

Recent developments and trends in the application of strontium and its isotopes in biological related fields

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1 **Abstract**

2

3 Strontium is a chemical element without biological functions in humans. In fact, only
4 two biological roles are known, both as a biomineral constituent. However, strontium
5 and calcium (a significant biometal) present chemical similarities; hence, the absorption
6 of the former by living organisms is plausible. Based on the particular properties of
7 isotopes of strontium several applications of this chemical element in biological
8 sciences have been developed. These include its radioactive and non-radioactive
9 isotopes in medical applications or resorting to its stable isotopes as analytical tools in
10 isotope fingerprinting ($^{87}\text{Sr}/^{86}\text{Sr}$) to study dietary habits and migration patterns of
11 ancient populations, food authentication and forensic sciences. This article, reviews
12 papers published between 2012-2016, highlights the use of strontium isotope ratios for
13 such biological related applications and compiles an analytical database, providing a
14 valuable tool for future studies in the area.

15

16 **Keywords**

17 Strontium; isotope ratio; biological marker; medicine; food authentication; dietary
18 habits; migration pattern; forensic science; MC ICP-MS; TIMS

19

20 **List of abbreviations**

21 A – amplitude of the interval

22 ATSDR – Agency for Toxic Substances and Disease Registry

23 BC – before christ

24 bw – bodyweight

25 ca – circa, approximately

26 CHILI - chicago instrument for laser ionization

27 ICP-Q-MS - inductively coupled plasma quadrupole mass spectrometry

28 IRMS – isotope ratio mass spectrometry

29 LA- MC ICP-MS – laser ablation multicollector inductively coupled plasma mass
30 spectrometry

31 MC ICP-MS - multicollector inductively coupled plasma mass spectrometry

32 n.a. – not available

33 PDO – protected designation of origin

34 RSD - relative standard deviation

35 TIMS - thermal ionization mass spectrometry

36 TPB – total procedural blank

37 1. Introduction

38

39 1.1 General considerations

40 Strontium is a very reactive metal that quickly oxidizes forming an oxide and therefore it
41 does not occur free in nature [1]. It is a lithophile metallic element, which is found in
42 nature as Sr^{2+} , and may substitute Ca^{2+} in a variety of rock-forming minerals,
43 particularly Ca rich minerals, including feldspar, gypsum, plagioclase, apatite and,
44 especially, calcite and dolomite [2,3]. Sr in rocks is found with variable concentrations
45 depending upon their nature and composition. In igneous rocks Sr is enriched in
46 basalts, andesites and dacites, while insignificant in ultramafic rocks [4,5]. In
47 sedimentary rocks Sr is enriched in carbonate rocks [5]. Weathering is responsible for
48 releasing strontium from rocks into soils and subsequently to plants and animals, and
49 for entering the oceans primarily by river transport of sediments [6]. Human activities
50 also contribute to the release of strontium into the atmosphere, as aerosols [7].

51 Strontium has four stable isotopes ^{88}Sr , ^{87}Sr , ^{86}Sr and ^{84}Sr with relative average Earth's
52 abundances of 82.5845%, 7.0015%, 9.8566% and 0.5574%, respectively [8]. These
53 were formed during the stellar synthesis [7]. ^{87}Sr has the particularity of being the only
54 stable isotope of strontium that is radiogenic. The radioactive decay of ^{87}Rb (half-life \approx
55 9.23×10^9 years [9]) into the radiogenic isotope ^{87}Sr leads to an increase in the natural
56 relative abundance of the last, which is more significant for both higher concentrations
57 of Rb and age of the soils as shown in Fig. 1. $^{87}\text{Sr}/^{86}\text{Sr}$ is considered a valuable tracer
58 of strontium in rocks and minerals since it can be related to their Rb/Sr [10], providing
59 valuable information on both age and geochemical origin of the geologic materials
60 [5,11]. Current $^{87}\text{Sr}/^{86}\text{Sr}$ values of geochemical reservoirs and rocks can be found
61 between 0.702 for the depleted mantle (low Rb/Sr) and above 0.943 for old continental
62 crust [12]

63 Once absorbed by plants the $^{87}\text{Sr}/^{86}\text{Sr}$ value is kept across the trophic levels since,
64 unlike the organic components of foodstuffs that can be influenced by agronomical
65 conditions [13] or by technological factors (e.g. extraction systems, processing
66 filtrations, storage conditions) [14,15], Therefore, $^{87}\text{Sr}/^{86}\text{Sr}$ is constant across the food
67 web, since they are not apparently influenced by external factors (e.g. pollution,
68 climate) or fractionation after absorption by living organisms [5,6]. Such has been
69 demonstrated by matching fish scales and otoliths to the surrounding water [16] or by
70 studying strontium isotope ratios across three trophic levels (soil-plant-butterfly) [17]. In
71 addition, strontium presents chemical similarities with calcium (an important element for

72 all organisms), hence promoting the uptake of the former by plants and animals [6],
73 regardless of its biological relevancy. Therefore $^{87}\text{Sr}/^{86}\text{Sr}$ in biological samples,
74 independently of the trophic level, can be used as tracers for geographical provenance
75 since they reflect the original sources of strontium. Also radiogenic isotopes can be
76 used as geochemical tracers contributing in studies of chemical weathering and soil
77 genesis, cation provenance and mobility, and the chronostratigraphic correlation of
78 marine sediments[5].

79 Isotopic systems have been widely employed in various fields of research and several
80 applications, including in the Health Sciences [18]. It is possible to find several works
81 since the 1970s dealing with isotope geochemistry [19], climate and environmental
82 concerns [20,21] or even archaeology [22]. If at first, the most common isotopes in
83 such researches were mainly from light elements, such as hydrogen, oxygen, carbon,
84 nitrogen and sulphur; developments in the analytical techniques have allowed
85 broadening the range of elements, including the isotopic analysis of heavier elements
86 such as strontium.

87 Additionally to its four stable isotopes, strontium has twenty nine radioactive isotopes
88 [7], which defines as the property of a nuclide of undergoing spontaneous nuclear
89 transformations with the emission of radiation [23]. The unstable ^{89}Sr and ^{90}Sr result
90 from anthropogenic activity [24]. They are formed during nuclear reactor operations
91 and nuclear explosions by the fission of uranium and plutonium (^{235}U , ^{238}U or ^{239}Pu) [7].
92 Some of these radioactive isotopes have already demonstrated its usefulness in
93 different medical applications as will be discussed in chapter 2.1.

94 Due to its potential application in a diversity of research areas strontium has been the
95 focus of interest in several studies as can be seen in recent reviews. Review papers
96 have been published in 2004 on the biological role of strontium [1] and in 2006 on the
97 biogeochemistry of strontium [6]. From to 2005 to present several reviews including,
98 but not exclusively, strontium isotopic analysis can be found in the literature, focused
99 on different subjects, such as geochemistry, ecogeochemistry and archaeology [25–27]
100 as well as analytical methodologies [28–30]. Food authentication presents itself as the
101 application with most review papers on the subject of stable isotopic techniques. This is
102 most likely due to consumer's growing interest and concern towards food safety as well
103 as current legislation. Although strontium is mentioned in some of such papers [31–36]
104 the remaining are restricted to Isotope Ratio Mass Spectrometry (isotopic composition
105 of light elements) leaving out the non-traditional heavier isotopes [37–40]. Most reviews
106 published have mainly aimed at the different applications of stable isotope analysis.

107 Based on these we will in addition compile a database of values for different biological
108 matrices providing a valuable tool for future works.

109 The isotope ratio analysis data treatment is just as important as the analytical
110 techniques employed in the isotope ratio measurements. Several statistical tools have
111 already been described in previous papers [31,32,41] and therefore the topic is out of
112 the scope of the current work.

113 Over the last 4 years an increasing number of studies have been published covering
114 the use of strontium isotopes in distinct areas of biological research. This review
115 focuses on strontium and its relationships with biological structures as well as the
116 potential applications of its isotopes in biological sciences and correlated scientific
117 fields. We will consider the application of strontium isotope ratios in health and
118 medicine as well as in fields associated with biological samples, namely food
119 authentication, archaeology and forensic sciences, reviewing scientific papers
120 published in the last five years (2012 to 2016), and therefore covering a time period for
121 which the topic has not yet been discussed. This wide approach based on strontium
122 can be helpful as support of a more integrated research in biological related sciences.

123

124 1.2 Biological role and toxicity

125

126 Strontium is considered a non-essential trace element for humans [42]. In fact, there
127 are only two organisms for which its biological role has been identified, both are
128 biominerals. The Acantharea, is a small group of protists that precipitate a strontium
129 salt as a major exoskeleton constituent, celestite (strontium sulfate, SrSO_4) [43]. The
130 second is a cyanobacterium that forms intracellular amorphous carbonate inclusions
131 containing strontium together with calcium, magnesium and barium, as benstonite [44].
132 These biominerals can provide information on the metabolism of those organisms, as
133 well as on the biogeochemical cycles of strontium or past environmental conditions. For
134 instances, the Sr/Ca value of corals is related to the temperature of water during
135 growth [45].

136 Strontium and calcium have similar atomic radius, 215 and 197pm, respectively, and
137 close chemical properties [46]. Also strontium is the sixteenth most abundant element
138 in the Earth's crust [47] and the ninth in seawater [48], with average values of 200-300
139 mg/kg and 8 mg/kg, respectively [6,24]. For such reasons, although apparently without
140 a biological role, strontium is found in several biological matrices. In table 1, values of
141 strontium in some biological samples are presented.

142

143 **Table 1** Strontium values in biological samples (mg/kg).

Matrix	Values (mg/kg)	Reference
Bread	0.607 – 1.53	[7,49]
Vegetables	0.007 - 12.6	
Cereals	0.376 - 1.3	
Fish	3.5	[7]
Milk	0.128 – 0.432	[49]
Eggs	0.345 – 0.792	
Olive oil	0.002 – 0.014	[50]
Human hair	0.7 – 45.1	[51,52]
Tooth enamel	332 – 826	[53]

144

145 The main pathway of exposure to strontium for humans is through the inhalation of
 146 aerosols and the ingestion of water and food [24], in particular of cereals and
 147 vegetables. It is estimated that a typical diet provides 2 to 4 mg of strontium per day [1].
 148 Strontium and calcium present similar distributions in the human body, with
 149 approximately 99% of the total body burden in the skeleton [24]. However, the total
 150 amount of strontium in human bodies is much smaller than calcium. While calcium
 151 represents 1.4% of total body mass, strontium accounts for only 0.00044% [1]. Several
 152 factors contribute to this, namely that calcium is more easily absorbed than strontium,
 153 the renal excretion of the last is three times higher than the former [1], and a much
 154 higher daily intake of calcium over strontium [7,54]. In addition, strontium suffers
 155 biopurification, i.e. for the next highest trophic level the Sr/Ca is reduced by a factor of
 156 five [6] and humans do not belong to the lowest trophic levels.

157 Although some strontium salts have been identified as genotoxic human carcinogens,
 158 namely strontium chromate (CrO_4Sr) used in the production of pigments, the toxicity is
 159 not caused by strontium but from hexavalent chromium [24]. According to the Agency
 160 for Toxic Substances and Disease Registry (ATSDR) there is no direct evidence of
 161 toxicity by stable strontium isotopes in humans under normal environmental exposures.
 162 A minimal risk level for intermediate duration oral exposure to stable strontium is 2
 163 mg/(kg.bw.day) [24].

164 On the other hand, exposure to radioactive strontium isotopes can lead to pathogenic
165 states, such as necrotic lesions and bone cancer, although the dose, the route of
166 exposure and the mass number of the isotope in question, affect the severity of the
167 disease. Within all of its radioactive isotopes ^{90}Sr is the most dangerous due to its
168 relatively long half-life (28.79 years [9]) and the bone-seeking properties of strontium
169 [24]. In fact, little interest on strontium in biology sciences occurred until the evidence
170 that ^{90}Sr could substitute calcium in bone [42].

171

172 1.3 Analytical methods

173

174 Isotope ratio mass spectrometry (IRMS) has been used for determination of lighter
175 isotopic composition elements (e.g., H, C, N, O and S), while thermal ionization mass
176 spectrometry (TIMS) was the unique technique that allowed the same purpose to the
177 'heavier' elements, with enough precision [55]. However, this technique is also
178 characterized by some disadvantages, such as limited ionization efficiency for
179 elements with ionization energy above 7.5 eV [55], extensive sample preparation and
180 long measurement time [56]. The development of the multicollector inductively coupled
181 plasma mass spectrometry (MC ICP-MS) brought several advantages over TIMS,
182 namely high ionization yield and versatile sample introduction systems well established
183 in ICP spectrometry and also, since isotopic determinations occur simultaneously, no
184 time-dependent mass fractionation as observed in TIMS analysis [57]. On the other
185 hand TIMS is less prone to matrix effects and presents lower instrumental isotopic
186 fractionation [27]. The radioactive decay of isotopes leads to extremely low differences
187 in isotopic compositions, thus few techniques are capable of correctly performing
188 isotope ratio measurements. Developments in the analytical instruments have provided
189 high precision and accuracy measurement which are a fundamental requirement for
190 the widespread use of isotope ratios in different applications [41]. Both TIMS and MC
191 ICP-MS have become advanced techniques for the measurement of non-traditional
192 isotopic compositions at high precision, namely strontium.

193 Recently the hypothesis of measuring the $^{87}\text{Sr}/^{86}\text{Sr}$ as part of proton activation analyses
194 method by using a proton accelerator was tested [58]. Results were compared with
195 TIMS and, although still at an early stage, were similar for SRM 987. Another new
196 technique proposed for isotope measurements of several elements in cosmochemistry
197 is the Chicago Instrument for Laser Ionization (CHILI). Still under optimization CHILI,
198 which has been designed for the analysis of small samples, has produced its first
199 meaningful scientific results for presolar grains [59].

200 Since our main goal is to present applications of strontium and its isotopes in biological
201 related fields as well as the analytical results obtained in such studies, a deeper
202 analysis of the analytical challenges associated with either technique is beyond the
203 scope of this review. The subject has already been approached by different authors
204 and thus will not be further developed here [11,27,36,60,61].

205 Strontium isotope ratios have been used over the past 40 years for geochronology or
206 as a geochemical tracers for past geological processes, such as the chemical
207 differentiation of the Earth, with special emphasis to $^{87}\text{Sr}/^{86}\text{Sr}$ ratio [62,63]. Nowadays
208 radiogenic isotopes are at the basis of various biological applications as presented in
209 the following chapters.

210

211 2. Applications in biological related fields

212

213 2.1 Medical applications

214

215 Even though strontium is considered without any biological role in humans some of its
216 radioactive isotopes have proven to be useful in medical applications. The mode of
217 decay as well as their half-life determines both toxicity and potential for medical
218 applications.

219 Since strontium and calcium have a similar behaviour in the human body, including the
220 same mechanisms for absorption from the gastrointestinal tract, bone accumulation,
221 blood clotting, muscular contraction, as shown in many pharmacological investigations
222 with isolated cells or organs, the response to stimulation tends to be weaker because
223 strontium is not so well adapted to these purposes [1,42] Both strontium and calcium
224 are excreted primarily in the urine. Strontium radioactive isotopes are used in several
225 medical applications. ^{82}Sr is used in nuclear medicine for the preparation of ^{82}Rb to
226 positron-emission tomography (PET) in cardiovascular diseases diagnosis [64], ^{85}Sr in
227 radiological imaging of bones [24] and metabolic studies [1], ^{89}Sr , that emits β^-
228 radiation, relieves pain, improving the quality of life of patients with bone metastases
229 [65] and low levels of ^{90}Sr irradiation prevents the reappearance of primary pterygia
230 [66].

231 In addition to its radioactive isotopes also stable strontium has been used in the
232 treatment of illness. The drug strontium ranelate (Protelos/Osseor), which is composed
233 by an organic moiety (ranelic acid) and two atoms of stable nonradioactive strontium
234 [67], has shown promising results in the treatment of post-menopausal osteoporosis,

235 by decreasing the risk of fractures. However, due to side effects, the European
236 Medicines Agency has recommended its use only in severe osteoporosis, for post-
237 menopausal women and adult men at high risk of fracture, and without a previous
238 history of heart or circulatory problems [68]. In addition, its administration to patients
239 with knee osteoarthritis has been described as a milestone, since it has produced
240 clinically meaningful effects on pain relief and physical functions [69].

241

242

243 2.2 Food provenance

244

245 Radioactive decay in rocks of different ages leads to different isotope ratios in the labile
246 fraction of the soils; the absorption of the isotopes by plants is reflected in the final food
247 products, giving a unique isotopic signature associated with a geographical
248 provenance, known as isotopic fingerprinting.

249 In recent years, it has been noticeable a growing interest by consumers on the
250 geographical origin of the food that they eat, to avoid serious foodborne diseases [13].

251 Furthermore, the European legislation on regional food protection considers the
252 authenticity as a quality criteria for the food, and its ingredients, subject that has gained
253 increasing importance over the past years [31].

