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A global dataset of helium isotopic data in tectonically and hydrothermally active geological environments

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Since the early 1970s, helium isotopes ^{3}He and ^{4}He have been used to trace the sources of deep-seated fluids in various geodynamic settings. Observed variations in the $^{3}He/^{4}He$ ratio measured at the surface are ascribed to source compositional variability or differences in the efficiency of mantle He transport through the continental crust. Given the high scientific relevance of helium isotopes across a wide range of geoscientific applications, it appears essential to compile existing bibliographic information on their global spatial distribution. Here, we present a dataset of the helium isotopic composition in geofluids from hydrothermal and tectonically active areas. Using two global databases published in 2006 and 2015 as a starting point, we have reviewed the existing international literature to compile a comprehensive database of data published up to 2024. The goal is to provide a resource for investigating potential relationships between helium isotopes with other geological, hydrogeological, and geophysical parameters and to formulate hypotheses regarding the role of geofluids in crustal deformation processes.

Background & Summary

Geochemical investigations of geofluids are crucial for gaining knowledge about the Earth and studying local and global tectonic and geodynamic evolutions. Efficient gathering, organization, and distribution of this kind of information are crucial for facilitating innovative and practical research in various fields, such as tectonics, volcanology, and geothermal energy, in the pursuit of a possible digital model of the Earth (e.g.[1–3]). Various global databases - often open access on websites - are available on rocks and minerals[4], general geochemistry (e.g., Geochemical Earth References Model or GERM[5]) or about geophysical parameters[6–9]. In contrast, there is less interest in the geochemical parameters of geofluids and their global distribution. Annually, the global volume of recorded data increases and is distributed among numerous individual publications. Over the past few decades, there has been a significant increase in knowledge about geofluid geochemistry, largely due to the widespread availability of advanced analytical equipment that enables the analysis of a complete set of elements and isotopes in water and associated gas species[10–13]. Consequently, global geochemical databases are expanding rapidly and are expected to continue increasing exponentially over the next decade: Milkov and Etiope[14], Etiope *et al.*[15] and Etiope[16] proposed global databases of geographical distribution and geochemical parameters of natural CH_4 emissions and hydrocarbons found in shales. Tamburello *et al.*[17,18] proposed two global databases about the geographical distribution of CO_2 geological emissions and thermal springs, respectively. Dugamin *et al.*[19] presented a geochemical database on brines from hydrocarbon and geothermal wells. Zgonnik[20] compiled a global database of hydrogen emissions from natural features and selected wells in various geological environments.

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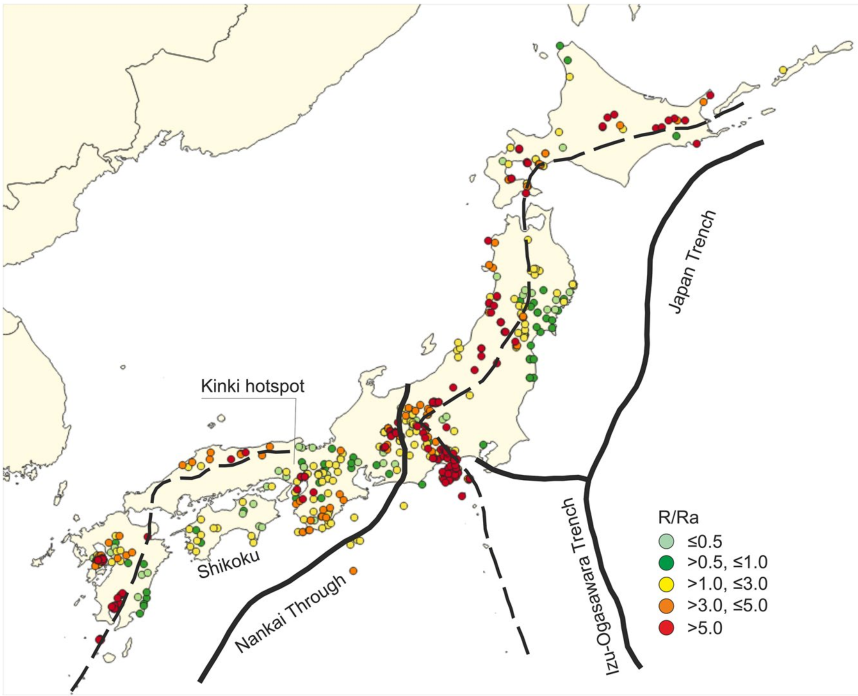

