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Reliable Determination of Ge in Solid Environmental Samples Using a Chemical Preparation Procedure Developed for Si Isotopes and ICP-MS Analysis

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**Reliable determination of Ge using the silicon isotopes
chemical preparation and ICP-MS analysis for solid
environmental samples.**

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Keywords:	germanium, ICP-MS, reference materials, soils, plants, sample digestion, cation exchange purification

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3 1 Reliable determination of Ge using the silicon isotopes chemical preparation and
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6 2 ICP-MS analysis for solid environmental samples.
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19 Abstract

20 Germanium (Ge) exists at trace levels in the Earth's crust and is a powerful geochemical

21 tracer of the silicon (Si) cycle. This study proposes a simple and reliable method for

22 determining Ge contents in environmental samples using ICP-MS. As Si and Ge have very

23 similar chemical properties, we investigated the applicability of the chemical preparation

24 procedure developed for Si isotopes to the analysis of Ge in environmental samples.

25 Advantages of this procedure are: (1) efficient removal of the matrix and main interferences

26 affecting Ge analyses by ICP-MS; (2) a low limit of detection (6 ng l^{-1}); (3) relative

27 repeatability of approximately 3% obtained on ^{74}Ge ; and (4) robustness and accuracy based

28 on agreement within errors with the published Ge concentrations for rock standards (BHVO-

29 2, AGV-2 and BCR-2). This procedure allows revising the Ge concentrations for 3 soils

30 standards ($1.67 \pm 0.09 \text{ } \mu\text{g g}^{-1}$; $2.41 \pm 0.18 \text{ } \mu\text{g g}^{-1}$; $1.89 \pm 0.10 \text{ } \mu\text{g g}^{-1}$ for GBW 07401, GBW 07404

31 and GBW 07407 respectively) and proposing a value for the ERM-CD281 plant standard

32 ($0.06 \pm 0.01 \text{ } \mu\text{g g}^{-1}$). This method provides a convenient procedure for determining Ge

33 concentrations in environmental samples and opens the possibility of coupling two tracers of

34 the Si biogeochemical cycle with a single analytical procedure.

35

36 Résumé

37 Le germanium (Ge), présent à des teneurs en trace dans la croûte terrestre, est un traceur
38 géochimique performant du cycle du silicium (Si). Cette étude propose une méthode simple,
39 rapide et fiable pour déterminer les concentrations en Ge dans les échantillons
40 environnementaux par ICP-MS. Vu les propriétés géochimiques très similaires entre Ge et Si,
41 nous avons investigué la pertinence de la procédure de mise en solution et de purification
42 développée pour les isotopes du silicium à l'analyse du Ge dans des échantillons
43 environnementaux. Les avantages de cette technique sont : (1) une élimination efficace de la
44 matrice et des interférences principales affectant l'analyse du Ge par ICP-MS ; (2) une limite
45 de détection de 6 ng l^{-1} ; (3) une répétabilité relative de 3% obtenue sur l'isotope ^{74}Ge ; (4) une
46 bonne fiabilité et justesse basées sur la concordance entre les valeurs de Ge publiées pour les
47 standards de roche (BHVO-2, AGV-2 et BCR-2) aux incertitudes près. Cette méthode a
48 permis de réévaluer les concentrations en Ge de 3 standards de sol ($1.67 \pm 0.09 \text{ } \mu\text{g g}^{-1}$;
49 $2.41 \pm 0.18 \text{ } \mu\text{g g}^{-1}$; $1.89 \pm 0.10 \text{ } \mu\text{g g}^{-1}$ pour GBW 07401, GBW 07404 et GBW 07407
50 respectivement) et de proposer une valeur pour le standard de plante ERM-CD281 (0.06 ± 0.01
51 $\mu\text{g g}^{-1}$). Cette méthode présente aussi le grand avantage de coupler deux traceurs du cycle du
52 silicium (à savoir les isotopes stables du silicium et le rapport Ge/Si), en une préparation
53 chimique unique.

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3 54 1. Introduction
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6 55 Germanium (Ge) exists at trace levels in the Earth's crust and is a powerful geochemical
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8 56 tracer of the silicon (Si) cycle. Like Si, Ge is a Group IV element. Both elements have
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10 57 identical outer electronic configurations and similar covalent radii (Ge: 1.22Å and Si 1.17Å;
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12 58 Höll et al., 2007). The geochemistry of Ge is dominated by its propensity to substitute for Si
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14 59 in silicate minerals, and thus closely follows Si through its biogeochemical cycle.
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16 60 Fundamentals of high and low-temperature geochemistry of Ge are reviewed in Rouxel and
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18 61 Luais (2017). To summarize, the Ge/Si ratio has been employed as a tracer of weathering
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20 62 processes (*e.g.*, Kurtz and Derry, 2004; Scribner et al., 2006; Opfergelt et al., 2010; Lugolobi
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22 63 et al., 2010), hydrothermal and geothermal activity (*e.g.*, Mortlock et al., 1993; Evans and
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24 64 Derry, 2002), biological processes (*e.g.*, Ellwood and Maher, 2003; Derry et al., 2005; Sutton
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26 65 et al., 2010), and flow paths (*e.g.*, Kurtz et al., 2011) in modern environments but also in
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28 66 paleo-environmental studies (*e.g.*, Filippelli et al., 2000; Hammond et al., 2004). The use of
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30 67 Ge/Si has recently been extended to the study of the Archean Si cycle (*e.g.*, Hamade et al.,
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32 68 2003; Frei and Polat, 2007; Delvigne et al., 2012; 2016). Another facet of Ge environmental
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34 69 research focuses on the potential economic resource of Ge in soils and plants as the Ge
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36 70 demand for new technologies is exploding while Ge is rare in natural environments
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38 71 (Rosenberg, 2009; Wiche et al., 2017). However, Ge content is often overlooked in the array
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40 72 of analyzed elements. This arises from the analytical difficulties to obtain reliable data
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42 73 because Ge concentrations in environmental samples are generally below the limit of
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44 74 detection of many modern analytical methods. In addition, Ge suffers from various
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46 75 interferences on its isotopes with ICP-MS techniques (mainly $^{56}\text{Fe}^{16}\text{O}$ on ^{72}Ge , $^{57}\text{Fe}^{16}\text{O}$ and
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48 76 $^{56}\text{FeH}^{16}\text{O}$ on ^{73}Ge , and ^{74}Se and $^{58}\text{Ni}^{16}\text{O}$ on ^{74}Ge). Interferences due to iron oxides are
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50 77 particularly problematic because some samples contain a few tenths of a percent of Fe while
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52 78 Ge is present at a $\mu\text{g g}^{-1}$ level. The $^{58}\text{Ni}^{16}\text{O}$ interference is also an issue as it combines the
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3 79 most abundant Ni and O isotopes ($^{58}\text{Ni}=68\%$; $^{16}\text{O}=99\%$). In addition, Ar-based molecular
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5 80 interferences ($^{40}\text{Ar}^{16}\text{O}_2$, $^{36}\text{Ar}^{36}\text{Ar}$ and $^{38}\text{Ar}^{36}\text{Ar}$ on ^{72}Ge , ^{73}Ge and ^{74}Ge , respectively) should
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7 81 also be monitored. Germanium is then often qualified as a “tricky” element to analyze and is
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9
10 82 not routinely determined in environmental samples.