254 Plants absorb elements mainly through their roots; therefore isotope ratios of plants
255 depend both on the soil and climate conditions in which they grow. These reflect
256 themselves on the isotopic composition of the final products, providing a unique
257 fingerprint for studying traceability of numerous foodstuffs. The development of new
258 advanced analytical techniques, over the last ten years, made possible the
259 determination of the geographic origin of most foodstuffs through the analysis of its
260 elemental and isotopic compositions [13]. Multi-isotope or single-isotope ratios can
261 provide unique and representative fingerprints, thus making it possible to discriminate
262 the origin of food samples.

263 Strontium is usually easily absorbed from soil by plants, even though there is no direct
264 evidence of any metabolic function of the element in plants [7]. Hence, the strontium
265 isotopic signature is a fingerprint representative of the soil on which plants were
266 cultivated. It has been shown for rice and hot peppers, that the contribution of bedrock
267 and the silicate fraction of the soil to bioavailable strontium is insignificant, while the
268 composition of the water and the exchangeable fraction of the soil have the higher
269 influence on bioavailable strontium [70]. On the other hand, Song et al. showed,
270 through the analyses of fruits leaves, rocks and soils, that, except in the silicate

271 fractions, strontium isotope ratios of bedrocks were maintained in soils and plants [71],
272 Once absorbed, strontium is distributed to other parts of the plant such as leaves or
273 fruits, turning it into a constituent of foodstuffs and thus entering the food web [7].
274 Subsequently, examples of foodstuffs will be presented.

275 Wine is most likely the food commodity with the highest number of studies in the area
276 of geographical origin authentication. This is probably due to the strict regulation of this
277 market and to the high commercial value achieved by wines from certain “Protected
278 Designation of Origin” (PDO). It has been recognized for a long time that the terroir
279 from which the wine is originated is essential to ensure its final quality. In 2013 a study
280 on Lambrusco wines, reported a good match between the strontium isotope ratios
281 monitored in the bio-available fraction of soils and their respective grape juices values
282 [72]. Even so a few years later, and although the strontium isotopic signature between
283 soils and Lambrusco wines were in agreement, it was not possible to distinguish
284 products from different years [73]. The same conclusions were obtained by Marchionni
285 *et al.* [74] since this study showed no influence of the production year or the
286 winemaking process in the $^{87}\text{Sr}/^{86}\text{Sr}$. Instead the authors concluded that the isotopic
287 fingerprint of wines is mainly determined by the bioavailable fraction of the soils on
288 which the vineyards are settled.

289 Olive oils present sensory and nutritional properties often related to the geographical
290 origin and cultivar of the olive fruits employed [34]. It is a relevant constituent of the
291 Mediterranean diet and the European Union is responsible for 77% of olive oil world
292 production and 70% of consumption, mainly produced by Mediterranean countries [75].
293 However, only recently the first work using strontium isotopes to trace the origin of olive
294 oils was published [50]. Despite of a complex matrix with high fat and low strontium
295 content (caused by its ionic form), the authors developed and validated a method for
296 strontium extraction for seven samples.

297 Other matrices, such as cheese, exhibited a wide variation in the $^{87}\text{Sr}/^{86}\text{Sr}$ which
298 allowed to distinguish products from different farmers [76] while in Italian tomatoes and
299 tomato derived products strontium isotope ratios were sufficiently discriminative to
300 successfully distinguish these from similar Chinese products [77].

301 In 2014 the origin of peanuts from different countries was compared exhibiting ratios of
302 $^{87}\text{Sr}/^{86}\text{Sr}$ below 0.702 [78], as can be seen in the table 2. However, such value has
303 been considered the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ value currently found in Earth [6,12] and in
304 accordance with the results found in our review, some relevant questions may be
305 raised regarding the methodology applied. First and most importantly, is the analytical
306 method used, inductively coupled plasma - quadrupole mass spectrometry (ICP-Q-

307 MS). It is generally accepted that, unlike MC ICP-MS or TIMS (precision better than
308 0.005%), ICP-Q-MS does not provide a high enough precision for the determination of
309 isotope ratios since at best it is 0.05% [79]. Moreover, the extraction of strontium from
310 matrix was carried out using HNO₃ combined with sonication, while the most common
311 procedure is solid phase extraction following digestion, which could have led to some
312 bias in sample preparation.

313 Table 2 summarizes recent results of the strontium isotopic signature from food
314 sources.

315 ⁸⁷Sr/⁸⁶Sr has also been employed in identifying the origin of fish as well as to
316 distinguish between farmed and wild fishes [16,80–82]. On the basis of such
317 application is the fact that, similarly to what happens in human skeletal tissues (see 2.3
318 Bioarchaeology), strontium replaces for calcium in otoliths and scales. Comparing the
319 strontium isotope ratios in such calcified tissues to the values of surrounding waters
320 provides a tool to identify the origin and migration habits of such animals. While otoliths
321 are the most common structure for determining the origin of fish [81–88] scales and fin
322 rays have been suggested as a promising nonlethal alternative for provenance studies
323 [16,80,89].

324

325 **Table 2** Application of strontium isotope ratios in food authentication.

Matrices	Number of samples	Range of $^{87}\text{Sr}/^{86}\text{Sr}$			Analytical technique	Reference
		Minimum	Maximum	Mean		
Chinese cabbage	160 (cabbage)	0.70814	0.72018	0.71139	TIMS	[90]
	36 (soil)	0.70639	0.72836	0.71649		
Kimchi	29 (unwashed Kimchi)	n.a.	n.a.	0.71060	MC ICP-MS	[91]
	29 (washed Kimchi)	n.a.	n.a.	0.71099		
Hot pepper and rice	77 (plants)	0.70803	0.73909	0.71712	MC ICP-MS	[70]
	137 (soils)	0.70646	0.76470	0.71891		
	191 (water)	0.70698	0.75753	0.71881		
Rice	350 (rice)	0.704	0.721	0.709	HR-ICP-MS	[92]
Beef	206 (beef)	0.70628	0.71649	0.70978	TIMS	[93]
Onions	139 (onions)	0.70395	0.72099	0.70987	MC ICP-MS	[94]
Olive oil	7	0.70727	0.70914	0.70836	TIMS	[50]
Tomato	118 (tomato and tomato derived products)	0.70793	0.71051	0.70899	TIMS	[77]
Wine	10 (soils)	0.70772	0.71115	0.71097	TIMS	[95]
	30 (must)	0.70706	0.71266	0.70987		

	186	0.70839	0.70964	n.a.	MC ICP-MS	[73]
	22	0.7130	0.7175	n.a.	ICP-Q-MS	[96]
	45	0.70679	0.71131	0.70865	TIMS	[74]
	16 (wine)	0.70886	0.71040	n.a.		
	16 (branch)	ca. 0.7086	ca. 0.7108	n.a.	MC ICP-MS	[72]
	80 (soils)	0.70867	0.71300	n.a.		
	4 (grape)	0.70894	0.71062	0.70984		
	15 (must)	0.70899	0.71038	0.70953		
	23 (wine)	0.70898	0.71057	0.7096	TIMS	[97]
	6 (soil)	0.70995	0.71142	0.71058		
	12 (rocks)	0.70885	0.71796	0.71147		
	6 (wine)	0.708	0.715	0.710	ICP-Q-MS	[98]
	16 (grapes)	0.70945	0.71522	0.71163		
	17 (wines)	0.70988	0.71546	0.71206		
	13 (bulk soil)	0.71203	0.73418	0.72002	TIMS	[99]
	9 (labile soil)	0.70979	0.71546	0.71182		
	14 (cheese)	0.70950	0.71360	0.71156		
Cheese	12 (milk)	0.70961	0.71425	0.71192	TIMS	[76]
	6 (soil)	0.70955	0.71453	0.71185		
Coffee beans	13	0.70472	0.72027	0.70781	MC ICP-MS	[100]

Tea leaves	14	0.70482	0.71462	0.70965	MC ICP-MS	[101]
Peanut	200	ca.0.695	ca.0.726	ca.0.712	ICP-Q-MS	[78]
Poultry	105	0.70706	0.71114	0.70865	TIMS	[102]
Beer	80	ca.0.707	ca.0.718	n.a.	MC ICP-MS	[103]
Wheat	80	0.7073 ^a	0.7089 ^a	0.7081 ^a	TIMS	[104]
	54	0.711	0.712	0.71154	TIMS	[105]
Honey	79	0.7125 ^a	0.7172 ^a	0.7152 ^a	TIMS	[106]

326 ^a mean value of a region. Original values are not supplied

327

328

329 2.3 Bioarchaeology

330

331 In animals the strontium isotopic composition is a function of the surrounding
332 environment and dietary habits [5]. $^{87}\text{Sr}/^{86}\text{Sr}$ values of skeletal tissues have been used
333 to study dietary (in conjunction with other isotopic systems) and migration patterns of
334 ancient human and animal populations. In fact the employment of stable isotopes ratios
335 in archaeological studies has increased to such an extent in the latest years that they
336 are now regarded as routine analysis in researches dealing with such topics [107].

337 The similarities between calcium and strontium's chemical characteristics explains the
338 accumulation of strontium in bones and teeth [both materials in mammals are mainly
339 hydroxyapatite, $\text{Ca}_5(\text{PO}_4)_3(\text{OH})$]. However, unlike bone, that rebuilds itself through life,
340 as part of the body's maintenance, dental enamel formed during infancy remains
341 unaltered throughout the years, therefore its isotopic signature is representative of the
342 diet during the formation period of the teeth [108–110]. Post mortem diagenesis of
343 bones and teeth is defined as alteration occurring in the physical, chemical or
344 microstructural composition of such tissues following its deposition in the environment
345 [111]. Enamel is known to be less prone to post mortem diagenesis than dentine and
346 bone, which have been considered unreliable markers of strontium since they mainly
347 reflect the bioavailable strontium of burial place [112,113]. Since not all teeth are
348 formed at the same time, isotope ratios of the enamel from different teeth will represent
349 different periods of a person's life [114]. It is for this reason that the analysis of
350 strontium isotopes in tooth enamel from burial populations, has been widely applied in
351 the last years to study human migrations, hunting, trading areas and diet habits
352 amongst ancient populations [109,115–117]. It is not expectable to find an absolute
353 value for a certain geographical region. Instead a range of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ in the
354 area of interest should be considered as baseline [110]. Two possible approaches have
355 been suggested either by resorting to local fauna remains or the average of human
356 dental enamel [118]. In Germany the comparison between water, soils, floral and faunal
357 samples, both modern and archaeological, showed that contemporary water and
358 vegetation samples, particularly tree leaves, served as the best proxy for local
359 bioavailable strontium [119]. More recently it has been proposed the application of
360 Bayesian mixing analysis as a statistical technique to understand results from isotope
361 ratio analysis, which according to the authors allows interpreting strontium values
362 within a context [120].

363 A compilation of scientific results using strontium isotopes in diet and migratory
364 patterns of ancient human populations is presented in table 3.

365 **Table 3** Application of strontium isotope ratios in migration and diet studies.

Matrices	Number of samples	Range of $^{87}\text{Sr}/^{86}\text{Sr}$			Analytical technique	Geographical area	Reference
		Minimum	Maximum	Mean			
Tooth enamel	1 (human) ^a	0.7202	0.7211	0.7207	LA- MC ICP-MS	South Africa	[121]
	6 (human)	0.70941	0.71057	0.70980	MC ICP-MS	Mongolia	[122]
	20 (faunal)	0.70817	0.70831	0.70824			
	86 (human)	0.70766	0.70850	0.70812	TIMS	Guatemala	[123]
	19 (human)	0.7090	0.7109	0.7099	TIMS	Isle of Man	[124]
	3 (plants)	0.7091	0.7113	0.7103			
	29 (human)	0.70809	0.71167	0.70920	TIMS	England	[125]
	33 (human)	0.7092	0.7134	0.7104	TIMS	Wales	[126]
	133 (human)	0.70837	0.71085	0.70944	MC ICP-MS	United States of America	[108]
	20 (faunal)	0.70888	0.70968	0.70933			
	15 (human)	0.7076	0.7088	0.7084	MC ICP-MS	Vanuatu	[127]
	55 (human)	0.70670	0.72073	0.71012	MC ICP-MS	Portugal	[109]
	22 (faunal)	0.70550	0.71328	0.71031			
	100 (human)	0.70818	0.71066	0.70886	TIMS	South eastern Arabia	[115]
	104 (faunal)	0.70808	0.71042	0.70860			
53 (human)	0.7086	0.7169	0.7101	TIMS	Germany	[128]	
32 (human)	0.7046	0.7117	n.a.	TIMS	Honduras	[110]	

	77 (human)	0.7113	0.72802	0.71618		Pakistan	
	21 (faunal)	0.71471	0.72112	0.71771	TIMS	India	[53]
	3 (sediments)	0.71553	0.71594	0.71565			
	15 (human)	0.70607	0.70863	0.70781	TIMS	Belize	[129]
	109 (human)	0.7077	0.7391	0.7157		Island of Oland	
	21 (faunal)	0.7098	0.7215	0.7155	TIMS	(Baltic)	[120]
	127 (domestic animals)	0.7080	0.7101	0.7093	MC ICP-MS	India	[130]
	20 (human)	0.70828	0.71236	0.7096	TIMS	Londinium (London, England in the Roman period)	[131]
	117 (human)	0.70822	0.71621	0.71093	MC ICP-MS	Germany	[132]
	105 (human)	0.70100	0.71398	0.70911		Italy	
	2 (faunal)	0.70933	0.71031	0.70982	TIMS		[133]
	14 (human)	0.71027	0.71359	0.71168	TIMS	Portugal	[134]
	34 (human)	0.70573	0.71069	0.70764	MC ICP-MS	Peru	[135]
	41 (human)	0.70589	0.74985	0.71984	MC ICP-MS	Brazil	[136]
	35 (human)	0.70794	0.71262	0.70905		England	
	3 (faunal)	0.70774	0.71059	0.70885	TIMS		[137]
	8 (human)	0.71100	0.71956	0.71449		Estonia	
	7 (faunal)	0.71056	0.71594	0.71217	TIMS		[138]
	2 (human)	0.71100	0.71106	0.71103	TIMS	England	[139]
Tooth enamel and	12 (human enamel)	0.70820	0.71314	0.71060	MC ICP-MS	France	[140]

bone	13 (human bones)	0.70976	0.71226	0.71064			
	60 (human enamel)	0.70849	0.70925	0.70890			
	12 (human bones)	0.70871	0.70897	0.70883	TIMS	Japan	[141]
	42 (plants)	0,71071	0.70909	0.70696			
	12 (human enamel)	0.70824	0.71099	0.71017			
	10 (human bones)	0.70906	0.70974	0.70928	MC ICP-MS	Ireland	[142]
	2 (faunal enamel)	0.70909	0.70914	0.70912			
	9 (faunal bones)	0.70925	0.70995	0.70950			
	19 (human enamel)	0.70561	0.70747	0.70641	MC ICP-MS	Peru	[143]
	12 (human bones)	0.70617	0.70690	0.70661			
	1 (human enamel)	0.70883	0.70883	0.70883			
	2 (human bones)	0.70745	0.70806	0.70776	MC ICP-MS	Chile	[144]
	2 (plants)	0.70700	0.71031	0.70866			
	115 (human enamel)	0.70911	0.71067	0.70987	MC ICP-MS	Hungary	[145]
	45 (human bones)	0.70919	0.71057	0.70997			
	45 (human enamel)	0.70758	0.71252	0.70829	TIMS and		
	12 (human bones)	0.70776	0.70886	0.70817	MC ICP-MS	Chile	[146]
	22 (gazelle enamel)	0.70761	0.70842	0.70813			
	22 (gazelle bone)	0.70793	0.70825	0.70813	TIMS	Anatolia (Turkey)	[147]
	6 (faunal bone)	0.70810	0.70827	0.70817			
14 (human enamel)	0.70668	0.71006	0.70935				
11 (human bone)	0.70887	0.70992	0,70926	TIMS	China	[148]	

66 (human enamel)	0.70829	0.71431	0.70970			
2 (human bone)	0.70957	0.70995	0.70976	TIMS	Hungary	[149]
22 (plants)	0.70688	0.71255	0.70938			
6 (human enamel)	0.70669	0.70785	0.70693			
3 (human bones)	0.70630	0.70642	0.70635	MC ICP-MS	United States of America	[150]
7 (faunal bones)	0.70663	0.70691	0.70675			
38 (human enamel)	0.710	0.733	0.717			
3 (faunal enamel)	0.722	0.739	0.728	TIMS	Sweden	[151]
3 (faunal bones)	0.728	0.737	0.734			
36 (human enamel)	0.70891	0.70957	0.70920			
3 (human bones)	0.70933	0.70946	0.70938	MC ICP-MS	Spain	[152]
2 (faunal enamel)	0.70921	0.70924	0.70923			
3 (human enamel)	0.70846	0.70896	0.70868			
17 (human calcined bones)	0.70660	0.71362	0.70896	MC ICP-MS	Ireland	[153]
32 (human enamel)	0.70827	0.70880	0.70860			
33 (human bone)	0.70820	0.70871	0.70855			
4 (faunal enamel)	0.70858	0.70863	0.70860	TIMS	Italy	[154]
7 (faunal bone)	0.70817	0.70856	0.70838			
13 (human enamel)	0.70868	0.71234	0.70959			
29 (human bone)	0.70864	0.70946	0.70896			
1 (faunal enamel)	0.70890	0.70890	0.70890	MC ICP-MS	Spain	[155]
6 (faunal bone)	0.70861	0.70901	0.70884			

