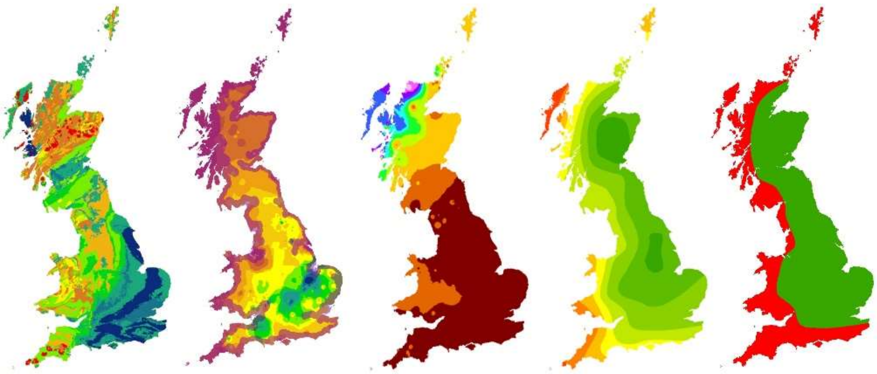
User Guide for the Biosphere Isotope Domains GB dataset and web portal.

NERC Geochronology and Tracers Facility, and Informatics Programmes.

Open Report OR/22/036



BRITISH GEOLOGICAL SURVEY

NERC GEOCHRONOLOGY AND TRACERS FACILITY, AND INFORMATICS

OPEN REPORT OR/22/036

User Guide for the Biosphere Isotope Domains GB dataset and web portal.

JA Evans, K Mee, CA Chenery, AP Marchant

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Front cover

Biosphere Isotope Domains (V2) maps for (L-R) strontium, sulphur, lead and oxygen (from drinking water).

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Foreword

This user guide is for the Biosphere Isotope Domains GB (V2) dataset, which includes: (1) a GIS layer of strontium, sulphur, lead and oxygen isotopes; (2) datasets for strontium, sulphur and lead isotope measurements from samples across Great Britain (published separately and available via BGS Biosphere Isotope Domains GB website); and (3) a web portal for viewing and querying the data. The primary application of such datasets is for determining the provenance of skeletal material, although the data may also be of use in modern traceability studies of fauna and flora.

Acknowledgements

This work was largely funded by the NERC isotope facilities steering committees (NIGFSC / NEIF) and builds on version 1 of the dataset that was co-funded by BGS' Digital programme. The sulphur layer was developed in conjunction with the British Academy/Leverhulme funded Wet Feet project: SRG1819\190163 and ERC-ADG grant 834087: COMMIOS, contributed to the development of the site. Contains Ordnance Survey data © Crown copyright and database right 2022.

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1 About the Biosphere Isotope Domains GB (V2) dataset

1.1 BACKGROUND

Over the last 25 years there has been a huge development in the application of isotopes as tracers for environment, diet and origin, in fauna and flora, both ancient and modern. The principle behind the use of tracers is that elements such as strontium (Sr), sulphur (S), lead (Pb), oxygen (O), carbon (C), and nitrogen (N) are incorporated into tooth enamel (Sr, O, Pb) and bone and dentine collagen (C, N, S) which preserve the life signature post burial. Since the isotope composition of the elements provides information about the environment and diet, the data can be used to constrain these factors in human and animal studies, both ancient and modern. However, the method is dependent on the quality of the reference dataset, and such reference data is dispersed, variable and limited in coverage. The aim of this dataset is to create a model for isotope variation across Great Britain that can be developed through time. The Biosphere Isotope Domains GB (V2) dataset and web portal, provide multi-isotope coverage, with documented uncertainties, of the isotope variations in strontium, sulphur, lead and oxygen. The datasets for Sr, S and Pb data are available for downloading. In addition, users of the web portal can input their own sample information to determine the regions across Great Britain best matched to their isotope data. [*See section 3.5 for a precise description of the dataset coverage].

1.2 WHO MIGHT REQUIRE THE DATA?

The primary users of this resource will be archaeologists using skeletal analysis to study the geographic origins, movements and diet in past people and populations. The data can also be used in modern studies of bird and fish migration, tracking sources of illegal importation of materials such as hard wood and ivory and authentication of food origins.

1.3 WHAT THE DATASET SHOWS?

The Biosphere Isotope Domains GB (V2) dataset consists of 3 components:

1) A GIS dataset showing the distribution of four isotope domains across Great Britain: strontium, sulphur, lead and oxygen (which includes both groundwater and tooth enamel).
2) Sample data for strontium, sulphur and lead isotope values, used in deriving the domain ranges in the map. The Biosphere Isotope Domains GB (V2) GIS layer contains the following isotope domains across Great Britain, presented as 1 km hexagon cells:

    a) **Strontium**: Great Britain has been subdivided into a number of domains based on the underlying geology (see Section 3.2.1), with each domain being described by their median strontium isotope value and embedded interquartile and 90% ranges.
    b) **Sulphur**: This is an interpolated map of S data from plants across Great Britain with a coastal domain overlay.
    c) **Lead**: Based predominantly on previously published datasets and its construction is described in Evans et al. (2022).
    d) **Oxygen (groundwater)**: This oxygen domain shows isotope variations in groundwater across Great Britain, as published by Darling et al. (2003).
    e) **Oxygen (tooth enamel):** This oxygen domain shows isotope variations in tooth enamel given as the mean and 1SD of “local” populations as described in Evans et al. (2012).

3) An accompanying web portal for viewing and interrogating the GIS data, and for downloading all GIS and sample data, available here: https://www.bgs.ac.uk/datasets/biosphere-isotope-domains-gb/

2 Technical Information

2.1 SCALE

The dataset is represented by 1 km hexagon cells (1 km cell edge) and has been derived from the BGS Geology 50k (1:50,000 in scale), therefore providing 50 m ground resolution.

2.2 FIELD DESCRIPTIONS

Table 1 Attribute table fields and field descriptions

FIELD NAME	FIELD TYPE	DESCRIPTION
SR_DOMAIN	String (80)	Name of the strontium domain (based on geology, unit age, geography)
SR_MN	Double	Minimum strontium isotope value
SR_MX	Double	Maximum strontium isotope value
SR_MEAN	Double	Mean strontium isotope value
SR_1SD	Double	Strontium isotope value to 1 standard deviation
SR_MEDIAN	Double	Median strontium isotope value
SR_INTERQ	Double	Interquartile range of strontium isotope values
SR_Q1	Double	First quartile strontium isotope value
SR_Q3	Double	Third quartile strontium isotope value
SR_PC05	Double	5th percentile of strontium isotope value
SR_PC95	Double	95th percentile of strontium isotope value
SR_N	Double	Number of sample measurements used in statistical analysis
S_PLANT_MN	Double	Minimum sulphur (δ34S) isotope value from plant samples
S_PLANT_MX	Double	Maximum sulphur (δ34S) isotope value from plant samples
S_COAST_MN	Double	Minimum sulphur (δ34S) isotope value for the coastal zone
S_COAST_MX	Double	Maximum sulphur (δ34S) isotope value for the coastal zone
PB_MIN	Double	Minimum lead ($^{206}Pb/^{204}Pb$) isotope value
PB_MAX	Double	Maximum lead ($^{206}Pb/^{204}Pb$) isotope value
O_H2O_MN	Double	Minimum oxygen isotope value from water samples
O_H2O_MX	Double	Maximum oxygen isotope value from water samples
O_TE_MN	Double	Minimum oxygen isotope value from tooth enamel
O_TE_MX	Double	Maximum oxygen isotope value from tooth enamel
OPVSMOW_MN	Double	Minimum $\delta18O_{PhosVSMOW}$ value
OPVSMOW_MX	Double	Maximum $\delta18O_{PhosVSMOW}$ value
OCVSMOW_MN	Double	Minimum $\delta18O_{CarbVSMOW}$ value
OCVSMOW_MX	Double	Maximum $\delta18O_{CarbVSMOW}$ value
OCVPDB_MN	Double	Minimum $\delta18O_{CarbVPDB}$ value
OCVPDB_MX	Double	Maximum $\delta18O_{CarbVPDB}$ value
DATASET	String (30)	Dataset name
VERSION	String (80)	Version number of the Biosphere Isotope Domains GB GIS dataset

3 Creation of the Dataset

3.1 ISOTOPE METHODOLOGY

3.1.1 Overview

This dataset brings together an update to the Sr isotope biosphere map published by Evans et al. (2018), a new sulphur dataset for plants in England and Wales, a Pb isotope layer (Evans et al. 2022), the oxygen isotope groundwater map published by Darling et al. (2003), and the oxygen isotope composition of human tooth enamel based on Evans et al. (2012). These domain maps can be interrogated singly or in combination to produce a distribution map of the different isotope compositions that can be found across Great Britain. This is Version 2 of the dataset, which will continue to be developed over time as more samples are collated.

3.1.2 Sample types

A variety of sample types have been used in this study. They represent different aspects of the biosphere and hydrosphere and are sampled at different scales.

Water (Sr study). This includes river water, pond/lake water, borehole, and tap waters. River water samples provide an average value for the catchment areas of the stream or river. They can have variable isotope composition depending upon season and rainfall (Shand et al., 2007) and may introduce values into an area that are typical of the upper catchment rather than water from the immediate area of interest. Borehole water will provide an aquifer value most appropriate to wells and mineral water. Modern tap water will be the average of a large modern catchment system or possibly desalinated water in some parts of the world. Lake water will be a mixture of rainwater, river feeder system and equilibration with the lakebed.

