JAAS

PAPER

View Article Online
View Journal | View Issue

Cite this: *J. Anal. At. Spectrom.*, 2025, **40**, 2783

Fully automated dual-column purification procedure for Pb from biological materials for subsequent high-precision isotopic analysis

Anika Retzmann, *[a] Kerri A. Miller,[b] Sebastian Champagne,[c] Gabriella Gelinas[a] and Michael E. Wieser[a]

A fully automated dual-column purification procedure for Pb from biological samples, designed for subsequent Pb isotopic analysis, is presented that utilizes the prep*FAST* MC™ system (Elemental Scientific), Nobias Chelate-PA1 resin (Hitachi High-Tech Fielding Corporation) and DGA resin (TrisKem International). The procedure developed allows the unattended processing of approx. 15–20 samples per day and offers several advantages: low and reproducible blanks (<0.05 ng), no carry over or memory effects, high reusability (>50 uses), high Pb yields (99% ± 15%, 2 SD, $N = 23$), and strong robustness to matrix variations across biological samples (*i.e.,* bone, hair). Additionally, Pb isotopic analysis using MC-ICP-MS showed no significant on-column fractionation. The measured $^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, and $^{208}Pb/^{204}Pb$ isotope abundance ratios of biological reference materials (*i.e.,* NIST SRM 1400, ERM-DB001, GBW07601) are consistent with published values. For the hair reference material GBW09101, a $^{208}Pb/^{206}Pb$ isotope abundance ratio of 2.12045 ± 0.00054 (*i.e.*, $\delta(^{208}Pb/^{206}Pb)_{SRM981} = -21.99‰ \pm 0.24‰$) ($U$, $k = 2$), a $^{207}Pb/^{206}Pb$ isotope abundance ratio of 0.86292 ± 0.00014 (*i.e.*, $\delta(^{207}Pb/^{206}Pb)_{SRM981} = -56.56‰ \pm 0.14‰$) ($U$, $k = 2$), and a $^{208}Pb/^{204}Pb$ isotope abundance ratio of 38.451 ± 0.022 (*i.e.*, $\delta(^{208}Pb/^{204}Pb)_{SRM981} = 47.09‰ \pm 0.51‰$) ($U$, $k = 2$) are proposed.

Received 18th June 2025
Accepted 18th August 2025

DOI: 10.1039/d5ja00240k

rsc.li/jaas

1. Introduction

Lead (Pb) is a natural toxic trace element that is non-essential to life[1] and ubiquitous in the environment (partly anthropogenically driven).[2] It has played an important role in technological developments and remains one of today's most persistent and widespread anthropogenic pollutants.[3] Animals and humans are generally exposed to Pb from dietary (food and water) intakes,[4] which currently represent more than 90% of the total exposure,[3,5,6] as well as from inhalation.[7,8] Exposure to Pb in the modern population has strongly decreased over the last 40

[a]*University of Calgary, Department of Physics and Astronomy, 2500 University Dr. NW, Calgary, AB T2N 1N4, Canada. E-mail: anika.retzmann@ucalgary.ca*
[b]*University of Calgary, Arnie Charbonneau Cancer Institute, 3280 Hospital Dr. NW, Calgary, AB T2N 4Z6, Canada*
[c]*University of Calgary, Department of Earth, Energy, and Environment, 2500 University Dr. NW, Calgary, AB T2N 1N4, Canada*

Anika Retzmann

Anika Retzmann earned her PhD in Analytical Chemistry in 2020 from the University of Natural Resources and Life Sciences, Vienna, under the supervision of Prof. Thomas Prohaska. She went on to complete postdoctoral research at Montanuniversität Leoben and the Bundesanstalt für Materialforschung und-prüfung. Since 2023, she has been a postdoctoral fellow of the German National Academy of Sciences Leopoldina, conducting research in Prof. Michael Wieser's group at the University of Calgary, Canada. Anika's research focuses on the analysis of stable metal isotope abundance ratios and their application to research questions in the fields of environmental science, archaeometry, biomedicine, and life sciences. She is particularly interested in developing advanced analytical tools, including fully automated analyte purification procedures and high-precision mass spectrometry, to investigate the roles of essential elements in biological systems through their isotopic signatures. Most recently, Anika pioneered the combination of the MICAP ion source using nitrogen plasma with multi-collector mass spectrometry for stable metal isotopic analysis. Her work supports innovation in both analytical methodology and its practical application.

years. However, Pb remains a contaminant of public health concern.[3,9]

Pb has four stable isotopes, *i.e.*, ^{204}Pb, ^{206}Pb, ^{207}Pb and ^{208}Pb, with the three heavier isotopes being formed as end-products of radioactive decays from ^{235}U, ^{238}U and ^{232}Th.[10] This leads to variability in their abundances in terrestrial materials depending on the half-life of parent isotopes, the initial Pb, U and Th concentrations, and the time elapsed since they were formed.[3] The high-precision analysis of the resulting radiogenic Pb isotopic compositions in biological materials (*e.g.*, hair, teeth, blood) are highly relevant in a variety of fields. For example, Pb isotopes have been used as source and process tracers in environmental research,[11] to examine differences in Pb exposure and to trace the movement of individuals in archaeological and anthropological studies,[12,13] to link a suspect to a crime scene or to predict possible region-of-origin of unidentified human remains in forensic studies,[14,15] and in biomedical studies to address modern human Pb exposure[3] and its prevention.[16,17]

The variations in radiogenic Pb isotopic compositions are significant and measurable when using appropriate methods like multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) and suitable calibration strategies. Apart from the issue of instrumental isotopic fractionation (IIF),[18] accurate Pb isotopic analyses by MC-ICP-MS suffers from spectral interferences (*i.e.*, isobaric elemental ions (*e.g.*, $^{204}Hg^{+}$ on $^{204}Pb^{+}$) and polyatomic ions (*e.g.*, TlH^{+} on $^{204}Pb^{+}$ and $^{206}Pb^{+}$)) and non-spectral interferences (mainly matrix effects from Na, Mg, K, and Ca).[19] For decades, the method of choice to purify and isolate Pb from these interferences was ion-exchange or ion-extraction chromatography by means of manual gravity flow procedures.[20] These manual protocols are time-consuming, labor-intensive, and prone to operator-related errors, resulting in reduced reproducibility and increased procedural blanks.[20,21]

