
From geochemistry to ecotoxicology of rare earth elements in aquatic environments: Diversity and uses of normalization reference materials and anomaly calculation methods

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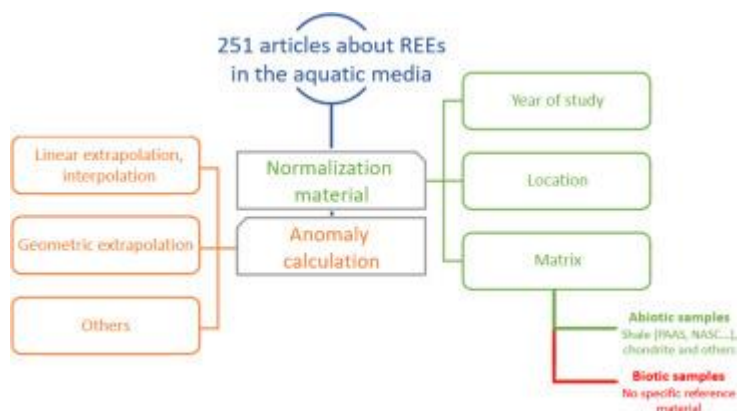
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Abstract :

The geochemistry of rare earth elements (REEs) has been studied for a long time and has allowed us to highlight enrichments or depletions of REEs in aquatic ecosystems and to estimate anthropogenic inputs through normalization of data to different reference materials. This review of current literature on REE normalization highlighted the large number of different reference materials (a total of 12), as well as different anomaly calculation methods. This statement showed a real need for method harmonization to simplify the comparison between studies, which is currently very difficult. Normalization to Post-Archean Australian Shale (PAAS) emerged as being the most used (33 % of reported studies) regardless of the location and the nature of the studied samples and seem to of higher quality. The interest of other reference materials was nevertheless underlined, as they could better represent the geographical situation or the nature of samples. Two main anomaly calculation methods have been highlighted: the linear interpolation/extrapolation and the geometric extrapolation using logarithmic modeling. However, due to variations in the estimation of neighbors' values, these two methods produce many different equations for anomaly calculation of a single element. Current normalization practices based on shales and chondrites are suitable for abiotic samples but are questionable for biota. Indeed, normalization is increasingly used in studies addressing ecotoxicological issues which focus on biota and often aim to estimate the anthropogenic origin of bioaccumulated REEs. Due the interspecific variability, as well as the complexity of mechanisms occurring in organisms when exposed to contaminants, new reference materials need to be established to consider the bioaccumulation/metabolization processes and the anthropogenic inputs of REEs based on the results of biotic samples.

Graphical abstract



Highlights

► Reference materials for REEs and anomaly calculation methods need to be harmonized. ► Among all reference materials, PAAS is the most used for the study of abiotic samples. ► No specific reference material exists nowadays for biotic samples normalization. ► New references for biota are needed to consider interspecific differences. ► PAAS should be systematically used to allow better comparison between REE studies.

Keywords : REEs, PAAS, chondrite, abiotic compartments, biota.

1. Introduction

The use of rare earth elements (REEs) in industries and particularly for future technologies are of growing importance and make REEs critical and strategically important raw materials in the functioning of the global economy. They enter in the composition of many products like batteries, LED lighting, permanent magnets, fertilizers, or contrast agent for medical imaging. They are also increasingly used in high-tech devices, *e.g.*, liquid crystal displays or communication devices. Moreover, they contribute to the substitution of oil and nuclear energies as they are extremely used in the renewable energy sector: in wind turbines, electric cars, catalytic converters or solar panels, etc. **(Castor and Hedrick, 2006; Bru et al., 2015)**. This way, due to their worldwide popularity, the global extraction and the use of REEs in anthropogenic activities continue to rise, leading to an increase of environmental concentrations which can disrupt natural biogeochemical cycles and lead to their gradual enrichment in aquatic environment **(De Baar et al., 1985a, b; Bau and Dulski, 1996; Alibo and Nozaki, 1999; Kulaksiz and Bau, 2013; Merschel and Bau, 2015)**. The increase of REEs in the environment is a threat for the living organisms since they can lead to negative impacts at different biological and ecological organization levels as reported in studies focusing on laboratory exposures **(Cui et al., 2012; Hanana et al., 2017; Cardon et al., 2019; Freitas et al., 2020)**.

REEs represent the group of the fifteen lanthanoids (from lanthanum ($Z = 57$) to lutetium ($Z = 71$)) to which yttrium ($Z = 39$) and scandium ($Z = 21$) are often added because of similar chemical properties (column III of the periodic classification). Two main classifications exist. One separates REEs depending on their electronic configuration into two groups: the light rare earth elements (LREEs) composed of lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm) and europium (Eu) and the heavy rare earth elements (HREEs) comprising gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu) **(Castor and Hedrick, 2006)**. The other separates them depending on their atomic weight into three groups: the LREEs (Ce to Pm), the medium rare earth elements (MREEs) (Sm to Gd) and the HREEs (Tb to Lu) **(Mehmood, 2018)**. Yttrium (Y) is always classified in the heavy rare earth element group due to its chemical similarities even if it has a lower

atomic weight. On the contrary, scandium (Sc) is often excluded due to its different chemical properties. Apart from scandium, REEs have coherent chemical properties derived from the similar electronic configuration across the series (partially filling 4f electron shell), providing remarkable electromagnetic properties sought in many fields as mentioned above.

More and more studies about REEs are currently carried out and focus on aquatic environment. Enrichments in La, Gd and Sm have already been reported in watercourses (**Elbaz-Poulichet et al., 2002; Kulaksiz and Bau, 2013; Merschel and Bau, 2015**) but despite these observations, current knowledge on their risk to environment is piecemeal and define REEs as emerging contaminants. To remedy this lack, some studies aimed to investigate the environmental levels and impacts of anthropogenic uses of REEs (**Moller et al., 2002; Klaver et al., 2014; Hissler et al., 2015; Song et al., 2017**). However, as these contaminants are naturally present in the earth's crust at concentrations from 0.5 to 70 ppm (**Buissette and Le Mercier, 2019**), distinguishing anthropogenic and background contributions can be difficult. In this context, normalization methods have been used and consist in calculating the ratio of concentrations measured in matrix of interest to concentrations measured in reference materials. Normalization permits to flatten REE spectra allowing to overcome the Oddo-Harkins Rule effect (elements with even atomic number show higher abundances in the crust than the ones with odd atomic number) and to better visualize and calculate anomalies that characterize REE enrichments or depletions. This procedure was elaborated in the aim of characterizing and understanding geochemical behavior of REEs in natural environments (**Sholkovitz et al., 1989; Elderfeld et al., 1990; De Baar et al., 1991; Sholkovitz et al., 1994; Sholkovitz, 1995**). Most REEs are found in nature at the trivalent oxidation level, which is the most stable. However, some can be oxidized to the tetravalent form, like Ce, or reduced to the bivalent form, like Eu, in particular redox conditions and of temperature (**De Baar et al., 1985a**). This approach allows to investigate particular speciation processes of REEs occurring in the environment and to assess anthropogenic inputs. It was first used by geochemists to characterize water and sediment (**Elderfeld and Creaves, 1982; Sholkovitz, 1988**), but it has now been extended to biota and is increasingly used in order to further investigate the risks REEs pose to the environment. Although this procedure could be very useful in the ecotoxicological and the biogeochemical fields as it can be performed on different materials (such as water, sediment or biota) (**Rabiet et al., 2009; Li et al., 2013; Yang et al., 2016**), the considerable number of normalization reference materials and methods for anomaly estimation can make REE studies difficult to apprehend for non-geochemists. Added to this, it makes the comparison between studies difficult and sometimes even impossible.

This review, summarizing literature about REEs in the aquatic media, aims to facilitate the apprehension of environmental studies on REEs for non-geochemists through the analysis of the diversity and the evolution of uses of the different normalization reference materials that exist nowadays as well as the major methods for the calculation of REE anomalies. The most used reference

materials are defined and compared then reported according to the location, the year of study and the matrices. Finally, the limits of their applications for ecotoxicological issues as well as associated research needs and prospects are discussed.

2. Literature search strategy and data analyses

The bibliographic research was carried out using different combinations of keywords in ScienceDirect and Google Scholar databases: *rare earth elements, lanthanoids, lanthanide(s), normalization, fractionation, partitioning, speciation, bioaccumulation, biomonitoring, monitoring, anomaly/ies, seawater, freshwater, groundwater, pore water, water, sediment, biota, species/organisms, aquatic, marine* and the names of individual REEs. This research only focused on scientific published articles and allowed to identify an exhaustive list of 251 ones from the beginning of the use of normalization and anomaly calculation; the last update being in November 2021. The articles were sorted and selected manually by reading the entire papers and the following exclusion criteria were applied: studies not being research articles, studies about REEs but not performing normalization or anomaly calculation, studies not treating about aquatic environments, or dealing with wastewater treatment plant (WWTP) effluents or tap water only. Thus, only studies dealing with natural aquatic environments were included: marine and freshwater environments, surface water and groundwater. No geographical or temporal restrictions were applied in order to describe the diversity of the REE normalization practices, their evolution and to understand the current uses.

Normalization material as well as anomaly calculation methods were identified in each publication. In order to investigate the influence of the year of publication, the location and the studied matrix on the practices, the articles were classified by three methods into (i) four subgroups for the year of publication: 1962-1990, 1991-2000, 2001-2010, 2011-2022, each containing 26, 38, 44 and 143 publications respectively, (ii) four subgroups regarding the location: America/Atlantic Ocean, Europe/Africa, Asia/Australia/Pacific Ocean and Worldwide (not corresponding to any other subgroup) each regrouping 53, 76, 103 and 18 articles respectively and (iii) three subgroups according to the studied matrix: water, sediment and aquatic biota, each comprising 97, 88 and 24 publications respectively.

Then, to analyze differences in the use of normalization reference materials depending on the considered factor of influence (year of study, location, and matrix), the percentages of use of each normalization material for each subgroup of the three classifications mentioned above were calculated. To be more representative of current habits, the percentages according to locations and matrix have also been calculated considering only articles published in the last decade. For the matrix influence, 42 articles dealt with both two or three matrices. Consequently, normalization materials used have been

identified for each matrix and have been added to the percentage calculation of their corresponding subgroup (water, sediment, aquatic biota).

Finally, articles calculating anomalies were classified into three groups depending on the calculation method used: (i) linear extrapolation or interpolation using close or distant neighboring elements, (ii) geometric extrapolation using logarithmic modeling, (iii) completely different calculation method; each containing 130, 12 and 9 publications respectively. Moreover, for each REE, anomaly calculation equations have been listed and a total of 5 recurrent equations have been highlighted for Ce, Eu and Gd which correspond to the three main REEs considered in terms of anomalies in the scientific literature. Then, the percentages of use of these equations have been calculated.

3. Literature overview

3.1. Main existing normalization reference materials

Several normalization reference materials exist and are used when investigating on REE environmental concentrations and fate. They can be gathered into two main types: shales, representative of average composition of the upper continental crust, and chondrites (either ordinary or carbonaceous) corresponding to bulk earth. A wide number of datasets exist and are currently used for both materials.

For shale normalization, up to five different datasets are commonly used (**Table 1**), *i.e.* PAAS, NASC, WSA, EUS and AS. Firstly, the “Post-Archean Australian Shale” (PAAS) is widely used and has been initially established from twenty-three samples of Australian shale by **Nance and Taylor (1976)** and later mathematically updated by **McLennan (1989)**. New data established on nine other samples from Australian shales and analytically improved by **Pourmand et al. (2012)** is also frequently used. The analytical determination is supposed to give more accurate REE concentrations compared to theoretical estimation performed for Tm and Lu concentrations initially. Secondly, the “North American Shale Composite” (NASC) is another set of data measured by **Haskin and Haskin (1966)** and other co-workers (**Haskin et al., 1966a**) in a composite powder constituted by a pool of a wide number of samples (forty in total) from the United States (20), Zimbabwe (3), Antarctic (2) and unknown locations (15). The concentrations, not complete for all the REEs at the beginning (**Gromet et al., 1984; Goldstein and Jacobsen, 1988**), were analytically updated (**McLennan, 1989**) to constitute a set commonly used for normalization. The “World Average Shale” (WSA) is a set calculated by **Piper (1974)** after **Haskin and Haskin (1966)** based on REE concentrations measured in shales from North America, Europe, and Russia. The “European Shale” (EUS) is a dataset originally analyzed by **Minami in 1935** on a European shale composite sample and has later been

improved by **Haskin and Haskin (1966)**. Recently, **Bau et al. (2018)** proposed a new set of data for EUS, based on the same composite sample analyzed with improved analytical methods. Finally, the “Archean Shale” (AS) is another dataset established by **McLennan and Taylor (1984)** on Archean shale samples and is more representative of Archean upper continental crust than the others previously described.

As for shales, many datasets are also available for chondrite normalization (**Table 1**). The first one is a set regrouping REE concentrations measured in ordinary chondrites (L6, H-group) from the Leede meteorite shower (Oklahoma, November 1943) by **Masuda et al. (1973)**. Many other sets were established on carbonaceous chondrites (CI). One of them was determined by **Evensen et al. (1978)** on fifteen chondrite samples, later mathematically revised by **Taylor and McLennan (1985)**. **Anders and Grevesse (1989)** and **Sun and McDonough (1989)** also determined two others. Sometimes data from various chondrite types (carbonaceous (types I, II and III), ordinary (H and L groups), soko-banjitic and enstatitic chondrites) were used to establish reference REE mean concentrations (**Schmitt et al., 1963; Haskin et al., 1966b**).

Other materials than shales and chondrites can also be used to normalize REE concentrations (**Table 1**), *i.e.* MUQ, UCC, MORB, DMM WRAS and WRAC. The “Mud from Queensland” (MUQ) is a recent dataset proposed by **Kamber et al. (2005)** for normalization. It is based on measures of thirty-three alluvial fine-grained sediment samples from Australia. Moreover, analyses of the composition of insoluble elements in fine-grained clastic sedimentary rocks or glacial deposits allowed to estimate the composition of “Upper Continental Crust” (UCC) providing three different datasets used for REE normalization as well. The first one was established by **Taylor and McLennan (1985)** and was revised by the **same authors in 1995**. The second one also considering the composition of rocks exposed at the surface was reported by **Wedepohl in 1995**. Then, more recently, **Rudnick and Gao (2003)** proposed a new updated dataset that is now commonly used. The “Mid-Ocean Ridge Basalt” (MORB) dataset is based on the analysis of oceanic basalts and is sometimes used for normalization as it is more representative of the oceanic crust composition. **Sun and McDonough (1989)** provided two MORB datasets: the first one defined as normal-type (N-type) and the second one as enriched-type (E-type). Another dataset defined as MORB average has also been reported by **Taylor and McLennan in 2002**. **Workman and Hart** proposed in **2005** a new calculated dataset supposed to be representative of “Depleted mid-ocean ridge basalt mantle” (DMM) and is, as MORB, sometimes used in studies for REE normalization. In **2015, Bayon et al.** established two new datasets: the “World River Average Silt” (WRAS) and the “World River Average Clay” (WRAC) meant to be representative of the average composition of the weathered and eroded upper continental crust. These sets are based on the REE measures of twenty-two samples from rivers from all around the world and might get used in the next years for normalization. Finally, many studies performed

what is called “local” normalization. It consists in normalizing REE concentrations in the matrix of interest to concentrations measured in another matrix coming from the same study site.

3.2. Comparison of normalization reference materials

All the concentration values of the different datasets of normalization previously presented are reported in the **Table 1**. Globally, the datasets determined from a same reference material are quite similar. Nevertheless, some sets stand out more from the others with different concentrations (particularly for light REEs). For PAAS, **Pourmand et al. (2012)** dataset presents higher LREE concentrations than previous studies (**Nance and Taylor, 1976; Taylor and McLennan, 1985; McLennan, 1989**). This is explained by improved instrumentation leading to a better accuracy of REE measures. The same observation is possible for EUS: **Minami (1975)** dataset shows much lower concentrations of LREEs than the two other datasets (**Haskin and Haskin, 1966; Bau et al., 2018**) for the same reasons. Moreover, it appears that all shale normalizations (PAAS, NASC, WSA and EUS) have similar concentration values (**Table 1**). Only two shale datasets differ from the others with lower REE concentrations (especially for LREEs): **Minami's EUS** with distant points for La, Ce, Pr, Gd, Ho and Lu and **McLennan and Taylor's AS** with distant points for La, Ce, Pr and Nd (**Fig. 1.A**). MUQ, UCC, WRAS and WRAC also have relatively close patterns whereas MORB is differentiating from the other normalizations with much lower REE values, especially for LREEs (La to Sm) (**Sun and McDonough, 1989; Taylor and McLennan, 2002**). These differences can be explained by its representativity to the oceanic crust compared to the representativity to the continental crust of the other ones (**Table 1, Fig. 1.A**). Finally, the values obtained for chondrites and DMM are the most standing out from the other normalization patterns with much lower concentrations for all REEs, probably due to the specific meteoric origin of chondrite (**Table 1**).

As for the shales, variations among chondrite datasets can also be observed. The three CI chondrites have similar values (**Evensen et al., 1978; Anders and Grevesse, 1989; Sun and McDonough, 1989**) whereas the fourth one (**Taylor and McLennan, 1985**) is standing out and is closer to the ordinary chondrites (**Masuda et al., 1973; Haskin et al., 1966a, b; Schmitt et al., 1963**) (**Fig. 1.A**). This difference is probably because it is a mathematic revision of **Evensen et al. (1978)** data made by **Taylor and MacLennan** (values multiplied by 1.5) in 1985, while the other pattern determinations were analytical. Chondrite-normalized REE patterns can help to qualitatively differentiate reference datasets based on the flatness of the pattern. For this purpose, REE levels in reference materials were normalized to chondrite (**Anders and Grevesse, 1989**) and their REE pattern is presented in **Fig. 1.B**. Most of the reference datasets have a similar pattern with LREE enrichment, as supposed in the earth's crust and a europium anomaly. AS, MORB and Minami's EUS are diverging with a lower LREE enrichment than the other datasets (especially MORB). Various element

anomalies (Gd, Tb, Ho, Tm Yb and Lu) are depicted in several patterns (**Minami's EUS**, **Piper's WSA**, **Wedepohl et al. UCC**) certainly due to earlier analytical methods introducing bias.

3.3. Normalization practices

3.3.1. Global normalization practices

An overview of the bibliographic research that has been carried out in order to list the different existing REE normalization reference materials is shown in the **Table S1**. A wide number of studies have been carried out over the past sixty years. A total of 251 publications ranging from 1962 to 2022 and studying various matrices (water, sediment, aquatic biota) of natural aquatic environments have been reported. Samples from many different locations were analyzed (France, Italy, Japan, China, Pacific and Atlantic Oceans, USA, etc.). Most of the studies focused on natural water samples (either sea or freshwater) and sediment rather than aquatic biota. Indeed, for biota, only a few numbers of studies performing a normalization of REE concentrations have been reported. A wide set of normalization materials have been used in the different studies. Sometimes, different materials have also been used in a same study (*e.g.* **Alibo and Noral i, 1999**; **Elias et al., 2019**). More than ten normalization reference materials are thus listed (PAAS, NASC, WSA, chondrite, MUQ, UCC, EUS, MORB, DMM, AS, WRAS/WRAC and local) implying even many more datasets.

A summary of the **Table S1** can be seen in the **Fig. 2**. PAAS is the most common normalization material used in the past sixty years, reaching 33% of the published studies. The second is chondrite with 17.3%, closely followed by NASC, WSA and local normalization with 14.8, 12.3 and 11.6% respectively. The seven other normalization materials (DMM, MUQ, UCC, EUS, MORB, AS and WRAS) are less employed with percentages of use ranging from 0.3 to 5%.

3.3.2. Evolution over time

The **Fig. 3** summarizes the use of different normalization reference materials over time. The articles were divided into four groups, the period before 1990 and after, each decade until 2022. For each one, the percentages of use of each normalization material have been calculated.

In the early years (1962 to 1990), only five normalization reference materials were used (**Fig. 3.A**). The most widely used was the WSA reaching 54.3% of the studies, compared to the four others: chondrite, local, NASC and PAAS with percentages ranging from 2.9 to 17.1%. Later, between 1991 and 2000, NASC and PAAS became more widely used, representing 19.2 and 17.3% of the reference materials (**Fig. 3.B**) explaining the decrease of WSA normalization (54.3 to 30.8%). Local and chondrite normalizations carried on being used almost similar to the last decade with 19.2 and 11.5%

respectively. At the beginning of the 21st century (2001 to 2010), the use of NASC increased with a percentage reaching 36%, close to PAAS percentage of 32% (**Fig. 3.C**). Local normalization was less used during this decade (4%) and chondrite stayed used in 12% of the studies. This last decade (2011 to 2022) is marked by the increase of the number of normalization materials used, reaching eleven (**Fig. 3.D**). NASC normalization that was predominant in the previous decade became less employed (8.8%) and the frequency of PAAS kept an important percentage up to 43.6%, just as well as chondrite with 20.4%. Local and UCC normalizations were used in 10.5 and 8.3% of the studies.

3.3.3. Evolution according to the location

The different normalization practices are based on datasets established on measures of various materials from several continents. The location of the studied samples might have influenced the researchers in choosing the normalization reference material they should employ. Aiming to highlight different uses depending on the location of the studied samples, the 251 articles were divided into four groups, each representing a part of the world except for the one considering worldwide studies (**Fig. 4**).

