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SrIsoMed: An open access strontium isotopes database for the Mediterranean

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ABSTRACT

This paper presents SrIsoMed, an open access and open source searchable database of published $^{87}Sr/^{86}Sr$ values from countries that have coastlines on the Mediterranean Sea. The Mediterranean has been characterized by pronounced human mobility at different regional scales, as well as extensive material cultural networks, making it a prime area for strontium isotopic analyses for palaeomobility and provenance studies. SrIsoMed follows the example of several recent initiatives that have compiled isotopic data in searchable web-based databases, and its interactive maps and search functionalities are anticipated to make it an important research tool. With this paper we wish not only to increase the visibility and subsequent use of this database, but also to invite scholars to contribute data and bring to our attention omissions or suggestions for further future improvement.

1. Introduction

Strontium isotopes ($^{87}Sr/^{86}Sr$) have been used extensively in archaeology to trace the provenance of a number of inorganic (mostly stone and vitreous materials) and organic material types. The primary focus of the application of Sr isotopes, however, has undoubtedly been palaeomobility studies. Their use is based on the principle that they exhibit regional variation based on the age and composition of the underlying bedrock, though their value is also affected by atmospheric inputs, such as air blown dust and sea-spray (Bentley, 2006). Through weathering, $^{87}Sr/^{86}Sr$ passes from the bedrock to the soil, and gets absorbed by plants, entering the food chain. Through the consumption of plants, animals and water, strontium isotopes are incorporated into human tissues (Bentley, 2006). By measuring the $^{87}Sr/^{86}Sr$ values in human enamel, which forms from infancy to adolescence (depending on the tooth) and does not remodel later in life, we obtain the strontium signature of the region where individuals spent their early life, during tooth formation. Thus, comparing enamel $^{87}Sr/^{86}Sr$ values with the baseline of bioavailable strontium in the area where the individuals were found, we can determine whether these individuals also spent their childhood in the same location. These baselines are usually created through the measurement of modern plants, water and (archaeological) animal teeth from taxa with small home ranges (Hartman and Richards, 2014; Lengfelder et al., 2019). If the individuals exhibit $^{87}Sr/^{86}Sr$ values different from the baseline at the excavation site, they are considered 'non-local' and they are assumed to have moved to the burial site at some point in life after tooth formation.

Over the past decade, publications employing strontium isotope ratio analysis in archaeology have proliferated worldwide but at the same time, the limitations of their interpretative potential have been better understood. A key limitation is the issue of equifinality, which means that several parts of the world may exhibit comparable bioavailable $^{87}Sr/^{86}Sr$ ranges because they have the same bedrock and/or similar atmospheric inputs (Bentley, 2006). This implies that individuals who are non-local (or even appear local) to the burial site, may have originated from several different locations. Interpreting the meaning of being 'non-local' is further complicated by the lack of bioavailable $^{87}Sr/^{86}Sr$ baselines for the largest part of the world. As a result, most studies conclude that some individuals per assemblage are non-local but they cannot determine if these non-locals represent people from a nearby community or long-distance migrants, thus limiting the interpretative potential of the results (e.g. Nikita et al., 2021). To amend this issue, several recent studies have engaged in systematic sampling of plants, water, animals, and/or soil in order to map bioavailable $^{87}Sr/^{86}Sr$ in different regions (Frank et al., 2021; Ladegaard-Pedersen et al., 2020). In addition, attempts have been made to create bioavailable strontium

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isoscapes, that is, predict the values of bioavailable strontium given a number of geological and atmospheric factors using machine learning (Bataille et al., 2018). A notable recent initiative in this direction was the generation of a global bioavailable strontium isoscape by Bataille et al. (2020), compiling global bioavailable $^{87}Sr/^{86}Sr$ data, mapping variability in rock, accounting for environmental inputs, and employing machine learning to predict bioavailable $^{87}Sr/^{86}Sr$. The authors' model explained 60% of the variance of the global bioavailable $^{87}Sr/^{86}Sr$ dataset, successfully predicting bioavailable $^{87}Sr/^{86}Sr$ in data-rich regions but highlighting the need for more research in geologically complex and data-poor regions.

