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A global dataset of fluid-based pre-seismic anomalies in crustal environments

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1 Introduction

Seismic phenomena are among the deadliest geological disasters, together with other natural calamities such as volcanic eruptions, tsunamis, landslides and floodings (Ritchie et al., 2022; Reid and Mooney, 2023), as they can cause hundreds of thousands of casualties and extensive damage to infrastructure and communities (Lomnitz, 1994; Samardjieva and Badal, 2002; Holzer and Savage, 2013). Earthquake prediction remains one of the most elusive and controversial objectives in Earth science, due to the intrinsic complexity of deciphering the preparatory phases that lead to rupture within the seismogenic crust. Despite sustained research efforts, a general consensus on the feasibility and reliability of earthquake forecasting has yet to emerge. Several authors have emphasized the critical role played by fluid circulation in the seismic cycle and fault dynamics (e.g., Miller et al., 2004; Sibson, 2014; Doglioni et al., 2014; Smeraglia et al., 2016; Chiarabba et al., 2018; Chiodini et al., 2004; 2020; Calderoni et al., 2025). The hypothesis that overpressured fluids weaken faults and reduce the effective normal stress required for rupture initiation is widely accepted in the scientific literature.

Growing attention is being devoted to the possibility that circulating fluids may carry precursory messages of an impending seismic event. Such changes, referred to as pre-seismic anomalies, may manifest as transient, statistically significant deviations in chemical or physical parameters of fluids or host rocks prior to rupture, and may be detectable at distances of several kilometres from the fault zone. The term "seismic precursor" is commonly defined as "a change in a measured quantity that occurs prior to an earthquake that does not originate from any process other than those that lead to the earthquake" (Wang and Manga, 2021). Numerous potential precursors have been proposed over the past decades, although their validation remains a topic of debate. The spectrum of reported pre-seismic anomalies includes ground deformation, thermal anomalies, changes in groundwater level and temperature, soil gas emissions, hydrogeochemical fluctuations, and perturbations in electromagnetic, ionospheric, and magnetospheric fields. Among these, fluid-related geochemical and physical anomalies are the most frequently documented in the literature and are often associated with crustal volumes characterized by high structural permeability and stress-induced fracture networks.

These mostly involve radon, ion concentrations, and groundwater level, across different tectonic contexts. It has been proposed that in such settings, pre-existing heterogeneities can act as amplifiers of stress accumulation and fluid migration, thereby enhancing the detectability of pre-seismic signals (Healy and Urban, 1985; King, 1986; Wakita et al., 1988; Ito et al., 1999; Tsai et al., 2017).

Modern Earth Sciences now possess the methodological capacity to investigate these phenomena through a multidisciplinary approach that integrates geophysical, geochemical, geodetic, hydrological, meteorological, and hydrogeological data. This integration is crucial to elucidate the coupling between fluid dynamics and seismicity, and to distinguish clear precursory patterns from background variability due to non-seismogenetic source. In this context, the present work provides a curated, systematically organized dataset of studies reporting fluid-related pre-seismic anomalies preceding crustal earthquakes. This resource is intended to serve the scientific community with the broader purpose to identify in the future which parameters, geological settings, and timescales show the greatest promise for future operational monitoring.

2 Previous studies of pre-seismic anomalies

Over the past decades, a considerable number of works have focused on identifying anomalous precursory signals in earthquake-prone areas, with the ultimate aim of improving short-term earthquake forecasting and understanding the role of fluids in seismogenesis. One of the earliest documented attempts to link natural fluids and seismic activity dates back to 1956, when S. Okabe investigated correlations between local seismicity and near-surface atmospheric radon content in Japan. Although Okabe's findings were pioneering, more concrete evidence emerged a decade later with the documentation of a gradual increase in radon concentrations in well waters preceding the M5.3 Tashkent earthquake of 1966 April, 26th in Uzbekistan (Ulomov and Mavashev, 1967; 1971; Sadovsky et al., 1972). This observation marked a turning point, encouraging systematic geochemical and hydrogeochemical monitoring in seismically active regions, and it is widely recognized as a seminal contribution that catalysed the field of earthquake fluid-related research globally.