Fig. 1 Geographical distribution of thermal springs in Japan with a color code indicating the range of measured $^3He/^4He$ ratios reported as R/Ra values. Plate boundaries (bold lines) and the volcanic front (dashed lines) are reported from the original drawing of[33].

In contrast, the noble gas community dramatically lacks such open-access databases, making data mining and review articles a laborious effort for a single researcher. Helium isotopes have been successfully applied for more than 40 years as index of magma ascent towards the earth's surface (e.g.[21–24]) and over time have become established as the tracers of choice for identifying the upwelling of deep fluids within hydrothermal/geothermal systems (e.g.[25]), and in areas lacking active volcanism (e.g.[26,27]).

Recent studies suggested that helium isotopes are also essential for identifying active faults in areas of active crustal deformation (e.g.[26,28–32]). It has been largely demonstrated that mapping geochemical information into a tectonic and geophysical framework facilitates a deeper understanding of fluid movement in the Earth's crust, and virtually all crustal processes. A classic example from literature showing the strict relation between tectonic features and processes and the helium isotopic composition of thermal fluids is that of the Japanese Archipelago (e.g.[33–37]). Herein, we re-examine the most significant results previously obtained using the data gathered for this study (Fig. 1). Since the seminal work of[33], a direct relationship has been established between the higher, mantle-like $^3He/^4He$ ratios and the position of the volcanic front, as well as the two adjacent areas of the back-arc and the forearc. In NE Japan, the highest mantle-like helium isotopic signatures in thermal springs are found at the apex of the volcanic front and in the back-arc region. At the same time, in the forearc, the proximity of the subducting plate releases fluids containing radiogenic helium, which lowers the $^3He/^4He$ ratios in spring's fluids. This relation is less evident in SW Japan because high $^3He/^4He$ values are also found in the forearc, possibly caused by incipient recent magmatism and a warmer, younger plate subducting[33]. There are two anomalies in Japan, the so-called Kinki hotspot, which is centered around the Arima hot spring area, located between Kobe and Osaka cities, and the Shikoku Island, central Japan (Fig. 1).

The Kinki region is non-volcanic, yet the measured $^3He/^4He$ ratios in springs as Arima reach values of 7.4Ra with 90% of the helium being mantle-derived[34]. There are at least two possible explanations to this anomaly. Matsumoto *et al.*[34] suggested the presence of fluids derived from the dehydration of a steeply subducting Philippine plate, scavenging pure mantle helium from the mantle wedge and arising to the surface. Based on tomography imaging and the geographical distribution of helium anomalies, Sano *et al.*[37] suggested that the slab contains the remnant of an old spreading center that plays the role of a slab tear fissure where pure mantle helium arises directly in the Kinki area.

Shikoku Island springs contain very radiogenic $^3He/^4He$ ratios ranging from 0.21 to 2.5 Ra (e.g.[35]). According to the distribution of crustal microearthquakes and their focal mechanisms, the geotectonic environment beneath Shikoku Island is subject to a stress field with extremely low crustal seismicity. This argues against migration of aqueous fluids from the subcrustal lithosphere, as in the Kinki hotspot[34], resulting in a relatively small influence of mantle-derived helium at the surface. Umeda *et al.*[35] suggested that this area contains an aged mantle helium signal related to Miocene magmatism (with a R/Ra of 3.4 or less) and atmospheric and radiogenic helium from local sources. This area is affected by a smaller number of earthquakes than the surrounding area, yet far from being aseismic, with events of M 4 to 5 and rarer ones with M 6.3 or higher. This calls for further models to be explored to understand the complex relationship between tectonics and helium isotopes in springs in this region of central Japan.

