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article in press

What about Volcanic Ash? A Bibliometric Analysis

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Abstract

Volcanic ash, a byproduct of explosive eruptions, exerts widespread impacts on both natural and human systems. This study presents the first comprehensive bibliometric analysis of global research on volcanic ash presented in English, aiming to examine its structure, evolution, and emerging trends. Using data from the Scopus database up to December 31, 2024, statistical, bibliometric, and network analysis techniques were applied to evaluate publication dynamics, scientific impact, conceptual relationships, and thematic evolution.

Results reveal a sustained increase in scientific production, with peaks following major eruptions. The United States, the United Kingdom, Japan, and Italy are the leading contributors, while participation from China has grown in recent years. Four main research clusters were identified, focused on geological stratigraphy, eruptive dynamics, ash distribution, and physicochemical properties. Niche, motor, and basic themes, such as basin, formation, sediment, volcano, eruption, and deposit, highlight the centrality of geological processes in the field. Meanwhile, soil, effect, and property appear as emerging or declining themes, suggesting a growing yet variable interest in environmental and material implications of volcanic ash. By identifying the field's intellectual structure, emerging themes, and persistent knowledge gaps, this study provides a foundation for guiding future research and fostering the integration of geoscientific, environmental, health, and engineering approaches to address the complex challenges posed by volcanic ash.

1 Introduction

36 1.1 Volcanic Ash

37 Volcanic eruptions emit large amounts of pyroclastic particles. Among these, volcanic ash –tephra particles smaller
38 than 2 mm in diameter (e.g., Thorarinsson, 1944; White and Houghton, 2006; Zimanowski et al., 2003)– is
39 particularly important due to its widespread impacts. This fine material, composed of magmatic glass, rock
40 fragments, and crystals, is released during eruptions and can affect diverse aspects of terrestrial life, referred to as its
41 life cycle (Paredes-Mariño et al., 2022).

42 Volcanic ash formation is primarily driven by brittle fragmentation of ascending magma during explosive eruptions,
43 triggered by rapid decompression and volatile expansion, or by water/magma interaction (Büttner et al., 1999;
44 Dingwell, 1996; Mader et al., 1994; Papale, 1999). As a result, ash particles retain vital information about pre-
45 fragmentation magma conditions (Cassidy et al., 2015; Matsumoto and Geshi, 2021; Wright et al., 2012). Beyond
46 this initial stage, ash particles may be further modified by secondary fragmentation processes (Dufek and Manga,
47 2008; Jones et al., 2016; Mueller et al., 2017).

48 After fragmentation, ash particles are incorporated into eruptive columns that ascend buoyantly to varying altitudes,
49 occasionally (rarely) exceeding 50 km, with dispersion influenced by prevailing atmospheric winds. Deposition may
50 occur at distances as far as several hundred to thousands of kilometers from the source (Bonadonna et al., 2015;
51 Carey and Bursik, 2015; Sparks, 1986). Furthermore, most particles finer than 125 μm settle out as particle
52 aggregates, which exert a fundamental control on particles' settling velocities and atmospheric dispersal within
53 eruptive clouds (Brown et al., 2012, and references therein; James et al., 2002; 2003; Kueppers et al., 2011;
54 Taddeucci et al., 2011).

55 Because ash transport and deposition largely control the spatial distribution of impacts, accurately characterizing
56 these processes is essential for volcanic hazard assessment. Accordingly, a variety of mathematical models and
57 numerical tools have been developed to simulate and predict the dispersion and sedimentation of volcanic ash across
58 different atmospheric layers and varying meteorological conditions. Notable examples include ATLAS (Reckziegel,
59 et al., 2019), FALL3D (Folch et al., 2020), HYSPLIT (Draxler and Hess, 1998), NAME (Beckett et al., 2020),
60 Tephra2 (Bonadonna et al., 2005; Connor and Connor, 2006; Volentik et al., 2009), and Ash3D (Schwaiger et al.,
61 2012), among others.

62 Following deposition, unconsolidated ash accumulations are subject to remobilization by multiple transport agents,
63 including wind (e.g., Dominguez et al. 2020; Gillete, 1981; Mingari et al., 2017), fluvial processes (Beigt et al., 2016;
64 2019; Córdoba et al., 2015; Hayes et al., 2002; Major et al., 2016; Mulas et al., 2019; Segschneider et al., 2002), and,
65 where volcanic material is deposited onto water bodies, floating transport and pumice rafting (e.g., Jokiel and Cox,
66 2003; Oppenheimer, 2003), all of which influencing the ultimate distribution and long-term impacts of ash deposits.

67 Unlike other types of atmospheric dusts, volcanic ash possesses a distinctive set of physicochemical properties
68 controlled by magma composition, cooling history, eruption style, and interactions with the volcanic plume and
69 atmosphere (Ayrís and Delmelle 2012). Freshly fallen ash can thus interact with surface processes and alter
70 environmental chemistry (e.g., Ayrís and Delmelle, 2012), affect water quality (Stewart et al., 2006; 2009; 2022),
71 promote corrosion of metallic components (Barnard, 2010; Wilson et al., 2009; 2012; Witham, 2005), and exhibit

electrical conductivity when wet due to leached electrolytes (Gordon et al., 2005; Nagai and Nakada, 2022; Wardman et al., 2012a; 2012b).

Although volcanic ash typically does not pose a direct threat to human life (Jenkins et al., 2015), it can have multiple and substantial long-term health and socio-economic consequences. Fine ash particles ($<10\ \mu\text{m}$), for example, contribute to respiratory and cardiovascular morbidity through inhalation (Baxter et al., 2014; Horwell et al., 2023; Horwell and Baxter, 2006), while soluble salts and trace metals can contaminate water and food supplies (e.g., Cronin et al. 2000; Gudmundsson, 2011; Sergeeva et al., 2024; Simbaña-Rivera et al., 2025; Stewart et al., 2006; 2009). Ashfall can also affect agriculture and livestock systems, including fluoride-related toxicity, altered antioxidant properties, and heavy metal accumulation in crops (Cronin et al., 2003; Mihai et al., 2025; Witham, 2005). Moreover, exposure to ashfall events has been linked to psychological stress, exacerbating mental health issues in affected communities (e.g., Fourgassie et al., 2025; Shore et al. 1986).

Critical infrastructure, defined as assets essential for the functioning of society and the economy (Platt, 1991), can face extensive damage and disruption from volcanic ashfall across vast areas (Jenkins et al., 2015; Wilson et al., 2012). These impacts may arise not only from widespread ash accumulations, but also from cascading failures within increasingly interconnected and interdependent network of systems (Mitra and Shaw, 2023). Key sectors at risk include electricity, oil and gas, water supply, wastewater management, HVAC systems, telecommunications, building facilities (e.g., Gordon et al., 2005; Nagai and Nakada, 2022; Wardman et al., 2012a), and various transport modes, including ground transport (Blake, 2016; Blake et al., 2016; 2017; Blong 1984; Wilson et al., 2012; 2013), aviation (e.g., Alexander, 2013; Casadevall, 1994; Guffanti et al., 2010; Guffanti and Tupper, 2015; Prata and Rose, 2015; Song et al., 2023), and shipping (e.g., Salgado et al., 2023). Clean-up operations are widely recognized as crucial measures for mitigating such impacts in urban environments (Hayes et al., 2015; 2017), including severe outcomes such as roof collapses caused by ash loading (Horwell and Baxter, 2006; Kwame Quainoo et al., 2022; Spence et al., 2005). However, these operations often pose considerable logistical, economic, and safety challenges, due to the time, cost, and risks associated with ash removal (Blong, 1984; Jenkins et al., 2015; Wilson et al., 2012).

Beyond its hazardous impacts, volcanic ash also constitutes an important archive of environmental and human history. Once deposited, ash can be preserved in terrestrial, lacustrine, marine, and glacial environments, forming distinct stratigraphic layers that serve as key chronological markers for reconstructing past eruptions, paleoenvironmental conditions, and sedimentary processes (e.g., Alloway et al., 2018; 2024; Lowe, 2011; Lowe and Alloway, 2015; Lowe and Tonkin, 2010). In ice cores, volcanic ash provides independent chronological constraints that complement isotopic dating methods and refine paleoclimate reconstructions (e.g., Davies et al., 2004; Hillenbrand et al., 2008; Kekonen et al., 2005; Kurbatov et al., 2006; Narcisi et al., 2010). In marine systems, volcanic ash may also release nutrients that stimulate biological productivity and influence the global carbon cycle (Fiantis et al., 2019; Frogner et al., 2001). More recently, tephra deposits and cryptotephra have become increasingly important in archaeological studies (e.g., Davies, 2015 and references therein; Lane et al., 2017; Riede and Thastrup, 2013).

Throughout history, volcanic ashfall from major explosive eruptions has profoundly shaped human societies, leaving traces in historical records, myths, and cultural narratives (Cashman and Cronin, 2008), also influencing land use,

109 agriculture, and even construction practices. The pozzolanic properties of volcanic ash, for instance, have been
110 recognized since ancient times through their contribution to Roman cement production, and continue to be explored
111 in modern material sciences as sustainable alternatives for cement production (Cascone et al., 2024; Rosales et al.,
112 2022; Viramonte et al., 2025).

113 Considering the diversity of characteristics, processes, and consequences associated with volcanic ash, the topic has
114 garnered sustained attention from multiple scientific disciplines and perspectives. Its complex and far-reaching
115 impacts have led to the development of a broad and multidisciplinary body of research across different historical
116 periods, geographic regions, and academic communities.

117 **1.2 Bibliometric Analysis**

118 To comprehensively understand the evolution of research on volcanic ash, this study employs a bibliometric analysis.
119 Bibliometric analysis is a quantitative method that uses statistical and network-based techniques to evaluate large
120 volumes of scientific literature, with the aim of identifying trends, research constituents, collaborations, emerging
121 themes, and the intellectual construction of knowledge (Donthu et al., 2021; Passas, 2024). In contrast, a systematic
122 literature review is a qualitative and interpretative approach that focuses on synthesizing and critically evaluating the
123 content of selected studies to answer specific research questions (Passas, 2024; Snyder, 2019).

124 Thus, while both approaches analyze scientific publications, they differ in scope and objectives: bibliometric analysis
125 emphasizes the macro-level structure and dynamics of scientific production through indicators such as citation
126 networks, co-authorship, and thematic mapping, whereas systematic reviews emphasize the micro-level assessment
127 and synthesis of research findings from individual articles (Donthu et al., 2021; Zupic and Čater, 2015). Importantly,
128 bibliometric analysis does not aim to provide an exhaustive content synthesis of each paper, but rather to map and
129 quantify the overall landscape of knowledge production.

130 Bibliometric analysis enables the quantitative examination of scientific literature and its associated academic impact,
131 as assessed through bibliometric indicators such as publication and citation metrics, allowing researchers to identify
132 patterns in knowledge production, collaboration networks, thematic evolution, and the overall evolution of a research
133 field (Öztürk et al., 2024; Passas, 2024). To the best of the authors' knowledge, no bibliometric analysis focusing
134 specifically on volcanic ash has been conducted to date.

135 This study aims to provide a statistical analysis of the metadata, identifying publication trends and research
136 collaborations. Additionally, it seeks to assess the academic impact, identifying core and emerging research themes,
137 and map the intellectual structure of the field through word relationships, and network structures. The study will also
138 trace the evolution of ideas over time and summarize findings through visual and analytical representations.

139 The methodology includes data collection, cleaning, and analysis using tools such as R (R Core Team, 2024),
140 Bibliometrix (Aria and Cuccurullo, 2017), and Tableau (Tableau Software, 2024), followed by visualization and
141 interpretation of the results. This approach not only provides a systematic overview of the field but also offers
142 insights into the dynamics of scientific production, collaboration networks, and thematic evolution, ultimately
143 contributing to a deeper understanding of research on volcanic ash.

144

145 **2 Methods**

146 This bibliometric analysis followed the structured procedures suggested by Passas (2024) and Öztürk et al. (2024),
147 adapted into six main phases: (i) definition of objectives and expected results, (ii) bibliographic search for metadata,
148 (iii) data cleaning and preprocessing, (iv) statistical analysis, (v) visualization of results, and (vi) interpretation and
149 writing.

150 **2.1 Objectives**

151 This study aims to examine trends and patterns in the multidisciplinary research on volcanic ash by applying
152 bibliometric techniques to a large body of scientific metadata. The analysis is designed to quantify the overall volume
153 of research and provide descriptive statistics of the dataset, while also identifying temporal publication dynamics
154 across years, words, and journals.

155 In addition, the study explores the conceptual and thematic landscape of volcanic ash research by identifying central
156 and emerging topics, analyzing relationships among key concepts, and tracing the evolution of ideas over time. Co-
157 word analysis is employed to understand the flow of scientific information, while visualization techniques are used to
158 represent these patterns in a systematic and interpretable manner. Overall, the objectives of this methodology are to
159 provide both a structural overview of the field and insights into its thematic and intellectual development.