An issue with many published $^{87}Sr/^{86}Sr$ data is that in most cases these are presented either as tables inside the main text of the publications or as spreadsheets in supplementary material. This format may limit their discoverability and accessibility, especially by scholars with no institutional access to major publications, while it also precludes their expansion and interactive use in combination to other published datasets, even from the same region (an issue also flagged by Klein et al., 2022). Hence, what is still lacking is a database where all published $^{87}Sr/^{86}Sr$ values are compiled and easily searchable. Such a database would allow scholars to directly identify all parts of the world (based on current published data) where bioavailable strontium matches the $^{87}Sr/^{86}Sr$ values seen in the archaeological materials under study in each case, suggesting possible points of origin for these materials. In addition, the compilation of published bedrock $^{87}Sr/^{86}Sr$ values, along with the bioavailable ones, could facilitate further modeling initiatives in the future towards creating isoscapes.

This paper presents SrIsoMed, a searchable database of published $^{87}Sr/^{86}Sr$ values from countries that have coastlines on the Mediterranean Sea. SrIsoMed aims at filling the gap discussed above for a region the connectivity of which has been highlighted since Paleolithic times (Simmons, 2016). The Mediterranean has indeed been characterized by extensive human mobility at different regional scales, as well as extensive material cultural networks (Broodbank, 2013; Van Dommelen and Knapp, 2010), making it a prime area for strontium isotopic analyses for palaeomobility and provenance studies.

SrIsoMed follows the example of several recent initiatives that have compiled isotopic data in searchable web-based databases. Such databases usually focus on specific chemical elements, for example GlobaLID is a web application for the compilation and processing of worldwide Pb isotope data (Klein et al., 2022), while the IRHUM database contains bioavailable strontium isotope data for France (Willmes et al., 2014). Other databases include several chemical elements for specific parts of the world, such as dIANA, which compiles $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ values in the Baltic Sea area (Etu-Sihvola et al., 2019), IBERLID, which is a database of lead isotope data from the Iberian Peninsula (de Madinabeitia et al., 2021), or ARCHIPELAGO, which contains human carbon and nitrogen stable isotope data from Japanese archaeological sites (Fernandes et al., 2021). In light of the surge in the publication of isotopic data and their compilation in different databases, notable initiatives to create common repositories or bring together multiple repositories, with an emphasis on the metadata schemes that will accompany the submitted data have emerged, such as IsoBank (Pauli et al., 2015) and IsoMemo (https://www.isomemo.com).

Among the recent initiatives in organizing published isotopic data in searchable databases, the one that has been the main inspiration behind SrIsoMed is IsoArcH (Salesse et al., 2018). IsoArcH initially compiled carbon, nitrogen, oxygen, strontium and sulphur isotopic data from bioarchaeological samples from the Graeco-Roman World and its margins, dating from the 12th c. BCE to the 8th c. CE. Nonetheless, it now aspires to compile bioarchaeological isotopic values from any time period and any part of the world. At the moment, the database includes data for approximately 13,300 humans, animals, plants, and organic residues (https://isoarch.eu, last accessed 29 April 2022). SrIsoMed largely focuses on the same geographical area as the initial IsoArcH focus, and includes strontium isotopes, which is one of the elements covered in IsoArcH. However, SrIsoMed samples encompass both organic and inorganic materials, amounting to over 11,400 values, while the search options and output allow users to straightforwardly identify potential points of origin for individuals and materials across the Mediterranean, thus enhancing its applicability in palaeomobility and provenance studies, as well as in extracting data for the creation of isoscapes.

2. Description of SrIsoMed

2.1. Data compilation

The $^{87}Sr/^{86}Sr$ data for SrIsoMed were compiled by the first author from 268 studies. The data and associated information included in this database are presented as given in the original publications but the accuracy of their collection cannot be verified. However, all data come from published research papers and graduate theses, which have been through peer-review. The database currently comprises 11,436 values of organic and inorganic materials. Besides the $^{87}Sr/^{86}Sr$ values, additional information extracted from the publications includes the measurement error, the exact type of sample to which each measurement corresponds, the date of the samples, and the publication from which each value was derived. We are currently also in the process of adding the type of instrument used for the measurement of $^{87}Sr/^{86}Sr$ values (e.g. MC-ICP-MS, TIMS) as well as the value used for NBS987.