A restricted number of normalization reference materials is used in studies carried out on samples from America to Atlantic Ocean. PAAS normalization is indeed the most used material with a percentage reaching 32.9% (**Fig. 4.A**). Local and WSA follow with an equal percentage of 21.4% and surprisingly NASC percentage is lower (12.9%). For works focusing on samples from Europe to Africa, PAAS normalization appears mostly used again in 43.8% of the articles, followed by NASC and chondrite with 21.3 and 14.6 % respectively (**Fig. 4.B**) whereas EUS is used in only 5.6% of the studies. Compared to the two other world parts, studies carried out on samples from Asia, Australia and Pacific Ocean show a large variety of normalization materials (**Fig. 4.C**). PAAS is mostly used with a percentage of 27.1%, followed by chondrite, WSA and NASC normalizations with percentages of 24.1, 14.3 and 10.5% respectively. In addition to these four normalizations, seven others are also employed: local, UCC, MUQ, DMM, MORB, WRAS and AS. Lastly, regarding the Worldwide group (**Fig. 4.D**), PAAS and WSA are mostly used (29.2 and 20.8% respectively) and NASC, local, chondrite, UCC and WRAS are less used with percentages ranging from 4.2 to 16.7%.

As shown in the **Fig. 3**, the choice of the normalization reference material highly depends on the year of the publication. Therefore, to be representative of the current practices, the percentages in each part of the world have been calculated considering studies carried out during the last decade only (**Fig. 4.E, F, G, H**). With these new considerations, only four different normalization reference materials are employed in the studies carried out on samples from America to Atlantic Ocean: mostly PAAS (66.7%), then local normalization (18.5%), NASC and chondrite (both 7.4%) (**Fig. 4.E**). For Europe to Africa, PAAS normalization is again mainly used, reaching a percentage of 49.2% (**Fig.**

4.F) and EUS increased (5.6 to 7.7%). Publications on samples from Asia, Australia and Pacific Ocean, still show a wide number of normalization materials in the past decade (**Fig. 4.G**). PAAS and chondrite are preponderant (30.4 and 29.1% each) and are followed by many other normalization reference materials like UCC, NASC, local, etc. Finally, there is an increase of the use of PAAS during the last decade (29.2 to 50%) in the Worldwide group (**Fig. 4.H**). UCC is also more employed with 20% and is followed by chondrite, local and WRAS with an equal percentage of 10%.

3.3.4. Evolution according to the studied matrix

Normalization practices also depend on the studied matrix as shown in the **Fig. 5**. Studies were split into three groups, representing main investigated natural matrices, *i.e.*, water, sediment and aquatic biota.

Globally, a wide range of normalization materials were used for characterizing the three matrices, but some preferences can be highlighted. For works focusing on water samples, PAAS is mostly used, with 40.1%, followed by NASC normalization, reaching 16.6% (**Fig. 5.A**). Local and WSA normalizations are also employed with respective percentages of 14.6 and 14%. For sediment samples, PAAS and chondrite normalizations come first, appearing in 26.6 and 23.4% of the studies, followed by four other normalizations (NASC, WSA, local and UCC) representing 9.1 to 15.6% (**Fig. 5.B**). About aquatic biota, less normalization reference materials are mentioned in studies (**Fig. 5.C**). As for both other matrices, PAAS is mainly used, reaching 37%. Chondrite and local normalizations are also often used with 26.1 and 15.2%, respectively; whereas, NASC and WSA are less employed (8.7%).

Here again to be representative of the current practices, percentages were also calculated considering only the last decade (**Fig. 5.D, E, F**). For water samples, PAAS is predominant reaching 65.1% of the articles (**Fig. 5.D**). Local normalization is also employed at 14.3%. Many normalization reference materials have been used in studies about sediment samples and have similar percentages (**Fig. 5.E**) to those obtained considering all the studies. PAAS and chondrite come first with percentages of 35 and 23.3% and they are followed by UCC and NASC with 13.6 and 11.7%, respectively. Studies investigating on aquatic biota samples mainly used PAAS (42.1%), chondrite (28.9%) and local normalization the last decade (**Fig. 5.F**).

3.3.5. Overview

To summarize, PAAS appears to be the most used material followed by chondrite, NASC, and local normalization. The investigation of the trend according to the year of publication showed that

over time more and more normalization reference materials were used, with WSA predominant in the early years, and, PAAS and chondrite nowadays. Depending on the location of the studies, preferences are observable. Independently of time, PAAS remains the mostly used material in America/Atlantic Ocean and Europe/Africa regions, as well as in the Worldwide group; whereas, chondrite is particularly used in the Asia/Australia/Pacific Ocean region. Considering the matrix influence, PAAS is also preferentially used for water, coming close with chondrite for aquatic biota samples. No real preferential material has been highlighted for sediment samples, independently of the year of the publication, even if PAAS and chondrite are the first ones.

3.4. Anomaly calculation methods

3.4.1. Diversity of the methods

Measuring and normalizing REE concentrations in different matrices of interest generally lead to anomaly calculation for specific REEs. This procedure allows REE environmental enrichment or depletion to be highlighted, and therefore could inform on particular fractionation processes and/or anthropogenic inputs.

Out of the 251 studies reported in the **Table S1**, 151 proceeded to anomaly calculations representing 60.2% of the studies. Anomalies are most of the time quantified by linear extrapolation or interpolation using neighboring elements. (**Elbaz-Poulichet et al., 2002; Klaver et al., 2014; Ponnurangam et al., 2015; Briant et al., 2021 etc.**). Values > 1 indicate positive anomalies and values < 1 indicate negative anomalies. This method assumes that the difference in concentrations between neighboring pairs is constant. However, as it is not always the case, anomalies are sometimes calculated by geometric extrapolation using logarithmic modeling (**Kulaksiz and Bau, 2011; 2013; Merschel et al., 2015**). A reference equation following linear extrapolation method has been elaborated by **Alibo and Nevaki (1999)** for anomaly calculation:

$$REE_n / REE^*_n = 2[REE]_n / ([REE]_{n-1} + [REE]_{n+1})$$

with n corresponding to the atomic number of the studied REE, and * corresponding to the geogenic background concentrations. Despite this general equation, the **Table S1** highlights not less than 82 different equations used for anomaly calculation of REEs. These equations have been established either following the two main methods mentioned above or other. Therefore, equations and their corresponding articles, can be gathered into three groups. Most of the studies calculated anomaly on the basis of linear extrapolation/interpolation (86.1%) using either close (76.8%) or distant (9.3%) neighboring elements rather than based on geometric extrapolation (7.9%). Some other studies used another method of calculation, completely diverging from the reference equation (6%).

The **Table S1** also clearly shows that many different equations are used to calculate the anomaly for a same element. A total of 5 recurrent equations have been listed: 3 for Ce, 1 for Eu and 1 for Gd. These three REEs are indeed the most studied ones in terms of anomalies. After identifying these 5 recurrent equations, their percentages of use in articles have been calculated and are presented in the **Fig. 6**.

3.4.2. Ce anomaly

Cerium is the main element for which anomalies are calculated, since cerium negative anomaly is a characteristic of seawater (**Piper and Bau, 2013**) and many listed publications are focusing on seawater samples (**Table S1**). Indeed, under oxic conditions, trivalent Ce can be easily oxidized to the tetravalent state on the surface of Mn oxides (**German and Elderfield, 1990**). The solubility of Ce is thus decreased, leading to a Ce depletion in solution relatively to the other trivalent REEs. Out of the 151 publications performing anomaly calculations, 116 focused on Ce and a total of 20 different equations have been reported for the calculation. Among these equations, 3 have been highlighted as the most often used, as shown in the **Fig. 6**. The first equation (eq. (1)), mentioned in 33.9% of the studies, corresponds to the reference one, proposed by **Alibo and Nozaki (1999)**:

$$\text{eq. (1): } \text{Ce/Ce}^* = 2\text{Ce}_N / (\text{La}_N + \text{Pr}_N) = \text{Ce}_N / (0.5\text{La}_N + 0.5\text{Pr}_N) = \text{Ce}_N / [(\text{La}_N + \text{Pr}_N)/2]$$

with N corresponding to normalized concentrations. The two others employed equations (eq. (2) and (3)) reach 22.3 and 18.2% of the studies, respectively:

$$\text{eq. (2): } \text{Ce/Ce}^* = \text{Ce}_N / [(\text{La}_N \cdot \text{Pr}_N)^{0.5}] = \text{Ce}_N / \sqrt{\text{La}_N \cdot \text{Pr}_N}$$

$$\text{eq. (3): } \text{Ce/Ce}^* = 3\text{Ce}_N / (2\text{La}_N + \text{Nd}_N) = \text{Ce}_N / [(2\text{La}_N + \text{Nd}_N)/3]$$

These 3 equations are based on linear extrapolation and use more or less close neighbors' concentrations for calculation (either La and Pr or La and Nd). Finally, 25.6% of the studies employ other equations than eq. (1), (2) and (3) for cerium anomaly calculation like eq. (4) which is also often used and is based on geometric extrapolation:

$$\text{eq. (4): } \text{Ce/Ce}^* = \log [\text{Ce}_N / (2/3\text{La}_N + 1/3\text{Nd}_N)]$$

Moreover, some authors calculate Ce anomaly based on Pr and Nd concentrations rather than La and Nd concentrations with the following eq. (5) and (6) to avoid bias involved by the possible overabundance of La in natural systems (**Lawrence et al., 2006b**):

$$\text{eq. (5): } \text{Ce/Ce}^* = \text{Ce}_N / [\text{Pr}_N \cdot (\text{Pr}_N / \text{Nd}_N)]$$

$$\text{eq. (6): } \text{Ce/Ce}^* = \text{Ce}_N / (2\text{Pr}_N - \text{Nd}_N)$$

3.4.3. Eu anomaly

Europium is the second main element for which anomalies are calculated. Out of the 151 articles performing an anomaly calculation, 72 calculated europium anomaly and up to 18 different equations have been reported in these publications. A specific equation, using linear close neighbors' concentrations interpolation (Sm and Gd), is used in most of the studies (eq. (7)) reaching 49.3% of the articles *versus* 50.7% using other equations (**Fig. 6**):

$$\text{eq. (7): } \text{Eu}/\text{Eu}^* = \text{Eu}_N / [(\text{Sm}_N \cdot \text{Gd}_N)^{0.5}] = \text{Eu}_N / \sqrt{(\text{Sm}_N \cdot \text{Gd}_N)}$$

with N corresponding to normalized concentrations. The second mainly used equation is one corresponding to **Alibo and Nozaki's** reference equation (eq. (8)) representing 15.5% of the 50.7% others:

$$\text{eq. (8): } \text{Eu}/\text{Eu}^* = 2\text{Eu}_N / (\text{Sm}_N + \text{Gd}_N)$$

Also, as Gd is often demonstrating anomalous chemical behavior, authors sometimes use the Tb neighboring element instead to calculate Eu anomaly as in the eq. (9):

$$\text{eq. (9): } \text{Eu}/\text{Eu}^* = \text{Eu}_N / (0.67\text{Sm}_N + 0.33\text{Tb}_N)$$

3.4.4. Gd anomaly

The third main element for which anomalies are calculated is gadolinium. Indeed, research leads a great interest to this element because it is widely used in medicine (as contrast agent in MRI (magnetic resonance imaging)) which causes considerable anthropogenic input in the environment (**Elbaz-Poulichet et al., 2002; Bau et al., 2006; Hatje et al., 2016**). Out of the 151 publications proceeding to anomaly calculation, 43 calculated Gd anomaly and a total of 15 different equations have been reported. Although many equations are used, only one is mostly mentioned, corresponding to a linear extrapolation using normalized close neighbors' concentrations (Sm and Tb) and reaching 39.6% of the studies (**Fig. 6**):

$$\text{eq. (10): } \text{Gd}/\text{Gd}^* = \text{Gd}_N / (0.33\text{Sm}_N + 0.67\text{Tb}_N)$$

with N corresponding to normalized concentrations. Nevertheless, 60.4% of the other studies use many other equations for Gd anomaly calculation. As for europium, the second mainly used equation for Gd is one corresponding to **Alibo and Nozaki's** reference equation (eq. (11)) representing 8.3% of the 60.4% others:

$$\text{eq. (11): } \text{Gd}/\text{Gd}^* = 2\text{Gd}_N / (\text{Eu}_N + \text{Tb}_N)$$

Two others can also be cited as they are often used (eq. (12) and (13)):

$$\text{eq. (12): } \text{Gd/Gd}^* = \text{Gd}_N / [(\text{Tb}_N^2 \cdot \text{Sm}_N)^{1/3}]$$

$$\text{eq. (13): } \text{Gd/Gd}^* = \text{Gd}_N / (0.4\text{Nd}_N + 0.6\text{Dy}_N)$$

3.4.5. Other anomalies

Anomalies are calculated for many other REEs (La, Pr, Lu, Sm, Yb, Nd, Tm, Y, Tb, Dy and Ho) as reported in the **Table S1**. However, for all these REEs, no equation was standing out from others. For this reason, no percentages of use were calculated.

4. Preferred reference material, limits, and improvements

As depicted in the **Table S1**, many normalization reference materials exist and are commonly used in studies about REEs in aquatic ecosystems, based on the use of a various number of datasets. These different methods lead to a heterogeneity of REE normalization and complicate the comparison of results between studies employing different methods (**Table 1**) even if the conclusion could be the same using different reference materials and/or anomaly equations. The five main normalization reference materials involve PAAS, chondrite, NASC, WSA, local normalization, with PAAS being the most common (**Fig. 2**). The consideration of the articles depending on the publication year allows to observe that the normalization of concentrations started in 1962 with only five normalization materials. WSA was globally the predominantly used method, allowing easy comparisons between studies (**Fig. 3.A**). However, all datasets used at this time were based on values determined with anterior analytical methods that were later questioned for the accuracy of their representativity to the continental crust. New datasets based on improved analytical methods or new normalization materials were established over time, multiplying widely the number of reference material available nowadays for REE normalization. Even if these new sets are supposed to allow more accurate characterizations of REE concentrations in the environment, due to the higher performances of the analytical instrumentation, in fact, they make the comparison of study results complicated (**Fig. 3.B, C, D**). Nevertheless, depending on the location of the studied samples, it is understandable to use the reference material corresponding to the same geographic region. It is not the case for two out of the three established world regions. Indeed, NASC is not the most used normalization reference material in the American region (**Fig. 4.A, E**); and although EUS is only used in the European region, it is not used as much as PAAS (**Fig. 4.B, F**). For Australia/Asia region, PAAS is the main reference material but it is closely followed by chondrite although it does not specifically correspond to this geographical area (**Fig. 4.C, G**). Finally, for the Worldwide group, PAAS is again mostly used (**Fig. 4.D, H**). These

differences in use of reference materials between regions, not following the geographical location of the study site, are not that surprising. Indeed, many of these reference materials are established either on composite samples (EUS and NASC) or by estimation / calculation based on several samples from various world regions (WSA, WRAC, WRAS and UCC). They are therefore not intended to be representative of a specific geographic location but of a global average of continental crust REE composition (**Gromet et al., 1984; Bau et al., 2018**). Thus, the choice of reference material highly depends on author and peers' preferences/habits or other parameters like the nature of studied samples. Preferences have also been highlighted depending on the studied matrix. Considering natural water samples, PAAS is mostly used (**Fig. 5.A, D**). For sediment, no normalization material is standing out among the wide number of different reference materials that are used (**Fig. 5.B, E**). For aquatic biota samples, PAAS, chondrite and local normalization are commonly used (**Fig. 5.C, F**). This can be explained by the nature of the samples and depends on the study objective. Chondrites are meant to represent the initial condition of the earth's crust at the time of formation (**Nance and Taylor, 1976**). Therefore, chondrite-normalization highlights post-earth formation processes. However, as chondrites are pretty different to most studied samples, by their nature and REE composition, they do not really allow to estimate inter-sample variations and are mainly used in igneous geochemistry and cosmochemistry (**McLennan, 1989; Bau et al., 2018**). Regarding shales, they are meant to be parallel to the average upper continental crust composition (**Taylor and McLennan, 1985**) and they have a closer nature/REE composition to the studied samples allowing to better detect differences between samples. Shale-normalization can help to understand the exact nature of sources and inter-sample variations and is therefore more used in sedimentary, aqueous and environmental geochemistry (**Bau et al., 2018**). Thus, for sediment samples various material can be used to characterize REE fractionation but for water samples, PAAS is preferred. Indeed, when studying marine phases, chondrite-normalization emphasizes the differences of samples to chondrites (due to their extremely contrasting REE concentrations rather than highlighting the lesser but significant differences between individual marine phases (**Spencer, 1974**), which isn't a problem encountered with PAAS. This explains differences of reference material uses for water and sediment samples but not for aquatic biota. Indeed, neither chondrite nor shale come close to the biota matrix nature, therefore both are often used. The local normalization is also often employed as it could be more representative of the local biota exposure (both geogenic and anthropogenic). Finally, normalization to a matrix of the same nature might be more appropriate for biota.

Many studies used different normalization materials to characterize their impact on the concentrations and patterns of REEs. Two studies performed both PAAS and NASC normalizations (**Alibo and Nozaki, 1999; Elias et al., 2019**), and allowed to highlight that even if there are slight differences of HREE reference values between them (**Alibo and Nozaki, 1999**), REE patterns are globally similar. Three studies comparing chondrite and PAAS normalization, by performing both of

them on the same data (**Rezaee et al., 2009; 2010; Li et al., 2013**), concluded to great differences of produced REE patterns especially for LREEs and also often for HREEs. Moreover, in many cases, PAAS and local normalizations are used in a same study (**Nozaki et al., 1999; Strady et al., 2015; Hatje et al., 2016**). Differences on LREEs and HREEs have been observed but are less obvious than those between chondrite and PAAS. To confirm these observations and in order to analyze variations in REE patterns after performing different normalizations, values from several studies about various matrices (aquatic biota, sediment and natural water) have been obtained. Then, all normalization materials that are available and used nowadays were applied to the data and the REE spectra are presented in the **Fig. 7**. Only one dataset for each reference material was used to perform data normalization. The most recent dataset was selected for all materials (PAAS, WSA, EUS, chondrite, MUQ, UCC, MORB, WRAS, DMM) as it is supposed to be more accurate due to updated analytical methods and if it was not complete, the latest complete for all REE's dataset was chosen (NASC). AS and WRAC normalizations were not performed as they are less used. For the three studied matrices (aquatic biota, sediment and natural water), REE patterns produced from shale (PAAS, NASC, WSA and EUS), MUQ and WRAS normalizations are very similar (**Fig. 7. A-C**). REE patterns for UCC normalization slightly differ from the ones obtained with the six previous normalizations (**Fig. 7. A-C**). This result is particularly noticeable for sediment and water on HREEs (**Fig 7. B, C**), even if the pattern remains very close to the others. MORB is again contrasting with all other normalizations with higher LREE enrichments showed in all three patterns of studied samples. Finally, as mentioned before, REE patterns obtained with chondrite and DMM normalizations are diverging, especially for LREEs which have higher levels than the others (**Fig. 7. A-C**). Considering other scientific articles performing several normalizations and dealing with few differences between REE patterns, these results highlight a great similarity of patterns obtained after shale-normalizations regardless of their origin. Consequently, it would be possible to compare data from studies already published which used different shale normalizations (PAAS, NASC, WSA and EUS).

No harmonization about the reference material used for normalization exists for REE patterns, but this review highlights PAAS as the most used normalization reference material. Added to its popularity, PAAS was recently updated by **Pourmand et al. in 2012** allowing better accuracy of REE measurements due to improved analytical methods (MC-ICP-MS (Multiple Collector - Inductively Coupled Plasma - Mass Spectrometry)) leading to a better estimation of continental crust composition compared to other references, like NASC or WSA, that were elaborated based on anterior analytical methods that can induce bias (NAA (Neutron Activation Analysis) or ID-MS (Isotope Dilution - Mass Spectrometry)). Moreover, PAAS not being a shale composite avoids potential inclusion of aberrant material as it can be the case with a composite sample like for NASC or EUS (**McLennan, 1989**). Finally, as described earlier, PAAS allows to better highlight differences between samples due to its similarity in REE composition; whereas, it is not always possible when using chondrite-normalization.

Therefore, and for all of these reasons, it could be advised to favor PAAS-normalization when investigating on REEs. This way, comparisons between studies from all around the world would be possible. However, depending on the location, the studied matrix or the study objective, other normalizations might give more precise information and have a great interest. These other ways of normalization, representing geographical situation and/or being more representative of the sample matrix (*e.g.*, MORB, EUS, local normalization, etc.) should be used in these studies in addition to PAAS.

Regarding anomaly calculation, even if a reference equation has been proposed by **Alibo and Nozaki (1999)**, this review highlights that many different equations are used to calculate REE anomalies. In most of the studies, anomalies are quantified by linear extrapolation or interpolation using either close or distant corrected neighbors' concentrations. Indeed, depending on the environmental characteristics of the studied samples, direct neighbors' concentrations cannot be used to calculate an element anomaly as it presents itself an anomaly. To minimize bias involved by neighbor's anomalies, either various distant neighbors or geometric extrapolation methods are used multiplying the number of equations seen in the literature (**Lawrence et al., 2006b**). This phenomenon might therefore be the explanation for the wide number of different equations reported in this review for the calculation of the anomaly of a single element (**Fig. 6**). In some cases, anomaly calculation equations are really diverging from the reference one and no real explanations about the choice or the establishment of the equation are given in the articles. These reasons should be really mentioned as it would help to better understand the results and to compare anomalies from diverse studies. Several studies devoted an important interest in comparing anomaly values obtained by using different equations for their calculation. **Lawrence et al. (2006b)** investigated differences of anomaly obtained for La, Ce, Gd and Eu after using either linear or geometric methods. It highlighted up to 30% differences in La anomaly values between the two applied methods, but less than 2% of variation for Ce, Gd and Eu anomalies. In the same way, **Louis et al. (2020)** tested four different equations for the calculation of Gd anomalies and demonstrated that using an equation based on Nd and Dy tend to maximize the anomaly whereas using one involving Sm and Nd tend to minimize it. Thus, the choice of the method or equation to calculate an anomaly highly conditions the produced results which can lead to misinterpretations if they are inaccurate. Moreover, in some publications, authors employ the modeling of the shape of the normalized REE pattern using a third-order polynomial fit to calculate an element anomaly (**Moller et al., 2002; 2003; Hatje et al., 2016; Pereto et al., 2020; da Costa et al., 2021**). This method could be more accurate avoiding bias as it allows to exclude from the model, elements that might have an anomalous chemical behavior as it is often the case for Eu and Ce. Its systematic use could help to homogenate anomaly calculation to reduce the number of equations used for the same element and to simplify the understanding and the comparison of the studies. However, as

it is more challenging to implement than using an already established equation, this method is not really popularized.