160 **2.2 Bibliographic search**

161 The bibliographic search was conducted in the Scopus database (Burnham, 2006), selected for its broad
162 multidisciplinary coverage and high-quality metadata, which facilitate bibliometric analyses. The data were retrieved
163 through the Scopus API to enable systematic and reproducible data collection. However, it is important to note that
164 no single database provides complete coverage of the scientific literature, and reliance on Scopus alone may lead to
165 partial representation of the research landscape (Gerasimov et al., 2024; Mongeon and Paul-Hus, 2016).

166 The search criteria consisted of all scientific articles that contain in their title, keywords, or abstract the terms defined
167 by the query (*volcan** AND *ash*). This approach captures lexical variants of “volcano” (e.g., volcanic, volcanoes)
168 while requiring the explicit presence of “ash”. In this way, we ensure that the term *ash* refers specifically to volcanic
169 ash; studies referring to volcanic plumes or clouds without explicitly mentioning ash were not included. The time
170 period analyzed was determined through 31/12/2024. Only articles and reviews were selected, excluding other
171 document types, as they represent peer-reviewed scientific contributions and are commonly used as reliable sources
172 in bibliometric analyses (Ramos-Rodríguez and Ruiz-Navarro, 2004). The analysis was further restricted to
173 publications written in English to ensure consistency in data processing and comparability across records. However,
174 this decision may exclude relevant contributions published in other languages and may bias the analysis toward
175 research communities with greater representation in English-language journals (e.g., Jackson and Kuriyama, 2019;

176 Morrison et al., 2012). The search was carried out on 02/01/2025, downloading the metadata in Bibtex and CSV
177 formats from a total of 12,534 articles.

178 **2.3 Pre-processing**

179 A data cleaning process was carried out. This consisted of removing duplicates using the R revtools library
180 (Westgate, 2019). Starting from a dataset of 12,534 articles, the cleaning process involved two steps: (1) 54
181 duplicates were removed (duplicate rate 0.43%), leaving 12,480 articles; and (2) 24 further entries were removed
182 because they contained insufficient metadata (e.g. authorship and other fields) to identify and complete the
183 corresponding reference (missing data rate 0.19%). The resulting dataset comprised 12,456 articles for analysis.

184 **2.4 Analysis**

185 Various bibliometric techniques and statistical analyses were applied to examine the structure and evolution of the
186 literature on the subject. The methods employed include bibliometric indicators, citation analysis, and the application
187 of laws governing scientific publication patterns. The definitions and references of the main bibliometric concepts
188 and indicators used in the analysis, together with the corresponding figures, are summarized in Supplementary Table
189 S1.

190 The bibliometric analysis was performed using the Bibliometrix package in R (R Core Team, 2024), which facilitated
191 the calculation of various bibliometric indicators. Additional analyses and measurements were conducted using
192 spreadsheets and R. Descriptive statistics, including measures of central tendency and dispersion, as well as
193 regression analysis and trend evaluation, were applied to examine the data. Additionally, a temporal distribution
194 analysis was conducted to assess the frequency of term usage, the journal, affiliation, and countries over time,
195 providing insights into their continued relevance.

196 At the level of individual articles, two complementary indicators are considered: the *total number of citations*
197 (absolute value) and the citation density. *Citation density* is defined as the ratio between the total number of citations
198 received by an article and the number of years elapsed since its publication. The *average citations per year* is the
199 mean citation density of all articles published in a given year (Aria and Cuccurullo, 2017).

200 *Bradford's law* (Bradford, 1934) was used to identify the core journals in volcanic ash research and to examine the
201 distribution of the scientific literature across publication sources. According to this law, a small number of journals
202 tend to account for a large proportion of publications on a given topic, whereas a larger number of journals contribute
203 progressively fewer articles (Alvarado, 2016).

204 The *H-index* (Hirsch, 2005) was used to assess the scientific impact of authors and sources. It is defined as the
205 highest number h of articles published by an author that have at least h citations. The other articles published by the
206 same author have less than h citations. Likewise for sources, the *H-index*, is defined as the highest number h such
207 that h documents in the set of articles published by a source have at least h citations each. The *local H-index*

measures the impact of a source within the analyzed dataset, based on the number of publications and citations restricted to that collection (Aria and Cuccurullo, 2017).

The analysis of the *most frequent words* provides insight into the predominant approaches and areas of investigation. The word list is derived from the most frequent terms found in the authors' keywords (Donthu et al., 2021). However, it is important to note that there is an absence of this data in 42% of articles. In the total data set, there are no missing titles. In this case, in the absence of keywords, the word analysis is carried out from the titles (Donthu et al., 2021). For example, Emich et al. (2020), state that the keywords have been available since 2003, and for studies with earlier times, they analyzed the words in the title.

Prior to these analyses, text preprocessing was applied to ensure consistency and reduce noise across all word-based analyses. Non-informative terms (e.g., articles, prepositions) were removed using a predefined removal list. In addition, a synonym list was used to merge equivalent terms (e.g., singular and plural forms or closely related expressions with the same meaning). Both lists were initially generated automatically and subsequently reviewed and refined manually based on the full set of analyzed terms.

To map the conceptual and social architecture of the research field, *network analysis* was conducted using the bibliometrix R-package. This approach utilizes quantitative metrics to identify the evolution and structure of scientific communities through the construction of specialized matrices (Aria and Cuccurullo, 2017).

Co-word analysis is a technique used to uncover the conceptual map of a scientific domain by examining the patterns of term co-occurrence. The analysis is calculated by generating a co-occurrence matrix, where nodes represent individual words and edges signify the frequency with which these terms appear together in the same title. This method allows for the identification of core themes and emerging trends within the dataset by mapping the strength of the links between specific concepts.

The *co-occurrence* network analysis was performed using title terms, as they were available for all records, whereas keywords were incomplete in the dataset. The analysis was conducted using the biblioshiny interface of the Bibliometrix package. The network was constructed using association strength normalization, with clusters identified using the Walktrap algorithm, and the network layout generated using the automatic layout option. The number of nodes was set to 50, corresponding to the most frequent terms in the dataset. A minimum of two edges per node was required, and isolated nodes were removed. A repulsion force of 0.1 was applied to improve node separation and visualization clarity (Aria and Cuccurullo, 2017). The same network construction and visualization settings were applied to the country collaboration network described below.

The *thematic map* was constructed based on co-occurrence network data. The size of each circle corresponds to the occurrence frequency of the word. The x-axis represents centrality, indicating the degree of interaction with other groups, while the y-axis represents density and the thematic development over time (Cahlik, 2000). Based on these axes, topics are classified into four categories: a) Motor themes (upper-right quadrant): These topics exhibit high centrality and high density, meaning they are well-developed and essential for structuring research. b) Niche themes

(upper-left quadrant): These topics have high density but low centrality, making them highly specialized but of limited overall relevance. c) Emerging or declining themes (lower-left quadrant): These topics have both low density and low centrality, indicating that they are either marginal (in terms of connections to the general network) or underdeveloped. d) Basic themes (lower-right quadrant): These topics have high centrality but low density, meaning they serve as fundamental concepts for transdisciplinary research (Alkhamash, 2023).

The social structure of the field was assessed through a *country collaboration network*, which illustrates the degree of international scientific cooperation. This analysis is based on the affiliation metadata (C1 field tag) of the authors. The network is calculated by quantifying the frequency of joint publications between different countries. Nodes are countries and links are co-authorships' countries (Glanzel and Schubert, 2004). The same network construction and visualization settings described above were applied to the country collaboration network.

Centrality metrics are obtained for each node to determine its strategic position within the international research landscape. These metrics include betweenness centrality (BC), closeness centrality (CC), and pageRank centrality (PR) values. From these values, we can identify pivotal countries that facilitate the diffusion of knowledge by acting as bridges (high BC value; Freeman, 1978). Furthermore, CC identifies countries with the shortest communication paths to the rest of the network; the more direct its ties with other nations, the greater its capacity for rapid information dissemination and systemic influence (high CC value; Freeman, 1978). Finally, we can note those influential countries characterized by significant collaborations with other highly central nodes. This indicates that their prominence stems not only from a high volume of collaborations but also from the quality and importance of their international partnerships (high PR value; Brin and Page, 1998; Yan and Ding, 2009; 2011).

2.5 Visualization

The visualization of bibliometric data was carried out using a combination of tools and software to ensure clarity and interpretability of the results. The primary tools used for visualization were R, with the ggplot2 library (Wickham, 2011), and Biblioshiny (Aria and Cuccurullo, 2017), which allowed for the creation of detailed graphs and charts. Additionally, Tableau was employed to generate additional visualizations.

2.6 Interpretation and Writing

The interpretation of the bibliometric data was guided by the objectives outlined in the study. The results were analyzed in the context of existing literature, with a focus on identifying trends, collaborations, and thematic shifts in volcanic ash research. The findings were organized into coherent sections, each addressing a specific aspect of the bibliometric analysis, such as general overview, journal information, affiliations, words, conceptual structure, and social structure.

3 Results and Discussion

3.1 Overview: Descriptive information

275 The descriptive indicators of the term “volcanic ash” in science, during the time span until 2024 yield a total of
 276 29,466 authors publishing 12,456 documents in 2,245 different journals.

277 The annual scientific production is represented in Figure 1. Scientific publications on volcanic ash in the analyzed
 278 dataset date back to 1887. Until 1955, scientific production remained relatively limited, with only sporadic
 279 publications on the subject. From 1955 onwards, a general trend of increasing publications on volcanic ash can be
 280 observed, with peaks of accelerated growth that mostly coincided with large eruptions. The eruption of Bezymianny
 281 volcano (VEI: 5; Gorshkov, 1959) in the Kamchatka Peninsula, is one of the major eruptions occurring during this
 282 period, although the subsequent increase in scientific production cannot be directly attributed to this event. The
 283 eruption of Mount Saint Helens in 1980 (Casadevall and Greenland, 1981; Fruchter et al., 1980) marks the first sharp
 284 increase in scientific production on volcanic ash.

285 Reference points for eruptions with a volcanic explosivity index (VEI) of 5 or higher are included in Figure 1. Some
 286 recent VEI 4 events were also included due to the broad impact of volcanic ash on different human sectors, such as
 287 the 2010 Eyjafjallajökull volcanic eruption (Gudmundsson et al., 2010). The data regarding eruptions and their
 288 corresponding VEI values were obtained from the Global Volcanism Program (2024).

289 The average (mean) citation per year on volcanic ash (Figure 2) follows an increasing trend that accompanies the
 290 growth in the number of articles. This trend is not merely a reflection of the higher volume of publications: an
 291 increase in average citations indicates that individual studies in this field are receiving greater attention than before.
 292 In bibliometric terms, this suggests that volcanic ash has become a more influential topic in the academic community,
 293 as growth in publications does not necessarily cause a parallel increase in citation impact (Sjögarde and Didegah,
 294 2022).

295 The most cited articles and their citation density values are listed in Table S2 (Supplementary Material). Climate-
 296 related impacts of volcanic activity are prominently represented. The most cited article focuses on volcanic eruptions
 297 and their influence on global climate. Other highly cited studies address northern hemispheric temperature variations,
 298 ecosystem responses, and historical climate shifts linked to volcanic events. The list also includes geochronological
 299 methods for reconstructing geological timelines and mass extinctions, as well as environmental and ecological
 300 impacts such as aerosol interactions and photosynthetic adaptations. Additional topics include health risks and
 301 industrial applications of volcanic-derived materials, advances in remote sensing and real-time monitoring
 302 technologies, and sustainable reuse of volcanic ash in construction materials. Together, these themes reflect the
 303 multidisciplinary scope of volcanic ash research, bridging paleoclimatology, environmental science, and industrial
 304 innovation.

305 The relationship between absolute citations and citation density for articles with fewer than 500 citations is shown in
 306 Figure 3a. In this larger set, the relationship appears sparse, but proportional and consistent, suggesting that outside
 307 the most cited works, the general literature on volcanic ash follows a regular pattern: as citation counts increase,
 308 citation density also tends to rise in a predictable manner.

309 By contrast, the articles with more than 500 citations (Figure 3b) display a weaker positive trend ($R^2 = 16\%$, $p <$
310 0.05) and higher variability. Some articles achieve disproportionately high citation density compared with others with
311 similar citation counts. This indicates heterogeneous citation dynamics among the most influential papers, where
312 certain works accumulate citations steadily over long periods, while others concentrate citations rapidly within a
313 shorter time frame.

314 **3.2 Journals**

315 The profile of the most prolific journals publishing on volcanic ash is represented in Figure 4a, which includes only
316 journals whose number of publications is greater than 65 during the analyzed period. However, a large number of
317 journals have published fewer than 65 articles on the topic. In fact, the majority of journals represented in the dataset
318 have a single published article (Figure 4b).