Groundwater (O study). Groundwater $\delta^{18}O$ represents a long-term bulk rainfall composition and is reasonably representative of long-term rainfall across the British Isles. Groundwater samples were collected from shallow boreholes, local wells and pumping stations across England, Scotland, Wales and Northern Ireland* (see Darling et al., 2003). [*NB: Northern Ireland is not included in the Biosphere Isotope Domains GB (V2) dataset – see section 3.5 for full coverage details].

Plants (Sr study). Plants provide a direct biosphere measurement. The advantages of plant samples are that they are ubiquitous and reliably geolocated. However, they only sample a small area of land and assumptions must be made about the relationship between the isotope composition of a plant and that of the fauna which consume them. In addition, they may reflect modern rather than historic compositions. The plants collected for Sr analysis are generally collected away from agricultural land to avoid fertilizer contamination. Published data are incorporated where available and sources are given below in Table 2.

Plants (S study). A number of factors contribute to the S isotope composition recorded by modern plants, and these include 1) the underlying geology, 2) the hydrology of the soil 3), the proximity to marine influences and 4) modern pollution. The majority of plants analysed for sulphur isotope composition were collected initially for Sr analysis and their sources are given in Table 2. Other sample sources include GEMAS (Geochemical Mapping of Agricultural Soils of Europe) and a British Academy/Leverhulme Trust small research grant. Data from East Anglia, come, in part, from an active Midlands4Cities PhD project and these data, whilst used to create the interpolated map, are redacted from the data table until the project is completed.

Archaeological dentine/bone (Sr study). This material has the advantage that, when buried, it will equilibrate with strontium in groundwater close to the time of burial (Trueman et al., 2004) and thus provides a method for looking at the strontium isotope composition of diagenetic fluids from the past and provides a comparison with modern data. It is commonly used as a reference sample for the local burial environment for provenance studies based on tooth enamel and hence a number of dentine or bone analyses have been accumulated though time.

Minerals (Pb study). The Pb isotope data are derived from the analysis minerals, the majority of which are from published sources. For details see Evans et al. 2022.

Table 2 The prefix of sample names and the source of their Sr isotope data used to create the Sr isotope domains map. Some samples were also used in the S domain map creation.

Sample prefix	Data Source
AJ, ADF and GM, Ex, SO, UK, WDR	Müldner et al. (2022)
AULD	Lamb et al. (2012)
CATT	Chenery et al. (2011)
CHE, COV	Trickett (2007)
DS	Brettell et al. (2012)
AR, DWPLANT, SCAR, Hull, SRA, SUMB, Wales, LLyn, S105, ARD, HIGH, EBP, CORN, HWP, E-Scat, EBP,ORK, Frobost, Aberd, GP, SN, Exmoor, Bam, PH, Sf, Egrut, Lap, Rep, BCAS, Tabley, Bees, GIR, Al, KL, E-pool, HARW, LIZ, KL, FISH	Evans et al. (2010)
Gals, SPR-1, 77, 89, 209, 341, 357, G, F, MW, WIN, WH	Montgomery (2002), Montgomery et al. (2003)
GLR, G-V	Chenery et al. (2010)
GRIS	Melton et al. (2010)
JMPD	Montgomery (*pers comm.*)
JMW	Montgomery et al. (2006)
KET	Evans and Tatham (2004)
KILN, PRES	Montgomery et al. (in prep)
Lf, WD, GBASE and some GEMAS, Biff, Bie	Warham (2012)
LJ	L. Johnson, PhD (2018)
PDW	Montgomery (unpublished *pers comm.*)
Plant	Madgwick et al. (2019)
RED, OYC, CUR	Evans and Bullman (2009)
RS	Schulting et al. (2019) (NB: RS prefix added)
SK	Parker Pearson et al. (2016)
SKYE	Evans et al. (2009)
S-Wales, SRA, Lund, 474405, SOU, USK, ASV, Shetland GEMAS, BCAS, GBASE, CAJ, Maes, Ger, Caith	NIGL (unpublished); GEMAS sample details Riemann et al. (2014)
SWF	Johnson et al. (2022)
Westness	Montgomery et al. (2014)
WW	Snoeck et al. (2018)
WWH	Jay et al. (2013)
YRS	Leach et al. (2009)

3.2 GIS METHODOLOGY

3.2.1 Strontium isotope domains

The Sr isotope domains were created by categorising the geology of Great Britain into 3 broad geological groups (igneous, metamorphic, sedimentary) and then into 17 further sub-categories based on the 1,047 rock classification descriptions of the BGS Geology 50k (V8) mapping (Table 3). These were then subdivided into the final 94 Sr domains based on geology, age and geography, (also derived from the BGS Geology 50k (V8)). The Sr isotope ranges were derived from > 1300 samples from plants, water and bones from across Great Britain (Figure 1), as well as theoretical interpolations. The full strontium isotope dataset is available to download from the Biosphere Isotope Domains section of the BGS website:

https://www.bgs.ac.uk/datasets/biosphere-isotope-domains-gb/.

Table 3 The list of 17 geological groups created from the 1,047 rock classification descriptions from the BGS Geology 50K dataset. *Mudrock includes clays; **Non-carbonate includes chloride, ferruginous, phosphate and siliceous precipitates.

Geological group
Igneous / acid
Igneous / granite
Igneous / intermediate-basic
Metamorphic / basic
Metamorphic / calc-silicate
Metamorphic / gneiss / acid
Metamorphic / gneiss / basic
Metamorphic / pelite
Metamorphic / psammite
Metamorphic / schist
Metamorphic / schist / basic
Metamorphic / slate
Metamorphic / thermal
Sedimentary / mudrock*
Sedimentary / precipitate / carbonate
Sedimentary / precipitate / non-carbonate**
Sedimentary / sand-silt

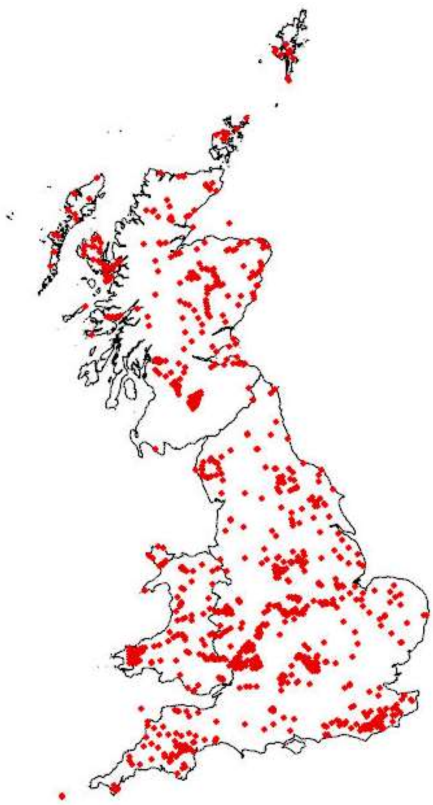

Figure 1 Distribution of samples collected across Great Britain used in defining the Sr isotope domains. Contains Ordnance Survey data © Crown copyright and database right 2023.

Once the domains were determined, the map was divided into 1 km hexagons, (each hexagon side length being 1 km) (Figure 2). Each hexagon was assigned strontium values based on the domain that covered the largest area of that cell. A list of all 94 Sr domains is given in Appendix 1.

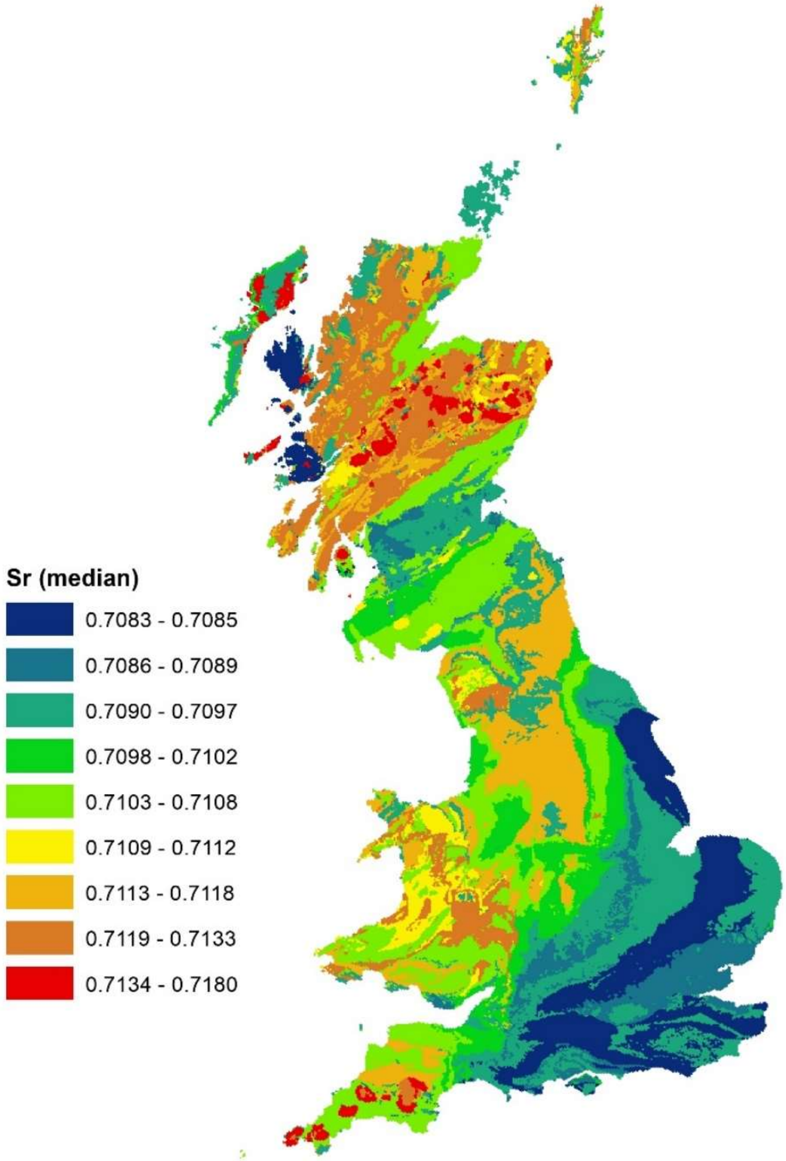

Figure 2 $^{87}Sr/^{86}Sr$ isotope domains (median Sr value). Contains Ordnance Survey data © Crown copyright and database right 2023.