Tooth enamel and dentine	34 (human enamel)	0.70997	0.71103	0.71043	TIMS	Central Asia (Pamir Plateau)	[156]
	12 (faunal bones)	0.71030	0.71053	0.71043			
	36 (human enamel)	0.70763	0.71384	0.71127	MC ICP-MS	Germany	[157]
	8 (human bones)	0.70941	0.71008	0.70974			
	3 (faunal bones)	0.70900	0.70922	0.70914			
	76 (human enamel)	0.70725	0.71923	0.71296	MC ICP-MS	Germany	[158]
	5 (human dentine)	0.70904	0.71416	0.71195			
	7 (human enamel)	0.70871	0.70956	0.70907	TIMS	England	[159]
	4 (human dentine)	0.70957	0.70981	0.70969			
	7 (plants)	0.70856	0.71041	0.70922			
	4 (faunal)	0.70804	0.70830	0.70821			
	12 (human enamel)	0.70816	0.71024	0.70941	TIMS	France	
	4 (human dentine)	0.70883	0.70993	0.70941			
	5 (human enamel)	0.70792	0.70999	0.70846	TIMS	Germany	
	2 (human dentine)	0.70789	0.70810	0.70710			
	32 (human enamel)	0.70798	0.71049	0.70962	TIMS	England	[160]
8 (human dentine)	0.70777	0.71002	0.70840				
28 (human enamel)	0.70860	0.71200	0.70970	TIMS	United States of America	[161]	
28 (human dentine)	0.70828	0.71080	0.70934				
23 (human enamel)	0.70879	0.71645	0.71016	TIMS	Netherlands	[117]	
3 (human dentine)	0.70902	0.71101	0.71021				
3 (faunal enamel)	0.70901	0.70996	0.70936				
7 (plants)	0.71113	0.71156	0.71134				

	95 (cattle teeth)	0.70786	0.71448	0.70965	TIMS	England	[114]
	12 (human enamel)	0.7076	0.7081	0.7079	MC ICP-MS	Jordan	[162]
	8 (human dentine)	0.7077	0.7081	0.7079			
Various	11 (human enamel)	0.71061	0.71203	0.71134	TIMS	Libya	[163]
	5 (faunal enamel)	0.71085	0.71150	0.71161			
	1 (faunal bone)	0.71098	0.71098	0.71098			
	3 (shells)	0.71031	0.71129	0.71081			
	19 (human enamel)	0.70897	0.71329	0.71038	TIMS	Denmark	[164]
	6 (faunal)	0.70927	0.71143	0.71039			
	24 (human enamel)	0.70740	0.70940	0.70838	MC ICP-MS	Germany	[165]
	8 (human dentine)	0.70773	0.70868	0.70827			
	7 (snail shell)	0.70570	0.70947	0.70755			
	11 (plants)	0.70616	0.71087	0.70843			
	21 (sheep enamel)	0.70880	0.70961	0.70934	TIMS	Spain	[166]
	3 (sheep dentine)	0.70945	0.70955	0.70951			
	2 (faunal)	0.70951	0.70953	0.70952			
	124 (faunal)	0.70694	0.74614	0.71103	MC ICP-MS	Siberia	[167]
179 (plants)	0.70673	0.75225	0.71215				
60 (water)	0.70711	0.77350	0.71386				
39 (human teeth)	0.70801	0.72991	0.71496				

64(human teeth)	0.70888	0.71188	0.70950			
8 (human bones)	0.70901	0.70939	0.70919	TIMS	Germany	[168]
5 (pig enamel)	0.70888	0.70907	0.70896		Italy	

366 ^a the sample was analysed 14 times

367

368

369 The joint analysis of oxygen and strontium isotopes evidenced the maritime trading
370 activities of populations from northern Netherlands during early medieval period,
371 revealed some possibilities about their diets [117]. In the same way the study of
372 strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) and oxygen ($\delta^{18}\text{O}$), established that tooth pendants were
373 exchanged and/or transported over vast distances across the Caribbean [169]. On the
374 other hand, crossing strontium and lead (is not an essential metal, but as divalent ion
375 can replace calcium in some cases) isotopic data revealed dietary patterns of the Indus
376 Civilization (2600-1900 BC) which were unnoticeable by analysing each element
377 independently [53]. The same isotopic combination proved to be useful to distinguish
378 between natives and migrants of the ancient Roman London [131]. The combination of
379 geochemical data from $^{87}\text{Sr}/^{86}\text{Sr}$ with ^{14}C , $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$, evidenced the existence of
380 two different diets in a population from middle Holocene Early Bronze Age in Siberia,
381 corresponding to local and nonlocal individuals [170].

382 In marine products, unlike the Earth's crust, $^{87}\text{Sr}/^{86}\text{Sr}$ is constant throughout the oceans
383 at a given period of time. Isotope ratios of sea shells (composed by calcium salts,
384 mainly carbonates) reflect the seawater ratio at the time of their formation and are
385 useful tools in investigating the source of archaeological shell artefacts [6].

386 Strontium isotopes have proved to be a reliable biological marker in the study of past
387 human and animal migrations. Nonetheless the obtained results may be refined by
388 complementing with information from other isotopic system, either from light elements
389 [117,169], rare earth elements such as Nd [171,172] or even heavy elements like lead
390 ([53])

391 2.4 Forensic science

392

393 It is possible to determine the provenance of unidentified corpses by studying stable
394 isotopes in body tissue materials such as teeth, bones, hair and nails (table 4). These
395 provide information of different periods from childhood to death of a human [173].

396 However, in forensic sciences it is more common the use of light isotopes (C, H, O and
397 N) [174–176] rather than strontium isotopes most likely due to analytical challenges in
398 the preparation of samples associated with the metal.

399 In hair, the $^{87}\text{Sr}/^{86}\text{Sr}$ is not exclusively controlled by water or diet intake [52]. In fact,
400 both internal and external factors, diet and environment, respectively, have an
401 influence on the isotope ratio and must be taken into consideration when studying this
402 matrix. Hence, two potential methods have been suggested to separate endogenous
403 strontium from exogenous strontium [51]. However, there still isn't a consensual

404 method for such purpose. Although Font et al. showed that the migrations across
405 geographical areas can stay recorded in scalp hair by the $^{87}\text{Sr}/^{86}\text{Sr}$ isotope depending
406 on a monthly timescale, however, further studies are recommended by the authors to
407 confirm this possibility [177].

408 For human skeletal remains, namely tooth enamel and bone, strontium isotopic
409 analyses allow to reduce potential areas of residence and even the total exclusion of
410 some regions, thus giving complementary information that may be clarified by other
411 techniques [118]. The use of multidisciplinary approaches is valuable in the
412 identification of human remains [178]. Tooth enamel is formed during childhood and,
413 unlike hair, is not influenced by exogenous sources of strontium, hence it is a good
414 marker for determining the place of birth or growing location during infancy. This was
415 verified in search of the provenance of two unidentified World War II casualties. The
416 combination of oxygen and strontium isotope ratios suggested the South Coast and/or
417 Central Eastern part of the United Kingdom as probable origin of these casualties
418 [179].

419 A more recent application of strontium in forensic sciences has been developed in the
420 last decade, as a tool to diagnose death by drowning [180–183] and even to be related
421 with different time-lapses of the agonal period [184]. Due to the high levels of this metal
422 in oceans, in seawater drowning the serum levels and mean concentration of strontium
423 in the right ventricle are significantly higher compared to the left ventricle. It has been
424 shown that serum levels of strontium are in fact a highly sensitive marker of water
425 aspiration, particularly in the case of seawater drowning, while in freshwater drowning
426 combining strontium with other trace elements increases the chances of a correct
427 diagnosis [183,185].

428

429

430 **Table 4**

431 Application of strontium isotope ratios in forensic sciences.

Matrices	Number of samples	Range of $^{87}\text{Sr}/^{86}\text{Sr}$			Analytical technique	Reference
		Minimum	Maximum	Mean		
	11 (bulk hair)	0.70909	0.71040	0.70968		
Human hair	23 (hair strands)	0.70990	0.71062	0.70965	TIMS	[52]
	8 (water)	0.70801	0.71011	0.70922		
Human hair	22	0.70909	0.71469	0.712023	MC ICP-MS	[51]
Tooth enamel	1	0.71103	0.71103	0.71103	MC ICP-MS	[178]
Tooth dentine	1	0.70910	0.70910	0.70910		
Tooth enamel	5	0.70908	0.70945	0.70926	TIMS	[179]

432

433

434 2.5 Current questions

435

436 As may be seen in Fig. 2, the variation of the $^{87}\text{Sr}/^{86}\text{Sr}$ within most matrices is rather
437 small. The lowest value described in literature is for peanut, 0.695, while the highest
438 was 0.74985, found in human enamel. The isotope ratios of faunal and floral samples
439 cover a large range of values thus presenting very high amplitude of the intervals ($A =$
440 maximum-minimum). Both these groups are used for establishing baselines in
441 bioarchaeological studies, and therefore are extremely diverse in type, number and
442 origin of samples, which may explain such high variability. Apart from flora, human
443 enamel presents the highest amplitude in values ($A=0.045$) which is due to the
444 elevated number of samples analysed during the last 5 years ($n=1930$) from 51
445 different locations. Human enamel is by far the most characterized matrix in terms of
446 strontium isotope ratios.

447 Rice and hot pepper presented a very broad interval of values ($A=0.031$), however
448 through the data available in the literature it is not possible to distinguish between the
449 two matrices and therefore reduce the amplitude of the interval. The study on olive oil
450 samples, with only 7 samples from two different provenances, registered the lowest
451 amplitude ($A=0.002$). Nonetheless the authors were able to distinguish between
452 samples originating from Morocco and France with the developed method.

453 Amongst food matrices peanuts present the lowest and second highest $^{87}\text{Sr}/^{86}\text{Sr}$ as
454 well as the largest interval amplitude ($A=0.031$). Despite the large number of samples
455 analysed in the study ($n=200$ from 5 countries) this may be an indication that the
456 method employed, ICP-Q-MS, is not as precise as TIMS or MC ICP-MS, the more
457 common methods of choice.

458 Quality control is of uttermost importance in order to obtain precise and accurate
459 results. The use of clean room facilities as well as correcting for ^{87}Rb interferences
460 during analytical measurements seem to be practices well implemented in the
461 determination of strontium isotope ratios. However scarce information regarding quality
462 control data is presented and the terminology employed tends to be incoherent or
463 unclear as to the form of calculation. Terms like internal repeatability, external
464 repeatability, internal reproducibility, external reproducibility or total reproducibility
465 seem to be used in an inconsistent way by different authors, who sometimes also
466 associate the use of replicates with the evaluation of reproducibility. In addition the
467 information on the expression of uncertainty and its form of calculation (standard,
468 combined or expanded)), is often missing. Such behaviour makes it difficult to compare
469 results amongst studies, since comparability depends on the applied calibration

470 strategies and the reported uncertainties, as stated in a recent publication dealing with
471 uncertainty calculation of isotope amount ratios [61]. With the creation of isotope
472 databases comparability amongst analytical methods, and thus amongst the data
473 produced, assumes particular importance [27]. Table 5 presents examples on the
474 information regarding sample preparation and method performance provided by some
475 of the reviewed papers. Repeatability is considered as within-run precision, while
476 between-run precision represents reproducibility [27]. Other uncertainty contributors
477 were not taken into consideration since its report in scientific papers is occasional and
478 unclear. In general papers dealing with food authentication report more information on
479 quality data when compared to the remaining applications, and therefore were selected
480 to prepare table 5.

481 As may be observed from table 5, when dealing with reference materials within-run
482 precision is quite equivalent for TIMS and MC ICP-MS. In the case of SRM 987 it is
483 generally between 0.01 and 0.02%, for both methods while in food matrices it varies
484 between 0.0004% in wine and 0.3% in honey. Within-run precision is primarily
485 influenced by the nature of samples rather than the analytical technique.

486

487

488

489

490 **Table 5** Sample preparation and quality control data in food provenance studies

Matrix	Analytical technique	Sample preparation		Within run precision (RSD%)	Between run precision (RSD%)	Ref
		Mineralisation	Separation of strontium from interferents			
Olive oil	TIMS	2–100 g of olive oil + 3 ml H ₂ O ₂ + 21 ml HNO ₃ (7 N) were placed on a hotplate (120 °C, 48 h) followed by calcination (650 °C, 2h). The dry residue was dissolved with 0.5 ml of HNO ₃ (2 M) and placed on a hotplate (5–10 min)	Eichrom Sr resin	0.01% (olive oil)	0.001% (SRM987) 0.002-0.01% (olive oil)	[50]
Tomato products	TIMS	250–300 mg of freeze-dried tomato products + 2–3 mL of HNO ₃ were subjected to microwave assisted digestion or chemical mineralization. Samples were evaporated to dryness and re-dissolved in 10 mL of 8 M HNO ₃ .	Eichrom Sr resin. 5 mL of sample + 2–3 mL HNO ₃ (6–7 mol L ⁻¹). The eluate containing Sr was submitted to dry evaporation, recovered with 50 µL of HNO ₃ 1% and, later on, reduced at the time of the deposition on the filament.	SRM 987	0.006 - 0.05%	[77]
Hot pepper and rice	MC ICP-MS	0.7 g of hot pepper and rice + concentrated HNO ₃ and a 4:1 (v/v) mixture of ultrapure concentrated HNO ₃ and HClO ₄ (reagent grade) for complete digestion. Samples were dried in Teflon vessels and re-dissolved in 8 M HNO ₃ .	Eichrom Sr resin	n.a	0.001%. (SRM987)	[70]
Coffee Beans	MC ICP-MS	50 mg of freeze dried powdered coffee beans was digested in a 2:1 solution of HNO ₃ and H ₂ O ₂ (120 °C, 2 h). The solution was then diluted to a final volume of 10 ml using Milli-Q water and stored for further chemical and isotopic analysis. Approximately 450 ng Sr from the sample solution was evaporated on a hot plate to dryness at 90 °C and then re-dissolved in 0.5 ml of 3 N HNO ₃ .	Eichrom Sr resin. The resin was washed with 3 ml of 3 N HNO ₃ , 3 ml of Milli-Q water and 5 ml of 6 N HCl in sequence, and then pre-conditioned with 1 ml of 3 N HNO ₃ . The sample solution was loaded and interferences removed with 8 ml of 3 N HNO ₃ . The Sr fraction was eluted with 4 ml of Milli-Q water.	n.a.	0.001% (SRM 987)	[100]
Milk and cheese	TIMS	Freeze dried milk and cheese samples were dissolved in a mixture of 6 N HCl and 16 N HNO ₃ using an Anton Paar High Pressure Asher.(300 °C, 130 bar, 2 h). The dissolved samples were subsequently treated with concentrated HNO ₃ and H ₂ O ₂ (30%). The samples were evaporated to dryness and re-dissolved in 3 N HNO ₃ .	Eichrom Sr resin	0.01% (cheese)	0.002% (SRM987) 0.001 - 0.03% (cheese)	[76]

