IUPAC Technical Report

Tyler B. Coplen* and Yesha Shrestha

Isotope-abundance variations and atomic weights of selected elements: 2016 (IUPAC Technical Report)

DOI 10.1515/pac-2016-0302

Received March 25, 2016; accepted September 26, 2016

Abstract: There are 63 chemical elements that have two or more isotopes that are used to determine their standard atomic weights. The isotopic abundances and atomic weights of these elements can vary in normal materials due to physical and chemical fractionation processes (not due to radioactive decay). These variations are well known for 12 elements (hydrogen, lithium, boron, carbon, nitrogen, oxygen, magnesium, silicon, sulfur, chlorine, bromine, and thallium), and the standard atomic weight of each of these elements is given by IUPAC as an interval with lower and upper bounds. Graphical plots of selected materials and compounds of each of these elements have been published previously. Herein and at the URL <http://dx.doi.org/10.5066/F7GF0RN2>, we provide isotopic abundances, isotope-delta values, and atomic weights for each of the upper and lower bounds of these materials and compounds.

Keywords: atomic weights; boron, bromine; carbon; chlorine; hydrogen; isotopic abundances; lithium; magnesium; nitrogen; oxygen; silicon; sulfur; thallium.

CONTENTS

1. INTRODUCTION	1204
2. HYDROGEN	1212
3. LITHIUM.....	1213
4. BORON	1214
5. CARBON	1214
6. NITROGEN.....	1215
7. OXYGEN	1215
8. MAGNESIUM	1217
9. SILICON.....	1218
10. SULFUR	1218
11. CHLORINE.....	1219
12. BROMINE	1219
13. THALLIUM.....	1219
MEMBERSHIP OF THE SPONSORING BODY.....	1219
REFERENCES	1219

Article note: Sponsoring body: IUPAC Inorganic Chemistry Division Committee: see more details on page 1219. This article is a U.S. Government work and is in the public domain in the USA.

***Corresponding author:** Tyler B. Coplen, U.S. Geological Survey, Reston, Virginia, USA, e-mail: tbcoplen@usgs.gov.
<http://orcid.org/0000-0003-4884-6008>

Yesha Shrestha: U.S. Geological Survey, Reston, Virginia, USA. <http://orcid.org/0000-0002-9714-8516>

1 Introduction

Once in a while, a really big discovery is made in science, a discovery that affects all mankind. Such was the discovery of radioactivity by Becquerel [1] in 1896, which effected a paradigm shift in our view of matter. An outcome of this finding was that the spontaneous decay of atoms from one chemical element to another gives rise to the possibility that atoms of the same chemical element might have different atomic weights (also called relative atomic masses). In 1911, Soddy demonstrated that mesothorium 1 (^{228}Ra) was chemically identical to radium [2], and he concluded that there were chemical elements having different atomic weights. Soddy coined the name “isotope” for these atoms of a chemical element having different atomic weights. Three years later, J. J. Thomson discovered that neon had isotopes with mass numbers 20 and 22 [3]. This discovery ushered in a new field in spectroscopy – the “spectroscopy of mass.”

The atomic weight of element E, $A_r(E)$, in a material P is determined from the relation

$$A_r(E)_P = \sum [x(^iE)_P \times A_r(^iE)] \quad (1)$$

where $x(^iE)_P$ is the amount fraction of isotope iE in material P (also called the isotopic abundance or the mole fraction) and $A_r(^iE)$ is the relative atomic mass of isotope iE , where i is the mass number. The summation is over all stable isotopes of the element plus selected radioactive isotopes (having sufficiently long half-lives that characteristic terrestrial isotopic compositions can be determined, which enables a standard atomic weight to be determined) of the element. The atomic-mass values used to calculate the atomic-weight values given here derive from the 2012 Atomic Mass Evaluation [4].

In contrast to the atomic weight of an element in any given material, the standard atomic weight is a quantity that represents the atomic weight of an element in any normal material. By a normal material, the Commission on Isotopic Abundances and Atomic Weights means a material from a terrestrial source that satisfies the following criteria [5]:

“The material is a reasonably possible source for this element or its compounds in commerce, for industry or science; the material is not itself studied for some extraordinary anomaly and its isotopic composition has not been modified significantly in a geologically brief period.”

Because of variations in isotopic abundances in various sources of some chemical elements, the standard atomic weight must be given with larger uncertainty for these elements than the measured atomic weight in any given sample of that element.

The identification of variations in abundances of stable isotopes and their effect on atomic weights was recognized at the September 1951 meeting of the Commission on Atomic Weights of the International Union of Pure and Applied Chemistry (IUPAC) and an atomic-weight “range” was assigned to an element – 32.066 ± 0.003 to sulfur [6]. By 1967, recognized variations in isotopic abundances caused the Commission to assign atomic-weight uncertainties to six elements (hydrogen, boron, carbon, oxygen, silicon, and sulfur) [7].

During the meeting of the Commission on Atomic Weights and Isotopic Abundances at the General Assembly of IUPAC in 1985 in Lyon, France, the Working Party on Natural Isotopic Fractionation (subsequently named the Subcommittee on Natural Isotopic Fractionation) was formed to investigate the effects of isotope-abundance variations of elements upon their standard atomic weights and atomic-weight uncertainties [8, 9]. The aims of the Subcommittee were to (1) identify elements for which the uncertainties of the standard atomic weights are larger than measurement uncertainties in materials of natural terrestrial origin because of isotope-abundance variations caused by physical and chemical fractionation processes (excluding variations caused by radioactivity), and (2) provide information about the range of atomic-weight variations in specific substances and chemical compounds of each of these elements. The Subcommittee’s reports [8, 9] compiled ranges of isotope-abundance variations and corresponding atomic weights in selected materials from peer-reviewed publications for twenty chemical elements (hydrogen, lithium, boron, carbon, nitrogen, oxygen, magnesium, silicon, sulfur, chlorine, calcium, chromium, iron, copper, zinc, molybdenum, palladium, tellurium, and thallium). Graphical plots were presented for 15 elements

[8, 9]. Atomic weights calculated from published variations in isotopic abundances for some elements can span relatively large intervals. For example, the atomic weight of hydrogen in normal materials (its standard atomic weight) spans the interval from 1.007 84 to 1.008 11 [8–10], whereas the uncertainty of the atomic weight calculated from the best measurement of the isotopic abundance of hydrogen is $\pm 0.000\,000\,05$ [11, 12], which is approximately 5000 times smaller than the difference between the lower and higher bounds. The Subcommittee's reports formed the basis of the Commission's decision in 2009 to express the standard atomic weight of ten elements (hydrogen, lithium, boron, carbon, nitrogen, oxygen, silicon, sulfur, chlorine, and thallium) as intervals to indicate that standard atomic weights are not always constants of nature [13, 14]. In 2011, the Commission decided to express the standard atomic weights of two more elements (magnesium and bromine) as intervals [15].

The span of atomic-weight values in normal terrestrial materials is termed the interval. The interval $[a, b]$ is the set of values x for which $a \leq x \leq b$, where $b > a$ and where a and b are the lower and upper bounds, respectively [16]. Neither the lower nor upper bounds have any uncertainty associated with them; each is a considered decision by the Commission based on professional evaluation and judgment. Writing the standard atomic weight of hydrogen as “[1.007 84, 1.008 11]” indicates that its atomic weight in any normal material will be greater than or equal to 1.007 84 and will be less than or equal to 1.008 11. Thus, the atomic-weight interval is said to encompass atomic-weight values of all normal materials. The range of an interval is the difference between b and a , that is $b - a$ [16]; thus, the range of the atomic-weight interval of hydrogen is calculated as $1.008\,11 - 1.007\,84 = 0.000\,27$. The interval designation does not imply any statistical distribution of atomic-weight values between the lower and upper bounds (e.g. the mean of a and b is not necessarily the most likely value) [13]). Similarly, the interval does not convey a simple statistical representation of uncertainty.

The lower bound of an atomic-weight interval is determined from the lowest atomic weight determined by the Commission's review and evaluation of peer-reviewed literature, and this evaluation takes into account the uncertainty of the measurement result as well as the variation in isotopic abundance of natural materials. Commonly, isotope-delta measurements [17–20] are the basis for the determination of the lower and upper atomic-weight bounds [8, 9]. The isotope delta is obtained from isotope-number ratio $R(^i\text{E}, ^j\text{E})_{\text{p}}$

$$R(^i\text{E}, ^j\text{E})_{\text{p}} = \frac{N(^i\text{E})_{\text{p}}}{N(^j\text{E})_{\text{p}}} \quad (2)$$

where $N(^i\text{E})_{\text{p}}$ and $N(^j\text{E})_{\text{p}}$ are the numbers of each isotope, and ^iE denotes the higher (superscript i) and ^jE the lower (superscript j) atomic mass number of chemical element E in substance P. The isotope-delta value (symbol δ), also called the relative isotope-ratio difference, is a differential measurement obtained from isotope-number ratios of substance P and a reference material, Ref.

$$\delta(^i\text{E}, ^j\text{E})_{\text{p,Ref}} = \frac{R(^i\text{E}, ^j\text{E})_{\text{p}} - R(^i\text{E}, ^j\text{E})_{\text{Ref}}}{R(^i\text{E}, ^j\text{E})_{\text{Ref}}} \quad (3)$$

A more convenient short-hand notation for the isotope-delta value is typically found in scientific publications; $\delta(^i\text{E}, ^j\text{E})_{\text{p,Ref}}$ is shortened to $\delta^i\text{E}_{\text{Ref}}$ or to $\delta^i\text{E}$. For example, $\delta(^{13}\text{C}, ^{12}\text{C})_{\text{p,VPDB}}$ is shortened to either $\delta^{13}\text{C}_{\text{VPDB}}$ or $\delta^{13}\text{C}$ [17, 20], where VPDB is the Vienna Pee Dee belemnite–LSVEC scale for carbon isotope-delta measurements [21]. Isotope-delta values are small numbers and therefore frequently presented in multiples of 10^{-3} or per mil (symbol ‰).