The domains are populated with data from *c.* 1300 samples and the domain ranges are given at two search levels. Because the data is derived from plant analysis, but generally used for searches on human origins, the first option is to use the 50% central data set. This is recommended because the relationship between plant and human data suggests that the averaging process in human consumption reduced the data spread by half (Evans et al., 2012). However, for studies other than human origin studies (modern plants, herbivore origins) a wider range of plant data may be more appropriate and so the 90% central data set is available. Figure 3 highlights this difference.

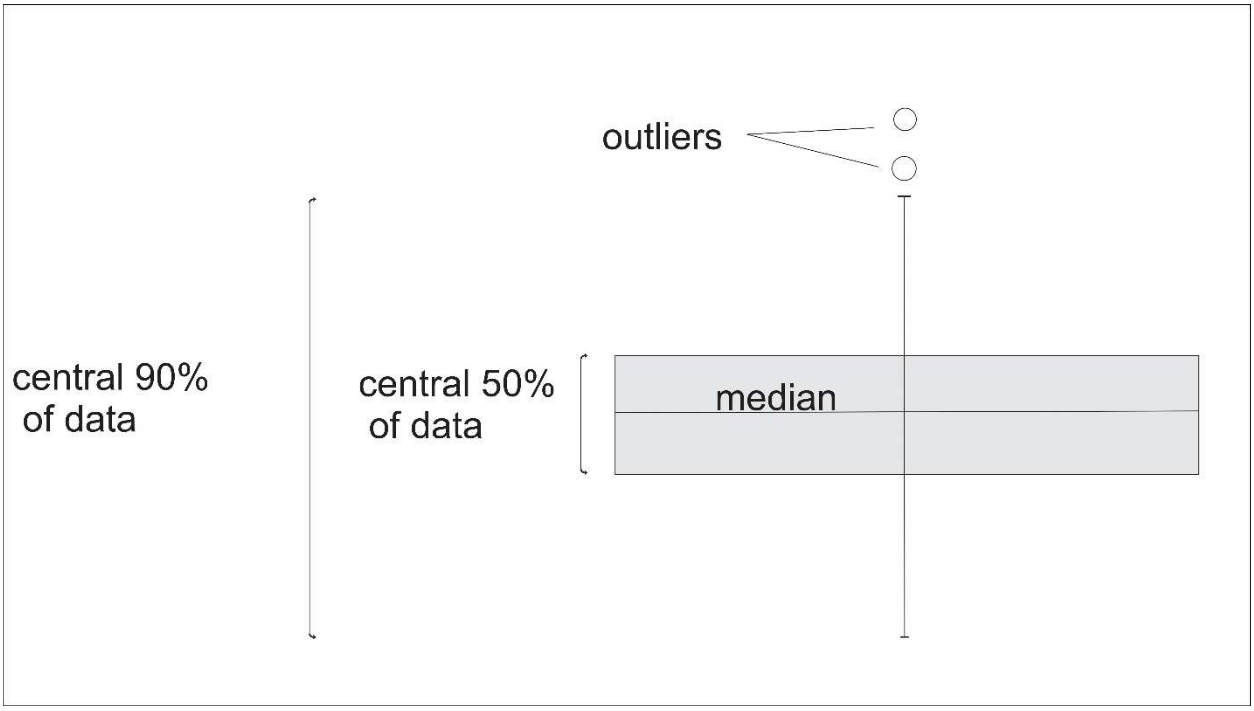

Figure 3 Description of the two data ranges used to population the Sr domains.

3.2.2 Sulphur isotope domains

The sulphur isotope map is a composite map of an interpolated data set, with a coastal domain superimposed upon it. The rational for this combined approach is that, while the interpolation approach satisfies the need to show the variable nature of the composition of sulphur across Great Britain, the lack of sample sites within 10-15 km of the coast means that the marine influence on sulphur isotope compositions along much of the coastline is not adequately represented.

The interpolated sulphur isotope map is based on plant material and uses *c.*500 samples to define $\delta^{34}S$ zones based on natural breaks within the interpolated data (Figure 4). The data range between $\delta^{34}S$ = -31.6 to +22.6‰. Duplicate analyses (n=21 pairs) run between the 2017 and 2021 data sets give an average difference of 1.6‰.

The overlain coastal domain is based on transect inland from the coast that shows that the marine influence is more extensive on the west coast, up to 15 km inland, than on the east coast which extends 10 km inland (Figures 4c and 5). This domain is affected directly by marine incursion, sea splash and by precipitation containing dissolved S from sea spray aerosol with isotopic values comparable to marine values. The value range for this coastal domain is fixed at 8.8‰ to 21‰ and equates to the two classes in the sulphur plant domains map with the highest S values. Hexagons not within the coastal zone are given a no data value of -9999.

The new map reveals four dominant influences on sulphur across Great Britain: (1) marine proximity, (2) underlying geology, (3) the effect of soil hydrology and (4) regional climatic difference. It is important to note that this map is based on plants and the relationship between plant and fauna is not fully understood.

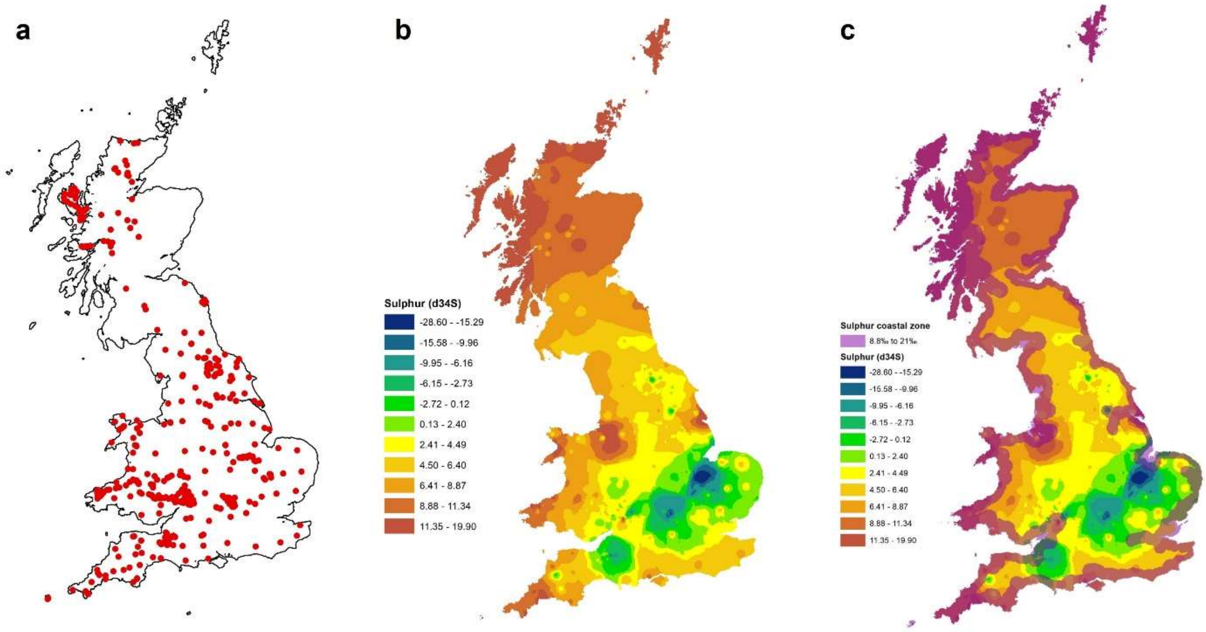

Figure 4 Distribution of (a) sulphur isotope plant samples, (b) interpolated sulphur domains and (c) sulphur coastal zone overlain on interpolated domains, across Great Britain. Contains Ordnance Survey data © Crown copyright and database right 2023.