Wine	MC ICP-MS	5 mL of wine + 5 mL HNO ₃ (microwave assisted digestion or low temperature)	Eichrom Sr resin SR-B100-S (50–100 lm). The resin is washed with 2 mL of high-purity water and activated by 5.5 mL of HNO ₃ 8 M; 5 mL of sample are loaded and the interferences are eluted with 3.5 mL of HNO ₃ 8 M. The Sr fraction was eluted with 7.5 mL of high purity water.	0.0005-0.001% (SRM 987) 0.001% (soil) 0.0004% (wine)	0.002% (SRM 987)	[72]
Grape components	TIMS	High pressure digestion: 5 g of grape components, previously dried (60 °C, 12 h) + 5 mL of concentrated ultrapure HNO ₃ and H ₂ O ₂ (120 °C, 2 h). The residue was then dried at 60 °C. The procedure was repeated until complete destruction of the organic matter; The residue was dissolved with ultrapure 2.5 N HCl. Thermal ashing: 8 g of grape components were dried at 60 °C in a clean nickel crucible, and then placed in a muffle furnace, (700 °C, 1 h). Ashes were then dissolved with ultrapure 2.5 N HCl.	Sr was separated from isobar by cation-exchange chromatography using Biorad AG 50W X8 resins (200–400 mesh) and ultrapure HCl as eluent.	0.001-0.004% (must)	0.001% (SRM 987)	[95]
Wine	MC ICP-MS	Microwave digestion: 5mL of wine + 5mL of HNO ₃ (room temperature, 2 h); Step 1 – 9min, up to 60 °C; Step 2 – 30min, up to 150 °C. Final volume was obtained by adding HNO ₃ to obtain a final solution of HNO ₃ 8 M. Low temperature procedure: 5mL of wine + 5mL of HNO ₃ (room temperature, 12 h). Final volume was obtained by adding HNO ₃ to obtain a final solution of HNO ₃ 8 M.	Eichrom Sr resin SR-B100-S (50–100 lm). The resin is washed with 2 mL of high-purity water and activated by 5.5 mL of HNO ₃ 8 M; 5 mL of sample are loaded and the interferences are eluted with 3.5 mL of HNO ₃ 8 M. The recovery of Sr is accomplished by using 7.5 mL of high purity water.	0.001% (wine)	0.002% (SRM987) 0.001% (wine)	[73]
Wine and grapes	TIMS	Wine and grape samples + 2mL of aqua regia (3:1 HCl/HNO ₃) + 1mL of ultrapure H ₂ O ₂ (24 h). Samples were then evaporated to dryness. This sequence was repeated until complete oxidation of the organic matter was attained. 1mL of 3 M HNO ₃ was added to dried samples, which were placed in an ultrasonic bath (10 min) and then centrifuged (10 min).	Eichrom Sr-spec resin (50–100 mesh)	0.01-0.08% (samples)	0.002% (SRM987)	[99]
Wine	TIMS	5 mL of wine was evaporated to dryness at 90 °C in cleaned PFA beakers. The residue was dissolved twice in 3 ml of ultrapure quality H ₂ O ₂ (30%) (40 °C, 1 day) and subsequently evaporated to dryness at 90 °C. The sample was then dissolved twice in 2 mL of suprapure concentrated HNO ₃ (150 °C, 1 day), evaporated to dryness, and dissolved again in 1 mL of 3 N HNO ₃ .	Sr-Spec resins (100–150 µm, Eichrom). After sample loading onto the column, 14 column volumes (CV) of 3 N HNO ₃ was added in three steps (including rinsing two times with 2 CV) to interferences. Sr was collected in clean PFA beakers using some 13 CV of Milli-Q water in three steps.	0.0006% (wines)	SRM987	[74]
Beer	MC ICP-MS	10 g of degassed beer was put in a cleaned Teflon vessel and heated on a hot plate until only a small amount of the sample remained. The sample was completely digested in a 6:1 mixture of HNO ₃ and HClO ₄ , and then in H ₂ O ₂ . Samples were dried in Teflon vessels and re-dissolved in 8 M HNO ₃ .	Eichrom Sr resin. Rb was eluted from the samples with 12 mL of 8 M HNO ₃ , followed by 16 mL of 1 M HNO ₃ for Ca and then Sr was collected in 8 mL MilliQ water.	n.a.	0.001% (SRM987)	[103]
Wheat	TIMS	5 g of dry wheat was placed in porcelain crucibles in a high-temperature muffle furnace (550–600 °C, 18 h). Residues were treated with concentrated HNO ₃ on a hot plate and then transferred	Ion exchange chromatography column	0.07% (wheat)	0.04% (SRM987)	[104]

back to the furnace. The residues were dissolved in 1 M HNO₃.

Honey	TIMS	100 g of honey was placed in the furnace: Step 1 – 8h, up to 600 °C; Step 2 – 10h, at 600 °C. Residues were treated with concentrated HNO ₃ on a hot plate and then transferred back to the furnace. The residues were dissolved in HNO ₃ .	Ion chromatography on a Sr-specific resin (Sr-spec).	0.2 - 0.3% (honey)	SRM 987	[106]
	TIMS	200 mg of the meat (freeze-dried or defatted dry mass) were weighed into a quartz crucible and thermally ashed (500 °C, 4 h). The remaining white ash was dissolved in concentrated HNO ₃ .	Sr-specific crown-ether resin (Sr-Spec®)	0.03% (beef)	0.004% (SRM987) 0.04-0.4% (beef)	[93]
Tea leaves	MC ICP-MS	0.25 g of dried powdered tea leaves+ 2 mL H ₂ O ₂ + 6 mL concentrated HNO ₃ . Microwave digestion: step 1 – 30 min, up to 190 °C; Step 2 – 40 min, at 190 °C. Solutions were filtered through a filter paper (MCE no. 42) and diluted to 12.5 mL with deionised water. Approximately 150 ng of Sr was evaporated to dryness on a hot plate (90 °C) and then re-dissolved in 0.5 mL of 3 M HNO ₃ .	Eichrom Sr resin. The resin was pre-washed with 3 mL of 3 M HNO ₃ , 3 mL Milli-Q water and 5 mL of 6 N HCl in sequence and then pre-conditioned with 1 mL of 3 M HNO ₃ . The sample solution was carefully loaded onto the column, where major matrix elements and Rb were removed by 4 mL of 3 M HNO ₃ . The Sr fraction was eluted with 4 mL of Milli-Q water.	0.015% (tea leaves)	0.001% (SRM987)	[101]

491

492 3. Future perspectives

493

494 Strontium in the biological sciences has a significant number of applications, namely in
495 health sciences (diagnosis and treatment, using radioactive or stable isotopes) and as
496 an analytical tool based on the isotopic signatures of biological samples to identify the
497 origin of foodstuffs, diet patterns, migration habits and forensic studies along with
498 palaeontology, archaeology and other sciences.

499 New developments concerning the application of strontium in health sciences are
500 possible, for example by using compounds of this metal associated to more efficient
501 delivery systems for diagnosis and treatment purposes.

502 It has been shown for plants [70], fish [16] and butterflies [17] that, $^{87}\text{Sr}/^{86}\text{Sr}$ does not
503 suffer fractionation from soil across trophic levels and may therefore serve as biological
504 markers for different applications. Thus, strontium isotope ratios could be inferred from
505 data on bioavailable strontium isotopes from soils, and comparing from different
506 geographical areas could give us information about evolution. Different attempts at
507 developing predictive models, isotope maps or isoscapes, have been made without
508 reaching consensus so far due to the complexity of the systems [186–189]. Although a
509 difficult task, establishing strontium isoscapes for geographical provenance of
510 foodstuffs would represent a breakthrough. Recently an archaeological bioavailable
511 strontium map of The Netherlands has been proposed [190]. Strontium isoscapes are
512 also available for Britain [191] while in France the IRHUM database provides a data
513 set of bioavailable strontium isotope ratios [192],

514 Taking into account that strontium is mainly inert for biological species, the ratio soil
515 species and among isotopes should follow similar patterns for some closely related
516 species, even far regarding their geographical location, then these isotopes could be a
517 tool applied to the biological evolution search.

518 To analytical purposes samples of calcium biominerals replaced by strontium in low
519 amounts (e.g. teeth, bones, shells), in other biological materials (e.g. hair, fruits) and
520 derivatives (e.g. wine, cheese) have been used. However, taking into account the
521 multiple diversity of biological roles of calcium, which is the most important element in
522 types of biominerals, the employment of strontium from other biological materials, is
523 expectable.

524 On the other hand, developments in analytical techniques and instruments with high
525 measurement precision, namely MC ICP-MS and TIMS, enabled identifying relevant
526 natural fractionation in the $^{88}\text{Sr}/^{86}\text{Sr}$ ratio considered until recently to be undetectable

527 and insignificant [193,194]. Souza et al. demonstrated that even though bedrock and
528 bulk soil present similar $\delta^{88/86}\text{Sr}$ values such is not extensive to plants. In fact isotope
529 fractionation of strontium within plants was noticeable, with the $\delta^{88/86}\text{Sr}$ values
530 decreasing while moving from roots to stems to foliar tissues [10]. This strontium
531 isotopic fractionation has been described as a temperature-dependent phenomena
532 [195]. Such knowledge may lead to innovative applications in various fields like geology
533 [11,196], hydrology and biology [197,198], in particular when combined with $^{87}\text{Sr}/^{86}\text{Sr}$..
534 Considering the natural fractionation of $^{88}\text{Sr}/^{86}\text{Sr}$ in samples, using traditional methods
535 to measure $^{87}\text{Sr}/^{86}\text{Sr}$ where the assumed constant value of $^{88}\text{Sr}/^{86}\text{Sr}$ (8.375209) is used
536 to correct for the instrument bias must be faced with caution [196].

537 Just like in ICP-MS, MC ICP-MS has the possibility of coupling to other analytical
538 techniques, such as Ablation, High Performance Liquid Chromatography or Gas
539 Chromatography opening up new possibilities with hyphenated techniques [28,121].
540 Laser ablation allows the direct analysis of solid samples thus overcoming the most
541 critical point of the analytical procedure, extraction of the strontium isotopes. This
542 technique has already been applied to different matrices as for example geological
543 materials [199] teeth and bones [121,200,201] or fish fin rays, scales and otoliths
544 [89,200]. If in future the analytical challenges associated with LA- MC ICP-MS are
545 overcome for isotopic analysis, it would represent a significant increase in analytical
546 productivity of solid samples. On the other hand chemical speciation either via Liquid or
547 Gas Chromatography has proven its importance in trace metals analysis, particularly in
548 environmental and food analysis due to its impact in human health [202–204]. It is thus
549 expected that similar studies focusing on isotopes may lead to new advances.

550 The determination of strontium isotope ratios in biological samples like bone or tooth
551 enamel is currently very well established in laboratories. In the case of foodstuffs it has
552 already been applied to a large variety of matrices and it is expected that, with proper
553 sample preparation development, the method could be applicable to all food
554 commodities.

555 Stable isotope analysis is a field of growing interest with large amounts of data
556 generated over the last few years. Nonetheless most of these values are dispersed
557 amongst scientific publications, including preliminary studies using a reduced number
558 of samples and geographical origins (are laid out within national boundaries or more
559 rarely including two countries). It would be most useful to compile, validate and
560 compare such data on an international database making the best use of them through
561 the employment of powerful statistical tools to allow comparative studies. Elemental
562 concentrations have been widely used to develop methods for authentication of

563 foodstuffs; however strontium isotope ratios have proved to be a more powerful tool for
564 such purpose. Nonetheless, in several cases using different techniques and crossing
565 more than one traceability marker could be valuable for a very precise tracing of the
566 geographical origin of foodstuffs, particularly in cases of similar geological environment.
567 The advantages of combining elemental concentrations and isotope ratios, both “light”
568 and “heavy” isotopes, should be a matter of interest in future research work. In the
569 specific case of processed foods or foodstuffs containing more than one ingredient,
570 and therefore with several influences on the strontium isotope ratios, this approach
571 might be particularly beneficial [76,100,103,205]. On the other hand, in archaeological
572 studies dealing either with past migrations, diet habits or trading activities it is common
573 to combine more than one isotopic system, in particular strontium and oxygen isotopes
574 [117,169]. It seems evident that in these studies such approach is more beneficial
575 rather than resorting only to strontium isotopes.

576 4. **Conclusions**

577
578 The present work provides information on the application of strontium and its isotopes
579 in a diversity of biological related research fields that comprises medicine, dietary
580 habits, migration patterns, food authentication and forensic sciences. It represents a
581 valuable tool for those conducting research on such analytical applications since it
582 compiles an extensive database containing results from the last 5 years.
583 Taking into account the characteristics of strontium isotopes, as well as its chemical
584 relationships with calcium, several possible applications are available. However, care
585 must be taken to ensure proper results. Hence, according to several authors the value
586 of $^{87}\text{Sr}/^{86}\text{Sr}$ should always be found above 0.702 for all types of samples collected in
587 natural environments, since this value corresponds to the minimum value currently
588 encountered in the Earth’s crust [6,12]. Lower values should be examined with caution
589 and analytical methods must be thoroughly validated.
590 The existence of an analytical quality system supporting results is essential; however
591 such control is either not implemented in analytical laboratories or it is not consistently
592 reported in recent publications. To facilitate such task the terminology employed in
593 analytical quality control should be harmonized amongst the scientific community. In
594 addition the development of matrix matching reference materials would be extremely
595 useful for future isotope ratio measurements.
596

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604 **References**

- 605 [1] P. Nielsen, The biological role of strontium, *Bone*. 35 (2004) 583–8.
606 doi:10.1016/j.bone.2004.04.026.
- 607 [2] J.A. Philpotts, C.C. Schnetzler, Phenocryst-matrix partition coefficients for K, Rb, Sr and Ba, with
608 applications to anorthosite and basalt genesis, *Geochimica et Cosmochimica Acta*. 34 (1970) 307–
609 322. doi:10.1016/0016-7037(70)90108-0.
- 610 [3] T. Waight, Rb–Sr Geochronology (Igneous Rocks), in: *Encyclopedia of Scientific Dating Methods*,
611 Springer Netherlands, Dordrecht, 2013: pp. 1–8. doi:10.1007/978-94-007-6326-5_105-1.
- 612 [4] United States Department of the Interior, Volcanic Rocks and Processes, in: *Geological Survey*
613 *Research*, United States Government Printing Office, Washington, 1973: pp. 141–142.
- 614 [5] R.C. Capo, B.W. Stewart, O.A. Chadwick, Strontium isotopes as tracers of ecosystem processes:
615 theory and methods, *Geoderma*. 82 (1998) 197–225. doi:10.1016/S0016-7061(97)00102-X.
- 616 [6] R.A. Bentley, Strontium isotopes from the earth to the archaeological skeleton: A review, *Journal*
617 *of Archaeological Method and Theory*. 13 (2006) 135–187. doi:10.1007/s10816-006-9009-x.
- 618 [7] V. Höllriegl, H.Z. München, Strontium in the Environment and Possible Human Health Effects,
619 *Encyclopedia of Environmental Health*. (2011) 268–275. doi:10.1016/B978-0-444-52272-6.00638-
620 3.
- 621 [8] J. Meija, T.B. Coplen, M. Berglund, W.A. Brand, P. De Bièvre, M. Gröning, et al., Isotopic
622 compositions of the elements 2013 (IUPAC Technical Report), *Pure and Applied Chemistry*. 88
623 (2016). doi:10.1515/pac-2015-0503.
- 624 [9] G. Audi, F.G. Kondev, M. Wang, B. Pfeiffer, X. Sun, J. Blachot, et al., The Nubase2012 evaluation
625 of nuclear properties, *Chinese Physics C*. 36 (2012) 1157–1286. doi:10.1088/1674-
626 1137/36/12/001.
- 627 [10] G.F. de Souza, B.C. Reynolds, M. Kiczka, B. Bourdon, Evidence for mass-dependent isotopic
628 fractionation of strontium in a glaciated granitic watershed, *Geochimica et Cosmochimica Acta*. 74
629 (2010) 2596–2614. doi:10.1016/j.gca.2010.02.012.
- 630 [11] H.D. Scher, E.M. Griffith, W.P. Buckley, Accuracy and precision of 88 Sr/ 86 Sr and 87 Sr/ 86 Sr
631 measurements by MC-ICPMS compromised by high barium concentrations, *Geochemistry*,
632 *Geophysics, Geosystems*. 15 (2014) 499–508. doi:10.1002/2013GC005134.
- 633 [12] M. Rosner, Geochemical and instrumental fundamentals for accurate and precise strontium
634 isotope data of food samples: Comment on “Determination of the strontium isotope ratio by ICP-
635 MS ginseng as a tracer of regional origin” (Choi et al., 2008), *Food Chemistry*. 121 (2010) 918–
636 921. doi:10.1016/j.foodchem.2010.01.019.
- 637 [13] S.A. Drivelos, C.A. Georgiou, Multi-element and multi-isotope-ratio analysis to determine the
638 geographical origin of foods in the European Union, *TrAC - Trends in Analytical Chemistry*. 40
639 (2012) 38–51. doi:10.1016/j.trac.2012.08.003.
- 640 [14] A. Ranalli, P. Cabras, E. Iannucci, S. Contento, Lipochromes , vitamins , aromas and other
641 components of virgin olive oil are affected by processing technology, *Food Chemistry*. 73 (2001)
642 445–451.
- 643 [15] A. Ranalli, A. Malfatti, L. Lucera, S. Contento, E. Sotiriou, Effects of processing techniques on the
644 natural colourings and the other functional constituents in virgin olive oil, *Food Research*
645 *International*. 38 (2005) 873–878. doi:10.1016/j.foodres.2005.02.011.

