mining) until the industrial revolution, a shift in isotopic composition in the more recent samples indicates that at least three components contribute to Os accumulation (Fig. 3b). A source with high Os concentration and unradiogenic Os isotopic composition points to metal production and catalysts, a source with low Os concentration and radiogenic Os isotopic composition is consistent with input from erosion, and a source with high Os concentration and radiogenic Os isotopic composition has been linked to fossil fuel combustion (Rauch et al. 2010).

The Os record at PVO indicates that fossil combustion is a source of PGE to the environment. Platinum concentrations in gasoline are on the order of 1–6 ng L^{-1}, corresponding to an emission of 0.1–0.6 ng km^{-1} for a gasoline consumption of 10 L per 100 km (Hoppstock and Michulitz 1997). Pt emissions from gasoline use are estimated at 1–8 kg yr^{-1}. Platinum concentrations in coal have been estimated at 0.1–1 ng g^{-1} (Oman et al. 1997), implying an emission of 0.001–0.2 metric tons yr^{-1} if emission rates are 0.1–2 %. These estimates are suggestive of fossil fuel combustion contributing to the global as well as urban PGE fluxes and cycles.

5.4 Source of PGE in Snow and Ice

Elevated PGE concentrations have been reported in European mountain regions and in Central Greenland. PGE sources at these sites have been identified using PGE ratios, atmospheric trajectory modelling and comparison of PGE concentration trends with metal use or anthropogenic activities. For instance, Pt, Pd, and Rh have been measured in fresh snow samples in the French Pyrenees Mountains. Atmospheric trajectory models indicate that elevated PGE concentrations are associated with both automobile catalyst emissions and Russian PGE production (Moldovan et al. 2007). The main advantages of these records are excellent chronologic information and the very low natural PGE background in ice and snow. However, these records must be interpreted with care, as the low natural background makes these matrices susceptible to contamination during and after sampling.

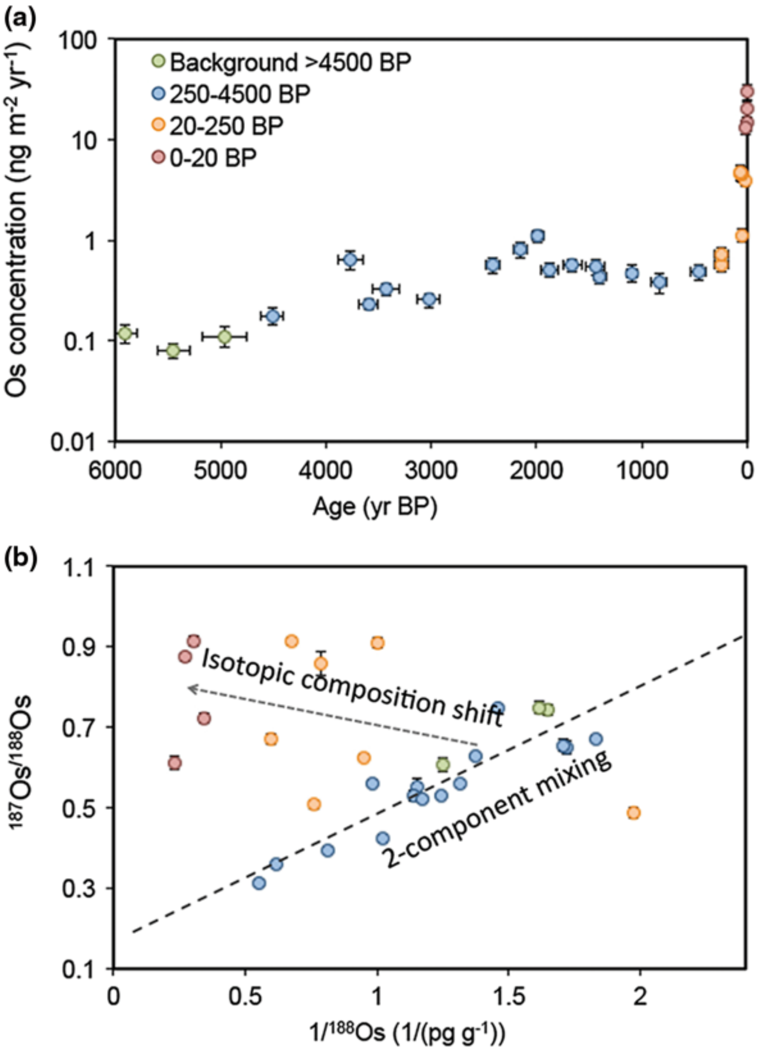
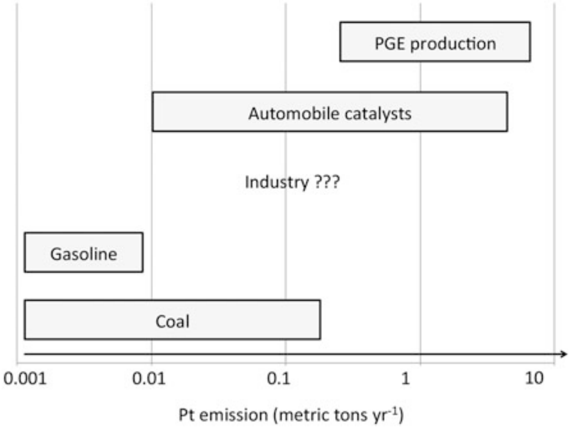