Early catalogues were compiled during the 1980s, notably by Teng (1980), Hauksson (1981), Friedmann (1985), King (1986), Roeloffs (1988), Thomas (1988), and Wakita et al. (1988), each documenting a range of potential precursory phenomena across different geological contexts. These pioneering compilations laid the foundation for more comprehensive databases and comparative studies. For example, Kissin and Grinevsky (1990) provided an extensive review of water level anomalies in the time window 1948–1980, covering several tectonic settings worldwide. Subsequent syntheses have attempted to refine observational strategies and conceptual models. Toutain and Baubron (1999) conducted an influential review of gas-geochemical anomalies reported from 1980 to 1995, underscoring the limitations of isolated observations and advocating for multiparametric monitoring networks. Hartmann and Levy (2005) elaborated on how gas and groundwater anomalies could be integrated into earthquake prediction protocols, while Du et al. (2008) explored correlations between geochemical signals and major historical earthquakes in China, highlighting both empirical evidence and interpretive challenges. Cicerone et al. (2009) offered a broad synthesis of anomalies from 1974 to 2004 across geochemical, hydrological, and geophysical domains, and critically assessed physical mechanisms that could explain the observations. Building on these earlier works, Martinelli and Dadomo (2017) examined the spatial variability of fluid-related anomalies using both historical and contemporary datasets, identifying the importance of geological setting, fault permeability, and aquifer structure in modulating signal detectability. Paudel et al. (2018) further addressed the challenge of discriminating between seismically induced anomalies and those resulting from non-tectonic factors such as meteorological variability, anthropogenic interference, or seasonal groundwater fluctuations. Based on previous compilations, Martinelli and Tamburello (2020) reinterpreted observational data on fluid-related earthquake precursors in relation to global geological and geophysical conditions suggesting regions potentially suitable for the implementation of dedicated monitoring networks. Finally, Wang and Manga (2021) further compiled and reanalysed global hydrological and hydrogeochemical observations preceding large earthquakes, underscoring the recurring ambiguity in determining the causal nature of many reported anomalies.

Among the most studied fluid-related precursors is radon (^{222}Rn), a radioactive noble gas often mobilized by stress-induced microfracturing or fluid advection. Radon anomalies have been widely reported in soil gas, groundwater, and the atmosphere, and numerous studies have explored their potential as earthquake precursors. Comprehensive reviews on radon in earthquake studies, including the influence of meteorological conditions, subsurface transport mechanisms, and measurement strategies, have been published by Ghosh et al. (2009), Immè and Morelli (2012), Gregorič et al. (2012), Petraki et al. (2015), Riggio and Santulin (2015), Woith (2015), Morales-Simfors et al. (2019), D'Incecco et al. (2021), Huang et al. (2024), and Nikolopoulos et al. (2024). Taken together, these studies have progressively shaped the conceptual framework of fluid-related earthquake research.

3 Dataset description

We have systematically reviewed pre-seismic anomalous variations reported in crustal environments across 28 countries worldwide (Figure 1). The compiled dataset comprises data extracted from over 300 time-series and approximately 160 peer-reviewed publications spanning the period from 1978 to 2025. These studies report chemical or physical fluid-related signals interpreted as occurring prior to selected seismic events. The dataset includes more than 900 anomalous signals temporally associated with over 500 earthquakes with magnitudes up to 9, for which focal depths and epicentral distances were compiled from the scientific literature. Earthquakes in the dataset include focal depths of up to 452 km and epicentral distances of up to ~1800 km from the monitoring sites where the anomalies were detected.

As depicted in Figure 2A, the dataset is dominated by earthquakes of intermediate magnitude ($4 < M < 6$), which represent