The location of each sample measured has been georeferenced, either using the longitude-latitude coordinates provided by the authors in the original publications or, when these were not available, by superimposing the maps provided by the authors on QGIS and then extracting the coordinates of each point using the 'Georeferencer' plugin in version 3.16.14-Hannover. All coordinates follow the EPSG 4326 (WGS84) frame, while an additional column in the database specifies how accurate they are—that is, whether they were extracted from the original papers or reconstructed by our team and, in the latter case, whether the reconstruction was based on sufficiently high resolution maps of the original papers or not. In cases where the original publications provided rather vague information regarding the sampling locations, there are no coordinates associated with the samples, as the error would have been too high.

Finally, for each sampling location, the database includes lithological classes and subclasses, extracted from the Global Lithological Map (GLiM v1.0) (Hartmann and Moosdorf, 2012). This information was deemed important in case users wish to employ SrIsoMed data for modeling purposes given the association between $^{87}Sr/^{86}Sr$ and the underlying geology. Note that lithological information is only provided in cases where the coordinates of the sampling locations are known (either provided in the original publications or retrieved by our team as described above).

2.2. Data description

Figs. 1 and 2 present the distribution of the data currently included in SrIsoMed per sample type and region, respectively. In terms of sample typologies, the majority of the data (7690 values) represent bioavailable $^{87}Sr/^{86}Sr$, that is, animal, human, plant, water, and soil (i.e. weathered bedrock), and the remaining 3746 geological or other samples. With respect to the geographic distribution of the samples, Italy is the best covered area in terms of published $^{87}Sr/^{86}Sr$, followed by France, and then Greece, the Levant and Spain. In contrast, limited data is available for North Africa and countries with a coastline on the Adriatic Sea.

2.3. Web application description

SrIsoMed is an open access and open source user-friendly web application for the collection and interactive search of published $^{87}Sr/^{86}Sr$ data. It can be accessed at https://srisomed.emmebioarch.co

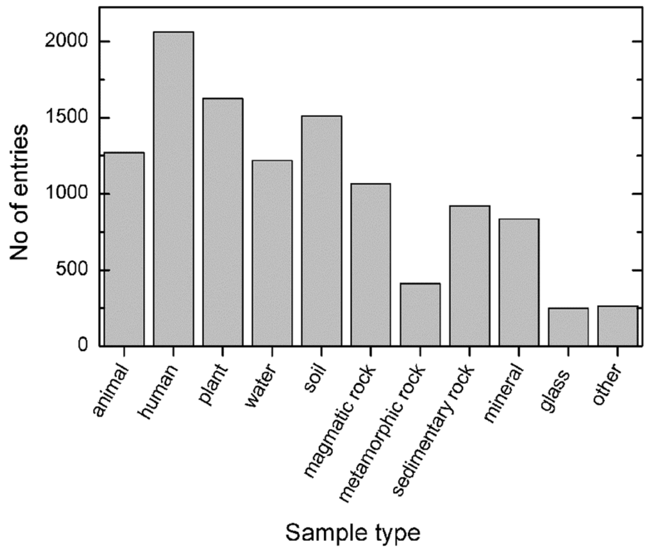

Fig. 1. Distribution of SrIsoMed data per sample type.

m, where different database search options are available, as well as information on our team, a brief user guide and the option to contribute additional data. The code used in the creation of SrIsoMed is available at https://gitlab.com/srisomed-project. Detailed information on web database architecture and database organization is provided in supplementary file 1.