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12 83 The majority of studies published so far on Ge have been carried out using the isotope-
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14 84 dilution hydride-generation ICP-MS technique (ID-HG-ICP-MS) developed by Mortlock and
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16 85 Froelich (1996) (Fillipelli et al., 2000; Kurtz et al., 2002; Evans and Derry, 2002; Derry et al.,
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18 86 2005; Wheat and McManus, 2005; Ellwood et al., 2006; Scribner et al., 2006; Blecker et al.,
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20 87 2007; Makishima and Nakamura, 2009; Lugolobi et al., 2010; Sutton et al., 2010). This is
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22 88 probably the most reliable and precise technique for Ge determination, although it requires a
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24 89 hydride generation system, which is not widespread in laboratories. Alternative techniques
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26 90 are: (1) graphite furnace atomic absorption spectrometry (GF-AAS) (McMahon et al., 2006);
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28 91 (2) ICP-MS analysis with or without high resolution (Hamade et al., 2003 ; Delvigne et al.,
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30 92 2009; Cornelis et al., 2010; Tribouvillard et al., 2011); (3) laser ablation ICP-MS analysis
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32 93 (Hamade et al., 2003; Shen et al., 2011; Belissont et al., 2014; Dong et al., 2015;); and (4) X-
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34 94 ray fluorescence spectrometer analysis (Frei and Polat, 2007). While valid for most geological
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36 95 samples, these techniques are working close to their limits of detection for environmental
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38 96 samples, such as plants that commonly range from 0.07 to 20 ng g⁻¹ (Derry et al., 2005;
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40 97 Blecker et al., 2007; Delvigne et al., 2009; Cornelis et al., 2010; Lugolobi et al., 2010). One
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42 98 option is to preconcentrate samples in order to reach concentrations above the detection
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44 99 limits. This was investigated by Soylak and Yigit (2015), who suggested a separation-
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46 100 preconcentration procedure using a polysulfone membrane filter combined with
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48 101 spectrophotometric measurements. This method has the disadvantage of requiring specific
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50 102 materials. For natural water samples, ID-HG-ICP-MS remains the only reliable technique
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52 103 thanks to its high precision and unequaled low detection limits.
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3 104 The objective of this study is to propose a simple and reliable alternative method determining
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5 105 Ge contents in solid environmental samples, with a notable focus on soils and plants using
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7 106 ICP-MS, a common instrument found in geochemistry laboratories. As silicon isotopes and
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9 107 Ge/Si ratios are complementary tracers of the Si biogeochemical cycle, we investigate the
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11 108 applicability of the chemical preparation procedure developed for silicon isotopes (Georg et
12
13 109 al., 2006) to the analysis of Ge in solid environmental samples.

110 2. Experimental

111 2.1. Material analyzed

112 Reference materials with the recommended values for Ge concentrations are scarce. Three
113 international geological USGS reference materials have been chosen in this study for
114 intercomparison with previous studies: BHVO-2 (basalt), AGV-2 (andesite), and BCR-2
115 (basalt). Despite certified values not being available for these standards, an increasing number
116 of published data provide constraints on Ge concentrations (Table 1). A considerable
117 compilation effort was undertaken by Jochum et al. (2016), which provides reference values
118 (or informative values) determined following ISO guidelines and IAG Certification Protocol
119 using data published between 1995 and 2015. In addition, to better fit the matrix of targeted
120 samples of soils and plants, we selected three soil standards from the Institute of Geophysical
121 and Geochemical Exploration (IGGE, Langfang, China) (GBW 07401, GBW 07404 and
122 GBW 07407, also known as GSS-1, GSS-4 and GSS-7) and a plant standard from European
123 Reference Material (ERM-CD281). Certified Ge concentrations are available for the soils
124 standards, but with low precision (Table 1), while no Ge data is provided for ERM-CD281.
125 Recently, additional data have been made available for GBW 07401-07408 standards (Liu et
126 al., 2014) (Table 1).

