

Analysis of Platinum Group Elements (PGEs), Silver, and Gold in Roadside Dust using Triple Quadrupole ICP-MS

Accurate, interference-free measurement of sub-ppb levels of the PGEs using the Agilent 8900 ICP-QQQ



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Introduction

There is increasing interest in monitoring the noble metals—that is the Platinum Group Elements (PGEs), Ru, Rh, Pd, Os, Ir, and Pt, together with Ag and Au—in the environment. The levels of these elements have increased due to deposition arising from automobile catalytic converters (1, 2). Precious metals are also used in healthcare and pharmaceuticals and in advanced technologies such as industrial catalysts, fuel cells, and electrodes, capacitors, and magnetic storage for consumer electronics. Production, use, and disposal of these products leads to wider release of the PGEs into the environment, which increases the need for routine monitoring of the metals in environmental samples. ICP-MS is widely used for analysis of trace levels of metals and metalloids, due to the technique's high sensitivity and multi-element capability. However, determination of the PGEs in samples such as soil and roadside dust is challenging for conventional single quadrupole ICP-MS because of the low concentration of the elements. Also, there is the potential for intense spectral overlaps from several common matrix elements, as shown in Table 1.

Table 1. Noble metal isotopic abundances (%) and potential spectral interferences on each isotope. Preferred isotopes for ICP-MS analysis are highlighted in yellow, secondary isotopes may be useful for data confirmation.

Mass	Analyte Isotope Abundance (%)				Potential Spectral Interferences				
	Ru	Rh	Pd	Ag	Isobaric	Hydride	Oxide/ Hydroxide	Argide	Other
96	5.54				Zr, Nb, Mo		SeO, BrOH		
98	1.87				Mo	MoH	SeO	NiAr	CuCl
99	12.76					MoH			ZnCl
100	12.6				Mo		SrO	NiAr	CuCl
101	17.06					MoH	RbO	NiAr	ZnCl
102	31.55		1.02				SrO	NiAr	CuCl, ZnCl
103		100					SrO, RbO	CuAr	ZnCl, Pb ⁺⁺
104	8.62		11.14				SrO	ZnAr	ZnCl, Pb ⁺⁺
105			22.33				YO, SrOH	CuAr	ZnCl
106			27.33		Cd		YOH, ZrO	ZnAr	
107				51.84			ZrO	ZnAr	
108			26.46		Cd		ZrO, MoO	ZnAr	
109				48.16			NbO		
110			11.72		Cd		ZrO, MoO		
	Os	Ir	Pt	Au					
184	0.02				W			NdAr	
186	1.59				W		YbO	NdAr	
187	1.96				Re	WH	YbO	SmAr	
188	13.24						YbO	SmAr, NdAr	
189	16.15						YbO	SmAr	
190	26.26		0.014				YbO	SmAr, NdAr	
191		37.3					LuO	EuAr	
192	40.78		0.782				YbO, LuO, HfO	SmAr	
193		62.7					HfO	EuAr	
194			32.97				HfO	SmAr, GdAr	
195			33.83				HfO	GdAr	
196			25.24		Hg		HfO	GdAr	
197				100			TaO, HfOH	GdAr	
198			7.163		Hg		WO, TaOH	GdAr	

Many different approaches have been employed in an attempt to avoid, correct, or resolve matrix-based spectral overlaps in ICP-MS, including mathematical correction, matrix removal, and magnetic sector High-Resolution (HR)-ICP-MS. However, mathematical corrections are often unreliable, and matrix elimination is time-consuming, expensive, and prone to errors and contamination. HR-ICP-MS seems an attractive option, as it should give certainty that the analyte has been resolved from the overlapping ion on the mass scale. But many common spectral interferences require mass resolution far beyond the capability of commercial HR-ICP-MS instruments. For example, resolving $^{103}\text{Rh}^+$ from $^{87}\text{Sr}^{16}\text{O}^+$ requires mass resolution ($M/\Delta M$) of 102,900; resolving $^{105}\text{Pd}^+$ from $^{89}\text{Y}^{16}\text{O}^+$, requires resolution of 27,600; and resolving $^{109}\text{Ag}^+$ from $^{93}\text{Nb}^{16}\text{O}^+$ requires resolution of 31,500. Current HR-ICP-MS instruments have a maximum mass resolution of 10,000, so are unable to separate any of these spectral overlaps.