SrIsoMed users can search the database either through the data filtering option and/or through the interactive map. Data filtering offers different options as filtering can be by country/region, sample type, lithology, and range of $^{87}Sr/^{86}Sr$ values (Fig. 3). The regional search adopts modern-day national borders; for simplicity, the term Levant has been adopted to jointly denote countries along the Levantine coast and Jordan. The samples have been categorized as: animal, human, plant, water, soil, magmatic rock, metamorphic rock, sedimentary rock, mineral, glass, other. The lithology follows the coding of lithological classes and subclasses adopted by the Global Lithological Map (GLiM v1.0); the search filter employs only the first level of these lithological classes. In all above search terms, multiple options can be selected simultaneously, i.e. multiple countries and multiple lithologies and multiple types of samples at once. The option to manually select a range of $^{87}Sr/^{86}Sr$ values is particularly useful when users wish to see which parts of the Mediterranean exhibit specific values to test potential points of origin for individuals or raw materials. The utility of this filtering option is maximized when simultaneously selecting the sample type; for example, to focus only on bioavailable samples in cases of palaeomobility research questions. In the results output, the users obtain the $^{87}Sr/^{86}Sr$ values and associated error, as stated in the original publication. In addition, the output gives the exact type of sample analyzed (instead of the simplified categories used for filtering purposes), sampling location (site name as well as latitude/longitude coordinates), local lithology at the sampling location, sample date, and publication from which the information was extracted. These results can be downloaded in TSV, JSON or PDF format. Note that TSV files can be straightforwardly opened in Microsoft Excel or other spreadsheet software programs.

The SrIsoMed interactive map shows the locations where there are available $^{87}Sr/^{86}Sr$ values (Fig. 4). The creation of the map was based on the latitude/longitude coordinates provided in the original publications. If these were not available, they were retrieved by the SrIsoMed team through georeferencing the maps given in the original publications, as described above. Even though every effort has been made to retrieve the location of every analyzed sample included in the database, this was not possible when the authors provided no or very generic maps. In such cases, the samples have been omitted from the map but they are still part of the database and can be found using the data filtering option. In the map, several locations are clustered together; the more sites a cluster includes, the darker its color. However, when zooming in a specific location, these clusters start breaking down to subclusters until individual points are visible (Fig. 5). When clicking with the mouse on any individual point, a dialog box presents the $^{87}Sr/^{86}Sr$ value and associated error, type of sample analyzed, sampling location (site name as well as latitude/longitude coordinates), local lithology, sample date, and publication.

Following the example of GlobaLID and the H2020 and Horizon Europe guidelines, SrIsoMed adopts the FAIR principles in data sharing (Wilkinson et al., 2016). In particular, the data of individual studies is now: a) Findable as it is compiled in a single database, while we aim at increasing the visibility of this initiative through conference presentations and the current publication, b) Accessible as SrIsoMed is open access and open source, and its data and metadata can be accessed without any registration or other requirements, c) Interoperable as data and metadata use a standard language, and d) Reusable as data and metadata are described in sufficient detail and can be downloaded in various formats (PDF, JSON and TSV) for further use.

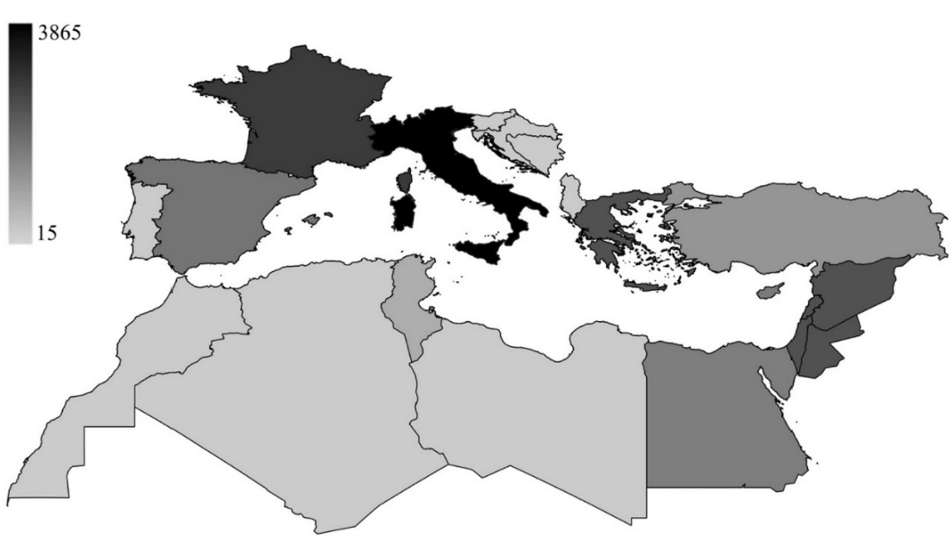

Fig. 2. Distribution of SrIsoMed data per region; heat map compiled in QGIS by second author using open-source shape files (https://www.diva-gis.org/).