	Sample type	Provider	Published value	rsd (2 σ)	n	References
BHVO-2	basalt	USGS	1.62±0.04 $\mu\text{g g}^{-1}$	2%	10	Jochum et al., 2016
			1.53 $\mu\text{g g}^{-1}$	0.2%	n.s.	Escoube et al., 2012
			1.59±0.04 $\mu\text{g g}^{-1}$	3%	3	Scribner et al., 2006
AGV-2	andesite	USGS	1.20±0.08 $\mu\text{g g}^{-1}$	7%	6	Jochum et al., 2016
BCR-2	basalt	USGS	1.46±0.26 $\mu\text{g g}^{-1}$	18%	6	Jochum et al., 2016
GBW 07401	soil	IGGE	1.50±0.04 $\mu\text{g g}^{-1}$	3%	6	Liu et al., 2014
			1.34±0.2 $\mu\text{g g}^{-1}$	15% *	at least 8	Wang et al., 2013
GBW 07404	soil	IGGE	2.10±0.02 $\mu\text{g g}^{-1}$	1%	6	Liu et al., 2014
			1.9±0.3 $\mu\text{g g}^{-1}$	16% *	at least 8	Wang et al., 2013
GBW 07407	soil	IGGE	1.6±0.3 $\mu\text{g g}^{-1}$	19% *	at least 8	Wang et al., 2013
ERM-CD281	plant	ERM	no data	-	-	-

Table 1. Reference materials analyzed in this study with their Ge concentrations and associated uncertainties. Values in bold are certified values while others are informative values. * refers to an uncertainty of 3 σ instead of 2 σ ; n.s.= not specified.

2.2. Sample digestion

Samples were digested following the procedure developed for silicon isotopes using a solid sodium hydroxide (NaOH) flux (Georg et al., 2006). Between 10-20 mg (200 mg up to 600 mg for ERM-CD281, the plant standard) of powdered samples were weighed directly into silver crucibles after drying for at least 24h at 105°C. Prior to the fusion, calcination steps were carried out to ensure the combustion of organic matter into CO₂. Calcinations were performed at 450°C with a 1 h stage at 250°C to ensure slow temperature increase. The 450°C calcination step lasted for at least 1 hour for soils, and 16 h for plants. In the case of plants, the total calcination procedure lasted at least 24 h. Qi et al., (2011) showed that calcination at 600°C does not induce Ge loss. Ashes were mixed with approximately 200 mg of NaOH and placed in a furnace at 720°C for 10 minutes. Fusion cakes were then allowed to dissolve overnight in ultrapure water with a brief ultrasonic bath to favor dissolution. Solutions were then quantitatively transferred into pre-cleaned HDPE bottles and acidified to pH ~2 with HNO₃. Due to the volatile behavior of Ge in the presence of halogens (HCl, HClO₄), only

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3 145 HNO₃ could be used (Luais, 2007; 2012). Acidification to pH~2 was important for Fe-rich
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5 146 samples to ensure a complete dissolution of Fe-oxides as well as ensuring a complete
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7 147 recovery during the following cationic purification (Fitoussi et al., 2009). At this pH, the
8
9 148 dominant Ge species is the Ge(OH)₄⁰ form (Pokrovski and Schott, 1998).

12 149 2.3. Sample purification

15 150 To overcome matrix effects and various interferences, which are complex to correct for,
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17 151 purification of samples appears to be an ideal approach. Perhaps more importantly, the
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19 152 elimination of matrix elements prior to analysis allows a substantial reduction in the dilution
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21 153 factor, which is of great interest for samples with low Ge contents. In addition, performance
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23 154 of ICP-MS can be fully exploited, as the sampling interface and the ion optics are not
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25 155 deteriorated due to salt depositions. A cation-free solution was obtained by passing the
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27 156 solution through a cation exchange column. This allowed for testing of the resin used for
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29 157 germanium isotopes chemical preparation, AG50W-X8 (100-200 mesh in H⁺ form; Bio-Rad)
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31 158 (Luais, 2007, 2012) using the column chemistry routine of silicon isotopes (Georg et al.,
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33 159 2006). Sample solutions were loaded on a Bio-Rad type column filled with 1.8 ml of
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35 160 AG50W-X8 cation-exchange resin, pre-cleaned with several rinsing with HCl, HNO₃ as
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37 161 detailed in the study of Georg et al., (2006) (Table 2). Before loading the sample on the resin,
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39 162 ultrapure water was passed into the resin to remove acids (Georg et al., 2006). The matrix
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41 163 (sodium from fusion and other cations from the sample itself) was retained on the resin, while
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43 164 anionic and neutral species (*e.g.*, Ge(OH)₄⁰ and Si(OH)₄⁰) passed through. To minimize the
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45 165 dilution due to elution, the sample volume was maximized (here ~ 10 ml of fused solution)
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47 166 while the volume of eluent was kept to a minimum of one resin bed volume (~ 2 ml) (Table
48
49 167 2). Since the Si and Ge species do not interact with the resin, the eluent is simply ultrapure
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51 168 water. Ge was collected in a ~ 12 ml cation-free solution. Recovered solutions were weighed
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53 169 to minimize uncertainties inherent to the imprecise volumes recovered. Regarding the
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170 removal of matrix element, Na is potentially the more difficult element to eliminate as it is the
 171 most abundant and resin shows a weak relative selectivity for Na. To warrant a good
 172 purification, resin is largely in excess based on expected resin capacity and fused sample
 173 concentrations. Indeed, a 10 ml fused solution (typically 0.5 meq) saturates the resin
 174 approximately 15% of its exchange capacity. Complete removal of ambient cationic species
 175 and especially problematic cations (*i.e.*, Fe, Ni, Zn) and Na was checked with ICP-MS.

BioRad AG50W-X8, 1.8 ml resin bed		
Separation stage	Solution matrix	Volume (ml)
Pre-cleaning	3N HCl	3 ml
Pre-cleaning	6N HCl	3 ml
Pre-cleaning	7N HNO ₃	3 ml
Pre-cleaning	10N HCl	3 ml
Pre-cleaning	6N HCl	3 ml
Pre-cleaning	3N HCl	3 ml
Rinse	ultrapure water	6 ml
Sample load	Acidified fused sample	10 ml
Elution	ultrapure water	2 ml

177 **Table 2.** Column chemistry routine of the preparation of a solid sample fused with NaOH flux
 178 adapted from Georg et al., 2006.