The most widely used approach to resolve the common polyatomic ion overlaps that occur in quadrupole ICP-MS is to use a Collision/Reaction Cell (CRC) pressurized with helium (He) cell gas. He mode enables selective attenuation of polyatomic ions using a process called kinetic energy discrimination (KED). However, some of the matrix-based interferences on the trace PGEs are at too high intensity to be completely removed using He KED mode. Also, some interferences, such as $^{206}\text{Pb}^{++}$ on Rh at mass 103, are caused by spectral overlaps that are not polyatomic ions, so He mode cannot remove them effectively.

In this work, an alternative approach to He KED was investigated, using an Agilent 8900 Triple Quadrupole ICP-MS (ICP-QQQ) to resolve the multiple, matrix-based interferences that affect analysis of the PGEs (3). The 8900 ICP-QQQ is a tandem mass spectrometer with two high performance, hyperbolic, quadrupole mass filters, one before (Q1) and one after (Q2) the ORS⁴ CRC. The tandem (MS/MS) configuration gives the possibility to use the additional quadrupole—Q1, before the CRC—to select the ions that can enter the cell. This allows the ion/molecule reaction chemistry to be precisely controlled, even when highly reactive cell gases such as ammonia (NH_3) are used in the CRC. Reaction chemistry processes happen much faster than He KED, so can provide more effective separation of trace analytes that are overlapped by intense spectral interferences. .

The 8900 ICP-QQQ includes UHMI (Ultra High Matrix Introduction) aerosol dilution technology, which increases plasma robustness and allows samples with higher Total Dissolved Solids (TDS) to be analyzed routinely. The 8900 with UHMI improves trace level analysis, as samples can be analyzed with minimal dilution, which reduces the risk of errors and contamination from the dilution step. Use of a more robust (hotter) plasma also increases ionization, improving sensitivity for poorly ionized noble metals such as Ir, Pt, and Au.

A series of synthetic matrix element mixes and a certified reference material (CRM) of road dust were used to evaluate the effectiveness and accuracy of the 8900 ICP-MS/MS method.

This work was performed in collaboration with the Université Gustave Eiffel, formerly IFSTTAR, Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (the French Institute of Science and Technology for Transport, Development and Networks).

Experimental

Instrumentation

An Agilent 8800 ICP-QQQ was used for initial measurements, with later work being performed using an Agilent 8900 ICP-QQQ model. Both instruments were operated in the standard configuration, which includes Ni interface cones and standard "x" type ion lens. The standard sample introduction system was used, consisting of a MicroMist nebulizer, Peltier-cooled quartz double-pass Scott-type spray chamber, and quartz torch with 2.5 mm injector. Preset plasma condition UHMI-4 (aerosol dilution factor of approximately 4) was selected for the analysis.

The interference removal capability of NH_3 reaction gas in MS/MS mode (both quadrupoles functioning as true mass filters) was assessed. Results acquired with NH_3 in MS/MS mode were compared to the data collected with no cell gas and in He KED mode, as typically used on single quadrupole ICP-MS. Three different NH_3 gas flow rates (Low (NH_3 -L), Medium (NH_3 -M), and High (NH_3 -H)) were used. The NH_3 cell modes used a cell gas of 10% NH_3 in He buffer gas, which controls the in-cell formation of unwanted reaction gas product ions. Details of all the cell gas modes and other acquisition conditions are given in Table 2.

Table 2. Agilent 8900 ICP-QQQ acquisition and CRC conditions.

	No Gas	He	NH ₃ -L	NH ₃ -M	NH ₃ -H
Acquisition Mode	SQ	SQ	MS/MS	MS/MS	MS/MS
Cell Gas	N/A	He	NH ₃	NH ₃	NH ₃
Gas Flow (mL/min)	N/A	5.0	2.0	3.0	5.0
Octopole Bias (V)	-8	-18	-5	-10	-12
KED (V)	+5		-8		
Cell Exit (V)	-90				
Deflect Lens (V)	20	0	10	6	2
Integration Time/Mass (s)	0.2	0.3	1	1	1

Method

The Background Equivalent Concentrations (BECs) of the PGEs were quantified in a series of synthetic interference solutions containing several potentially interfering matrix elements, either individually or in various combinations. The BECs for the PGEs were calibrated against simple, synthetic, non-matrix-matched calibration standards.