To match an isotope-delta scale of an element to an isotope-amount scale (both shown in Figs. 1–12), a substance is needed whose isotopic abundance is well known and whose isotope-delta value is also well known relative to the isotope-delta scale. Commonly this substance is an isotopic reference material that has served as the “best measurement” for determination of isotopic abundance [10]. For example, consider hydrogen, shown in Fig. 1. The $x(^2\text{H})$ scale is matched to the $\delta^2\text{H}_{\text{VSMOW}}$ scale through measurement of the isotopic reference material VSMOW (Vienna Standard Mean Ocean Water) (Fig. 1), which has been assigned the

Fig. 1: Variation in isotopic composition and atomic weight of selected hydrogen-bearing materials (modified from [9, 13]). VSMOW is the Vienna Standard Mean Ocean Water–Standard Light Antarctic Precipitation scale [22]. Isotopic reference materials are designated by solid black circles. The $\delta^2\text{H}$ scale and the ^2H amount-fraction scale were matched using the data of Hagemann et al. [12]. The expanded uncertainty in matching the atomic-weight and ^2H amount-fraction scales with the $\delta^2\text{H}$ scale is equivalent to 0.3 ‰.

Fig. 2: Variation in isotopic composition and atomic weight of selected lithium-bearing materials (modified from [9, 13]). LIVEC is a lithium carbonate isotopic reference material [8]. Isotopic reference materials are designated by solid black circles. The $\delta^7\text{Li}$ scale and the ^7Li amount-fraction scale were matched using the data of Qi et al. [23]. The expanded uncertainty in matching the atomic-weight and ^7Li amount-fraction scales with the $\delta^7\text{Li}$ scale is equivalent to 3 ‰.

Fig. 3: Variation in isotopic composition and atomic weight of selected boron-bearing materials (modified from [9, 13]). SRM 951 is a boric acid isotopic reference material [8]. Isotopic reference materials are designated by solid black circles. The $\delta^{11}\text{B}$ scale and ^{11}B amount-fraction scale were matched using the data of Catanzaro et al. [24]. The expanded uncertainty in matching the atomic-weight and ^{11}B amount-fraction scales with the $\delta^{11}\text{B}$ scale is equivalent to 0.8 ‰.

Fig. 4: Variation in isotopic composition and atomic weight of selected carbon-bearing materials (modified from [9, 13]). VPDB is the Vienna Pee Dee belemnite–LSVEC isotope scale [19]. Isotopic reference materials are designated by solid black circles. The $\delta^{13}\text{C}$ scale and ^{13}C amount-fraction scale were matched using the data of Chang and Li [25]. The expanded uncertainty in matching the atomic-weight and ^{13}C amount-fraction scales with the $\delta^{13}\text{C}$ scale is equivalent to 2.5 ‰.

Fig. 5: Variation in isotopic composition and atomic weight of selected nitrogen-bearing materials (modified from [9, 13]). Isotopic reference materials are designated by solid black circles. The $\delta^{15}\text{N}_{\text{Air-N}_2}$ scale and ^{15}N amount-fraction scale were matched using the data of Junk and Svec [26]. The expanded uncertainty in the atomic-weight and ^{15}N amount-fraction scales with the $\delta^{15}\text{N}_{\text{Air-N}_2}$ scale is equivalent to 1.1 ‰. The $\delta^{15}\text{N}_{\text{Air-N}_2}$ value of -150 ‰ for NO_x from a nitric acid plant is for a commercially available material that has been subjected to inadvertent isotopic fractionation [8] (see footnote m of the Table of Standard Atomic Weights 2011 [15]); thus, it is not included in the atomic-weight interval.

consensus $\delta^2\text{H}_{\text{VSMOW}}$ value of zero [22]. The hydrogen isotope-number ratio of VSMOW, $R(^2\text{H}, ^1\text{H})$, has been measured by Hagemann et al. [12] and is 0.000 155 74(5). This measurement serves as the “best measurement” of a single terrestrial source [11]. VSMOW is the zero point on the hydrogen isotope-delta scale and therefore $\delta^2\text{H}_{\text{VSMOW}} = 0$. Figure 1 and Table 1 shows $\delta^2\text{H}_{\text{VSMOW}}$ values for 19 materials or substances. The material having the lowest measured ^2H abundance is a natural gas sample from Kansas, USA (Fig. 1) [63], which has a $\delta^2\text{H}_{\text{VSMOW}}$ value of -836 ‰. For this sample, the amount fraction of ^2H , $x(^2\text{H})$, is 0.000 0255, and $A_r(\text{H})$ is 1.007 8507. The material having the highest measured ^2H abundance is benzaldehyde reagent produced by toluene catalytic oxidation (Fig. 1) [10], which has a $\delta^2\text{H}_{\text{VSMOW}}$ value of $+802$ ‰. For this sample, the amount fraction of ^2H , $x(^2\text{H})$, is 0.000 2806, and $A_r(\text{H})$ is 1.008 1074. If material P is the normal material having the lowest atomic weight of element E, then

$$\text{lower bound of atomic weight} = \text{lowest } A_r(\text{E})_p - U[A_r(\text{E})]_p \quad (4)$$

where $U[A_r(\text{E})]_p$ is the combined uncertainty that incorporates the uncertainty in the measurement of the delta value of material P and the uncertainty in relating the delta-value scale to the isotope-amount fraction and atomic-weight scales. The latter is the uncertainty in relating an isotope-delta scale to an atomic-weight scale. In an equivalent manner, the upper bound for the highest atomic weight is

$$\text{upper bound of atomic weight} = \text{highest } A_r(\text{E})_p - U[A_r(\text{E})]_p \quad (5)$$

Fig. 6: Variation in isotopic composition and atomic weight composition of selected oxygen-bearing materials (modified from [9, 13]). VSMOW is the Vienna Standard Mean Ocean Water–Standard Light Antarctic Precipitation scale [22] and VPDB is the Vienna Pee Dee belemnite–LSVEC isotope scale [21]. Isotopic reference materials are designated by solid black circles. The $\delta^{18}\text{O}_{\text{VSMOW}}$ scale and ^{18}O amount-fraction scale were matched using the data of Li et al. [27] and Baertschi [28]. The expanded uncertainty in the atomic-weight and ^{18}O amount-fraction scales with the $\delta^{18}\text{O}$ scale is equivalent to 0.3 ‰. The $\delta^{18}\text{O}_{\text{VSMOW}}$ value of -229 ‰ for CO tank gas is for a commercially available material that has been subjected to inadvertent isotopic fractionation [8] (footnote m of the Table of Standard Atomic Weights 2011 [15]); thus, it is not included in the atomic-weight interval.

Fig. 7: Variation in isotopic composition and atomic weight of magnesium in selected magnesium-bearing materials (modified from [9, 15]). The $\delta^{26/24}\text{Mg}$ measurements are expressed relative to the reference material DSM3 because many materials were measured relative to it [29]. However, DSM3 is not recommended as the international measurement standard for the $\delta^{26/24}\text{Mg}$ scale because the supply is exhausted. The $\delta^{26/24}\text{Mg}$ scale and ^{26}Mg amount-fraction scales were matched using data from [29]. The expanded uncertainty in matching the atomic-weight and ^{26}Mg amount-fraction scales with the $\delta^{26/24}\text{Mg}$ scale is equivalent to 1.1 ‰.

Fig. 8: Variation in isotopic composition and atomic weight of selected silicon-bearing materials (modified from [9, 13]). The isotopic reference material NBS 28 is optical quartz [8]. Isotopic reference materials are designated by solid black circles. IRMM-018 and NBS 28 have almost identical isotopic abundances and overlap. The $\delta^{30}\text{Si}$ scale (or $\delta^{30/28}\text{Si}$ scale, for specification with two isotopes) and ^{30}Si amount-fraction scale were matched using the data of De Bièvre et al. [30] and a $\delta^{30}\text{Si}$ value for IRMM-017 of -1.3‰ relative to NBS 28 [8]. The expanded uncertainty in the atomic-weight and ^{30}Si amount-fraction scales with the $\delta^{30}\text{Si}$ scale is equivalent to 0.23‰ .

Fig. 9: Variation in isotopic composition and atomic weight of selected sulfur-bearing materials (modified from [9, 13]). VCDT is Vienna Cañon Diablo troilite [8]. Isotopic reference materials are designated by solid black circles. The $\delta^{34}\text{S}$ scale (or $\delta^{34/32}\text{S}$ scale, for completeness) and ^{34}S amount-fraction scale were matched using the data of Ding et al. [31]. The expanded uncertainty in the atomic-weight and ^{34}S amount-fraction scales with the $\delta^{34}\text{S}$ scale is equivalent to 0.2‰ .

For each of the twelve elements having interval values of standard atomic weight, the Commission published a figure that displayed lower and upper bounds of isotope-delta values, isotopic abundances, and atomic weights in selected substances and materials (Figs. 1–12 [64]). The lower and upper bounds of the isotope-delta values of the selected substances and materials are compiled in Tables 1–12.

Fig. 10: Variation in isotopic composition and atomic weight of selected chlorine-bearing materials (modified from [9, 13]). SMOC is Standard Mean Ocean Chloride [8]. Isotopic reference materials are designated by solid black circles. The $\delta^{37}\text{Cl}$ scale and the ^{37}Cl amount-fraction scale were matched using the data of Shields et al. [32] and Xiao et al. [33]. The expanded uncertainty in the atomic-weight and ^{37}Cl amount-fraction scales with the $\delta^{37}\text{Cl}$ scale is equivalent to 2.5 ‰.

Fig. 11: Variation in isotopic composition and atomic weight of bromine in selected bromine-bearing materials (modified from [15]). SMOB is Standard Mean Ocean Bromide [20]. Isotopic reference materials are designated by solid black circles. The $\delta^{81}\text{Br}$ scale and the ^{81}Br amount-fraction scale were matched using data from [34, 35]. The expanded uncertainty in matching the atomic-weight and ^{81}Br amount-fraction scales with the $\delta^{81}\text{Br}$ scale is equivalent to 1.1 ‰.

Fig. 12: Variation in atomic weight with isotopic composition of selected thallium-bearing materials (modified from [9, 13]). The reference material SRM 997 is elemental thallium metal [8]. An isotopic reference material is designated by a solid black circle. The $\delta^{205}\text{Tl}$ scale and the ^{205}Tl amount-fraction scale were matched using the data of Dunstan et al. [36] and Rosman and Taylor [37]. The expanded uncertainty in the atomic-weight and ^{205}Tl amount-fraction scales with the $\delta^{205}\text{Tl}$ scale is equivalent to 0.4 ‰.

Table 1: Hydrogen isotopic compositions of selected hydrogen-bearing materials.