179 2.4. Sample introduction and mass spectrometry

180 Ge concentrations were measured using an ICP-MS Nexion 300X (Perkin Elmer) using a PFA
 181 nebulizer, a quartz cyclonic spray chamber and a SC-FAST DX-4 automated introduction
 182 system. Operating conditions are detailed in Table 3. A series of five standard solutions with
 183 different concentrations (50, 100, 250, 500, 1000 ng l⁻¹) were used to calibrate Ge
 184 concentrations. These calibration solutions were made from single element Ge standard 1000
 185 mg l⁻¹ solution (Chem Lab, Plasma HIQU, 2-5% HNO₃). To correct for instrumental drift,
 186 rhodium (Chem Lab, Plasma HIQU, 2-5% HNO₃) was introduced to sample solutions through
 187 a cross flow line injection resulting in a Rh concentration of 1.58 µg l⁻¹ in the analyzed
 188 solution. Ge isotopes 72, 73 and 74 were analyzed and provided consistent values, proving the

189 robustness of the method. However, Ge contents were determined using the ^{74}Ge isotope, the
 190 most abundant isotopes (36.28%), given higher sensitivity and lower detection limits
 191 compared to other isotopes. In the sequence, 400 ng l⁻¹ Ge standard solutions were measured
 192 after every 15 samples to check for instrumental drift and evaluate reproducibility.

Plasma power	1600 W
Torch	Quartz glass torch
Plasma Ar gas flow rate	15 l min ⁻¹
Auxiliary Ar gas flow rate	1.2 l min ⁻¹
Nebuliser Ar gas flow rate	0.95 - 1.05 l min ⁻¹ (optimized to minimize $^{140}\text{Ce}^{16}\text{O}^+ / ^{140}\text{Ce}^+ < 0.025$ and $^{70}\text{Ce}^{++} / ^{140}\text{Ce}^+ < 0.03$)
Nebuliser	PFA 0.4 ml min ⁻¹
Spray chamber	cyclonic (quartz)
Sample uptake rate	0.337 ml min ⁻¹
Interfaces cones	Nickel
Resolution	700
Typical ^{74}Ge sensitivity	~ 12000 cps μg^{-1} l
Typical ^{103}Rh sensitivity	~ 680000 cps μg^{-1} l

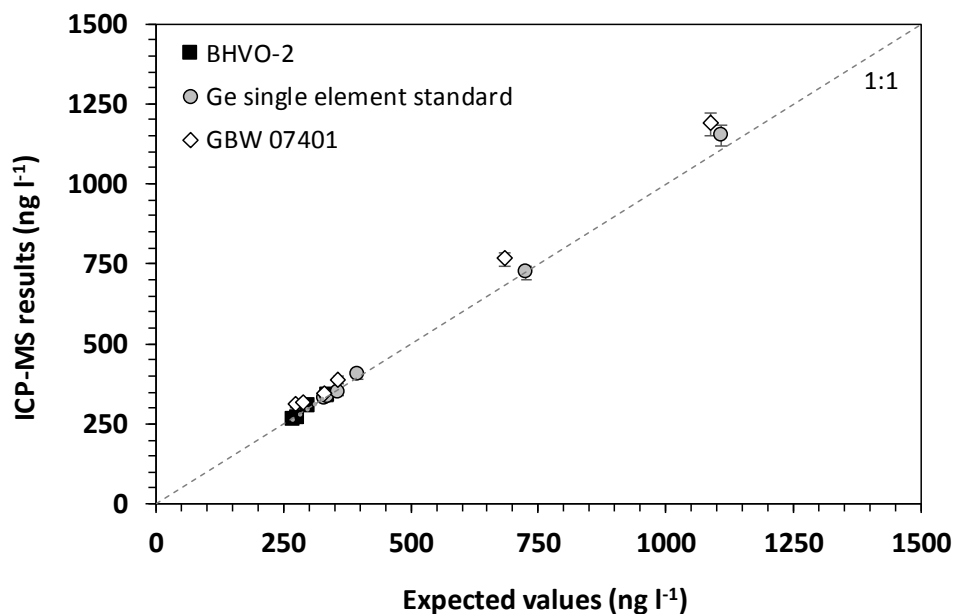
194 **Table 3.** Instrumental operating conditions for ICP-MS Nexion 300X

195 3. Results and discussion

196 3.1. Assessment of Ge recovery yields during chemical procedure

197 As the dominant Ge species after fusion is the $\text{Ge}(\text{OH})_4^0$, no affinity for cation exchange resin
 198 is expected and thus Ge should be quantitatively recovered through the chromatographic
 199 procedure. A complete Ge recovery (102±2%; n=6) during sample purification through
 200 cationic resin was obtained with single element Ge standard solution at different Ge
 201 concentrations (330 to 1100 ng l⁻¹; Fig. 1). To take into account matrix effects, recovery
 202 yields for BHVO-2 and GBW 07401 were determined by Ge standard addition to the fused
 203 solution before purification (Ge addition from 10 ng l⁻¹ to 100 ng l⁻¹; Fig. 1). The recovery
 204 yields for BHVO-2 (99±2%; n=4) indicated a complete recovery for Ge. In the case of GBW
 205 07401 (Ge addition from 10 ng l⁻¹ to 1000 ng l⁻¹; Fig. 1), recoveries of approximately 118±5%
 206 (n=6) were found when compared to the certified value (Wang et al., 2013). Considering the

207 Ge concentrations of Liu et al., (2014), who suggested that the Ge concentration of this
208 standard should be revised, our recovery yield was $109 \pm 2\%$ (Fig. 1). As the procedural blanks
209 displayed very low levels of Ge ($3 \pm 2 \text{ ng l}^{-1}$; $n=11$) and the given large error range associated
210 with the certified value of this standard (Table 1), we assume our recovery for this standard to
211 be complete. A better agreement would require refining the reference value for the GBW
212 07401 standard (see section 3.2). Based on single element Ge standard solution and BHVO-2,
213 we assume that Ge recovery is complete during cationic purification. The standard addition of
214 BHVO-2 and GBW 07401 show that Si and other neutral, as well as anionic species do not
215 create any matrix effect.