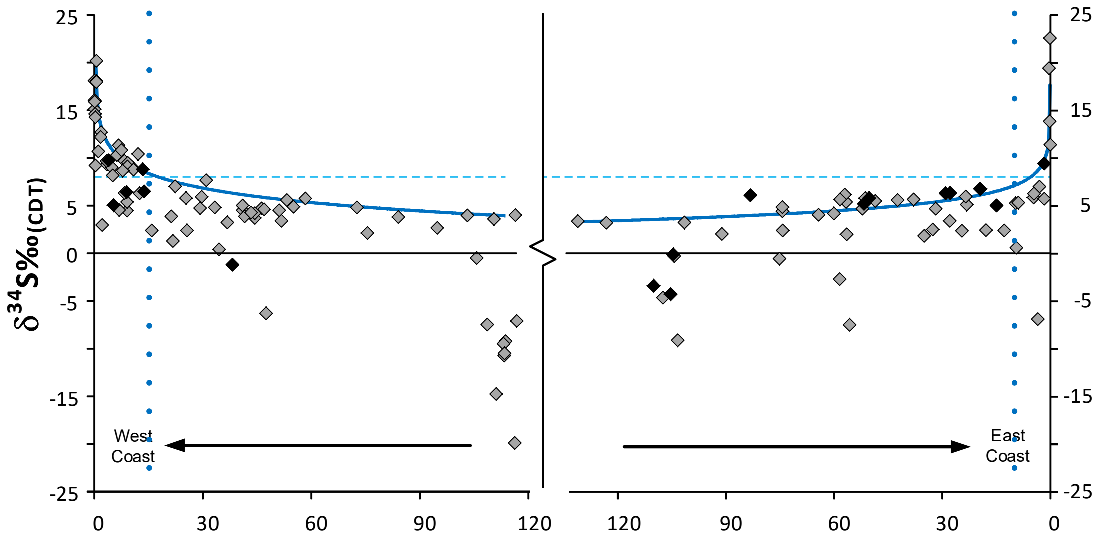

Figure 5 Scatter plot of δ34S values for all samples against their distance from the coast. Dashed line represents the lower δ34S value of the coastal effects zone; dotted lines indicate the extent of the coastal sea spray effect from the west coast (15 km) and the east coast (10 km).

Whilst the S domains map agrees with another recently published map based on insect compositions (Newton, 2021) its application to human data should be used with the understanding that:

a) It may not be valid to equate sulphur values in plants directly with faunal samples as there may be trophic shifts, (Nehlich, 2015).
b) We believe the effect of modern pollution is minimal post 2016 when most of the samples were collected (Zhao et al., 1998; Lamb et al., submitted), although this cannot be entirely excluded.

c) The level of regional variation seen in plant samples, may not mirror the natural variations seen in human and faunal samples which will average the plant samples over the time of consumption and collagen formation.

3.2.3 Lead isotope domains

Pb isotopes reflect the isotope zonation of Pb ore deposits across Great Britain. Their composition is dominated by the difference between Scotland, which is underlain by the ancient Laurentian crust, and England and Wales which are underlain by a much younger Avalonian crust.

The Pb domains map thus provides a spatial distribution of geogenic Pb isotope compositions unaffected by modern Pb pollution. It can be used in an archaeological context for samples that have not been influenced by anthropogenic Pb, either ancient or modern.

The Pb map was produced from *c.*600 samples (Figure 6a) used to define $^{206}Pb/^{204}Pb$ zones based on natural distribution breaks within the data. The majority of the data are taken from the compilation of Blicher-Toft et al. (2016). The dataset ranges in value from $^{206}Pb/^{204}Pb$ = 13.97 to 19 (Figure 6b). Details of the construction and assumptions used in this layer can be found in Evans et al. 2022.

Caution should be used in applying this map to non-mineral studies. This map can only be used in human and faunal provenance studies where there has been no exposure to anthropogenic Pb, and the resolution seen in the mineral data may not transmit directly into human and faunal samples.

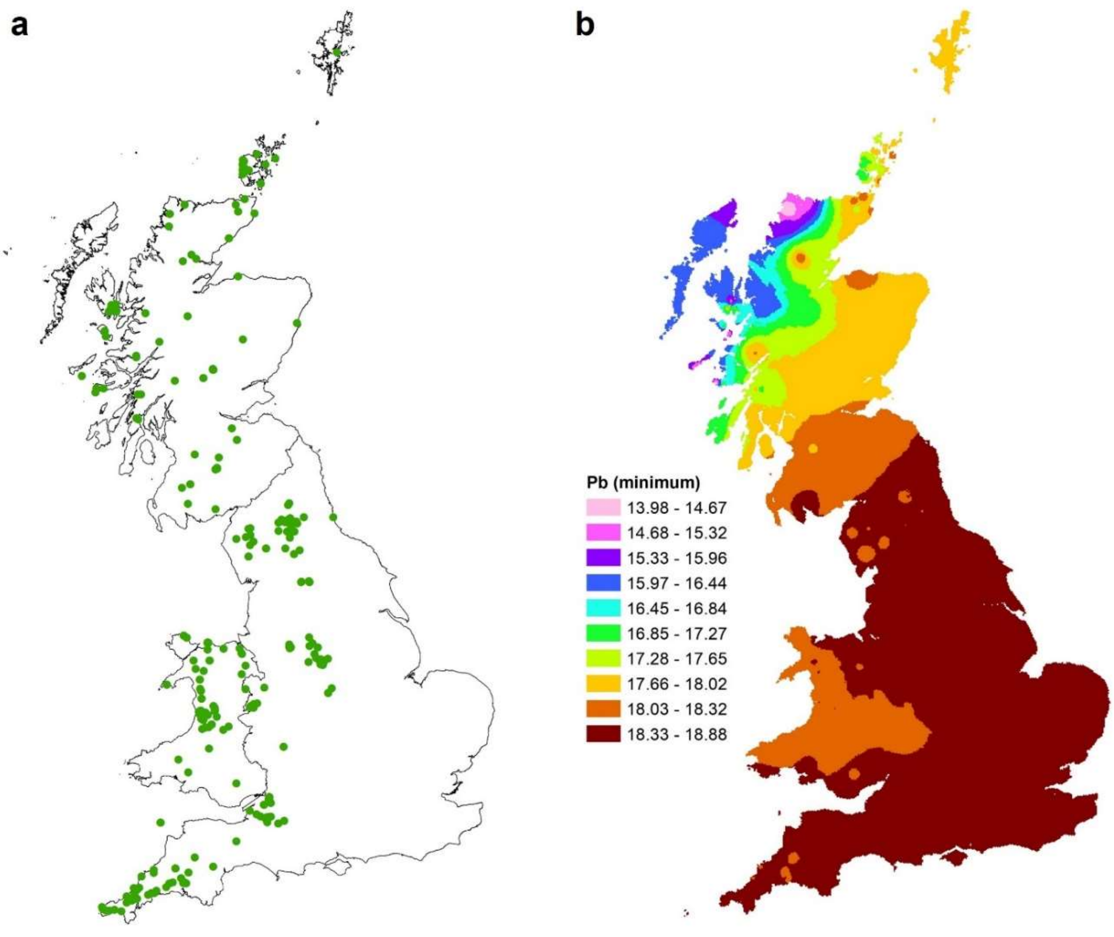

Figure 6 (a) Lead sample locations, and (b) lead ($^{206}Pb/^{204}Pb$) domains interpolated using natural breaks in the dataset. Contains Ordnance Survey data © Crown copyright and database right 2023.

3.2.4 Oxygen isotope domains

The oxygen isotope domains comprise two components: (1) data derived from groundwater samples $\delta^{18}O_{drinking\ water}$ ‰ (VSMOW) (Figure 7a) and (2) data derived from the measurement of $\delta^{18}O_{phos}$ ‰ (VSMOW) in human tooth enamel (Figure 7b). The groundwater data were first published by Darling et al. (2003) as a series of contours across Great Britain reflecting specific ranges of oxygen isotope values. The data on which the Darling paper was based is available at https://webapps.bgs.ac.uk/services/ngdc/accessions/index.html#item177214

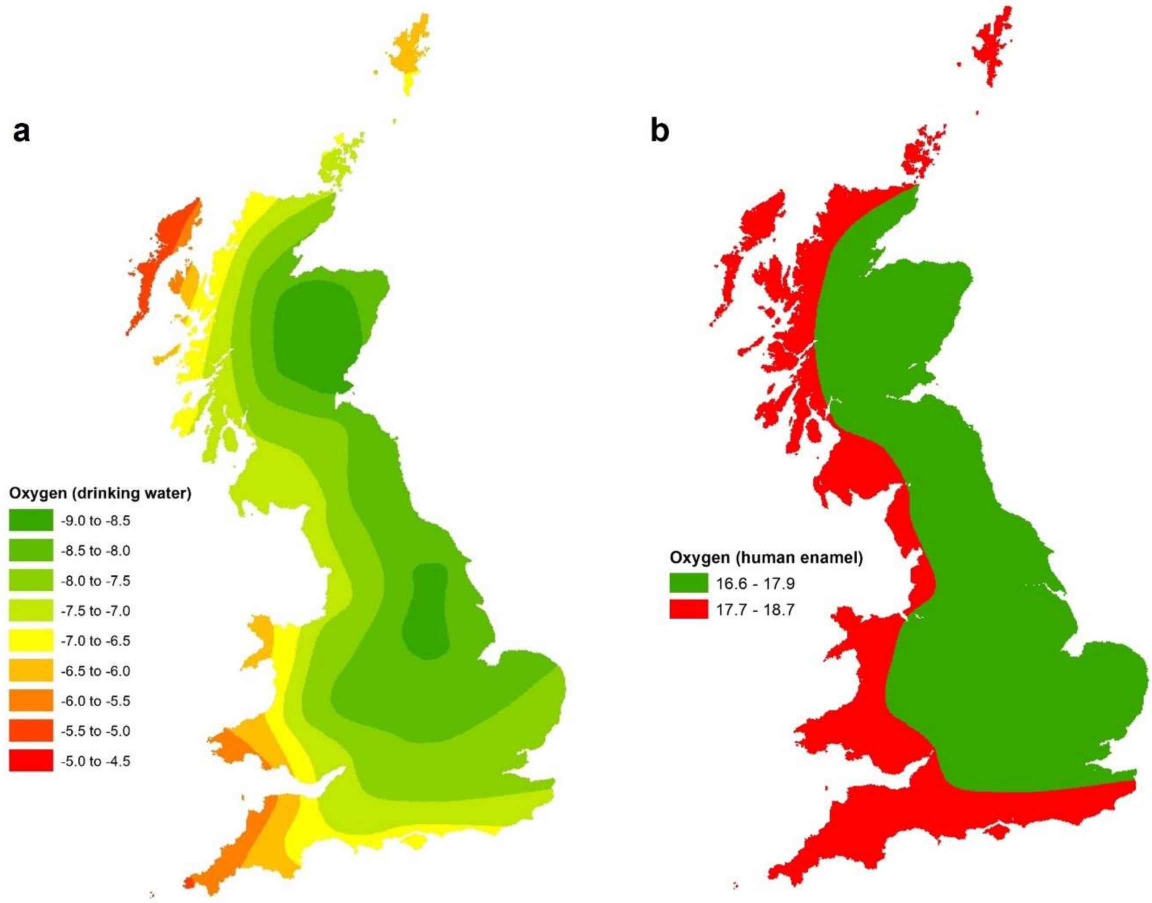

Figure 7 (a) $\delta^{18}O_{drinking\ water}$ ‰ (VSMOW) contours derived from the analysis of groundwater samples across Great Britain (after Darling et al., 2003), and (b) $\delta^{18}O_{phos}$ ‰ (VSMOW) in human tooth enamel. Contains Ordnance Survey data © Crown copyright and database right 2023.