Spike recoveries were measured for a spike containing 1 µg/L (ppb) of each of the PGEs, Ag, and Au in the highest, most complex synthetic matrix (all individual matrix components in one solution). To check the accuracy of the method for real sample analysis, the PGEs were also quantified in a digested CRM (BCR 723 Road Dust, IRMM, Geel, Belgium). The CRM has certified values for Rh, Pd, and Pt.

Data was acquired for all three cell gas modes during one visit to the sample vial, and three replicate measurements were acquired for each sample. The no gas and He mode conditions used Single Quad (SQ) mode (Q1 not operating as a mass filter) to replicate the interference removal performance achievable with single quadrupole ICP-MS. The NH₃ cell gas conditions used MS/MS mode with either on-mass measurement of the analyte ion, or mass-shift measurement where an analyte reaction product ion is measured. The indium (In) internal standard (ISTD) was added to the sample solutions online via the standard ISTD mixing T-connector.

Standards and sample preparation

Standards and interference matrices—most elements at 10 mg/L (ppm)—were prepared from single element 1000 or 10,000 mg/L stock solutions. The single and multiple matrix element mixes analyzed are shown in Table 3. All synthetic solutions were acidified to 4% HNO₃ and 12% HCl. This matrix is typical of the final acid concentration resulting from digestion of soil, dust, and mineral ore samples using aqua regia (a 1:3 mix of concentrated HNO₃/HCl).

The acid concentration in the synthetic samples matched the acid mix in the digested CRM. The CRM was prepared by mineralization of 0.5084 g of BCR 723 in 2 mL of concentrated HNO₃ and 6 mL of concentrated HCl. The volume was then brought up to 50 mL by addition of ultrapure water, giving a final matrix containing approximately 1% TDS in 16% aqua regia.

Results and discussion

Interference removal in complex synthetic matrices

The BEC results obtained in the study of matrix-based spectral interferences in the synthetic matrix solutions are shown in Table 3. The BECs for the PGEs in each of the matrix solutions are compared for no gas, He, and the optimum NH₃ mode (low, medium, or high NH₃ flow). The colored cells in Table 3 indicate the level of contribution that the matrix interferences made to the PGE BEC. For example, a matrix interference contribution causing a BEC of between 0.1 ppb and 1 ppb is indicated by the yellow shading. As can be seen from Table 3, Ru did not suffer significant interference in any of the synthetic matrices, even when measured in no gas mode. However, the other PGEs all suffered moderate or severe interference (up to 996 ppb BEC) in no gas mode. Interference contributions were higher than 10 ppb for Pd, Ag, Ir, Pt, and Au. The BECs for Rh and Os were lower, but still in the 100s of ng/L (ppt) or low ppb range.

The He mode data in Table 3 was evaluated to assess the relative performance of the standard single quadrupole ICP-MS approach to controlling polyatomic ions. Compared to no gas mode, He KED mode gave lower BECs for many of the PGEs, some improved by several orders of magnitude. But He mode was not able to completely resolve all the overlaps to a low enough level for trace analysis of all the PGEs. In He mode, the contribution of the spectral interferences from some of the matrix combinations was still in the ppb range for Pd, Ag, and Os and above 10 ppb for Ir, Pt, and Au.

By contrast, the optimum NH₃ mode significantly reduced the interference contributions on the PGEs in all the matrix solutions, including the most complex interference mix. BECs were lower than single or low 10s ppt for all the PGEs except Ir and Pt-195. The BECs for Ir and Pt in NH₃ mode remained a little higher at 0.1 to 0.2 ppb. But these BECs are still around 100x lower than was achieved in He mode and up to 1000x lower than in no gas mode. The improved interference removal capability provided by NH₃ in MS/MS mode allows the reliable quantitation of PGEs at ultra-trace levels in a complex environmental matrix such as roadside dust.