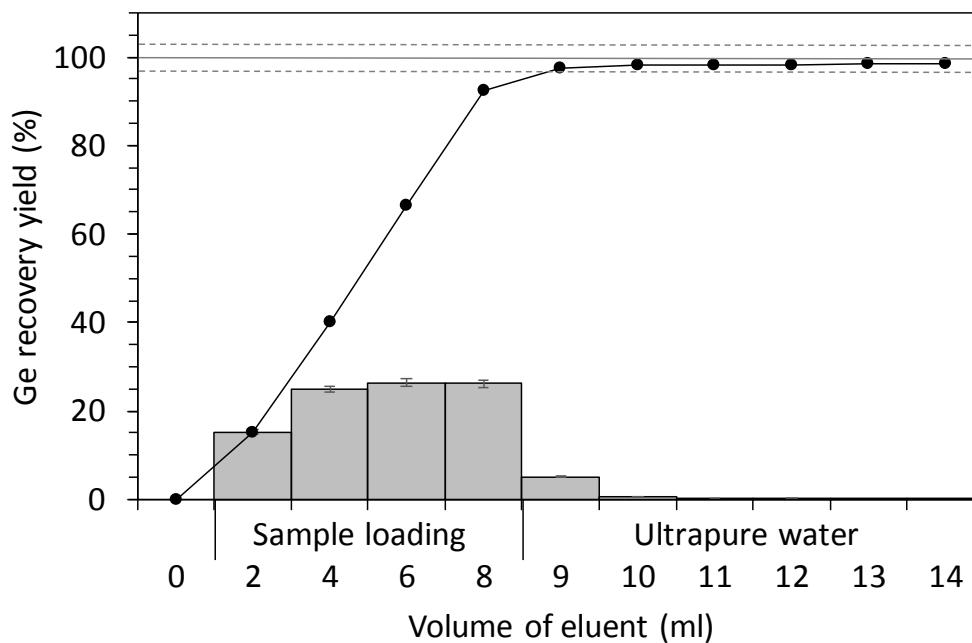
216

217 **Fig. 1** Comparison of the Ge concentrations obtained by ICP-MS after cationic purification
218 and expected values for single element Ge standard solution at various Ge concentrations
219 (gray circles) and reference materials (BHVO-2, black squares; GBW 07401, open diamonds)
220 with Ge standard addition (Ge addition from 10 ng l^{-1} to 1000 ng l^{-1}). The dashed gray line
221 represents a recovery yield of 100%. Expected values for reference materials are calculated

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222 considering Ge data from the literature (Escoube et al., 2012; Scribner et al., 2006 and Liu et
223 al., 2014, see section 3.2). Error bars represent the analytical repeatability (3%).

224 The separation efficiency is demonstrated by the elution curves of two samples (a single
225 element Ge standard solution and a fused BHVO-2) that were loaded onto the pre-cleaned
226 cation exchange resins (Fig. 2). Ge is not retained by the resin and migrates straight through
227 the column and nearly 90% of the loaded Ge is already recovered while the sample load is
228 still infiltrating the resin bed. The last 10% is recovered with 2 ml of ultrapure water (Fig. 2).

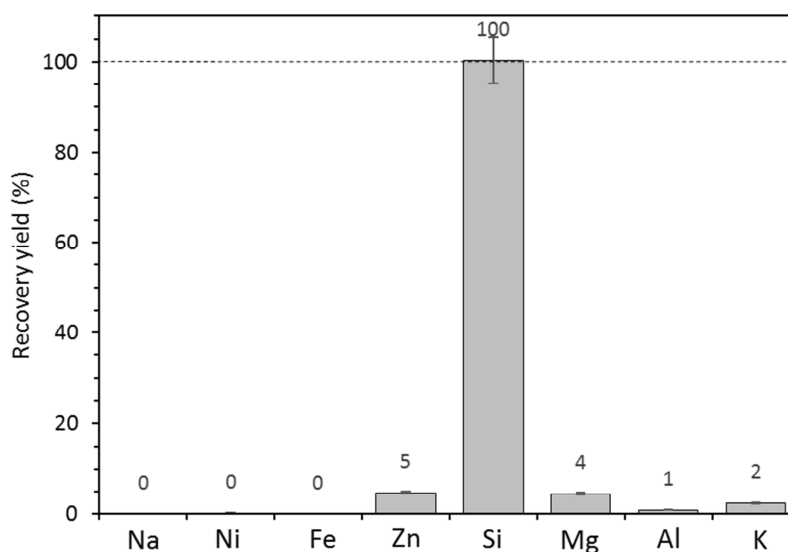


229
230 **Fig. 2** Elution of germanium during chemical purification of BHVO-2 on AG50W-X8 resin.

231 The black circles corresponds to the cumulated Ge recovered whereas grey bars represent Ge
232 recovered in each volume loaded. Error bars represent the analytical repeatability.

233 Furthermore, ICP-MS screening of the purified solution confirms the absence of major cations
234 and interfering cations after purification (Fig. 3). As demonstrated for Si by Georg et al.,
235 (2006), this shows a complete separation of Ge from the ambient cation matrix. Matrix effects
236 and interferences are then negligible and should not be corrected for, minimizing the errors in
237 Ge contents. In addition, Ar-based molecular interferences are not detectable in the blanks.

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239

240 **Fig. 3.** Recovery yields of the main matrix elements and interfering elements of NaOH fused
241 BHVO-2 after purification with AG50W-X8 resin.

242 Besides overcoming matrix effects and interferences, cationic purification has the advantage
243 to minimize the dilution for analysis, as samples are salt-free. Indeed, the above described
244 sample purification resulted in a dilution of the sample by a factor of 1.2. This is far less than
245 the dilution necessary to reduce total dissolved salt to the maximum of 0.1% accepted for
246 ICP-MS analysis (a dilution by a factor 2 being the minimum). However, some samples with
247 low Ge content might still be close to the detection limit. To overcome this issue, a
248 preconcentration step is helpful. A preconcentration step through low temperature evaporation
249 was feasible, as solutions were free of major elements, limiting the risk of precipitation. For
250 samples that might be close to detection limits, typically plants, an evaporation step at 60°C
251 on a hotplate was performed to increase Ge concentrations. In this study, a maximal
252 preconcentration factor of 2 was achieved without any modification of Ge recoveries. Indeed,
253 aliquots of purified solutions of geostandards BHVO-2, AGV-2 and BCR-2, with or without
254 evaporation, displayed similar Ge contents (Fig. 4).