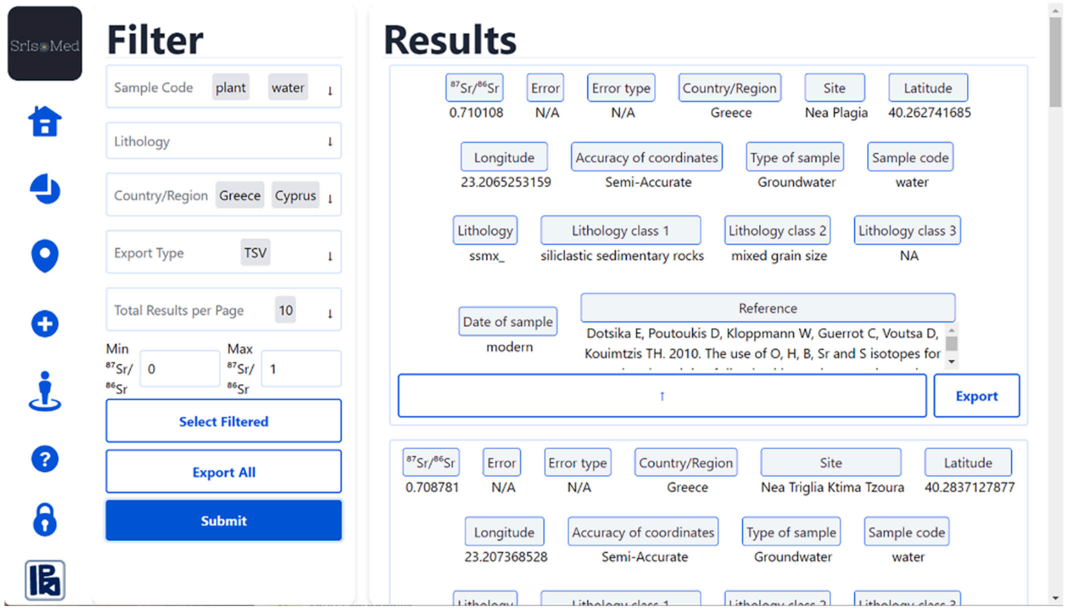

Fig. 3. Screenshot of the data filtering functionality in SrIsoMed.