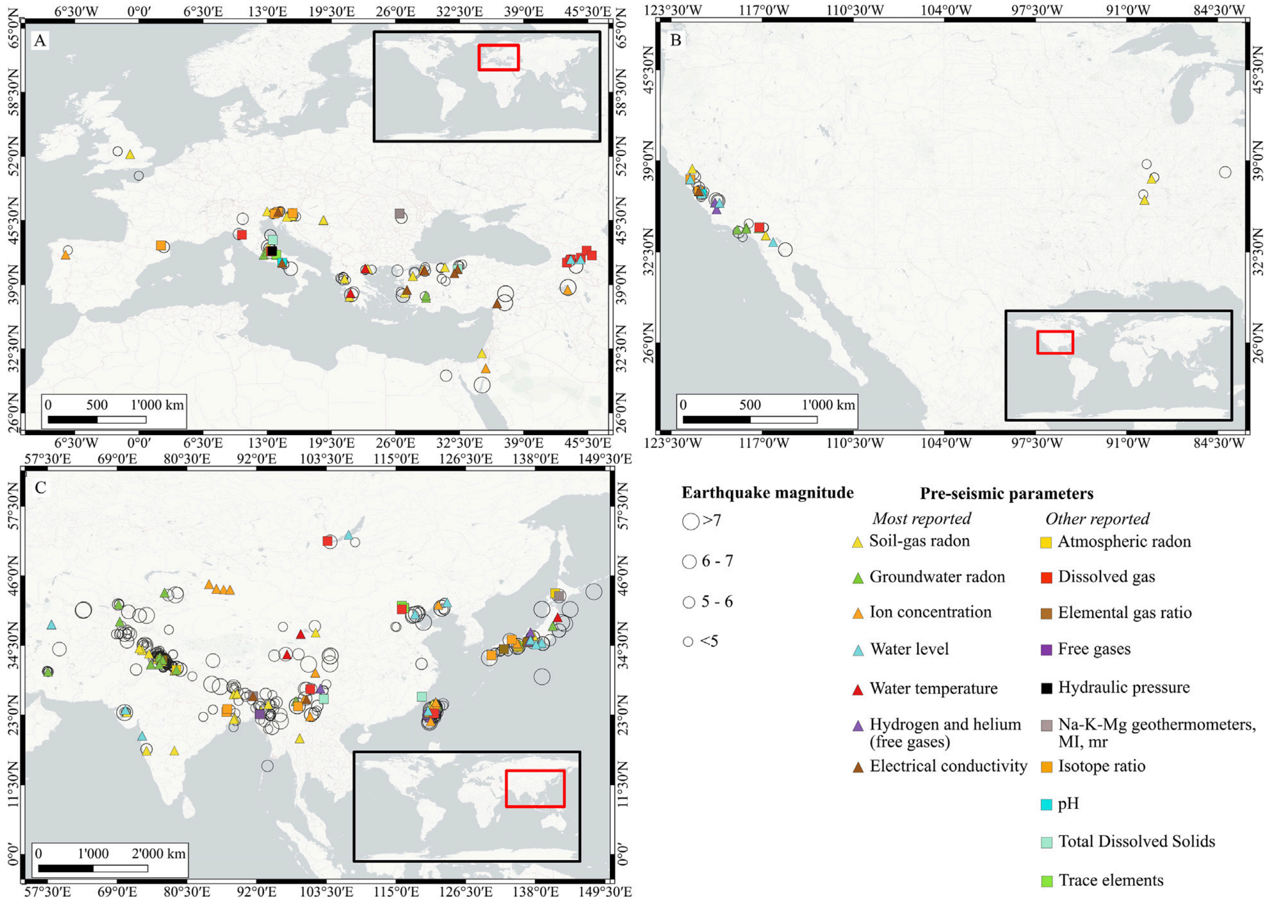

FIGURE 1
Global distribution maps (**(A)** European area; **(B)** North America area; **(C)** Asian area) of pre-seismic anomalous variations of fluid parameters in crustal environments, as reported in the scientific literature. Each colored symbol (triangle or square) indicates a monitoring site where an anomaly was detected. Where multiple types of anomalies were recorded at the same monitoring site (e.g., Zatolmin in Slovenia, Ayran springwater in Turkey, …) symbols may appear overlapped. Open circles indicate earthquakes related to the reported pre-seismic anomalies. MI = Maturity Index; mr = molar ratios.

the most frequent class, while lower (M < 4) and higher magnitudes (M > 6) are less common. Similarly, the majority of events are associated with shallow focal depths (<20 km), with a marked decrease in frequency at greater depths. A comparable pattern is observed for epicentral distance, with most anomalies occurring within 100 km of the monitoring site and progressively fewer events at larger distances. About 70% of all reported anomalies is derived from just four countries: India (~30%), China (~20%), Taiwan (~11%), and Japan (~8%). These are followed by the United States (~7%), Turkey (~5%), and Italy (~4%), collectively accounting for an additional 15% of the total. All remaining countries each contribute fewer than 3% of the recorded anomalies.