In the last decade, the focus has shifted to automated purification using 'custom-made'[22,23] and commercial automated chromatographic devices for unattended sample processing.[24] The prep*FAST* MC™ by Elemental Scientific[25] is an example of the latter and it is characterized by its speed and efficiency due to unattended operation, high-throughput, reproducible flow rates and elution volumes, and low procedural blanks.[20,21,26,27] Automating the Pb purification step is crucial to enable high-throughput Pb isotopic analyses as necessary for processing larger cohorts in archaeological/anthropological and biomedical studies. Although the prep*FAST* MC™ can be coupled online with an MC-ICP-MS, the Pb purification for isotopic analyses usually is carried out off-line. Furthermore, the prep*FAST* MC™ system employs automated sequential extraction protocols and, therefore, requires highly reusable resins that do not exhibit carry-over or memory effects of Pb from previous samples, which could bias the Pb isotopic analyses. Earlier studies have reported memory effects and limited reusability for commonly used ion-extraction and ion-exchange resins for Pb purification, such as Sr.Spec,[28] Pb.Spec and AG® 1-X8,[29–31] making them unsuitable for an automated workflow using the prep*FAST* MC™ system. As a result, previous studies have combined the prep*FAST* MC™ with the ion-extraction resin DGA,[32,33] which is highly reusable (>100 times[21]), for the automated purification of Sr and Pb from various samples types including biological materials.[20,21,26] Nevertheless, a major limitation of these procedures is that DGA resin also retains Ca under the same conditions as Sr and Pb.[21,34] Initial procedures using a bed volume of 1 mL had limited applicability for Sr and Pb, as only absolute Ca amounts of <100 μg could be tolerated.[20,21] Larger amounts of Ca led to a significant shift of the Pb elution peak and co-elution of Ca. A systematic study on the effect of increasing Ca amounts on the separation efficiency of Sr, Pb and Ca using DGA resin showed that a bed volume of 3 mL offers a more robust and efficient purification of Pb from Ca based on the significantly larger amount of the DGA resin, which can handle higher matrix loads (Ca ≤ 500 μg).[26]

In the present study, a novel chromatographic procedure is presented to purify Pb from biological samples for reliable and precise Pb isotopic analyses using MC-ICP-MS. This procedure utilizes a true one-stage dual-column setup at the prep*FAST* MC™ system similar to the setup recently presented for Zn.[27] The chromatographic purification combines an ion-exchange resin (*i.e.,* Nobias Chelate-PA1 resin) for pre-cleaning with an ion-extraction resin (*i.e.,* DGA resin) for final Pb isolation. In the present study, the procedure has been characterized for Pb purification from potential interferences, Pb blank contribution, column yields, matrix flexibility, repeatability, and precision.

2. Experimental section

2.1. Materials, reagents & reference materials

High-Quality water (HQ water, Type I reagent-grade water (18.2 MΩ cm)) was obtained from a purification system (PURELAB Plus, U.S. FILTER, ELGA LabWater, High Wycombe, UK). Analytical reagent-grade nitric acid ($w(HNO_3)$ = 67–70%, Aristar Plus, VWR International, Radnor, USA) and analytical reagent-grade hydrochloric acid ($w(HCl)$ = 34–37%, Aristar Plus, VWR International) were purified by double-subboiling using an acid purification system (Savillex, Eden Prairie, MN, US). Hydrogen peroxide ($w(H_2O_2)$ = 30%, Fisher Scientific, Ottawa, Canada) was used for sample digestion without any further purification. Diluted ammonium acetate ($w(NH_4Ac)$ = 0.1 mol L^{-1}, $w(NH_4Ac)$ = 0.01 mol L^{-1}) with a pH of 4–5 was prepared from ultra-pure glacial acetic acid (Aristar Ultra, VWR International) and ultra-pure ammonium hydroxide (Aristar Ultra, VWR International). Consumables (*e.g.*, centrifuge tubes, test tubes, pipette tips) were leached for at least one week with dilute nitric acid ($w(HNO_3)$ ≈ 3%) before use. Perfluoroalkoxy (PFA) screw cap vials (Savillex) were pre-cleaned in a two-step acid cleaning procedure using double-subboiled nitric acid. PFA digestion vessels (Anton Paar Instruments, Graz, Austria) were pre-cleaned by two rounds of blank digestions using 6 mL of double-subboiled nitric acid ($c(HNO_3)$ = 15.8 mol L^{-1}).

The Nobias Chelate-PA1 resin (Hitachi High-Tech Fielding Corporation, Tokyo, Japan) and the unbranched DGA resin (part. no. DN-B25-A, TrisKem International, Bruz, France, mean particle size of 100–150 μm) were soaked in diluted ethanol ($w(EtOH)$ ≈ 10%) before use. Empty PFA columns with a bed volume of 200 μL (part. no. CF-200, Elemental Scientific (ESI),

Table 1 Elemental mass concentrations of PseudoSample(1) and PseudoSample(2)

	Approx. mass concentrations (μg L^{-1})							
Sample ID	**Pb**	Na	Mg	K	Ca	Fe	Tl	Bi
PseudoSample(1)	**20**	1300	1000	1000	10 000	1000	20	20
PseusoSample(2)	**15**	1500	1000	1000	10 000	1000	20	—

Omaha, USA) and 500 μL (part. no. CF-200, ESI) as well as corresponding frits (part. no. CF-F-X4 and CF-F-X6, ESI) were pre-cleaned and stored in diluted nitric acid ($w(HNO_3) \approx 10\%$).

Throughout this study, "PseudoSample(1)" was used to characterize the elution profile of the Nobias Chelate-PA1 resin and DGA resin (see Section 3.1) and "PseudoSample(2)" was used to characterize the reusability of the Nobias Chelate-PA1 resin and the DGA resin (see Section 3.3). PseudoSample(1) was prepared from a multi-element stock solution (BDH89800-582, 100 μg mL^{-1}: Ca, Mg, K, Al, Ba, Be, Bi, B, Cd, Cr, Co, Cu, Ga, Fe, Pb, Li, Mn, Ni, Se, Na, Sr, Te, Tl, Zn, Aristar, VWR International), which was spiked with single-element standards of Na, Mg, K, Ca, and Fe (1000 μg mL^{-1}, Aristar, VWR International; Sigma-Aldrich, MerckSigma, Darmstadt, Germany). PseudoSample(2) was prepared from single-element standard of Na, Mg, K, Ca, Fe, and Tl (1000 μg mL^{-1}, Aristar, VWR International; Sigma-Aldrich, MerckSigma), and Pb (SRM 981, NIST, Gaithersburg, USA). The composition of PseudoSample(1) and (2) are given in Table 1.