319 The journals represented in Figure 4a are specialized in different research areas. These include volcanology,
320 geothermal energy, general geology and earth sciences, geophysics, climatology and atmospheric sciences,
321 paleosciences (paleogeography, paleoclimatology, paleontology), quaternary and geochronology, geochemistry and
322 mineralogy, soil science and agriculture, materials and construction, and multidisciplinary high-impact publications.
323 This highlights the breadth of areas covered by volcanic ash. In addition to these fields, there are a wide variety of
324 other subject areas whose journals have fewer publications than those already mentioned. Some of which are:
325 environmental and natural resources sciences, remote sensing, engineering, technology and practical applications,
326 oceanography and marine sciences, regional magazines, biological sciences and applied microbiology, glacier and
327 cryosphere sciences, environmental toxicology, and public health.

328 The journal with the highest number of publications is the Journal of Volcanology and Geothermal Research. The
329 observed journal distribution shows a small group of specialized outlets that concentrate a substantial share of
330 publications, while a very long tail of journals published sporadically on the topic. This pattern reflects both
331 specialization (core volcanology outlets) and the cross-cutting application of volcanic ash research across different
332 domains (e.g., materials, soil science, public health). Furthermore, it is important to note that the journals have
333 increased their publication about “volcanic ash” over the study period. This can be seen in Figure 5. In this figure,
334 there is a combination of different journals to improve the visualizations. The growth trend could be related to the
335 general increase in publications.

336 Bradford’s law (Alvarado, 2016; Bradford, 1934) was applied to identify core journals. The journal core for this topic
337 contains all journals whose cumulative number of publications is 73 or more during the entire period. That is, 26
338 different journals. In zone 2, there are 155 journals with between 10 and 69 publications on volcanic ash during the
339 study period. Finally, in the critical zone, zone 3, there are the last 2063 journals, with 5 or fewer publications in the
340 time considered. In the last group, there are 1288 journals with only 1 publication on volcanic ash in the whole
341 period. Figure 6 represents the core area and the name of the 26 journals most used by authors publishing on
342 volcanic ash.

343 The journals with the highest local H-index are presented in Figure 7. The three journals with the largest number of
344 publications on the topic (Figure 6) also rank highest in terms of local H-index. However, some journals appear in
345 only one of the two rankings. Both figures show only the journals that are in the top positions.

346 Journals with a high order in Bradford's law and a lower order in the H-index have more publications on volcanic
347 ash, but they have not been cited as much as in the total set of articles on this topic (analyzed articles) than others
348 with a lower Bradford index and a higher H-index. On the other hand, some journals, such as Nature, are not
349 specialized in volcanic ash research. Although they publish fewer articles on this topic than several specialized
350 journals, they rank relatively high in the H-index, indicating a higher citation impact per publication. Among the
351 journals with the highest H-index is Construction and Building Materials. This shows the relevance that volcanic ash
352 has in different areas of knowledge (applied sciences).

353 The comparison between Bradford zones and local H-index indicates that high productivity does not necessarily
354 imply greater per-article impact: several high-impact contributions are published outside the most prolific outlets.
355 Therefore, conclusions about 'leading journals' should consider both productivity and citation performance per
356 article. In addition, it is pertinent to note that the bibliometric indices applied here do not account for journal
357 longevity or active publication period, which may influence the visibility of newer journals in rankings based solely
358 on productivity and citation metrics.

359 **3.3 Affiliations**

360 The affiliation with the highest number of publications is the *Istituto Nazionale Di Geofisica E Vulcanologia* (Figure
361 8). Additionally, it can be observed in Figure 9 that this Institute has experienced a remarkable increase over time in
362 the number of publications compared to the other affiliations shown in the same figure, which have also exhibited
363 growth. The rise in the number of publications on the topic is similar across all other affiliations, regardless of their
364 geographical location.

365 **3.4 Countries**

366 As for the number of publications per country, it can be observed in Figure 10 that the fifteen countries with the
367 highest number of contributions over time have experienced a marked increase. However, the United States stands
368 out as the most productive country in terms of the number of publications. In comparison, when focusing only on
369 affiliations, the one with the highest number was an institution from Italy (*Istituto Nazionale Di Geofisica E*
370 *Vulcanologia*, Figure 9). The United Kingdom and Japan also exhibit long-term and continuous growth trajectories,
371 reflecting their historically consolidated volcanological research communities. In contrast, several countries display
372 more recent and accelerated growth patterns. Italy shows a marked increase in publication output after the early
373 2000s. China presents one of the most abrupt recent increases, with publication growth concentrated mainly during
374 the last decade. The other represented countries exhibit moderate but sustained increases. Understanding the
375 distribution of scientific production in different countries or institutions allows interested persons to establish or
376 strengthen collaborations, establish scholarships, and contact regional experts, among other benefits.

377 3.5 Documents: Words

378 The most relevant and recurring words in research involving volcanic ash are observed in Figure 11. The most
379 frequent words suggest that the literature on volcanic ash focuses on volcanic processes and eruptions; ash transport
380 and deposition modeling; effects and implications; formation and composition; featured geographic areas; and impact
381 on soils and environments.

382 Regarding the geographical and geological setting, the presence of *Japan* and *island* suggests that a large number of
383 studies have been conducted in island volcanic regions, particularly in Japan. It is important to note that 'island' is
384 explicitly mentioned as a descriptor in studies focusing on insular volcanoes, whereas in continental settings, such a
385 distinction is generally not specified, making direct comparisons between island and non-island regions less
386 straightforward. The term *basin* may reflect potential applications of tephrochronology as a stratigraphic tool, such as
387 correlating volcanic ash layers, reconstructing basin evolution, or assessing hydrocarbon-bearing sedimentary
388 systems. Lastly, *center* could refer to volcanic eruption centers or key research institutions in the field.

389 The frequency of certain words also suggests the relevance of applications and methodological approaches. For
390 example, *model* refers to the widespread use of mathematical and computational modeling. Words such as
391 *application*, *property*, and *characteristics* may highlight intrinsic attributes and their functional utilization in diverse
392 contexts.

393 The absence of terms related to risk and impact among the most frequent terms shown in Figure 11 suggests that
394 research on volcanic ash has mostly focused on natural processes rather than the consequences or societal aspects of
395 eruptions. Terms such as impact, hazard, health, risk, and protocol/s appear in article titles with a frequency of only
396 299, 281, 79, 75, and 6 respectively, each accounting for less than 2.5% of the analyzed articles.

397 Traditionally, volcanic ash studies have been strongly focused on understanding eruption dynamics, ash dispersal,
398 and sedimentation processes, which are the foundation of classical volcanology. The dominance of geological and
399 process-focused terms (e.g., eruption, deposit, basin) may reflect both a disciplinary bias and a true research focus.
400 While this pattern genuinely shows the traditional interest of volcanic ash studies in natural processes, it might also
401 partly come from structural and language biases in the data sources, which favor geoscience publications over
402 applied or interdisciplinary research. Research on social, environmental, or economic impacts is likely conducted
403 within other scientific fields, like disaster risk reduction or environmental health. These communities tend to publish
404 in different journals and use their own specific vocabulary, which could explain why they appear less in this
405 bibliometric analysis.

406 The frequency of words over time is represented in Figure 12. The circle is located at the year representing the
407 median between the years in which the term was most used. The lines extend between the 1st quartile and the 3rd
408 quartile of the years in which it was utilized. This means that the term does not necessarily start being used where the
409 line starts or stops where it ends. For each year, the term with the highest frequency among those whose median year

corresponds to that year is represented. Circle size is proportional to frequency of times the term appears within a title.

The term *Pembrokeshire* was used predominantly in earlier decades (1924-1956), with a low frequency (5). This region in Wales (United Kingdom) with the presence of Ordovician volcanic rocks was studied at that time. The term *Paricutin* (1948–2004) peaked in relevance in the 1950s, related to the 1943 eruption, but the term continues to appear sporadically. The term *tolerance*, which appears strongly between years 1963 and 1992, is associated particularly with *acidity*, *pH*, and *soils* (See network of association of terms in Figure S1 of Supplementary Material). The terms used consistently over time have been *soil*, *volcano*, *eruption*, *sediment*, and *deposit*. They have gained increasing interest over time and are still relevant today. Recent terms include *China*, where research on the topic has expanded. Other terms are *concrete*, *cement*, and *gangue*, which may indicate a recent trend in research on the use of volcanic ash in construction materials, showing a focus on industrial applications of volcanic ash.

The temporal distribution of terms reflects shifts in the research focus within the field of volcanic ash studies. That is, specific events, locations, or characteristics gain prominence in the literature as they become more relevant or widely investigated over time (e.g., Donthu et al., 2021). Early research trends, with terms such as *Pembrokeshire*, *Paricutin*, and *tolerance*, reflect an initial interest in identifying volcanic deposits and their local impact. Specific terms such as *Helen*, *Mount*, *Paricutin*, among others, refer to specific historical events that have been widely studied. Intermediate research trends, with terms such as *deep-sea*, *Tertiary*, and *Quaternary*, indicate an interest in historical geology and sedimentary processes. *Humic*, *montmorillonite*, and *allophane* suggest a focus on the chemical and mineralogical composition of the ash. Recent trends, with terms such as *eruption*, *deposit*, *basin*, *characteristic*, and *model* show an interest in the dynamic processes of eruptions and their geological impact. *Concrete*, *cement*, *mechanical*, and *gangue* reflect practical applications of volcanic ash in engineering and construction.

It is important to note that the increase in the number of publications over time may influence the absolute frequency of terms. However, this trend is also associated with a diversification of research topics, which can affect the distribution and prominence of terms across years.

The temporal distribution of terms reflects differences in their persistence and emergence within the literature, distinguishing long-standing concepts from more time-constrained or recent topics. A detailed representation of these patterns is provided in Table S3 in the Supplementary Material.

3.6 Conceptual Structure

The co-occurrence network (Figure 13) allows us to distinguish four central concepts that are fundamental in current research on volcanic ash. Each of these concepts forms connections, highlighting priority research areas or key themes within volcanic ash.

The first concept is related to Geological and Stratigraphic Frameworks of volcanic ash, emphasizing methodologies such as tephrochronology for correlating sedimentary formations, basin evolution, and mineralogical-geochemical

analyses. Within this group, the terms formation and basin display the highest betweenness centrality values, which connect the different terms in the group and are the most influential with high connections, while all the terms in this group are homogeneously interconnected.

The second concept, on Volcanology and Eruptive Dynamics, has as its main terms volcano and eruption. It is a group that focuses on the dynamics of volcanic eruptions, dispersion patterns, pyroclastic flows, volcanic plumes, and associated hazards. The terms volcano and eruption are the most interconnected to the other terms of the same group, they are also the ones that constitute more bridges between the other terms and the ones with the greatest connection with more connected terms.

A third concept is related to Ash Deposits and Distribution. It covers the study of the distribution, composition, and characteristics of volcanic ash deposits. The term deposit is the one that generates the greatest connection between other terms. This, along with tephra, are the ones that have the greatest connections with other closely connected terms. These two, along with center, are similar in relation to direct interconnection with many terms.

The fourth concept is focused on Physicochemical Properties of Ash. This cluster focuses on the impact of ash on soil, its chemical properties and composition. The term soil is the most central word, indicating its key role in the network through the interconnection between other terms. It is also the one with the greatest influence due to its high connection with other closely connected terms.

The thematic map in Figure 14 illustrates the roles of key concepts in the structure of knowledge on volcanic ash. The themes identified as both basic and motor are volcano, eruption, and deposit. The basic themes represent highly studied themes with a strong presence in the literature on the subject. These concepts are very well connected in the network (Cobo et al., 2011). Therefore, it can be deduced that studies on volcanic deposits and eruptions are a foundational pillar in research on volcanic ash.

Motor themes are those that are highly connected and have a strong impact on the field, thus driving research (Cobo et al., 2011). In addition to the previously mentioned terms, this group also includes basin, formation, and sediment. Their prominence suggests that volcanic ash layers are widely used as chronological markers in sedimentary sequences, particularly in tephrochronological studies (Smith & Albert, 2023). In many cases, these ash layers provide the only means to date sedimentary formations, which explains the frequent co-occurrence of these terms, rather than a focus on ash-related transport or depositional processes (Abbott et al., 2024; Hopkins et al., 2020; McLean et al., 2024). The latter three terms fall within the transitional category between niche and motor themes. Niche topics are those that are highly specialized, with strong development in a specific area (Cobo et al., 2011). However, in this case, these themes also show growing connectivity, placing them at the intersection between niche and motor categories.

Additionally, the map highlights emerging and declining themes, indicating topics that are either gaining traction or losing prominence. These topics have a low density in the network and may represent growing or declining areas (Cobo et al., 2011). The words in this group are soil, properties, and effect. Several studies have examined the effects

of volcanic ash on soil properties—nutrient availability, pH, and water retention—highlighting its importance for agricultural productivity, ecosystem resilience, and post-eruption recovery. Complementary research focuses on the ash's physicochemical attributes (grain size, mineralogy) for technical applications in construction materials and filtration systems. The term effects encompasses the impacts of volcanic ash on soil fertility and structure that determine crop performance; its role as a supplementary cementitious material enhancing the mechanical properties and sustainability of concrete; and its influence on cement manufacturing processes (e.g., Al Asmari et al., 2025; Hamada et al., 2023; Hatefi et al., 2024; Khan et al., 2022; Mihai et al., 2023; 2025; Saputra et al., 2022).