Table 3. PGE Background Equivalent Concentrations (BECs) in µg/L (ppb) due to matrix-based spectral overlaps measured in no gas, He, and NH₃ cell gas modes. Significant matrix interferences are indicated by colored cells: Yellow (BEC >0.1 ppb), orange (BEC >1 ppb), and red (BEC >10 ppb). MS/MS mode with NH₃ cell gas resolves interferences on all analytes. Note, some PGEs have two usable isotopes.

No cell gas, SQ mode BEC results (µg/L)												
Element	Ruthenium		Rhodium	Palladium	Silver		Osmium		Iridium	Platinum		Gold
Isotope	99	101	103	105	107	109	188	189	191	195	198	197
10 ppm Cu Zn	0.035	0.028	0.036	0.069	0.014	0.004	0.001	0.002	0.005	0.000	0.000	0.002
10 ppm Sr Rb	0.001	0.021	0.096	2.957	0.004	0.001	0.001	0.001	0.002	0.000	0.000	0.002
10 ppm Ni	0.001	0.004	0.002	0.020	0.007	0.008	0.001	0.003	0.005	0.000	0.000	0.001
10 ppm Mo	0.016	0.005	0.001	0.006	0.001	0.006	0.004	0.005	0.001	0.000	0.000	0.001
10 ppm Pb, 1 ppm Hg	0.000	0.000	0.254	0.004	0.002	0.004	0.011	0.012	0.006	0.000	666.924	0.001
10 ppm Zr Nb	0.000	0.000	0.001	0.829	10.436	34.858	0.018	0.018	0.004	0.005	5.270	0.127
10 ppm REE, Sc, Y	0.012	0.030	0.014	78.040	0.098	0.008	3.793	2.229	45.307	1.004	4.540	0.390
10 ppm Ta	0.000	0.001	0.000	0.004	0.001	0.001	0.001	0.001	0.001	0.090	45.386	62.760
10 ppm Hf	0.000	0.000	0.000	0.001	0.001	0.002	0.001	0.016	0.325	29.337	1.062	5.095
10 ppm W	0.001	0.000	0.000	0.001	0.000	0.002	0.004	0.001	0.001	0.005	104.237	0.614
10 ppm all, 1 ppm Hg	0.081	0.078	0.347	75.342	9.210	30.395	3.314	1.936	43.256	31.971	996.057	81.912

He cell gas, SQ mode BEC results (µg/L)												
Element	Ruthenium		Rhodium	Palladium	Silver		Osmium		Iridium	Platinum		Gold
Isotope	99	101	103	105	107	109	188	189	191	195	198	197
10 ppm Cu Zn	0.001	0.001	0.001	0.001	0.005	0.004	0.004	0.002	0.005	0.001	0.000	0.002
10 ppm Sr Rb	0.000	0.001	0.002	0.058	0.001	0.001	0.003	0.002	0.001	0.001	0.000	0.001
10 ppm Ni	0.001	0.000	0.000	0.004	0.005	0.007	0.004	0.003	0.004	0.000	0.000	0.000
10 ppm Mo	0.005	0.001	0.000	0.001	0.000	0.001	0.008	0.005	0.001	0.000	0.000	0.001
10 ppm Pb, 1 ppm Hg	0.000	0.000	0.468	0.001	0.004	0.003	0.016	0.013	0.007	0.000	602.063	0.000
10 ppm Zr Nb	0.000	0.000	0.000	0.038	0.479	0.155	0.023	0.019	0.002	0.004	3.969	0.041
10 ppm REE, Sc, Y	0.000	0.001	0.010	2.692	0.010	0.005	0.543	0.366	11.157	0.064	1.578	0.020
10 ppm Ta	0.002	0.000	0.000	0.002	0.001	0.000	0.002	0.002	0.001	0.055	16.102	25.002
10 ppm Hf	0.000	0.000	0.000	0.001	0.001	0.000	0.004	0.006	0.082	8.937	0.627	1.122
10 ppm W	0.001	0.000	0.000	0.000	0.001	0.001	0.007	0.003	0.001	0.002	36.586	0.199
10 ppm all, 1 ppm Hg	0.016	0.003	0.399	2.748	0.510	0.169	0.489	0.320	11.158	9.264	669.894	27.554