The following certified reference materials (CRMs) were analyzed throughout this study: NIST SRM 1400 (bone ash, NIST, Gaithersburg, USA), ERM-DB001 (human hair, ERM, Geel, Belgium), GBW07601 (human hair, CNRM, Beijing, China), and GBW09101 (human hair, CNRM). NIST SRM 981 (NIST), which is certified for absolute Pb isotopic composition, was used as quality control (QC) sample, as isotope reference material for standard-sample bracketing during MC-ICP-MS measurements and as δ-anchor for Pb isotopic analyses as recommended.[35]

2.2. Sample digestion

About 100 mg of the biological reference materials were weighed into 50 mL PFA digestion vessels (Anton Paar, Graz, Austria) and submerged in 5 mL concentrated double subboiled nitric acid. The dissolved samples were digested for 10 min at 200 °C with a microwave (Multiwave 5000, Anton Paar). After digestion, the solution was transferred quantitatively to a pre-cleaned 50 mL DigiTUBE (AnalytiChem Canada, Baie-d'Urfé, QC, Canada) and diluted to a final volume of 50 mL with HQ water. Analyte recoveries in the digests were found to be quantitative throughout all the experiments, and consequently, a complete digestion is assumed. Aliquots of each digest containing 20 ng Pb were transferred to a pre-cleaned 15 mL PFA screw cap vial (Savillex), evaporated to dryness at 80 °C, and redissolved in 2 mL of 0.01 mol L^{-1} ammonium acetate for subsequent automated dual-column purification procedure.

2.3. Prep*FAST* MC™ purification procedure

The low-pressure chromatography sample preparation system prep*FAST* MC™ (ESI) was used throughout this study to develop and perform the fully automated dual-column purification procedure for Pb. All purifications at the prep*FAST* MC™ were carried out offline. Two empty PFA columns were packed according to standard protocol,[20] one with 200 μL of Nobias Chelate-PA1 resin (Hitachi High-Tech Fielding Corporation) and a second one with 500 μL of DGA resin (TrisKem International), and utilized in a dual-column set-up. The automated dual-column purification was performed according to the procedure described in Table 2. The purified Pb fractions were collected in pre-cleaned PFA vials. At the end of each purification batch, the resins in the columns were stored in HQ water to minimize unwanted resin degradation.

The "calibration mode" of the prep*FAST* MC™ was utilized for the creation of the stepwise elution profile[20,26] of PseudoSample(1), ERM-DB001, and NIST SRM 1400 (see Section 3.1). For all other analyses of the samples (PseudoSample(2), QCs, biological CRMs), only a pooled Pb fraction (=4 mL of 5 mol L^{-1} nitric acid) was collected.

Table 2 Protocol for the automated purification procedure of Pb in a dual-column set-up (C1: 200 μL of Nobias Chelate-PA1 resin, C2: 500 μL of DGA resin) using prep*FAST* MC™

Step	Purification step (column)	Reagent	Volume (mL)	Flow rate (μL min^{-1})
1	Pre-cleaning (C2)	5 mol L^{-1} HNO_3	3	5000
2	Cleaning (C2)	0.1 mol L^{-1} HCl	3	5000
3	Conditioning (C2)	1.5 mol L^{-1} HNO_3	3	5000
4	Pre-cleaning (C1)	6 mol L^{-1} HCl	3	5000
5	Pre-cleaning (C1)	HQ water	3	5000
6	Cleaning (C1)	1.5 mol L^{-1} HNO_3	3	5000
7	Cleaning (C2)	HQ water	5	5000
8	Activating and conditioning (C1)	0.1 mol L^{-1} NH_4Ac	3	5000
9	Sample load (C1)	0.01 mol L^{-1} NH_4Ac	2	1000
10	Matrix wash (C1)	HQ water	6	2000
11	Transfer (C1 → C2)	1.5 mol L^{-1} HNO_3	3	1000
12	Matrix wash (C2)	1.5 mol L^{-1} HNO_3	2	2000
13	Pb elution (C2)	5 mol L^{-1} HNO_3	4	1000
14	Ca wash (C2)	0.1 mol L^{-1} HCl	4	5000

2.4. Multi-elemental analysis

Multi-elemental analysis was performed using an inductively coupled plasma mass spectrometer, ICP-MS (iCAP™ TQ, Thermo Fisher Scientific, Bremen, Germany) coupled to an autosampler (SC-4 DX FAST, ESI). The elemental quantifications were accomplished by external calibration (8-point calibration, for Pb ranging from 0.1 μg L^{-1} to 150 μg L^{-1}) with standards prepared volumetrically from multi-element stock solution (BDH89800-580, Aristar, VWR International) including 2 μg L^{-1} indium (In) as internal normalization standard. General instrumental settings are compiled in Table S1. The expanded uncertainties for multi-element analysis were estimated as 10%.

The analyte recoveries for the elution profiles (see Section 3.1), the reusability test (see Section 3.3), and the purified reference materials (see Section 3.4) were calculated as the amount of analyte extracted in each step or only the Pb fraction relative to the true amount of the analyte. The true analyte amounts were determined from an aliquot of PseudoSample(1) or (2), or from the sample digest.

2.5. Pb isotopic analyses

Measurement of the Pb isotope abundance ratios were performed using MC-ICP-MS (Neoma, Thermo Fisher Scientific) in the Cancer Metallomics Lab at the Arnie Charbonneau Cancer Institute, University of Calgary. The instrument is equipped with an autosampler (MicroDX, ESI) and a high sensitivity sample introduction system (APEX HF, ESI) in combination with a PFA nebulizer (ESI). The instrument was optimized daily using a solution of NIST SRM 981 for maximum intensity, signal stability, and peak shape. All measurements were performed in low resolution mode. General instrumental settings for the Pb isotopic measurements are compiled in Table S2.

The purified Pb fractions were evaporated at 80 °C, dissolved in 100 μL of concentrated nitric acid ($c(HNO_3) = 15.8$ mol L^{-1}) to remove residual acetates and evaporated again. For MC-ICP-MS measurements, the final residue was redissolved in 1 mL of diluted nitric acid ($w(HNO_3) = 2\%$) resulting in a Pb mass concentration of 20 μg L^{-1}. Data collection was accomplished with a total of 50 measurements per sample with an integration time of 4 s. IIF during the measurement was corrected following classical standard-sample-bracketing (SSB) approach.[18] Pb mass concentrations of sample and SSB standards were matched within 20%. The Pb digestion blanks and the Pb blank of the diluted nitric acid ($w(HNO_3) = 2\%$) used for the MC-ICP-MS measurements were found negligible with contribution of <0.4% and <0.03%, respectively. Absolute Pb isotope abundance ratios were calculated after correction of residual Hg interferences of $^{204}Hg^+$ on $^{204}Pb^+$ as described in Retzmann *et al.*.[20] In addition, the results of this study are reported in standard δ-notation (in ‰), which expresses the relative difference in Pb isotope abundance ratios between the sample and the assigned δ-zero anchor NIST SRM 981 (ref. 35) (δ-value = 0‰), in accordance with eqn (1):

$$\delta\left(^{20x}Pb/^{20y}Pb\right)_{SRM981} = \left(\frac{^{20x}Pb/^{20y}Pb_{sample}}{^{20x}Pb/^{20y}Pb_{SRM981}} - 1\right)\cdot 1000 \quad (1)$$

where $x = 8$ or 7 when $y = 6$, or $x = 8$ when $y = 4$.