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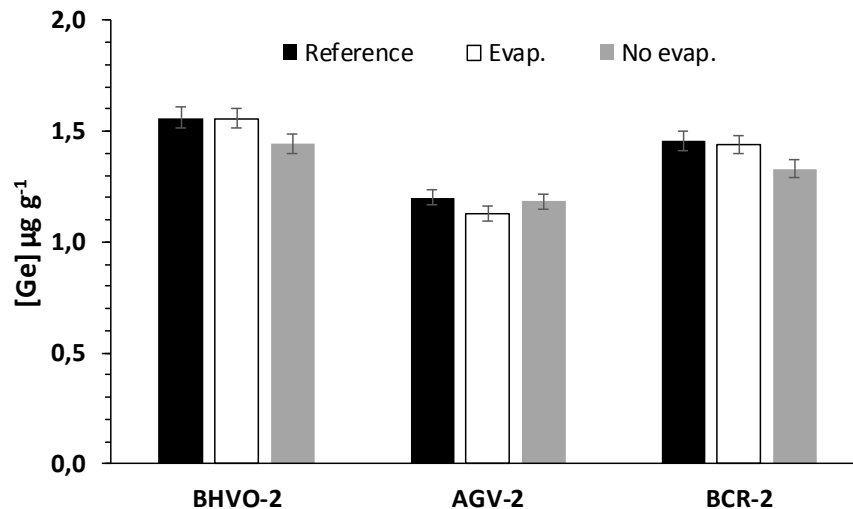


Fig. 4 Ge contents in reference materials (black; Escoube et al., 2012; Scribner et al., 2006; Jochum et al., 2016) compared to ICP-MS Ge contents obtained using our preparation protocol, with (white) or without a final evaporation step (gray). Error bars on our results represent an uncertainty of 3%, the ICP-MS analytical repeatability.

3.2. Detection limits, repeatability and accuracy

The contribution of Ge from the whole procedural chemistry blank was measured on 11 procedural blanks and has been found to be $3 \pm 2 \text{ ng l}^{-1}$ and indistinguishable from the instrumental blank. According to the IUPAC definition (IUPAC, 1997), method detection limits were calculated as the mean concentration of 11 procedural blanks plus three standard deviations of these 11 procedural blanks (Table 4). The lowest detection limit was obtained for ^{74}Ge (6 ng l^{-1}), the most abundant Ge isotope. For comparison, the detection limit for ^{72}Ge is 5 times higher, approximately 30 ng l^{-1} most likely due to the ArO_2 interference.

Considering that 20 mg of powdered sample was dissolved in 100 ml, this corresponds to a detection limit of approximately 0.03 µg g^{-1} in the solid sample (Table 4). For the plant standard (200-600 mg dissolved in 100 ml), the detection limit is approximately 0.001 µg g^{-1} in the solid sample. Additionally, the linearity limit was demonstrated over the entire

272 calibration range. The linearity limit was above 1000 ng l⁻¹, the highest standard in the
273 calibration curve, as the coefficient correlation of the calibration curve is above 0.995.

Method	Dissolution	Preliminary steps	DL in solution	DL in solid samples	Reproducibility	Difference with previously published values	Samples	References
ID-HG-ICP-MS	acid	ID	0.5 ng l ⁻¹ ^a	-	<3%	n.s.	natural waters	Evans and Derry, 2002
HR-ICP-MS	fusion	-	10 ng l ⁻¹	n.s.	4%	n.s.	plants and soils	Delvigne et al., 2009
ICP-MS	fusion	-	2 ng l ⁻¹	0.05 µg g ⁻¹	15%	n.s.	plants and soils	Cornelis et al., 2010
LA-ICP-MS	-	-	-	< 1 µg g ⁻¹	8% ^b	n.s.	rocks	Belissont et al., 2011; Shen et al., 2011
X-ray fluorescence	-	-	-	1.5 µg g ⁻¹ ^c	1%	15%	rocks	Frei and Polat, 2007
Spectrophotometry	acid	Polysulfone membrane filter	2 ng l ⁻¹	n.s.	5%	n.s.	waters and soils	Soylak and Yigit, 2015
ICP-MS	fusion	Cationic purification	6 ng l ⁻¹	0.03 µg g ⁻¹	3%	6%	plants, soils, rocks	This study

^a blank level

^b valid for Ge/Si ratio as detailed in Shen et al., 2011

^c minimum Ge concentration analyzed (no limit of detection provided)

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275 **Table 4.** Comparison of metrological characteristics of different techniques used for Ge
276 determination. n.s. = not specified. DL = detection limit.

277 The relative repeatability of ICP-MS analysis based on a Ge single element standard solution
278 (400 ng l⁻¹) and analyzed six times on a single day is 3% (n=6, confidence level 95%).

279 Similarly, four aliquots of one fused solution (BHVO-2) passed through four different
280 columns and analyzed twice on the same day gives a relative repeatability of 2%.