5. Further developments for ecotoxicological issues

REE normalization to reference material is for a long time used in geochemistry to investigate on rare earth elements' behavior in natural ecosystems. It is nowadays used increasingly for ecotoxicological issues dealing with many types of matrices, but mainly focusing on aquatic biota. For water and sediment samples, it makes sense to normalize REE concentrations with values from shales and chondrites, but not really for biota as many biological mechanisms (*e.g.*, uptake, biological membrane transfer, accumulation, metabolization, excretion) can occur within organisms. As it was demonstrated for non-essential metals or for essential metals in excess in cells, some of these processes control the intracellular homeostasis of each metal to limit their adverse effects on cell functioning (Luk et al., 2003; Martinez-Finley et al., 2012; Plindauer, 2012). These species- and tissue-dependent mechanisms directly impact the metal internalization. Even if the studies dealing with REE internalization are scarce, it can be assumed that some of these processes are elicited to control intracellular REE homeostasis.

Little is known about REE uptake and excretion but their similarities with Ca^{2+} could be a possible explanation for their internalization within cells. Indeed, trivalent REEs have varying ionic radii (from 9.6 to 11.5 nm) similar to calcium ions radius that is 9.9 nm. Because of this and due to their higher valency (+3), REEs might be able to bind in place of calcium (Cui et al., 2012). Moreover, as REEs are metals, it is possible that they are excreted due to different detoxification mechanism actors like metallothionein (MT) for example (Andrés et al., 2003; Kawagoe et al., 2005; Dubé et al., 2019; Hanana et al., 2021). As it has already been proved with non-essential metals, demonstrating various fates depending on the species due to different detoxifications capacities and inducing therefore diverse adverse toxic effects (Le Croizier et al., 2019), it might also be the case for REEs (Técher et al., 2020). Their bioaccumulation is, however, well documented. Many studies demonstrated REE bioaccumulation after laboratory exposures in various aquatic organisms like *Dreissena polymorpha*, *Mytilus galloprovincialis*, *Cyprinus carpio*, *Daphnia magna*, *Chironomus riparius* and *Oncorhynchus mykiss* (Qiang et al., 1994; Hanana et al., 2017; Cardon et al., 2019; Freitas et al., 2020). Some of them also highlighted different accumulations depending on the studied organ or on the exposure dose. Cardon et al. (2020) highlighted higher Y concentrations in the intestine of *O. mykiss* compared to the muscles, the liver and the gills. Moreover, Freitas et al. (2020) demonstrated higher Nd concentrations in *M. galloprovincialis* when exposed to high (40 $\mu\text{g/L}$) compared to low concentrations (2.5 $\mu\text{g/L}$). REE partitioning within cells was also investigated with subcellular fractionation studies and allows to characterize precisely REE accumulation and fate in cells and can

inform on potential detoxification processes. A study performed by **Cardon et al. (2019)** highlighted different REE accumulations in subcellular fractions depending on the species. REEs were mainly quantified in the metal detoxified fraction (MT and metal rich granules) for *D. magna* whereas they were mostly accumulated in the metal sensitive fraction (corresponding to cytosolic fraction containing mitochondria and heat denaturated proteins) in *O. mykiss*. Thus, these results demonstrate that accumulation and detoxification mechanisms are depending on the species. Although REEs can induce negative effects at high concentrations, they can also have positive effects at low concentrations (hormesis phenomenon, **Cook and Calabrese, 2007**). Indeed, some REEs can have a beneficial effect on organisms as they can have a role in functional and structural molecules in the biological system. Various favorable REE-associated effects have already been characterized on different species like enhancing growth (for example on *Dryopteris Erythrosora*, **Ozaki et al., 2000**) or increasing immunity responses for fish (**Abdelnour et al., 2019**). These results demonstrate that the presence of REEs in cell is not always involving an adverse effect.

Therefore, the complexity of living organisms cannot be considered with current normalization practices. The normalization of aquatic biota REE concentrations to current shale or chondrite reference materials can help to identify the biological mechanisms involved in REE bioaccumulation from the abiotic compartments. Nevertheless, due to biological processes mentioned above, it may not allow a reliable assessment of exposure to anthropogenic releases. For this purpose, the establishment of new datasets intended to specific aquatic biota is needed. Different ways could be explored. Organisms from sampling archives could be used as references since they can be considered as unexposed to anthropogenic REEs. Indeed, organisms subjected to time series sampling for monitoring programs could be used as reference and allow the estimation of background geogenic concentrations of the elements (e.g., ROCCH (Réseau d'Observation de la Contamination CHimique) program conducted by Ifremer (Institut français de recherche pour l'exploration de la mer) in the aim of French coast chemical monitoring with oyster and mussel sampling since 1974) (**Briant et al., 2021**). However, these archived organisms are not available for all the species and even if it would be required for each species, having species-depending reference materials wouldn't help homogeneity of normalization within aquatic biota. Nevertheless, the normalizations could be performed using REE patterns measured from organisms, representative of an order, as some studies highlighted similar biological processes among different species belonging to the same order. For example, **Perrat et al. (2017)** demonstrated similar Gd accumulations of two mollusk species (*Driessen rostriformis bugensis* and *Corbicula fluminea*), that were higher in the digestive gland compared to the gills. **Wang et al. (2019)** also highlighted similar REE accumulation for three species of fish (*Pagrosomus major*, *Tilapia nilotica* and *Harengula zunasi*). However, this study also showed different accumulation in mollusc and crustacean although they belong to the same phylum. Another way would be to consider: the REE concentrations measured in individuals sampled in pristine or most preserved sites as

reference pattern, as it is sometimes done in abiotic compartment studies (Costa et al., 2021a). This proposition assumes that the sites would present similar physical-chemical characteristics, except anthropogenic discharges, which is rarely the case and is therefore little used. Nevertheless, it has been successfully carried out by Pereto et al. (2020) in one of their studies; *Corbicula fluminea* was used as a sentinel species in the field for the determination of anthropogenic REE origin and Gd bioaccumulation in bivalves. Waiting for new references for aquatic biota, a double normalization seems the most appropriate. The first one using PAAS, as it combines many quality criteria and is the most commonly used, allowing to simplify the comparisons between different studies, and the second one using local normalization to help the interpretation of specific biological mechanisms.

6. Conclusion

This review highlights the wide number of datasets and normalization reference materials that exist nowadays to characterize REE environmental concentrations in aquatic systems. Many different equations for anomaly calculation are also reported from the literature. Homogenization of the use of these methods is necessary to simplify REE investigation and allow the comparison of results from different studies. PAAS normalization is the most commonly used and should be systematically employed because, in addition to its popularity, it meets many quality requirements: a recent update with accurate analytical methods, the detection of inter-samples variations, not based on a composite sample, which is not always the case for others. However, it could be completed with normalization to other reference materials, newly established, that can be more appropriate depending on both the studied location and matrix. Moreover, for articles already published, a comparison of studies that use either PAAS, NASC, WSA or FUS normalizations might be possible, as different studies, including this review, showed only few differences exist between the REE patterns they produce. For natural water and sediment samples, the use of current normalization materials (shale and chondrite) is suitable. Although a wide number of datasets and reference materials is available for abiotic compartment studies, this literature study highlights the lack of reference material that could serve ecotoxicological issues for the biotic compartment. New reference values need to be established in order to better consider the interspecific variability and to assess the anthropogenic origin of bioaccumulated REEs in exposed organisms from natural aquatic ecosystems.

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References

- Abdelnour, S. A., El-hack, M. E. A., Khafaga, A. F., Noreldin, A. E., Arif, M., Chaudhry, M. T., Losacco, C., Abdeen, A., & Abdel-daim, M. M. (2019). Science of the Total Environment Impacts of rare earth elements on animal health and production : Highlights of cerium and lanthanum. *Science of the Total Environment*, 672, 1021–1032. <https://doi.org/10.1016/j.scitotenv.2019.02.270>
- Adánez-Sanjuán, P., Llamas-Borrajó, J. F., García-Cortés, Á., & Locutura-Rupérez, J. (2021). Study of rare earth elements in overbank sediments under the influence of different geochemical-lithological environments. *Journal of Iberian Geology*, 47(3), 551–564. <https://doi.org/10.1007/s41513-021-00169-w>
- Adebayo, S. B., Cui, M., Hong, T., Akintomide, O., Kelly, R. P., & Johannesson, K. H. (2020). Rare earth element cycling and reaction path modeling across the chemocline of the Pettaquamscutt River estuary, Rhode Island. *Geochimica et Cosmochimica Acta*, 284, 21–42. <https://doi.org/10.1016/j.gca.2020.06.001>
- Akagi, T., & Edanami, K. (2017). Sources of rare earth elements in shells and soft-tissues of bivalves from Tokyo Bay. *Marine Chemistry*, 194, 55–62. <https://doi.org/10.1016/j.marcem.2017.02.009>
- Alhassan, A. B., & Aljahdali, M. O. (2021). Fractionation and distribution of rare earth elements in marine sediment and bioavailability in avicennia marina in central red sea mangrove ecosystems. *Plants*, 10, 1233. <https://doi.org/10.3390/plants10061233>
- Alibo, D. S., & Nozaki, Y. (1999). Rare earth elements in seawater: Particle association, shale-normalization, and Ce oxidation. *Geochimica et Cosmochimica Acta*, 63(2), 363–372.
- Anders, E., & Grevesse, N. (1989). Abundances of the elements: Meteoritic and solar. *Geochimica et Cosmochimica Acta*, 53, 197–214. [https://doi.org/10.1016/0016-7037\(89\)90286-X](https://doi.org/10.1016/0016-7037(89)90286-X)
- Andrés, D., Sanchez-Reus, I., Bautista, M., & Carrales, M. (2003). Depletion of Kupffer cell function by gadolinium chloride attenuates thioacetamide-induced hepatotoxicity Expression of metallothionein and HSP70. *Biochemical Pharmacology*, 66, 917–926. [https://doi.org/10.1016/S0006-2952\(03\)00443-X](https://doi.org/10.1016/S0006-2952(03)00443-X)
- Antonina, A. N., Shazili, N. A. M., Karimuzaman, B. Y., Ong, M. C., Rosnan, Y., & Sharifah, F. N. (2013). Geochemistry of the Rare Earth Elements (REE) Distribution in Terengganu Coastal Waters: A Study Case from Redang Island Marine Sediment. *Open Journal of Marine Science*, 3, 154–159. <https://doi.org/10.4236/ojms.2013.33017>
- Barber, L. B., Keefe, S. H., Antweiler, R. C., Taylor, H. E., & Wass, R. D. (2006). Accumulation of contaminants in fish from wastewater treatment wetlands. *Environmental Science and Technology*, 40, 603–611. <https://doi.org/10.1021/es0511787>
- Barrett, T. J., Jarvis, I., Hannington, M. D., & Thirlwall, M. F. (2021). Chemical characteristics of modern deep-sea metalliferous sediments in closed versus open basins, with emphasis on rare-earth elements and Nd isotopes. In *Earth-Science Reviews* (Vol. 222). Elsevier B.V. <https://doi.org/10.1016/j.earscirev.2021.103801>
- Bau, M., & Dulski, P. (1996). EPSL Anthropogenic origin of positive gadolinium anomalies in river waters. *Earth and Planetary Science Letters*, 143, 245–255.
- Bau, M., Balan, S., Schmidt, K., & Koschinsky, A. (2010). Rare earth elements in mussel shells of the Mytilidae family as tracers for hidden and fossil high-temperature hydrothermal systems. *Earth and Planetary Science Letters*, 299(3–4), 310–316. <https://doi.org/10.1016/j.epsl.2010.09.011>
- Bau, M., Knappe, A., & Dulski, P. (2006). Anthropogenic gadolinium as a micropollutant in river waters in Pennsylvania and in Lake Erie, northeastern United States. *Chemie Der Erde*, 66, 143–152. <https://doi.org/10.1016/j.chemer.2006.01.002>
- Bau, M., Koschinsky, A., Dulski, P., & Hein, J. R. (1996). Comparison of the partitioning behaviours of yttrium, rare earth elements, and titanium between hydrogenetic marine ferromanganese crusts and seawater. In *Geochimica et Cosmochimica Acta* (Vol. 60, Issue 10).

- Bau, M., Schmidt, K., Pack, A., Bendel, V., & Kraemer, D. (2018). The European Shale: An improved data set for normalisation of rare earth element and yttrium concentrations in environmental and biological samples from Europe. *Applied Geochemistry*, 90, 142–149. <https://doi.org/10.1016/j.apgeochem.2018.01.008>
- Bayon, G., Lambert, T., Vigier, N., De Deckker, P., Freslon, N., Jang, K., Larkin, C. S., Piotrowski, A. M., Tachikawa, K., Thollon, M., & Tipper, E. T. (2020). Rare earth element and neodymium isotope tracing of sedimentary rock weathering. *Chemical Geology*, 553, 119794. <https://doi.org/10.1016/j.chemgeo.2020.119794>
- Bayon, G., Toucanne, S., Skonieczny, C., André, L., Bermell, S., Cheron, S., Dennielou, B., Etoubleau, J., Freslon, N., Gauchery, T., Germain, Y., Jorry, S. J., Ménot, G., Monin, L., Ponzevera, E., Rouget, M. L., Tachikawa, K., & Barrat, J. A. (2015). Rare earth elements and neodymium isotopes in world river sediments revisited. *Geochimica et Cosmochimica Acta*, 170, 17–38. <https://doi.org/10.1016/j.gca.2015.08.001>
- Behrens, M. K., Muratli, J., Pradoux, C., Wu, Y., Böning, P., Brumsack, H. J., Goldstein, S. L., Haley, B., Jeandel, C., Paffrath, R., Pena, L. D., Schnetger, B., & Pahnke, K. (2016). Rapid and precise analysis of rare earth elements in small volumes of seawater - Method and intercomparison. *Marine Chemistry*, 186, 110–120. <https://doi.org/10.1016/j.marchem.2016.08.006>
- Behrens, M. K., Pahnke, K., Cravatte, S., Marin, F., & Jeandel, C. (2020). Rare earth element input and transport in the near-surface zonal current system of the Tropical Western Pacific. *Earth and Planetary Science Letters*, 549, 116496. <https://doi.org/10.1016/j.epsl.2020.116496>
- Benabdelkader, A., Taleb, A., Probst, J. L., Belaidi, N., & Probst, A. (2019). Origin, distribution, and behaviour of rare earth elements in river bed sediments from a carbonate semi arid basin (Tafna River, Algeria). *Applied Geochemistry*, 106, 96–111. <https://doi.org/10.1016/j.apgeochem.2019.05.005>
- Benaltabet, T., Gutner-Hoch, E., & Torfstein, A. (2021). Heavy Metal, Rare Earth Element and Pb Isotope Dynamics in Mussels During a Depuration Experiment in the Gulf of Aqaba, Northern Red Sea. *Frontiers in Marine Science*, 8, 669329. <https://doi.org/10.3389/fmars.2021.669329>
- Bertram, C. J., & Elderfield, H. (1993). The geochemical balance of the rare earth elements and neodymium isotopes in the oceans. *Geochimica et Cosmochimica Acta*, 57, 1957–1986.
- Blindauer, C. (2012). Homeostasis and distribution of essential metals in cells. *Biochem (Lond)*, 34(5), 4–13.
- Bonnail, E., Pérez-López, R., Sarmiento, A. M., Nieto, J. M., & DeValls, T. Á. (2017). A novel approach for acid mine drainage pollution biomonitoring using rare earth elements bioaccumulated in the freshwater clam *Corbicula fluminea*. *Journal of Hazardous Materials*, 338, 466–471. <https://doi.org/10.1016/j.jhazmat.2017.05.052>
- Borrego, J., López-González, N., Carro, B., & Lozano-Soria, O. (2004). Origin of the anomalies in light and middle REE in sediments of an estuary affected by phosphogypsum wastes (south-western Spain). *Marine Pollution Bulletin*, 49, 1045–1053. <https://doi.org/10.1016/j.marpolbul.2004.07.009>
- Bosco-Santos, A., Luiz-Silva, W., Silva-Filho, E. V. da, Souza, M. D. C. de, Dantas, E. L., & Navarro, M. S. (2017). Fractionation of rare earth and other trace elements in crabs, *Ucides cordatus*, from a subtropical mangrove affected by fertilizer industry. *Journal of Environmental Sciences*, 54, 69–76. <https://doi.org/10.1016/j.jes.2016.05.024>
- Bozau, E., Leblanc, M., Seidel, J. L., & Stärk, H. J. (2004). Light Rare Earth Elements enrichment in an acidic mine lake (Lusatia, Germany). *Applied Geochemistry*, 19, 261–271. [https://doi.org/10.1016/S0883-2927\(03\)00150-1](https://doi.org/10.1016/S0883-2927(03)00150-1)
- Briant, N., Le Monier, P., Bruzac, S., Sireau, T., Araújo, D. F., & Grouhel, A. (2021). Rare Earth Element in Bivalves' Soft Tissues of French Metropolitan Coasts: Spatial and Temporal Distribution. *Archives of Environmental Contamination and Toxicology*, 81, 600–611. <https://doi.org/10.1007/s00244-021-00821-7>
- Brito, P., Caetano, M., Martins, M. D., & Caçador, I. (2021). Effects of salt marsh plants on mobility and bioavailability of REE in estuarine sediments. *Science of the Total Environment*, 759, 144314. <https://doi.org/10.1016/j.scitotenv.2020.144314>

- Brito, P., Prego, R., Mil-Homens, M., Caçador, I., & Caetano, M. (2018). Sources and distribution of yttrium and rare earth elements in surface sediments from Tagus estuary, Portugal. *Science of the Total Environment*, 621, 317–325. <https://doi.org/10.1016/j.scitotenv.2017.11.245>
- Bru, K., Christmann, P., Labbé, J. F., & Lefebvre, G. (2015). Panorama 2014 du marché des Terres Rares. Rapport Public BRGM/RP-65330-FR.
- Buissette, V., & Le Mercier, T. (2019). Terres rares. Ref : TIP452WEB. Techniques de l'ingénieur Opérations unitaires. Génie de la réaction chimique. <https://doi.org/10.51257/a-v2-j6630>
- Caccia, V. G., & Millero, F. J. (2007). Distribution of yttrium and rare earths in Florida Bay sediments. *Marine Chemistry*, 104, 171–185. <https://doi.org/10.1016/j.marchem.2006.11.001>
- Cai, P., Cai, G., Li, X., Chen, X., Lin, J., Li, S., & Li, Z. (2021). Distribution and Source Determination of Rare Earth Elements in Sediment Collected From The Continental Shelf Off Hainan Island, China. *Environmental Science and Pollution Research*. <https://doi.org/10.21203/rs.3.rs-575805/v1>
- Cánovas, C. R., Basallote, M. D., & Macías, F. (2020). Distribution and availability of rare earth elements and trace elements in the estuarine waters of the Ría of Huelva (SW Spain). *Environmental Pollution*, 267, 115506. <https://doi.org/10.1016/j.envpol.2020.115506>
- Cardon, P., Roques, O., Caron, A., Rosabal, M., Fortin, C., & Amyot, M. (2020). Role of prey subcellular distribution on the bioaccumulation of yttrium (Y) in the rainbow trout. *Environmental Pollution*, 258, 113804. <https://doi.org/10.1016/j.envpol.2019.113804>
- Cardon, P., Triffault-Bouche, G., Caron, A., Rosabal, M., Fortin, C., & Amyot, M. (2019). Toxicity and Subcellular Fractionation of Yttrium in Three Freshwater Organisms: *Daphnia magna*, *Chironomus riparius*, and *Oncorhynchus mykiss*. *ACS Omega*, 4, 13747–13755. <https://doi.org/10.1021/acsomega.9b01238>
- Castor, S. B., & Hedrick, J. B. (2006). Rare Earth Elements. Society for Mining, Metallurgy and Exploration. *Industrial Minerals and Rocks*, 7, 769–792.
- Censi, P., Mazzola, S., Sprovieri, M., Bonanno, A., Patti, B., Punturo, R., Spoto, S. E., Saiano, F., & Alonzo, G. (2004). Rare earth elements distribution in seawater and suspended particulate of the Central Mediterranean Sea. *Chemistry and Ecology*, 20(5), 323–343. <https://doi.org/10.1080/02757540410001727954>
- Censi, P., Randazzo, L. A., D'Angelo, S., Saiano, F., Zuddas, P., Mazzola, S., & Cuttitta, A. (2013). Relationship between lanthanide contents in aquatic turtles and environmental exposures. *Chemosphere*, 91, 1130–1135. <https://doi.org/10.1016/j.chemosphere.2013.01.017>
- Censi, P., Sprovieri, M., Saiano, F., Di Geronimo, S. I., Larocca, D., & Placenti, F. (2007). The behaviour of REEs in Thailand's Mae Klong estuary: Suggestions from the Y/Ho ratios and lanthanide tetrad effects. *Estuarine, Coastal and Shelf Science*, 71, 569–579. <https://doi.org/10.1016/j.ecss.2006.09.003>
- Chaillou, G., Anschutz, P., Lavaux, G., & Blanc, G. (2006). Rare earth elements in the modern sediments of the Bay of Biscay (France). *Marine Chemistry*, 100, 39–52. <https://doi.org/10.1016/j.marchem.2005.09.007>
- Chaudhuri, S., & Cullers, R. L. (1979). The distribution of rare-earth elements in deeply buried gulf coast sediments. *Chemical Geology*, 24, 327–338.
- Chelnokov, G. A., Kharitonova, N. A., Bragin, I. V., Aseeva, A. V., Bushkareva, K. Y., & Liamina, L. A. (2020). The Geochemistry of Rare Earth Elements in Natural Waters and Secondary Mineral Sediments of Thermal Fields of Kamchatka. *Moscow University Geology Bulletin*, 75(2), 196–204. <https://doi.org/10.3103/S0145875220020027>
- Chen, J., Zou, J., Zhu, A., Shi, X., Nürnberg, D., Lembke-Jene, L., Tiedemann, R., Wang, K., Wu, Y., Dong, Z., Liu, J., & Dou, R. (2021b). Geochemistry of Surface Sediments From the Emperor Seamount Chain, North Pacific. *Frontiers in Earth Science*, 9, 674842. <https://doi.org/10.3389/feart.2021.674842>
- Chen, L., Jin, M., Wang, X., Wang, H., & Li, N. (2020). The effects of diagenetic processes and fluid migration on rare earth element and organic matter distribution in seep-related sediments: A case study from the South China Sea. *Journal of Asian Earth Sciences*, 191, 104233. <https://doi.org/10.1016/j.jseas.2020.104233>