3.7 Social Structure

The network of collaboration between Countries in Figure 15 allows us to visualize the USA (betweenness centrality, BC = 132.088; closeness centrality, CC = 0.02; pageRank centrality, PR = 0.118) and the UK (BC = 71.165, CC = 0.02, PR = 0.095) as the most influential nodes in the collaboration network. This indicates that these countries play a key role as intermediaries between different research groups and have connections to multiple regions. Germany (BC= 48.707, CC = 0.02, PR = 0.071) and France (BC = 32.917, CC = 0.02, PR = 0.056) are also key players, suggesting a strong connection in scientific collaborations within Europe. Italy (BC = 20.627, CC = 0.02, PR = 0.054) and Japan (BC = 17.422, CC = 0.018, PR = 0.03) also have a relevant role, although less central than the US and the UK.

Cluster 1 is composed of India, Indonesia, South Korea, Thailand, and the Philippines. It has low BC and PR values, indicating that these countries have more peripheral connections. India and Indonesia have the highest values within the group, indicating that they could be connection points within the region.

Cluster 2, comprising the US, UK, China, Canada, Australia, Brazil, Mexico, Denmark, etc., is the most influential group, with countries with the highest CC, BC, and PR values. The US and UK are the undisputed leaders in the network. China and Japan have a secondary, but relevant role. Countries such as Brazil, Colombia, Israel, and Turkey have comparatively lower BC, indicating that they are not key intermediaries.

Cluster 3, which consists of Turkey, Poland, Romania, Hungary, and Cameroon, has the lowest overall influence on the network. Turkey and Poland have the highest Betweenness values, suggesting that they can act as connectors within this cluster.

In cluster 4, which includes Germany, France, Italy, Spain, Argentina, Chile, Switzerland, etc., Germany and France are the most influential within the cluster, based on centrality measures. Spain and Switzerland have a relatively high PageRank, which indicates that they are well-connected countries within the group. Other countries contribute meaningfully to the network, although with comparatively lower centrality values. Countries such as Portugal, Finland, and Greece have less influence on the network.

Cluster 5, which consists only of Saudi Arabia, has a limited presence in the network, with low values of Betweenness and PageRank. Cluster 6, which only includes Malaysia, also has a peripheral role with low values of

centrality. Cluster 7, consisting of Egypt, represents the country with the least influence in the network, with the lowest values of Betweenness and PageRank. Overall, the countries with high intermediation and leadership in collaborations are the USA, the UK, Germany, and France. They are strategic for establishing new connections. China, Japan, Italy, Spain, and Switzerland show good connectivity but less intermediation. They are important in their region but do not lead the global network. In contrast, Egypt, Malaysia, Cameroon, Estonia, and Peru have a peripheral position and limited global influence. These findings indicate that there is a dominant Anglo-Saxon block (USA, UK, Canada, Australia), an influential European block (Germany, France, Italy, Spain), and other groups with less global impact.

518

519 **3.8 Knowledge gaps and future research directions: Bridging bibliometric evidence with** 520 **priority research needs for volcanic ash studies**

The bibliometric mapping highlights not only the central pillars of volcanic ash research but also makes evident the relative marginality of several applied and process-focused topics. Below we synthesize major knowledge gaps identified in recent literature and link them to the structural patterns revealed by the present analysis, to provide targeted recommendations for future research.

Health-related themes (e.g., terms like effects, properties) are emerging in the thematic map (low centrality/low density). Stewart et al. (2022) and Horwell et al. (2023) stress the lack of longitudinal epidemiological data, technologies, and rapid, standardized ash hazard protocols. Our bibliometric evidence confirms limited connectivity of health studies within the wider volcanic ash network, indicating a need for multi-site cohort studies and harmonized rapid-response sampling protocols to inform public health guidance.

Because the thematic map highlights “soil” as an emerging node, studies linking volcanic ash characteristics to agricultural performance need to be more developed. Recent research (e.g., Biass et al., 2022; Craig et al., 2016; Ligot et al., 2023; 2025; Mihai et al., 2025; Weir et al., 2024) emphasizes that ash impact on agriculture cannot be assessed by deposit thickness alone, since particle grain size, foliar retention, plant functional traits, and management conditions jointly determine vulnerability and yield outcomes. Experimental and remote-sensing approaches alike point to major knowledge gaps: the scarcity of field validations, comparative data across crop types and growth stages, and the integration of deposition metrics with agronomic and physiological measurements that connect ashfall to yield loss. Addressing these deficiencies would enable the translation of tephra–plant interaction models into actionable frameworks for agricultural risk assessment.

Marine and submarine impacts are not in the top tier of topics in the bibliometric map, while recent case studies highlight important ecosystem and depositional effects. Bisson et al. (2023) and Seabrook et al. (2023) note gaps in understanding ash influence on ocean optics, biogeochemistry and submarine deposition. Integrative campaigns combining in-situ sampling, satellite observations and sedimentary monitoring are required to enhance research into marine processes associated with ash.

Although deposit- and stratigraphy-focused publications dominate the literature, there are processes that remain underrepresented. Paredes-Mariño et al. (2022) explicitly call attention to uncertainties in ash lifecycle processes (ash generation, the process which controls effusive-explosive activities, low magnitude explosive events), and models, focusing their attention to improve the statistics, the use of machine learning, remote sensing, data assimilation, and inverse modeling in existing ash transport models. In our thematic network, the term *model* appears as part of the main cluster associated with *volcano*, identified as a basic and motor theme, reflecting its central role within the field. However, terms related to methodological advances, such as *machine learning*, *statistical modeling*, or *data assimilation*, are notably absent among the most frequent terms, suggesting that quantitative and computational innovations have not yet permeated the core of volcanic ash research. Addressing this gap requires coordinated field monitoring, laboratory experiments and integrated modelling to better capture the conditions, processes and deposit characteristics, and to arrive into risk mitigations and better communications.

Rahadiano et al. (2024) stress that uncertainty in ash-fall forecasts, strongly modulated by wind dynamics and seasonality, must be explicitly quantified through ensemble and sensitivity analyses, as uncertainty information is crucial for timely decision-making during fallout events. Complementary validation campaigns that integrate remote sensing, ground truthing, and probabilistic modelling would thus provide direct benefits for operational forecasting and disaster-risk management.

In terms of fine fraction characterization and interoperable databases, high-resolution descriptions of fine ash phases, mineralogy and density remain scarce. Benet et al. (2024) highlight the absence of comprehensive, standardized datasets that span size fractions relevant for atmospheric transport and health. Our results show weak connectivity for particle-characterization studies, suggesting that community efforts to build interoperable particle libraries and adopt machine-learning based classification would strongly improve model inputs and harmonize cross-study comparisons.

3.9 Limitations

This study is subject to several limitations inherent to the data selection and bibliometric approach employed. A primary constraint is the exclusive reliance on the Scopus database. While Scopus is a standard tool for bibliometric research, the use of a single bibliographic source provides less comprehensive coverage than the integration of several databases, as no single citation index is exhaustive (Burnham, 2006; Gerasimov et al., 2024). Consequently, this restriction introduces systematic biases that overrepresent English-language journals and specific regions, potentially leading to results that differ from those of other data sources (Mongeon and Paul-Hus, 2016; Tennant, 2020).

This bias is particularly relevant to volcanology, which historically emerged as a multilingual discipline. Much of the foundational research during the 19th and early 20th centuries was published in French, German, and Italian, languages that served as the early official media for seminal journals such as *Bulletin volcanologique*. For its first sixty years, the journal was under Italian editorial leadership, and its early history reflects a deeply international, non-Anglophone roots of volcanology (Cas, 2019; 2022). Consequently, restricting the dataset to English-language

578 publications may result in an incomplete representation of the intellectual foundations and early scientific
579 developments of volcanic ash research (Mongeon and Paul-Hus, 2016).

580 Furthermore, important regional bodies of knowledge remain underrepresented. Countries with intense volcanic
581 activity, such as Japan, Indonesia, and several Latin American nations, possess long-standing research traditions
582 often documented in local languages (Lerner et al., 2023; Hernández-Socha, 2023). Studies in related environmental
583 fields suggest that approximately 35% of relevant scientific documents are published in non-English languages , and
584 up to half of these may be unsearchable using English keywords (Amano et al., 2016). Ignoring this literature can
585 introduce significant gaps in understanding local hazard assessments and field-based observations (Amano et al.,
586 2016; Lerner et al., 2023). As a result, the geographic and institutional patterns identified in this study may reflect
587 linguistic accessibility and the ongoing "Anglicization" of science rather than the true global distribution of scientific
588 activity (Hernández-Socha, 2023; Lerner et al., 2023). Recent multilingual analyses confirm this linguistic
589 imbalance, demonstrating that English-language discourse dominates the online visibility of volcanic eruptions even
590 for events occurring in non-English-speaking regions, effectively disconnecting international attention from real-
591 world significance (Farquharson, 2025).

592 This language restriction also influences citation-based indicators. English-language publications generally achieve
593 higher international visibility, whereas non-English works —regardless of their scientific quality— frequently
594 receive fewer citations (Hernández-Socha, 2023; Van Leeuwen et al., 2001). This dynamic can “artificially” dilute
595 the impact scores of non-Anglophone research systems (Van Leeuwen et al., 2001, Vera-Baceta et al., 2019).

596 Furthermore, networks derived from this dataset are similarly affected. The analysis primarily captures interactions
597 among researchers who publish in English and English words, potentially leading to a systematic underestimation of
598 scientific cooperation occurring within non-English-speaking communities or in locally oriented research contexts
599 (Lerner et al., 2023). Recent analyses in volcanology highlight this gap, showing that approximately 40% of articles
600 concerning specific volcanoes do not include a locally domiciled author, suggesting a lack of inclusivity in
601 internationally visible datasets (Lerner et al., 2023).

602 Additionally, the scope of this study is bounded by the selection of specific document types, as the analysis was
603 restricted to original articles and reviews. While these represent the dominant modes of knowledge dissemination in
604 natural sciences and engineering, such a focus may omit significant contributions found in books, conference
605 proceedings, and technical reports (Mongeon and Paul-Hus, 2016).

606 A further temporal constraint concerns the completeness and reliability of records dating back to the late 19th
607 century. Bibliometric data from this era are often characterized by a systematic lack of critical metadata, such as
608 author affiliations and consistent indexing, a problem that is significantly more prevalent in older publications
609 (Lerner et al., 2023). Moreover, the spasmodic publication patterns and fragmented digitization of early volumes in
610 foundational journals —which often omit original covers and front-matter— limit the ability to accurately track early
611 institutional and geographic trends (Cas, 2019; 2022). Consequently, increases in research volume and citation

density during the early decades of the dataset should be interpreted as reflecting evolving database coverage and archiving practices rather than an absolute measure of scientific activity at that time.

Finally, it is worth noting that volcanology itself reflects a diversity of cultural and linguistic influences, as evidenced by its technical lexicon. Key terminology derived from diverse languages —such as *lahar* (Javanese), *jökulhlaup* (Icelandic), *pāhoehoe*, and *‘a‘ā* (Hawaiian)— underscores the global and culturally embedded nature of volcanic research (Harris et al., 2017). Restricting the corpus to English-language publications risks losing the epistemic diversity and local knowledge that these terms and their original descriptions represent (Lerner et al., 2023).

Taken together, these limitations indicate that the present analysis should be interpreted as a representation of the English-language scientific literature on volcanic ash, rather than a comprehensive account of all global research. Future studies could address this by incorporating multilingual databases or region-specific sources to achieve a more inclusive and historically complete perspective (Amano et al., 2016; Lynch et al., 2021).

623

624 4. Conclusions

This bibliometric analysis provides a comprehensive and structured overview of global research on volcanic ash, illustrating how the field has evolved and diversified over time. The sustained increase in publications, particularly following major eruptions, reflects both scientific responsiveness to volcanic crises and the expansion of long-term research agendas. The United States, the United Kingdom, Japan, and Italy stand out as the most productive countries, while contributions from China have grown notably in recent years. Despite this global expansion, the collaboration network remains uneven, with a few dominant institutions acting as central hubs.

The analysis reveals a gradual transition from traditional volcanological studies toward more integrated, hazard-oriented, and environmentally focused approaches. The increasing presence of multidisciplinary journals confirms that volcanic ash research is no longer confined to the geosciences, but has progressively incorporated environmental, engineering, health, and socio-economic perspectives.

Conceptual and thematic analyses indicate that research remains firmly grounded in fundamental themes, which continue to structure the field. However, the emergence of applied and niche topics demonstrates a growing effort to link the volcanic ash with environmental and human impacts. These emerging clusters point toward a broader and increasingly interdisciplinary research landscape.