281 Reference materials of different composition (BHVO-2; AGV-2; BCR-2; GBW 07401; GBW
282 07404; GBW 07407) were analyzed to evaluate the accuracy of results (Supplementary Table

283 1). However, the absence of properly certified Ge values complicated the exercise. As shown
284 in Fig. 5, our BHVO-2 data agree within 10% with the published value from the compilation

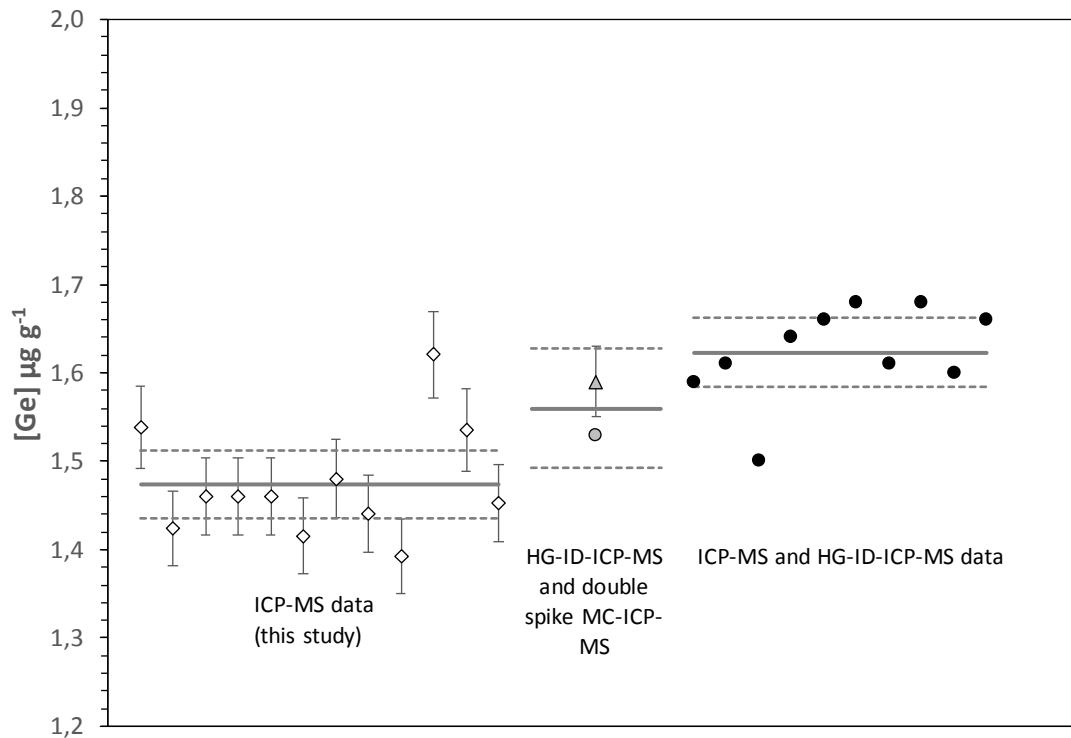
285 of Jochum et al. (2016) (Table 5). However, a careful sorting of compiled data reveals that
286 most of the dissolution protocols are not adapted to Ge, except for that of Scribner et al.

287 (2006). Indeed, all but one of the studies employed acid attacks using HCl, HClO₄ or HF (at
288 temperature above 60°C) or a combination of these, which induce loss of Ge (Luais et al.,

289 2012). Tests performed by Luais (2012) demonstrated that Ge loss is at 85% when HClO₄ is
290 employed in the acid dissolution mixture. In addition, it is unclear if ICP-MS analysis were

291 corrected for spectroscopic interferences and selected Ge isotopes were not specified. Thus,

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3 292 Ge might be underestimated due to potential Ge volatilization during dissolution, while
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5 293 uncorrected interferences would overestimate Ge content. In the literature, Ge contents
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7 294 estimated using specific techniques devoted to Ge analysis (ID-HG-ICP-MS or double-spike
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9 295 MC-ICP-MS) appear to be systematically lower than Ge contents estimated with ICP-MS
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11 296 techniques. In the case of BHVO-2, ID-HG-ICP-MS and double spike MC-ICP-MS
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13 297 techniques provided a compiled value of $1.56 \pm 0.07 \mu\text{g g}^{-1}$ (Table 5; Scribner et al., 2006;
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15 298 Escoube et al., 2012), while ICP-MS techniques (acid attacks and interferences corrections
16
17 299 not specified) averaged approximately $1.62 \pm 0.04 \mu\text{g g}^{-1}$ (Table 5; Jochum et al., 2016).
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19 300 Similarly, BHVO-1 data show a comparable shift between the two techniques ($1.46 \pm 0.12 \mu\text{g}$
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21 301 g^{-1} , $n=2$ for ID-HG-ICP-MS and double spike MC-ICP-MS; $1.64 \pm 0.06 \mu\text{g g}^{-1}$, $n=3$ for ICP-
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23 302 MS; Jochum et al., 2016). An intermediate Ge content ($1.58 \mu\text{g g}^{-1}$) is obtained by Luais
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25 303 (2012) using dedicated acid attack removing 80% of matrix analyzed by ICP-MS suggesting
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27 304 that discrepancy between techniques is likely induced by matrix and interferences. Despite
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29 305 being more limited in number, data acquired using isotope dilution techniques are the most
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31 306 robust (Escoube et al., 2012; Scribner et al., 2006). Considering the compiled values from
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33 307 these two studies, our BHVO-2 results agree within 6% (Fig. 5, Table 5).
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309 **Fig. 5** Ge content in BHVO-2 from our study (open diamonds), high quality data (gray
 310 symbols) from Escoube et al. (2012) (gray circle; double spike MC-ICP-MS), and Scribner et
 311 al. 2006 (gray triangle; ID-HG-ICP-MS), compiled data from Jochum et al. 2016 (filled
 312 circles; ICP-MS and one ID-HG-ICP-MS from Scribner et al., 2006). Bold and dashed lines
 313 represent the mean and uncertainties (95% confidence level) of each subgroup, respectively.
 314 Errors bars represent the analytical precision when provided (*i.e.*, the 3% repeatability in this
 315 study).

316 Regarding the other rock standards (AGV-2 and BCR-2), there is a better agreement between
 317 our data and the compiled data from Jochum et al., (2016) (Table 5). Considering these three
 318 rock standards, our data agree within ~5% with published values.

319 Regarding soil standards (GBW 07401, 07404, 07407), our results are systematically 20 to
 320 30% higher than certified values provided in Wang et al. (2013). However, a better agreement
 321 is noted when compared to data from Liu et al. (2014), suggesting that certified values should

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322 be revised. The use of HClO_4 in the sample decomposition procedure calls into question the
 323 accuracy of these data and may explain our systematically higher Ge contents.