Fractionation of oxygen isotope occurs when water is ingested, and this is why there is a significant difference in the isotope composition between the measured groundwater and the tooth enamel values (Levinson et al., 1987). The boundary in the tooth enamel dataset is taken as the -7.0‰ groundwater contour, with values of 16.6‰ to 17.9‰ to the east of -7.0 contour and values of 17.7‰ to 18.7‰ to the south and west of the contour (Figure 7b and Figure 8). For further details of these data see Evans et al. (2012).

This map is in three oxygen isotope formats: phosphate, carbonate oxygen relative to VSMOW (Vienna Standard Mean Ocean Water) and carbonate oxygen relative to VPDB (Vienna Pee Dee Belemnite). The conversion from $\delta^{18}O_{PhosVSMOW}$ to $\delta^{18}O_{carbVSMOW}$ is made using the equation $\delta^{18}O_{carbVSMOW}= (\delta^{18}O_{phosVSMOW} +9.6849)/1.0322$ (Chenery et al 2012), and the conversion from $\delta^{18}O_{carbVSMOW}$ to $\delta^{18}O_{CarbVPDB}$ is made using the equation $\delta^{18}O_{carbVPDB}=(0.97006*\delta^{18}O_{carbVSMOW})-29.94$ (Chenery et al 2012).

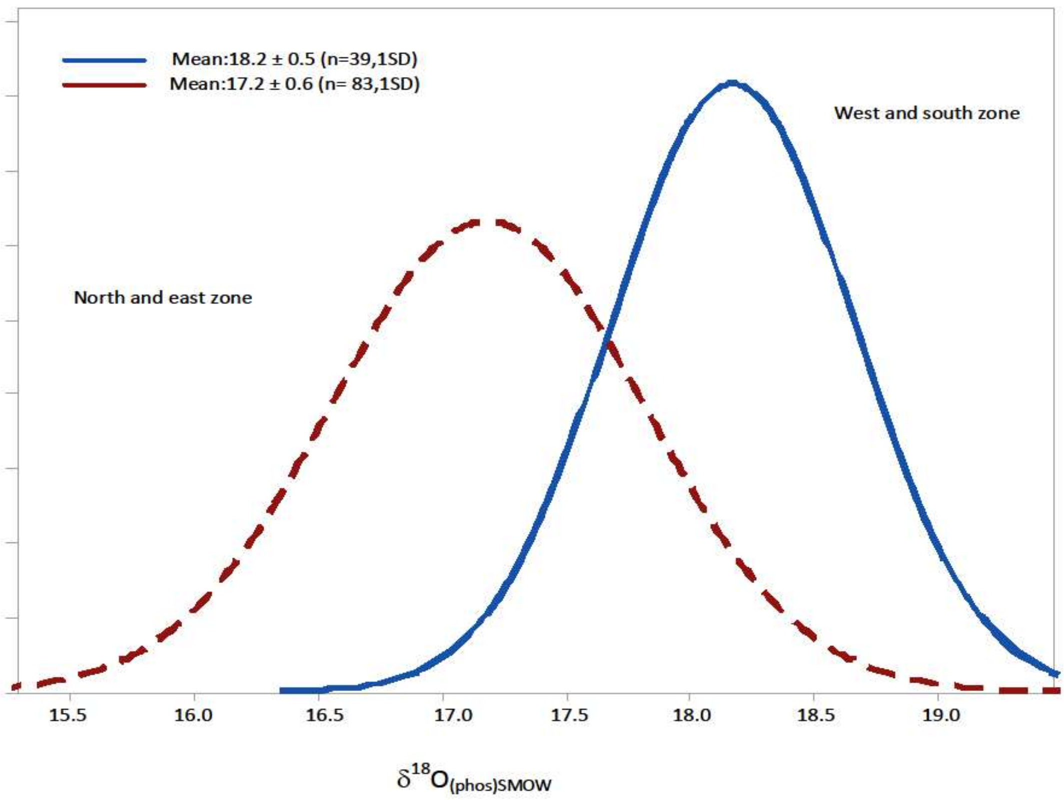

Figure 8 The datasets for the $\delta^{18}O_{phos}$‰ $_{(VSMOW)}$ human enamel which characterize the twofold subdivision of Great Britain.

3.3 USING THE WEB PORTAL

The webpage that hosts this site can be accessed here:

https://www.bgs.ac.uk/datasets/biosphere-isotope-domains-gb/

The Biosphere Isotope Domains (V2) GIS dataset can be interrogated by typing a value (or values) into the appropriate query boxes. The query will highlight in orange on the map all of the areas of Great Britain which fall within the designated statistical ranges. The highlighted areas therefore represent regions which **cannot be excluded** as a source/match for the interrogation.

The results can be downloaded by generating a report and map within the webpage.

3.4 DATASET HISTORY

This is Version 2 of the Biosphere Isotope Domains GB dataset.

- Much of the Sr data was published in Evans et al. (2018) but this has been added to considerably from both published and new datasets produced in collaboration with the National Environmental Isotope Facility (NEIF).
- Groundwater oxygen isotope data are from Darling et al. (2003).
- Human tooth enamel data are from Evans et al. (2012).
- Plant sulphur isotope data are predominantly from a new dataset produced by NEIF.

3.5 COVERAGE

The Biosphere Isotope Domains GB (V2) dataset covers Great Britain, which includes the Shetland Islands, Orkney Islands, Inner and Outer Hebrides, Isles of Scilly, the Isle of Wight and Lundy. It does not currently extend to Northern Ireland or the Isle of Man.

The Biosphere Isotope Domains GB (V2) dataset coverage is for all of Great Britain, as described above, although coverage for the different domains is variable.

Figure 9 The coverage of the Biosphere Isotope Domains (V2) dataset, including the Inner and Outer Hebrides, Shetland and Orkney Islands, Isle of Wight and the Scilly Isles. Contains Ordnance Survey data © Crown copyright and database right 2023.

3.6 DATA FORMAT

The Biosphere Isotope Domains GB (V2) dataset has been created as vector polygons which are available in ESRI ArcGIS (.shp) and GeoPackage (.gpkg) format. More specialised formats may be available upon request. The Sr, S and Pb isotope sample data that underpin this dataset are also available to download from:

https://www.bgs.ac.uk/datasets/biosphere-isotope-domains-gb/.

3.6.1 Shapefile

Included with the shapefile are .lyr files specifying the symbology for:

- Lead $206^{Pb}/204^{Pb}$ minimum
- Oxygen $\delta^{18}O$ drinking water ‰
- Oxygen human tooth enamel $\delta^{18}O$ phos ‰
- Sulphur $\delta^{34}S$ in plants
- Sulphur $\delta^{34}S$ representing the coastal zone
- Strontium median values

3.6.2 GeoPackage

The GeoPackage stores the same symbologies as the .lyr files within the GeoPackage.

The default symbology is Lead $206^{Pb}/204^{Pb}$ minimum.

To apply other symbologies, go to Layer Properties > Symbology > Style > Load Style (Figure 10).