- 646 [16] M. Pouilly, D. Point, F. Sondag, M. Henry, R. V. Santos, Geographical Origin of Amazonian
647 Freshwater Fishes Fingerprinted by 87 Sr/ 86 Sr Ratios on Fish Otoliths and Scales,
648 Environmental Science & Technology. 48 (2014) 8980–8987. doi:10.1021/es500071w.
- 649 [17] D.T.T. Flockhart, T.K. Kyser, D. Chipley, N.G. Miller, D.R. Norris, Experimental evidence shows no
650 fractionation of strontium isotopes (87 Sr/ 86 Sr) among soil, plants, and herbivores: implications
651 for tracking wildlife and forensic science, *Isotopes in Environmental and Health Studies*. 51 (2015)
652 372–381. doi:10.1080/10256016.2015.1021345.
- 653 [18] Committee on Biomedical Isotopes Institute of Medicine, *Isotopes for Medicine and the Life*
654 *Sciences*, National Academy Press, Washington, D.C., D.C., 1995.
655 <http://www.nap.edu/catalog/4818.html>.
- 656 [19] J. O'Neil, Stable isotope geochemistry, *REVIEWS OF GEOPHYSICS AND SPACE PHYSICS*. 17
657 (1979) 839–850.
- 658 [20] N. Walraven, B.J.H. van OS, G.T. Klaver, J.H. Baker, S.P. Vriend, Trace element concentrations
659 and stable lead isotopes in soils as tracers of lead pollution in Graft-De Rijp, the Netherlands,
660 *Journal of Geochemical Exploration*. 59 (1997) 47–58.
- 661 [21] R. Bowen, Oxygen isotopes as climatic indicators, *Earth-Science Reviews*. 2 (1966) 199–224.
662 doi:10.1016/0012-8252(66)90029-8.
- 663 [22] H.P. Schwarcz, J. Melbye, M. Anne Katzenberg, M. Knyf, Stable isotopes in human skeletons of
664 Southern Ontario: reconstructing Palaeodiet, *Journal of Archaeological Science*. 12 (1985) 187–
665 206. doi:10.1016/0305-4403(85)90020-2.
- 666 [23] R. van Grieken, M. de Bruin, Nomenclature for radioanalytical chemistry (IUPAC
667 Recommendations 1994), *Pure and Applied Chemistry*. 66 (1994). doi:10.1351/pac199466122513.
- 668 [24] U.S. Department of Health and Human Services. Public Health Service. Agency for Toxic
669 Substances and Disease Registry. *TOXICOLOGICAL PROFILE FOR STRONTIUM*, 2004.
- 670 [25] J. Aggarwal, J. Habicht-Mauche, C. Juarez, Application of heavy stable isotopes in forensic
671 isotope geochemistry: A review, *Applied Geochemistry*. 23 (2008) 2658–2666.
672 doi:10.1016/j.apgeochem.2008.05.016.
- 673 [26] B.E. Crowley, J.H. Miller, C.P. Bataille, Strontium isotopes (87 Sr/ 86 Sr) in terrestrial ecological
674 and palaeoecological research: empirical efforts and recent advances in continental-scale models,
675 *Biological Reviews*. (2015) n/a-n/a. doi:10.1111/brv.12217.
- 676 [27] J. Irrgeher, T. Prohaska, Application of non-traditional stable isotopes in analytical
677 ecogeochemistry assessed by MC ICP-MS - A critical review, *Analytical and Bioanalytical*
678 *Chemistry*. 408 (2016) 369–385. doi:10.1007/s00216-015-9025-3.
- 679 [28] P. Rodríguez-González, V.N. Epov, C. Pecheyran, D. Amouroux, O.F.X. Donard, Species-specific
680 stable isotope analysis by the hyphenation of chromatographic techniques with MC-ICPMS, *Mass*
681 *Spectrometry Reviews*. 31 (2012) 504–521. doi:10.1002/mas.20352.
- 682 [29] N. Vajda, C.K. Kim, Determination of radiostrontium isotopes: A review of analytical methodology,
683 *Applied Radiation and Isotopes*. 68 (2010) 2306–2326. doi:10.1016/j.apradiso.2010.05.013.
- 684 [30] F. Vanhaecke, L. Balcaen, D. Malinovsky, Use of single-collector and multi-collector ICP-mass
685 spectrometry for isotopic analysis, *Journal of Analytical Atomic Spectrometry*. 24 (2009) 863.
686 doi:10.1039/b903887f.
- 687 [31] a. Gonzalez, S. Armenta, M. de la Guardia, Trace-element composition and stable-isotope ratio
688 for discrimination of foods with Protected Designation of Origin, *TrAC - Trends in Analytical*
689 *Chemistry*. 28 (2009) 1295–1311. doi:10.1016/j.trac.2009.08.001.
- 690 [32] S. Kelly, K. Heaton, J. Hoogewerff, Tracing the geographical origin of food: The application of
691 multi-element and multi-isotope analysis, *Trends in Food Science and Technology*. 16 (2005) 555–
692 567. doi:10.1016/j.tifs.2005.08.008.
- 693 [33] G.P. Danezis, A.S. Tsagkaris, F. Camin, V. Brusica, C.A. Georgiou, Food authentication:
694 Techniques, trends & emerging approaches, *TrAC Trends in Analytical Chemistry*. (2016).
695 doi:10.1016/j.trac.2016.02.026.
- 696 [34] M. Janin, S. Medini, I. Técher, Methods for PDO olive oils traceability: state of art and discussion
697 about the possible contribution of strontium isotopic tool, *European Food Research and*
698 *Technology*. (2014). doi:10.1007/s00217-014-2279-8.
- 699 [35] Y. Zhao, B. Zhang, G. Chen, A. Chen, S. Yang, Z. Ye, Recent developments in application of
700 stable isotope analysis on agro-product authenticity and traceability, *Food Chemistry*. 145 (2014)
701 300–305. doi:10.1016/j.foodchem.2013.08.062.

- 702 [36] C. Baffi, P.R. Trincerini, Food traceability using the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio mass spectrometry,
703 European Food Research and Technology. (2016). doi:10.1007/s00217-016-2712-2.
- 704 [37] L.M. Reid, C.P. O'Donnell, G. Downey, Recent technological advances for the determination of
705 food authenticity, Trends in Food Science and Technology. 17 (2006) 344–353.
706 doi:10.1016/j.tifs.2006.01.006.
- 707 [38] D.M. a. M. Luykx, S. van Ruth, An overview of analytical methods for determining the geographical
708 origin of food products, Food Chemistry. 107 (2008) 897–911.
709 doi:10.1016/j.foodchem.2007.09.038.
- 710 [39] S. Primrose, M. Woolfe, S. Rollinson, Food forensics: Methods for determining the authenticity of
711 foodstuffs, Trends in Food Science and Technology. 21 (2010) 582–590.
712 doi:10.1016/j.tifs.2010.09.006.
- 713 [40] L. Rock, The use of stable isotope techniques in egg authentication schemes: A review, Trends in
714 Food Science and Technology. 28 (2012) 62–68. doi:10.1016/j.tifs.2012.04.002.
- 715 [41] Y. Oulhote, B. Le Bot, S. Deguen, P. Glorennec, Using and interpreting isotope data for source
716 identification, TrAC Trends in Analytical Chemistry. 30 (2011) 302–312.
717 doi:10.1016/j.trac.2010.10.015.
- 718 [42] N.R. Council, Mineral Tolerance of Animals: Second Revised Edition, (2005) 510.
- 719 [43] J. Decelle, P. Martin, K. Paborstava, D.W. Pond, G. Tarling, F. Mahé, et al., Diversity, ecology and
720 biogeochemistry of cyst-forming acantharia (radiolaria) in the oceans, PloS One. 8 (2013) e53598.
721 doi:10.1371/journal.pone.0053598.
- 722 [44] E. Couradeau, K. Benzerara, E. Gérard, D. Moreira, S. Bernard, G.E. Brown, et al., An early-
723 branching microbialite cyanobacterium forms intracellular carbonates, Science (New York, N.Y.).
724 336 (2012) 459–62. doi:10.1126/science.1216171.
- 725 [45] L. Zhao, B.R. Schöne, R. Mertz-Kraus, Controls on strontium and barium incorporation into
726 freshwater bivalve shells (*Corbicula fluminea*), Palaeogeography, Palaeoclimatology,
727 Palaeoecology. 465 (2017) 386–394. doi:10.1016/j.palaeo.2015.11.040.
- 728 [46] Infoplease, Periodic table, (n.d.). <http://www.infoplease.com/periodictable.php>.
- 729 [47] Wikipedia the free encyclopedia, Abundance of elements in Earth's crust, (2015).
730 https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust (accessed July 1,
731 2015).
- 732 [48] H. Sverdrup, M. Johnson, R. Fleming, Chemistry of Sea Water, in: The Oceans Their Physics,
733 Chemistry, and General Biology, Prentice-Hall, Inc., 1942: pp. 165–227.
734 <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:19+42.+The+oceans:+their+physi>
735 [cs,+chemistry+and+general+biology#0](http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:19+42.+The+oceans:+their+physi+cs,+chemistry+and+general+biology#0).
- 736 [49] S. Millour, L. Noël, R. Chekri, C. Vastel, A. Kadar, V. Sirot, et al., Strontium, silver, tin, iron,
737 tellurium, gallium, germanium, barium and vanadium levels in foodstuffs from the Second French
738 Total Diet Study, Journal of Food Composition and Analysis. 25 (2012) 108–129.
739 doi:10.1016/j.jfca.2011.10.004.
- 740 [50] S. Medini, M. Janin, P. Verdoux, I. Techer, Methodological development for $^{87}\text{Sr}/^{86}\text{Sr}$
741 measurement in olive oil and preliminary discussion of its use for geographical traceability of PDO
742 Nîmes (France), Food Chemistry. 171 (2015) 78–83. doi:10.1016/j.foodchem.2014.08.121.
- 743 [51] B.J. Tipple, T. Chau, L.A. Chesson, D.P. Fernandez, J.R. Ehleringer, Isolation of strontium pools
744 and isotope ratios in modern human hair, Analytica Chimica Acta. 798 (2013) 64–73.
745 doi:10.1016/j.aca.2013.08.054.
- 746 [52] G. Vautour, A. Poirier, D. Widory, Tracking mobility using human hair: What can we learn from
747 lead and strontium isotopes?, Science & Justice. 55 (2015) 63–71.
748 doi:10.1016/j.scijus.2014.10.001.
- 749 [53] B. Valentine, G.D. Kamenov, J.M. Kenoyer, V. Shinde, V. Mushrif-Tripathy, E. Otarola-Castillo, et
750 al., Evidence for Patterns of Selective Urban Migration in the Greater Indus Valley (2600-1900
751 BC): A Lead and Strontium Isotope Mortuary Analysis, PLOS ONE. 10 (2015) e0123103.
752 doi:10.1371/journal.pone.0123103.
- 753 [54] A.C. Ross, J.E. Manson, S.A. Abrams, J.F. Aloia, P.M. Brannon, S.K. Clinton, et al., The 2011
754 Report on Dietary Reference Intakes for Calcium and Vitamin D from the Institute of Medicine:
755 What Clinicians Need to Know, The Journal of Clinical Endocrinology & Metabolism. 96 (2011) 53–
756 58. doi:10.1210/jc.2010-2704.
- 757 [55] L. Balcaen, L. Moens, F. Vanhaecke, Determination of isotope ratios of metals (and metalloids) by
758 means of inductively coupled plasma-mass spectrometry for provenancing purposes — A review,

- 759 Spectrochimica Acta Part B: Atomic Spectroscopy. 65 (2010) 769–786.
760 doi:10.1016/j.sab.2010.06.005.
- 761 [56] L. Yang, Accurate and precise determination of isotopic ratios by MC-ICP-MS: a review., *Mass Spectrometry Reviews*. 28 (2009) 990–1011. doi:10.1002/mas.20251.
762
- 763 [57] E.M. Krupp, C. Pécheyran, H. Pinaly, M. Motelica-Heino, D. Koller, S.M.M. Young, et al., Isotopic
764 precision for a lead species (PbEt₄) using capillary gas chromatography coupled to inductively
765 coupled plasma-multicollector mass spectrometry, *Spectrochimica Acta Part B: Atomic Spectroscopy*. 56 (2001) 1233–1240. doi:10.1016/S0584-8547(01)00204-X.
766
- 767 [58] C.-K. Jeong, H. Jang, G.-J. Lee, Study on strontium isotope abundance-ratio measurements by
768 using a 13-MeV proton beam, *Journal of the Korean Physical Society*. 69 (2016) 1121–1124.
769 doi:10.3938/jkps.69.1121.
- 770 [59] T. Stephan, R. Trappitsch, A.M. Davis, M.J. Pellin, D. Rost, M.R. Savina, et al., CHILI – the
771 Chicago Instrument for Laser Ionization – a new tool for isotope measurements in
772 cosmochemistry, *International Journal of Mass Spectrometry*. 407 (2016) 1–15.
773 doi:10.1016/j.ijms.2016.06.001.
- 774 [60] J. Irrgeher, A. Zitek, M. Cervicek, T. Prohaska, Analytical factors to be considered for the
775 application of enriched strontium spikes to monitor biological systems, *J. Anal. At. Spectrom.* 29
776 (2014) 193–200. doi:10.1039/C3JA50212K.
- 777 [61] M. Horsky, J. Irrgeher, T. Prohaska, Evaluation strategies and uncertainty calculation of isotope
778 amount ratios measured by MC ICP-MS on the example of Sr, *Analytical and Bioanalytical Chemistry*. 408 (2016) 351–367. doi:10.1007/s00216-015-9003-9.
779
- 780 [62] B.L.A. Charlier, G.M. Nowell, I.J. Parkinson, S.P. Kelley, D.G. Pearson, K.W. Burton, High
781 temperature strontium stable isotope behaviour in the early solar system and planetary bodies,
782 *Earth and Planetary Science Letters*. 329–330 (2012) 31–40. doi:10.1016/j.epsl.2012.02.008.
- 783 [63] T. Kleine, Radiogenic Isotopes, in: *Encyclopedia of Astrobiology*, Springer Berlin Heidelberg,
784 Berlin, Heidelberg, 2011: pp. 1424–1430. doi:10.1007/978-3-642-11274-4_1343.
- 785 [64] A. V. Dunin, N.A. Nerozin, N.R. Togaeva, S. V. Khamyanov, V. V. Shapovalov, Extraction of Sr-82,
786 Raw Material for Radiopharmaceutical Production, *Pharmaceutical Chemistry Journal*. 48 (2014)
787 395–397. doi:10.1007/s11094-014-1118-3.
- 788 [65] I. Kuroda, Effective use of strontium-89 in osseous metastases, *Annals of Nuclear Medicine*. 26
789 (2012) 197–206. doi:10.1007/s12149-011-0560-5.
- 790 [66] X. jiao Qin, H. mei Chen, L. Guo, Y. yuan Guo, Low-dose strontium-90 irradiation is effective in
791 preventing the recurrence of pterygia: A ten-year study, *PLoS ONE*. 7 (2012).
792 doi:10.1371/journal.pone.0043500.
- 793 [67] J.- Reginster, Strontium Ranelate in Osteoporosis, *Current Pharmaceutical Design*. 8 (2002)
794 1907–1916. doi:10.2174/1381612023393639.
- 795 [68] European Medicines Agency, Protelos and Osseor Article-20 procedure - Protelos/Osseor to
796 remain available but with further restrictions, 2014.
797 http://www.ema.europa.eu/docs/en_GB/document_library/Referrals_document/Protelos_and_Osseor/European_Commission_final_decision/WC500173034.pdf.
798
- 799 [69] J.-Y. Reginster, C. Beaudart, A. Neuprez, O. Bruyère, Strontium ranelate in the treatment of knee
800 osteoarthritis: new insights and emerging clinical evidence., *Therapeutic Advances in*
801 *Musculoskeletal Disease*. 5 (2013) 268–276. doi:10.1177/1759720X13500862.
- 802 [70] B.-Y. Song, J.-S. Ryu, H.S. Shin, K.-S. Lee, Determination of the Source of Bioavailable Sr Using
803 ⁸⁷Sr/ ⁸⁶Sr Tracers: A Case Study of Hot Pepper and Rice, *Journal of Agricultural and Food Chemistry*. 62 (2014) 9232–9238. doi:10.1021/jf503498r.
804
- 805 [71] B.-Y. Song, M.K. Gautam, J.-S. Ryu, D. Lee, K.-S. Lee, Effects of bedrock on the chemical and Sr
806 isotopic compositions of plants, *Environmental Earth Sciences*. 74 (2015) 829–837.
807 doi:10.1007/s12665-015-4087-2.
- 808 [72] C. Durante, C. Baschieri, L. Bertacchini, M. Cocchi, S. Sighinolfi, M. Silvestri, et al., Geographical
809 traceability based on ⁸⁷Sr/⁸⁶Sr indicator: A first approach for PDO Lambrusco wines from
810 Modena, *Food Chemistry*. 141 (2013) 2779–87. doi:10.1016/j.foodchem.2013.05.108.
- 811 [73] C. Durante, C. Baschieri, L. Bertacchini, D. Bertelli, M. Cocchi, A. Marchetti, et al., An analytical
812 approach to Sr isotope ratio determination in Lambrusco wines for geographical traceability
813 purposes, *Food Chemistry*. 173 (2015) 557–63. doi:10.1016/j.foodchem.2014.10.086.
- 814 [74] S. Marchionni, E. Braschi, S. Tommasini, A. Bollati, F. Cifelli, N. Mulinacci, et al., High-precision
815 ⁸⁷Sr/⁸⁶Sr analyses in wines and their use as a geological fingerprint for tracing geographic