- Chen, X., Song, Y., Li, Y., Huang, Y., Zhou, X., & Fan, Y. (2021a). Provenance of sub-aerial surface sediments in the Tarim Basin, Western China. *Catena*, 198, 105014. <https://doi.org/10.1016/j.catena.2020.105014>
- Chi, G., Liu, B., Hu, K., Yang, J., & He, B. (2021). Geochemical composition of sediments in the Liao River Estuary and implications for provenance and weathering. *Regional Studies in Marine Science*, 45, 101833. <https://doi.org/10.1016/j.rsma.2021.101833>
- Chougong, D. T., Ekoa Bessa, A. Z., Ngueutchoua, G., Fouateu Yongue, R., Ntyam, S. C., & Armstrong-Altrin, J. S. (2021). Mineralogy and geochemistry of Lobé River sediments, SW Cameroon: Implications for provenance and weathering. *Journal of African Earth Sciences*, 183, 104320. <https://doi.org/10.1016/j.jafrearsci.2021.104320>
- Consani, S., & Cutroneo, L. (2021). Baseline on rare earth elements in the marine sediments of a Mediterranean commercial port as environmental tracers and their relationships with inorganic contaminants. *Marine Pollution Bulletin*, 173, 112961. <https://doi.org/10.1016/j.marpolbul.2021.112961>
- Cook, R., & Calabrese, E. J. (2007). The importance of hormesis to public health. *Ciência & Saúde Coletiva*, 12(4), 955-963. <https://doi.org/10.1289/ehp.8606>
- Costa, L., Johannesson, K., Mirlean, N., & Quintana, G. (2021b). Rare earth element distributions in salt marsh sediment cores reveal evidence of environmental lability during bioturbation and diagenetic processes. *Chemical Geology*, 584, 120503. <https://doi.org/10.1016/j.chemgeo.2021.120503>
- Costa, L., Mirlean, N., & Johannesson, K. H. (2021a). Rare earth elements as tracers of sediment contamination by fertilizer industries in Southern Brazil, Patos Lagoon Estuary. *Applied Geochemistry*, 129, 104965. <https://doi.org/10.1016/j.apgeochem.2021.104965>
- Cotten, J., Le Dez, A., Bau, M., Caroff, M., Maury, M., Orsini, P., Fourcade, S., Bohn, M., & Brousse, R. (1995). Origin of anomalous rare-earth element and yttrium enrichments in subaerially exposed basalts: Evidence from French Polynesia. *Chemical Geology*, 119, 115–138.
- Courtois, C., & Treuil, M. (1977). Distribution des terres rares et de quelques éléments en trace dans les sédiments récents des fosses de la mer rouge. *Chemical Geology*, 20, 57–72.
- Cui, J., Zhang, Z., Bai, W., Zhang, L., He, X., Ma, Y., Liu, Y., & Chai, Z. (2012). Effects of rare earth elements La and Yb on the morphological and functional development of zebrafish embryos. *Journal of Environmental Sciences*, 24(2), 209–213. [https://doi.org/10.1016/S1001-0742\(11\)60755-9](https://doi.org/10.1016/S1001-0742(11)60755-9)
- Culicov, O. A., Trtić-Petrović, T., Balvanović, R., Petković, A., & Ražić, S. (2021). Spatial distribution of multielements including lanthanides in sediments of Iron Gate I Reservoir in the Danube River. *Environmental Science and Pollution Research*, 28, 44877–44889. <https://doi.org/10.1007/s11356-021-13752-6> / Published
- da Costa, A. R. B., Rousseau, T. C. C., Maia, P. D., Amorim, A. M., Sodré, F. F., & Teixeira, C. E. P. (2021). Anthropogenic gadolinium in estuaries and tropical Atlantic coastal waters from Fortaleza, Northeast Brazil. *Applied Geochemistry*, 127, 104908. <https://doi.org/10.1016/j.apgeochem.2021.104908>
- Dang, D. H., Zhang, Z., Wang, W., Oursel, B., Juillot, F., Dupouy, C., Lemonnier, H., & Mounier, S. (2021). Tropical mangrove forests as a source of dissolved rare earth elements and yttrium to the ocean. *Chemical Geology*, 576, 120278. <https://doi.org/10.1016/j.chemgeo.2021.120278>
- Dauteuil, O., Jolivet, M., Dia, A., Murray-Hudson, M., Makati, K., Barrier, L., Bouhnik Le Coz, M., Audran, A., & Radenac, A. (2021). Trace Metal Enrichments in Water of the Okavango Delta (Botswana): Hydrological Consequences. *Geochemistry, Geophysics, Geosystems*, 22(5). <https://doi.org/10.1029/2021GC009856>
- De Baar, H. J. W. (1991). On cerium anomalies in the Sargasso Sea. *Geochimica et Cosmochimica Acta*, 55, 2981–2983. [https://doi.org/10.1016/0016-7037\(91\)90463-F](https://doi.org/10.1016/0016-7037(91)90463-F)
- De Baar, H. J. W., Bacon, M. P., & Brewer, P. G. (1983). Rare-earth distributions with a positive Ce anomaly in the Western North Atlantic Ocean. *Nature*, 301, 324–327.

- De Baar, H. J. W., Schijf, J., & Byrne, R. H. (1991). Solution chemistry of the rare earth elements in seawater. *European Journal of Solid State and Inorganic Chemistry*, 28, 357–373. <http://www.researchgate.net/publication/259564097>
- De Baar, H. J., Bacon, M. P., Brewer, P. G., & Bruland, K. W. (1985a). Rare earth elements in the Pacific and Atlantic Oceans*. *Geochimica et Cosmochimica Acta*, 49, 1943–1959.
- De Baar, H. J., Brewer, P. G., & Bacon, M. P. (1985b). Anomalies in rare earth distributions in seawater: Gd and Tb*. *Geochimica et Cosmochimica Acta*, 49, 1961–1969.
- de Campos, F. F., & Enzweiler, J. (2016). Anthropogenic gadolinium anomalies and rare earth elements in the water of Atibaia River and Anhumas Creek, Southeast Brazil. *Environmental Monitoring and Assessment*, 188(5). <https://doi.org/10.1007/s10661-016-5282-7>
- de Freitas, T. O. P., Pedreira, R. M. A., & Hatje, V. (2021). Distribution and fractionation of rare earth elements in sediments and mangrove soil profiles across an estuarine gradient. *Chemosphere*, 264, 128431. <https://doi.org/10.1016/j.chemosphere.2020.128431>
- Deepulal, P. M., Kumar, G., & Sujatha, C. H. (2012). Behaviour of REEs in a tropical estuary and adjacent continental shelf of southwest coast of India: Evidence from anomalies. *Journal of Earth System Science*, 121(5), 1215–1227.
- Delgado, J., Pérez-López, R., Galván, L., Nieto, J. M., & Boski, T. (2012). Enrichment of rare earth elements as environmental tracers of contamination by acid mine drainage in salt marshes: A new perspective. *Marine Pollution Bulletin*, 64, 1799–1808. <https://doi.org/10.1016/j.marpolbul.2012.06.001>
- Di Leonardo, R., Bellanca, A., Neri, R., Tranchida, G., & Mazzola, S. (2009). Distribution of REEs in box-core sediments offshore an industrial area in SE Sicily, Ionian Sea: Evidence of anomalous sedimentary inputs. *Chemosphere*, 77, 778–784. <https://doi.org/10.1016/j.chemosphere.2009.08.021>
- Dia, A., Gruau, G., Olivie-Lauquet, G., Riou, C., Mélenat, J., & Curmi, P. (2000). The distribution of rare earth elements in groundwaters: Assessing the role of source-rock composition, redox changes and colloidal particles. *Geochimica et Cosmochimica Acta*, 64(24), 4151–4151.
- Douville, E., Bienvenu, P., Charlou, J. L., Douville, J. P., Fouquet, Y., Appriou, P., & Gamo, T. (1999). Yttrium and rare earth elements in fluids from various deep-sea hydrothermal systems. *Geochimica et Cosmochimica Acta*, 63(5), 627–643.
- Dubé, M., Auclair, J., Hanana, H., Mercote, P., Gagnon, C., & Gagné, F. (2019). Gene expression changes and toxicity of selected rare earth elements in rainbow trout juveniles. *Comparative Biochemistry and Physiology, Part C*, 223, 88–95. <https://doi.org/10.1016/j.cbpc.2019.05.009>
- Duncan, T., & Shaw, T. J. (2003). The Mobility of Rare Earth Elements and Redox Sensitive Elements in the Groundwater/Seawater Mixing Zone of a Shallow Coastal Aquifer. *Aquatic Geochemistry*, 9, 233–255.
- Ekoa Bessa, A. Z., Ndjigui, P. D., Fuh, G. C., Armstrong-Altrin, J. S., & Betsi, T. B. (2021). Mineralogy and geochemistry of the Ossa lake Complex sediments, Southern Cameroon: implications for paleoweathering and provenance. *Arabian Journal of Geosciences*, 14, 322. <https://doi.org/10.1007/s12517-021-06591-9>
- Elbaz-Poulichet, F., & Dupuy, C. (1999). Behaviour of rare earth elements at the freshwater-seawater interface of two acid mine rivers: the Tinto and Odiel (Andalucia, Spain). *Applied Geochemistry*, 14, 1063–1072.
- Elbaz-Poulichet, F., Seidel, J.-L., & Othoniel, C. (2002). Occurrence of an anthropogenic gadolinium anomaly in river and coastal waters of Southern France. *Water Research*, 36, 1102–1105.
- Elderfield, H., & Greaves, M. J. (1981). Negative cerium anomalies in the rare earth element patterns of oceanic ferromanganese nodules. *Earth and Planetary Science Letters*, 55, 163–170.
- Elderfield, H., & Greaves, M. J. (1982). The rare earth elements in seawater. *Nature*, 296, 214–219.
- Elderfield, H., & Sholkovitz, E. R. (1987). Rare earth elements in the pore waters of reducing nearshore sediments. *Earth and Planetary Science Letters*, 82, 280–288.

- Elderfield, H., Hawkesworth, C. J., Greaves, M. J., & Calvert, S. E. (1981). Rare earth element geochemistry of oceanic ferromanganese nodules and associated sediments. *Geochimica et Cosmochimica Acta*, 45, 513–528.
- Elderfield, H., Upstill-Goddard, R., & Sholkovitz, E. R. (1990). The rare earth elements in rivers, estuaries, and coastal seas and their significance to the composition of ocean waters. *Geochimica et Cosmochimica Acta*, 54, 971–991.
- Elias, M. S., Ibrahim, S., Samuding, K., Kantasamy, N., Rahman, S. A., & Hashim, A. (2019). Rare earth elements (REEs) as pollution indicator in sediment of Linggi River, Malaysia. *Applied Radiation and Isotopes*, 151, 116–123. <https://doi.org/10.1016/j.apradiso.2019.05.038>
- Erel, Y., & Stolper, E. M. (1993). Modeling of rare-earth element partitioning between particles and solution in aquatic environments. *Geochimica et Cosmochimica Acta*, 51, 513–518.
- Evensen, N. M., Hamilton, P. J., & O’Nions, R. K. (1978). Rare-earth abundances in chondritic meteorites. *Geochimica et Cosmochimica Acta*, 42, 1199–1212. [https://doi.org/10.1016/0016-7037\(78\)90114-X](https://doi.org/10.1016/0016-7037(78)90114-X)
- Figueiredo, C., Caetano, M., Mil-Homens, M., Tojeira, I., Xavier, J. R., Rosa, R., & Raimundo, J. (2021). Rare earth and trace elements in deep-sea sponges of the North Atlantic. *Marine Pollution Bulletin*, 166, 112217. <https://doi.org/10.1016/j.marpolbul.2021.112217>
- Floback, A. E., & Moffett, J. W. (2021). Rare earth element distributions in the Arabian Sea reveal the influence of redox processes within the oxygen deficient zone. *Chemical Geology*, 577, 120214. <https://doi.org/10.1016/j.chemgeo.2021.120214>
- Freitas, R., Costa, S., Cardoso, C. E. D., Morais, T., Moleiro, P., Matias, A. C., Pereira, A. F., Machado, J., Correia, B., Pinheiro, D., Rodrigues, A., Colonia, J., Soares, A. M. V. M., & Pereira, E. (2020). Toxicological effects of the rare earth element neodymium in *Mytilus galloprovincialis*. *Chemosphere*, 244, 125457. <https://doi.org/10.1016/j.chemosphere.2019.125457>
- Freslon, N., Bayon, G., Birot, D., Bollinger, C., & Parrat, J. A. (2011). Determination of rare earth elements and other trace elements (Y, Mn, Co, Cr) in seawater using Tm addition and Mg(OH)₂ co-precipitation. *Talanta*, 85, 582–587. <https://doi.org/10.1016/j.talanta.2011.04.023>
- Ganai, J. A., & Rashid, S. A. (2015). Rare earth element geochemistry of the Permo-Carboniferous clastic sedimentary rocks from the Spiti Region, Tethys Himalaya: significance of Eu and Ce anomalies. *Chinese Journal of Geochemistry*, 34, 252–264. <https://doi.org/10.1007/s11631-015-0045-7>
- Garcia-Solsona, E., & Jeandel, C. (2020). Balancing Rare Earth Element distributions in the Northwestern Mediterranean Sea. *Chemical Geology*, 532, 119372. <https://doi.org/10.1016/j.chemgeo.2019.119372>
- Garcia-Solsona, E., Jeandel, C., Labatut, M., Lacan, F., Vance, D., Chavagnac, V., & Pradoux, C. (2014). Rare earth elements and Nd isotopes tracing water mass mixing and particle-seawater interactions in the SE Atlantic. *Geochimica et Cosmochimica Acta*, 125, 351–372. <https://doi.org/10.1016/j.gca.2013.10.009>
- German, C. R., & Elderfield, H. (1990). Application of the Ce anomaly as a paleoredox indicator: the ground rules. *Paleoceanography*, 5(5), 823–833.
- German, C. R., Klinkhammer, G. P., Edmond, J. M., Mitra, A., & Elderfield, H. (1990). Hydrothermal scavenging of rare-earth elements in the ocean. *Nature*, 345, 516–518.
- German, C. R., Masuzawa, T., Greaves, M. J., Elderfield, H., & Edmond, J. M. (1995). Dissolved rare earth elements in the Southern Ocean: Cerium oxidation and the influence of hydrography. *Geochimica et Cosmochimica Acta*, 59(8), 1551–1558.
- Gimeno Serrano, M. J., Auqué Sanz, L. F., & Nordstrom, D. K. (2000). REE speciation in low-temperature acidic waters and the competitive effects of aluminum. *Chemical Geology*, 165, 167–180. [https://doi.org/10.1016/S0009-2541\(99\)00166-7](https://doi.org/10.1016/S0009-2541(99)00166-7)
- Goldstein, S. J., & Jacobsen, S. B. (1988). Rare earth elements in river waters. *Earth and Planetary Science Letters*, 89, 35–47.

- Goldstein, S. J., & Jacobsen, S. B. (1988). Rare earth elements in river waters. *Earth and Planetary Science Letters*, 89, 35–47. [https://doi.org/10.1016/0012-821X\(88\)90031-3](https://doi.org/10.1016/0012-821X(88)90031-3)
- Gromet, L. P., Dymek, R. F., Haskin, L. A., & Korotev, R. L. (1984). The “North American shale composite”: Its compilation, major and trace element characteristics. *Geochimica et Cosmochimica Acta*, 48, 2469–2482. [https://doi.org/10.1016/0016-7037\(84\)90298-9](https://doi.org/10.1016/0016-7037(84)90298-9)
- Gruau, G., Dia, A., Olivie-Lauquet, G., Davranche, M., & Pinay, G. (2004). Controls on the distribution of rare earth elements in shallow groundwaters. *Water Research*, 38, 3576–3586. <https://doi.org/10.1016/j.watres.2004.04.056>
- Gu, Y. G., Gao, Y. P., Huang, H. H., & Wu, F. X. (2020). First attempt to assess ecotoxicological risk of fifteen rare earth elements and their mixtures in sediments with diffusive gradients in thin films. *Water Research*, 185, 116254. <https://doi.org/10.1016/j.watres.2020.116254>
- Guo, H., Zhang, B., Wang, G., & Shen, Z. (2010). Geochemical controls on arsenic and rare earth elements approximately along a groundwater flow path in the shallow aquifer of the Hetao Basin, Inner Mongolia. *Chemical Geology*, 270, 117–125. <https://doi.org/10.1016/j.chemgeo.2009.11.019>
- Guy, C., Daux, V., & Schott, J. (1999). Behaviour of rare earth elements during seawater-basalt interactions in the Mururoa Massif. *Chemical Geology*, 158, 21–35.
- Haley, B. A., & Klinkhammer, G. P. (2003). Complete separation of rare earth elements from small volume seawater samples by automated ion chromatography: Method development and application to benthic flux. *Marine Chemistry*, 82, 197–220. [https://doi.org/10.1016/S0304-4202\(03\)00070-7](https://doi.org/10.1016/S0304-4202(03)00070-7)
- Haley, B. A., Frank, M., Hathorne, E., & Pisiak, N. (2014). Biogeochemical implications from dissolved rare earth element and Nd isotope distributions in the Gulf of Mexico. *Geochimica et Cosmochimica Acta*, 126, 455–474. <https://doi.org/10.1016/j.gca.2013.11.012>
- Haley, B. A., Klinkhammer, G. P., & McManus, J. (2004). Rare earth elements in pore waters of marine sediments. *Geochimica et Cosmochimica Acta*, 68(6), 1265–1279. <https://doi.org/10.1016/j.gca.2003.09.012>
- Han, G., Yang, K., & Zeng, J. (2021). Distribution and fractionation of rare earth elements in suspended sediment of the Zhujiang River, Southwest China. *Journal of Soils and Sediments*, 21, 2981–2993. <https://doi.org/10.1007/s11368-021-03078-2>
- Hanana, H., Turcotte, P., André, C., Gagnon, C., & Gagné, F. (2017). Comparative study of the effects of gadolinium chloride and gadolinium based magnetic resonance imaging contrast agent on freshwater mussel, *Dreissena polymorpha*. *Chemosphere*, 181, 197–207. <https://doi.org/10.1016/j.chemosphere.2017.04.073>
- Hanana, H., Taranu, Z. E., Turcotte, P., Gagnon, C., Kowalczyk, J., & Gagné, F. (2021). Evaluation of general stress, detoxification pathway and genotoxicity in rainbow trout exposed to rare earth elements dysprosium and lutetium. *Ecotoxicology and Environmental Safety*, 208, 111588. <https://doi.org/10.1016/j.ecoenv.2020.111588>
- Hannigan, R. E., & Sholkovitz, E. R. (2001). The development of middle rare earth element enrichments in freshwaters: weathering of phosphate minerals. *Chemical Geology*, 175, 495–508. www.elsevier.com/locate/chemgeo
- Hannigan, R., Dorval, E., & Jones, C. (2010). The rare earth element chemistry of estuarine surface sediments in the Chesapeake Bay. *Chemical Geology*, 272(1–4), 20–30. <https://doi.org/10.1016/j.chemgeo.2010.01.009>
- Haskin, L. A., Frey, F. A., Schmitt, R. A., & Smith, R. H. (1966b). Meteoritic, solar and terrestrial rare-earth distributions. *Physics and Chemistry of the Earth*, 7, 167–321. [https://doi.org/10.1016/0079-1946\(66\)90004-8](https://doi.org/10.1016/0079-1946(66)90004-8)
- Haskin, L. A., Wildeman, T. R., Frey, F. A., Collins, K. A., Keedy, R., & Haskin, M. A. (1966a). Rare Earths in Sediments. *Journal of Geophysical Research*, 71(24).
- Haskin, L., & Gehl, M. A. (1962). The Rare-Earth Distribution in Sediments. *Journal of Geophysical Research*, 67(6), 2537–2541.