Although modeling constitutes an important component of volcanic ash research, our results indicate that advanced data-driven approaches (e.g., machine learning, data assimilation, inverse modeling) have not yet been fully integrated into the core of the field. This gap, also highlighted in recent literature, points to a potential direction for future research aimed at improving the accuracy and operational applicability of ash-dispersion forecasts.

Overall, volcanic ash research is structured around dominant themes that coexist with less connected applied areas. The results suggest that further development of multidisciplinary approaches may help expand the scope and societal relevance of volcanic ash research. Continued collaboration among geosciences, environmental sciences, engineering, health, and social disciplines is essential to bridge the gap between physical understanding and societal

647 application. Building on this evidence, our study serves as a strategic roadmap for the scientific community. By
648 highlighting the need for technological innovation and cross-disciplinary integration, we provide a foundation for
649 future efforts to transform theoretical knowledge into robust, real-world solutions for volcanic risk mitigation.

650

651 **Author contributions**

652 Reckziegel, Florencia: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization,
653 Writing – original draft, Project administration.

654 Salgado, Pablo: Conceptualization, Investigation, Validation, Writing – review and editing.

655 Báez, Walter: Conceptualization, Investigation, Validation, Writing – review and editing.

656 Cirer, Mercedes: Conceptualization, Validation, Writing – review and editing.

657 Viramonte, José Germán: Supervision, Writing – review and editing.

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664

665 **Data availability**

666 The data supporting this study were obtained from the Scopus database (Elsevier). Due to licensing restrictions, the
667 metadata cannot be publicly shared or deposited in an open repository. However, all data are reproducible through
668 the same search procedure described in the Methodology section. Derived bibliometric indicators and figures are
669 available from the corresponding author upon reasonable request.

670

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1114

1115 **Figures captions**

1116 *Figure 1: Annual scientific production on volcanic ash research (1887–2024), highlighting key volcanic eruptions*
 1117 *with a Volcanic Explosivity Index (VEI) of 5 or higher and selected VEI 4 events shown in blue.*

1118 *Figure 2: Average (mean) citation per year for publications on “volcanic ash”, showing the increasing influence of*
 1119 *research over time. The dashed line marks the year 2020, from which citation counts may be less representative due*
 1120 *to the shorter time available for subsequent citations.*

1121 *Figure 3: Positive relationship between number of citations and the density of citations received by publications per*
 1122 *year. a) Publications with up to 500 citations . b) Publications with the highest number of citations received (>500).*

1123 *Figure 4: a) Journals with the highest number of publications on volcanic ash.. b) Frequency distribution of journals*
 1124 *based on the number of articles published on volcanic ash.*

1125 *Figure 5: Journals with the highest number of publications over time. Journals are listed in descending order*
 1126 *according to their number of publications at the end of the period shown. The starting years of the journals are:*
 1127 *Journal Of Volcanology And Geothermal Research (1976), Bulletin Of Volcanology (1922), Bulletin Of The*
 1128 *Geological Society Of America (1890), Soil Science And Plant Nutrition (1955), Earth and Planetary Science Letters*
 1129 *(1966), Geology (1973), Geophysical Research Letters (1974), Journal Of Geophysical Research: Solid Earth*
 1130 *(1979), Special Paper Of The Geological Society Of America (1934), International Journal Of Coal Geology (1980),*
 1131 *Palaeogeography, Palaeoclimatology, Palaeoecology (1965), Quaternary Science Reviews (1982), Journal Of*
 1132 *Geophysical Research (1979), Geoderma (1967), Construction And Building Materials (1987), New Zealand Journal*

1133 *Of Geology And Geophysics (1958), Atmospheric Chemistry And Physics (1999), Frontiers In Earth Science (2013),*
1134 *Quaternary International (1989), Nature (1869), Science (1880).*

1135 *Figure 6: Bradford's Law applied to volcanic ash research, showing the distribution of scientific productivity across*
1136 *journals.*

1137 *Figure 7: Local impact of journals measured by the H-index, highlighting the most influential journals in volcanic*
1138 *ash research.*

1139 *Figure 8: Affiliations with the highest number of publications in volcanic ash research.*

1140 *Figure 9: Affiliation production over time, showing the increasing contribution of key institutions to volcanic ash*
1141 *research.*

1142 *Figure 10: Country production over time of the 15 countries that achieved the highest number of publications.*

1143 *Figure 11: Most frequent words in titles of publications on volcanic ash, indicating the predominant themes in the*
1144 *field.*

1145 *Figure 12: Temporal distribution of key terms in volcanic ash research.*

1146 *Figure 13: Co-occurrence network of title-terms in volcanic ash research, highlighting the central concepts and*
1147 *their interconnections.*

1148 *Figure 14: Thematic map of title concepts in volcanic ash research, showing the role of different themes in the*
1149 *knowledge structure. Colors indicate the different clusters identified in the network.*

1150 *Figure 15: Collaboration network among countries in volcanic ash research.*

1151 **Supplementary Material**

1152 *Figure S1: Neural network of term association for the word tolerance.*

1153 *Table S1. Definitions of bibliometric concepts and indicators used in the analysis.*

Concept/Indicator	Definition	Reference	Figure / supplementary material
Total number of citations	Absolute number of citations received by an article.	Aria and Cuccurullo (2017)	Figure 3; Table S2
Citation density	Ratio between the total number of citations received by an article and the number of years elapsed since its publication.	Aria and Cuccurullo (2017)	Figure 3; Table S2
Average citations per year	Mean citation density of all articles published in a given year.	Aria and Cuccurullo (2017)	Figure 2
Bradford's law	Describes the distribution of scientific publications across journals, whereby a small number of journals account for a large proportion of publications while progressively larger groups of journals contribute fewer publications.	Bradford (1934); Alvarado (2016)	Figure 6
H-index	Highest number h such that h publications have received at least h citations each.	Hirsch (2005)	
Local H-index	H-index calculated using publications and citations restricted to the analyzed dataset.	Aria and Cuccurullo (2017)	Figure 7
Most frequent words	Frequency-based analysis of terms appearing in authors' keywords or, when keywords are unavailable, in publication titles.	Donthu et al. (2021); Emich et al. (2020)	Figures 11, 12, Table S3
Network analysis	Quantitative analysis of relationships among entities through network structures, allowing the identification of structural patterns and communities.	Aria and Cuccurullo (2017)	Figures 13, 15, S1
Co-word analysis	Analysis of the co-occurrence of terms to identify conceptual relationships and map the conceptual structure of a research field.	Donthu et al. (2021); Aria and Cuccurullo (2017)	Figure 13, 14
Co-occurrence network	Network in which nodes represent terms and links represent their frequency of co-occurrence within the same titles.	Aria and Cuccurullo (2017)	Figure 13
Thematic map	Representation of themes according to their centrality and density, allowing their classification as motor, niche, emerging/declining, or basic themes.	Cahlik (2000); Alkhamash (2023)	Figure 14
Country collaboration network	Network representing scientific collaboration between countries based on joint publications.	Glänzel and Schubert (2004)	Figure 15
Betweenness centrality (BC)	Measure of the extent to which a node acts as a bridge between other nodes through shortest paths in the network.	Freeman (1978)	
Closeness	Measure based on the shortest communication paths	Freeman (1978)	

centrality (CC)	between a node and the other nodes in the network.		
PageRank centrality (PR)	Measure of node influence that considers not only the number of connections but also the importance of the nodes to which it is connected.	Brin and Page (1998); Yan and Ding (2009, 2011)	

1154

1155 **Table S2: Articles with more than 500 citations received and their citation density per year.**

Publications with more than 500 citations						
Title	Authors	Journal	DOI	Citations	Age	Density
VOLCANIC ERUPTIONS AND CLIMATE	ROBOCK A	REVIEWS OF GEOPHYSICS	10.1029/1998RG000054	1931	2000	77,24
SYNCHRONIZING ROCK CLOCKS OF EARTH HISTORY	KUIPER KF;DEINO A;HILGEN FJ;KRIJGSMAN W;RENNE PR;WIJBRANS JR	SCIENCE	10.1126/science.1154339	1281	2008	75,35
U-PB AGES FROM THE NEOPROTEROZOIC DOUSHANTUO FORMATION, CHINA	CONDON D;ZHU M;BOWRING S;WANG W;YANG A;JIN Y	SCIENCE	10.1126/science.1107765	1188	2005	59,40
REAL-TIME ENVIRONMENTAL APPLICATIONS AND DISPLAY SYSTEM: READY GRADIENTS IN SILICIC MAGMA CHAMBERS: IMPLICATIONS FOR LITHOSPHERIC MAGMATISM.	ROLPH G;STEIN A;STUNDER B	ENVIRONMENTAL MODELLING AND SOFTWARE	10.1016/j.envsoft.2017.06.025	1173	2017	146,63
	HILDRETH W	JOURNAL OF GEOPHYSICAL RESEARCH	10.1029/JB086iB11p10153	1171	1981	26,61

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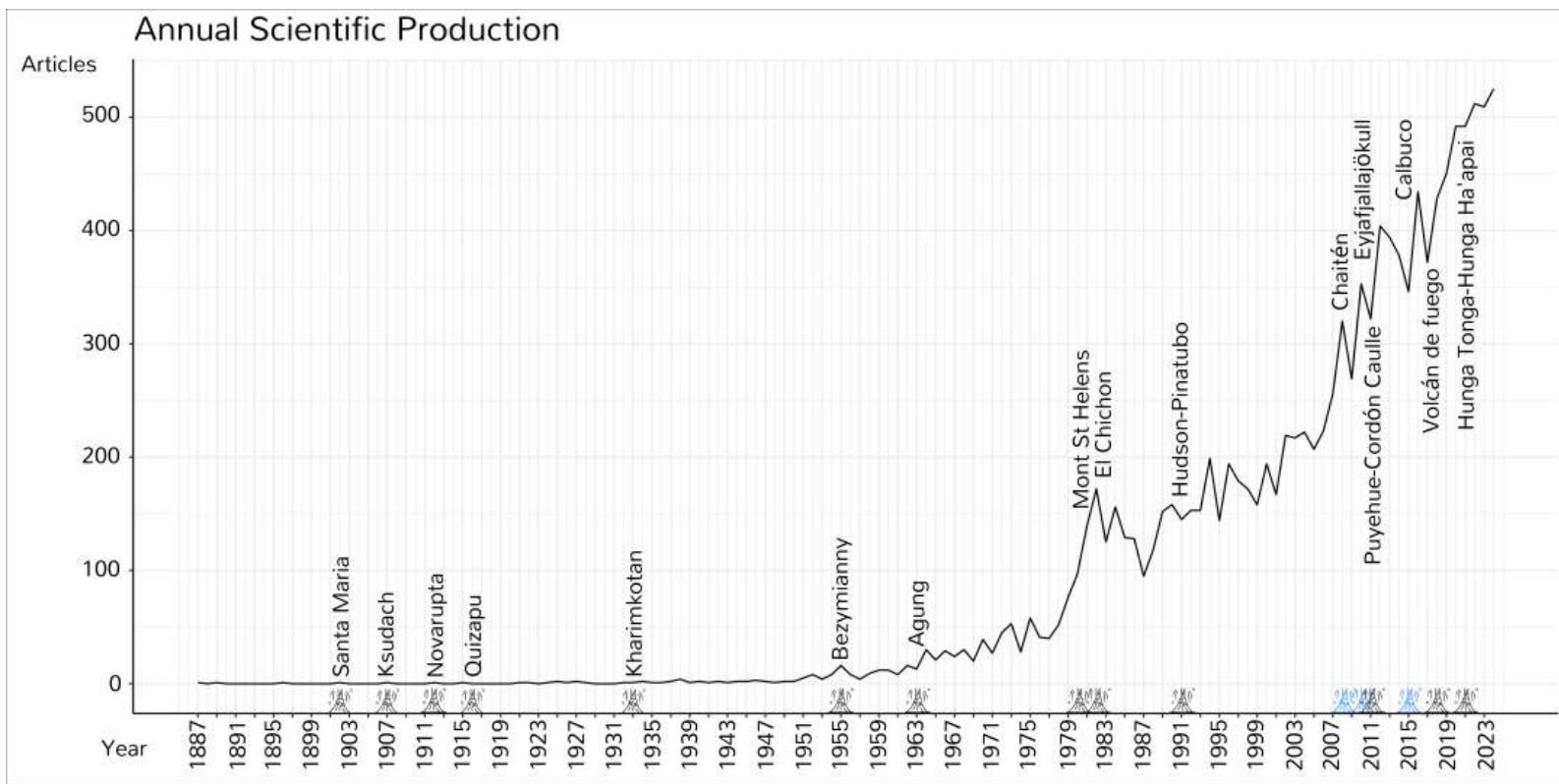
Table S3: Persistence and emergence patterns of the most frequent terms over time.