In this dataset, we report 18 pre-seismic parameters that can be grouped into three main classes based on their nature:

- Gas-geochemical parameters, including soil-gas radon, atmospheric radon, free gases (H_2, He, CO_2, Hg, thoron), and elemental gas ratios (He/Ar, CH_4/Ar, N_2/Ar, H_2/Ar, He/Rn);
- Hydrogeochemical parameters, including groundwater radon, major ion concentrations (Cl^-, SO_4^{2-}, HCO_3^-, F^-, NO_3^-, Na^+, Ca^{2+}, Mg^{2+}, K^+), trace elements (As, B, Ba, F, Cs, Cu, Fe, Li, Mn, Mo, Nb, Ni, Pb, Sc, Sr, Th, Ti, Tl, U, W, Zn), dissolved gases (He, CO_2, CH_4, Hg, N_2, H_2), isotopic ratios ($^3He/^4He$, $\delta^{18}O$, δ^2H, $^{206}Pb/^{207}Pb$, $^{206}Pb/^{208}Pb$), pH, total dissolved solids (TDS), Na-K-Mg geothermometers, maturity index (MI), and molar ratios (mr);
- Physical parameters, including groundwater level, water temperature, electrical conductivity, and hydraulic pressure.

To facilitate the identification of the most promising precursory indicators, parameters were further grouped according to their statistical recurrence in the literature (Figure 1), distinguishing between:

- Most reported parameters: those with > 10 documented anomalies, considered suitable for statistical analysis;
- Other reported parameters: those with ≤10 reported anomalies, included for completeness but not representative from a statistical standpoint.