The measurement uncertainty for the Pb isotopic analysis of PseudoSample(2) was estimated based on the precision of the measurement and the repeatability of the sample. The expanded uncertainties for the average of the biological reference materials were estimated based on precision of the measurement and the repeatability of the duplicate.

3. Results and discussion

In order to demonstrate that the novel chromatographic procedure using a dual-column setup with the prep*FAST* MC™ is valid for Pb isotopic analysis, the following criteria were investigated: (1) isolation of Pb from interferences and matrix elements for different biological matrices, (2) contamination and carry-over during processing, (3) column yields, and (4) application to bone and hair reference materials.

3.1. Elution profile

Previous studies[20,21,26] showed that chromatographic purifications using the ion-extraction resin DGA with sample loading from nitric acid ($c(HNO_3) = 1$–3 mol L^{-1}) are limited in presence of large Ca amounts due to peak shifting and co-elution of Ca. A dual-column procedure was therefore chosen in this study to ensure the highest possible matrix flexibility for biological samples, and enable the analysis of samples with low Pb amounts.

For the pre-cleaning step (=first column) in which the main matrix elements are to be removed, an ion-exchange resin, the Nobias Chelate-PA1 resin, was selected. This resin, first introduced by Sakamoto *et al.*,[36] is based on a hydrophilic methacrylate copolymer that is chemically modified with both ethylenediamine triacetic acid and iminodiacetic acid as chelating agent for metal capture.[37] It captures Pb, as well as transition metals and rare earth elements (REEs), without the influence of alkali/alkaline-earth metals (*e.g.*, Na, Mg, K, Ca) and potential interferences like Tl under pH conditions of >3.[37,38] Pb and most other elements retained are released from Nobias Chelate-PA1 resin in ≥1 mol L^{-1} nitric or hydrochloric acid.[38] Furthermore, Nobias Chelate-PA1 is a highly reusable resin and has been used, for example, for automated purification of Cu and Ni for subsequent isotopic analysis.[39]

For the key purification step (=second column) of Pb in the dual-column procedure, an ion-extraction resin, the DGA resin, was therefore selected. The DGA resin is a synthesized tridentate ligand (*i.e.*, N,N,N′N′ tetraoctyl-1,5-diglycolamide) with a high affinity for lanthanides, actinides and rare earth elements.[32,33] Pb is well retained on DGA resin from 1–3 mol L^{-1} nitric acid, while matrix elements (*i.e.*, Na, Mg, Al, K, Fe) and spectral interferences (*i.e.*, Hg and Tl) are not retained under these conditions.[33] Any remaining Ca and potential present REEs are also retained under these conditions, however, Pb is released from DGA resin in >5 mol L^{-1} nitric acid while Ca and REEs remain retained.[20,21,33]

To the authors' knowledge, this study is the first to use the combination of Nobias Chelate-PA1 resin and DGA resin for the

purification of Pb from biological samples and subsequent isotopic analysis. Preliminary testing demonstrated successful column conditioning, sample load, and matrix wash for Nobias Chelate-PA1 resin using 0.1 mol L^{-1} ammonium acetate, 0.01 mol L^{-1} ammonium acetate, and HQ water. However, using only HQ water led to reduced Pb recovery with increasing use of the resin material which is incompatible for the automated purification procedure using prep*FAST* MC™, as this system requires resins to last at least throughout a single purification run (*e.g.*, 20 samples). Previous studies reported that ammonium acetate was needed to activate the resin material.[40] In order to minimize potential alterations in the retention behavior of Pb on DGA resin caused by the presence of ammonium acetate, a 0.1 mol L^{-1} ammonium acetate solution was solely used for activating and conditioning the Nobias Chelate-PA1 resin. For sample loading, a lower concentration of 0.01 mol L^{-1} ammonium acetate was applied, which was sufficient to redissolve the biological reference materials, while HQ water was used for matrix wash. Pb elution in 1–2 mol L^{-1} nitric acid or hydrochloric acid was tested and was found quantitatively at 15-times the column bed volume. Similarly, preliminary testing for DGA resin showed effective column conditioning, sample loading, and matrix washing with 1–2 mol L^{-1} nitric acid. For the final purification procedure, 1.5 mol L^{-1} nitric acid was chosen for these steps to ensure consistent purification performance despite minor variations in acidity. In this procedure, the additional step of Sr removal, as described in the previous studies,[20,26] was omitted because Sr is not retained by the Nobias Chelate-PA1 resin and therefore not transferred to the DGA resin. Finally, Pb elution in 5 mol L^{-1} nitric acid was successfully tested, yielding quantitative Pb recoveries at eight-times the column bed volume.

Overall, this procedure allows Pb to be eluted from Nobias Chelate-PA1 resin in 1.5 mol L^{-1} nitric acid and directly loaded on DGA resin in the same acid. There are no intermediate sample handling steps including evaporation and redissolving as required in previous multiple-stage procedures using prep*FAST* MC™.[39,41]

Fig. 1 shows the elution profile for Pb as well as potentially interfering isobaric elements (*i.e.*, Tl) and major matrix elements (*i.e.*, Na, Mg, K, Ca, Fe) in PseudoSample(1) for the dual-column procedure using the prep*FAST* MC™ according to Table 2. Variations in matrix composition could potentially alter the elution profile of the automated dual-column purification resulting in incomplete Pb elution and possible isotope fractionation.[41] Hence, two different types of biological CRMs, *i.e.*, hair and bone, with Ca/Pb mass fraction ratios of approx. 400 and 60 000 were tested as well. Pb is recovered quantitatively in the final Pb fraction (104% ± 15% (*U*, $k = 2$)), which excludes the possibility of operationally induced isotopic fractionation during sample processing. Pb is purified from isobaric elements (*i.e.*, Tl) and major matrix elements (*i.e.*, Na, Mg, K, Ca) during sample load and matrix wash on the Nobias Chelate-PA1 resin. During the transfer from the Nobias Chelate-PA1 resin onto the DGA resin and the matrix wash on the DGA resin, Pb is purified from any remaining matrix as well as from Hg and Fe. Note, Hg is not quantified in the elution profile, but ^{202}Hg signals