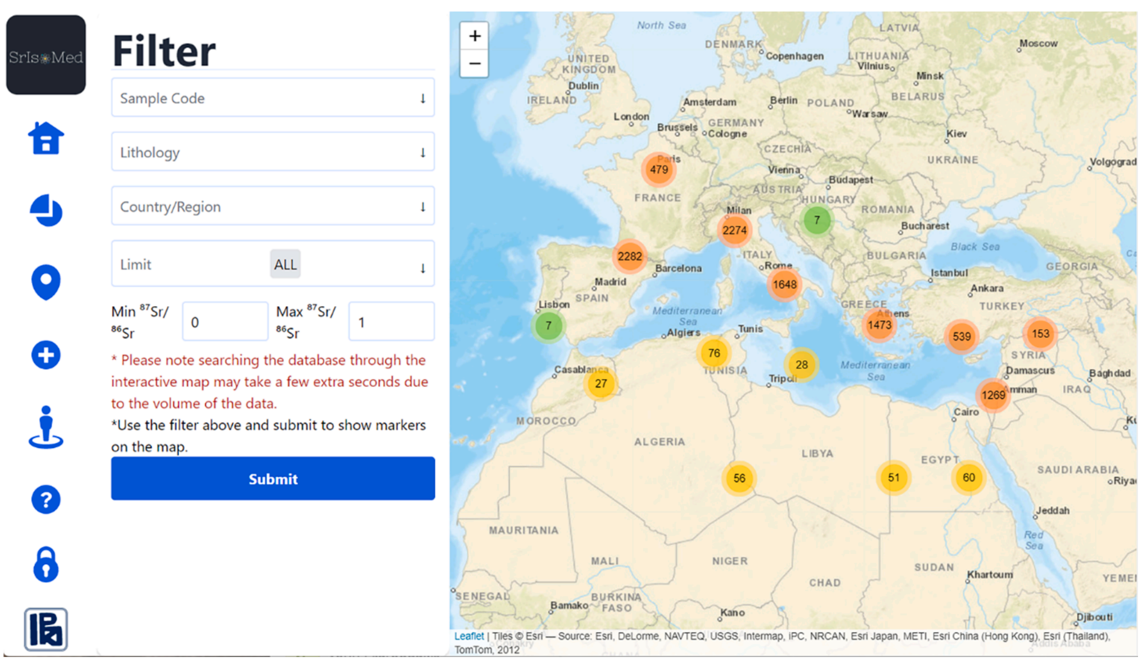

Fig. 4. Screenshot of the interactive map; overall view of the Mediterranean.

3. Brief application

To illustrate the research potential of SrIsoMed, let us examine a brief case study based on the research by one of our team members (E.N.). A recent paper (Nikita et al., 2021) examined levels of human mobility in Cyprus during the Early Christian and Late Byzantine/Frankish periods. Strontium isotopic analysis was performed on the enamel of 24 human skeletons from the site of the Hill of Agios Georgios in Nicosia and the obtained $^{87}Sr/^{86}Sr$ values were compared against the bioavailable strontium isotope baseline of Cyprus produced by Ladegaard-Pedersen et al. (2020), using soil leachates, plants, and water in order to identify non-locals. One of the 24 skeletons did not match the bioavailable baseline anywhere in southern Cyprus based on current data, while several of the remaining individuals did not match the baseline around Nicosia; however, they could have originated elsewhere in Cyprus. Based on these results, Nikita et al. (2021) concluded that although there was considerable mobility in Cyprus, especially in the Late Byzantine/Frankish period, it may well have been of a regional character rather than represent long-distance migration, with one potential exception.

If we use the interactive SrIsoMed map to identify the potential location of the individual who had $^{87}Sr/^{86}Sr = 0.709510$ and did not match any currently available Cypriot baseline, we obtain the results of Fig. 6. Note that in the search criteria, we have selected plant, soil and water as sample types in order to get bioavailable data, and we have set the $^{87}Sr/^{86}Sr$ range from 0.7094 to 0.7096 so that it is above and below the value of the individual under study. We see that these values match several sites across the Mediterranean, thus the individual under question may have originated in the Levant or Greece, but also from further