Terms - temporal distribution		
Q1 and Q3 separated by several decades	Close Q1 and Q3	Q3 in 2023 or 2024
Wide temporal distribution, indicating that they have maintained their relevance for a long time.	Narrow temporal distribution, suggesting that their use was more concentrated in a specific period.	Most recent terms suggest emerging research areas
• soil (1989-2015): 26 years.	• potassium-argon (1970-1978): 8 years.	• concrete, cement, mechanical (2023), gangue (2024): Use of volcanic ash in construction

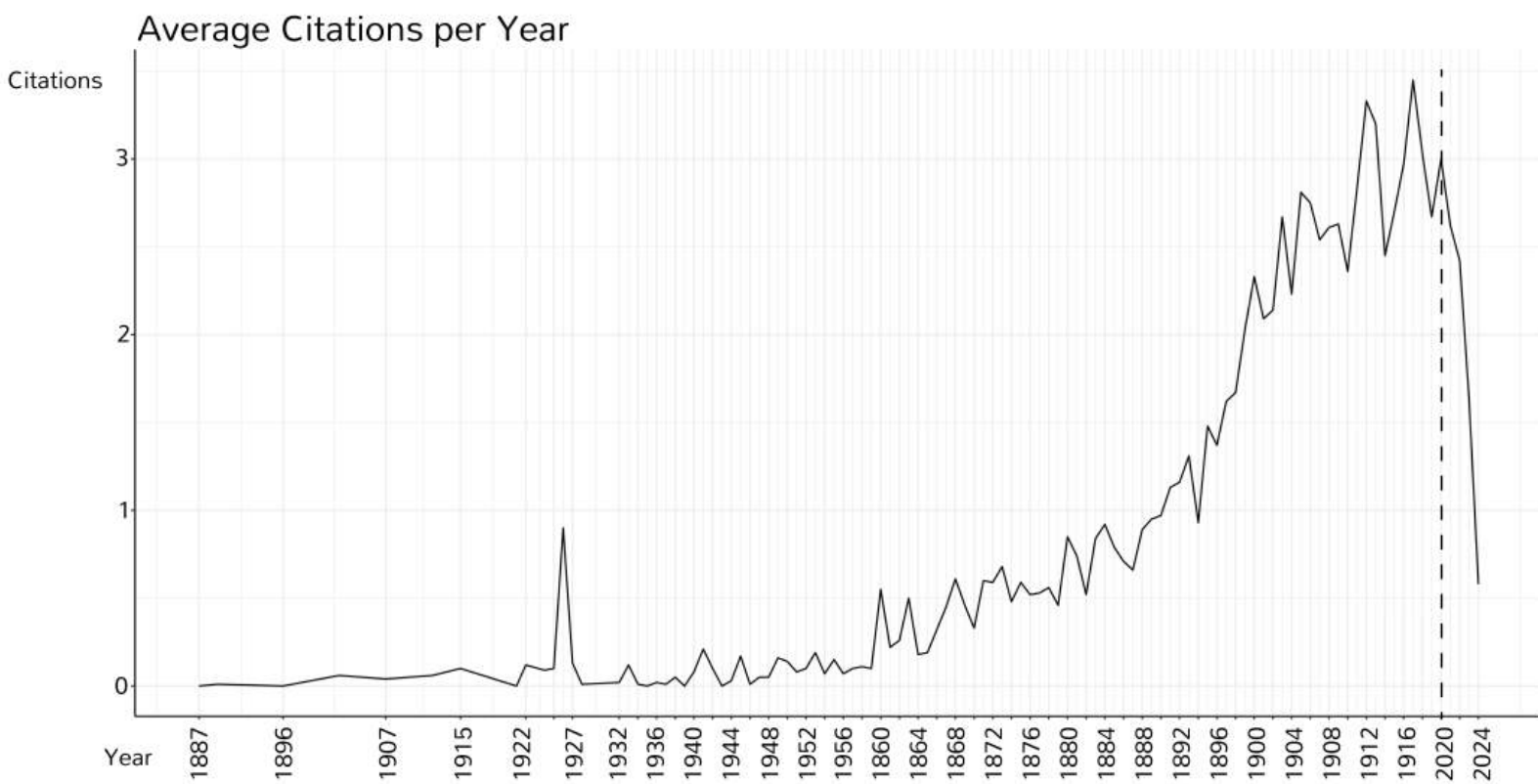
• rock (1987-2016): 29 years. • mineral (1990-2017): 27 years. • sediment (1993-2017): 24 years.	• citrus (1970-1973): 3 years. • bacillus (1977-1994): 17 years. • francois (1973-1981): 8 years.	materials or industrial applications. • palma (2024): Related to the eruption of the volcano in La Palma (Spain) in 2021.
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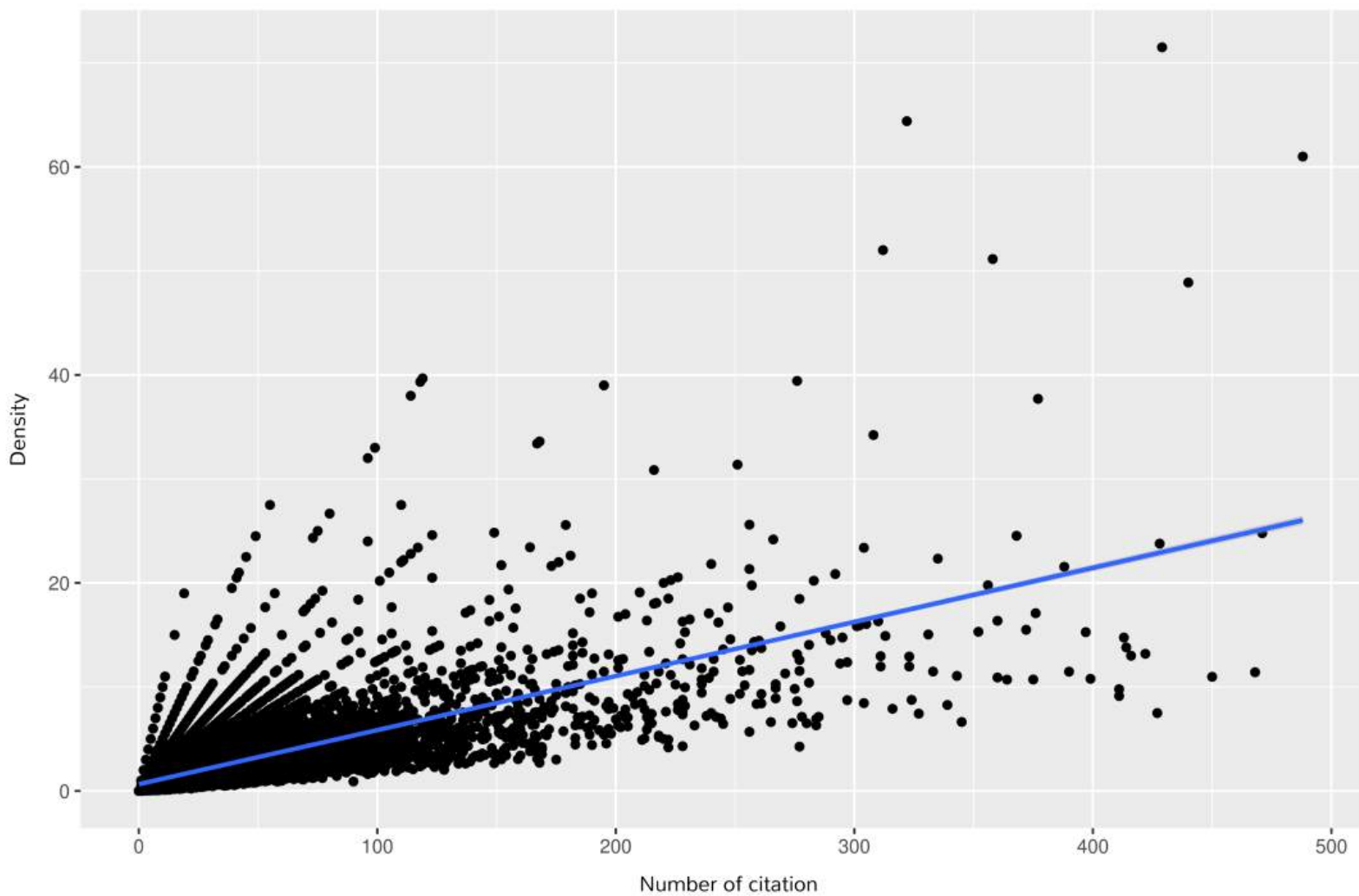
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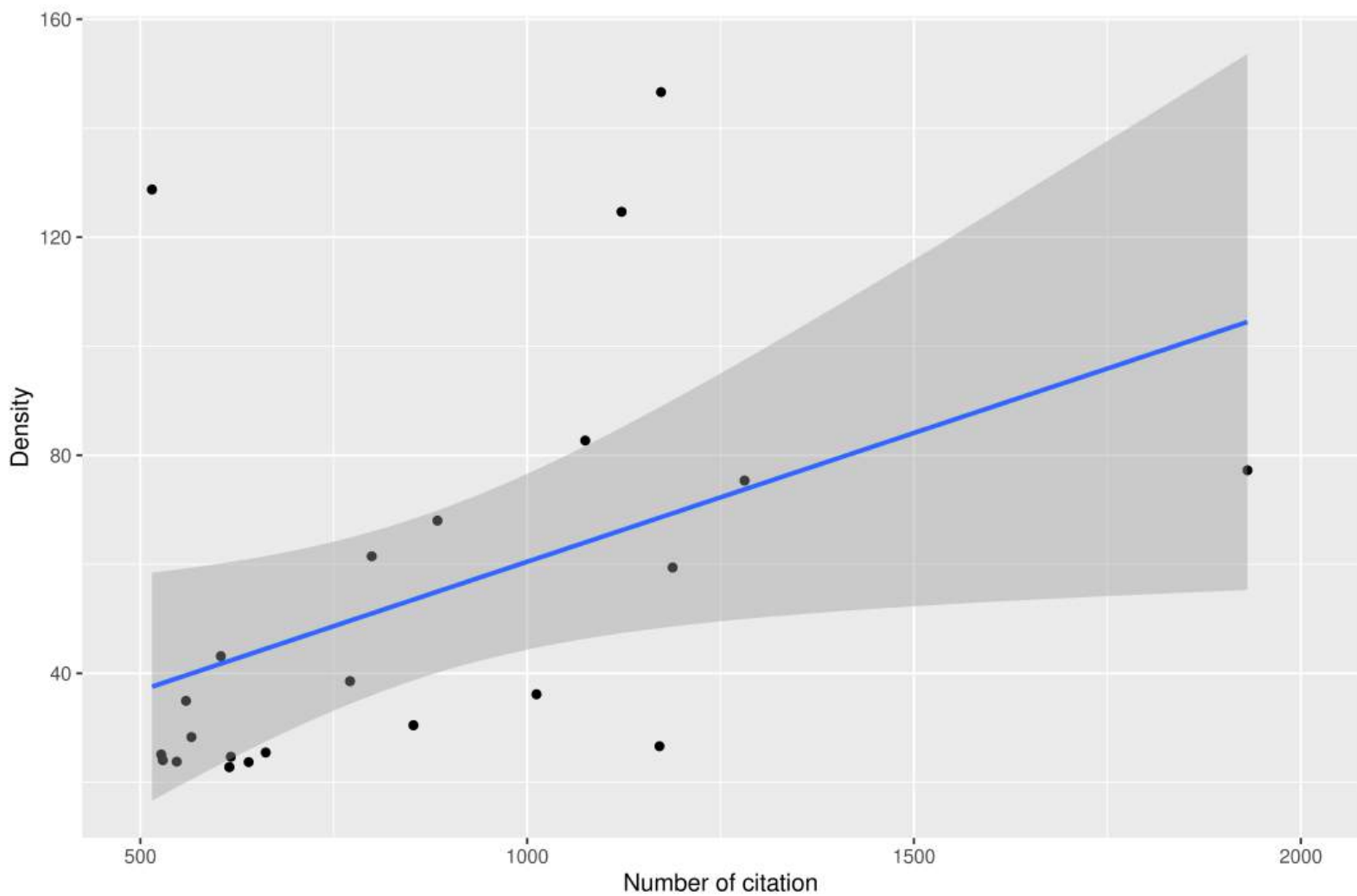
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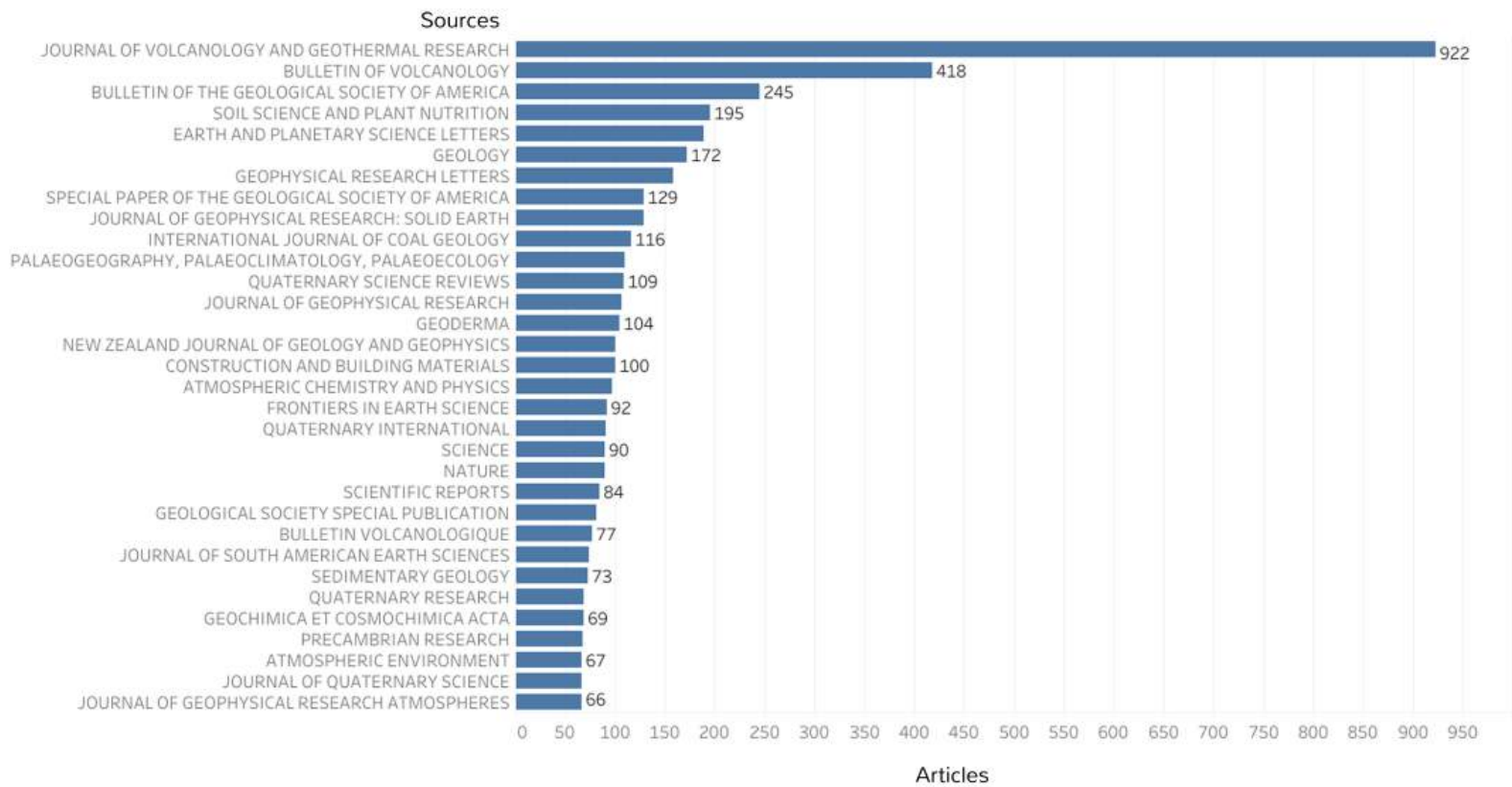
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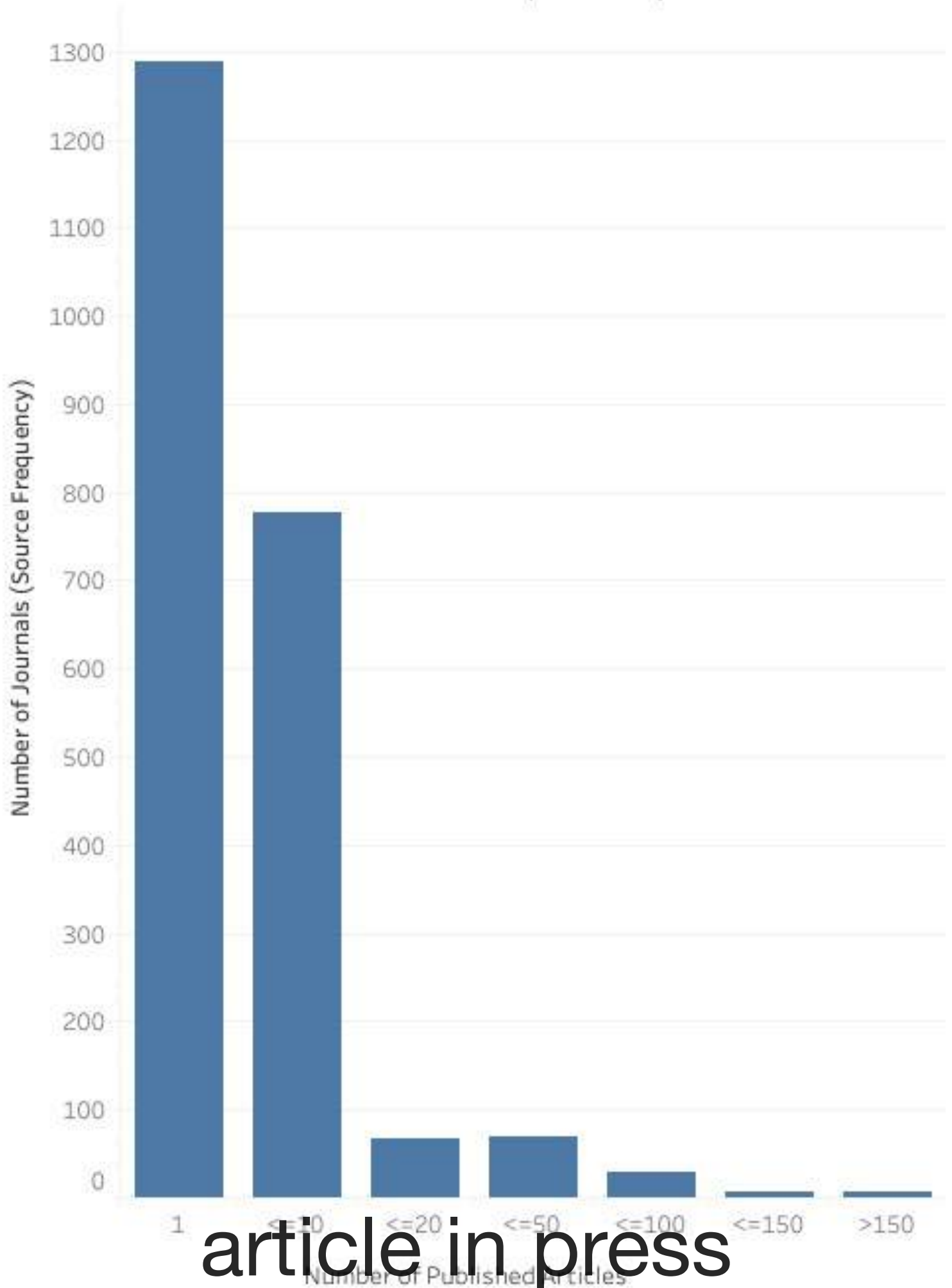