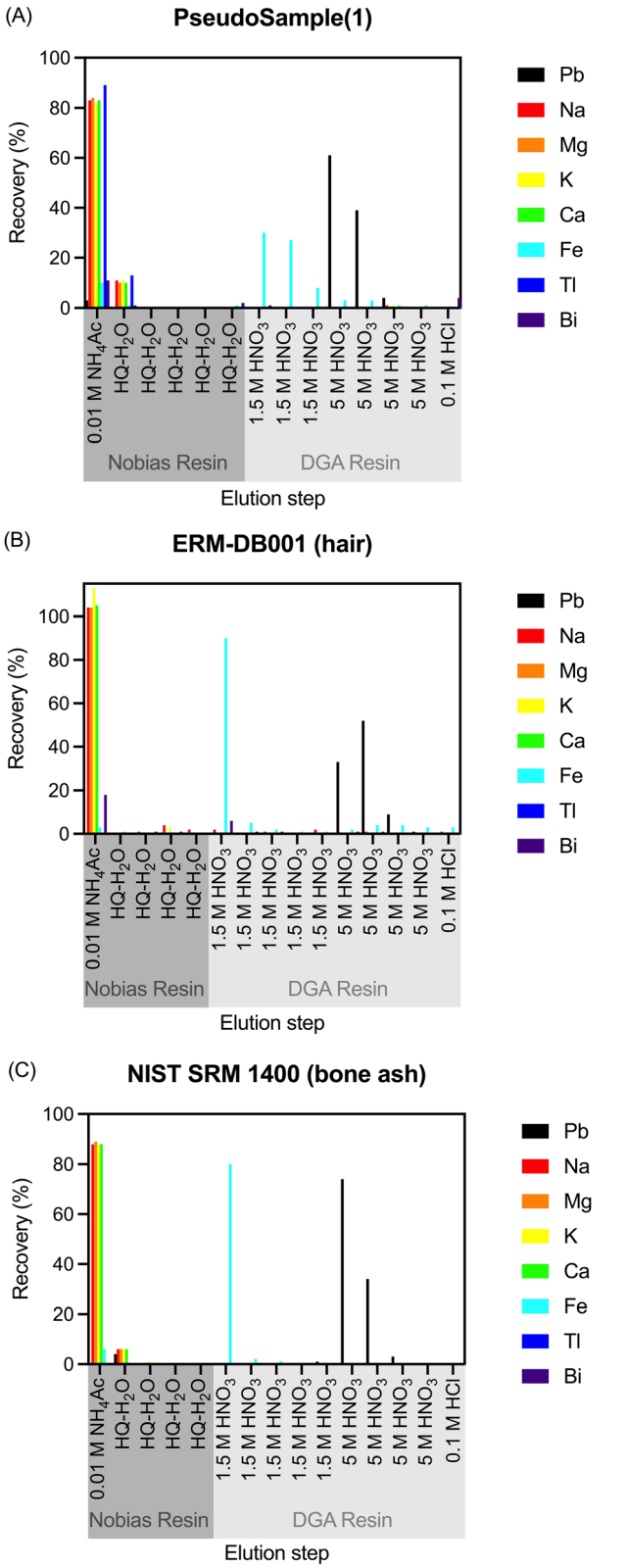

Fig. 1 Elution profile using dual-column procedure for (A) PseudoSample(1), (B) ERM-DB001 (hair) and (C) NIST SRM 1400 (bone ash) with elution volumes of 2 mL at the Nobias Chelate-PA1 resin and elution volumes of 1 mL at the DGA resin, except for Ca fraction in 0.1 mol L^{-1} hydrochloric acid with a volume of 6 mL. Relative uncertainty of 10% (U_{rel}, $k = 2$).

detected in the final Pb fractions were <0.2 mV which is considered negligible. The final Pb fraction from the automated dual-column purification procedure is very clean and therefore will not cause any bias, neither from isobaric interferences (*i.e.*, Tl, Hg) nor from matrix elements: It contains Na/Pb < 1.5, Mg/Pb < 0.6, K/Pb < 1.1, Ca/Pb < 11.3, Fe/Pb < 2.0, and Tl/Pb < 0.002.

Previous studies using DGA resin for Pb purification reported that the applicability for Pb is limited, as only absolute Ca amounts of <100 μg could be tolerated for 1 mL bed volume and <500 μg could be tolerated for 3 mL bed volume.[20,21,26] For the elution profile of the bone (*i.e.*, NIST SRM 1400), an absolute amount of 40 ng Pb was purified which corresponds to approx. 2000 μg of Ca. This significantly larger amount of Ca is not a problem for the smaller DGA column (*i.e.*, 500 μL) with the present procedure, as Ca is already separated by the Nobias Chelate-PA1 resin.

3.2. Contamination and carry-over

Reusing the same resins for high precision Pb isotope abundance ratios requires that Pb blanks and Pb carry-over from previous samples are negligible.[20,26] Initial test of the dual-column procedure indicated total procedural Pb blanks of approx. 0.06 ng prior to any samples and approx. 0.16 ng when alternated with PseudoSample(2). This observed Pb carry-over is most-likely caused by the Nobias Chelate-PA1 resin as previous studies using DGA resin did not report carry-over for Pb.[20,26] The implementation of an additional pre-cleaning step for the Nobias Chelate-PA1 resin with 6 mol L^{-1} hydrochloric acid (see Table 2) lead to improved Pb blanks and eliminated carry-over. The total procedural Pb blanks of the final procedure were consistent at 0.03 ng ± 0.02 ng (2 SD, $N = 5$). Despite the dual-column set-up, this Pb blank is significantly lower than previous studies that reported Pb blanks of approx. 0.12 ng when using 1 mL DGA columns and <0.5 ng when using 3 mL DGA columns.[20,26] Further, the Pb blank contribution is less than 0.25% for a Pb load of approx. 20 ng which can be considered negligible.

3.3. Column yields and column life span

Isotopic fractionation of Pb might occur during the automated dual-column purification procedure, and if this takes place it will be most likely during sample loading and Pb elution. Previous studies reported no on-column fractionation for Pb recoveries as low as 75% when using only DGA resin for purification.[20,26] However, the high Pb yields (≥90%) achieved with this procedure ensured that practically all Pb was retained and released by the resins, thereby eliminating potential on-column isotopic fractionation and inaccurate measurement of Pb isotope abundance ratios, which was demonstrated by comparing processed to unprocessed NIST SRM 981 solutions.

Fifteen aliquots of the PseudoSample(2) solution were purified re-using the same resin materials according to the purification protocol described in Table 2. The Pb yield of these aliquots is 101% ± 14% (2 SD, $N = 15$) (see Fig. 2A) which shows reliable, quantitative recovery over a series of at least 15 purifications. These high Pb recovery rates of the dual-column purification procedure eliminate the need to monitor for potential isotopic fractionation during chromatography and simplifies sample preparation and subsequent Pb isotope measurements. Furthermore, the $\delta^{208}Pb/^{206}Pb_{SRM981}$ value of the PseudoSample(2) solution was 0.00‰ ± 0.10‰ (2 SD, $N = 15$) (see Fig. 2B). Since the purified Pb fractions of PseudoSample(2) were compared to NIST SRM 981 which was used to prepare the PseudoSample(2) solution, the δ-value of 0 indicates that the dual-column purification procedure does not induce isotope fractionation. This observation is supported by the $\delta^{207}Pb/^{206}Pb_{SRM981}$ and $\delta^{208}Pb/^{204}Pb_{SRM981}$ values for PseudoSample(2) which are all overlapping withing uncertainty with the δ-zero anchor (see Fig. S1A and B). The Pb yields and the $\delta^{208}Pb/^{206}Pb_{SRM981}$ values indicate high reliability and high repeatability of the automated dual-column purification procedure for subsequent Pb isotopic analysis. Further, no apparent systematic change in $\delta^{208}Pb/^{206}Pb_{SRM981}$ values were observed with Pb yields of at least 89% ($R^2 = 0.34$) (see Fig. S2). This suggests that, under the given conditions, the Pb isotopic composition does not fractionate significantly on the two columns to induce systematic bias in the isotopic composition of the sample.