Substance	Minimum $10^3 \delta^2\text{H}_{\text{VSMOW}}$		Maximum $10^3 \delta^2\text{H}_{\text{VSMOW}}$	
	Value	Reference	Value	Reference
Water				
Sea water (deep)	−2.5	[38]	+3.2	[38]
Other (naturally occurring)	−495	[39]	+129	[40]
Fruit juice and wine	−43	[41]	+47	[42]
Silicates				
Pectolite	−429	[43]	−281	[43]
Other	−208	[44]	+5	[45]
Hydroxides				
Aluminum and iron	−220	[46]	−8	[47, 48]
Organic hydrogen				
Non-marine organisms	−237	[49]	+66	[50]
Marine organisms	−166	[51]	−13	[51]
Organic sediments	−103	[52]	−59	[53]
Coal	−162	[54]	−65	[55]
Crude oil	−163	[51]	−80	[51]
Ethanol (naturally occurring)	−272	[56]	−200	[56]
Reagents (synthetic)	−140	[56]	+802	[10]
Methane				
Atmospheric	−232	[57]	−71	[58]
Other (naturally occurring)	−531	[53, 59]	−133	[60]
Hydrogen gas				
Air	−136	[61]	+180	[62]
Other (naturally occurring)	−836	[63]	−250	[44]
Commercial tank gas	−813	[8]	−56	[8]
Automobile exhaust and industrial contamination	−690	[62]	−147	[62]

[Values normalized such that the $\delta^2\text{H}_{\text{VSMOW}}$ of SLAP (Standard Light Antarctic Precipitation) is -428‰ exactly relative to VSMOW (Vienna Standard Mean Ocean Water).].

A supplemental file [232] lists the atomic weight and the isotopic abundances for each isotope of each of the twelve elements for each substance and material shown in Figs. 1–12 and Tables 1–12. Many uses of atomic-weight data, such as for trade and commerce, need a value that is not an interval. For these purposes, the Commission provides conventional atomic-weight values [64], and the associated isotope-delta and isotope-amount-fraction values are listed in the supplemental file [232]. Additionally, the supplemental file lists the isotope-delta value and isotopic abundances of all stable isotopes corresponding to the lower and upper bounds of the standard atomic weights of the twelve elements discussed here. For the four elements with more than two stable isotopes, we assume mass-dependent isotopic fractionation when calculating isotopic abundances and atomic weights from isotope-delta values. For oxygen, $R(^{17}\text{O}, ^{16}\text{O})_{\text{sample}}/R(^{17}\text{O}, ^{16}\text{O})_{\text{VSMOW}} = (R(^{18}\text{O}, ^{16}\text{O})_{\text{sample}}/R(^{18}\text{O}, ^{16}\text{O})_{\text{VSMOW}})^{0.528}$, where the value 0.528 was determined by Meijer and Li [233]. For magnesium, $R(^{25}\text{Mg}, ^{24}\text{Mg})_{\text{sample}}/R(^{25}\text{Mg}, ^{24}\text{Mg})_{\text{DSM3}} = (R(^{26}\text{Mg}, ^{24}\text{Mg})_{\text{sample}}/R(^{26}\text{Mg}, ^{24}\text{Mg})_{\text{DSM3}})^{0.5}$; for silicon, $R(^{29}\text{Si}, ^{28}\text{Si})_{\text{sample}}/R(^{29}\text{Si}, ^{28}\text{Si})_{\text{NBS28}} = (R(^{29}\text{Si}, ^{28}\text{Si})_{\text{sample}}/R(^{29}\text{Si}, ^{28}\text{Si})_{\text{NBS28}})^{0.5}$; for sulfur, $R(^{33}\text{S}, ^{32}\text{S})_{\text{sample}}/R(^{33}\text{S}, ^{32}\text{S})_{\text{NBS28}} = (R(^{34}\text{S}, ^{32}\text{S})_{\text{sample}}/R(^{34}\text{S}, ^{32}\text{S})_{\text{NBS28}})^{0.5}$ and $R(^{34}\text{S}, ^{32}\text{S})_{\text{sample}}/R(^{34}\text{S}, ^{32}\text{S})_{\text{NBS28}} = (R(^{36}\text{S}, ^{32}\text{S})_{\text{sample}}/R(^{36}\text{S}, ^{32}\text{S})_{\text{NBS28}})^{0.5}$.

2 Hydrogen

Table 1 lists $\delta^2\text{H}_{\text{VSMOW}}$ values of the extremes of hydrogen-bearing substances and materials shown in Fig. 1.

Table 2: Lithium isotopic compositions of selected lithium-bearing materials.

Substance	Minimum $10^3 \delta^7\text{Li}_{\text{LSVEC}}$		Maximum $10^3 \delta^7\text{Li}_{\text{LSVEC}}$	
	Value	Reference	Value	Reference
Marine sources				
Sea water	+32.4	[65]	+33.9	[66]
Hydrothermal fluids	+2.6	[67]	+11	[68]
Foraminifera and carbonate sediments	−10	[69]	+42	[69]
Brines and pore water	+1	[70]	+56.3	[65]
Non-marine sources				
Surface water	+15.5	[71]	+34.4	[66]
Ground and thermal water	−19	[8]	+10	[8]
Contaminated ground water	+10	[8]	+354	[8]
Lithium in rocks				
Basalt (unaltered)	+3.4	[71]	+6.8	[71]
Basalt (altered)	−2.1	[71]	+13.5	[72]
Rhyolite	−3.5	[73]	−3.5	[73]
Granite	0	[8]	+11.2	[74]
Limestone	−3.5	[73]	+33.5	[69]
Phosphates				
LiAlFPO_4 (amblygonite)	−13	[75]	+7.4	[76]
Silicates				
Spodumene	−12.6	[75]	+11.8	[8]
Lepidolite	−6.6	[75]	+7.2	[75]
Reagents				
^6Li depleted compounds	+434	[77]	+3013	[77]
Other reagents	−11	[77]	+23	[77]

Table 3: Boron isotopic composition of selected boron-bearing materials.

Substance	Minimum $10^3 \delta^{11}\text{B}_{\text{SRM951}}$		Maximum $10^3 \delta^{11}\text{B}_{\text{SRM951}}$	
	Value	Reference	Value	Reference
Marine sources				
Sea water	+38.4	[78]	+40.4	[79]
Evaporated sea water	+36.5	[78]	+58.5	[80]
Hydrothermal fluids	+30.0	[81]	+36.8	[81]
Evaporite minerals	+18.2	[82]	+31.7	[82]
Carbonates (Skeletal parts and formations)	+4.0	[83]	+32.2	[83]
Non-marine sources				
Rain water	+0.8	[84]	+35	[84]
Brines, surface and ground waters	−21.3	[85]	+59.2	[78]
Hydrothermal fluids	−9.3	[86]	+29.1	[80]
Evaporite minerals	−31.3	[87]	+7.3	[88]
Igneous rocks	−17.0	[89]	−1.7	[81]
Metamorphic rocks	−34.2	[90]	+22	[91]
Sediments	−17	[92]	+26.2	[92]
Organic boron	−12	[93]	+29.3	[94]

3 Lithium

Table 2 lists $\delta^7\text{Li}_{\text{LSVEC}}$ values of the extremes of lithium-bearing substances and materials shown in Fig. 2, where LSVEC is the lithium carbonate isotopic reference material whose $\delta^7\text{Li}_{\text{LSVEC}}$ value is zero by consensus [20].

Table 4: Carbon isotopic composition of selected carbon-bearing materials.

Substance	Minimum $10^3 \delta^{13}\text{C}_{\text{VPDB}}$		Maximum $10^3 \delta^{13}\text{C}_{\text{VPDB}}$	
	Value	Reference	Value	Reference
Carbonate and bicarbonate				
Sea water	−0.8	[95]	+2.2	[95]
Other water	−37.1	[96]	+37.5	[97]
Metamorphic and igneous rock	−11.9	[98]	+24.8	[99]
Typical marine carbonate rock	−6	[100]	+6	[100]
Other carbonate	−64.5	[101]	+21.1	[101]
Carbon dioxide				
Air	−8.2	[102]	−6.7	[103]
Soil gas	−31.0	[104]	+6.9	[105]
Volcanic gas	−37	[106]	+23	[106]
Oil, gas, coal, and landfills	−37.6	[107]	+28	[108]
Commercial tank gas and reference materials	−54	[8]	−28.76	[109]
Oxalates				
Whewellite	−31.7	[110]	+33.7	[111]
Carbon monoxide				
Air	−31.5	[112]	−22	[113]
Organic carbon				
Land plants (C3 metabolic process)	−35	[114]	−21	[115]
Land plants (C4 metabolic process)	−16	[115]	−9	[115]
Land plants (CAM metabolic process)	−34	[116]	−10	[114]
Marine organisms	−74.3	[117]	−2	[118]
Marine sediments and compounds	−130.3	[119]	+7	[116]
Coal	−30	[116]	−19	[116]
Crude oil	−44	[120]	−16.8	[120]
Ethanol (naturally occurring)	−32	[56]	−10.3	[56]
Elemental carbon				
Graphite	−41	[116]	+6.2	[121]
Diamonds	−34.4	[122]	+5	[123]
Ethane				
Hydrocarbon gas	−55.6	[124]	+6.6	[125]
Methane				
Air	−50.6	[126]	−39	[127]
Marine and other sources	−109	[128]	+12.7	[125]
Fresh water sources	−86	[129]	−50	[128]
Commercial tank gas	−51	[8]	−38	[8]

4 Boron

Table 3 lists $\delta^{11}\text{B}_{\text{SRM951}}$ values of the extremes of boron-bearing substances and materials shown in Fig. 3, where SRM 951 is the boric acid isotopic reference materials whose $\delta^{11}\text{B}_{\text{SRM951}}$ value is zero by consensus [20].

5 Carbon

Table 4 lists $\delta^{13}\text{C}_{\text{VPDB}}$ values of the extremes of carbon-bearing substances and materials shown in Fig. 4, where VPDB signifies the Vienna Pee Dee belemnite scale by assigning a $\delta^{13}\text{C}_{\text{VPDB}}$ value of +1.95 ‰ to NBS 19 calcium carbonate by international consensus [124, 234].

Table 5: Nitrogen isotopic composition of selected nitrogen-bearing materials.