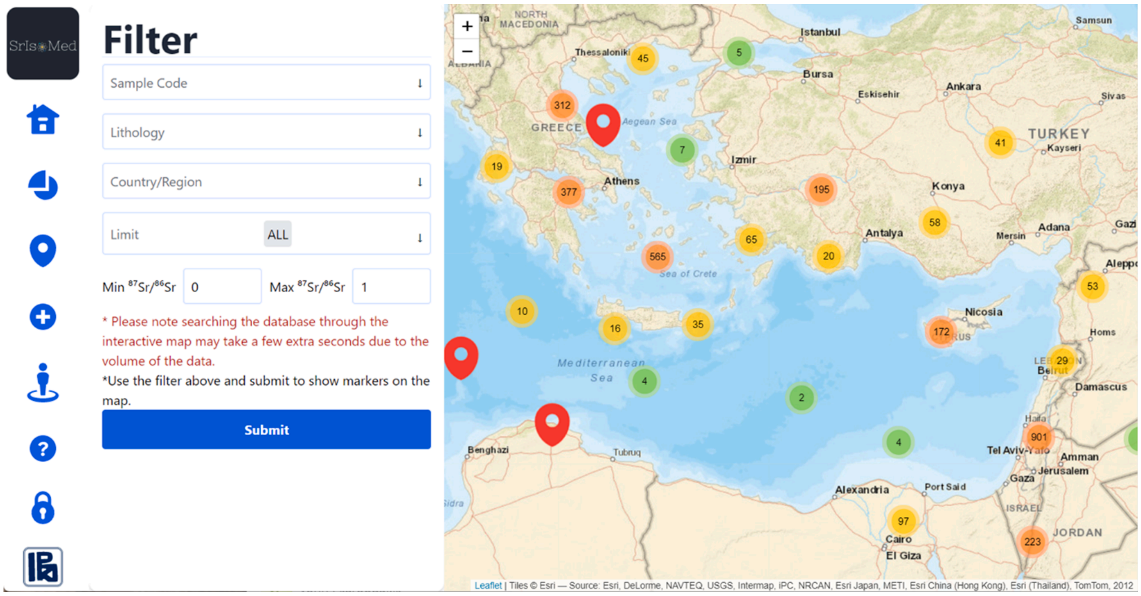

Fig. 5. Screenshot of the interactive map; part of eastern Mediterranean.

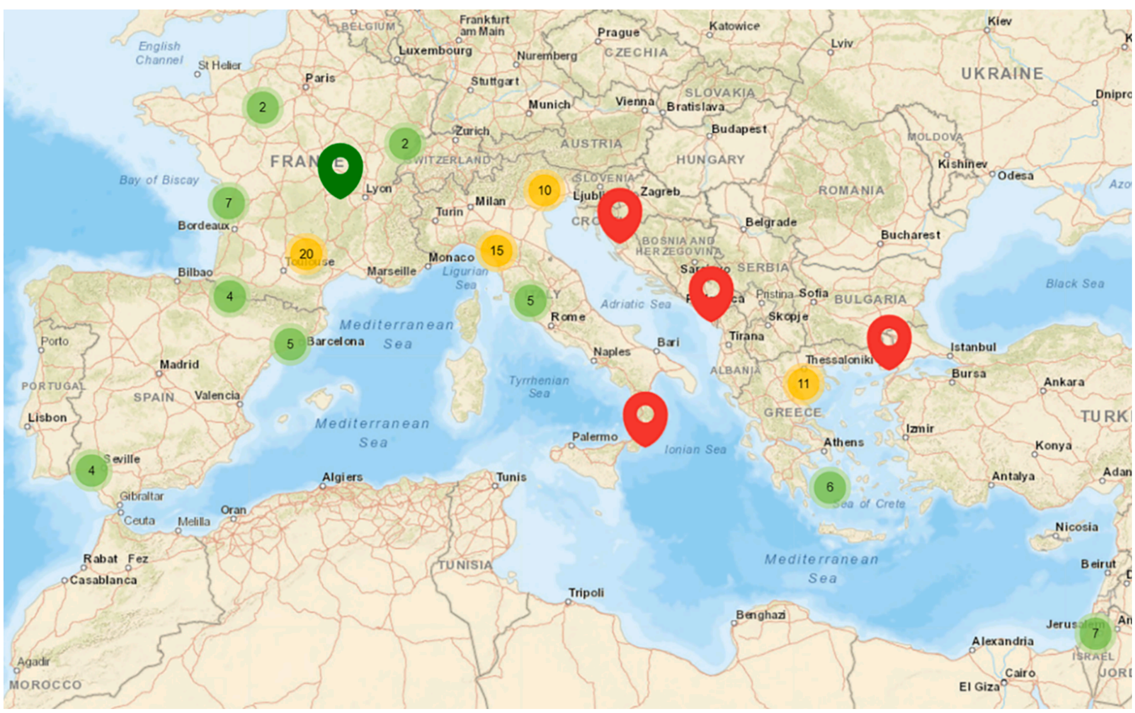

Fig. 6. Screenshot of SrIsoMed interactive map showing the potential point of origin of the non-Cypriot individual from the Hill of Agios Georgios when setting minimum $^{87}Sr/^{86}Sr = 0.7094$ and maximum $^{87}Sr/^{86}Sr = 0.7096$.

away in Italy, France or Spain (Fig. 6). The same pattern, though with fewer cases, is obtained when we narrow down the $^{87}Sr/^{86}Sr$ range to 0.70945–0.70955 (Fig. 7). Of course, we cannot exclude the possibility that there are more locations with the same range of values that have not been analyzed yet, thus they are not included in SrIsoMed, just as we cannot exclude the possibility that this individual originated in an area away from the Mediterranean altogether. Even though SrIsoMed cannot overcome the issue of equifinality and decidedly identify the point of origin of past individuals, it does offer a clearer idea of the multiple potential places of origin, based on currently available data. These potential places of origin could then be examined in association to the mortuary record, historical information and other available data to narrow down further the place of origin of the individuals. Such study is ongoing at the Hill of Agios Georgios.