- Haskin, M. A., & Haskin, L. A. (1966). Rare Earths in European shales: a Redetermination. *Science*, 154, 507–509.
- Hatipoğlu Temizel, E., Gültekin, F., & Fırat Ersoy, A. (2020). Major, trace, and rare earth element geochemistry of the Ayder and İkizdere (Rize, NE Turkey) geothermal waters: Constraints for water–rock interactions. *Geothermics*, 86, 101810. <https://doi.org/10.1016/j.geothermics.2020.101810>
- Hatje, V., Bruland, K. W., & Flegal, A. R. (2016). Increases in Anthropogenic Gadolinium Anomalies and Rare Earth Element Concentrations in San Francisco Bay over a 20 Year Record. *Environmental Science and Technology*, 50, 4159–4168. <https://doi.org/10.1021/acs.est.5b04322>
- Hissler, C., Hostache, R., Iffly, J. F., Pfister, L., & Stille, P. (2015). Anthropogenic rare earth element fluxes into floodplains: Coupling between geochemical monitoring and hydrodynamic sediment transport modelling. *Comptes Rendus - Geoscience*, 347, 294–303. <https://doi.org/10.1016/j.crte.2015.01.003>
- Hissler, C., Stille, P., Iffly, J. F., Guignard, C., Chabaux, F., & Pfister, L. (2016). Origin and Dynamics of Rare Earth Elements during Flood Events in Contaminated River Basins: Sr-Nd- ϵ_{Nd} Isotopic Evidence. *Environmental Science and Technology*, 50(9), 4624–4631. <https://doi.org/10.1021/acs.est.5b02560>
- Huang, J., Hills, J., Teasdale, P. R., Panther, J. G., Wang, F., & Welsh, D. T. (2021). Evaluation of the Chelex-DGT technique for the measurement of rare earth elements in the porewater of estuarine and marine sediments. *Talanta*, 230, 122315. <https://doi.org/10.1016/j.talanta.2021.122315>
- Iwamori, H., Nakamura, H., Chang, Q., Morikawa, N., & Hara, T. (2020). Multivariate statistical analyses of rare earth element compositions of spring waters from the Arima and Kii areas, Southwest Japan. *Geochemical Journal*, 54, 165–182. <https://doi.org/10.2343/GEOCHEM.J.2.0583>
- Jiao, Y., Yang, L., Kong, Z., Shao, L., Wang, G., Ren, X., & Liu, Y. (2021). Evaluation of trace metals and rare earth elements in mantis shrimp *Oratosquilla oratoria* collected from Shandong Province, China, and its potential risks to human health. *Marine Pollution Bulletin*, 162, 111815. <https://doi.org/10.1016/j.marpolbul.2020.111815>
- Johannesson, K. H., Zhou, X., Guo, C., Stetzenbach, K. J., & Hodge, V. F. (2000). Origin of rare earth element signatures in groundwaters of circumneutral pH from southern Nevada and eastern California, USA. *Chemical Geology*, 164, 239–257. www.elsevier.com/locate/chemgeo
- Jung, H. S., Kim, J., Lim, D., Jeong, D., Lee, J., & Xu, Z. (2021). REE fractionation and quantification of sediment source in the Yellow Sea mud deposits, East Asian marginal sea. *Continental Shelf Research*, 217, 104374. <https://doi.org/10.1016/j.csr.2021.104374>
- Kajiya, T., Aihara, M., & Hirata, S. (2004). Determination of rare earth elements in seawater by inductively coupled plasma mass spectrometry with on-line column pre-concentration using 8-quinolinole-immobilized fluorinated metal-oxide glass. *Spectrochimica Acta - Part B*, 59, 543–550. <https://doi.org/10.1016/j.sab.2003.12.019>
- Kamber, B. S., Greig, A., & Collerson, K. D. (2005). A new estimate for the composition of weathered young upper continental crust from alluvial sediments, Queensland, Australia. *Geochimica et Cosmochimica Acta*, 69(4), 1041–1058. <https://doi.org/10.1016/j.gca.2004.08.020>
- Kawagoe, M., Hirasawa, F., Wang, S. C., Liu, Y., Ueno, Y., & Sugiyama, T. (2005). Orally administered rare earth element cerium induces metallothionein synthesis and increases glutathione in the mouse liver. *Life Sciences*, 77, 922 – 937. <https://doi.org/10.1016/j.lfs.2005.02.004>
- Khan, R., Mohanty, S., & Sengupta, D. (2021). Elemental distribution in core sediments of Podampata coast, eastern Odisha, India: potentiality of rare earth elements and Th exploration. *Arabian Journal of Geosciences*, 14, 81. <https://doi.org/10.1007/s12517-020-06371-x> Published
- Khorasanipour, M., & Rashidi, S. (2020). Geochemical fractionation pattern and environmental behaviour of rare earth elements (REEs) in mine wastes and mining contaminated sediments; Sarcheshmeh mine, SE of Iran. *Journal of Geochemical Exploration*, 210, 106450. <https://doi.org/10.1016/j.gexplo.2019.106450>

- Kikawada, Y., Oi, T., Honda, T., Oosaka, T., & Kakihana, H. (1993). Lanthanoid abundances of acidic hot spring and crater lake waters in the Kusatsu-shirane volcano region, Japan. *Geochemical Journal*, 27, 19–33.
- Klaver, G., Verheul, M., Bakker, I., Petelet-Giraud, E., & Négrel, P. (2014). Anthropogenic Rare Earth Element in rivers: GADOLINIUM and lanthanum. Partitioning between the dissolved and particulate phases in the Rhine River and spatial propagation through the Rhine-Meuse Delta (the Netherlands). *Applied Geochemistry*, 47, 186–197. <https://doi.org/10.1016/j.apgeochem.2014.05.020>
- Klinkhammer, G., Elderfield, H., & Hudson, A. (1983). Rare earth elements in seawater near hydrothermal vents. *Nature*, 305, 185–188.
- Klinkhammer, G., German, C. R., Elderfield, H., Greaves, M. J., & Mitra, A. (1994). Rare earth elements in hydrothermal fluids and plume particulates by inductively coupled plasma mass spectrometry. *Marine Chemistry*, 45, 179–186.
- Knappe, A., Möller, P., Dulski, P., & Pekdeger, A. (2005). Positive gadolinium anomaly in surface water and ground water of the urban area Berlin, Germany. *Chemosphere*, 65, 167–189. <https://doi.org/10.1016/j.chemer.2004.08.004>
- Kulaksiz, S., & Bau, M. (2007). Contrasting behaviour of anthropogenic gadolinium and natural rare earth elements in estuaries and the gadolinium input into the North Sea. *Earth and Planetary Science Letters*, 260, 361–371. <https://doi.org/10.1016/j.epsl.2007.06.016>
- Kulaksiz, S., & Bau, M. (2011). Rare earth elements in the Rhine river, Germany: First case of anthropogenic lanthanum as a dissolved microcontaminant in the hydrosphere. *Environment International*, 37, 973–979. <https://doi.org/10.1016/j.envint.2011.02.018>
- Kulaksiz, S., & Bau, M. (2013). Anthropogenic dissolved and colloid/nanoparticle-bound samarium, lanthanum and gadolinium in the Rhine River and the impending destruction of the natural rare earth element distribution in rivers. *Earth and Planetary Science Letters*, 362, 3–5. <https://doi.org/10.1016/j.epsl.2012.11.033>
- Kumar, K., Saion, E., Halimah, M. K., Yan, C. K., & Hamzah, M. S. (2014). Rare earth element (REE) in surface mangrove sediment by instrumental neutron activation analysis. *Journal of Radioanalytical and Nuclear Chemistry*, 301, 667–676. <https://doi.org/10.1007/s10967-014-3221-z>
- Lagarde, M., Lemaitre, N., Planquette, H., Grenier, M., Belhadj, M., Lherminier, P., & Jeandel, C. (2020). Particulate rare earth element behavior in the North Atlantic (GEOVIDE cruise). *Biogeosciences*, 17, 5539–5561. <https://doi.org/10.5194/bg-17-5539-2020>
- Larkin, C. S., Piotrowski, A. M., Mindhaw, R. S., Bayon, G., Hilton, R. G., Baronas, J. J., Dellinger, M., Wang, R., & Tipper, E. T. (2021). Constraints on the source of reactive phases in sediment from a major Arctic river using neodymium isotopes. *Earth and Planetary Science Letters*, 565, 116933. <https://doi.org/10.1016/j.epsl.2021.116933>
- Larsen, W., Liu, X. M., & Riveros-Iregui, D. A. (2021). Rare earth element behavior in springs and streams on a basaltic island: San Cristóbal, Galápagos. *Applied Geochemistry*, 131, 105004. <https://doi.org/10.1016/j.apgeochem.2021.105004>
- Lawrence, M. G. (2010). Detection of anthropogenic gadolinium in the Brisbane River plume in Moreton Bay, Queensland, Australia. *Marine Pollution Bulletin*, 60, 1113–1116. <https://doi.org/10.1016/j.marpolbul.2010.03.027>
- Lawrence, M. G., & Kamber, B. S. (2006). The behaviour of the rare earth elements during estuarine mixing-revisited. *Marine Chemistry*, 100, 147–161. <https://doi.org/10.1016/j.marchem.2005.11.007>
- Lawrence, M. G., Greig, A., Collerson, K. D., & Kamber, B. S. (2006b). Rare earth element and yttrium variability in South East Queensland waterways. *Aquatic Geochemistry*, 12, 39–72. <https://doi.org/10.1007/s10498-005-4471-8>

- Lawrence, M. G., Jupiter, S. D., & Kamber, B. S. (2006a). Aquatic geochemistry of the rare earth elements and yttrium in the Pioneer River catchment, Australia. *Marine and Freshwater Research*, 57, 725–736. <https://doi.org/10.1071/MF05229>
- Le Croizier, G., Lacroix, C., Artigaud, S., Le Floch, S., Munaron, J.-M., Raffray, J., Penicaud, V., Rouget, M.-L., Laë, R., & Luis, T. de M. (2019). Metal subcellular partitioning determines excretion pathways and sensitivity to cadmium toxicity in two marine fish species. *Chemosphere*, 217, 754–762. <https://doi.org/10.1016/j.chemosphere.2018.10.212>
- Le Goff, S., Barrat, J. A., Chauvaud, L., Paulet, Y. M., Gueguen, B., & Ben Salem, D. (2019). Compound-specific recording of gadolinium pollution in coastal waters by great scallops. *Scientific Reports*, 9, 8015. <https://doi.org/10.1038/s41598-019-44539-y>
- Lecomte, K. L., Sarmiento, A. M., Borrego, J., & Nieto, J. M. (2017). Rare earth elements mobility processes in an AMD-affected estuary: Huelva Estuary (SW Spain). *Marine Pollution Bulletin*, 121, 282–291. <https://doi.org/10.1016/j.marpolbul.2017.06.030>
- Lei, Z., Xu, H., Jiang, T., & Yan, D. (2021). In-situ major and rare earth elements constraint on the growth mechanism of calcite cement in shallow marine sandstone: An example from the Donghe sandstones, Tabei uplift, Tarim Basin, NW China. *Marine and Petroleum Geology*, 134, 105325. <https://doi.org/10.1016/j.marpetgeo.2021.105325>
- Lerat-Hardy, A., Coynel, A., Dutruch, L., Pereto, C., Bossy, C., Gu Diaz, T., Capdeville, M. J., Blanc, G., & Schäfer, J. (2019). Rare Earth Element fluxes over 15 years in a major European Estuary (Garonne-Gironde, SW France): Hospital effluents as a source of increasing gadolinium anomalies. *Science of the Total Environment*, 656, 409–420. <https://doi.org/10.1016/j.scitotenv.2018.11.343>
- Lerat-Hardy, A., Coynel, A., Schäfer, J., Marache, A., Pereto, C., Bossy, C., Capdeville, M. J., & Granger, D. (2021). Impacts of Highway Runoff on Metal Contamination Including Rare Earth Elements in a Small Urban Watershed: Case Study of Bordeaux Metropole (SW France). *Archives of Environmental Contamination and Toxicology*. <https://doi.org/10.1007/s00244-021-00815-4>
- Leybourne, M. I., Goodfellow, W. D., Boyle, D. R., & Hall, G. M. (2000). Rapid development of negative Ce anomalies in surface waters and contrasting REE patterns in groundwaters associated with Zn±Pb massive sulphide deposits. *Applied Geochemistry*, 15, 705–723.
- Li, C. S., Shi, X. F., Kao, S. J., Liu, Y. C., Lyu, H. H., Zou, J. J., Liu, S. F., & Qiao, S. Q. (2013). Rare earth elements in fine-grained sediments of major rivers from the high-standing island of Taiwan. *Journal of Asian Earth Sciences*, 69, 39–47. <https://doi.org/10.1016/j.jseaes.2013.03.001>
- Li, J. X., Zheng, L., Sun, C., Jiang, F. H., Yin, X. F., Chen, J. H., Han, B., & Wang, X. R. (2016). Study on Ecological and Chemical Properties of Rare Earth Elements in Tropical Marine Organisms. *Chinese Journal of Analytical Chemistry*, 44(10), 1539–1546. [https://doi.org/10.1016/S1872-2040\(16\)60963-5](https://doi.org/10.1016/S1872-2040(16)60963-5)
- Li, J., Sun, C., Jiang, F., Gao, F., & Zheng, Y. (2021). Distribution pattern and geochemical analysis of rare earth elements in deep-ocean sediments. *Journal of Oceanology and Limnology*, 39, 79–88. <https://doi.org/10.1007/s00343-020-9249-8>
- Liu, H., Li, L., Wang, X., Ren, Y., & Shi, X. (2021). Determination of Rare Earth Elements in Pore Water Samples of Marine Sediments Using an Offline Preconcentration Method. *Archives of Environmental Contamination and Toxicology*, 81, 553–563. <https://doi.org/10.1007/s00244-020-00793-0>
- Liu, S., Zhang, H., Zhu, A., Wang, K., Chen, M. Te, Khokiattiwong, S., Kornkanitnan, N., & Shi, X. (2019). Distribution of rare earth elements in surface sediments of the western Gulf of Thailand: Constraints from sedimentology and mineralogy. *Quaternary International*, 527, 52–63. <https://doi.org/10.1016/j.quaint.2018.08.010>
- López-González, N., Borrego, J., Carro, B., Grande, J., de la Torre, M., & Valente, T. (2012). Rare-earth-element fractionation patterns in estuarine sediments as a consequence of acid mine drainage: A case study in SW Spain. *Boletín Geológico y Minero*, 123(1), 55–64.

- Louis, P., Messaoudene, A., Jrad, H., Abdoul-Hamid, B. A., Vignati, D. A. L., & Pons, M. N. (2020). Understanding Rare Earth Elements concentrations, anomalies and fluxes at the river basin scale: The Moselle River (France) as a case study. *Science of the Total Environment*, 742, 140619. <https://doi.org/10.1016/j.scitotenv.2020.140619>
- Lu, B., Qiu, Z., Zhang, B. H., Li, J., & Tao, H. F. (2020). Geological significance of rare earth elements in marine shale during the Late Ordovician–Early Silurian in Sichuan Basin, South China. *Geological Journal*, 1–20. <https://doi.org/10.1002/gj.4027>
- Ludden, J. N., & Thompson, G. (1979). An evaluation of the behavior of the rare earth elements during the weathering of sea-floor basalt. *Earth and Planetary Science Letters*, 43, 85–92.
- Luk, E., Jensen, L. T., & Culotta, V. C. (2003). The many highways for intracellular trafficking of metals. *Journal of Biology Inorganic and Chemistry*, 8, 803–809. <https://doi.org/10.1007/s00775-003-0482-3>
- Luo, Y., Li, G., Xu, W., Liu, J., Cheng, J., Zhao, J., & Yan, W. (2021). The effect of diagenesis on rare earth element geochemistry of the Quaternary carbonates at an isolated coral atoll in the South China Sea. *Sedimentary Geology*, 420, 105933. <https://doi.org/10.1016/j.sedgeo.2021.105933>
- Ma, L., Dang, D. H., Wang, W., Evans, R. D., & Wang, W. X. (2019). Rare earth elements in the Pearl River Delta of China: Potential impacts of the REE industry on water, suspended particles and oysters. *Environmental Pollution*, 244, 190–201. <https://doi.org/10.1016/j.envpol.2018.10.015>
- MacMillan, G. A., Chételat, J., Heath, J. P., Mickpegak, R., & Amyot, M. (2017). Rare earth elements in freshwater, marine, and terrestrial ecosystems in the eastern Canadian Arctic. *Environmental Science: Processes and Impacts*, 19(10), 1336–1345. <https://doi.org/10.1039/c7em00082k>
- Manoj, M. C., Thakur, B., & Uddandam, P. R. (2021). Controls on rare earth elements distribution from Kerala coast, southwest India over the past 2000 years. *Environmental Forensics*. <https://doi.org/10.1080/15275922.2021.1940383>
- Martin, E. E., Blair, S. W., Kamenov, G. D., Scher, J. D., Bourbon, E., Basak, C., & Newkirk, D. N. (2010). Extraction of Nd isotopes from bulk deep sea sediments for paleoceanographic studies on Cenozoic time scales. *Chemical Geology*, 269, 414–431. <https://doi.org/10.1016/j.chemgeo.2009.10.016>
- Martinez-finley, E. J., Chakraborty, S., Freeman, S. J. B., & Aschner, M. (2012). Cellular transport and homeostasis of essential and nonessential metals. *Metallomics*, 4, 593–605. <https://doi.org/10.1039/c2mt00185c>
- Mashitah, S. M., Shazili, N. A. M., & Kashid, M. K. A. (2012). Elemental concentrations in Brown Seaweed, *Padina* sp. along the east coast of Peninsular Malaysia. *Aquatic Ecosystem Health and Management*, 15, 267–278. <https://doi.org/10.1080/1634988.2012.705774>
- Masuda, A. (1975). Abundances of monoisotopic REE, consistent with the Leedy chondrite values. *Geochemical Journal*, 9, 183–184. <https://doi.org/10.2343/geochemj.9.183>
- Masuda, A., Nakamura, N., & Tanaka, T. (1973). Fine structures of mutually normalized rare-earth patterns of chondrites. *Geochimica et Cosmochimica Acta*, 37, 239–248. [https://doi.org/10.1016/0016-7037\(73\)90131-2](https://doi.org/10.1016/0016-7037(73)90131-2)
- Masuzawa, T., & Koyama, M. (1989). Settling particles with positive Ce anomalies from the Japan sea. *Geophysical Research Letters*, 16(6), 503–506.
- McLennan, S. M., & Taylor, S. R. (1984). Archaean Sedimentary Rocks and Their Relation to the Composition of the Archaean Continental Crust. *Archaean Geochemistry*, 47–72. https://doi.org/10.1007/978-3-642-70001-9_3
- McLennan, S.M. (1989). Rare earth elements in sedimentary rocks: influence of provenance and sedimentary processes. In: Lipin, B.R., McKay, G.A. (Eds.), *Geochemistry and Mineralogy of Rare Earth Elements, Reviews in Mineralogy*, vol. 21. Mineral. Soc. Am, Washington, pp. 169 – 200.
- Mehmood, M. (2018). Rare Earth Elements - A Review. *Journal of Ecology & Natural Resources*, 2(2). <https://doi.org/10.23880/JENR-16000128>

- Merschel, G., & Bau, M. (2015). Rare earth elements in the aragonitic shell of freshwater mussel *Corbicula fluminea* and the bioavailability of anthropogenic lanthanum, samarium and gadolinium in river water. *Science of the Total Environment*, 533, 91–101. <https://doi.org/10.1016/j.scitotenv.2015.06.042>
- Merschel, G., Bau, M., Baldewein, L., Dantas, E. L., Walde, D., & Böhn, B. (2015). Tracing and tracking wastewater-derived substances in freshwater lakes and reservoirs: Anthropogenic gadolinium and geogenic REEs in Lake Paranoá, Brasilia. *Comptes Rendus - Geoscience*, 347, 284–293. <https://doi.org/10.1016/j.crte.2015.01.004>
- Minami, E. (1935). Gehalte an seltenen Erden in europäischen und japanischen Tonschiefern. *Nach. Ges. Wiss. Goettingen* 1, 155–170 2, Math-Physik KL.IV.
- Mitra, A., Elderfield, H., & Greaves, M. J. (1994). Rare earth elements in submarine hydrothermal fluids and plumes from the Mid-Atlantic Ridge. *Marine Chemistry*, 46, 217–235.
- Mohammad, A. M. (2021). Rare earth elements geochemistry of recent clastic sediments from different environments from part of the eastern coast of India. *Journal of Sedimentary Environments*, 6, 431–445. <https://doi.org/10.1007/s43217-021-00071-6>
- Möller, P., Dulski, P., & Luck, J. (1992). Determination of rare earth elements in seawater by inductively coupled plasma-mass spectrometry. *Spectrochimica Acta*, 47B(12), 1379–1387.
- Möller, P., Dulski, P., Bau, M., Knappe, A., Pekdeger, A., & Sommer-Von Jarmersted, C. (2000). Anthropogenic gadolinium as a conservative tracer in hydrology. *Journal of Geochemical Exploration*, 69–70, 409–414. www.elsevier.nl/locate/jgeoexp
- Möller, P., Morteani, G., & Dulski, P. (2003). Anomalous Gadolinium, Cerium, and Yttrium contents in the Adige and Isarco River waters and in the water of their tributaries (Provinces Trento and Bolzano/Bozen, NE Italy). *Acta Hydrochimica et Hydrobiologica*, 31(3), 225–239. <https://doi.org/10.1002/ahch.200300492>
- Möller, P., Paces, T., Dulski, P., & Morteani, G. (2002). Anthropogenic Gd in surface water, drainage system, and the water supply of the City of Prague, Czech Republic. *Environmental Science and Technology*, 36(11), 2387–2394. <https://doi.org/10.1021/es010235q>
- Mouchi, V., Godbillot, C., Forest, V., Uliakov, M., Lartaud, F., De Rafélis, M., Emmanuel, L., & Verrecchia, E. P. (2020). Rare earth elements in cystic shells: Provenance discrimination and potential vital effects. *Biogeosciences*, 17, 2205–2217. <https://doi.org/10.5194/bg-17-2205-2020>
- Munemoto, T., Solongo, T., Okuyama, A., Fukushi, K., Yunden, A., Batbold, T., Altansukh, O., Takahashi, Y., Iwai, H., & Nagao, S. (2020). Rare earth element distributions in rivers and sediments from the Erdenet Cu–Mo mining area, Mongolia. *Applied Geochemistry*, 123, 104800. <https://doi.org/10.1016/j.apgeochem.2020.104800>
- Murray, R. W., Buchholtz, J., Brink, M. R., Brumsack, H. J., Gerlach, D. C., & PRICE Russ, G. (1991). Rare earth elements in Japan Sea sediments and diagenetic behavior of Ce/Ce*: Results from ODP Leg 127. *Geochimica et Cosmochimica Acta*, 55, 2453–2466.
- Nakamura, H., Chiba, K., Chang Q, Nakai S, Kazahaya, K., & Iwamori, H. (2015). Rare earth elements of the Arima spring waters, southwest Japan: Implications for fluid–crust interaction during ascent of deep brine. *Geology & Geophysics*, 4(5). <https://doi.org/10.4172/jgg.1000217>
- Nakamura, H., Chiba, K., Chang, Q., Morikawa, N., Kazahaya, K., & Iwamori, H. (2016). Origin of the Arima-type and Associated Spring Waters in the Kinki District, Southwest Japan. *Journal of Geology & Geosciences*, 5(2). <https://doi.org/10.4172/2329-6755.1000240>
- Nance, W. B., & Taylor, S. R. (1976). Rare earth element patterns and crustal evolution-I. Australian post-Archean sedimentary rocks. *Geochimica et Cosmochimica Acta*, 40, 1539–1551.
- Nath, B. N., Balaram, V., Sudhakar, M., & Plüger, W. L. (1992a). Rare earth element geochemistry of ferromanganese deposits from the Indian Ocean. *Marine Chemistry*, 38, 185–208.
- Nath, B. N., Roelandts, I., Sudhakar, M., & Plüger, W. L. (1992b). Rare earth element patterns of the central Indian basin sediments related to their lithology. *Geophysical Research Letters*, 19(12), 1197–1200.