Substance	Minimum $10^3 \delta^{15}\text{N}_{\text{Air-N}_2}$		Maximum $10^3 \delta^{15}\text{N}_{\text{Air-N}_2}$	
	Value	Reference	Value	Reference
Nitrate				
Air (aerosols and precipitation)	−16	[130]	+18	[131]
Sea water and estuaries	−6	[132]	+20	[133, 134]
Ground water and ice	−7	[135]	+150	[136]
Soil extracts	−23	[137]	+46	[138]
Desert salt deposits	−5	[139]	+15	[140]
Synthetic reagents and fertilizers	−23	[141]	+15	[142]
Nitrite				
Ground waters	−30	[143]	+55	[143]
Synthetic reagents	−80	[8]	+4	[8]
Nitrogen oxide gases				
N ₂ O in air (troposphere)	0	[144]	+10	[145]
N ₂ O in sea water	+3	[146]	+38	[147]
N ₂ O in ground water	−55	[143]	+53	[143]
NO _x in air	−15	[131]	+5	[130]
NO _x from nitric acid plant	−150	[130]		
Nitrogen gas				
Air	0	[148]	0	[148]
Ground waters	−3	[149]	+5	[150]
Volcanic gases and hot springs	−10	[151]	+16	[152]
Sedimentary basins	−49	[153]	+46	[154]
Commercial tank gas	−5	[155]	+3	[156]
Organic nitrogen				
Plants and animals	−49	[137]	+31	[137]
Marine particulate organic matter	−3	[157]	+46	[157]
Bituminous sediments, peat, and coal	−3	[158]	+13	[159]
Crude oil	+1	[160]	+7	[154, 160]
Soils	−29	[137]	+38	[161]
Synthetic reagents and fertilizers	−3	[142]	+6	[142]
Biological fertilizers	+3	[142]	+15	[142]
Nitrogen in rocks				
Metamorphic rocks	+1	[162]	+17	[163]
Igneous rocks	−36	[164]	+31	[165]
Diamonds	−37	[164]	+14	[164]
Ammonium				
Air (ammonia gas)	−15	[130]	+28	[131]
Air (aerosols and precipitation)	−14	[166]	+14	[167]
Sea water and estuaries	+2	[168]	+42	[169]
Soil extracts	−7	[170]	+50	[161]
Volcanic gas condensates	−31	[171]	+13	[158, 171]
Synthetic reagents and fertilizers	−5	[142]	+11	[172]

6 Nitrogen

Table 5 lists $\delta^{15}\text{N}_{\text{Air-N}_2}$ values of the extremes of nitrogen-bearing substances and materials shown in Fig. 5, where the subscript Air-N₂ signifies the isotopic reference material atmospheric nitrogen, which has a $\delta^{15}\text{N}_{\text{Air-N}_2}$ value of zero.

7 Oxygen

Table 6 lists $\delta^{18}\text{O}_{\text{VSMOW}}$ values of the extremes of oxygen-bearing substances and materials shown in Fig. 6.

Table 6: Oxygen isotopic composition of selected oxygen-bearing materials.

Substance	Minimum $\delta^{18}\text{O}$ Value		Maximum $\delta^{18}\text{O}$ Value	
	$\delta^{18}\text{O}$	Reference	$\delta^{18}\text{O}$	Reference
Oxygen gas				
Air	+23.8	[173]	+23.8	[173]
Water				
Sea water	−1	[174]	+0.6	[174]
Continental water	−62.8	[175]	+31.3	[40]
Fruit juice and wine	−4.4	[41]	+15.3	[176]
Carbon monoxide				
Air	−6.9	[112]	+1.7	[112]
Commercial tank gas	−229	[8]	+7.6	[8]
Carbon dioxide				
Air	+40	[177]	+53.0	[178]
Commercial tank gas	+3.9	[179]	+22.2	[109]
Carbonates				
Typical marine carbonate	+26	[180]	+34	[180]
Igneous (carbonatite)	−1.3	[181]	+7.7	[182]
Other carbonate	−20.5	[183]	+36.4	[184]
Nitrogen oxides				
N ₂ O (air and water)	+20	[185]	+109	[147]
Nitrate (air and water)	−2.5	[186]	+76	[187]
Oxides				
Al and Fe oxides	−15.5	[46]	+16	[48]
Chert	+9.4	[188]	+45	[189]
Phosphates				
Skeletal parts	+6	[190]	+26.7	[191]
Phosphorite rocks	+8.6	[192]	+25.1	[193]
Silicates	−16.2	[194]	+34.9	[195]
Sulfates				
Air	−19	[196]	+14.1	[197]
Sea water	+9.3	[198]	+9.6	[198]
Other water	−19.8	[199]	+23.2	[200]
Minerals	−10.0	[201]	+31.2	[202, 203]
Plants and animals				
Cellulose, lipids, and tissue	−4.3	[204]	+37.0	[50]

[Values normalized such that the $\delta^{18}\text{O}_{\text{VSMOW}}$ of SLAP (Standard Light Antarctic Precipitation) is −55.5 ‰ exactly relative to VSMOW (Vienna Standard Mean Ocean Water).]

Table 7: Magnesium isotopic composition of selected magnesium-bearing materials.

Substance	Minimum $10^3 \delta^{26/24}\text{Mg}$		Maximum $10^3 \delta^{26/24}\text{Mg}$	
	Value	Reference	Value	Reference
Water				
Sea water	−1	[205]	−0.69	[205]
Rivers and streams	−1.82	[206]	−0.08	[207]
Rain	−0.75	[207]	−0.5	[207]
Igneous and metamorphic rock				
Olivine	−3.01	[208]	1.03	[208]
Others	−0.75	[205]	0.14	[205]
Carbonates (biological and non-biological)	−5.57	[209]	−1.04	[209]
Organic matter	−3.55	[205]	0.73	[207]
Elemental magnesium	−0.82	[210]	0.54	[210]

Table 8: Silicon isotopic composition of selected silicon-bearing materials.

Substance	Minimum $10^3 \delta^{30}\text{Si}_{\text{NBS28}}$		Maximum $10^3 \delta^{30}\text{Si}_{\text{NBS28}}$	
	Value	Reference	Value	Reference
Igneous rocks	−1.0	[211]	+0.4	[212]
Metamorphic rocks	−1.1	[213]	+1.1	[214]
Vein quartz and silicified rocks	−1.5	[213]	+1.1	[214]
Sedimentary rocks				
Quartz sandstones	−0.2	[215]	+0.2	[213]
Clay minerals	−2.6	[211]	+1.5	[211]
Sinter	−3.4	[211]	+0.2	[211]
Sea-floor hydrothermal siliceous precipitates	−3.1	[216]	0.0	[213]
Other siliceous rocks	−0.8	[213]	+3.4	[217]
Dissolved silica	−0.4	[211]	+3.4	[217]
Biogenic silica	−3.7	[211]	+2.5	[211]
Elemental silicon	−1.3	[8]	+0.5	[8]

Table 9: Sulfur isotopic composition of selected sulfur-bearing materials.

Substance	Minimum $10^3 \delta^{34}\text{S}$		Maximum $10^3 \delta^{34}\text{S}$	
	Value	Reference	Value	Reference
Sulfate				
Atmospheric	−30	[8]	30	[8]
Surface water/ground water	−22	[8]	135	[8]
Modern ocean	20.7	[8]	21.3	[8]
Mineral	−43	[8]	−3	[8]
Commercial	−3	[8]	30	[8]
Sulfuric acid	−3	[8]	12	[8]
Reagents	−34	[8]	26	[8]
Sulfur dioxide				
Atmospheric	−39	[8]	33	[8]
Reagents	0.8	[8]	1.6	[8]
Elemental sulfur				
Native	−30	[8]	16	[8]
Commercial	−4	[8]	28	[8]
Organic sulfur				
Soil	−31	[8]	31	[8]
Vegetation	−33	[8]	32	[8]
Animals	−10	[8]	21	[8]
Fossil fuels	−11	[8]	28	[8]
Reagents	1	[8]	18	[8]
Sulfide				
Atmospheric H_2S	−21	[8]	20	[8]
Thermogenic H_2S	0	[8]	30	[8]
Surface water/ground water	−55	[8]	30	[8]
Minerals	−54	[8]	70	[8]
Reagent H_2S	1	[8]	23	[8]
Other reagents	−33	[8]	23	[8]

8 Magnesium

Table 7 lists $\delta^{26/24}\text{Mg}_{\text{DSM3}}$ values of the extremes of magnesium-bearing substances and materials shown in Fig. 7 relative to the isotopic reference material DSM3 [20].

Table 10: Chlorine isotopic composition of selected chlorine-bearing materials.

Substance	Minimum $10^3 \delta^{37}\text{Cl}_{\text{SMOC}}$		Maximum $10^3 \delta^{37}\text{Cl}_{\text{SMOC}}$	
	Value	Reference	Value	Reference
Chlorides				
Sea water	−0.15	[218]	+0.94	[33]
Ground, surface, pore, and oil formation waters	−7.7	[219]	+2.94	[220]
Hydrothermal fluid-inclusion water	−1.1	[221]	+0.8	[221]
Halite	−0.2	[222]	+0.7	[223]
Sylvite	−0.5	[224]	+0.3	[224]
Rock or sediments	+0.2	[225]	+7.5	[225]
Organic solvents				
CH ₃ Cl	−6.0	[226]	+4.0	[227]
Other (trichloroethylene, and others)	−2.5	[104]	+4.4	[104]

Table 11: Bromine isotopic composition of selected bromine-bearing materials.

Substance	Minimum $10^3 \delta^{81}\text{Br}_{\text{SMOB}}$		Maximum $10^3 \delta^{81}\text{Br}_{\text{SMOB}}$	
	Value	Reference	Value	Reference
Inorganic bromide				
Sea water	0	[34]	0	[34]
Saline waters and salt deposits	−0.8	[228]	3.35	[228]
Organic compounds	−4.3	[229]	0.2	[229]
Elemental bromine	−1.34	[35]	0.86	[35]

Table 12: Thallium isotopic composition of selected thallium-bearing materials.