- 816 provenance, *Journal of Agricultural and Food Chemistry*. 61 (2013) 6822–31.
817 doi:10.1021/jf4012592.
- 818 [75] International olive council, *World Olive Oil Figures - International Olive Council*, (n.d.).
819 <http://www.internationaloliveoil.org/estaticos/view/131-world-olive-oil-figures> (accessed January 7,
820 2015).
- 821 [76] R. Stevenson, S. Desrochers, J.-F. Hélie, Stable and radiogenic isotopes as indicators of agri-food
822 provenance: Insights from artisanal cheeses from Quebec, Canada, *International Dairy Journal*.
823 (2015). doi:10.1016/j.idairyj.2015.04.003.
- 824 [77] P.R. Trincerini, C. Baffi, P. Barbero, E. Pizzoglio, S. Spalla, Precise determination of strontium
825 isotope ratios by TIMS to authenticate tomato geographical origin, *Food Chemistry*. 145 (2014)
826 349–355. doi:10.1016/j.foodchem.2013.08.030.
- 827 [78] Y. Zhu, A. Hioki, K. Chiba, Measurement of strontium isotope ratio in nitric acid extract of peanut
828 testa by ICP-Q-MS after removal of Rb by extraction with pure water, *Talanta*. 119 (2014) 596–
829 600. doi:10.1016/j.talanta.2013.11.058.
- 830 [79] K. G. Heumann, S. M. Gallus, G. Rädlinger, J. Vogl, Precision and accuracy in isotope ratio
831 measurements by plasma source mass spectrometry, *Journal of Analytical Atomic Spectrometry*.
832 13 (1998) 1001. doi:10.1039/a801965g.
- 833 [80] B.A. Wolff, B.M. Johnson, C.M. Landress, B. Gillanders, Classification of hatchery and wild fish
834 using natural geochemical signatures in otoliths, fin rays, and scales of an endangered catostomid,
835 *Canadian Journal of Fisheries and Aquatic Sciences*. 70 (2013) 1775–1784. doi:10.1139/cjfas-
836 2013-0116.
- 837 [81] J. Martin, G. Bareille, S. Berail, C. Pecheyran, F. Daverat, N. Bru, et al., Spatial and temporal
838 variations in otolith chemistry and relationships with water chemistry: a useful tool to distinguish
839 Atlantic salmon *Salmo salar* parr from different natal streams, *Journal of Fish Biology*. 82 (2013)
840 1556–1581. doi:10.1111/jfb.12089.
- 841 [82] J. Martin, G. Bareille, S. Berail, C. Pecheyran, F. Gueraud, F. Lange, et al., Persistence of a
842 southern Atlantic salmon population: diversity of natal origins from otolith elemental and Sr isotopic
843 signatures, *Canadian Journal of Fisheries and Aquatic Sciences*. 70 (2013) 182–197.
844 doi:10.1139/cjfas-2012-0284.
- 845 [83] S.R. Brennan, D.P. Fernandez, C.E. Zimmerman, T.E. Cerling, R.J. Brown, M.J. Wooller,
846 Strontium isotopes in otoliths of a non-migratory fish (slimy sculpin): Implications for provenance
847 studies, *Geochimica et Cosmochimica Acta*. 149 (2015) 32–45. doi:10.1016/j.gca.2014.10.032.
- 848 [84] C.C. Muhlfeld, S.R. Thorrold, T.E. McMahon, B. Marotz, B. Gillanders, Estimating westslope
849 cutthroat trout (*Oncorhynchus clarkii lewisi*) movements in a river network using strontium
850 isoscapes, *Canadian Journal of Fisheries and Aquatic Sciences*. 69 (2012) 906–915.
851 doi:10.1139/f2012-033.
- 852 [85] J.I. Macdonald, D.G. McNeil, D.A. Crook, *Asteriscus v. lapillus*: comparing the chemistry of two
853 otolith types and their ability to delineate riverine populations of common carp *Cyprinus carpio*,
854 *Journal of Fish Biology*. 81 (2012) 1715–1729. doi:10.1111/j.1095-8649.2012.03443.x.
- 855 [86] B.A. Wolff, B.M. Johnson, A.R. Breton, P.J. Martinez, D.L. Winkelman, B. Gillanders, Origins of
856 invasive piscivores determined from the strontium isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) of otoliths, *Canadian*
857 *Journal of Fisheries and Aquatic Sciences*. 69 (2012) 724–739. doi:10.1139/f2012-009.
- 858 [87] A.J. Padilla, R.J. Brown, M.J. Wooller, Determining the Movements and Distribution of
859 Anadromous Bering Ciscos by Use of Otolith Strontium Isotopes, *Transactions of the American*
860 *Fisheries Society*. 145 (2016) 1374–1385. doi:10.1080/00028487.2016.1225599.
- 861 [88] R. Johnson, J. Garza, R. MacFarlane, C. Grimes, C. Phillis, P. Koch, et al., Isotopes and genes
862 reveal freshwater origins of Chinook salmon *Oncorhynchus tshawytscha* aggregations in
863 California's coastal ocean, *Marine Ecology Progress Series*. 548 (2016) 181–196.
864 doi:10.3354/meps11623.
- 865 [89] M. Willmes, J.J.G. Glessner, S.A. Carleton, P.C. Gerrity, J.A. Hobbs, $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio
866 analysis by laser ablation MC-ICP-MS in scales, spines, and fin rays as a nonlethal alternative to
867 otoliths for reconstructing fish life history, *Canadian Journal of Fisheries and Aquatic Sciences*. 73
868 (2016) 1852–1860. doi:10.1139/cjfas-2016-0103.
- 869 [90] Y.-S. Bong, W.-J. Shin, M.K. Gautam, Y.-J. Jeong, A.-R. Lee, C.-S. Jang, et al., Determining the
870 geographical origin of Chinese cabbages using multielement composition and strontium isotope
871 ratio analyses, *Food Chemistry*. 135 (2012) 2666–2674. doi:10.1016/j.foodchem.2012.07.045.
- 872 [91] Y.-S. BONG, M.K. GAUTAM, M.-R. LA, K.-S. LEE, Geographic Origins of Korean and Chinese
873 Kimchi Determined by Multiple Elements, *Bioscience, Biotechnology, and Biochemistry*. 76 (2012)

- 874 2096–2100. doi:10.1271/bbb.120471.
- 875 [92] K. Ariyama, M. Shinozaki, A. Kawasaki, Determination of the Geographic Origin of Rice by
876 Chemometrics with Strontium and Lead Isotope Ratios and Multielement Concentrations, *Journal*
877 *of Agricultural and Food Chemistry*. 60 (2012) 1628–1634. doi:10.1021/jf204296p.
- 878 [93] S. Rummel, C.H. Dekant, S. Hölzl, S.D. Kelly, M. Baxter, N. Marigheto, et al., Sr isotope
879 measurements in beef—analytical challenge and first results, *Analytical and Bioanalytical*
880 *Chemistry*. 402 (2012) 2837–2848. doi:10.1007/s00216-012-5759-3.
- 881 [94] H. HIRAOKA, S. MORITA, A. IZAWA, K. AOYAMA, K.-C. SHIN, T. NAKANO, Tracing the
882 Geographical Origin of Onions by Strontium Isotope Ratio and Strontium Content, *Analytical*
883 *Sciences*. 32 (2016) 781–788. doi:10.2116/analsci.32.781.
- 884 [95] R. Petrini, L. Sansone, F.F. Slejko, A. Bucciatti, P. Marcuzzo, D. Tomasi, The (87)Sr/(86)Sr
885 strontium isotopic systematics applied to Glera vineyards: a tracer for the geographical origin of
886 the Prosecco, *Food Chemistry*. 170 (2015) 138–44. doi:10.1016/j.foodchem.2014.08.051.
- 887 [96] J.R. Fernandes, L. Pereira, P. Jorge, L. Moreira, H. Gonçalves, L. Coelho, et al., Wine
888 fingerprinting using a bio-geochemical approach, *BIO Web of Conferences*. 5 (2015) 2021.
889 doi:10.1051/bioconf/20150502021.
- 890 [97] S. Marchionni, A. Bucciatti, A. Bollati, E. Braschi, F. Cifelli, P. Molin, et al., Conservation of
891 87Sr/86Sr isotopic ratios during the winemaking processes of “Red” wines to validate their use as
892 geographic tracer, *Food Chemistry*. 190 (2016) 777–785. doi:10.1016/j.foodchem.2015.06.026.
- 893 [98] S. Catarino, C. Moreira, A. Kaya, R.B. de Sousa, A. Curvelo-Garcia, M. de Pinho, et al., Effect of
894 new and conventional technological processes on the terroir marker 87 Sr/ 86 Sr, *BIO Web of*
895 *Conferences*. 7 (2016) 2003. doi:10.1051/bioconf/20160702003.
- 896 [99] V. Vinciguerra, R. Stevenson, K. Pedneault, A. Poirier, J.-F. Hélie, D. Widory, Strontium isotope
897 characterization of wines from Quebec, Canada, *Food Chemistry*. 210 (2016) 121–128.
898 doi:10.1016/j.foodchem.2016.04.017.
- 899 [100] H.-C. Liu, C.-F. You, C.-Y. Chen, Y.-C. Liu, M.-T. Chung, Geographic determination of coffee
900 beans using multi-element analysis and isotope ratios of boron and strontium, *Food Chemistry*.
901 142 (2014) 439–45. doi:10.1016/j.foodchem.2013.07.082.
- 902 [101] C.-T. Chang, C.-F. You, S.K. Aggarwal, C.-H. Chung, H.-C. Chao, H.-C. Liu, Boron and strontium
903 isotope ratios and major/trace elements concentrations in tea leaves at four major tea growing
904 gardens in Taiwan, *Environmental Geochemistry and Health*. 38 (2016) 737–748.
905 doi:10.1007/s10653-015-9757-1.
- 906 [102] G. Rees, S.D. Kelly, P. Cairns, H. Ueckermann, S. Hoelzl, A. Rossmann, et al., Verifying the
907 geographical origin of poultry: The application of Stable Isotope and Trace Element (SITE)
908 Analysis, *Food Control*. (2016). doi:10.1016/j.foodcont.2016.02.018.
- 909 [103] Y.-S. Bong, J.-S. Ryu, S.-H. Choi, M.-R. La, K.-S. Lee, Investigation of the geographical
910 provenance of the beer available in South Korea using multielements and isotopes, *Food Control*.
911 60 (2016) 378–381. doi:10.1016/j.foodcont.2015.08.017.
- 912 [104] N.S. Podio, M. V. Baroni, R.G. Badini, M. Inga, H.A. Ostera, M. Cagnoni, et al., Elemental and
913 Isotopic Fingerprint of Argentinean Wheat. Matching Soil, Water, and Crop Composition to
914 Differentiate Provenance, *Journal of Agricultural and Food Chemistry*. 61 (2013) 3763–3773.
915 doi:10.1021/jf305258r.
- 916 [105] H. Liu, Y. Wei, H. Lu, S. Wei, T. Jiang, Y. Zhang, et al., Combination of the 87Sr/86Sr ratio and
917 light stable isotopic values ($\delta^{13}C$, $\delta^{15}N$ and δD) for identifying the geographical origin of winter
918 wheat in China, *Food Chemistry*. 212 (2016) 367–373. doi:10.1016/j.foodchem.2016.06.002.
- 919 [106] M. V. Baroni, N.S. Podio, R.G. Badini, M. Inga, H.A. Ostera, M. Cagnoni, et al., Linking Soil,
920 Water, and Honey Composition To Assess the Geographical Origin of Argentinean Honey by
921 Multielemental and Isotopic Analyses, *Journal of Agricultural and Food Chemistry*. 63 (2015)
922 4638–4645. doi:10.1021/jf5060112.
- 923 [107] C.A. Makarewicz, J. Sealy, Dietary reconstruction, mobility, and the analysis of ancient skeletal
924 tissues: Expanding the prospects of stable isotope research in archaeology, *Journal of*
925 *Archaeological Science*. 56 (2015) 146–158. doi:10.1016/j.jas.2015.02.035.
- 926 [108] P.A. Slater, K.M. Hedman, T.E. Emerson, Immigrants at the Mississippian polity of Cahokia:
927 Strontium isotope evidence for population movement, *Journal of Archaeological Science*. 44
928 (2014) 117–127. doi:10.1016/j.jas.2014.01.022.
- 929 [109] A.J. Waterman, D.W. Peate, A.M. Silva, J.T. Thomas, In search of homelands: Using strontium
930 isotopes to identify biological markers of mobility in late prehistoric Portugal, *Journal of*

- 931 Archaeological Science. 42 (2014) 119–127. doi:10.1016/j.jas.2013.11.004.
- 932 [110] D.T. Price, S. Nakamura, S. Suzuki, J.H. Burton, V. Tiesler, New isotope data on Maya mobility
933 and enclaves at Classic Copan, Honduras, *Journal of Anthropological Archaeology*. 36 (2014) 32–
934 47. doi:10.1016/j.jaa.2014.02.003.
- 935 [111] J. Pokines, S. Symes, *Manual of Forensic Taphonomy*, 2013.
- 936 [112] M. Sponheimer, J.A. Lee-Thorp, Enamel diagenesis at South African Australopith sites:
937 Implications for paleoecological reconstruction with trace elements, *Geochimica et Cosmochimica*
938 *Acta*. 70 (2006) 1644–1654. doi:10.1016/j.gca.2005.12.022.
- 939 [113] P. Budda, J. Montgomery, B. Barreiro, R.G. Thomas, Differential diagenesis of strontium in
940 archaeological human dental tissues, *Applied Geochemistry*. 15 (2000) 687–694.
- 941 [114] C. Minniti, S. Valenzuela-Lamas, J. Evans, U. Albarella, Widening the market. Strontium isotope
942 analysis on cattle teeth from Owslebury (Hampshire, UK) highlights changes in livestock supply
943 between the Iron Age and the Roman period, *Journal of Archaeological Science*. 42 (2014) 305–
944 314. doi:10.1016/j.jas.2013.10.008.
- 945 [115] L.A. Gregoricka, Residential mobility and social identity in the periphery: strontium isotope analysis
946 of archaeological tooth enamel from southeastern Arabia, *Journal of Archaeological Science*. 40
947 (2013) 452–464. doi:10.1016/j.jas.2012.07.017.
- 948 [116] J.E. Laffoon, G.R. Davies, M.L.P. Hoogland, C.L. Hofman, Spatial variation of biologically available
949 strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) in an archipelagic setting: a case study from the Caribbean,
950 *Journal of Archaeological Science*. 39 (2012) 2371–2384. doi:10.1016/j.jas.2012.02.002.
- 951 [117] E. McManus, J. Montgomery, J. Evans, A. Lamb, R. Brettell, J. Jelsma, “To the Land or to the
952 Sea”: Diet and Mobility in Early Medieval Frisia, *The Journal of Island and Coastal Archaeology*. 8
953 (2013) 255–277. doi:10.1080/15564894.2013.787565.
- 954 [118] P. Degryse, D. De Muynck, S. Delporte, S. Boyen, L. Jadoul, J. De Winne, et al., Strontium
955 isotopic analysis as an experimental auxiliary technique in forensic identification of human
956 remains, *Analytical Methods*. 4 (2012) 2674. doi:10.1039/c2ay25035g.
- 957 [119] A.-F. Maurer, S.J.G. Galer, C. Knipper, L. Beierlein, E. V. Nunn, D. Peters, et al., Bioavailable
958 $^{87}\text{Sr}/^{86}\text{Sr}$ in different environmental samples — Effects of anthropogenic contamination and
959 implications for isoscapes in past migration studies, *Science of The Total Environment*. 433 (2012)
960 216–229. doi:10.1016/j.scitotenv.2012.06.046.
- 961 [120] H. Wilhelmson, T. Ahlström, Iron Age migration on the island of Öland: Apportionment of strontium
962 by means of Bayesian mixing analysis, *Journal of Archaeological Science*. 64 (2015) 30–45.
963 doi:10.1016/j.jas.2015.09.007.
- 964 [121] P.J. Le Roux, J. a. Lee-Thorp, S.R. Copeland, M. Sponheimer, D.J. de Ruiter, Strontium isotope
965 analysis of curved tooth enamel surfaces by laser-ablation multi-collector ICP-MS,
966 *Palaeogeography, Palaeoclimatology, Palaeoecology*. (2014). doi:10.1016/j.palaeo.2014.09.007.
- 967 [122] B.L. Turner, M.K. Zuckerman, E.M. Garofalo, A. Wilson, G.D. Kamenov, D.R. Hunt, et al., Diet and
968 death in times of war: isotopic and osteological analysis of mummified human remains from
969 southern Mongolia, *Journal of Archaeological Science*. 39 (2012) 3125–3140.
970 doi:10.1016/j.jas.2012.04.053.
- 971 [123] L.E. Wright, Immigration to Tikal, Guatemala: Evidence from stable strontium and oxygen isotopes,
972 *Journal of Anthropological Archaeology*. 31 (2012) 334–352. doi:10.1016/j.jaa.2012.02.001.
- 973 [124] K.A. Hemer, J.A. Evans, C.A. Chenery, A.L. Lamb, No Man is an island: evidence of pre-Viking
974 Age migration to the Isle of Man, *Journal of Archaeological Science*. 52 (2014) 242–249.
975 doi:10.1016/j.jas.2014.08.031.
- 976 [125] E.J. Kendall, J. Montgomery, J.A. Evans, C. Stantis, V. Mueller, Mobility, mortality, and the middle
977 ages: Identification of migrant individuals in a 14th century black death cemetery population,
978 *American Journal of Physical Anthropology*. 150 (2013) 210–222. doi:10.1002/ajpa.22194.
- 979 [126] K.A. Hemer, J.A. Evans, C.A. Chenery, A.L. Lamb, Evidence of early medieval trade and migration
980 between Wales and the Mediterranean Sea region, *Journal of Archaeological Science*. 40 (2013)
981 2352–2359. doi:10.1016/j.jas.2013.01.014.
- 982 [127] R. Kinaston, S. Bedford, M. Richards, S. Hawkins, A. Gray, K. Jaouen, et al., Diet and Human
983 Mobility from the Lapita to the Early Historic Period on Uripiv Island, Northeast Malakula, Vanuatu,
984 *PLoS ONE*. 9 (2014) e104071. doi:10.1371/journal.pone.0104071.
- 985 [128] K.-G. Sjögren, T.D. Price, K. Kristiansen, Diet and Mobility in the Corded Ware of Central Europe,
986 *PLOS ONE*. 11 (2016) e0155083. doi:10.1371/journal.pone.0155083.