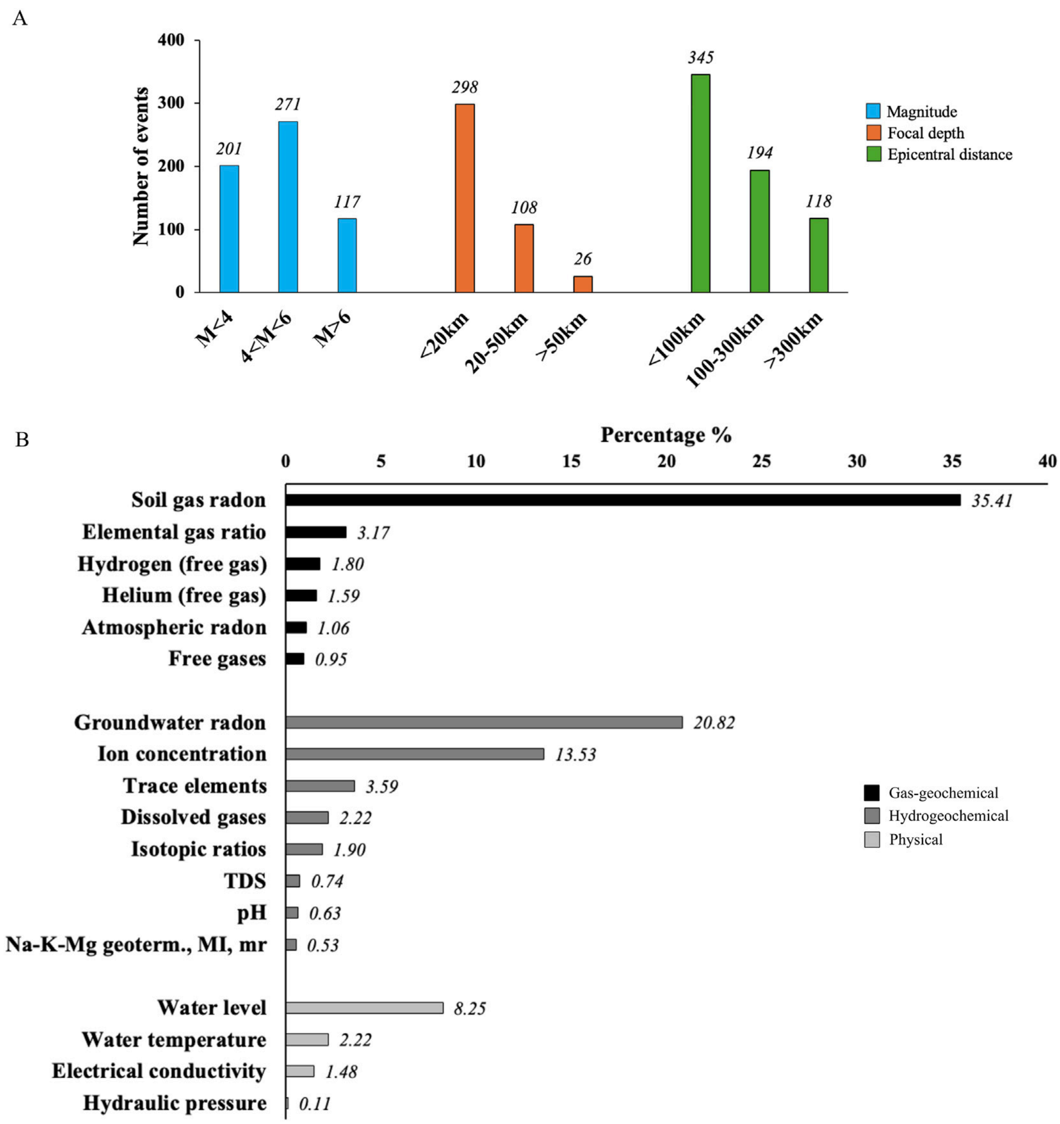

FIGURE 2
(A) Histograms showing the distribution of earthquake magnitudes, focal depths and epicentral distances. **(B)** Histograms showing the percentage of anomalous cases per category, further grouped as gas-geochemical (black), hydrogeochemical (dark gray) and physical (light gray), over the total amount of reported anomalies. MI = Maturity Index; mr = molar ratios; TDS = Total Dissolved Solids.

This dual criterion, combining the type of parameter with its frequency of documentation, provides a consistent framework for comparative analysis and helps to emphasize the relative significance of each anomaly type within the broader context of earthquake precursor research. The inclusion of each anomaly was guided by strict criteria. We considered only those signals with a clear temporal correlation to a specific seismic event and documented in peer-reviewed scientific publications. In particular, in order to enable spatial relationship between the earthquake and associated anomalies we only included those for which detailed metadata of the seismic events were available (e.g., epicentral distance and/or geographical coordinates of the monitoring site). One or more anomalies can be associated with a single earthquake event As shown in Figure 2B, radon constitutes the most frequently reported precursor among gas-hydrogeochemical signals (~35% in soil gas and ~20% in groundwater), while major ion concentrations and water-level changes also represent a relevant class of precursors accounting for ~13% and ~9% of reports, respectively.

For each reported anomaly, we extracted detailed metadata from the original publication, including:

- Absolute value of the anomaly (Av) and associated measuring unit (Mu),
- Background value (Bv) and/or the value preceding the anomaly (Pv)
- Time-lag before the earthquake (Tl),
- Country where the anomaly has been detected
- Geographical coordinates of the monitoring site recording the anomaly

- Date, time, magnitude, focal depth and geographical coordinates of the earthquake
- Epicentral distance between the earthquake and the monitoring site
- Focal mechanism (i.e., rake angle) and associated faulting style
- Tectonic regime of the area where the earthquake occurred.

In addition, the dataset includes a percentage variation calculation that accounts for the deviation of the anomaly from the a reference value (i.e., background when provided or the value preceding the anomaly in the absence of the background). This could be a starting point for future studies comparing data from different sources. Percentage variation was calculated using the following formula:

$$Variation\,\% = \frac{\Delta V}{Bv\ or\ Pv}\,x\,100$$

where ΔV is the difference between the anomaly value and Bv or Pv. When the same anomaly was cited in multiple studies, we prioritized the most recent or most complete version of the time series.

Rake values of the focal mechanism were reported for each earthquake, when available from global and national earthquake catalogs (e.g., USGS, https://earthquake.usgs.gov/earthquakes/search/; ISC, https://www.isc.ac.uk/iscbulletin/; INGV, https://terremoti.ingv.it/en). These data were compiled together with the associated faulting style (i.e., reverse, strike-slip, and normal). In addition, the regional tectonic regime where each seismic event occurred was classified as compressive, transform or extensional, as well as mixed tectonic settings (transpressional and transtensional) and stable continental regions (cratonic areas).

4 Data usage

The dataset is designed to support a wide range of applications aimed at investigating the behaviour of crustal fluids in the earthquake preparatory phase. Users should consider that the reported anomalies are associated with a specific seismic event, accompanied by both quantitative descriptors (e.g., anomaly value, delta variation, percentage variation, time-lag, magnitude, focal depth) and contextual metadata (e.g., geographic coordinates, epicentral distance, faulting style, tectonic regime). The data can be interpreted at multiple levels. For instance, they can be used to explore temporal relationships between anomaly onset and earthquake occurrence, as well as to investigate the sensitivity of specific geochemical or physical parameters to stress changes. At the regional or global scale, the dataset enables statistical analyses aimed at identifying recurring patterns across faulting styles, tectonic settings, epicentral distances, magnitude or focal depth ranges. In summary, the dataset is particularly useful to:

- evaluate the consistency and robustness of earthquake precursors;
- perform statistical investigations aimed at identifying recurring patterns across faulting styles, tectonic setting, epicentral distances, magnitude, focal depth ranges, etc;
- carry out comparative studies of different classes of fluid-related signals (e.g., gas vs. hydrogeochemical anomalies)
- integrate geophysical or geodetic datasets to explore multi-parameter precursor frameworks.