Substance	Minimum $10^3 \delta^{205}\text{Tl}$		Maximum $10^3 \delta^{205}\text{Tl}$	
	Value	Reference	Value	Reference
Igneous rocks	−0.18	[230]	+0.35	[230]
Sedimentary rocks	+0.33	[231]	+1.43	[231]
Reagents	−0.14	[230]	+0.02	[230]

9 Silicon

Table 8 lists $\delta^{30}\text{Si}_{\text{NBS28}}$ values of the extremes of silicon-bearing substances and materials shown in Fig. 8, where the subscript NBS28 signifies the isotopic reference material NBS 28 silica sand, which has a $\delta^{30}\text{Si}_{\text{NBS28}}$ value of zero.

10 Sulfur

Table 9 lists $\delta^{34}\text{S}_{\text{VCDT}}$ values of the extremes of sulfur-bearing substances and materials shown in Fig. 9, where VCDT is Vienna Cañon Diablo troilite [8], which is assigned a $\delta^{34}\text{S}_{\text{VCDT}}$ value of zero.

11 Chlorine

Table 10 lists $\delta^{37}\text{Cl}_{\text{SMOC}}$ values of the extremes of chlorine-bearing substances and materials shown in Fig. 10, where SMOC is Standard Mean Ocean Chloride [20].

12 Bromine

Table 11 lists $\delta^{81}\text{Br}_{\text{SMOB}}$ values of the extremes of bromine-bearing substances and materials shown in Fig. 11, where SMOB is Standard Mean Ocean Bromide [20].

13 Thallium

Table 12 lists $\delta^{205}\text{Tl}_{\text{SRM997}}$ values of the extremes of thallium-bearing substances and materials shown in Fig. 12, where the subscript SRM997 is the elemental thallium standard reference material SRM 997.

Membership of the sponsoring body

Membership of the IUPAC Inorganic Chemistry Division Committee for the period 2014–2015 was as follows:

President: J. Reedijk (Netherlands); **Secretary:** M. Leskelä (Finland); **Vice President:** L. R. Öhrström (Sweden); **Past President:** R. D. Loss; **Titular Members:** T. Ding (China); M. Drábik (Slovakia); E. Y. Tshuva (Israel); D. Rabinovich (USA); T. Walczyk (Republic of Singapore); M. E. Wieser (Canada); **Associate Members:** J. Buchweishaija (Tanzania); J. Garcia-Martinez (Spain); P. Karen (Norway); A. Kilic (Turkey); K. Sakai (Japan); R.-N. Vannier (France); **National Representatives:** F. Abdul Aziz (Malaysia); L. Armelao (Italy); A. Badshah (Pakistan); V. Chandrasekhar (India); J. Galamba Correia (Portugal); S. Kalmykov (Russia); L. Meesuk (Thailand); S. Mathur (Germany); B. Prugovecki (Croatia); N. Trendafilova (Bulgaria).

Membership of the IUPAC Commission on Isotopic Abundances and Atomic Weights for the period 2014–2015 was as follows:

Chair: J. Meija (Canada); **Secretary:** T. Prohaska (Austria); **Titular Members:** W. A. Brand (Germany); M. Gröning (Austria); R. Schönberg (Germany); X.-K. Zhu (China); **Associate Members:** T. Hirata (Japan); J. Irrgeher (Austria); J. Vogl (Germany); **National Representatives:** P. De Bièvre (Belgium); T. B. Coplen (USA); *Ex-officio member:* J. Reedijk (Netherlands).

Acknowledgments: We thank Dr. Juris Meija (National Research Council Canada, Ottawa, Canada) and Prof. B. Brynn Hibbert (University of New South Wales, Sydney, Australia) for their valuable suggestions that improved this manuscript. The support of the U.S. Geological Survey National Research Program made this report possible. The following IUPAC projects contributed to this Technical Report: 2011-040-2-200, 2015-030-2-200, and 2011-0271-200.

References

- [1] A. Becquerel. *Comptes Rendus* **9**, 145 (1839).
- [2] F. Soddy. *J. Chem. Soc. Trans.* **99**, 72 (1911).
- [3] J. Thomson. *Phil. Mag.* **24**, 668 (1912).
- [4] M. Wang, G. Audi, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, B. Pfeiffer. *Chinese Phys C* **36**, 1603 (2012).
- [5] H. S. Peiser, N. E. Holden, P. De Bièvre, I. L. Barnes, R. Hagemann, J. R. de Laeter, T. J. Murphy, E. Roth, M. Shima, H. G. Thode. *Pure Appl. Chem.* **56**, 695 (1984).

- [6] E. Wichers. *J. Am. Chem. Soc.* **74**, 2447 (1952).
- [7] "Atomic Weights of the Elements 1967", *Pure Appl. Chem.* **18**, 569 (1969).
- [8] T. B. Coplen, J. A. Hopple, J. K. Böhlke, H. S. Peiser, S. E. Rieder, H. R. Krouse, K. J. R. Rosman, T. Ding, R. D. Vocke, Jr., K. Révész, A. Lamberty, P. Taylor, P. De Bièvre. U.S. Geological Survey Water-Resources Investigations Report 01-4222 (2002).
- [9] T. B. Coplen, J. K. Böhlke, P. De Bièvre, T. Ding, N. E. Holden, J. A. Hopple, H. R. Krouse, A. Lamberty, H. S. Peiser, K. Révész, S. E. Rieder, K. J. R. Rosman, E. Roth, P. D. P. Taylor, R. D. Vocke, Jr., Y. K. Xiao. *Pure Appl. Chem.* **74**, 1987 (2002).
- [10] M. Butzenlechner, A. Rossmann, H. L. Schmidt. *J. Agric. Food. Chem.* **37**, 410 (1989).
- [11] M. Berglund, M. E. Wieser. *Pure Appl. Chem.* **83**, 397 (2011).
- [12] R. Hagemann, G. Nief, E. Roth. *Tellus* **22**, 712 (1970).
- [13] M. E. Weiser, T. B. Coplen. *Pure Appl. Chem.* **83**, 359 (2011).
- [14] T. B. Coplen, N. Holden. *Chem. Internal.* **33**, 10 (2011).
- [15] M. E. Wieser, N. Holden, T. B. Coplen, J. K. Böhlke, M. Berglund, W. A. Brand, P. De Bièvre, M. Gröning, R. D. Loss, J. Meija, T. Harata, T. Prohaska, R. Schoenberg, G. O'Connor, T. Walczyk, S. Yoneda, X.-K. Zu. *Pure Appl. Chem.* **85**, 1047 (2013).
- [16] BIPM. International Vocabulary of Metrology – Basic and General Concepts and Associated Terms (VIM), 3rd ed. Geneva (2008 version with corrections), Bureau International des Poids et Mesures. JCGM 200:2012 at <http://www.bipm.org/en/publications/guides/vim>.
- [17] T. B. Coplen. *Rapid Commun. Mass Spectrom.* **25**, 2538 (2011).
- [18] H. C. Urey. *Science* **108**, 489 (1948).
- [19] W. A. Brand, T. B. Coplen. *Isotopes Environ. Health Stud.* **48**, 393 (2012).
- [20] W. A. Brand, T. B. Coplen, J. Vogl, M. Rosner, T. Prohaska. *Pure Appl. Chem.* **86**, 425 (2014).
- [21] T. B. Coplen, W. A. Brand, M. Gehre, M. Gröning, H. A. Meijer, B. Toman, R. M. Verkouteren. *Anal. Chem.* **78**, 2439 (2006).
- [22] R. Gonfiantini. *Nature* **271**, 534 (1978).
- [23] H. P. Qi, P. D. P. Taylor, M. Berglund, P. De Bièvre. *Int. J. Mass Spectrom.* **171**, 263 (1997).
- [24] E. J. Catanzaro, C. E. Champion, E. L. Garner, G. Marinenko, K. M. Sappenfield, W. R. Shields. *NBS Special Publication 260-17*: U.S. Printing Office, Washington, D.C., **260**, p. 11 (1970).
- [25] T. L. Chang, W. J. Li. *Chin. Sci. Bull.* **35**, 290 (1990).
- [26] G. Junk, H. J. Svec. *Geochim. Cosmochim. Acta* **14**, 234 (1958).
- [27] W. J. Li, B. L. Ni, D. Q. Jin, T. L. Chang. *Kexue Tongbao* **33**, 1610 (1988).
- [28] P. Baertschi. *Earth Planet. Sci. Lett.* **31**, 341 (1976).
- [29] M. Bizzarro, C. Paton, K. Larsen, M. Schiller, A. Trinquier, D. Ulfbeck. *J. Anal. At. Spectrom.* **26**, 565 (2011).
- [30] P. De Bièvre, S. Valkiers, H. S. Peiser. *J. Res. Natl. Inst. Stand. Technol.* **99**, 201 (1994).
- [31] T. Ding, S. Valkiers, H. Kipphardt, P. De Bièvre, P. D. P. Taylor, R. Gonfiantini, H. R. Krouse. *Geochim. Cosmochim. Acta* **65**, 2433 (2001).
- [32] W. R. Shields, T. J. Murphy, E. L. Garner, V. H. Dibeler. *J. Am. Chem. Soc.* **84**, 1519 (1962).
- [33] Y. K. Xiao, Z. Yinming, W. Qingzhong, W. Haizhen, L. Weiguo, C. J. Eastoe. *Chem. Geol.* **182**, 655 (2002).
- [34] O. Shouakar-Stash, S. K. Frape, R. J. Drimmie. *Anal. Chem.* **77**, 4027 (2005).
- [35] E. Catanzaro, T. Murphy, E. Garner, W. Shields. *J. Res. Natl. Bur. Std.* **68A**, 593 (1964).
- [36] L. Dunstan, J. Gramlich, I. Barnes, W. Purdy. *J. Res. Natl. Bur. Stand.* **85**, 1 (1980).
- [37] K. Rosman, P. Taylor. *Pure Appl. Chem.* **70**, 217 (1998).
- [38] A. C. Redfield, I. Friedman. *Symposium on Marine Geochemistry*: Univ. Rhode Island, Occasional Publication, **3**, 149 (1965).
- [39] J. Jouzel, C. Lorius, J. R. Petit, C. Genthon, N. I. Barkov, V. M. Kotlyakov, V. M. Petrov. *Nature* **329**, 403 (1987).
- [40] J.-C. Fontes, R. Gonfiantini. *Earth Planet. Sci. Lett.* **3**, 258 (1967).
- [41] J. Bricout, L. Merlivat, J. Ch. Fontes. *Comptes Rendus* **274**, 1803 (1973).
- [42] G. J. Martin, C. Guillou, M. L. Martin, M. T. Cabanis, Y. Tep, J. Aerny. *J. Agric. Food. Chem.* **36**, 316 (1988).
- [43] D. B. Wenner. *Geochim. Cosmochim. Acta* **43**, 603 (1979).
- [44] I. Friedman, J. R. O'Neil. In *Handbook of Geochemistry II-1*, K. H. Wedepohl (Ed.), p. 1B1, Section 1-B Isotopes in Nature, Springer-Verlag, Berlin, Germany (1978).
- [45] C. M. Graham, S. M. F. Sheppard. *Earth Planet. Sci. Lett.* **49**, 237 (1980).
- [46] C. J. Yapp. "Climate change in continental isotopic records", P.K. Swart et al. (Eds.), p. 285, *Geophysical Monograph* 78. American Geophysical Union, Washington, DC (1993).
- [47] C. Bernard. Composition isotopique des minéraux secondaires des bauxites, Problèmes de genèse, Ph.D. Thesis. University of Paris, Paris (1978).
- [48] M. I. Bird, A. R. Chivas, A. S. Andrew. *Geochim. Cosmochim. Acta* **53**, 1411 (1989).
- [49] H. Schütze, G. Strauch, K. Wetzel. In *Stable Isotopes, Analytical Chemistry Symposia Series*, Proceedings of the 4th International Conference, Jülich, H.-L. Schmidt et al. (Eds.), p. 121, Elsevier Scientific Publishing Co, Amsterdam, The Netherlands (1982).
- [50] L. O. Sternberg, M. J. DeNiro, H. B. Johnson. *Plant Physiol.* **74**, 557 (1984).
- [51] W. E. Schiegl, J. C. Vogel. *Earth Planet. Sci. Lett.* **7**, 307 (1970).
- [52] W. E. Schiegl. *Science* **175**, 512 (1972).
- [53] R. S. Oremland, M. J. Whiticar, F. E. Strohmaier, R. P. Kiene. *Geochim. Cosmochim. Acta* **52**, 1895 (1988).