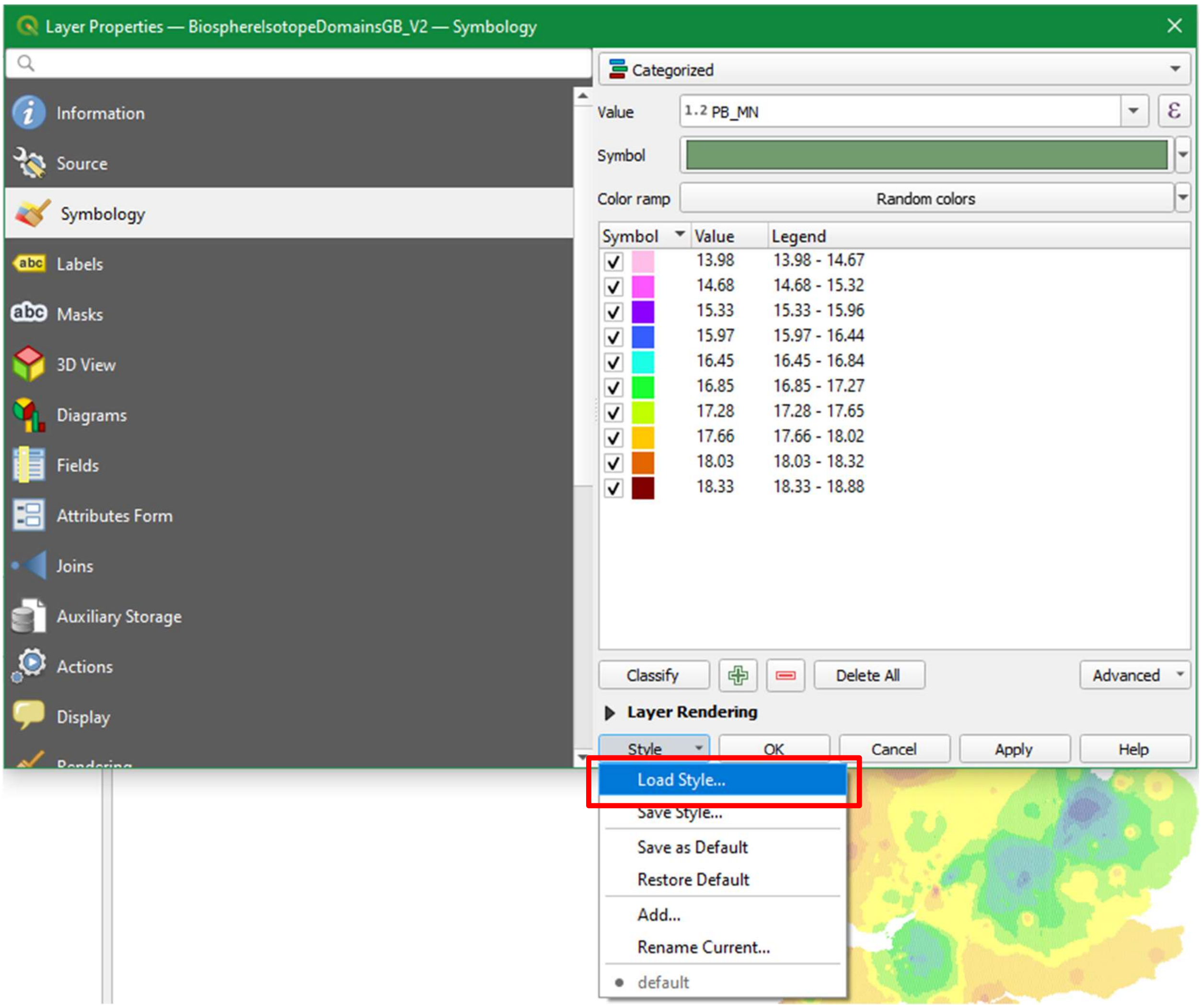

Figure 10 QGIS Layer Properties Window with "Load Style…" option highlighted.

This will open the Databases Styles Manager (Figure 11). Ensure "Load Style" dropdown at the top has "From Database (GeoPackage)" selected. Select the style to apply and choose "Load Style". This will load the style in the Layer Properties window; click "OK" or "Apply" to apply the new symbology to the data.

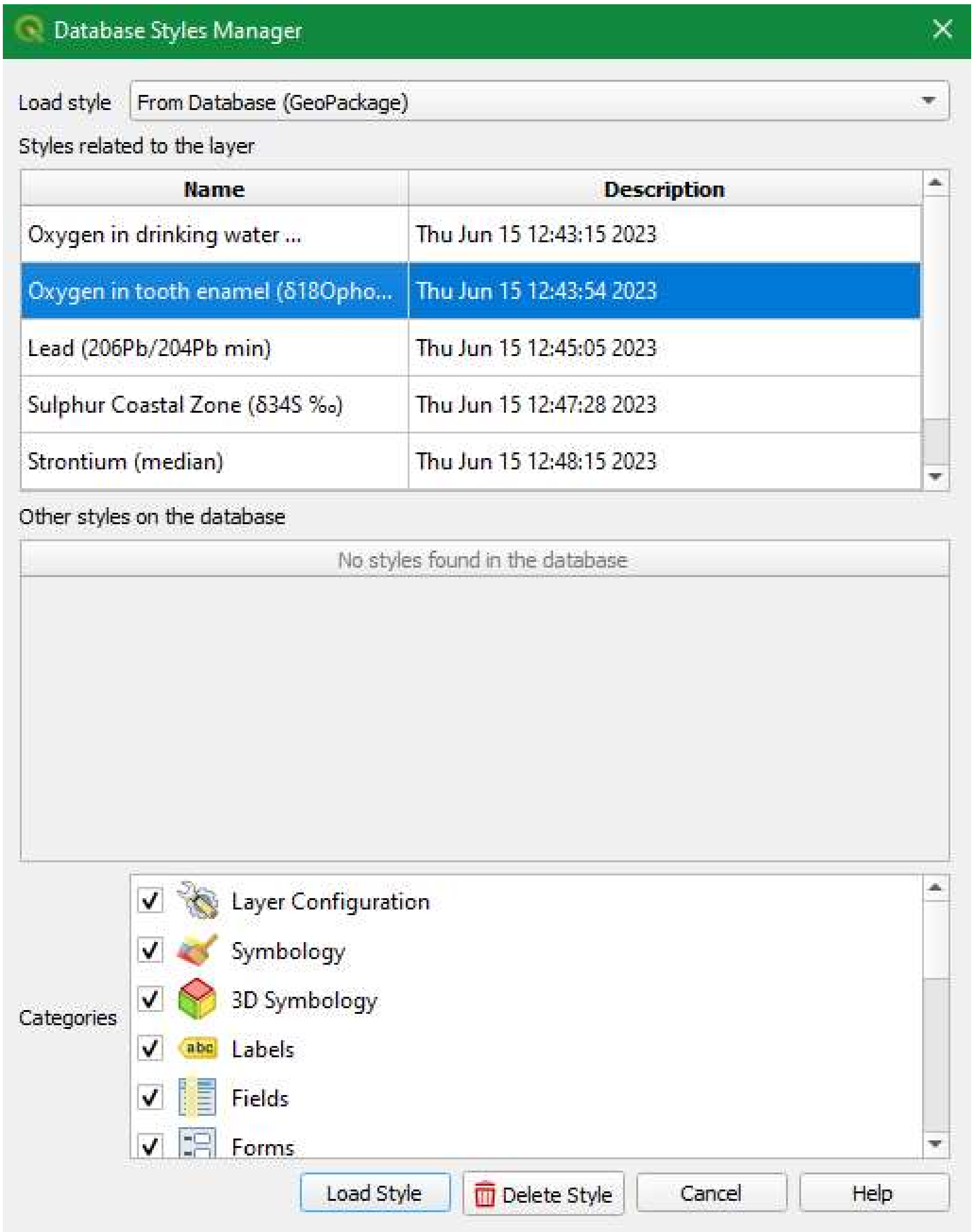

Figure 11 Database Styles Manager Window with "Oxygen in tooth enamel" style selected.

3.7 LIMITATIONS

There are a few limitations that should be taken into account when using the Biosphere Isotope Domains GB (V2) dataset.

3.7.1 Data density and statistical reliability

- The strontium domains that have been constructed have variable numbers of samples with which to define their statistical characteristics. Some of the large datasets e.g., CRETACEOUS: Sedimentary - precipitate/carbonate (i.e. chalk; n=111) and JURASSIC: Sedimentary – mudrock (i.e. Jurassic clay; n=111) can be viewed as statistically robust, whereas others display a large range of values over a limited number of samples, such as the ORDOVICIAN: Igneous – granite of Scotland (n=2).

- Areas for which there are no data have been extrapolated using comparable datasets. For example, there are no data from the PERMIAN: Sedimentary - mudrocks so the data from PERMIAN: Sedimentary – sand-silt has been used as a proxy. See Appendix 2 for a table of data absent domains and their substitutions. These domains represent a relatively small proportion of the map.

3.7.2 Application constraints

- The strontium isotope data is derived, predominantly, from plant samples, but is generally used for searches on human origins. In order to use the more diverse plant data for human use it is recommended that the 50% central data set is used because the relationship between plant and human data suggests that the averaging process in human consumption reduced the data spread by a half (Evans et al 2012). However, for studies other than human origin studies (modern plants, herbivore origins) a wider range of plant data may be more appropriate and so the 90% central data set is available. All of the strontium domains represent a mixture between $^{87}Sr/^{86}Sr$ originating from soils with a variable contribution from rainwater and therefore it is expected that the extent of rainfall and water logging will affect the bioavailable values. Some sense of this variation can be derived from comparison of the 5, 25, 50, 75, and 95% interval maps given on the layers tab.
- The human enamel oxygen isotope layer is based on populations that are taken to be sedentary based on non-isotope criteria and the search ranges are set at the one standard deviation data range.
- **Note:** Oxygen isotope composition is species-dependent, so the human tooth enamel layer is only appropriate for the interpretation of human data.
- Caution should be used in applying the Pb isotope map to non-mineral studies as the resolution seen in the mineral data may not transmit directly into human and faunal samples. This map can only be used in human and faunal provenance studies where there has been no exposure to anthropogenic Pb.
- It is important to note that the sulphur isotope map is based on plants and the relationship between plant and fauna is not fully understood. While this map agrees with a recently published map based on insect compositions (Newton, 2021) its application to human data should be used with the understanding that (1) it may not be valid to equate sulphur values in plants directly with faunal samples as there may be trophic shifts, (Nehlich, 2015); (2) we believe the effect of modern pollution is minimal post 2016 when most of the samples were collected, (Zhao et al., 1998 and Lamb et al., in prep), however it cannot entirely be excluded; and (3) the level of regional variation seen in plant samples, may not mirror the natural variations seen in human and faunal samples which will average the plant samples over the time of consumption and collagen formation.