- 987 [129] A.D. Somerville, M.J. Schoeninger, G.E. Braswell, Political alliance, residential mobility, and diet at
988 the ancient Maya city of Pusilha, Belize, *Journal of Anthropological Archaeology*. 41 (2016) 147–
989 158. doi:10.1016/j.jaa.2015.11.004.
- 990 [130] B. Chase, D. Meiggs, P. Ajithprasad, P.A. Slater, Pastoral land-use of the Indus Civilization in
991 Gujarat: faunal analyses and biogenic isotopes at Bagasra, *Journal of Archaeological Science*. 50
992 (2014) 1–15. doi:10.1016/j.jas.2014.06.013.
- 993 [131] H. Shaw, J. Montgomery, R. Redfern, R. Gowland, J. Evans, Identifying migrants in Roman
994 London using lead and strontium stable isotopes, *Journal of Archaeological Science*. 66 (2016)
995 57–68. doi:10.1016/j.jas.2015.12.001.
- 996 [132] C. Knipper, M. Fragata, N. Nicklisch, A. Siebert, A. Szécsényi-Nagy, V. Hubensack, et al., A
997 distinct section of the early bronze age society? Stable isotope investigations of burials in
998 settlement pits and multiple inhumations of the Únětice culture in central Germany, *American
999 Journal of Physical Anthropology*. 159 (2016) 496–516. doi:10.1002/ajpa.22892.
- 1000 [133] K. Killgrove, J. Montgomery, All Roads Lead to Rome: Exploring Human Migration to the Eternal
1001 City through Biochemistry of Skeletons from Two Imperial-Era Cemeteries (1st-3rd c AD), *PLOS
1002 ONE*. 11 (2016) e0147585. doi:10.1371/journal.pone.0147585.
- 1003 [134] A.F. Carvalho, F. Alves-Cardoso, D. Gonçalves, R. Granja, J.L. Cardoso, R.M. Dean, et al., The
1004 Bom Santo Cave (Lisbon, Portugal): Catchment, Diet, and Patterns of Mobility of a Middle
1005 Neolithic Population, *European Journal of Archaeology*. 19 (2016) 187–214.
1006 doi:10.1179/1461957115Y.0000000014.
- 1007 [135] D.S. Kurin, E.M. Lofaro, D.E. Gómez Choque, J. Krigbaum, A Bioarchaeological and
1008 Biogeochemical Study of Warfare and Mobility in Andahuaylas, Peru (ca. <sc>ad</sc> 1160-
1009 1260), *International Journal of Osteoarchaeology*. 26 (2016) 93–103. doi:10.1002/oa.2398.
- 1010 [136] M.Q.R. Bastos, R. V. Santos, S.M.F. M. de Souza, C. Rodrigues-Carvalho, R.H. Tykot, D.C. Cook,
1011 et al., Isotopic study of geographic origins and diet of enslaved Africans buried in two Brazilian
1012 cemeteries, *Journal of Archaeological Science*. 70 (2016) 82–90. doi:10.1016/j.jas.2016.04.020.
- 1013 [137] S. Neil, J. Evans, J. Montgomery, C. Scarre, Isotopic evidence for residential mobility of farming
1014 communities during the transition to agriculture in Britain, *Royal Society Open Science*. 3 (2016)
1015 150522. doi:10.1098/rsos.150522.
- 1016 [138] E. Oras, V. Lang, E. Rannamäe, L. Varul, M. Kansa, J. Limbo-Simovart, et al., TRACING
1017 PREHISTORIC MIGRATION: ISOTOPE ANALYSIS OF BRONZE AND PRE-ROMAN IRON AGE
1018 COASTAL BURIALS IN ESTONIA, *Estonian Journal of Archaeology*. 20 (2016) 3.
1019 doi:10.3176/arch.2016.1.01.
- 1020 [139] A.L. Lamb, J.E. Evans, R. Buckley, J. Appleby, Multi-isotope analysis demonstrates significant
1021 lifestyle changes in King Richard III, *Journal of Archaeological Science*. 50 (2014) 559–565.
1022 doi:10.1016/j.jas.2014.06.021.
- 1023 [140] G. Goude, F. Castorina, E. Herrscher, S. Cabut, M.A. Tafuri, First Strontium Isotope Evidence of
1024 Mobility in the Neolithic of Southern France, *European Journal of Archaeology*. 15 (2012) 421–
1025 439. doi:10.1179/1461957112Y.0000000017.
- 1026 [141] S. Kusaka, T. Nakano, W. Morita, M. Nakatsukasa, Strontium isotope analysis to reveal migration
1027 in relation to climate change and ritual tooth ablation of Jomon skeletal remains from western
1028 Japan, *Journal of Anthropological Archaeology*. 31 (2012) 551–563.
1029 doi:10.1016/j.jaa.2012.05.004.
- 1030 [142] K.J. Knudson, B. O'Donnabhain, C. Carver, R. Cleland, T.D. Price, Migration and Viking Dublin:
1031 paleomobility and paleodiet through isotopic analyses, *Journal of Archaeological Science*. 39
1032 (2012) 308–320. doi:10.1016/j.jas.2011.09.014.
- 1033 [143] M.R. Buzon, C.A. Conlee, A. Simonetti, G.J. Bowen, The consequences of Wari contact in the
1034 Nasca region during the Middle Horizon: archaeological, skeletal, and isotopic evidence, *Journal of
1035 Archaeological Science*. 39 (2012) 2627–2636. doi:10.1016/j.jas.2012.04.003.
- 1036 [144] K.J. Knudson, W.J. Pestle, C. Torres-Rouff, G. Pimentel, Assessing the life history of an andean
1037 traveller through biogeochemistry: Stable and radiogenic isotope analyses of archaeological
1038 human remains from Northern Chile, *International Journal of Osteoarchaeology*. 22 (2012) 435–
1039 451. doi:10.1002/oa.1217.
- 1040 [145] J.I. Giblin, K.J. Knudson, Z. Bereczki, G. Pálfi, I. Pap, Strontium isotope analysis and human
1041 mobility during the Neolithic and Copper Age: a case study from the Great Hungarian Plain,
1042 *Journal of Archaeological Science*. 40 (2013) 227–239. doi:10.1016/j.jas.2012.08.024.
- 1043 [146] K.L. Nado, S.J. Marsteller, L.M. King, B.M. Daverman, C. Torres-Rouff, K.J. Knudson,
1044 EXAMINING LOCAL SOCIAL IDENTITIES THROUGH PATTERNS OF BIOLOGICAL AND

- 1045 CULTURAL VARIATION IN THE SOLCOR AYLLU, SAN PEDRO DE ATACAMA, CHILE,
1046 Chungará (Arica). 44 (2012) 341–357. doi:10.4067/S0717-73562012000200010.
- 1047 [147] C. Lang, J. Peters, N. Pöllath, K. Schmidt, G. Grupe, Gazelle behaviour and human presence at
1048 early Neolithic Göbekli Tepe, south-east Anatolia, *World Archaeology*. 45 (2013) 410–429.
1049 doi:10.1080/00438243.2013.820648.
- 1050 [148] X. Zhang, J. Burton, Z. Jin, M. Xiao, A. Fan, J. Xu, Isotope studies of human remains from
1051 Mayutian, Yunnan Province, China, *Journal of Archaeological Science*. 50 (2014) 414–419.
1052 doi:10.1016/j.jas.2014.08.001.
- 1053 [149] K.W. Alt, C. Knipper, D. Peters, W. Müller, A.-F. Maurer, I. Kollig, et al., Lombards on the Move –
1054 An Integrative Study of the Migration Period Cemetery at Szólád, Hungary, *PLoS ONE*. 9 (2014)
1055 e110793. doi:10.1371/journal.pone.0110793.
- 1056 [150] J.W. Eerkens, G.H. Barford, G.A. Jorgenson, C. Peske, Tracing the mobility of individuals using
1057 stable isotope signatures in biological tissues: “locals” and “non-locals” in an ancient case of
1058 violent death from Central California, *Journal of Archaeological Science*. 41 (2014) 474–481.
1059 doi:10.1016/j.jas.2013.09.014.
- 1060 [151] Y. Bäckström, T.D. Price, Social identity and mobility at a pre-industrial mining complex, Sweden,
1061 *Journal of Archaeological Science*. 66 (2016) 154–168. doi:10.1016/j.jas.2016.01.004.
- 1062 [152] K.W. Alt, S. Zesch, R. Garrido-Pena, C. Knipper, A. Szécsényi-Nagy, C. Roth, et al., A Community
1063 in Life and Death: The Late Neolithic Megalithic Tomb at Alto de Reinoso (Burgos, Spain), *PLOS*
1064 *ONE*. 11 (2016) e0146176. doi:10.1371/journal.pone.0146176.
- 1065 [153] C. Snoeck, J. Pouncett, G. Ramsey, I.G. Meighan, N. Mattielli, S. Goderis, et al., Mobility during
1066 the neolithic and bronze age in northern ireland explored using strontium isotope analysis of
1067 cremated human bone, *American Journal of Physical Anthropology*. 160 (2016) 397–413.
1068 doi:10.1002/ajpa.22977.
- 1069 [154] M.A. Tafuri, P.D. Fullagar, T.C. O’Connell, M.G. Belcastro, P. Iacumin, C. Conati Barbaro, et al.,
1070 Life and Death in Neolithic Southeastern Italy: The Strontium Isotopic Evidence, *International*
1071 *Journal of Osteoarchaeology*. 26 (2016) 1045–1057. doi:10.1002/oa.2516.
- 1072 [155] G. HUELGA-SUAREZ, S. DIEZ-FERNÁNDEZ, M. MOLDOVAN, A.F. PARDIÑAS, B. LÓPEZ, J.I.
1073 GARCÍA ALONSO, The quest for the soldier’s rest: combining anthropological and
1074 archaeochemical approaches to study social and occupational diversity in the medieval graveyard
1075 of San Andrés de Arroyo (Palencia, Spain), *Anthropological Science*. 124 (2016) 169–184.
1076 doi:10.1537/ase.161005.
- 1077 [156] X. Wang, Z. Tang, J. Wu, X. Wu, Y. Wu, X. Zhou, Strontium isotope evidence for a highly mobile
1078 population on the Pamir Plateau 2500 years ago, *Scientific Reports*. 6 (2016) 35162.
1079 doi:10.1038/srep35162.
- 1080 [157] C. Knipper, C. Meyer, F. Jacobi, C. Roth, M. Fecher, E. Stephan, et al., Social differentiation and
1081 land use at an Early Iron Age “princely seat”: bioarchaeological investigations at the Glauberg
1082 (Germany), *Journal of Archaeological Science*. 41 (2014) 818–835. doi:10.1016/j.jas.2013.09.019.
- 1083 [158] V.M. Oelze, J.K. Koch, K. Kupke, O. Nehlich, S. Zäuner, J. Wahl, et al., Multi-isotopic analysis
1084 reveals individual mobility and diet at the early iron age monumental tumulus of magdalenenberg,
1085 germany, *American Journal of Physical Anthropology*. 148 (2012) 406–421.
1086 doi:10.1002/ajpa.22063.
- 1087 [159] R. Brettell, J. Evans, S. Marzinzik, A. Lamb, J. Montgomery, “Impious Easterners”: Can Oxygen
1088 and Strontium Isotopes Serve as Indicators of Provenance in Early Medieval European Cemetery
1089 Populations?, *European Journal of Archaeology*. 15 (2012) 117–145.
1090 doi:10.1179/1461957112Y.0000000001.
- 1091 [160] M. Jay, J. Montgomery, O. Nehlich, J. Towers, J. Evans, British Iron Age chariot burials of the
1092 Arras culture: a multi-isotope approach to investigating mobility levels and subsistence practices,
1093 *World Archaeology*. 45 (2013) 473–491. doi:10.1080/00438243.2013.820647.
- 1094 [161] F.Ö. Dudás, S.A. LeBlanc, S.W. Carter, S.A. Bowring, Pb and Sr concentrations and isotopic
1095 compositions in prehistoric North American teeth: A methodological study, *Chemical Geology*. 429
1096 (2016) 21–32. doi:10.1016/j.chemgeo.2016.03.003.
- 1097 [162] M.A. Beherec, T.E. Levy, O. Tirosh, M. Najjar, K.A. Knabb, Y. Erel, Iron Age Nomads and their
1098 relation to copper smelting in Faynan (Jordan): Trace metal and Pb and Sr isotopic measurements
1099 from the Wadi Fidan 40 cemetery, *Journal of Archaeological Science*. 65 (2016) 70–83.
1100 doi:10.1016/j.jas.2015.10.006.
- 1101 [163] S. di Lernia, M.A. Tafuri, Persistent deathplaces and mobile landmarks: The Holocene mortuary
1102 and isotopic record from Wadi Takarkori (SW Libya), *Journal of Anthropological Archaeology*. 32