NH ₃ cell gas, MS/MS mode BEC results (µg/L)												
Element	Ruthenium		Rhodium	Palladium	Silver		Osmium		Iridium	Platinum		Gold
Isotope	99	101	103	105	107	109	188	189	191	195	198	197
NH ₃ flow rate (mL/min)	3.0	3.0	3.0	5.0	5.0	5.0	2.0	2.0	3.0	5.0	5.0	5.0
MS/MS mode	On-mass	On-mass	On-mass	On-mass	On-mass	On-mass	Mass-shift	Mass-shift	Mass-shift	Mass-shift	Mass-shift	Mass-shift
Mass Pair (Q1 - Q2)	99 - 99	101 - 101	103 - 103	105 - 105	107 - 107	109 - 109	188 - 203	189 - 204	191 - 206	195 - 229	198 - 232	197 - 231
10 ppm Cu Zn	0.002	0.001	0.000	0.000	0.004	0.004	0.002	0.004	0.003	0.000	0.000	0.001
10 ppm Sr Rb	0.000	0.003	0.009	0.012	0.000	0.001	0.002	0.003	0.003	0.000	0.000	0.000
10 ppm Ni	0.001	0.001	0.000	0.003	0.005	0.008	0.004	0.003	0.005	0.000	0.000	0.000
10 ppm Mo	0.001	0.001	0.000	0.001	0.000	0.001	0.004	0.008	0.003	0.001	0.003	0.000
10 ppm Pb, 1 ppm Hg	0.000	0.000	0.000	0.001	0.002	0.003	0.010	0.011	0.010	0.000	0.004	0.001
10 ppm Zr Nb	0.000	0.000	0.000	0.002	0.004	0.006	0.020	0.018	0.005	0.001	0.002	0.000
10 ppm REE, Sc, Y	0.000	0.001	0.009	0.017	0.002	0.006	0.050	0.046	0.105	0.008	0.031	0.001
10 ppm Ta	0.000	0.000	0.000	0.000	0.000	0.002	0.004	0.007	0.003	0.001	0.000	0.000
10 ppm Hf	0.001	0.000	0.000	0.000	0.000	0.001	0.007	0.009	0.036	0.113	0.003	0.000
10 ppm W	0.000	0.000	0.000	0.000	0.000	0.002	0.009	0.007	0.006	0.000	0.000	0.000
10 ppm all, 1 ppm Hg	0.002	0.004	0.020	0.044	0.022	0.023	0.030	0.017	0.183	0.137	0.023	0.002

Spike recoveries, detection limits (DLs) and BECs in a complex matrix mix

To evaluate more specifically the accuracy of the ICP-MS/MS method, a 1 µg/L (ppb) PGE spike was measured in the highest and most complex synthetic interference solution. The mix contained 10 ppm of all interfering elements (listed in Table 3) except for Hg, which was present at 1 ppm. The PGE spike concentrations were quantified in no gas, He, and the optimum NH₃ cell gas mode. As shown in Figure 1, the PGE spike concentrations measured in no gas mode were strongly affected by spectral overlaps formed from the matrix elements. The matrix interferences in He mode were lower, but several of the measured results were still far above the true spike concentrations. The NH₃ mode results are all free from significant overlap, with measured PGE spike concentrations close to the true value of 1 ppb.

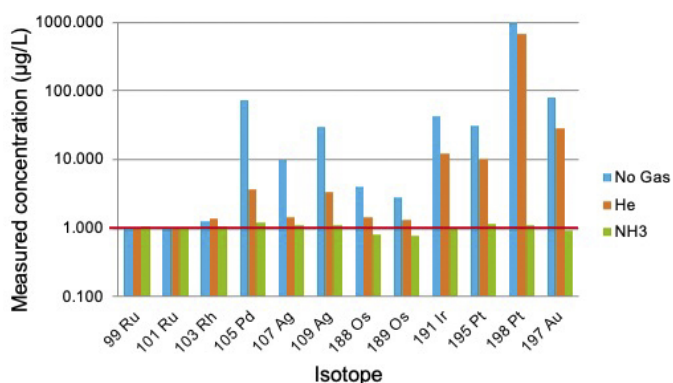


Figure 1. Reported concentrations of the PGEs spiked at 1 ppb in the most complex mixed matrix, measured in three different gas modes.