3.8 DATA SOURCES

The data for this website has predominantly been produced at the NEIF laboratories and published as collaborative studies. Increasingly, such data is becoming available from other laboratories, and this has been incorporated where available. Below we list the data sources used in this upgrade:

- Barreiro (1995)
- Blaxland et al. (1979)
- Blichert-Toft et al. (2016)
- Brettell et al. (2012)
- Chenery et al. (2010)
- Darling et al. (2003)
- Evans et al. (2022)
- Evans and Tatham (2004)
- Evans et al. (2009)
- Evans et al. (2010)

- Evans and Bullman (2009)
- Jay et al. (2013)
- Johnson (2018)
- Johnson et al. (2022)
- Lamb et al. (2012)
- Leach et al. (2009)
- Madgwick et al. (2019)
- Melton et al. (2010)
- Montgomery (2002)
- Montgomery et al. (2006)
- Montgomery et al. (2003)
- Montgomery et al. (2014)
- Moore (submitted)
- Müldner et al. (2011)
- Müldner et al. (2022)
- Parnell and Swainbank (1985)
- Pearson et al. (2016)
- Schulting et al. (2019)
- Shepherd et al (2000)
- Snoeck et al. (2018)
- Shepherd et al. (2000)
- Trickett (2007)
- Unpublished data (this study)
- Warham (2012)

4 Licensing Information

4.1 BGS LICENCE TERMS

To encourage the use and re-use of this data we have made it available under the Open Government Licence (www.nationalarchives.gov.uk/doc/open-government-licence/version/3/), subject to the following acknowledgement accompanying the reproduced BGS materials: "Contains British Geological Survey materials ©UKRI 2023".

The Open Government Licence is a simple and straightforward licence that allows anyone - businesses, individuals, charities and community groups - to re-use public sector information without having to pay or get permission.

4.2 OPENGEOSCIENCE

This dataset falls under BGS' OpenGeoscience portfolio of datasets and services. OpenGeoscience provides a wide range of freely available geoscience information allowing you to view maps, download data, scans, photos and other information. The services available under OpenGeoscience include:

- Map viewers
- Apps
- Downloadable data
- Web services
- Photos and images
- Publications
- Scanned records
- Collections

Please refer to OpenGeoscience (www.bgs.ac.uk/Opengeoscience) for more information and for a full listing of datasets and services available under this service.

4.3 DATA ACKNOWLEDGMENTS

Please use the following acknowledgements when using Biosphere Isotope Domains GB.

4.4 CONTACT INFORMATION

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Glossary

Term	Explanation
Biosphere	The regions of the surface and atmosphere of the earth or another planet occupied by living organisms.
Count	The number of sample values used to define a category within an isotope domain (given in the field **SR_N** of the GIS dataset).
Domain	Refers to the 4 different elements (Sr, O, S, Pb) and their isotope variations described in this dataset.
Hexagon	The shape of the cells in the map representing the isotope domains data.
Hydrosphere	Refers to atmospheric water (precipitation), surface and groundwater.
Interquartile range	Is a measure of statistical dispersion, being equal to the difference between 75th and 25th percentiles centred around the median of the sample, excluding statistical outliers.
Isotope	Each of two or more forms of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence differ in relative atomic mass but not in chemical properties; in particular, a radioactive form of an element.
Median*	Denoting or relating to a value or quantity lying at the midpoint of a frequency distribution of observed values or quantities, such that there is an equal probability of falling above or below it.
Maximum value	The highest value in a data set.
Mean*	The central value of a discrete set of numbers: specifically, the sum of the values divided by the number of values.
Minimum value	The lowest value in a data set.
Statistical uncertainty	The margin of error of a measurement, when explicitly stated, and is given by a range of values likely to enclose the true value.
1 Standard deviation (1SD)	A measure, for a set of data, of the spread from its mean. It is calculated as $\sqrt{\sum \frac{(x-\bar{x})^2}{n-1}}$ or the square root of variance by determining the variation between each data point relative to the mean.
1st Quartile (Q1*)	The lower half of the interquartile range representing the upper 25 to 50% of the data set, excluding statistical outliers (**SR_Q1** field in the GIS dataset).
3rd Quartile (Q3*)	The upper half of the interquartile range representing the upper 50 to 75% of the data set, excluding statistical outliers (**SR_Q3** field in the GIS dataset).

**Calculated using Excel functions.*

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Appendix 1

The 94 strontium domains are listed in the table below, with the naming format 'AGE: Primary rock type – secondary rock type (location).

Strontium domain name
CAMBRIAN: Igneous - acid (Scotland and Wales)
CAMBRIAN: Igneous - intermediate-basic (England, Scotland and Wales)
CAMBRIAN: Sedimentary - mudrock (England and Wales)
CAMBRIAN: Sedimentary - mudrock (Scotland)
CAMBRIAN: Sedimentary - precipitate/carbonate (Scotland)
CAMBRIAN: Sedimentary - sand-silt (England and Wales)
CAMBRIAN: Sedimentary - sand-silt (Scotland)
CARBONIFEROUS: Igneous - granite (England and Scotland)
CARBONIFEROUS: Igneous - granite (Isles of Scilly)
CARBONIFEROUS: Igneous - intermediate-basic (England, Scotland and Wales)
*CARBONIFEROUS: Igneous thermal alteration and high Rb (England)
CARBONIFEROUS: Sedimentary - mudrock (England, Scotland and Wales)
CARBONIFEROUS: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
CARBONIFEROUS: Sedimentary - precipitate/non-carbonate (England and Wales)
CARBONIFEROUS: Sedimentary - sand-silt (Central and Northern England and Wales)
CARBONIFEROUS: Sedimentary - sand-silt (Scotland)
CARBONIFEROUS: Sedimentary - sand-silt (Southern England and Wales)
CENOZOIC: Igneous - acid (Scotland)
CENOZOIC: Igneous - granite (Lundy)
CENOZOIC: Igneous - granite (Scotland)
CENOZOIC: Igneous - intermediate-basic (England, Scotland and Wales)
CENOZOIC: Sedimentary - mudrock (England, Scotland and Wales)
CENOZOIC: Sedimentary - precipitate/carbonate (England)
CENOZOIC: Sedimentary - sand-silt (England, Scotland and Wales)
CENOZOIC: Sedimentary (Machair)
CRETACEOUS: Sedimentary - mudrock (England and Wales)
CRETACEOUS: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
CRETACEOUS: Sedimentary - sand-silt (England and Scotland)
DEVONIAN: Igneous - acid (England and Scotland)
DEVONIAN: Igneous - granite (Lake District and Southern Uplands)
DEVONIAN: Igneous - granite (Scotland)
DEVONIAN: Igneous - intermediate-basic (England, Scotland and Wales)
DEVONIAN: Sedimentary - mudrock (England, Scotland and Wales)
DEVONIAN: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
DEVONIAN: Sedimentary - sand-silt (England)
DEVONIAN: Sedimentary - sand-silt (Orkney and Shetland Islands)
DEVONIAN: Sedimentary - sand-silt (Scotland)
JURASSIC: Sedimentary - mudrock (England, Scotland and Wales)
JURASSIC: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
JURASSIC: Sedimentary - precipitate/non-carbonate (England)
JURASSIC: Sedimentary - sand-silt (England and Scotland)

NONE: Igneous - intermediate-basic (Scotland)
ORDOVICIAN: Igneous - acid (England and Wales)
ORDOVICIAN: Igneous - acid (Scotland)
ORDOVICIAN: Igneous - granite (England and Wales)
ORDOVICIAN: Igneous - granite (Scotland)
ORDOVICIAN: Igneous - intermediate-basic (England, Scotland and Wales)
ORDOVICIAN: Igneous thermal alteration (Scotland)
ORDOVICIAN: Sedimentary - mudrock (England and Wales)
ORDOVICIAN: Sedimentary - mudrock (Scotland)
ORDOVICIAN: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
ORDOVICIAN: Sedimentary - precipitate/non-carbonate (Scotland)
ORDOVICIAN: Sedimentary - sand-silt (England and Wales)
ORDOVICIAN: Sedimentary - sand-silt (Scotland)
PERMIAN: Igneous - intermediate-basic (England and Scotland)
PERMIAN: Sedimentary - mudrock (England, Scotland and Wales)
PERMIAN: Sedimentary - precipitate/carbonate (England and Scotland)
PERMIAN: Sedimentary - sand-silt (England, Scotland and Wales)
PRECAMBRIAN: Igneous - acid (England and Wales)
PRECAMBRIAN: Igneous - granite (England and Wales)
PRECAMBRIAN: Igneous - granite (Hebrides)
PRECAMBRIAN: Igneous - granite (Scotland)
PRECAMBRIAN: Igneous - intermediate-basic (Charnwood)
PRECAMBRIAN: Igneous - intermediate-basic (England and Wales)
PRECAMBRIAN: Igneous - intermediate-basic (Scotland)
PRECAMBRIAN: Igneous (Malverns Complex)
PRECAMBRIAN: Metamorphic - calc-silicate (Scotland and Wales)
PRECAMBRIAN: Metamorphic - gneiss/acid (England and Wales)
PRECAMBRIAN: Metamorphic - gneiss/acid (Scotland)
PRECAMBRIAN: Metamorphic - gneiss/basic (Scotland)
PRECAMBRIAN: Metamorphic - pelite (England and Wales)
PRECAMBRIAN: Metamorphic - pelite (Scotland)
PRECAMBRIAN: Metamorphic - psammite (England and Wales)
PRECAMBRIAN: Metamorphic - psammite (Scotland)
PRECAMBRIAN: Metamorphic - schist (England and Wales)
PRECAMBRIAN: Metamorphic - schist (Scotland)
PRECAMBRIAN: Metamorphic - schist/basic (England, Scotland and Wales)
PRECAMBRIAN: Sedimentary - precipitate/carbonate (Scotland)
SILURIAN: Igneous - acid (England, Scotland and Wales)
SILURIAN: Igneous - granite (Scotland - Grampians)
SILURIAN: Igneous - granite (Scotland - Highlands)
SILURIAN: Igneous - granite (Scotland - Southern Uplands)
SILURIAN: Igneous - intermediate-basic (England, Scotland and Wales)
SILURIAN: Igneous thermal alteration and high Rb (Scotland)
SILURIAN: Sedimentary - mudrock (England and Scotland)
SILURIAN: Sedimentary - mudrock (Wales)
SILURIAN: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
SILURIAN: Sedimentary - sand-silt (England and Wales)