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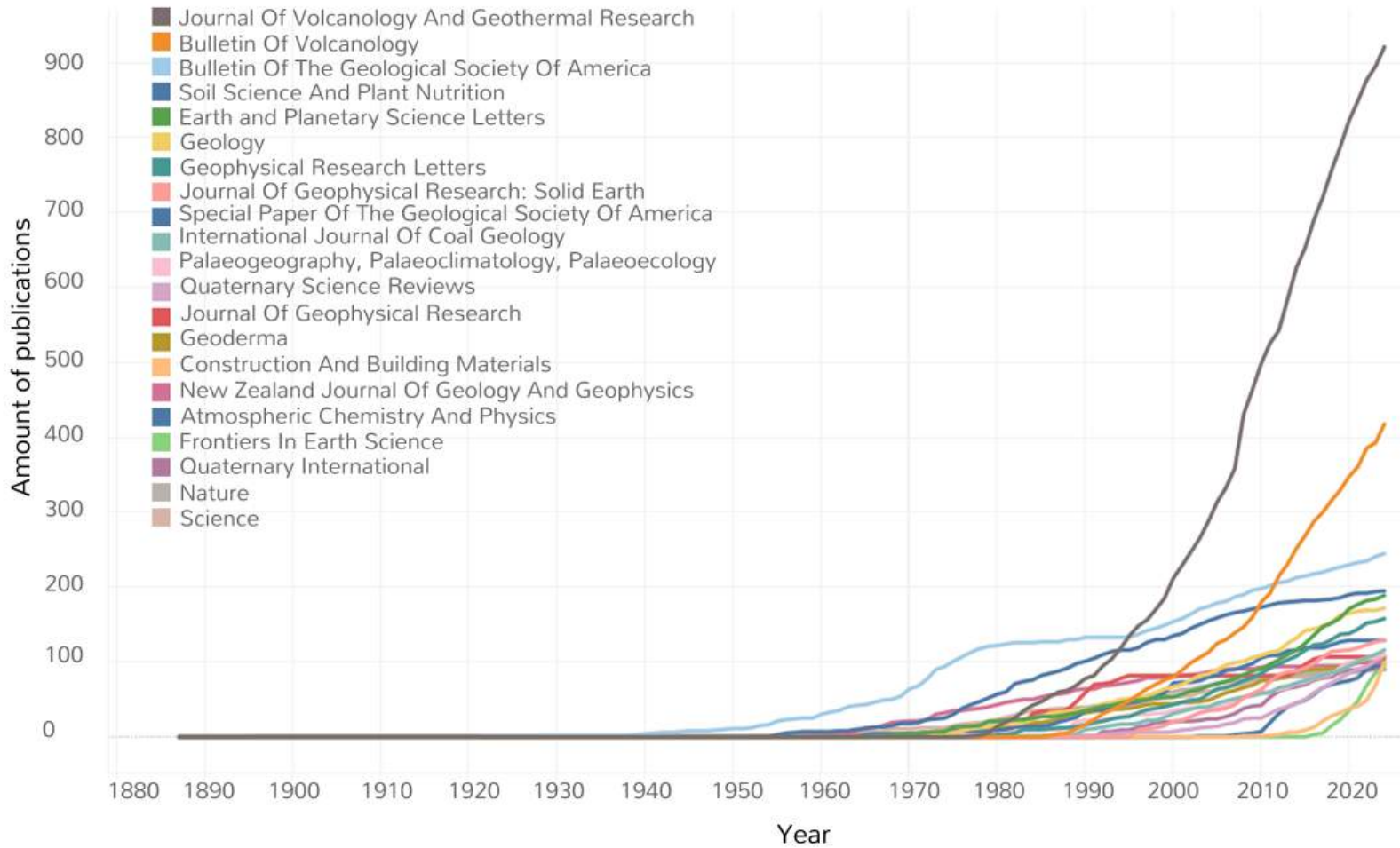


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Number of Articles published by Source