- [54] J. W. Smith, R. J. Pallasser. *Am. Assoc. Pet. Geol. Bull.* **80**, 891 (1996).
- [55] C. Redding. In *4th International Conference on Geochronology, Cosmochronology and Isotope Geology*, U.S. Geological Survey Open-File Report 78-701, U.S. Geological Survey Open-File Report p. 348 (1978).
- [56] P. Rauschenbach, H. Simon, W. Stichler, H. Moser. *Z. Naturforsch* **34**, 1 (1979).
- [57] A. K. Snover, P. D. Quay, W. M. Hao. *Global Biogeochem. Cycles* **14**, 11 (2000).
- [58] M. Wahlen. *Annu. Rev. Earth. Planet. Sci.* **21**, 407 (1993).
- [59] R. S. Oremland, L. G. Miller, M. J. Whiticar. *Geochim. Cosmochim. Acta* **51**, 2915 (1987).
- [60] M. Schoell. *Geochim. Cosmochim. Acta* **44**, 649 (1980).
- [61] I. Friedman, T. G. Scholz. *J. Geophys. Res.* **79**, 785 (1974).
- [62] B. Gonsior, I. Friedman, G. Lindenmayr. *Tellus* **18**, 256 (1966).
- [63] R. M. Coveney, E. D. Goebel, E. J. Zeller, G. A. M. Dreschhoff, E. E. Angino. *Am. Assoc. Pet. Geol. Bull.* **71**, 39 (1987).
- [64] J. Meija, T. B. Coplen, M. Berglund, W. A. Brand, P. De Bièvre, M. Gröning, N. E. Holden, J. Irrgeher, R. D. Loss, T. Walczyk, T. Prohaska. *Pure Appl. Chem.* **88**, 265 (2016).
- [65] C.-F. You, L.-H. Chan. *Geochim. Cosmochim. Acta* **60**, 909 (1996).
- [66] C. Lui-Heung, J. M. Edmond. *Geochim. Cosmochim. Acta* **52**, 1711 (1988).
- [67] C. Lui-Heung, J. M. Gieskes, Y. Chen-Feng, J. M. Edmond. *Geochim. Cosmochim. Acta* **58**, 4443 (1994).
- [68] L.-H. Chan, J. M. Edmond, G. Thompson. *J. Geophys. Res.* **98** (B6), 9653 (1993).
- [69] J. Hoefs, M. Sywall. *Geochim. Cosmochim. Acta* **61**, 2679 (1997).
- [70] R. D. Vocke, Jr., E. S. Beary, R. J. Walker. In *V.M. Goldschmidt Conference; programs and abstracts*, p. 89, Geochemical Society, (1990).
- [71] L.-H. Chan, J. M. Edmond, G. Thompson, K. Gillis. *Earth Planet. Sci. Lett.* **108**, 151 (1992).
- [72] L.-H. Chan, C.-F. You, W. P. Leeman. In *Geological Society of America, 1995 annual meeting*, 1995 annual meeting, p. 38 (1995).
- [73] T. D. Bullen, Y. K. Kharaka. In *Proceedings of the 7th International Symposium on Water-Rock Interaction*, Y. K. Kharaka, and A.S. Maest (Eds.), p. 887 (1992).
- [74] P. B. Tomascak, S. J. Lynton, R. J. Walker, E. J. Krogstad. In *The Origin of Granites and Related Rocks: U.S. Geological Survey Circular*, M. Brown, and P. M. Piccoli (Eds.), p. 151 (1995).
- [75] A. E. Cameron. *J. Am. Chem. Soc.* **77**, 2731 (1955).
- [76] H. J. Svec, A. R. Anderson. *Geochim. Cosmochim. Acta* **29**, 633 (1965).
- [77] H. P. Qi, T. B. Coplen, Q. Zh. Wang, Y. H. Wang. *Anal. Chem.* **69**, 4076 (1997).
- [78] A. Vengosh, A. R. Chivas, M. T. Mcculloch, A. Starinsky, Y. Kolodny. *Geochim. Cosmochim. Acta* **55**, 2591 (1991).
- [79] M. Nomura, T. Kanzaki, T. Ozawa, M. Okamoto, H. Kakihana. *Geochim. Cosmochim. Acta* **46**, 2403 (1982).
- [80] U. S. Klötzli. *Chem. Geol. (Isotope Geosci. Sect.)* **101**, 111 (1992).
- [81] A. J. Spivack, J. M. Edmond. *Geochim. Cosmochim. Acta* **51**, 1033 (1987).
- [82] G. H. Swihart, P. B. Moore, E. L. Callis. *Geochim. Cosmochim. Acta* **50**, 1297 (1986).
- [83] A. Vengosh, Y. Kolodny, A. Starinsky, A. R. Chivas, M. T. Mcculloch. *Geochim. Cosmochim. Acta* **55**, 2901 (1991).
- [84] A. J. Spivack. Boron Isotope Geochemistry, Ph.D. Joint Program in Oceanography. Massachusetts Institute of Technology, Boston (1986).
- [85] S. Tonarini, M. Pennisi, A. Adorni-Braccesi, A. Dini, G. Ferrara, R. Gonfiantini, M. Gröning, M. Wiedenbeck. *Geostand. Newslett.* **27**, 21 (2003).
- [86] M. R. Palmer, N. C. Sturchio. *Geochim. Cosmochim. Acta* **54**, 2811 (1990).
- [87] H. O. Finley, A. R. Eberle, C. J. Rodden. *Geochim. Cosmochim. Acta* **26**, 911 (1962).
- [88] E. K. Agyei, C. C. McMullen. *Can. J. Earth Sci.* **5**, 921 (1968).
- [89] R. B. Trumbull, M. Chaussidon. *Chem. Geol.* **153**, 125 (1999).
- [90] G. Wang, Y. K. Xiao. *Rock Mineral Anal.* **19**, 169 (2000).
- [91] G. H. Swihart, P. B. Moore. *Geochim. Cosmochim. Acta* **53**, 911 (1989).
- [92] T. Ishikawa, E. Nakamura. *Earth Planet. Sci. Lett.* **117**, 567 (1993).
- [93] M. E. Wieser, S. S. Iyer, H. R. Krouse, M. I. Cantagallo. *Appl. Geochem.* **16**, 317 (2001).
- [94] R. A. Vanderpool, P. E. Johnson. *J. Agric. Food. Chem.* **40**, 462 (1992).
- [95] P. M. Kroopnick. *Deep-Sea Res.* **32**, 57 (1985).
- [96] A. Nissenbaum, B. J. Presley, I. R. Kaplan. *Geochim. Cosmochim. Acta* **36**, 1007 (1972).
- [97] G. E. Claypool, C. N. Threlkeld, P. N. Mankeiwicz, M. A. Arthur, T. F. Anderson. In *Initial Reports- Deep Sea Drilling Project*, v. **84**, p. 683 (1985).
- [98] P. Deines, D. P. Gold. *Geochim. Cosmochim. Acta* **37**, 1709 (1973).
- [99] P. Deines. *Geochim. Cosmochim. Acta* **32**, 613 (1968).
- [100] L. S. Land. In *Concepts and Models of Dolomite Formation*, D. A. Zenger (Ed.), Society Economic Paleontology Mineralogy, Special Publications, v. **28**, p. 87 (1980).
- [101] W. G. Deuser. *Earth Planet. Sci. Lett.* **8**, 118 (1970).
- [102] C. D. Keeling, S. C. Piper, M. Heimann. A three-dimensional model of atmospheric CO₂ transport based on observed winds: 4. Mean annual gradients and interannual variations. In *Aspects of climate variability in the Pacific and the Western Americas*, D. H. Peterson (Ed.), American Geophysical Union, Washington, DC, 305 (1989). doi: 10.1029/GM055p0305.