- Ndjigui, P. D., Bassanak Ongboye, P. R., & Ndong Bidzang, F. (2021). TiO₂-Zr-Th-Y-rare-earth elements ore deposit in unconsolidated fine-grained sediments from Tongo Gandima in the Bétaré Oya Gold district, Eastern Cameroon. *Geological Journal*, 1–23. <https://doi.org/10.1002/gj.4061>
- Noack, C. W., Dzombak, D. A., & Karamalidis, A. K. (2014). Rare earth element distributions and trends in natural waters with a focus on groundwater. *Environmental Science and Technology*, 48, 4317–4326. <https://doi.org/10.1021/es4053895>
- Nozaki, Y., Alibo, D.-S., Amakawa, H., Gamo, T., & Hasumoto, H. (1999). Dissolved rare earth elements and hydrography in the Sulu Sea. *Geochimica et Cosmochimica Acta*, 63(15), 2171–2181.
- Nozaki, Y., Lerche, D., Alibo, D. S., & Tsutsumi, M. (2000). Dissolved indium and rare earth elements in three Japanese rivers and Tokyo Bay: Evidence for anthropogenic Gd and In. *Geochimica et Cosmochimica Acta*, 64(23), 3975–3982.
- Olmez, I., Sholkovtzt, E. R., Hermann, D., & Eganhouse, R. P. (1991). Rare Earth Elements in Sediments off Southern California: A New Anthropogenic Indicator. *Environ. Sci. Technol*, 25, 310–316. <https://pubs.acs.org/sharingguidelines>
- Otsuka, M., & Terakado, Y. (2003). Rare earth element abundances in high phosphorus and low iron groundwaters from the Nishinomiya district, Japan: Variations in Ce anomaly, redox state and heavy rare earth enrichment. *Geochemical Journal*, 37, 1–19.
- Overare, B., Azmy, K., Garzanti, E., Osokpor, J., Ogbe, O. B., & Avwenagha, E. O. (2021). Decrypting geochemical signatures in subsurface Niger delta sediments: Implication for provenance, weathering, and paleo-environmental conditions. *Marine and Petroleum Geology*, 126, 104879. <https://doi.org/10.1016/j.marpetgeo.2020.104879>
- Ozaki, T., Enomoto, S., Minai, Y., Ambe, S., Ambe, F., & Makide, Y. (2000). Beneficial Effect of Rare Earth Elements on the Growth of *Dryopteris F. thymosora*. *Journal of Plant Physiology*, 156, 330–334. [https://doi.org/10.1016/S0176-1617\(00\)80070-X](https://doi.org/10.1016/S0176-1617(00)80070-X)
- Paffrath, R., Pahnke, K., Behrens, M. K., Reckhardt, A., Ehlert, C., Schnetger, B., & Brumsack, H. J. (2020). Rare Earth Element Behavior in a Sandy Subterranean Estuary of the Southern North Sea. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00424>
- Paffrath, R., Pahnke, K., Böning, P., Rutgers van der Loeff, M., Valk, O., Gdaniec, S., & Planquette, H. (2021). Seawater-Particle Interactions of Rare Earth Elements and Neodymium Isotopes in the Deep Central Arctic Ocean. *Journal of Geophysical Research: Oceans*, 126(8). <https://doi.org/10.1029/2021JC017423>
- Palmer, M. R. (1985). Rare earth elements in foraminifera tests. *Earth and Planetary Science Letters*, 73, 285–298.
- Pastorino, P., Brizio, P., Abete, M. C., Bertoli, M., Oss Noser, A. G., Piazza, G., Prearo, M., Elia, A. C., Pizzul, E., & Squadrone, S. (2020). Macrobenthic invertebrates as tracers of rare earth elements in freshwater watercourses. *Science of the Total Environment*, 698, 134282. <https://doi.org/10.1016/j.scitotenv.2019.134282>
- Peng, X., Feng, C., & Guo, L. (2021). Sedimentary geochemistry of the Weihe River sediments, Central China: implications for provenance and weathering. *Arabian Journal of Geosciences*, 14, 604. <https://doi.org/10.1007/s12517-021-06888-9>
- Pereto, C., Coynel, A., Lerat-Hardy, A., Gourves, P. Y., Schäfer, J., & Baudrimont, M. (2020). Corbicula fluminea: A sentinel species for urban Rare Earth Element origin. *Science of the Total Environment*, 732, 138552. <https://doi.org/10.1016/j.scitotenv.2020.138552>
- Perrat, E., Parant, M., Py, J., Rosin, C., & Cossu-leguille, C. (2017). Bioaccumulation of gadolinium in freshwater bivalves. *Environ. Sci. Pollut. Res.*, 24, 12405–12415. <https://doi.org/10.1007/s11356-017-8869-9>
- Petelet-Giraud, E., Klaver, G., & Negrel, P. (2009). Natural versus anthropogenic sources in the surface- and groundwater dissolved load of the Dommel river (Meuse basin): Constraints by boron and strontium isotopes and gadolinium anomaly. *Journal of Hydrology*, 369, 336–349. <https://doi.org/10.1016/j.jhydrol.2009.02.029>

- Picone, M., Distefano, G. G., Corami, F., Franzoi, P., Redolfi Bristol, S., Basso, M., Panzarin, L., & Volpi Ghirardini, A. (2022). Occurrence of rare earth elements in fledgelings of *Thalasseus sandvicensis*. *Environmental Research*, 204, 112152. <https://doi.org/10.1016/j.envres.2021.112152>
- Piepgas, D. J., & Jacobsen, S. B. (1992). The behavior of rare earth elements in seawater: Precise determination of variations in the North Pacific water column. *Geochimica et Cosmochimica Acta*, 56, 1851–1862.
- Pignotti, E., Dinelli, E., & Birke, M. (2017). Geochemical characterization and rare earth elements anomalies in surface- and groundwaters of the Romagna area (Italy). *Rend. Fis. Acc. Lincei*, 28, 265–279. <https://doi.org/10.1007/s12210-016-0561-3>
- Piper, D. Z. (1974). Rare earth elements in the sedimentary cycle: A summary. *Chemical Geology*, 14, 285–304. [https://doi.org/10.1016/0009-2541\(74\)90066-7](https://doi.org/10.1016/0009-2541(74)90066-7)
- Piper, D. Z., & Bau, M. (2013). Normalized Rare Earth Elements in Water, Sediments, and Wine : Identifying Sources and Environmental Redox Conditions. *American Journal of Analytical Chemistry*, 4, 69–83.
- Piper, D. Z., & Graef, P. A. (1974). Rare-earth elements in sediments from the east pacific rise. *Marine Geology*, 17, 287–297.
- Piper, D. Z., Baedeker, P. A., Crock, J. G., Burnett, W. C., & Loebner, L. J. (1988). Rare earth elements in the phosphatic-enriched sediment of the peru shelf. *Marine Geology*, 80, 279–285.
- Ponnurangam, A., Bau, M., Brenner, M., & Koschinsky, A. (2015). Mussel shells of *Mytilus edulis* as bioarchives of the rare earth elements and yttrium distribution in seawater and the potential impact of pH and temperature on the partitioning behaviour. *Biogeosciences Discussions*, 12, 14911–14939. <https://doi.org/10.5194/bgd-12-14911-2015>
- Ponnurangam, A., Bau, M., Brenner, M., & Koschinsky, A. (2016). Mussel shells of *Mytilus edulis* as bioarchives of the distribution of rare earth elements and yttrium in seawater and the potential impact of pH and temperature on their partitioning behavior. *Biogeosciences*, 13, 751–760. <https://doi.org/10.5194/bg-13-751-2016>
- Pourmand, A., Dauphas, N., & Ireland, T. R. (2012). A novel extraction chromatography and MC-ICP-MS technique for rapid analysis of REE, Sc and Y: Revising CI-chondrite and Post-Archean Australian Shale (PAAS) abundances. *Chemical Geology*, 271, 58–54. <https://doi.org/10.1016/j.chemgeo.2011.08.011>
- Qiang, T., Xiao-rong, W., Li-qing, T., & Le-mei, D. (1994). Bioaccumulation of the rare earth elements lanthanum, gadolinium and yttrium in carp (*Cyprinus carpio*). *Environmental Pollution*, 85, 345–350. [https://doi.org/10.1016/0269-7491\(94\)00057-4](https://doi.org/10.1016/0269-7491(94)00057-4)
- Quinn, K. A., Byrne, R. H., & Schijf, J. (2004). Comparative Scavenging of Yttrium and the Rare Earth Elements in Seawater: Competitive Influences of Solution and Surface Chemistry. *Aquatic Geochemistry*, 10, 59–80.
- Rabiet, M., Brissaud, F., Seidel, J. L., Pistre, S., & Elbaz-Poulichet, F. (2005). Deciphering the presence of wastewater in a medium-sized Mediterranean catchment using a multitracer approach. *Applied Geochemistry*, 20, 1587–1596. <https://doi.org/10.1016/j.apgeochem.2005.04.005>
- Rabiet, M., Brissaud, F., Seidel, J. L., Pistre, S., & Elbaz-Poulichet, F. (2009). Positive gadolinium anomalies in wastewater treatment plant effluents and aquatic environment in the Hérault watershed (South France). *Chemosphere*, 75, 1057–1064. <https://doi.org/10.1016/j.chemosphere.2009.01.036>
- Rabiet, M., Togola, A., Brissaud, F., Seidel, J. L., Budzinski, H., & Elbaz-Poulichet, F. (2006). Consequences of treated water recycling as regards pharmaceuticals and drugs in surface and ground waters of a medium-sized mediterranean catchment. *Environmental Science and Technology*, 40, 5282–5288. <https://doi.org/10.1021/es060528p>
- Rahlf, P., Laukert, G., Hathorne, E. C., Vieira, L. H., & Frank, M. (2021). Dissolved neodymium and hafnium isotopes and rare earth elements in the Congo River Plume: Tracing and quantifying continental inputs into the southeast Atlantic. *Geochimica et Cosmochimica Acta*, 294, 192–214. <https://doi.org/10.1016/j.gca.2020.11.017>

- Ramos-Vázquez, M. A., & Armstrong-Altrin, J. S. (2021). Provenance of sediments from Barra del Tordo and Tesoro beaches, Tamaulipas State, northwestern Gulf of Mexico. *Journal of Palaeogeography*, 10, 20. <https://doi.org/10.1186/s42501-021-00101-4>
- Ren, J., Liu, Y., Wang, F., He, G., Deng, X., Wei, Z., & Yao, H. (2021). Mechanism and influencing factors of REY enrichment in deep-sea sediments. *Minerals*, 11, 196. <https://doi.org/10.3390/min11020196>
- Rezaee, K., Saion, E. B., Wood, A. K., & Abdi, M. R. (2009). Rare earth elements distribution in marine sediments of Malaysia coasts. *Journal of Rare Earths*, 27(6), 1066–1071.
- Rezaee, K., Saion, E. B., Wood, A. K., & Abdi, M. R. (2010). Rare earth elements determination and distribution patterns in surface marine sediments of the South China Sea by INAA, Malaysia. *Journal of Radioanalytical and Nuclear Chemistry*, 283, 823–829. <https://doi.org/10.1007/s10967-009-0421-z>
- Rudnick, R. L., & S. Gao. (2003). 3.01 Composition of the Continental Crust. In *The Crust*.
- Ruhlin, D. E., & Owen, R. M. (1986). The rare earth element geochemistry of hydrothermal sediments from the East Pacific Rise: Examination of a seawater scavenging mechanism. *Geochimica et Cosmochimica Acta*, 50, 393–400.
- Saha, N., Webb, G. E., Zhao, J. X., Lewis, S. E., Duc Nguyen, A., & Ren, Y. (2021). Spatiotemporal variation of rare earth elements from river to reef continuum aids monitoring of terrigenous sources in the Great Barrier Reef. *Geochimica et Cosmochimica Acta*, 299, 85–112. <https://doi.org/10.1016/j.gca.2021.02.014>
- Sakamoto, N., Kano, N., & Imaizumi, H. (2008). Biosorption of uranium and rare earth elements using biomass of algae. *Bioinorganic Chemistry and Applications*, 2008, 8. <https://doi.org/10.1155/2008/706240>
- Sanders, L. M., Luiz-Silva, W., Machado, W., Sanders, J. J., Marotta, H., Enrich-Prast, A., Bosco-Santos, A., Boden, A., Silva-Filho, E. V., Santos, I. R., & Patchineelam, S. R. (2013). Rare earth element and radionuclide distribution in surface sediments along an estuarine system affected by fertilizer industry contamination. *Water, Air, and Soil Pollution*, 224. <https://doi.org/10.1007/s11270-013-1742-7>
- Sandu, M. C., Soroaga, L. V., Balaban, S. I., Chelariu, C., Chiscan, O., Iancu, G. O., Arsene, C., & Olariu, R. I. (2021). Trace elements distribution in stream sediments of an abandoned U mining site in the Eastern Carpathians, Romania, with particular focus on REEs. *Geochemistry*, 81, 125761. <https://doi.org/10.1016/j.chemer.2021.125761>
- Sasmaz, A., Zuddas, P., Cangemi, M., Piazzese, D., Ozek, G., Venturi, M., & Censi, P. (2021). Zirconium and hafnium fractionation and distribution of Rare Earth Elements in neutral–alkaline waters: Case study of Lake Van hydrothermal system, Turkey. *Journal of Geochemical Exploration*, 226, 106784. <https://doi.org/10.1016/j.gexp.2021.106784>
- Sawatari, H., Toda, T., Saizumi, T., Kimata, C., Itoh, A., & Haraguchi, H. (1995). Multielement determination of Rare Earth Elements in coastal seawater by Inductively coupled plasma mass spectrometry after preconcentration using chelating resin. *Bulletin of the Chemical Society of Japan*, 68, 3065–3070.
- Schmitt, R. A., Smith, R. H., Lasch, J. E., Mosen, A. W., Olehy, D. A., & Vasilevskis, J. (1963). Abundances of the fourteen rare-earth elements, scandium, and yttrium in meteoritic and terrestrial matter. *Geochimica et Cosmochimica Acta*, 27, 577–622. [https://doi.org/10.1016/0016-7037\(63\)90014-0](https://doi.org/10.1016/0016-7037(63)90014-0)
- Seo, H., & Kim, G. (2020). Rare earth elements in the East Sea (Japan Sea): Distributions, behaviors, and applications. *Geochimica et Cosmochimica Acta*, 286, 19–28. <https://doi.org/10.1016/j.gca.2020.07.016>
- Sergeeva, A., Zinicovscaia, I., Grozdov, D., & Yushin, N. (2021). Assessment of selected rare earth elements, HF, Th, and U in the Donetsk region using moss bags technique. *Atmospheric Pollution Research*, 12, 101165. <https://doi.org/10.1016/j.apr.2021.101165>
- Shen, X., Chai, M., Yang, F., Cao, Y., & Li, R. (2021). Occurrence and contamination of rare earth elements in urban mangroves of shenzhen, south china. *Sustainability*, 13, 2503. <https://doi.org/10.3390/su13052503>
- Sholkovitz, E. (1995). The Aquatic Chemistry of Rare Earth Elements in Rivers and Estuaries. *Aquatic Geochemistry*, 1, 1–34.

- Sholkovitz, E. R. (1988). Rare earth elements in the sediments of the north atlantic ocean, amazon delta, and east china sea: reinterpretation of terrigenous input patterns to the oceans. *American Journal of Science*, 288, 236–281.
- Sholkovitz, E. R. (1990). Rare-earth elements in marine sediments and geochemical standards*. *Chemical Geology*, 88, 333–347.
- Sholkovitz, E. R. (1992). Chemical evolution of rare earth elements: fractionation between colloidal and solution phases of filtered river water. *Earth and Planetary Science Letters*, 114, 77–84.
- Sholkovitz, E. R. (1993). The geochemistry of rare earth elements in the Amazon River estuary. *Geochimica et Cosmochimica Acta*, 57, 2181–2190.
- Sholkovitz, E. R., & Schneider, D. L. (1991). Cerium redox cycles and rare earth elements in the Sargasso Sea. *Geochimica et Cosmochimica Acta*, 55, 2737–2743.
- Sholkovitz, E. R., Landing, W. M., & Lewis, B. L. (1994). Ocean particle chemistry: The fractionation of rare earth elements between suspended particles and seawater. *Geochimica et Cosmochimica Acta*, 58(6), 1567–1579.
- Sholkovitz, E. R., Piepgras, D. J., & Jacobsen, S. B. (1989). The pore water chemistry of rare earth elements in Buzzards Bay sediments. *Geochimica et Cosmochimica Acta*, 53, 2841–2846.
- Sholkovitz, E., & Shen, G. T. (1995). The incorporation of rare earth elements in modern coral. *Geochimica et Cosmochimica Acta*, 59(13), 2749–2756.
- Silva-Filho, E. V., Sanders, C. J., Bernat, M., Figueiredo, A. M. G., Sella, S. M., & Wasserman, J. (2011). Origin of rare earth element anomalies in mangrove sediments, Sertão da Bay, SE Brazil: Used as geochemical tracers of sediment sources. *Environmental Earth Sciences*, 64, 1257–1267. <https://doi.org/10.1007/s12665-011-0942-y>
- Singh, P., Yadav, J. K., Jigyasu, D. K., Singh, S., Kumar, N., Singh, I. B., & Singh, M. (2021). Biotite as a geoinicator of rare earth element contamination in Gomati River Basin, Ganga Alluvial Plain, northern India. *Environmental Monitoring and Assessment*, 123, 361. <https://doi.org/10.1007/s10661-021-09105-y>
- Smedley, P. L. (1991). The geochemistry of rare earth elements in groundwater from the Carnmenellis area, southwest England. *Geochimica et Cosmochimica Acta*, 55, 2167–2779.
- Sojka, M., Choiński, A., Ptak, M., & Siepak, M. (2021). Causes of variations of trace and rare earth elements concentration in lakes bottom sediments in the Bory Tucholskie National Park, Poland. *Scientific Reports*, 11, 244. <https://doi.org/10.1038/s41598-020-80137-z>
- Song, H., Shin, W. J., Ryu, J. S., Shin, H. S., Chung, H., & Lee, K. S. (2017). Anthropogenic rare earth elements and their spatial distributions in the Han River, South Korea. *Chemosphere*, 172, 155–165. <https://doi.org/10.1016/j.chemosphere.2016.12.135>
- Squadrone, S., Brizio, P., Battuello, M., Nurra, N., Sartor, R. M., Benedetto, A., Pessani, D., & Abete, M. C. (2017). A first report of rare earth elements in northwestern Mediterranean seaweeds. *Marine Pollution Bulletin*, 122, 236–242. <https://doi.org/10.1016/j.marpolbul.2017.06.048>
- Squadrone, S., Brizio, P., Stella, C., Favaro, L., Da Rugna, C., Florio, D., Gridelli, S., & Abete, M. C. (2019b). Feathers of Humboldt penguin are suitable bioindicators of Rare Earth Elements. *Science of the Total Environment*, 678, 627–631. <https://doi.org/10.1016/j.scitotenv.2019.05.032>
- Squadrone, S., Brizio, P., Stella, C., Mantia, M., Battuello, M., Nurra, N., Sartor, R. M., Orusa, R., Robetto, S., Brusa, F., Mogliotti, P., Garrone, A., & Abete, M. C. (2019). Rare earth elements in marine and terrestrial matrices of Northwestern Italy: Implications for food safety and human health. *Science of the Total Environment*, 660, 1383–1391. <https://doi.org/10.1016/j.scitotenv.2019.01.112>
- Strady, E., Kim, I., Radakovitch, O., & Kim, G. (2015). Rare earth element distributions and fractionation in plankton from the northwestern Mediterranean Sea. *Chemosphere*, 119, 72–82. <https://doi.org/10.1016/j.chemosphere.2014.05.049>