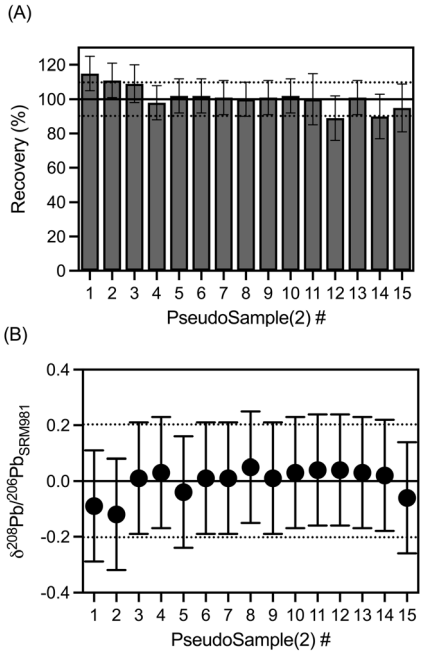

Fig. 2 Repeatability of (A) Pb yields and (B) $\delta^{208}Pb/^{206}Pb_{SRM981}$ values of PseudoSample(2) repeats ($N = 15$) processed through the automated dual-column purification procedure. Error bars correspond to expanded uncertainties (U, $k = 2$).

It is expected that Pb yields will decrease with column degradation indicating the end of the column life span.[42] Throughout this study, up to 50 samples were processed on the same resins without any signs of degradation. In previous studies, Nobias Chelate-PA1 resin and DGA resin have proved high reusability (Nobias: >400 times,[39] DGA: >100 times[20,21,26]), consequently a similar life span is expected in the dual-column set-up. However, it is recommended that the column

Table 3 Comparison of δ-values and absolute isotope abundance ratios for $^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, and $^{208}Pb/^{204}Pb$ of geological and biological reference materials obtained in this study with literature data. Errors were considered to be equal to expanded uncertainty (U, $k = 2$)[a]

CRM	$^{208}Pb/^{206}Pb$ isotope abundance ratio	$\delta(^{208}Pb/^{206}Pb)_{SRM981}$ value (‰)	$^{207}Pb/^{206}Pb$ isotope abundance ratio	$\delta(^{207}Pb/^{206}Pb)_{SRM981}$ value (‰)	$^{208}Pb/^{204}Pb$ isotope abundance ratio	$\delta(^{208}Pb/^{204}Pb)_{SRM981}$ value (‰)
NIST SRM 1400 (bone ash)	2.10336 ± 0.00044 (this study)	−29.86 ± 0.20 (this study)	0.85319 ± 0.00015 (this study)	−67.18 ± 0.16 (this study)	38.636 ± 0.016 (this study)	52.14 ± 0.39 (this study)
	2.10334 ± 0.00024 (ref. 26)	−29.87 ± 0.07 (ref. 26)	0.85340 ± 0.00031 (ref. 26)	−66.95 ± 0.17 (ref. 26)	38.6820 ± 0.0037 (ref. 26)	51.55 ± 0.26 (ref. 26)
	2.10280 ± 0.00080 (ref. 43 and 44)	−30.12 ± 0.37 (ref. 43 and 44)	0.85260 ± 0.00030 (ref. 43 and 44)	−67.83 ± 0.36 (ref. 43 and 44)	38.598 ± 0.031 (ref. 43 and 44)	51.09 ± 0.86 (ref. 43 and 44)
	2.1020 ± 0.0030 (ref. 45)	−30.49 ± 1.38 (ref. 45)	0.8520 ± 0.0010 (ref. 45)	−68.49 ± 1.09 (ref. 45)		
ERM-DB001 (human hair)	2.10615 ± 0.00033 (this study)	−28.58 ± 0.13 (this study)	0.86605 ± 0.00012 (this study)	−53.12 ± 0.11 (this study)	37.936 ± 0.015 (this study)	33.10 ± 0.34 (this study)
	2.1047 ± 0.0023 (ref. 46)	−29.27 ± 1.06 (ref. 46)	0.86609 ± 0.00055 (ref. 46)	−53.08 ± 0.60 (ref. 46)		
GBW07601 (human hair)	2.11994 ± 0.00035 (this study)	−22.22 ± 0.14 (this study)	0.86221 ± 0.00013 (this study)	−57.32 ± 0.12 (this study)	38.464 ± 0.017 (this study)	47.46 ± 0.42 (this study)
	2.1167 ± 0.0034 (ref. 46)	−23.71 ± 1.56 (ref. 46)	0.86202 ± 0.00071 (ref. 46)	−57.53 ± 0.78 (ref. 46)	38.4773 ± 0.0022 (ref. 47)	47.80 ± 0.60 (ref. 47)
	2.11984 ± 0.00012 (ref. 47)	−22.26 ± 0.06 (ref. 47)	0.86229 ± 0.00015 (ref. 47)	−57.23 ± 0.16 (ref. 47)		
GBW09101 (human hair)	2.12045 ± 0.00054 (this study)	−21.99 ± 0.24 (this study)	0.86292 ± 0.00014 (this study)	−56.56 ± 0.14 (this study)	38.451 ± 0.022 (this study)	47.09 ± 0.51 (this study)

[a] Calculated δ-value using certified value of NIST SRM 981.

performance is monitored for Pb yield and isotope fractionation by processing of a QC solution every five to ten samples.

3.4. Application to bone and hair CRMs

Finally, the automated dual-column purification procedure was validated by applying it to biological reference materials with varying matrix composition. Duplicates of the biological bone reference material (*i.e.*, NIST SRM 1400) and hair reference materials (*i.e.*, ERM-DB001, GBW07601, GBW09101) were processed in random order. The Pb yield remained high across these biological matrices with 95% ± 14% (2 SD, $N = 8$) (see Table S3). The repeatability (expressed as RSD) of the absolute Pb isotope abundance ratios is <0.01% for the duplicates (see Table S3). This indicates high repeatability of the automated dual-column purification procedure across the tested biological samples.