- [103] C. D. Keeling. *Geochim. Cosmochim. Acta* **13**, 322 (1958).
- [104] R. Aravena, S. K. Frape, B. J. Moore, E. M. Van Warmerdam, R. J. Drimmie. *Water Res. Manage.* **1**, 31 (1996).
- [105] K. Notsu, K. Sugiyama, M. Hosoe, A. Uemura, Y. Shimoike, F. Tsunomori, P. A. Hernandez. In *Eleventh Annual VM Goldschmidt Conference. Abstract 3224, LPI Contribution NO. 1088*, Lunar and Planetary Institute, Houston (CD-ROM), (2001).
- [106] V. M. Valysaev, Y. I. Grinchenko, V. Ye. Yerokhin, V. S. Prokhorov, G. A. Titkov. *Lithol. Miner. Resour.* **20**, 62 (1985).
- [107] G. J. Wasserburg, E. Mazor, R. H. Zartman. In *Earth and Science Meteoritics*, J. Geiss, E.D. Goldberg (Eds.), p. 219, Amsterdam, The Netherlands (1963).
- [108] M. J. Whiticar, M. Hovland, M. Kastner, J. Sample. In *Proceedings of the Ocean Drilling Program, Scientific Results*, B. Carson, G. Westbrook (Eds.), p. 385, v. 146, (1995).
- [109] NIST. Report of Investigation, Reference Materials 8562–8564, Gaithersburg, Maryland, National Institute of Standards and Technology.
- [110] K. Žák, R. Skála. *Chem. Geol. (Isotope Geosci. Sect.)* **106**, 123 (1993).
- [111] B. A. Hofmann, S. M. Bernasconi. *Chem. Geol.* **149**, 127 (1998).
- [112] C. A. Brenninkmeijer. *J. Geophys. Res. Atmos.* **98**, 10595 (1993).
- [113] C. M. Stevens, L. Krout, D. Walling, A. Venters, A. Engelkemeir, L. E. Ross. *Earth Planet. Sci. Lett.* **16**, 147 (1972).
- [114] M. H. O'Leary. *Biosci.* **38**, 328 (1988).
- [115] B. N. Smith, B. Turner. *Am. J. Bot.* **62**, 541 (1975).
- [116] P. Deines. In *Handbook of environmental isotope geochemistry, Volume 1, The Terrestrial Environment*, A.P. Fritz, J. Ch. Pontes (Eds.), p. 329, Elsevier Scientific Publishing Co., Amsterdam, The Netherlands (1980).
- [117] C. K. Paull, A. J. T. Jull, L. J. Toolin, T. Linick. *Nature* **317**, 709 (1985).
- [118] H. P. Schwarcz. In *Handbook of Geochemistry*, K.H. Wedepohl (Ed.), p. 6B1, The Stable Isotopes of Carbon, Springer-Verlag, Berlin, Germany **Section B-1**, (1969).
- [119] M. Elvert, E. Suess, J. Greinert, M. J. Whiticar. *Org. Geochem.* **31**, 1175 (2000).
- [120] Z. Sofer. *Am. Assoc. Pet. Geol. Bull.* **68**, 31 (1984).
- [121] E. D. Ghent, J. R. O'Neil. *Can. J. Earth Sci.* **22**, 324 (1985).
- [122] E. Galimov. *Geochem. International.* **22**, 118 (1985).
- [123] J. Harris. In *Mantle xenoliths*, P.H. Nixon (Ed.), p. 477, John Wiley and Sons Ltd., New York (1987).
- [124] G. Hut. *Consultants' group meeting on stable isotope reference samples for geochemical and hydrological investigations: IAEA, Vienna 16–18 September 1985: Report to the Director General, International Atomic Energy Agency* (1987).
- [125] P. Gerling, M. J. Whiticar, E. Faber. *Adv. Org. Geochem.* **13**, 335 (1988).
- [126] D. A. Merritt, J. M. Hayes, D. J. DesMarais. *J. Geophys. Res. Atmos.* **100**, 1317 (1995).
- [127] A. E. Bainbridge, H. E. Suess, I. Friedman. *Nature* **192**, 648 (1961).
- [128] M. J. Whiticar, E. Faber, M. Schoell. *Geochim. Cosmochim. Acta* **50**, 693 (1986).
- [129] R. S. Oremland, G. M. King. In *Microbial Mats: Physiological Ecology of Benthic Microbial Communities*, Y. Cohen, E. Rosenberg (Eds.), p. 180, American Society for Microbiology, Washington, DC (1989).
- [130] T. H. E. Heaton. *Atmos. Environ.* **21**, 843 (1987).
- [131] H. Moore. *Atmos. Environ.* **11**, 1239 (1977).
- [132] N. Ostrom. Stable isotopic variation in particulate organic matter and dissolved inorganic compounds in a northern fjord: Implications for present and past environments, Ph.D Dissertation. Memorial University of Newfoundland, Newfoundland, Canada (1992).
- [133] A. Mariotti, C. Lancelot, G. Billen. *Geochim. Cosmochim. Acta* **48**, 549 (1984).
- [134] S. G. Horrigan, J. P. Montoya, J. L. Nevins, J. J. McCarthy. *Estuar. Coast. Shelf Sci.* **30**, 393 (1990).
- [135] A. Mariotti, A. Landreau, B. Simon. *Geochim. Cosmochim. Acta* **52**, 1869 (1988).
- [136] H. D. Freyer, K. Kobel, R. J. Delmas, D. Kley, M. R. Legrand. *Tellus B* **48**, 93 (1996).
- [137] E. Wada, R. Shibata, T. Torii. *Nature* **292**, 327 (1981).
- [138] C. Kreitler. Determining the source of nitrate in groundwater by nitrogen isotope studies, Ph.D. Dissertation. University of Texas Austin, Texas, Bureau of Economic Geology Report of Investigations No. 83 (1974).
- [139] J. K. Böhlke, G. E. Ericksen, K. Revesz. *Chem. Geol.* **136**, 135 (1997).
- [140] J. N. Densmore, J. K. Böhlke. In *Interdisciplinary Perspectives on Drinking Water Risk Assessment and Management*, E.G. Reichard, F.S. Hauchman, A.M. Sancha (Eds.), p. 63, International Association of Hydrological Sciences Publication 260, (2000).
- [141] H. D. Freyer, A. I. M. Aly. *J. Environ. Qual.* **3**, 405 (1974).
- [142] G. B. Shearer, D. H. Kohl, B. Commoner. *Soil Science* **118**, 308 (1974).
- [143] J. K. Böhlke, R. L. Smith, K. M. Revesz, T. Yoshinari. *Trans. Am. Geophys. Union* **81**, S186 (2000).
- [144] H. Moore. *Tellus* **26B**, 169 (1974).
- [145] N. Yoshida, S. Matsuo. *Geochem. J.* **17**, 231 (1983).
- [146] N. Yoshida, H. Morimoto, M. Hirano, I. Koike, S. Matsuo, E. Wada, T. Saino, A. Hattori. *Nature* **342**, 895 (1989).
- [147] T. Yoshinari, M. A. Altabet, S. W. A. Naqvi, L. Codispoti, A. Jayakumar, M. Kuhland, A. Devol. *Mar. Chem.* **56**, 253 (1997).
- [148] A. Mariotti. *Nature* **303**, 685 (1983).
- [149] J. C. Vogel, A. S. Talma, T. H. E. Heaton. *J. Hydrol.* **50**, 191 (1981).