With specific reference to potential correlations between helium isotopic composition, active faults, and crustal deformation, this work presents a global dataset of helium isotopic composition in geofluids sampled in various geological settings[38]. The dataset, hosted in the Zenodo repository (https://doi.org/10.5281/zenodo.14904325), incorporates peer-reviewed international literature up to 2024 and benefits from cross-referencing with data from existing databases. This compilation effort, focused on helium isotopes, aims to expand the suite of essential parameters for investigating the role of geofluids in crustal processes at global or macro-regional scales. Making this type of information readily available for future studies could be beneficial for developing more robust models and ensuring more accurate interpretations on the role of geofluids in the geodynamic processes shaping the Earth.

Methods

Dataset design criteria. During the compilation of the dataset, we applied the following primary criteria: (i) only data from peer-reviewed publications were included; (ii) we only considered data related to modern fluids, i.e., we excluded noble gas data from paleo-fluids, i.e. extracted from mineral inclusions (e.g.[39]); (iii) for sampling locations with multiple analyses over time, only the sample with the highest $^3He/^4He$ ratio was considered. This latter criterion addresses the need to identify the most representative value of the deep component, aligning with the dataset's primary purpose of enabling large-scale correlations with significant geological and/or geophysical parameters (e.g.[32]). Within this framework, the temporal variability of the helium isotopic signature, although potentially substantial for investigating local-scale interactions between different components, is not considered relevant. This is based on the common assumption that within a time series, the sample exhibiting the highest $^3He/^4He$ ratio is least affected by potential mixing with meteoric and crustal components. A similar approach has been previously adopted, e.g., for investigating mantle sources related to ore deposits (e.g.[40]).

Criteria for selecting new data included the availability of full geographical coordinates or, at a minimum, sufficiently accurate location maps within the original manuscripts that allowed for the approximate determination of the sampling point's coordinates. We have approximated their location using GIS-based georeferencing for several samples where exact geographic coordinates were not provided in the original publications. For georeferenced samples lacking geographical coordinates in the original publications, a maximum positional uncertainty of about 10 km is estimated. This offers a robust approximation, facilitating the comparison of our He dataset with various global maps of geophysical parameters (e.g., heat flow, S-wave attenuation) which are typically available with a spatial resolution of 1 degree latitude by 1 degree longitude, i.e., roughly more than 110 km resolution, for the best scenarios (e.g.[6,8]). It is worth noting that the available geographical coordinates were cross-checked, revealing that less than 5% of the data reported uncorrected values that needed to be georeferenced.

Data from hydrocarbon reservoirs were excluded due to the complex geological setting of these systems, where the interplay of generation, migration, accumulation, and mixing of fluids from different sources makes it difficult to establish correlations between helium isotopic composition and tectonic activity. Furthermore, due to commercial confidentiality, oil and gas noble gas compositional catalogs remain biased by the largely incomplete data set. Helium is often measured by oil companies with significant uncertainties and without isotopic information (mainly ^4He elemental concentration). Yet databases are available. For example, USGS has compiled a database with more than 13,000 helium concentration data from oil/gas wells in the United States but lacks isotopic composition data[41].

The presented dataset was constructed by manually entering data from selected publications published up to December 2024. The entered data was then cross-referenced with two previously published global databases: (i) the USGS database[42] (hereafter referred to as 'USGS_db'), and (ii) the database compiled by[43] (hereafter referred to as 'PLK_db'). This cross-checking process helped to minimize data entry and location errors.

The USGS_db is a Microsoft Excel file that includes approximately 5,000 entries of data published up to 2003 on noble gas concentrations and isotopic ratios from volcanic systems in Mid-Ocean ridges, ocean islands, seamounts, and oceanic and continental arcs. Sometimes, the dataset includes multiple analyses from the same sampling location. Data on the isotopic composition of higher noble gases (e.g., Ar, Kr, Xe) is sometimes available, accompanied by other significant geochemical parameters, such as carbon isotopic composition or $CO_2/^3He$ ratio. The sources from which the data were obtained are fully documented.