In Table 3, the δ-values and absolute isotope abundance ratios for $^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, and $^{208}Pb/^{204}Pb$ of the different bone and hair reference materials are reported and compared to data reported by previous studies. Overall, the values reported by the present study for the NIST SRM 1400, ERM-DB001 and GBW07601 overlap within uncertainty with previous reported data. For the hair reference material GBW09101, a $^{208}Pb/^{206}Pb$ isotope abundance ratio of 2.12045 ± 0.00054 (*i.e.*, $\delta(^{208}Pb/^{206}Pb)_{SRM981} = -21.99‰ \pm 0.24‰$) ($U$, $k = 2$), a $^{207}Pb/^{206}Pb$ isotope abundance ratio of 0.86292 ± 0.00014 (*i.e.*, $\delta(^{207}Pb/^{206}Pb)_{SRM981} = -56.56‰ \pm 0.14‰$) ($U$, $k = 2$), and a $^{208}Pb/^{204}Pb$ isotope abundance ratio of 38.451 ± 0.022 (*i.e.*, $\delta(^{208}Pb/^{204}Pb)_{SRM981} = 47.09‰ \pm 0.51‰$) ($U$, $k = 2$) are proposed. The close agreement between results for NIST SRM 1400, ERM-DB001, and GBW07601 and their respective literature values further demonstrates that the developed automated dual-column purification procedure is free from significant carry-over, memory effects, or on-column fractionation, and yields results comparable to those obtained by more labor-intensive and error-prone methods. Overall, this indicates high accuracy and high flexibility for biological matrices using the procedure described here.

4. Conclusion

In order to fully exploit the potential of applying Pb isotope abundance variation data in biological materials across various fields such as archaeology, environmental sciences, forensic, and biomedicine, more robust and reproducible protocols are required that enable routine analysis with high sample throughput. This work describes a new rapid purification procedure that utilizes automated chromatography for purifying Pb from biological samples (*i.e.,* bone, hair) using a prep*FAST* MC™ system for subsequent isotope analysis by MC-ICP-MS.

The dual-column purification procedure developed effectively isolates Pb from biological matrix elements, thus avoiding spectral interferences and minimizing matrix effects during the isotopic analysis. A quantitative recovery of Pb is achieved and the total procedural Pb blanks are negligible for Pb isotopic analysis. The dual-column purification procedure for Pb was validated using bone and hair reference materials (*i.e.,* NIST SRM 1400, ERM-DB001, GBW07601). Purification of these samples by the prep*FAST* MC™ system followed by Pb isotopic analysis using MC-ICP-MS generated δ-values and absolute isotope abundance ratios for $^{208}Pb/^{206}Pb$, $^{207}Pb/^{206}Pb$, and $^{208}Pb/^{204}Pb$ that agreed well with previously reported data. Duplicate digestions and repeated purification indicated overall low uncertainties.

Author contributions

AR: conceptualization, methodology, validation, investigation, writing – original Draft, review & editing, visualization, project administration. KAM: methodology, investigation, writing – review & editing. SC: methodology, investigation. GG: methodology, investigation. MEW: investigation, resources, writing – review & editing.

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

Data and prep*FAST* MC™ methods (incl. submethods) will be made available on request.

Supplementary information is available and includes detailed instrumental settings for ICP-MS and MC-ICP-MS measurements, additional data not presented in Table 3, and supplementary plots related to Fig. 2. See DOI: **https://doi.org/10.1039/d5ja00240k**.

Acknowledgements

AR is funded by the Leopoldina Postdoc Scholarship (LPDS 2022-14) from the German National Academy of Sciences. MEW is supported by an NSERC Discovery Grant. KAM is supported by operational funding from the Canadian Cancer Society. The Cancer Metallomics Lab at the Arnie Charbonneau Cancer Institute's Environmental Cancer Hub is supported by funding from the Canada Foundation for Innovation, the Alberta Cancer Foundation, the Government of Alberta, and the Robson DNA Science Centre at the University of Calgary. The authors would like to thank Michael Nightingale and Bernhard Mayer from the Applied Geochemistry Group at University of Calgary for the opportunity to use their iCAP™ TQ ICP-MS for multi-element measurements.

References

1 R. A. Kehoe, *Pharmacol. Ther., Part A*, 1976, **1**, 161–188.
2 A. L. Wani, A. Ara and J. A. Usmani, *Interdiscip. Toxicol.*, 2015, **8**, 55–64.
3 J. C. J. Petit, N. Mattielli, J. De Jong, E. Bouhoulle, W. Debouge, P. Maggi, G. Hublet, N. Fagel, C. Pirard,