- [150] R. L. Smith, B. L. Howes, J. H. Duff. *Geochim. Cosmochim. Acta* **55**, 1815 (1991).
- [151] B. Marty, E. Gunnlaugsson, A. Jambon, N. Oskarsson, M. Ozima, F. Pineau, P. Torssander. *Chem. Geol.* **91**, 207 (1991).
- [152] P. Allard. In *Forecasting Volcanic Events, Developments in Volcanology*, H. Tazieff, J.-C. Sabroux (Eds.), p. 337, Elsevier, New York **v. 1**, (1983).
- [153] L. Stroud, T. O. Meyer, D. E. Emerson. U.S. Department of the Interior, Bureau of Mines, Report of Investigation 6936 (1967).
- [154] V. R. Eichmann, A. Plate, W. Behrens, H. Kroepelin. *Erdoel Kohle* **24**, 2 (1971).
- [155] G. B. Shearer, J. O. Legg. *Soi. Sci. Soc. Am. Proc.* **39**, 896 (1975).
- [156] M. Zschiesche. Entwicklung proben chemischen Verfahren zur Bestimmung der isotonen Zusammensetzung des N aus Gasen, Gesteinen, und N-Lieferanten für bakteriologische Modelluntersuchungen, Ph.D. Dissertation. Karl-Marx-Universität, Leipzig, Germany (1972).
- [157] M. A. Altabet, J. J. McCarthy. *Deep Sea Res. Part A. Ocean. Res. Papers* **32**, 755 (1985).
- [158] T. Hoering. *Science* **122**, 1233 (1955).
- [159] D. Rigby, B. D. Batts. *Chem. Geol.* **58**, 273 (1986).
- [160] T. C. Hoering, H. E. Moore. *Geochim. Cosmochim. Acta* **13**, 225 (1958).
- [161] H. Mizutani, H. Hasegawa, E. Wada. *Biogeochemistry* **2**, 221 (1986).
- [162] G. E. Bebout, M. L. Fogel. *Geochim. Cosmochim. Acta* **56**, 2839 (1992).
- [163] D. Haendel, K. Muhle, H.-M. Nitzsche, G. Stiehl, U. Wand. *Geochim. Cosmochim. Acta* **50**, 749 (1986).
- [164] D. P. Matthey, L. P. Carr, R. H. Carr, I. P. Wright, C. T. Pillinger. In *The Early Earth: The Interval from Accretion to the Older Archean*, Lunar and Planetary Institute Technical Report, **v. 85-01**, p. 59 (1985).
- [165] K. Mayne. *Geochim. Cosmochim. Acta* **12**, 185 (1957).
- [166] H. D. Freyer. *Tellus A* **30**, 83 (1978).
- [167] L. J. Moore, L. A. Machlan, W. R. Shields, E. L. Garner. *Anal. Chem.* **46**, 1082 (1974).
- [168] D. J. Velinsky, M. L. Fogel, J. F. Todd, B. M. Tebo. *Geophys. Res. Lett.* **18**, 649 (1991).
- [169] D. J. Velinsky, J. R. Pennock, J. H. Sharp, L. A. Cifuentes, M. L. Fogel. *Mar. Chem.* **26**, 351 (1989).
- [170] H. D. Freyer. *Pure Appl. Geophys.* **116**, 393 (1978).
- [171] V. F. Volynets, I. K. Zadorozhny, K. P. Florensky. *Geokhimiya* **5**, 587 (1967).
- [172] M. Drechsler. Entwicklung einer probenchemischen Methode zur Präzisionsisotopenanalyse am Stickstoff biogener Sedimente: Aussagen der Stickstoffisotopenvariationen zur Genese des Stickstoffs in Erdgasen, Ph.D. Dissertation. AdW der DDR, Leipzig, Germany (1976).
- [173] P. Kroopnick, H. Craig. *Science* **175**, 54 (1972).
- [174] H. Craig. In *McGraw-Hill Yearbook of Science and Technology*, p. 268, Isotopic Composition of Ocean Water, McGraw-Hill, New York (1967).
- [175] L. Aldaz, S. Deutsch. *Earth Planet. Sci. Lett.* **3**, 267 (1968).
- [176] E. A. Calwell. An understanding of factors controlling isotopic ratios of wine as a potential surrogate of past precipitation, M.Sc. Thesis. University of Nevada, Las Vegas, Nevada (1995).
- [177] R. J. Francey, P. P. Tans. *Nature* **327**, 495 (1987).
- [178] M. H. Thiemens, T. L. Jackson, K. Mauersberger, B. Schueler, J. Morton. *Geophys. Res. Lett.* **18**, 669 (1991).
- [179] T. B. Coplen, C. Kendall, J. Hopple. *Nature* **302**, 236 (1983).
- [180] K. J. Murata, I. Friedman, B. M. Madsen. In U.S. Geological Survey Professional Paper 614-B, p. B1 (1969).
- [181] G. D. Garlick. "The stable isotopes of oxygen", in *Handbook of Geochemistry*, K.H. Wedepohl (Ed.), p. 8B1, Springer-Verlag, Berlin, Germany (1969).
- [182] K. Suwa, S. Oana, H. Wada, S. Osaki. *Phys. Chem. Earth* **9**, 735 (1975).
- [183] G. Faure, J. Hoefs, L. M. Jones, J. B. Curtis, D. E. Pride. *Nature* **332**, 352 (1988).
- [184] A. Makhnach, N. Mikhajlov, V. Shimanovich, I. Kolosov. *Sediment Geol* **94**, 85 (1994).
- [185] T. Pérez, S. E. Trumbore, S. C. Tyler, E. A. Davidson, M. Keller, P. B. de Camargo. *Global Biogeochem. Cycles* **14**, 525 (2000).
- [186] A. Amberger, H. L. Schmidt. *Geochim. Cosmochim. Acta* **51**, 2699 (1987).
- [187] K. W. J. Williard, D. R. DeWalle, P. J. Edwards, W. E. Sharpe. *J. Hydrol.* **252**, 174 (2001).
- [188] L. P. Knauth, D. R. Lowe. *Earth Planet. Sci. Lett.* **41**, 209 (1978).
- [189] L. D. Labeyrie, J. J. Pichon, M. Labracherie, P. Ippolito, J. Duprat, J. C. Duplessy. *Nature* **322**, 701 (1986).
- [190] Y. Kolodny, B. Luz, O. Navon. *Earth Planet. Sci. Lett.* **64**, 398 (1983).
- [191] J. D. Bryant, B. Luz, P. N. Froelich. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* **107**, 303 (1994).
- [192] A. Longinelli, S. Nuti. *Earth Planet. Sci. Lett.* **5**, 13 (1968).
- [193] A. Shemesh, Y. Kolodny, B. Luz. *Earth Planet. Sci. Lett.* **64**, 405 (1983).
- [194] P. Blattner, G. W. Grindley, C. J. Adams. *Geochim. Cosmochim. Acta* **61**, 569 (1997).
- [195] J. K. Böhlke, J. C. Alt, K. Muehlenbachs. *Can. J. Earth Sci.* **21**, 67 (1984).
- [196] A. L. Norman, H. R. Krouse. In *Atmospheric Chemistry, Papers from the 9th World Clean Air Congress*, Critical Issues in the Global Environment, Air and Waste Management Association, Pittsburgh, Pennsylvania, **v. 2**, Paper IU8.01 (1992).
- [197] Y. Mizutani, T. A. Rafter. *Geochem. J.* **6**, 183 (1973).

- [198] A. Longinelli. In *Handbook of Environmental Isotope Geochemistry, Volume 3*, P. Fritz, J. Ch. Fontes (Eds.), p. 219, Elsevier Scientific Publishing Co., Amsterdam, The Netherlands (1989).
- [199] M. J. Hendry, H. R. Krouse, M. A. Shakur. *Water Resour. Res.* **25**, 567 (1989).
- [200] A. Longinelli, H. Craig. *Science* **156**, 56 (1967).
- [201] C. J. Yonge, H. R. Krouse. *Chem. Geol. (Isotope Geosci. Sect.)* **65**, 427 (1987).
- [202] H. Sakai. *Geochem. J.* **5**, 79 (1971).
- [203] M. P. Cecile, M. A. Shakur, H. R. Krouse. *Can. J. Earth Sci.* **20**, 1528 (1983).
- [204] J. Dunbar, A. T. Wilson. *Anal. Chem.* **54**, 590 (1982).
- [205] E. B. Bolou-Bi, N. Vigier, A. Brenot, A. Poszwa. *Geostandards Geoanal. Res.* **33**, 95 (2009).
- [206] E. Tipper, A. Galy, M. Bickle. *Earth Planet. Sci. Lett.* **247**, 267 (2006).
- [207] E. B. Bolou-Bi, N. Vigier, A. Poszwa, J.-P. Boudot, E. Dambrine. *Geochim. Cosmochim. Acta* **87**, 341 (2012).
- [208] N. Pearson, W. Griffin, O. Alard, S. Y. O'Reilly. *Chem. Geol.* **226**, 115 (2006).
- [209] F. Wombacher, A. Eisenhauer, F. Böhm, N. Gussone, M. Regenberg, W.-C. Dullo, A. Rüggeberg. *Geochim. Cosmochim. Acta* **75**, 5797 (2011).
- [210] A. Galy, N. S. Belshaw, L. Halicz, R. K. O'Nions. *Int. J. Mass Spectrom.* **208**, 89 (2001).
- [211] C. Douthitt. *Geochim. Cosmochim. Acta* **46**, 1449 (1982).
- [212] D. L. Lu, G. J. Wan. *Geol. Explor.* **28**, 28 (1992).
- [213] T. Ding, S. Jiang, D. Wan, Y. Li, J. Li, H. Song, Z. Liu, X. Yao. *Silicon Isotope Geochemistry*, Geological Publishing House, Beijing (1996).
- [214] M. J. Huang, R. Q. Li, D. Y. Liu, Z. J. Shen, S. H. Tang, W. S. Chen. A study on exploration mineralogy and mineral prediction of rock-bounded metallogenic series of ore deposits in southern Hunan (in Chinese). *Hunan Bureau of Geology and Mineral Resources*, 97 (1991).
- [215] I. Basile-Doelsch, J. D. Meunier, C. Parron. *Nature* **433**, 399 (2005).
- [216] S. Y. Wu. *The submarine hydrothermal chimney of the Mariana Trough and sediments in the Philippine Sea (in Chinese)*. Oceanic Publishing House, Beijing (1991).
- [217] D. Tiping, W. Defang, L. Jincheng, J. Shaoyong, S. Hebing, L. Yanhe, L. Zhijian. *Kuangchang Dizhi (Mineral Deposits)* **7**, 90 (1988).
- [218] R. S. Kaufmann, A. Long, D. J. Campbell. *Am. Assoc. Pet. Geol. Bull.* **72**, 839 (1988).
- [219] B. Ransom, A. J. Spivack, M. Kastner. *Geology* **23**, 715 (1995).
- [220] W. G. Liu, Y. K. Xiao, Q. Z. Wang, H. P. Qi, Y. H. Wang, Z. M. Zhou, P. V. Shirodkar. *Chem. Geol.* **136**, 271 (1997).
- [221] R. S. Kaufman, S. Arnórsson. "37Cl/35Cl ratios in Icelandic geothermal waters", *Fifth International Symposium on Water Rock Interaction, Extended Abstracts: v. 5*, p. 325 (1986).
- [222] A. Long, C. J. Eastoe, R. S. Kaufmann, J. G. Martin, L. Wirt, J. B. Finley. *Geochim. Cosmochim. Acta* **57**, 2907 (1993).
- [223] R. S. Kaufmann, A. Long, H. W. Bentley, S. N. Davis. *Nature* **309**, 338 (1984).
- [224] T. C. Hoering, P. L. Parker. *Geochim. Cosmochim. Acta* **23**, 186 (1961).
- [225] A. J. Magenheimer, A. J. Spivack, P. J. Michael, J. M. Gieskes. *Earth Planet. Sci. Lett.* **131**, 427 (1995).
- [226] N. Tanaka, D. M. Rye. *Nature* **353**, 707 (1991).
- [227] N. Jendrzewski, H. G. M. Eggenkamp, M. L. Coleman. *Appl. Geochem.* **16**, 1021 (2001).
- [228] O. Shouakar-Stash, S. V. Alexeev, S. K. Frape, L. P. Alexeeva, R. J. Drimmie. *Appl. Geochem.* **22**, 589 (2007).
- [229] D. Carrizo, M. Unger, H. Holmstrand, P. Andersson, Ö. Gustafsson, S. P. Sylva, C. M. Reddy. *Environ. Chem.* **8**, 127 (2011).
- [230] M. Rehkämper, A. N. Halliday. *Geochim. Cosmochim. Acta* **63**, 935 (1999).
- [231] M. Rehkämper, M. Frank, A. Halliday, J. Hein. In *11th Biannual Symposium, Strassbourg, Book of Abstracts*, (2001).
- [232] T. B. Coplen, Y. Shrestha. *Tables and Charts for Isotope-Abundance Variations and Atomic Weights of Selected Elements: 2016: U.S. Geological Survey Data Release*, (2016) <http://dx.doi.org/10.5066/F7GF0RN2>.
- [233] H. A. J. Meijer, W. J. Li. *Isotopes Environ. Health Stud.* **34**, 349 (1998).
- [234] I. Friedman, J. O'Neil, G. Cebula. *Geostand. Newslett.* **6**, 11 (1982).

Note: Republication or reproduction of this report or its storage and/or dissemination by electronic means is permitted without the need for formal IUPAC or De Gruyter permission on condition that an acknowledgment, with full reference to the source, along with use of the copyright symbol ©, the name IUPAC, the name De Gruyter, and the year of publication, are prominently visible. Publication of a translation into another language is subject to the additional condition of prior approval from the relevant IUPAC National Adhering Organization and De Gruyter.