Table 4 shows the DL and BEC for each PGE in the optimum NH₃ cell gas mode. The DLs were calculated from three times the standard deviation of a low standard (10 ppt) divided by the slope of the calibration. The BECs were calculated from the blank intensity divided by the sensitivity. The DLs and BECs for the PGEs measured in NH₃ mode were all in the low or sub-ppt range despite the reduction in sensitivity that occurs due to the use of aerosol dilution with UHMI. The low DLs and BECs indicate that the 8900 ICP-QQQ can achieve excellent detection capability, even when combined with the very robust plasma conditions needed for routine analysis of high matrix sample digests.

The low DLs and BEC are partly due to the optimized configuration of the 8900 ICP-QQQ, which gives extremely low background signals. For example, 0 cps were measured in the calibration blank for Os, Ir, and Au in NH₃ mode. A second factor is the highly selective reaction chemistry in the CRC when the 8900 is operated in MS/MS mode with NH₃ cell gas. The MS/MS configuration uses Q1 to select the specific mass of ions that are allowed to enter the CRC and react. Q1 ensures that only the selected analyte ions and on-mass interfering ions enter the CRC, so the reactions are controlled and predictable, leading to very effective resolution of the interfering ions. No new potentially overlapping product ions can form from ions at other masses, because all other masses are excluded from the CRC when Q1 is operating as a true mass filter.

Table 4 also shows the percent recoveries for the 1 ppb PGE spike in the highest, most complex mixed matrix solution. All recoveries in NH₃ mode were within 10% of the target value, with the exception of Os, which suffers from chemical instability in the presence of HNO₃. Osmium stability can be improved by reducing the HNO₃ concentration in the solutions and increasing the HCl concentration.

Table 4. PGE DLs, BECs, and recoveries of a 1 ppb spike in a complex synthetic interference matrix.

Element	Mass Pair (Q1 - Q2)	DL (ng/L)	BEC (ng/L)	1 ppb Spike Recovery (%)
Ru	99 - 99	1.691	1.123	104
Ru	101 - 101	0.67	0.129	101
Rh	103 - 103	0.653	0.126	101
Pd	105 - 105	5.541	2.133	108
Ag	107 - 107	3.78	5.288	106
Ag	109 - 109	0.849	0.327	107
Os	188 - 203	6.245	3.704	81
Os	189 - 204	6.558	3.571	78
Ir	191 - 206	8.566	5.882	103
Pt	195 - 229	6.247	1.202	102
Pt	198 - 232	2.232	0.918	109
Au	197 - 231	7.592	4.348	91

Recovery of PGEs in CRM BCR 723 Road Dust

The aqua regia digestion of CRM BCR 723 Road Dust was analyzed to evaluate the accuracy of the ICP-MS/MS method for quantitative analysis of the PGEs in a representative complex sample matrix. BCR 723 Road Dust has certified values for Rh, Pd, and Pt, and the recoveries for these elements in NH₃ mode on the 8900 ICP-QQQ are shown in Figure 2.

For all three certified elements, the values measured using the 8900 ICP-QQQ in NH₃ mode were in good agreement with the certified values. For Rh and Pt, the 8900 mean measured concentrations were almost identical to the certified mean

values, and the measured precision (n=3) was less than 2% RSD. For Pd, the 8900 result was a little higher than the certified mean value, but still within the 95% confidence limits. The Pd result measured by the 8900 method is close to the limit of quantification (LOQ), as indicated by the relatively high RSD of 7%. However, note that the uncertainty of the certified value is also high at 31% (6.1 ± 1.9 µg/kg), due to the low concentration of the element. The certified value for Pd is also based on results from only 8 of the 20 labs that participated in the CRM certification exercise, further illustrating the difficulty of measuring this element at the low levels present in BCR 723.