As is clear from the above information and brief case study, SrIsoMed does not address the issue of equifinality that characterizes strontium isotopic studies and it cannot possibly identify with certainty the point of origin of any specific individual (or artefact if used in provenance studies). Its contribution lies in identifying potential places of origin for individuals (or artefacts) based on currently published $^{87}Sr/^{86}Sr$ values across the Mediterranean. Thus, it can push interpretation beyond a superficial local-nonlocal characterization. Naturally, this application suffers from the limitation that several parts across the Mediterranean have no published $^{87}Sr/^{86}Sr$ values, which can lead to biased

Fig. 7. Screenshot of SrIsoMed interactive map showing the potential point of origin of the non-Cypriot individual from the Hill of Agios Georgios when setting minimum $^{87}Sr/^{86}Sr = 0.70945$ and maximum $^{87}Sr/^{86}Sr = 0.70955$.

interpretations if users falsely assume that SrIsoMed covers sufficiently the entire region. In such cases, it is advisable to use an isoscape approach and the power of SrIsoMed could be as an initial dataset for generating isoscapes, for example, refining the Bataille et al (2020) worldwide bioavailable Sr dataset for the Mediterranean region. In addition, we must note that it is essential that users employ the correct type of samples for their research question. For instance, when wishing to identify the potential origin of a 'non-local' individual, bioavailable $^{87}Sr/^{86}Sr$ should be used, such as that obtained from measuring plants, soil and water. Human and animal values could also be included in relevant searches but given their high mobility, it is very likely that many of them will not accurately reflect the bioavailable $^{87}Sr/^{86}Sr$ at the site where they were retrieved; thus their inclusion may also cause biased interpretations.

4. Conclusions and future developments

SrIsoMed is an open access and open source database of published strontium isotopic values ($^{87}Sr/^{86}Sr$) in countries that have coastlines on the Mediterranean Sea. Its interactive map and database querying options are anticipated to promote palaeomobility and provenance studies in the region, which has been characterized throughout its history by pronounced connectivity. SrIsoMed aspires to continuously expand in order to reflect the ever-increasing strontium isotopic research in Mediterranean countries. Our team is systematically monitoring the publication of new works and will be updating the database at regular intervals. Furthermore, users can upload their own generated data using the Contribute tab. In this tab users may download and fill in the 'Sample file template'; note that the template is in TSV format but, as specified above, it can be easily opened using Microsoft Excel or other spreadsheets. The Excel file 'Predetermined values for categorical variables' can also be downloaded through the Contribute tab and specifies the values that are appropriate for the categorical variables of the database. Finally, users can upload the filled in template and submit it. The data will be automatically incorporated to the master database, and the SrIsoMed team will check new submissions regularly to ensure there is no error. SrIsoMed's long-term sustainability will be ensured by embedding this initiative within the activities of the Leventis Chair in Archaeological Sciences at the Cyprus Institute, which aims at promoting the archaeological sciences in the eastern Mediterranean. We would be deeply grateful if you could bring to our attention corrections and omissions so that SrIsoMed evolves into a cooperative initiative. To contact us, please use the Feedback form in the Contribute tab or email directly one of the SrIsoMed team members.

CRediT authorship contribution statement

Efthymia Nikita: Conceptualization, Data curation, Funding acquisition, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing. **Mahmoud Mardini:** Data curation, Software, Validation. **Mohamad Mardini:** Data curation, Methodology, Software. **Patrick Degryse:** Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data can be downloaded from https://srisomed.emmebioarch.com/

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2022.103606.

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