Fig. 3 **a** Changes in Os accumulation in Northwest Spain; **b** Plot of $^{187}Os/^{188}Os$ versus $1/^{188}Os$ showing a shift in isotopic composition at the Penido de Vello bog. The pre-industrial period (>250 BP) is characterized by a two-component mixing between an Os-poor radiogenic (high $^{187}Os/^{188}Os$) source and an Os-rich unradiogenic (low $^{187}Os/^{188}Os$) source. The $^{187}Os/^{188}Os$ deviate from the two-component mixing line after the onset of the industrial revolution. *Error bars* represent 2 standard deviations (Rauch et al. 2010)

Elevated PGE concentrations have been reported in ice at Summit in Central Greenland, with a sharp concentration increase after 1990 (Barbante et al. 2001). PGE abundance ratios in Greenland ice and atmospheric trajectory models make contributions from multiple sources such as automobile traffic and Russian smelters, likely (Rauch et al. 2005b). The late increase in PGE concentrations in Greenland

Fig. 4 Estimates of annual global emissions from identified anthropogenic PGE sources into the atmosphere. No estimates are provided for industrial emissions owing to unavailability of emission rates



compared to the introduction of catalysts in the USA in 1975 may point to the predominance of Europe as a source area, as catalysts were introduces in Europe about a decade later. Curiously, there is no direct relationship between the concentration trend in Greenland and either Russian production or the PGE demand for catalysts. It is therefore likely that elevated PGE concentrations in central Greenland are the result of long-range transport from both urban areas where automobile exhaust catalysts are in use and Russian smelters. It would be worthwhile to scrutinize these ice records for the temporal evolution of other tracers of anthropogenic contamination. Such records may point to yet undiscovered sources of PGE to the environment.

6 Conclusion

Available information on the emission and environmental occurrence of PGE indicates that automobile catalysts may not be the single most important PGE source, but that anthropogenic PGE emissions stem from a range of anthropogenic activities. In urban areas, potential sources include automobile catalysts, industrial processing, fossil fuel combustion and medical centers. The dispersion of PGE from urban sources and emissions from PGE production facilities contribute to the global biogeochemical cycles of PGE. A comparison of atmospheric PGE emissions from a variety of potential sources indicates that PGE production activities, automobile catalysts and coal combustion are potentially equally important sources of PGE (Fig. 4). There are, however, significant uncertainties in emission estimates owing to significant variations in reported emission estimates. For instance, while available data are consistent with the release of PGE from industrial activities, it is not yet possible to quantify industrial PGE emissions. A further complication lies in our limited understanding of PGE dispersion that makes it very challenging to determine the geographical extent of PGE contamination from these sources.

Further research should focus on two parallel approaches; firstly, emission rates from identified PGE sources should be better quantified and dispersion mechanisms assessed in an attempt to determine the extent of PGE contamination from each source. Secondly, detailed environmental records should be obtained and source identification methods refined in order to assess the contribution from different PGE sources, and to detect any yet unidentified sources of PGE to the environment.

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