Sample type	Ge value (this study)	n	Difference with published values	Published values	n	Technique	References	
BHVO-2	basalt	1.47±0.04 $\mu\text{g g}^{-1}$	11	9%	1.62±0.04 $\mu\text{g g}^{-1}$	10	ICP-MS but one	Jochum et al., 2016
				8%	1.56±0.04 $\mu\text{g g}^{-1}$ ^a	3	ID-HG-ICP-MS and double spike MC-ICP-MS	Scribner et al., 2006 and Escoube et al., 2012
AGV-2	andesite	1.14±0.08 $\mu\text{g g}^{-1}$	6	5%	1.20±0.08 $\mu\text{g g}^{-1}$	6	ICP-MS	Jochum et al., 2016
BCR-2	basalt	1.43±0.14 $\mu\text{g g}^{-1}$	5	2%	1.46±0.26 $\mu\text{g g}^{-1}$	6	ICP-MS but one	Jochum et al., 2016
GBW 07401	soil	1.67±0.09 $\mu\text{g g}^{-1}$	11	11%	1.50±0.04 $\mu\text{g g}^{-1}$	6	ICP-MS	Liu et al., 2014
				25%	1.34±0.2 $\mu\text{g g}^{-1}$	at least 8	n.s.	Wang et al., 2013
GBW 07404	soil	2.41±0.18 $\mu\text{g g}^{-1}$	4	15%	2.10±0.02 $\mu\text{g g}^{-1}$	6	ICP-MS	Liu et al., 2014
				27%	1.9±0.3 $\mu\text{g g}^{-1}$	at least 8	n.s.	Wang et al., 2013
GBW 07407	soil	1.89±0.10 $\mu\text{g g}^{-1}$	3	18%	1.6±0.3 $\mu\text{g g}^{-1}$	at least 8	n.s.	Wang et al., 2013
ERM-CD281	plant	70±3 ng g^{-1}	9				ICP-MS	This study

324 ^a Compiled value of average values of each study and uncertainty values (95% confidence limit)

325 **Table 5.** Comparison of Ge contents in different reference materials between this study and
 326 data from the literature. n.s. = not specified. Uncertainties are provided with 95% confidence
 327 level.

328 To provide the first Ge data on a plant standard, the standard ERM-CD281 was analyzed. Its
 329 Ge content is estimated to be approximately 70±3 ng g^{-1} (n=9; Supplementary Table 1).

330 3.3. Perspectives

331 This method provides a convenient procedure for determining accurate and precise Ge
 332 concentrations in rocks, soils and plants. Additionally, the combination of Ge concentrations
 333 with $\delta^{30}\text{Si}$ analyses is the great advantage of this method, as both Si cycle tracers can be
 334 analyzed from a single procedure allowing a better understanding of the continental Si cycle.
 335 As emphasized in Cornelis et al. (2011), the combination of Ge/Si ratios and silicon isotopes
 336 turned out to be a great asset for tracing the sources and fate of Si in the critical zone, where
 337 numerous co-occurring processes are difficult to decipher.

338 The method can likely be expanded to water samples under the condition of respecting the
 339 detection limits. The purification step of this procedure would then be suitable for
 340 hydrothermal fluids (12±13 $\mu\text{g l}^{-1}$ up to 50 $\mu\text{g l}^{-1}$; Evans and Derry, 2002) and soil solutions

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3 341 (7.1±1.4 µg l⁻¹; Cornelis et al., 2010). However, the analysis of silicon isotopes on the same
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5 342 chemical preparation may not be straightforward because of DOC and anions responsible for
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7 343 isotopic bias (Hughes et al., 2011). Water samples with lower Ge contents, such as freshwater
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9 344 and seawater, might be pre-concentrated using Mg-coprecipitation (Escoube, 2008). As many
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11 345 other elements are scavenged by this method, the Mg-coprecipitation should be followed by
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13 346 the cationic purification step. As both Ge and Si recoveries are complete during Mg-
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15 347 coprecipitation (Escoube, 2008; Cardinal et al., 2005), the analysis of silicon isotopes and Ge
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17 348 concentrations could again be performed on the same preparation. However, as anionic
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19 349 species will not be removed completely, care should be taken to control the bias induced by
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21 350 anionic species on δ³⁰Si analysis (Hughes et al., 2011).
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26 351 In addition to silicon isotopes analysis, this method paves the way towards a new approach to
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28 352 perform Ge isotopes in soils and plants, which has never been done before. Combining silicon
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30 353 isotopes, germanium isotopes and Ge/Si ratios would be a powerful multi-proxy approach to
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32 354 tackle continental Si biogeochemical cycle.
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35 355 4. Conclusions

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38 356 The fusion and purification technique based on the Si isotopes preparation protocol (Georg et
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40 357 al., 2006) allows precise determination of Ge concentrations in environmental samples down
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42 358 to a detection limit of approximately 6 ng l⁻¹. Analyses performed on ⁷⁴Ge, the most abundant
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44 359 isotope, show the best precision of approximately 3%. Accuracy, difficult to assess given the
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46 360 scarcity of reliable data available for comparison, was assessed with an error of approximately
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48 361 5%. This method provides data with equivalent or better metrological characteristics than
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50 362 other published procedures and analytical techniques except for ID-HG-ICP-MS, which
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52 363 shows the best precision and lowest detection limit (Table 4) but is much more time
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54 364 consuming. In addition to the reliability of generated data, this technique has two major
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3 365 advantages: (1) it does not require peculiar instruments such a hydride generation system, not
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5 366 found in most laboratories unless specific needs, and (2) Ge concentrations and Si isotopic
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7 367 analysis can be performed on the same solution. This last point represents a precious gain of
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10 368 time in terms of sample preparation as one procedure serves to perform both analyses. A
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12 369 systematic coupling of Ge/Si ratios and $\delta^{30}\text{Si}$ compositions is a great asset in the interpretation
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14 370 of the Si cycle, as both tracers are very complementary.

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