The PLK_db is an MS Excel file released in 2015 that comprises over 7,200 data points, including multiple analyses for some samples. The dataset is extensive, providing compositional details for the full suite of noble gases and, in some cases, major gas chemistry. For each data point, the source is indicated, including, in some instances, comments and other general information about sampling and/or analysis. Most of the data originates from regional literature, which is not always readily accessible. The database contains numerous analyses of gases from hydrocarbon reservoirs and natural gas fields, as well as unpublished data that are not relevant to the purpose of the new dataset presented here.

Several recently compiled macro-regional datasets have also been used to cross-validate the accuracy and completeness of our dataset, which include present-day geofluids analyses for Iceland[44], Andean Cordillera in South America[45], western part of Northern America[46,47], hydrothermal/geothermal features of Mexico[48] and worldwide volcanoes in arc-related settings[49].

Dataset structure. Our dataset (hereafter referred to as CNR-IGG_db) has a relatively simple structure. For each data entry, we provided geographic information, the isotopic composition of helium, the He/Ne ratio (when available), and information on the year of publication and the bibliographic citation. The dataset includes both descriptive and quantitative geographic information. Descriptive geographic data are provided at three levels:

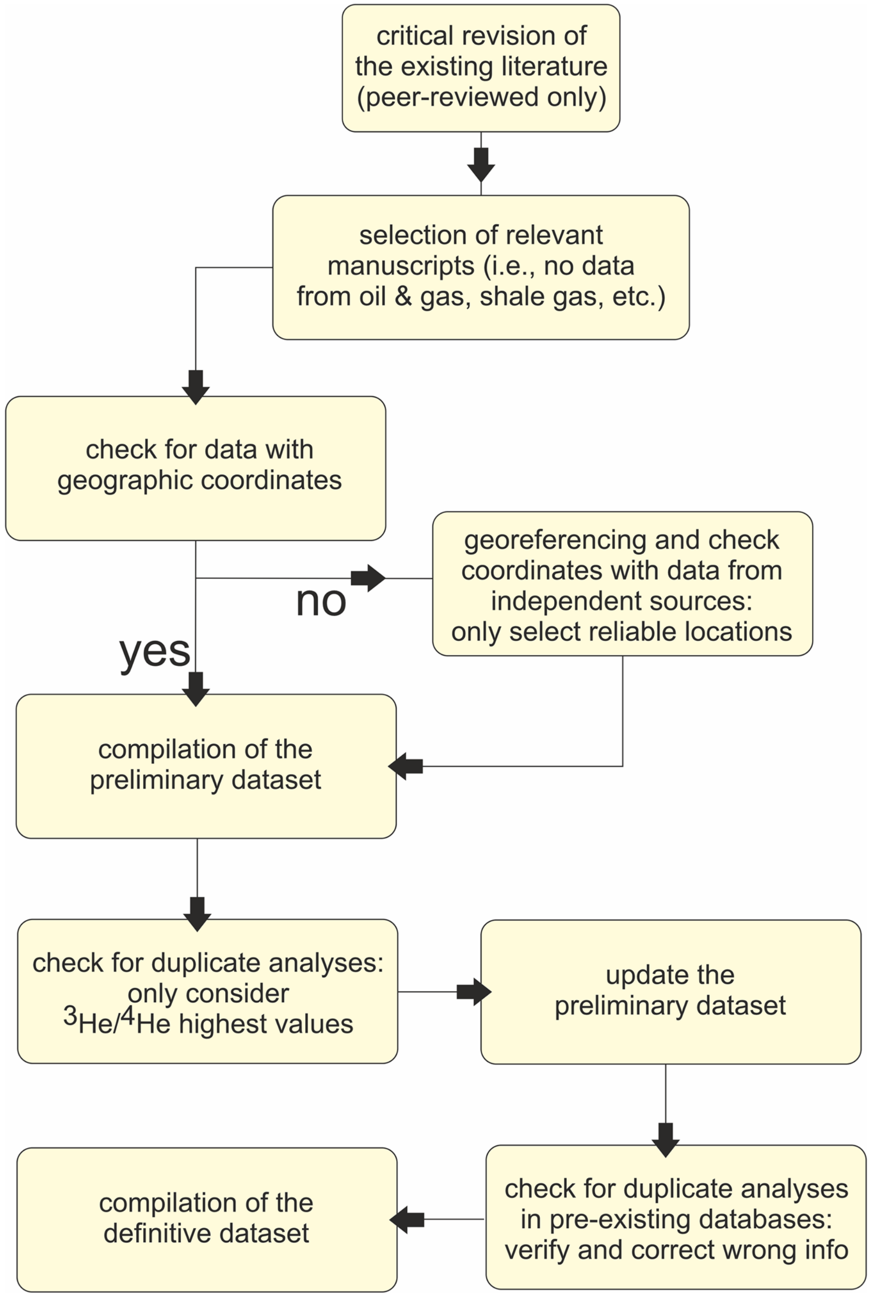

Fig. 2 Flowchart illustrating the dataset compilation procedure.