5 Concluding remarks and future directions

This dataset provides a structured basis for reproducible analyses, promoting the development of standardized approaches to evaluate fluid-related earthquake precursors and supporting future efforts toward integrated, data-driven seismic hazard assessment.

Among gas-hydrogeochemical parameters, soil-gas radon appears to be the most prominent fluid-related precursor. Its widespread occurrence across different tectonic settings and sensitivity to stress-induced fracturing make it one of the most extensively investigated parameters in earthquake-related monitoring studies. Groundwater radon also appears particularly promising due to its tendency to exhibit longer time-lags before seismic events, potentially offering a broader temporal window for anomaly detection. Major ion concentrations and water-level variations represent additional robust indicators of crustal fluid perturbations, especially when integrated within continuous multi-parametric monitoring frameworks. Conversely, water temperature and electrical conductivity anomalies, though occasionally reported, are more sensitive to environmental noise and require long-term baselines to be effectively interpreted. Finally, parameters such as hydrogen, helium, isotopes, and trace elements, often characterized by high-amplitude anomalies, remain less systematically investigated likely due to technical and logistical constraints.

We emphasize that the significance of any signal must be evaluated in relation to the tectonic context, the nature of the monitored parameter, and the site-specific geological-hydrogeological framework. The apparent regional clustering of pre-seismic anomalies likely reflects the uneven global distribution of observational capacities, driven by the scarcity of systematic, long-term monitoring programs across vast areas of the world. This uneven coverage significantly limits the ability to detect, characterize, and compare such phenomena in a consistent and reliable manner. These insights strengthen the rationale for implementing high-resolution, multi-parametric networks in active crustal environments.

Several initiatives worldwide have demonstrated the feasibility and utility of integrated monitoring, including Japan (Yasuoka et al., 2009), China (Du et al., 2008; Huang et al., 2017), India (Arora et al., 2012), Taiwan (Fu et al., 2021). In Italy, continuous multi-parametric observations have proven essential for investigating potentially earthquake-related signals. In this context, integrated monitoring infrastructures such as MUDA (Multiparametric Database; Massa et al., 2024; Ferrari et al., 2024) and TABOO (The Alto-Tiberina Near-Fault Observatory; Caracausi et al., 2023; Chiaraluce et al., 2014) networks developed by INGV provide valuable long-term observations of hydrogeochemical, geophysical, and environmental parameters across the most seismically active regions in the Italian territory. These experiences further highlight the importance of integrated monitoring strategies combining geochemical and geophysical observations with environmental parameters in order to improve the interpretation of earthquake-related anomalies. Such multi-parametric frameworks are essential for discriminating local environmental forcings on monitored parameters and consequently identify signals potentially associated with crustal stress variations and seismic activity, particularly in tectonically active regions characterized by complex fluid circulation processes.

To address all of these aspects, we propose that future research and monitoring programs prioritize:

- standardized reporting of anomaly features, including baseline values, peak amplitude, time-lag, and spatial relation to the earthquakes;
- multiparametric integration of geochemical, hydrological, and geophysical data at shared sites;
- long-term monitoring, independent of seismic occurrence, to capture both short- and long-term variations;
- adoption of data science tools such as machine learning, real-time assimilation, and pattern recognition to identify anomalous trends.

Data availability statement

The dataset generated for this study can be found in the Zenodo Open Access data repository as Ventura Bordenca et al. (2026).

Author contributions

CVB: Conceptualization, Investigation, Writing – review and editing, Data curation, Methodology, Formal Analysis, Writing – original draft. MM: Writing – review and editing, Supervision, Resources, Conceptualization, Funding acquisition. AR: Conceptualization, Writing – review and editing, Funding acquisition, Resources, Supervision. EF: Writing – review and editing. NC: Writing – review and editing. MB: Writing – review and editing. AP: Writing – review and editing. AS: Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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