- 1103 (2013) 1–15. doi:10.1016/j.jaa.2012.07.002.
- 1104 [164] T.D. Price, J.N. Nielsen, K.M. Frei, N. Lynnerup, Sebbersund: isotopes and mobility in an
1105 11th–12th c. AD Danish churchyard, *Journal of Archaeological Science*. 39 (2012) 3714–3720.
1106 doi:10.1016/j.jas.2012.06.015.
- 1107 [165] V.M. OELZE, O. NEHLICH, M.P. RICHARDS, “THERE’S NO PLACE LIKE HOME’-NO ISOTOPIC
1108 EVIDENCE FOR MOBILITY AT THE EARLY BRONZE AGE CEMETERY OF SINGEN,
1109 GERMANY, *Archaeometry*. 54 (2012) 752–778. doi:10.1111/j.1475-4754.2011.00644.x.
- 1110 [166] S. Valenzuela-Lamas, S. Jiménez-Manchón, J. Evans, D. López, R. Jornet, U. Albarella, Analysis
1111 of seasonal mobility of sheep in Iron Age Catalonia (north-eastern Spain) based on strontium and
1112 oxygen isotope analysis from tooth enamel: First results, *Journal of Archaeological Science:
1113 Reports*. 6 (2016) 828–836. doi:10.1016/j.jasrep.2015.08.042.
- 1114 [167] I. Scharlotta, A. Weber, Mobility of middle Holocene foragers in the Cis-Baikal region, Siberia:
1115 Individual life history approach, strontium ratios, rare earth and trace elements, *Quaternary
1116 International*. 348 (2014) 37–65. doi:10.1016/j.quaint.2014.03.040.
- 1117 [168] M. Scheeres, C. Knipper, M. Hauschild, M. Schönfelder, W. Siebel, D. Vitali, et al., Evidence for
1118 “Celtic migrations”? Strontium isotope analysis at the early La Tène (LT B) cemeteries of
1119 Nebringen (Germany) and Monte Bibeale (Italy), *Journal of Archaeological Science*. 40 (2013)
1120 3614–3625. doi:10.1016/j.jas.2013.05.003.
- 1121 [169] J.E. Laffoon, R. Rodríguez Ramos, L. Chanlatte Baik, Y. Narganes Storde, M. Rodríguez Lopez,
1122 G.R. Davies, et al., Long-distance exchange in the precolonial Circum-Caribbean: A multi-isotope
1123 study of animal tooth pendants from Puerto Rico, *Journal of Anthropological Archaeology*. 35
1124 (2014) 220–233. doi:10.1016/j.jaa.2014.06.004.
- 1125 [170] A.W. Weber, O.I. Goriunova, Hunter–gatherer migrations, mobility and social relations: A case
1126 study from the Early Bronze Age Baikal region, Siberia, *Journal of Anthropological Archaeology*.
1127 32 (2013) 330–346. doi:10.1016/j.jaa.2012.01.006.
- 1128 [171] T. Tütken, T.W. Vennemann, H.-U. Pfretzschner, Nd and Sr isotope compositions in modern and
1129 fossil bones – Proxies for vertebrate provenance and taphonomy, *Geochimica et Cosmochimica
1130 Acta*. 75 (2011) 5951–5970. doi:10.1016/j.gca.2011.07.024.
- 1131 [172] M. Pérez de Nanclares, J.-E. Dessen, K.-A. Rørvik, Y. Thomassen, M.S. Thomassen, Feasibility of
1132 using rare earth elements (REEs) to mark and identify escaped farmed Atlantic salmon *Salmo
1133 salar* L., *Aquaculture Research*. 47 (2016) 1885–1898. doi:10.1111/are.12647.
- 1134 [173] C. Lehn, A. Rossmann, M. Graw, Provenancing of unidentified corpses by stable isotope
1135 techniques - presentation of case studies., *Science & Justice : Journal of the Forensic Science
1136 Society*. 55 (2015) 72–88. doi:10.1016/j.scijus.2014.10.006.
- 1137 [174] C. Lehn, C. Lihl, A. Roßmann, Change of geographical location from Germany (Bavaria) to USA
1138 (Arizona) and its effect on H-C-N-S stable isotopes in human hair, *Isotopes in Environmental and
1139 Health Studies*. 51 (2015) 68–79. doi:10.1080/10256016.2014.995645.
- 1140 [175] S.J. McLean, H. Ikegaya, P.J. Saukko, H.Y. Zheng, T. Akutsu, D. Miyamori, et al., A trial of the
1141 utilization of stable isotope analysis for the estimation of the geographic origins of unidentified
1142 cadavers., *Forensic Science International*. 232 (2013) 237.e1-5.
1143 doi:10.1016/j.forsciint.2013.07.019.
- 1144 [176] K. Alkass, H. Saitoh, B.A. Buchholz, S. Bernard, G. Holmlund, D.R. Senn, et al., Analysis of
1145 radiocarbon, stable isotopes and DNA in teeth to facilitate identification of unknown decedents,
1146 *PloS One*. 8 (2013) e69597. doi:10.1371/journal.pone.0069597.
- 1147 [177] L. Font, G. van der Peijl, I. van Wetten, P. Vroon, B. van der Wagt, G. Davies, Strontium and lead
1148 isotope ratios in human hair: investigating a potential tool for determining recent human
1149 geographical movements, *Journal of Analytical Atomic Spectrometry*. 27 (2012) 719.
1150 doi:10.1039/c2ja10361c.
- 1151 [178] M. Haeusler, C. Haas, S. Lösch, N. Moghaddam, I.M. Villa, S. Walsh, et al., Multidisciplinary
1152 Identification of the Controversial Freedom Fighter Jörg Jenatsch, Assassinated 1639 in Chur,
1153 Switzerland, *PLOS ONE*. 11 (2016) e0168014. doi:10.1371/journal.pone.0168014.
- 1154 [179] L. Font, G. Jonker, P.A. van Aalderen, E.F. Schiltmans, G.R. Davies, Provenancing of unidentified
1155 World War II casualties: Application of strontium and oxygen isotope analysis in tooth enamel,
1156 *Science & Justice : Journal of the Forensic Science Society*. 55 (2015) 10–7.
1157 doi:10.1016/j.scijus.2014.02.005.
- 1158 [180] J. Azparren, A. Fernandez-Rodriguez, G. Vallejo, Diagnosing death by drowning in fresh water
1159 using blood strontium as an indicator, *Forensic Science International*. 137 (2003) 55–59.
1160 doi:10.1016/S0379-0738(03)00284-6.

- 1161 [181] J.E. Azparren, C. Cubero, E. Perucha, P. Martínez, G. Vallejo, Comparison between lung weight
1162 and blood strontium in bodies found in seawater, *Forensic Science International*. 168 (2007) 128–
1163 132. doi:10.1016/j.forsciint.2006.07.001.
- 1164 [182] J.E. Azparren, E. Perucha, P. Martínez, R. Muñoz, G. Vallejo, Factors affecting strontium
1165 absorption in drownings, *Forensic Science International*. 168 (2007) 138–42.
1166 doi:10.1016/j.forsciint.2006.07.003.
- 1167 [183] M.D. Pérez-Cárceles, S. del Pozo, A. Sibón, J.A. Noguera, E. Osuna, M.A. Vizcaya, et al., Serum
1168 biochemical markers in drowning: Diagnostic efficacy of Strontium and other trace elements,
1169 *Forensic Science International*. 214 (2012) 159–166. doi:10.1016/j.forsciint.2011.07.047.
- 1170 [184] J. Azparren, A. Ortega, H. Bueno, M. Andreu, Blood strontium concentration related to the length
1171 of the agonal period in seawater drowning cases, *Forensic Science International*. 108 (2000) 51–
1172 60. doi:10.1016/S0379-0738(99)00200-5.
- 1173 [185] M.D. Pérez-Cárceles, A. Sibón, M.L. Gil Del Castillo, M.A. Vizcaya, E. Osuna, T. Casas, et al.,
1174 Strontium levels in different causes of death: diagnostic efficacy in drowning, *Biological Trace
1175 Element Research*. 126 (2008) 27–37. doi:10.1007/s12011-008-8180-1.
- 1176 [186] J.C. Hegg, B.P. Kennedy, A.K. Fremier, Predicting strontium isotope variation and fish location
1177 with bedrock geology: Understanding the effects of geologic heterogeneity, *Chemical Geology*.
1178 360–361 (2013) 89–98. doi:10.1016/j.chemgeo.2013.10.010.
- 1179 [187] S.R. Brennan, C.E. Torgersen, J.P. Hollenbeck, D.P. Fernandez, C.K. Jensen, D.E. Schindler,
1180 Dendritic network models: Improving isoscapes and quantifying influence of landscape and in-
1181 stream processes on strontium isotopes in rivers, *Geophysical Research Letters*. 43 (2016) 5043–
1182 5051. doi:10.1002/2016GL068904.
- 1183 [188] C.P. Bataille, G.J. Bowen, Mapping $^{87}\text{Sr}/^{86}\text{Sr}$ variations in bedrock and water for large scale
1184 provenance studies, *Chemical Geology*. 304–305 (2012) 39–52.
1185 doi:10.1016/j.chemgeo.2012.01.028.
- 1186 [189] C.P. Bataille, J. Laffoon, G.J. Bowen, Mapping multiple source effects on the strontium isotopic
1187 signatures of ecosystems from the circum-Caribbean region, *Ecosphere*. 3 (2012) art118.
1188 doi:10.1890/ES12-00155.1.
- 1189 [190] L.M. Kootker, R.J. van Lanen, H. Kars, G.R. Davies, Strontium isoscapes in The Netherlands.
1190 Spatial variations in $^{87}\text{Sr}/^{86}\text{Sr}$ as a proxy for palaeomobility, *Journal of Archaeological Science:
1191 Reports*. 6 (2016) 1–13. doi:10.1016/j.jasrep.2016.01.015.
- 1192 [191] J.A. Evans, J. Montgomery, G. Wildman, N. Boulton, Spatial variations in biosphere $^{87}\text{Sr}/^{86}\text{Sr}$ in
1193 Britain, *Journal of the Geological Society*. 167 (2010) 1–4. doi:10.1144/0016-76492009-090.
- 1194 [192] M. Willmes, L. McMorro, L. Kinsley, R. Armstrong, M. Aubert, S. Eggins, et al., The IRHUM
1195 (Isotopic Reconstruction of Human Migration) database – bioavailable strontium
1196 isotope ratios for geochemical fingerprinting in France, *Earth System Science Data*. 6 (2014) 117–
1197 122. doi:10.5194/essd-6-117-2014.
- 1198 [193] N. Shalev, B. Lazar, L. Halicz, M. Stein, I. Gavrieli, A. Sandler, et al., Strontium Isotope
1199 Fractionation in Soils and Pedogenic Processes, *Procedia Earth and Planetary Science*. 7 (2013)
1200 790–793. doi:10.1016/j.proeps.2013.03.074.
- 1201 [194] L. Halicz, I. Segal, N. Fruchter, M. Stein, B. Lazar, Strontium stable isotopes fractionate in the soil
1202 environments?, *Earth and Planetary Science Letters*. 272 (2008) 406–411.
1203 doi:10.1016/j.epsl.2008.05.005.
- 1204 [195] J. Fietzke, A. Eisenhauer, Determination of temperature-dependent stable strontium isotope ($^{88}\text{Sr}/^{86}\text{Sr}$)
1205 fractionation via bracketing standard MC-ICP-MS, *Geochemistry, Geophysics,
1206 Geosystems*. 7 (2006) n/a-n/a. doi:10.1029/2006GC001243.
- 1207 [196] J. Ma, G. Wei, Y. Liu, Z. Ren, Y. Xu, Y. Yang, Precise measurement of stable ($\delta^{88}\text{Sr}/^{86}\text{Sr}$) and
1208 radiogenic ($^{87}\text{Sr}/^{86}\text{Sr}$) strontium isotope ratios in geological standard reference materials using
1209 MC-ICP-MS, *Chinese Science Bulletin*. 58 (2013) 3111–3118. doi:10.1007/s11434-013-5803-5.
- 1210 [197] K.T. SMITH, G.W. WHITLEDGE, Evaluation of a stable-isotope labelling technique for mass
1211 marking fin rays of age-0 lake sturgeon, *Fisheries Management and Ecology*. 18 (2011) 168–175.
1212 doi:10.1111/j.1365-2400.2010.00771.x.
- 1213 [198] L.A. Neymark, W.R. Premo, N.N. Mel'nikov, P. Emsbo, Precise determination of $\delta^{88}\text{Sr}$ in rocks,
1214 minerals, and waters by double-spike TIMS: a powerful tool in the study of geological, hydrological
1215 and biological processes, *J. Anal. At. Spectrom.* 29 (2014) 65–75. doi:10.1039/C3JA50310K.
- 1216 [199] P.Z. Vroon, B. van der Wagt, J.M. Koornneef, G.R. Davies, Problems in obtaining precise and
1217 accurate Sr isotope analysis from geological materials using laser ablation MC-ICPMS, *Analytical*

1218 and Bioanalytical Chemistry. 390 (2008) 465–476. doi:10.1007/s00216-007-1742-9.

1219 [200] J. Irrgeher, P. Galler, T. Prohaska, $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ratio measurements by laser ablation
 1220 multicollector inductively coupled plasma mass spectrometry: Reconsidering matrix interferences
 1221 in biopatites and biogenic carbonates, *Spectrochimica Acta Part B: Atomic Spectroscopy*. 125
 1222 (2016) 31–42. doi:10.1016/j.sab.2016.09.008.

1223 [201] M. Willmes, L. Kinsley, M.-H. Moncel, R.A. Armstrong, M. Aubert, S. Eggins, et al., Improvement of
 1224 laser ablation in situ micro-analysis to identify diagenetic alteration and measure strontium isotope
 1225 ratios in fossil human teeth, *Journal of Archaeological Science*. 70 (2016) 102–116.
 1226 doi:10.1016/j.jas.2016.04.017.

1227 [202] C. B'Hymer, J.A. Caruso, Selenium speciation analysis using inductively coupled plasma-mass
 1228 spectrometry, *Journal of Chromatography A*. 1114 (2006) 1–20.
 1229 doi:10.1016/j.chroma.2006.02.063.

1230 [203] O.F.X. Donard, F.M. Martin, Hyphenated techniques applied to environmental speciation studies,
 1231 *TrAC Trends in Analytical Chemistry*. 11 (1992) 17–26. doi:10.1016/0165-9936(92)80115-M.

1232 [204] J.A. Caruso, M. Montes-Bayon, Elemental speciation studies—new directions for trace metal
 1233 analysis, *Ecotoxicology and Environmental Safety*. 56 (2003) 148–163. doi:10.1016/S0147-
 1234 6513(03)00058-7.

1235 [205] G. Fortunato, K. Mumic, S. Wunderli, L. Pillonel, J.O. Bosset, G. Gremaud, Application of strontium
 1236 isotope abundance ratios measured by MC-ICP-MS for food authentication, *Journal of Analytical
 1237 Atomic Spectrometry*. 19 (2004) 227. doi:10.1039/b307068a.

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1242 Fig.1. Conservative isotope ratio throughout the food chain

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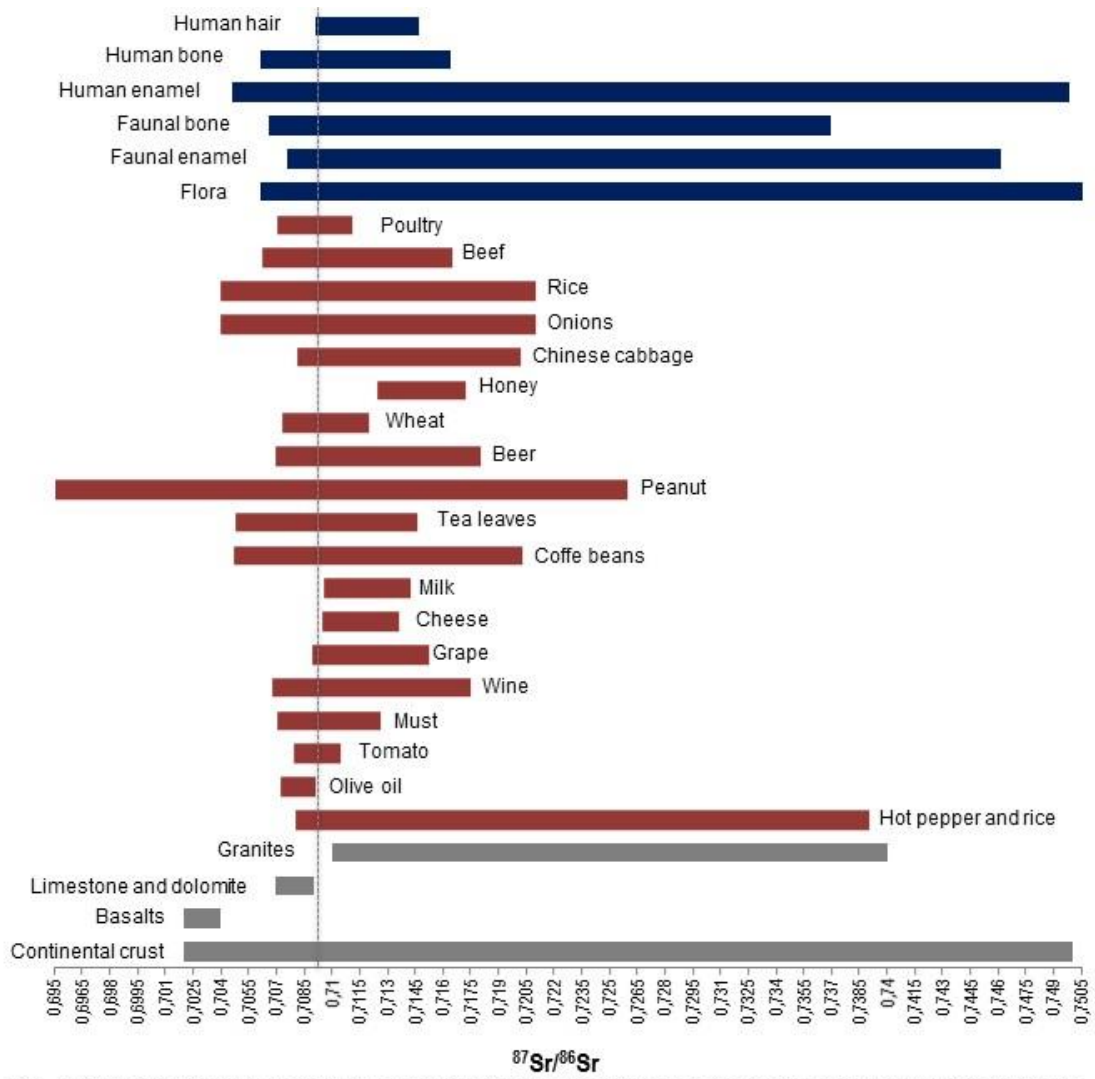


Fig 2 – Analysis of the $^{87}\text{Sr}/^{86}\text{Sr}$ per matrix. Blue bars represent samples from bioarchaeological studies, red bars represent foodstuffs and grey bars examples of the bedrock [6]. Vertical dotted line represents modern seawater ratio (0.7092) [6].

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