(i) macro-region or country, (ii) geological setting or geographical region, and (iii) specific location or feature. Quantitative data includes latitude and longitude coordinates based on the WGS84 datum (decimal degrees). Helium isotopic composition is presented in multiple formats, each in a separate column, according to the conventions employed in the original manuscripts. These include: (i) measured $^3He/^4He$ ratio, (ii) $^3He/^4He$ ratio normalized to the atmospheric reference value (here the value adopted is 1.384×10^{-6}[50]), $(R/Ra)_m$; and (iii) $^3He/^4He$ ratio normalized to the atmospheric reference value and corrected for atmospheric contamination $(R/Ra)_c$ using classical formulas from[51],[52]. For a given sample, there may be multiple data formats. Similarly, two fields have been provided for the He/Ne ratio, reflecting the different formats found in the literature: (i) He/Ne ratio; (ii) $^4He/^{20}Ne$ ratio. The dataset is currently structured as an MS Excel file with more than 6400 data entries. Approximately 61% and 34% of the data can be traced back to manuscripts published in the last 20 and 10 years, respectively. The final sources included in this dataset are listed in refs. [26,27,30,31,33,35,37,45–48,52–519]. Figure 2 illustrates the main phases of the process utilized for selecting data of interest, verifying the reliability of the acquired information, and subsequently performing any essential adjustments.

In its current form, the dataset (see Fig. 3 for the location of the data points) should be considered primarily as an initial working platform, with the prospect of evolving into a continuously updated and refined repository accessible to the entire scientific community via a dedicated website (hedb.cnr.it). The long-term goal is to