SILURIAN: Sedimentary - sand-silt (Scotland)
TRIASSIC: Sedimentary - mudrock (England, Scotland and Wales)
TRIASSIC: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
TRIASSIC: Sedimentary - precipitate/non-carbonate (England and Wales)
TRIASSIC: Sedimentary - sand-silt (England, Scotland and Wales)
TRIASSIC: Sedimentary - sand-silt (Sherwood Forest)

Appendix 2

The domains for which there are no representative data and the proxy data used as a substitute.

Data absent domain	Domain data used for data absent domains
CAMBRIAN: Sedimentary - mudrock (Scotland)	CAMBRIAN: Sedimentary - mudrock (England and Wales)
CAMBRIAN: Sedimentary - sand-silt (Scotland)	CAMBRIAN: Sedimentary - sand-silt (England and Wales)
CRETACEOUS: Igneous - intermediate/basic (England and Scotland)	CARBONIFEROUS: Igneous - intermediate-basic (England, Scotland and Wales)
CENOZOIC: Igneous - acid (Scotland)	CENOZOIC: Igneous - granite (Scotland)
CENOZOIC: Sedimentary - precipitate/carbonate (England)	CENOZOIC: Sedimentary (Machair)
DEVONIAN: Igneous - granite (Lake District and Southern Uplands)	DEVONIAN: Igneous - acid (England and Scotland)
DEVONIAN: Igneous - granite (Scotland)	DEVONIAN: Igneous - acid (England and Scotland)
SILURIAN: Igneous - acid (England, Scotland and Wales)	DEVONIAN: Igneous - acid (England and Scotland)
PERMIAN: Igneous - intermediate/basic (England and Scotland)	DEVONIAN: Igneous - intermediate-basic (England, Scotland and Wales)
DEVONIAN: Sedimentary - precipitate/carbonate (England, Scotland and Wales)	JURASSIC: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
JURASSIC: Sedimentary - sand-silt (England and Scotland)	JURASSIC: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
PRECAMBRIAN: Sedimentary - precipitate/carbonate (Scotland)	JURASSIC: Sedimentary - precipitate/carbonate (England, Scotland and Wales)
CAMBRIAN: Igneous - acid (Scotland and Wales)	ORDOVICIAN: Igneous - acid (England and Wales)
ORDOVICIAN: Igneous - acid (Scotland)	ORDOVICIAN: Igneous - acid (England and Wales)
NONE: Igneous - intermediate/basic (Scotland)	ORDOVICIAN: Igneous - intermediate/basic (Scotland, England and Wales)
SILURIAN: Igneous - intermediate/basic (England, Scotland and Wales)	ORDOVICIAN: Igneous - intermediate/basic (Scotland, England and Wales)
ORDOVICIAN: Sedimentary - mudrock (Scotland)	ORDOVICIAN: Sedimentary - mudrock (England and Wales)
PERMIAN: Sedimentary - mudrock (England, Scotland and Wales)	PERMIAN: Sedimentary - sand-silt (England, Scotland and Wales)
PRECAMBRIAN: Igneous - granite (England and Wales)	PRECAMBRIAN: Igneous - acid (England and Wales)
CAMBRIAN: Igneous - intermediate-basic (England, Scotland and Wales)	PRECAMBRIAN: Igneous - intermediate/basic (England and Wales)
PRECAMBRIAN: Igneous - granite (Scotland)	PRECAMBRIAN: Igneous - intermediate/basic (England and Wales)
PRECAMBRIAN: Igneous - intermediate/basic (Scotland)	PRECAMBRIAN: Igneous - intermediate/basic (England and Wales)

PRECAMBRIAN: Igneous - intermediate-basic (Charnwood)	PRECAMBRIAN: Igneous - intermediate/basic (England and Wales)
PRECAMBRIAN: Metamorphic - gneiss/basic (Scotland)	PRECAMBRIAN: Igneous - intermediate/basic (England and Wales)
PRECAMBRIAN: Metamorphic - schist/basic (England, Scotland and Wales)	PRECAMBRIAN: Igneous - intermediate/basic (England and Wales)
PRECAMBRIAN: Metamorphic - gneiss/acid (England and Wales)	PRECAMBRIAN: Metamorphic - gneiss/acid (Scotland)
PRECAMBRIAN: Metamorphic - pelite (England and Wales)	PRECAMBRIAN: Metamorphic - pelite (Scotland)
PRECAMBRIAN: Metamorphic - schist (Scotland)	PRECAMBRIAN: Metamorphic - psammite (Scotland)
SILURIAN: Igneous - granite (Scotland - Southern Uplands)	SILURIAN: Igneous - granite (Scotland - Highlands)
ORDOVICIAN: Igneous - thermal alteration (Scotland)	SILURIAN: Igneous thermal alteration and high Rb (Scotland)
SILURIAN: Sedimentary - mudrock (England and Scotland)	SILURIAN: Sedimentary - mudrock (Wales)
SILURIAN: Sedimentary - precipitate/carbonate (England, Scotland and Wales)	TRIASSIC: Sedimentary - precipitate/carbonate (England, Scotland and Wales)

Appendix 3

Colour lookup tables for GIS layers.

Strontium

VALUE (STRONTIUM MEDIAN)	RED	GREEN	BLUE	HEX	LOOKS LIKE
0.7083 - 0.7085	11	44	122	#0B2C7A	
0.7086 - 0.7089	24	117	140	#18758C	
0.7090 - 0.7097	27	168	124	#1BA87C	
0.7098 - 0.7102	6	212	27	#06D41B	
0.7103 - 0.7108	123	237	0	#7BED00	
0.7109 - 0.7112	252	240	3	#FCF003	
0.7113 - 0.7118	240	180	17	#F0B411	
0.7119 - 0.7133	219	122	37	#DB7A25	
0.7134 - 0.7180	230	0	0	#E60000	

Sulphur

VALUE (SULPHUR δ34S) Plants	RED	GREEN	BLUE	HEX	LOOKS LIKE
-28.60 - -15.29	11	44	122	#0B2C7A	
-15.58 - -9.96	22	103	138	#16678A	
-9.95 - -6.16	32	153	143	#20998F	
-6.15 - -2.73	20	186	95	#14BA5F	
-2.72 - 0.12	0	219	0	#00DB00	
0.13 - 2.40	123	237	0	#7BED00	
2.41 - 4.49	255	255	0	#FFFF00	
4.50 - 6.40	245	202	12	#F5CA0C	
6.41 - 8.87	237	161	19	#EDA113	
8.88 - 11.34	214	111	43	#D66F2B	
11.35 - 19.90	194	82	60	#C2523C	

VALUE (SULPHUR δ34S) Coastal zone	RED	GREEN	BLUE	HEX	LOOKS LIKE
8.8 - 21	132	0	168	#8400A8	

Lead

VALUE (LEAD 206Pb/204Pb MINIMUM)	RED	GREEN	BLUE	HEX	LOOKS LIKE
13.98 - 14.67	255	190	232	#FFBEE8	
14.68 - 15.32	255	87	255	#FF57FF	
15.33 - 15.96	140	0	255	#8C00FF	
15.97 - 16.44	54	94	255	#365EFF	
16.45 - 16.84	28	255	232	#1CFFE8	
16.85 - 17.27	25	255	48	#19FF30	
17.28 - 17.65	191	255	0	#BFFF00	
17.66 - 18.02	255	200	0	#FFC800	
18.03 - 18.32	227	102	0	#E36600	
18.33 - 18.88	128	0	0	#800000	

Oxygen – drinking water

VALUE (OXYGEN $\delta^{18}O_{drinking\ water}$ ‰)	RED	GREEN	BLUE	HEX	LOOKS LIKE
-9.0 - -8.5	56	168	0	#38A800	
-8.5 - -8.0	94	189	0	#5EBD00	
-8.0 - -7.5	139	209	0	#8BD100	
-7.5 - -7.0	193	232	0	#C1E800	
-7.0 - -6.5	255	255	0	#FFFF00	
-6.5 - -6.0	255	191	0	#FFBF00	
-6.0 - -5.5	255	128	0	#FF8000	
-5.5 - -5.0	255	64	0	#FF4000	
-5.0 - -4.5	255	0	0	#FF0000	

Oxygen – human enamel

VALUE (OXYGEN $\delta^{18}O_{phos}$ ‰)	RED	GREEN	BLUE	HEX	LOOKS LIKE
16.6 - 17.9	56	168	0	#38A800	
17.7 - 18.7	255	0	0	#FF0000	