- Strauch, G., Möder, M., Wennrich, R., Osenbrück, K., Gläser, H. R., Schladitz, T., Müller, C., Schirmer, K., Reinstorf, F., & Schirmer, M. (2008). Indicators for assessing anthropogenic impact on urban surface and groundwater. *Journal of Soils and Sediments*, 8(1), 23–33. <https://doi.org/10.1065/jss2007.06.234>
- Sultan, K., & Shazili, N. A. (2009). Rare earth elements in tropical surface water, soil and sediments of the Terengganu River Basin, Malaysia. *Journal of Rare Earths*, 27(6), 1072–1078. [https://doi.org/10.1016/S1002-0721\(08\)60391-9](https://doi.org/10.1016/S1002-0721(08)60391-9)
- Sun, S. S., & McDonough, W. F. (1989). Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes. *Geological Society Special Publication*, 42, 313–345. <https://doi.org/10.1144/GSL.SP.1989.042.01.19>
- Tang, S., Zheng, C., Chen, M., Du, W., & Xu, X. (2020). Geobiochemistry characteristics of rare earth elements in soil and ground water: a case study in Baotou, China. *Scientific Reports*, 10, 11740. <https://doi.org/10.1038/s41598-020-68661-4>
- Taylor, S. R., & McLennan, S. M. (1995). The geochemical the continental evolution crust. *Reviews of Geophysics*, 33(2), 241–265.
- Taylor, S., & McLennan, S.M. (1985). *The continental crust: its composition and evolution*. Oxford: Blackwell Scientific Publications, 312pp.
- Taylor, S.R., McLennan, S.M., 2002. Chemical composition and element distribution in the Earth's crust. In: *Encyclopedia of Physical Science and Technology*, vol. 2, third ed. Academic Press, New York, pp. 697–719
- Técher, D., Grosjean, N., Sohm, B., Blaudez, D., & Le Jean, M. (2020). Not merely noxious? Time-dependent hormesis and differential toxic effects systematically induced by rare earth elements in *Escherichia coli*. *Environmental Science and Pollution Research*, 27, 5640–5649. <https://doi.org/10.1007/s11356-019-07002-z>
- Tepe, N., & Bau, M. (2016). Behavior of rare earth elements and yttrium during simulation of arctic estuarine mixing between glacial-fed river waters and seawater and the impact of inorganic (nano-)particles. *Chemical Geology*, 438, 134–145. <https://doi.org/10.1016/j.chemgeo.2016.06.001>
- Thibault de Chanvalon, A., Metzger, E., Moret, A., Knoery, J., Chiffolleau, J. F., & Brach-Papa, C. (2016). Particles transformation in estuaries: Fe, Mn and REE signatures through the Loire Estuary. *Journal of Sea Research*, 118, 103–112. <https://doi.org/10.1016/j.seares.2016.11.004>
- Todorović, M., Ćuk Đurović, M., Štbački, J., & Papić, P. (2020). Rare earth elements in mineral waters in Serbia. *Environmental Earth Science*, 79, 290. <https://doi.org/10.1007/s12665-020-09029-9>
- Toyoda, K., & Tokonami, M. (1996). Diffusion of rare-earth elements in fish teeth from deep-sea sediment. In *Nature* (Vol. 345).
- Toyoda, K., Nakamura, Y., & Masuda, A. (1990). Rare earth elements of Pacific pelagic sediments. *Geochimica et Cosmochimica Acta*, 54, 1093–1103.
- Tranchida, G., Oliveri, E., Angelone, M., Bellanca, A., Censi, P., D'Elia, M., Neri, R., Placenti, F., Sprovieri, M., & Mazzola, S. (2011). Distribution of rare earth elements in marine sediments from the Strait of Sicily (western Mediterranean Sea): Evidence of phosphogypsum waste contamination. *Marine Pollution Bulletin*, 62, 182–191. <https://doi.org/10.1016/j.marpolbul.2010.11.003>
- Tricca, A., Stille, P., Steinmann, M., Kiefel, B., Samuel, J., & Eikenberg, J. (1999). Rare earth elements and Sr and Nd isotopic compositions of dissolved and suspended loads from small river systems in the Vosges mountains France , the river Rhine and groundwater. *Chemical Geology*, 160, 139–158.
- Trotter, J. A., Barnes, C. R., & McCracken, A. D. (2016). Rare earth elements in conodont apatite: Seawater or pore-water signatures? *Palaeogeography, Palaeoclimatology, Palaeoecology*, 462, 92–100. <https://doi.org/10.1016/j.palaeo.2016.09.007>
- Valdés-Vilchis, S., Sánchez-Beristain, F., Bernal, J. P., & Juárez-Aguilar, E. A. (2021). Rare Earth Elements and Yttrium (REE+Y) patterns in recent *Anadara brasiliana* shells from Playa Norte, Barra de Cazonos (Veracruz,

- Mexico): Evidence of anthropogenic contamination linked to river output? *Journal of South American Earth Sciences*, 110, 103368. <https://doi.org/10.1016/j.jsames.2021.103368>
- Verplanck, P. L., Taylor, H. E., Nordstrom, D. K., & Barber, L. B. (2005). Aqueous stability of gadolinium in surface waters receiving sewage treatment plant effluent Boulder Creek, Colorado. *Environmental Science and Technology*, 39(18), 6923–6929. <https://doi.org/10.1021/es048456u>
- Vinnarasi, F., Srinivasamoorthy, K., Saravanan, K., Gopinath, S., Prakash, R., Ponnumani, G., & Babu, C. (2020). Rare earth elements geochemistry of groundwater from Shanmuganadhi, Tamilnadu, India: Chemical weathering implications using geochemical mass-balance calculations. *Geochemistry*, 80, 125668. <https://doi.org/10.1016/j.chemer.2020.125668>
- Wang, Y. L., Liu, Y.-G., & Schmitt, R. A. (1986). Rare earth element geochemistry of South Atlantic deep sea sediments: Ce anomaly change at-54 My. *Geochimica et Cosmochimica Acta*, 50, 1337–1355.
- Wang, Z., Shu, J., Wang, Z., Qin, X., & Wang, S. (2022). Geochemical behavior and fractionation characteristics of rare earth elements (REEs) in riverine water profiles and sentinel Clam (*Corbicula fluminea*) across watershed scales: Insights for REEs monitoring. *Science of the Total Environment*, 803, 150090. <https://doi.org/10.1016/j.scitotenv.2021.150090>
- Wang, Z., Yin, L., Xiang, H., Qin, X., & Wang, S. (2019). Accumulation patterns and species-specific characteristics of yttrium and rare earth elements (YREEs) in biological matrices from Maluan Bay, China: Implications for biomonitoring. *Environmental Research*, 179. <https://doi.org/10.1016/j.envres.2019.108804>
- Wang, Z., Yin, L., Xiang, H., Qin, X., & Wang, S. (2019). Accumulation patterns and species-specific characteristics of yttrium and rare earth elements (YREEs) in biological matrices from Maluan Bay, China: Implications for biomonitoring. *Environmental Research*, 179, 108804. <https://doi.org/10.1016/j.envres.2019.108804>
- Wedepohl, K. H. (1995). The composition of the continental crust. *Geochimica et Cosmochimica Acta*, 59(7), 1217–1232.
- Workman, R. K., & Hart, S. R. (2005). Major and trace element composition of the depleted MORB mantle (DMM). *Earth and Planetary Science Letters*, 231, 53–72. <https://doi.org/10.1016/j.epsl.2004.12.005>
- Wyndham, T., McCulloch, M., Fallon, S., & Alibert, C. (2004). High-resolution coral records of rare earth elements in coastal seawater: Biogeochemical cycling and a new environmental proxy. *Geochimica et Cosmochimica Acta*, 68(9), 2067–2080. <https://doi.org/10.1016/j.gca.2003.11.004>
- Yang, K., Han, G., Zeng, J., & Zhou, W. (2021). Distribution, fractionation and sources of rare earth elements in suspended particulate matter in a tropical agricultural catchment, northeast Thailand. *PeerJ*, 9. <https://doi.org/10.7717/peerj.10850>
- Yang, L., Wang, X., Nie, H., Zhao, L., Wang, G., & Liu, Y. (2016). Residual levels of rare earth elements in freshwater and marine fish and their health risk assessment from Shandong, China. *Marine Pollution Bulletin*, 107, 393–397. <https://doi.org/10.1016/j.marpolbul.2016.03.034>
- Yu, M., Shi, X., Huang, M., Liu, J., Yan, Q., Yang, G., Li, C., Yang, B., Zhou, T., Bi, D., Wang, H., & Bai, Y. (2021b). The transfer of rare earth elements during early diagenesis in REY-rich sediments: An example from the Central Indian Ocean Basin. *Ore Geology Reviews*, 136, 104269. <https://doi.org/10.1016/j.oregeorev.2021.104269>
- Yu, Y., Lin, L., & Nan, H. (2021a). Trace and rare-earth element characteristics of fine-grained sediments in the Upper Triassic Xujiahe Formation in the western Sichuan Basin, SW China: implications for the provenance and depositional environment. *Carbonates and Evaporites*, 36, 8. <https://doi.org/10.1007/s13146-020-00670-w>
- Zhang, J., & Nozaki, Y. (1998). Behavior of rare earth elements in seawater at the ocean margin: A study along the slopes of the Sagami and Nankai troughs near Japan. *Geochimica et Cosmochimica Acta*, 62(8), 1307–1317.

- Zhang, J., Wang, Z., Wu, Q., An, Y., Jia, H., & Shen, Y. (2019). Anthropogenic rare earth elements: Gadolinium in a small catchment in Guizhou Province, Southwest China. *International Journal of Environmental Research and Public Health*, 16, 4052. <https://doi.org/10.3390/ijerph16204052>
- Zhang, X., Zhang, H., Chang, F., Xie, P., Li, H., Wu, H., Ouyang, C., Liu, F., Peng, W., Zhang, Y., Liu, Q., Duan, L., & Ashraf, U. (2021). Long-range transport of aeolian deposits during the last 32 kyr inferred from rare earth elements and grain-size analysis of sediments from Lake Lugu, Southwestern China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 567, 110248. <https://doi.org/10.1016/j.palaeo.2021.110248>
- Zhang, Y., Gao, X., & Arthur Chen, C. T. (2014). Rare earth elements in intertidal sediments of Bohai Bay, China: Concentration, fractionation and the influence of sediment texture. *Ecotoxicology and Environmental Safety*, 105, 72–79. <https://doi.org/10.1016/j.ecoenv.2014.04.006>
- Zhao, Z., Wang, H., & Zhao, Z. (2021). Fractionation and provenances of rare earth elements in coastal sediments in tropical China. *Journal of Coastal Conservation*, 25, 13. <https://doi.org/10.1007/s11852-021-00803-w/Published>
- Zhong, W., Yu, J., Ye, S., Tang, X., Wei, Z., Quan, M., & Li, T. (2021). Rare earth element geochemistry of lake sediments from the eastern Nanling Mountain area (South China) and its implication for East Asian monsoon related chemical weathering over the past ~47 000 years. *Boreas*, 50(4), 1179–1189. <https://doi.org/10.1111/bor.12533>
- Zhou X, Chen X, Fan Y, Lu X, & Chen X. (2021). Discussion on the sedimentary environment and provenance of surface sediment in Luoyuan Bay offshore of Fujian Province. *Quaternary Sciences*, 41(5), 1281–1293.
- Zhou, Y., Yang, X., Zhang, D., Mackenzie, L. L., & Chen, B. (2021). Sedimentological and geochemical characteristics of sediments and their potential correlations to the processes of desertification along the Keriya River in the Taklamakan Desert, western China. *Geomorphology*, 375, 107560. <https://doi.org/10.1016/j.geomorph.2020.107560>
- Zhu, Y., Hattori, R., Rahmi, D., Okuda, S., Itoh, A., Fujimori, E., Umemura, T., & Haraguchi, H. (2005). Fractional distributions of trace metals in surface water of Lake Biwa as studied by ultrafiltration and ICP-MS. *Bulletin of the Chemical Society of Japan*, 78, 1970–1976. <https://doi.org/10.1246/bcsj.78.1970>
- Zhu, Y., Hoshino, M., Yamada, H., Itoh, A., & Haraguchi, H. (2004). Gadolinium anomaly in the distributions of rare earth elements observed for coastal seawater and river waters around Nagoya city. *Bulletin of the Chemical Society of Japan*, 77, 1835–1842. <https://doi.org/10.1246/bcsj.77.1835>
- Zhu, Y., Nakano, K., Shikamori, Y., & Itoh, A. (2021). Direct determination of rare earth elements in natural water samples by inductively coupled plasma tandem quadrupole mass spectrometry with oxygen as the reaction gas for separating spectral interferences. *Spectrochimica Acta - Part B Atomic Spectroscopy*, 179, 106100. <https://doi.org/10.1016/j.sab.2021.106100>
- Zhu, Z., & Zheng, A. (2018). Fast determination of yttrium and rare earth elements in seawater by inductively coupled plasma-mass spectrometry after online flow injection pretreatment. *Molecules*, 23(2), 489. <https://doi.org/10.3390/molecules23020489>

Figures and tables :

Table 1. REE concentrations in different reference materials used for rare earth elements normalization.

Reference material	Study	REEs (ppm)														
		Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
PAAS	1	28	38	80	8.9	32	5.6	1.1	4.2	0.77	4.4	1	2.9	0.5	2.8	0.5
	2-3	27	38.2	79.6	8.83	33.9	5.55	1.08	4.66	0.774	4.68	0.991	2.85	0.405	2.82	0.433
	4	27	44.56	88.25	10.15	37.32	6.884	1.215	6.043	0.801	5.325	1.053	3.075	0.451	3.012	0.4386
NASC	5-6	27	32	70	7.9	31	5.7	1.24	5.21	0.85	5	1.04	3.4	0.5	3.1	0.48
	7	-	31.1	66.7	-	27.4	5.59	1.18	-	0.85	-	-	-	-	3.06	0.456
	2-3	27	32	73	7.9	33	5.7	1.24	5.2	0.85	5.8	1.04	3.4	0.5	3.1	0.48
	8	-	34	66.7	-	30.1	5.8	1.15	5.12	-	4.67	-	2.73	-	2.67	0.41
WSA	9	-	41	83	10.1	38	7.5	1.61	6.35	1.23	5.5	1.34	3.75	0.63	3.53	0.61
EUS	10	30	16	33	4.9	28	1.6	1.2	8.5	1	6.2	1.9	3.3	0.26	3.9	1.1
	6	31.8	41.1	81.3	10.4	40.1	7.3	1.52	6.03	1.05	-	1.2	3.55	0.56	3.29	0.58
	11	31.9	44.3	88.5	10.6	39.5	7.2	1.48	6.34	0.944	5.86	1.17	3.43	0.492	3.26	0.485
AS	12	-	20	42	4.9	21	4	1.2	3.4	0.57	3.4	0.74	2.1	0.3	2	0.31
Chondrite	13	-	0.378	0.976	-	0.710	0.23	0.0866	0.311	-	0.39	-	0.255	-	0.249	0.0387
	5-14-15''	1.9	0.32	0.9	0.13	0.57	0.21	0.074	0.31	0.051	0.3	0.074	0.21	0.032	0.18	0.032
	16	-	0.2446	0.6379	0.0963	0.4738	0.1540	0.05802	0.2043	0.03745	0.2541	0.0567	0.166	0.02561	0.1651	0.02539
	2	2.1	0.367	0.957	0.127	0.711	0.231	0.087	0.306	0.058	0.381	0.0851	0.249	0.0356	0.248	0.0381
	17	1.56	0.2347	0.6032	0.0891	0.4524	0.1471	0.056	0.1966	0.0363	0.2427	0.0556	0.1589	0.0242	0.1625	0.0243
	18	1.57	0.237	0.612	0.095	0.467	0.153	0.058	0.2055	0.0374	0.254	0.0566	0.1655	0.0255	0.17	0.0254
MUQ	19	31.85	32.51	71.09	8.46	32.91	6.88	1.57	6.36	0.99	5.89	1.22	3.37	0.51	3.25	0.49
UCC	2-20	22	30	64	7.1	26	4.5	0.88	3.8	0.64	3.5	0.8	2.3	0.33	2.2	0.32
	21	20.7	32.3	65.7	6.3	25.9	4.7	0.95	2.8	0.5	2.9	0.62	-	-	1.5	0.27
	22	21	31	63	7.1	27	4.7	1	4	0.7	3.9	0.83	2.3	0.3	2	0.31
MORB	18*	28	2.5	7.5	1.32	7.3	2.63	1.02	3.68	0.67	4.55	1.01	2.97	0.456	3.05	0.455
	18°	22	6.3	15	2.05	9	2.6	0.91	2.97	0.53	3.55	0.79	2.31	0.356	2.37	0.354
	23	32	3.7	11.5	1.8	10	3.3	1.3	4.6	0.87	5.7	1.3	3.7	0.54	3.7	0.56
DMM	24	3.328	0.192	0.550	0.107	0.581	0.239	0.096	0.358	0.070	0.505	0.115	0.348	-	0.365	0.058

WRAS	25	29.40	37.80	77.7	8.77	32.69	6.15	1.188	5.19	0.819	4.95	1.019	2.97	-	3.01	0.456
WRAC	25	29.84	44.61	89.2	9.69	35.6	6.70	1.383	5.37	0.831	4.87	0.980	2.78	-	2.72	0.406

1: Nance and Taylor 1976, 2: Taylor and McLennan 1985, 3: McLennan 1989, 4: Pourmand et al. 2012, 5: Haskin et al. 1966a, 6: Haskin and Haskin 1966, 7: Gromet et al. 1984, 8: Goldstein and Jacobsen 1988, 9: Piper 1974, 10: Minami 1935, 11: Bau et al. 2018, 12: McLennan and Taylor 1984, 13: Masuda et al. 1973; Masuda 1975, 14: Schmitt et al. 1963, 15: Haskin et al. 1966b, 16: Evensen et al. 1978, 17: Anders and Grevesse 1989, 18: Sun and McDonough 1989 (*N-Type, °E-type), 19: Kamber et al. 2005, 20: Taylor and McLennan 1995, 21: Wedepohl 1995, 22: Rudnick and Gao 2003, 23: Taylor and McLennan 2002, 24: Workman and Hart 2005, 25: Bayon et al. 2015. “ : note that Haskin et al. 1966a, b have different concentration values than Schmitt et al. 1963 for Ce and Tb that are respectively: 0.84 and 0.058 ppm.

PAAS: Post-Archean Australian Shale, NASC: North American Shale Composite, WSA: World Shale Average, EUS: European Shale, AS: Archean Shale, MUQ: Mud from Queensland, UCC: Upper Continental Crust, MORB: Mid-Ocean Ridge Basalt, DMM: Depleted Mid-ocean ridge basalt Mantle, WRAS: World River Average Silts and WRAC: World River Average Clays.

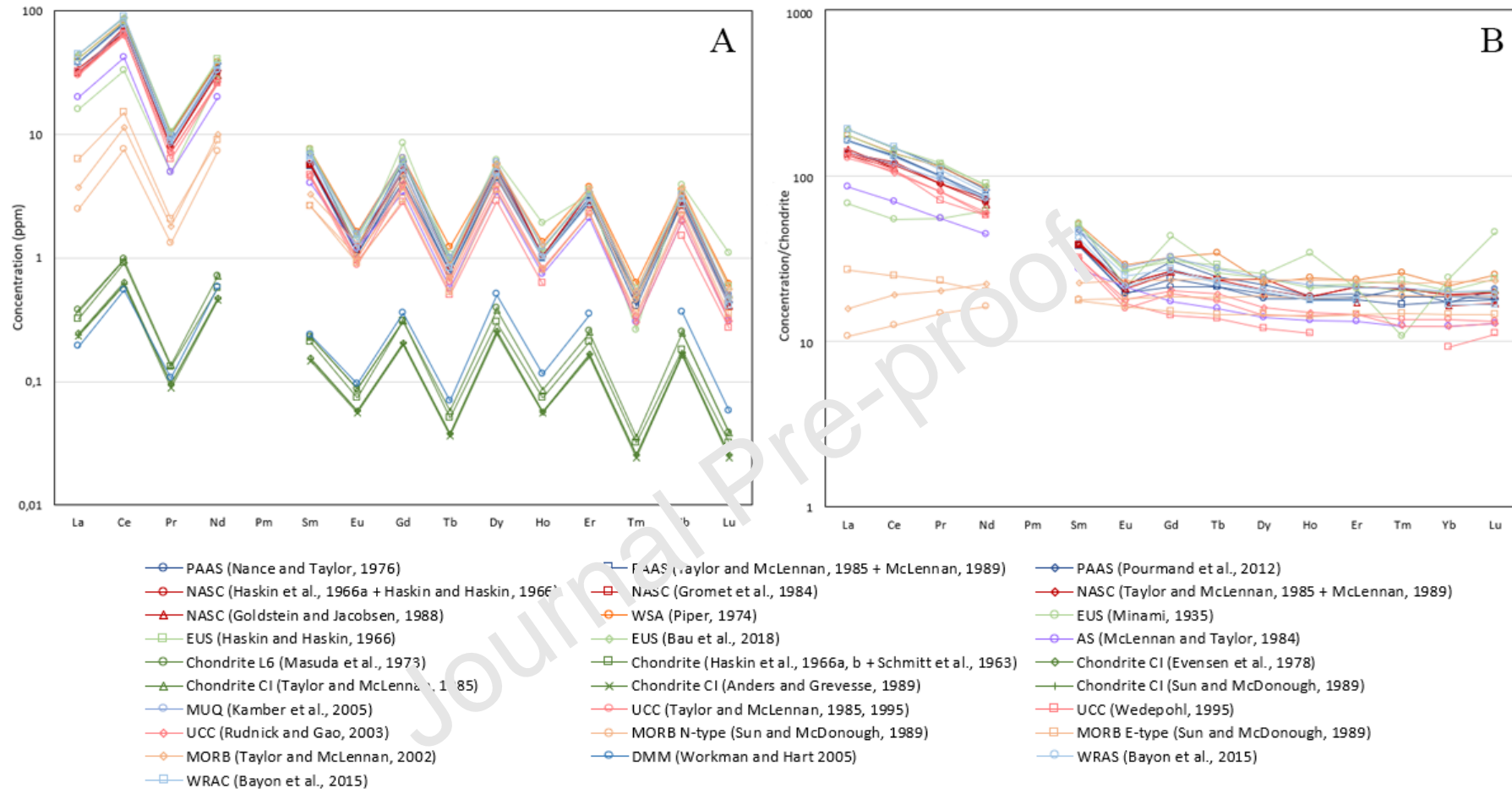


Fig. 1. A. REE concentrations in different published datasets used for normalization of REEs. B. Chondrite-normalized REE patterns for different published datasets used for REE normalization. PAAS: Post-Archean Australian Shale, NASC: North American Shale Composite, WSA: World Shale Average, EUS: European Shale, AS: Archean Shale, MUQ: Mud from Queensland, UCC: Upper Continental Crust, MORB: Mid- Ocean Ridge Basalt, DMM: Depleted Mid-ocean ridge basalt Mantle, WRAS: World River Average Silts and WRAC: World River Average Clays. Chondrite normalization was performed using Anders and Grevesse (1989) dataset.