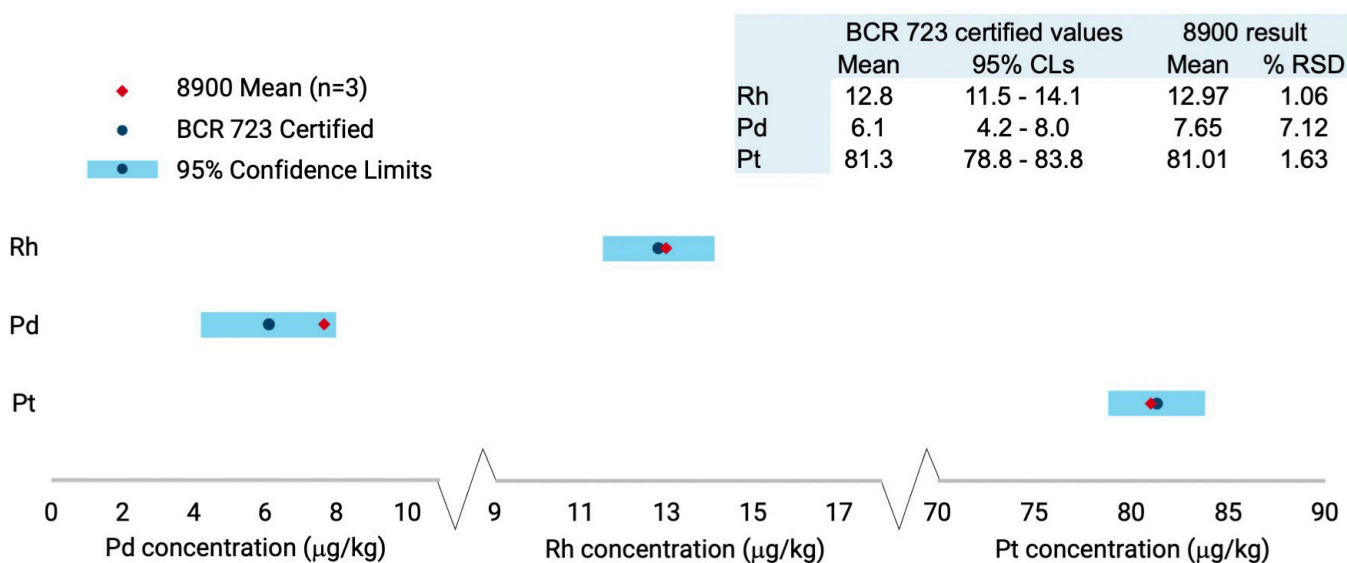


Figure 2. Agilent 8900 ICP-MS/MS measured results compared to certified mean values and uncertainty ranges (95% confidence limits) for Rh, Pd, and Pt in CRM BCR 723 Road Dust.

Conclusion

A method has been developed for the routine analysis of the PGEs and other noble metals in high and complex matrices using the Agilent 8900 ICP-QQQ in MS/MS mode with NH₃ cell gas. Using the UHMI aerosol dilution system, the ICP-MS was able to tolerate the high levels of TDS (~10 g/L, 1%) in an aqua regia digest of a Road Dust CRM sample. UHMI enables high matrix sample digests such as soil, roadside dust, and mining samples to be analyzed with minimal dilution, avoiding potential problems of dilution errors or contamination from the diluent.

The 8900 ICP-QQQ method used MS/MS mode with NH₃ cell gas to resolve matrix-based interferences on the noble metals. The ability of ICP-MS/MS to resolve severe spectral interferences on the PGEs was shown by the low BECs obtained in a range of complex synthetic matrices. The method was further validated by demonstrating accurate spike recovery of the PGEs in the most complex matrix mix and accurate recovery of the certified elements in a Road Dust CRM sample. Potential matrix-based spectral interferences that cannot be addressed either by He KED mode on single quadrupole ICP-MS or by High Resolution ICP-MS were resolved successfully using the ICP-MS/MS method with NH₃ cell gas.

The 8900 ICP-QQQ offers a unique combination of exceptional matrix tolerance due to the robust UHMI plasma conditions, together with the low background and effective control of NH₃ reactions due to the MS/MS configuration. This combination allowed the development of a method that enables the accurate, interference-free measurement of sub-ppb levels of the PGEs with good precision in complex sample matrices.

The method is suitable for routine environmental monitoring of trace PGEs, as well as other applications such as mineral prospecting, extraction, and processing/reprocessing of the PGEs.

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