C. Charlier and R. Suzanne, *Sci. Total Environ.*, 2024, **950**, 174763.
4 M. Chiaradia, A. Gallay and W. Todt, *Appl. Geochem.*, 2003, **18**, 353–370.
5 M. Sy, D. Eleftheriadou, C. Jung, O. Lindtner, S. Karakitsios, D. Sarigiannis, T. Weber, M. Kolossa-Gehring and M. Greiner, *Exposure Health*, 2023, **16**, 21–39.
6 I. Martorell, G. Perello, R. Marti-Cid, J. M. Llobet, V. Castell and J. L. Domingo, *Biol. Trace Elem. Res.*, 2011, **142**, 309–322.
7 N. W. Bower, S. R. Getty, C. P. Smith, Z. R. Simpson and J. M. Hoffman, *Int. J. Osteoarchaeol.*, 2005, **15**, 360–370.
8 B. L. Gulson, in *Handbook of Environmental Isotope Geochemistry: Vol I*, ed. M. Baskaran, Springer Berlin Heidelberg, Berlin, Heidelberg, 2012, pp. 769–785, DOI: 10.1007/978-3-642-10637-8_36.
9 T. R. Van de Wiele, A. G. Oomen, J. Wragg, M. Cave, M. Minekus, A. Hack, C. Cornelis, C. J. Rompelberg, L. L. De Zwart, B. Klinck, J. Van Wijnen, W. Verstraete and A. J. Sips, *J. Environ. Sci. Health, Part A: Toxic/Hazard. Subst. Environ. Eng.*, 2007, **42**, 1203–1211.
10 J. R. De Laeter, J. K. Böhlke, P. De Bièvre, H. Hidaka, H. S. Peiser, K. J. R. Rosman and P. D. P. Taylor, *Pure Appl. Chem.*, 2003, **75**, 683–800.
11 J. G. Wiederhold, *Environ. Sci. Technol.*, 2015, **49**, 2606–2624.
12 T. J. A. Munkittrick, T. L. Varney and V. Grimes, *J. Archaeol. Sci.*, 2023, **156**, 105803.
13 J. A. Evans, V. Pashley, K. Mee, D. Wagner, M. Parker Pearson, D. Fremondeau, U. Albarella and R. Madgwick, *PLoS One*, 2022, **17**, e0274831.
14 E. J. Bartelink and L. A. Chesson, *Forensic Sci. Res.*, 2019, **4**, 29–44.
15 L. M. Kootker, S. T. M. Ammer, D. J. Wescott, G. R. Davies and H. L. Mickleburgh, *Int. J. Leg. Med.*, 2024, **138**, 151–164.
16 K. Samekova, C. Firbas, J. Irrgeher, C. Opper, T. Prohaska, A. Retzmann, C. Tschegg, C. Meisslitzer, A. Tchaikovsky, G. Gouya, M. Freissmuth and M. Wolzt, *Sci. Rep.*, 2021, **11**, 14796.
17 J. Irrgeher, T. Berger, A. Tchaikovsky, C. Tschegg, G. Gouya, P. Lechner, A. Retzmann, C. Opper, C. Firbas, M. Freissmuth, K. Peschel-Credner, K. Anderle, C. Meisslitzer, M. Wolzt and T. Prohaska, *Anal. Bioanal. Chem.*, 2022, **415**, 255–268.
18 L. Yang, S. Tong, L. Zhou, Z. Hu, Z. Mester and J. Meija, *J. Anal. At. Spectrom.*, 2018, **33**, 1849–1861.
19 T. Prohaska, Chapter 7 Interferences, *Sector Field Mass Spectrometry for Elemental and Isotopic Analysis*, ed. T. Prohaska, J. Irrgeher, A. Zitek, and N. Jakubowski, The Royal Society of Chemistry, 2015, pp. 121–125.
20 A. Retzmann, T. Zimmermann, D. Profrock, T. Prohaska and J. Irrgeher, *Anal. Bioanal. Chem.*, 2017, **409**, 5463–5480.
21 S. J. Romaniello, M. P. Field, H. B. Smith, G. W. Gordon, M. H. Kim and A. D. Anbar, *J. Anal. At. Spectrom.*, 2015, **30**, 1906–1912.
22 F. Y. Zhou, D. He, X. Miao, C. Yang, J. H. Dong, H. T. Zheng, Z. Cheng, X. Liu and Z. L. Zhu, *Anal. Chem.*, 2021, **93**, 7196–7203.
23 D. Peng, X. Yu, X. Li, A. Sun, L. Wang, T. Wang and J. Xu, *J. Sep. Sci.*, 2023, **46**, e2200905.
24 B. M. Mahan, F. Wu, A. Dosseto, R. Chung, B. Schaefer and S. Turner, *J. Anal. At. Spectrom.*, 2020, **35**, 863–872.
25 S. J. Romaniello, G. W. Gordon, D. Wiederin, P. Field and A. D. Anbar, *Goldschmidt 2012*, Montréal, 2012.
26 T. Zimmermann, A. Retzmann, M. Schober, D. Pröfrock, T. Prohaska and J. Irrgeher, *Spectrochim. Acta, Part B*, 2019, **151**, 54–64.
27 A. Retzmann, K. A. Miller, F. A. A. Mohamed and M. E. Wieser, *Anal. Bioanal. Chem.*, 2025, **417**, 835–846.
28 C. Deniel and C. Pin, *Anal. Chim. Acta*, 2001, **426**, 95–103.
29 C.-F. Li, L.-J. Feng, X.-C. Wang, S.-A. Wilde, Z.-Y. Chu and J.-H. Guo, *J. Anal. At. Spectrom.*, 2017, **32**, 1938–1945.
30 J.-M. Zhu, G. Wu, X. Wang, G. Han and L. Zhang, *J. Anal. At. Spectrom.*, 2018, **33**, 809–821.
31 G. Wu, J.-M. Zhu, X. Wang, G. Han, D. Tan and S.-J. Wang, *J. Anal. At. Spectrom.*, 2019, **34**, 1639–1651.
32 E. P. Horwitz, D. R. McAlister, A. H. Bond and R. E. Barrans, *Solvent Extr. Ion Exch.*, 2005, 23.
33 A. Pourmand and N. Dauphas, *Talanta*, 2010, **81**, 741–753.
34 A. Retzmann, D. Walls, K. A. Miller, J. Irrgeher, T. Prohaska and M. E. Wieser, *Anal. Bioanal. Chem.*, 2022, **414**, 675–689.
35 W. A. Brand, T. B. Coplen, J. Vogl, M. Rosner and T. Prohaska, *Pure Appl. Chem.*, 2014, **86**, 425–467.
36 H. Sakamoto, K. Yamamoto, T. Shirasaki and Y. Inoue, *Bunseki Kagaku*, 2006, **55**, 133–139.
37 Hitachi High-Technologies Corporation, Packing material for HITACHI Solid Phase Extraction. NOBIAS CHELATE-PA1 GEL (Instruction Manual), https://hk.techcomp.com.hk/EN//school/weihu/2006.shtml, (accessed April 22, 2025).
38 Y. Sohrin, S. Urushihara, S. Nakatsuka, T. Kono, E. Higo, T. Minami, K. Norisuye and S. Umetani, *Anal. Chem.*, 2008, **80**, 6267–6273.
39 X. Bian, S. C. Yang, R. J. Raad, N. J. Hawco, J. Sakowski, K. F. Huang, K. P. Kong, T. M. Conway and S. G. John, *Anal. Chim. Acta*, 2024, **1312**, 342753.
40 G. Giakisikli, A. A. Quezada, J. Tanaka, A. N. Anthemidis, H. Murakami, N. Teshima and T. Sakai, *Anal. Sci.*, 2015, **31**, 383–389.
41 J. A. Kidder, A. Voinot, K. V. Sullivan, D. Chipley, M. Valentino, D. Layton-Matthews and M. Leybourne, *J. Anal. At. Spectrom.*, 2020, **35**, 776–783.
42 T. G. Enge, M. P. Field, D. F. Jolley, H. Ecroyd, M. H. Kim and A. Dosseto, *J. Anal. At. Spectrom.*, 2016, **31**, 2023–2030.
43 J. Yoshinaga, *Tohoku J. Exp. Med.*, 1996, **178**, 37–47.
44 T. A. Hinners, R. Hughes, P. M. Outridge, W. J. Davis, K. Simon and D. R. Woolard, *J. Anal. At. Spectrom.*, 1998, **13**, 963–970.
45 N. N. Aung, J. Uryu, T. Fau-Yoshinaga and J. Yoshinaga, *Anal. Sci.*, 2004, **20**, 195–198.
46 K. Rodiouchkina, I. Rodushkin, S. Goderis and F. Vanhaecke, *Sci. Total Environ.*, 2022, **808**, 152059.
47 G. Wu, J.-M. Zhu, D. Tan, G. Han, L. Zhang and K. Ren, *Acta Geochim.*, 2017, **36**, 421–425.