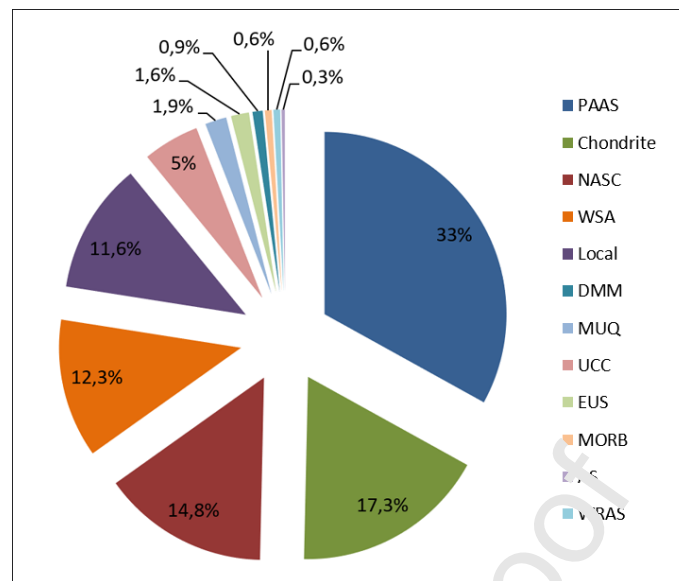


Fig. 2. Percentage of different normalization reference materials used when studying REEs over the past 60 years. Pie chart established on the basis of bibliographic research presented in Table S1 containing 251 publications in total. PAAS: Post-Archean Australian Shale, NASC: North American Shale Composite, WSA: World Shale Average, DMM: Depleted Mid-ocean ridge basalt Mantle, MUQ: Mud from Queensland, UCC: Upper Continental Crust, EUS: European Shale, MORB: Mid-Ocean Ridge Basalt, AS: Archean Shale and WRAS: World River Average Silts, Local: Normalization using local concentrations either from local references or from concentrations reported among same study or previous ones.

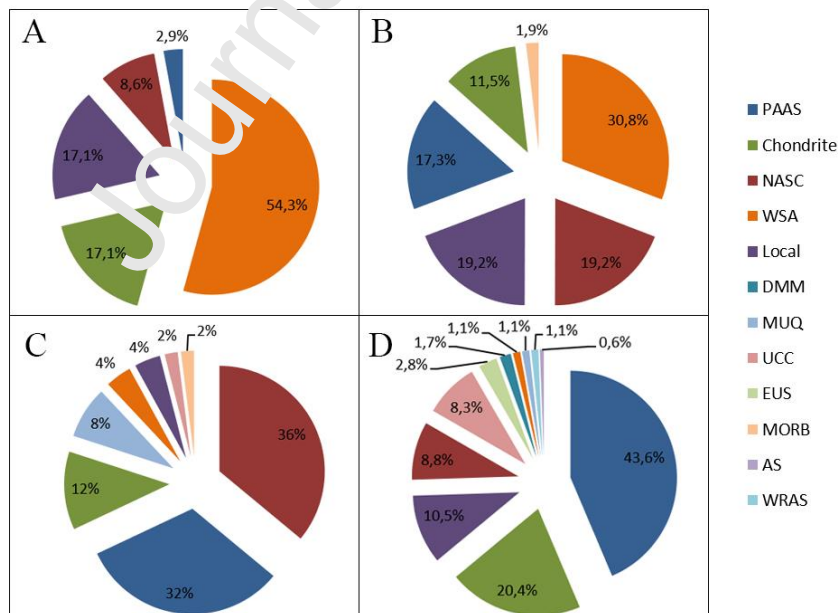


Fig. 3. Percentage of the different normalization reference materials used depending on the year of the study. A. Percentage calculated for the 26 articles published between 1962 and 1990, B. Percentage calculated for the 38 articles published from 1991 to 2000, C. Percentage calculated for the

44 articles published between 2001 and 2010 and **D**. Percentage calculated for the 143 articles published from 2011 to 2022. For every chart, articles published in the bordering years are included. PAAS: Post-Archean Australian Shale, NASC: North American Shale Composite, WSA: World Shale Average, DMM: Depleted Mid-ocean ridge basalt Mantle, MUQ: Mud from Queensland, UCC: Upper Continental Crust, EUS: European Shale, MORB: Mid-Ocean Ridge Basalt, AS: Archean Shale and WRAS: World River Average Silts, Local: Normalization using local concentrations either from local references or from concentrations reported among same study or previous ones.

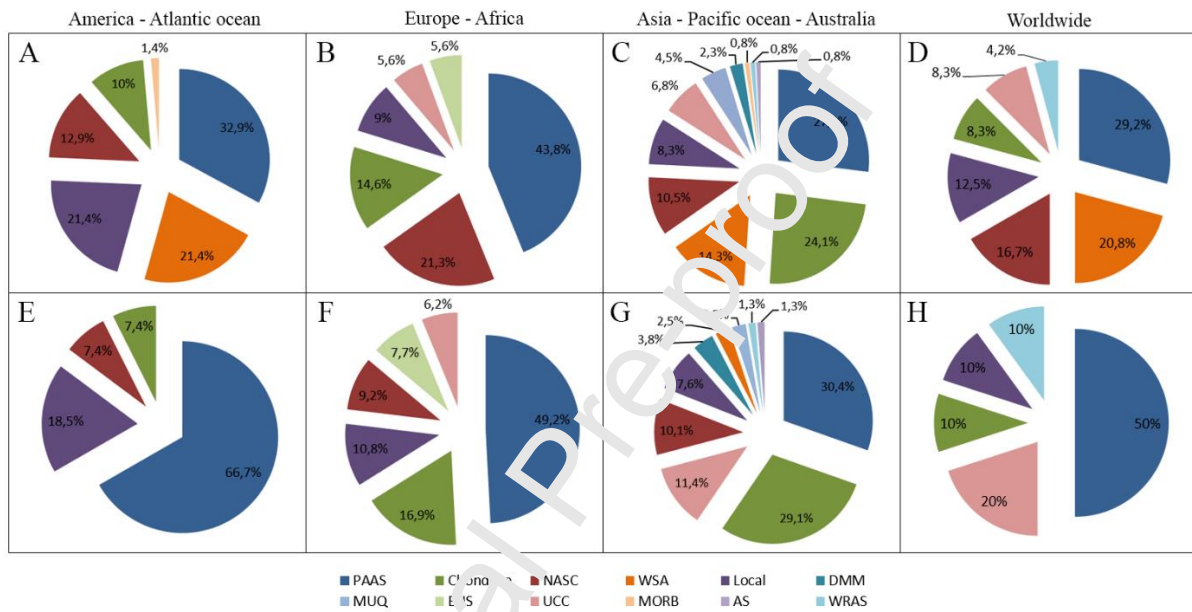


Fig. 4. Percentage of the different normalization reference materials used depending on the location of studied samples (A, B, C, D: including all studies from the last 60 years and E, F, G, H: including only studies published in the last 10 years (2010 to 2022 included)). A. Percentage calculated for the “America/Atlantic Ocean” group corresponding to 53 articles, **B.** Percentage calculated for “Europe/Africa” group containing 76 articles, **C.** Percentage calculated for the “Asia/Australia/Pacific Ocean” group containing 103 articles and **D.** Percentage calculated for the “Worldwide” group corresponding to 18 articles. **E.** Percentage calculated for the “America/Atlantic Ocean” group corresponding to 22 articles, **F.** Percentage calculated for “Europe/Africa” group containing 54 articles, **G.** Percentage calculated for the “Asia/Australia/Pacific Ocean” group containing 60 articles and **H.** Percentage calculated for the “Worldwide” group corresponding to 7 articles. PAAS: Post-Archean Australian Shale, NASC: North American Shale Composite, WSA: World Shale Average, DMM: Depleted Mid-ocean ridge basalt Mantle, MUQ: Mud from Queensland, UCC: Upper Continental Crust, EUS: European Shale, MORB: Mid-Ocean Ridge Basalt, AS: Archean Shale and WRAS: World River Average Silts, Local: Normalization using local

concentrations either from local references or from concentrations reported among same study or previous ones.

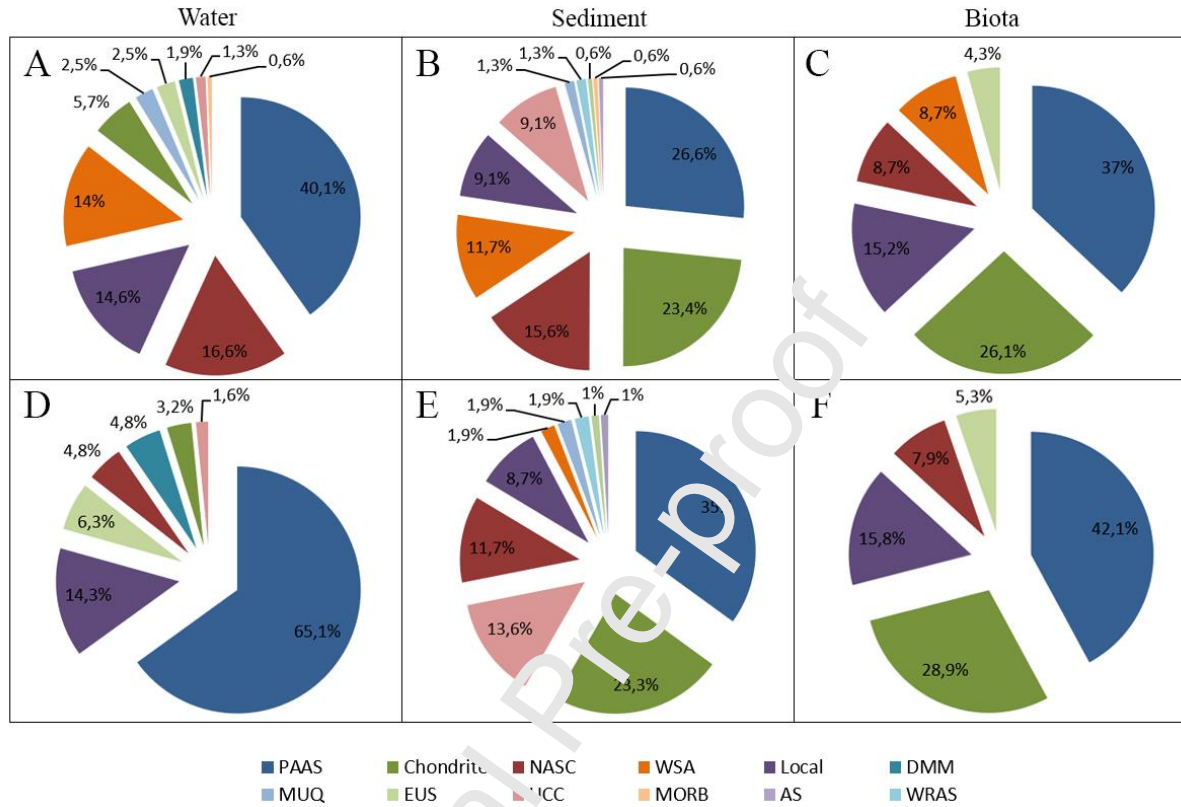


Fig. 5. Percentage of the different normalization reference materials used depending on the material studied (A, B, C: including all studies from the last 60 years and D, E, F: including only studies published in the last 10 years (2010 to 2022 included)). A. Percentage calculated for water samples corresponding to 47 articles, **B.** Percentage calculated for sediment samples comprising 88 articles and **C.** Percentage calculated for biota samples corresponding to 24 articles. **D.** Percentage calculated for water samples corresponding to 39 articles, **E.** Percentage calculated for sediment samples comprising 62 articles and **F.** Percentage calculated for biota samples corresponding to 21 articles. Some publications were studying several materials (42 articles for A, B and C and 21 publications for D, E and F), normalization materials used in these studies have been identified for each material and has been added to the calculation of percentage of their corresponding group (water, sediment, biota). PAAS: Post-Archean Australian Shale, NASC: North American Shale Composite, WSA: World Shale Average, DMM: Depleted Mid-ocean ridge basalt Mantle, MUQ: Mud from Queensland, UCC: Upper Continental Crust, EUS: European Shale, MORB: Mid-Ocean Ridge Basalt, AS: Archean Shale and WRAS: World River Average Silts, Local: Normalization using local concentrations either from local references or from concentrations reported among same study or previous ones.

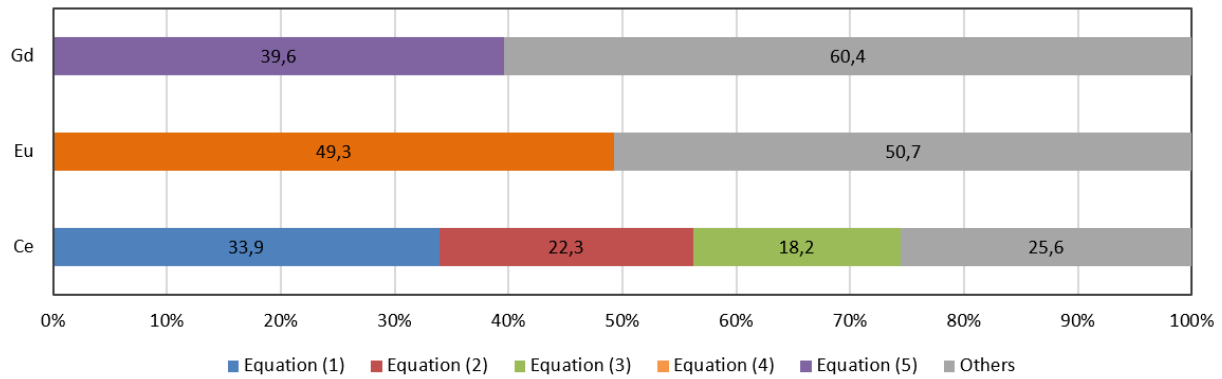


Fig. 6. Percentage of articles using the five main anomaly calculation equation. For cerium based on 116 articles, for europium based on 72 articles and for gadolinium based on 43 articles.

$$(1) \text{Ce/Ce}^* = 2\text{Ce}_N / (\text{La}_N + \text{Pr}_N) = \text{Ce}_N / (0.5\text{La}_N + 0.5\text{Pr}_N) = \text{Ce}_N / [(\text{La}_N + \text{Pr}_N)/2]$$

$$(2) \text{Ce/Ce}^* = \text{Ce}_N / [(\text{La}_N \cdot \text{Pr}_N)^{0.5}] = \text{Ce}_N / \sqrt{\text{La}_N \cdot \text{Pr}_N}$$

$$(3) \text{Ce/Ce}^* = 3\text{Ce}_N / (2\text{La}_N + \text{Nd}_N) = \text{Ce}_N / [(2\text{La}_N + \text{Nd}_N)/3]$$

$$(4) \text{Eu/Eu}^* = \text{Eu}_N / [(\text{Sm}_N \cdot \text{Gd}_N)^{0.5}] = \text{Eu}_N / \sqrt{(\text{Sm}_N \cdot \text{Gd}_N)}$$

$$(5) \text{Gd/Gd}^* = \text{Gd}_N / (0.33\text{Sm}_N + 0.67\text{Tb}_N)$$

Others: For cerium, equation used for anomaly calculation different from eq. (1), (2) and (3); for europium, equation used for anomaly calculation different from eq. (4); for gadolinium, equation used for anomaly calculation different from eq. (5), with N corresponding to normalized concentrations and * corresponding to geogenic background concentrations.

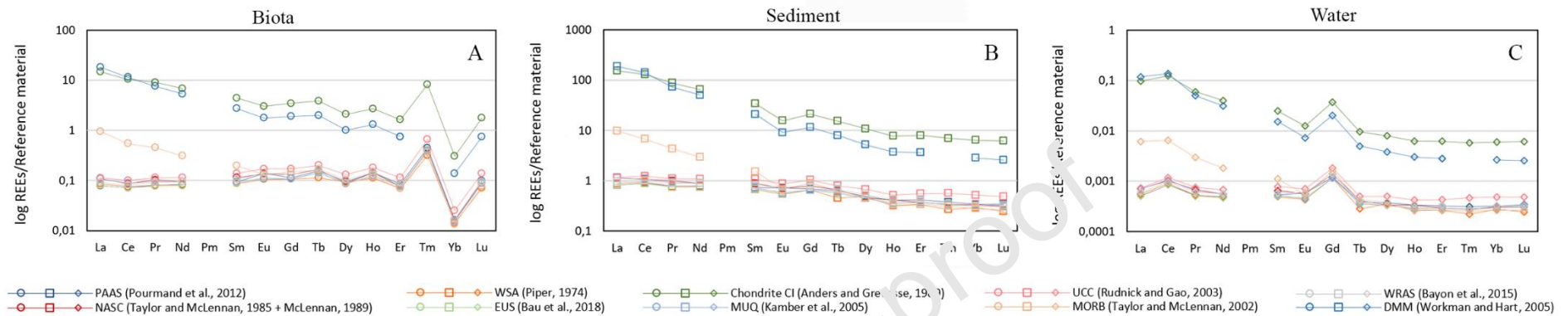
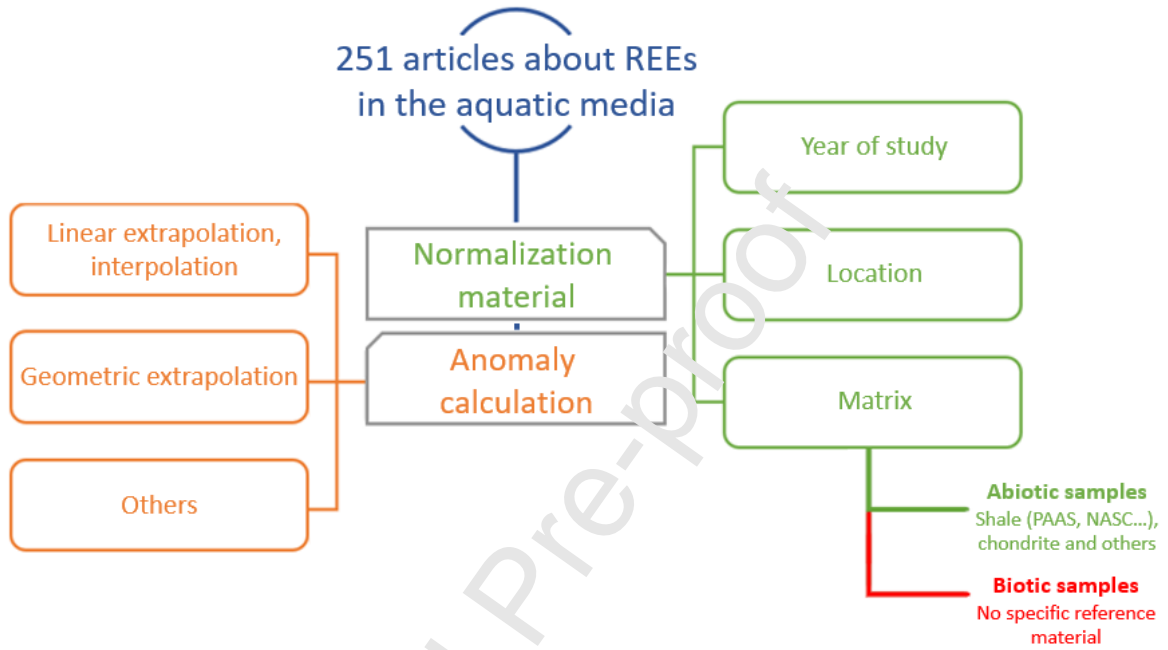


Fig. 7. Normalization patterns (PAAS, NASC, WSA, EUS, chondrite, MUQ, UCC, MORB, WRAS and DMM) of REEs measured in different environmental matrices. A. For biota samples, **B.** for sediment samples and **C.** for natural water samples. REE concentrations used for biota normalizations come from a study by Squadrone et al. (2017) on Mediterranean sea weeds (data for *Codium bursa* were used), those of sediments are taken from Hannigan's study (2010) on Chesapeake Bay's surface sediments and water concentrations come from a study by Merschel et al. (2015) on Lake Paranoa. PAAS: Post-Archean Australian Shale, NASC: North American Shale Composite, WSA: World Shale Average, EUS: European Shale, Chondrite CI: Carbonaceous chondrite, MUQ: Mud from Queensland, UCC: Upper Continental Crust, MORB: Mid-Ocean Ridge Basalt, WRAS: World River Average Silts and DMM: Depleted Mid-ocean ridge basalt Mantle

Graphical abstract



Highlights

- Reference materials for REEs and anomaly calculation methods need to be harmonized
- Among all reference materials, PAAS is the most used for the study of abiotic samples
- No specific reference material exists nowadays for biotic samples normalization
- New references for biota are needed to consider interspecific differences
- PAAS should be systematically used to allow better comparison between REE studies

Journal Pre-proof