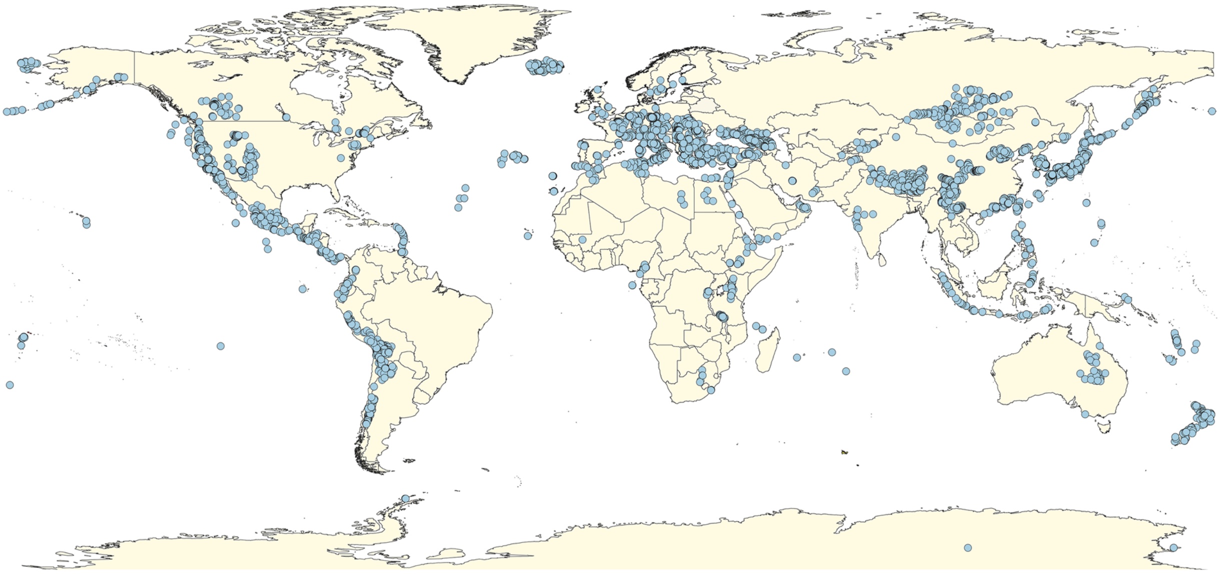

Fig. 3 Location of data points from CNR-IGG_db.

column header	description
#ID	progressive datum number
GEOGRAPHICAL_information_1	macro-region or country
GEOGRAPHICAL_information_2	geological setting or geographical region
GEOGRAPHICAL_information_3	specific location or feature
Lat_N	Latitude North, WGS84 (decimal degrees)
Long_E	Longitude East, WGS84 (decimal degrees)
(R/Ra)s	selected/unspecified $^3He/^4He$ ratio normalized to the atmospheric reference value [#]
(R/Ra)c	$^3He/^4He$ ratio normalized to the atmospheric reference value [§] and corrected for atmospheric contamination
(R/Ra)m	$^3He/^4He$ ratio normalized to the atmospheric reference value [§]
(3He/4He)m	$^3He/^4He$ measured ratio (* 10^{-6})
He/Ne	He/Ne mol/mol ratio
4He/20He	$^4He/^{20}He$ mol/mol ratio
Year	publication year
Reference	source publication from which the data was derived
doi / url	available persistent publication identifier

Table 1. Dataset variables. [#] selected $^3He/^4He$ value for each sample, used as official value for the database, when multiple conventions are listed [§] the atmospheric reference value adopted here is 1.384 × 10-6, as given by[50].

encourage voluntary contributions from researchers to maintain and enrich the dataset, following the collaborative model adopted by other resources (e.g., GERM[5]).

Data Records

Online documents supporting this study are available at the Zenodo repository as "A global dataset of helium isotopic data in tectonically and hydrothermally active geological environments"[38]). This repository includes two files: (1) Helium isotope dataset in MS Excel format. (2) List (in Adobe PDF format) of the literature references supporting data for 6463 helium isotope analyses worldwide. A detailed description of the variables included in the database (i.e., the column headers) is provided in Table 1.

Technical Validation

The primary source of inaccuracy in the information contained within the dataset is related to the absence or imprecision of the geographical coordinates indicated in the original source manuscripts. There is no automatic procedure to reduce this uncertainty. We then proceeded to verify the correct location of each point on the map, seeking information from other sources, primarily from other publications containing analyses of other geochemical parameters for the same points of interest. Additional verifications were also performed using geo-referencing procedures, utilizing the open-source software QGIS (GIS Development Team. QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://www.qgis.org/). To validate the procedure, coordinates from our dataset were compared against those of shared points in existing published datasets. This comparison highlighted several inaccuracies in the previously published datasets and manuscripts. Although the overall accuracy of our point locations cannot be precisely quantified, we estimate - excluding any data entry errors - that the maximum inaccuracy is well below a cautionary threshold of 10 km.

Data availability

The dataset is publicly available in the Zenodo repository, accession number 14904325 (https://doi.org/10.5281/zenodo.14904325).

Code availability

Dataset development did not necessitate any software creation.

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Competing interests

The authors declare no competing interests.

Additional information

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