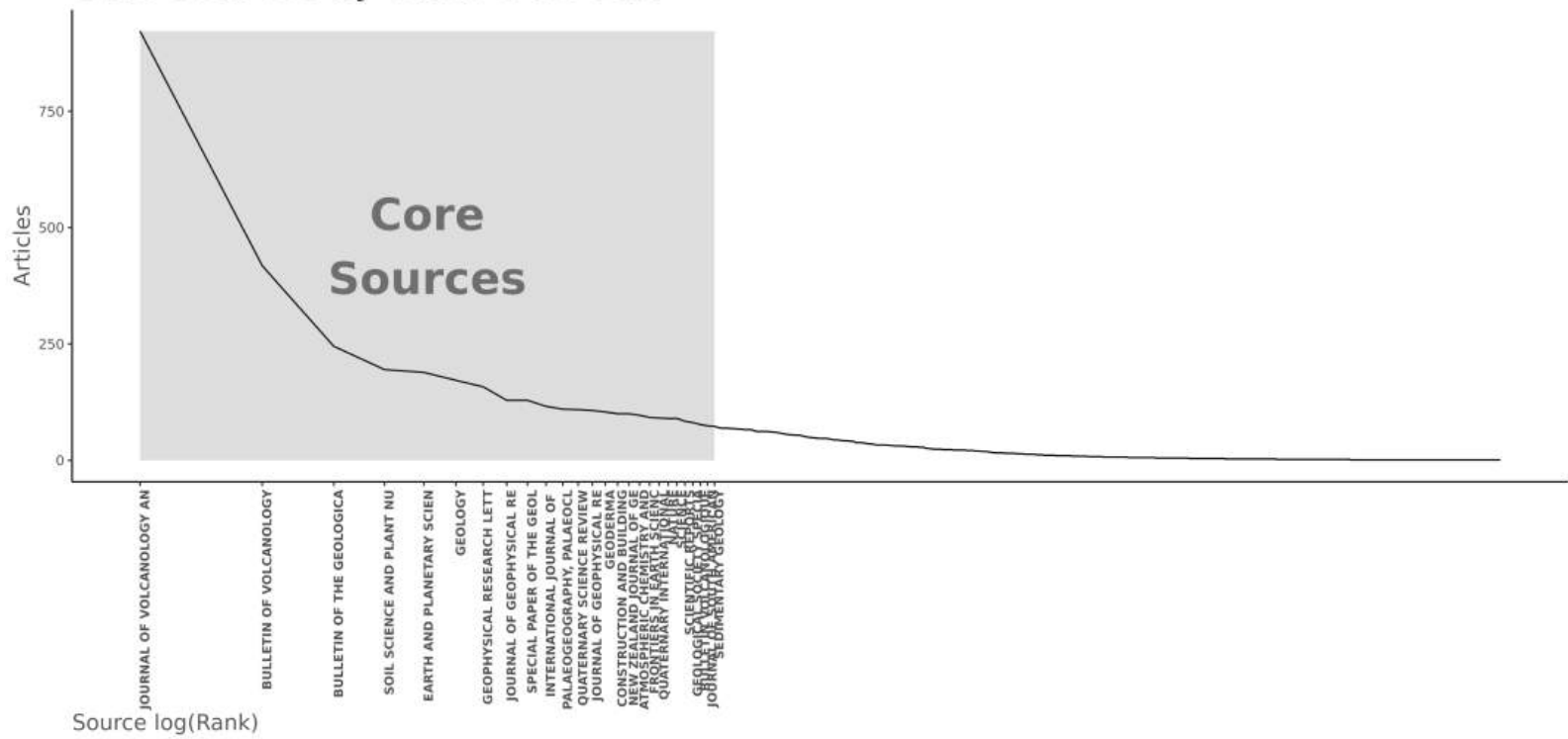


Sources' Production over Time

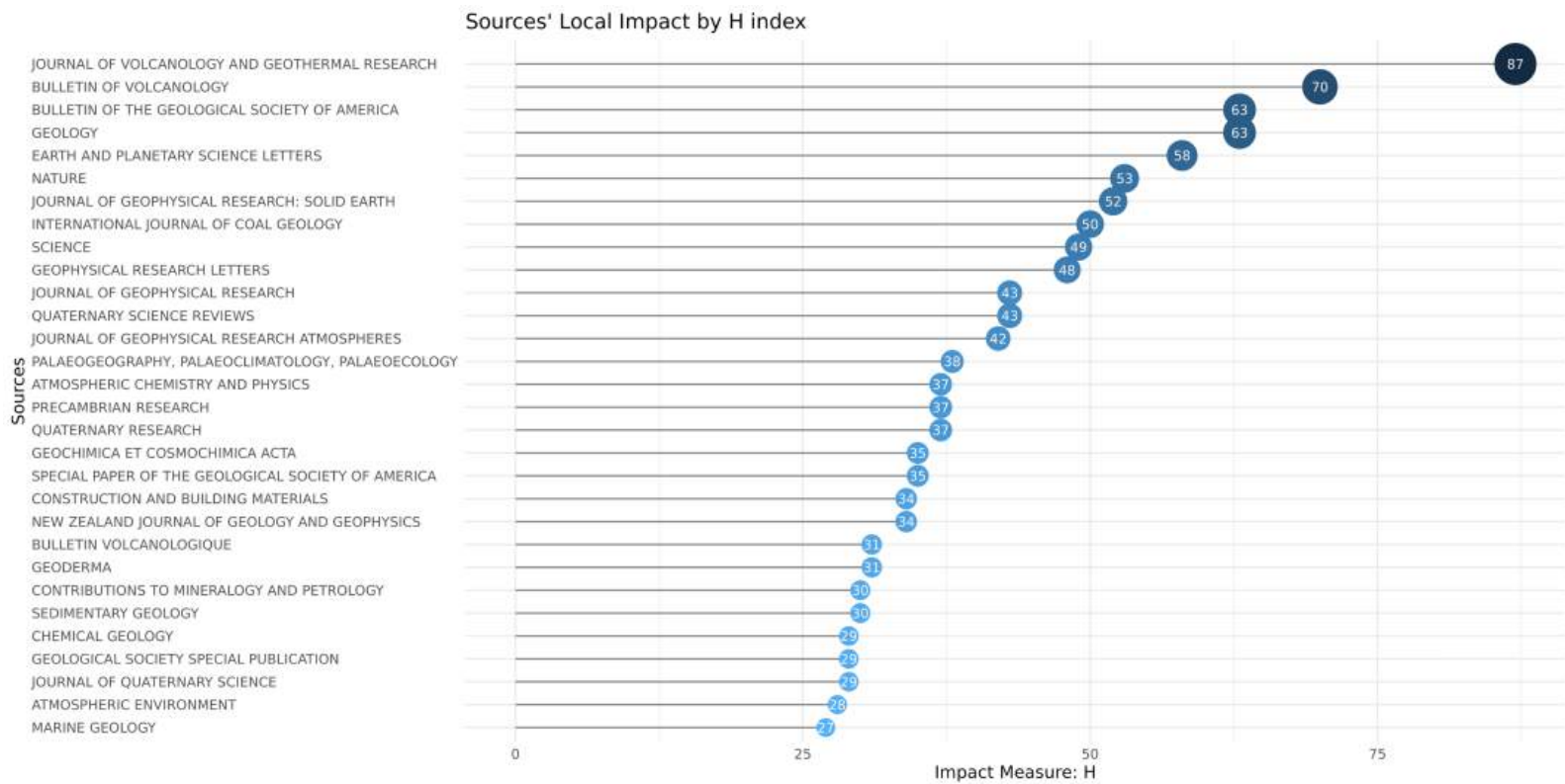


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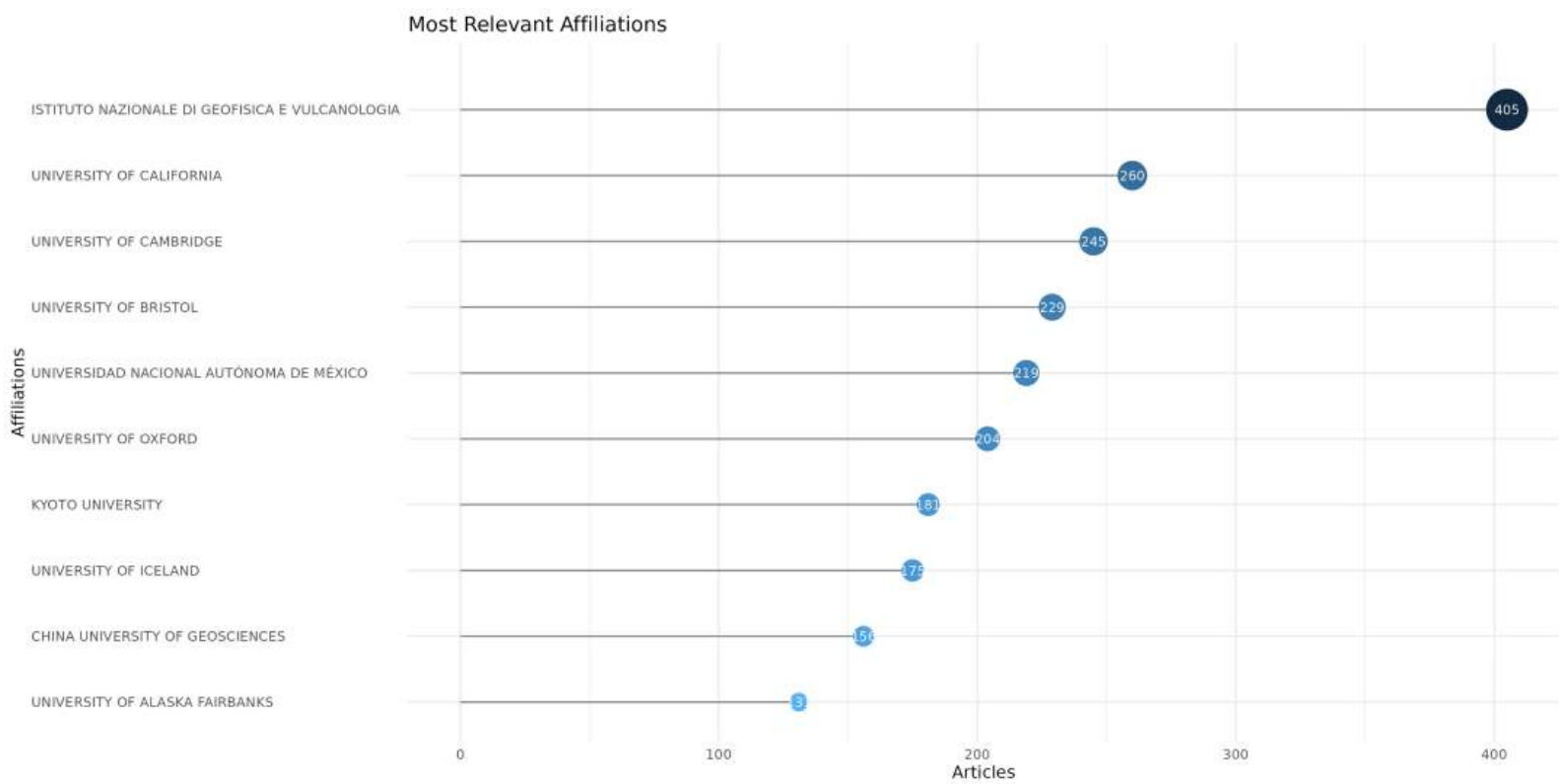
Core Sources by Bradford's Law



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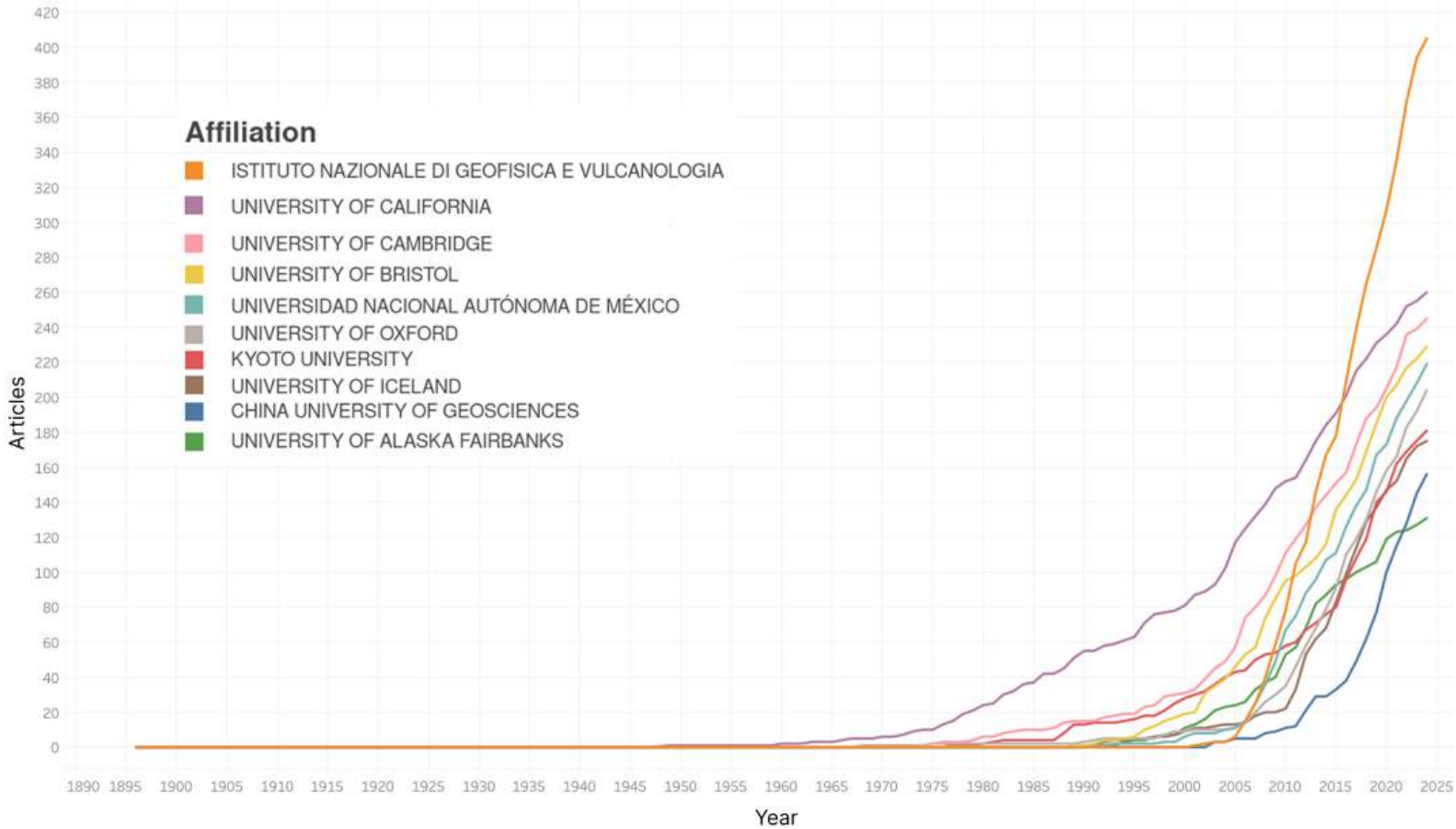


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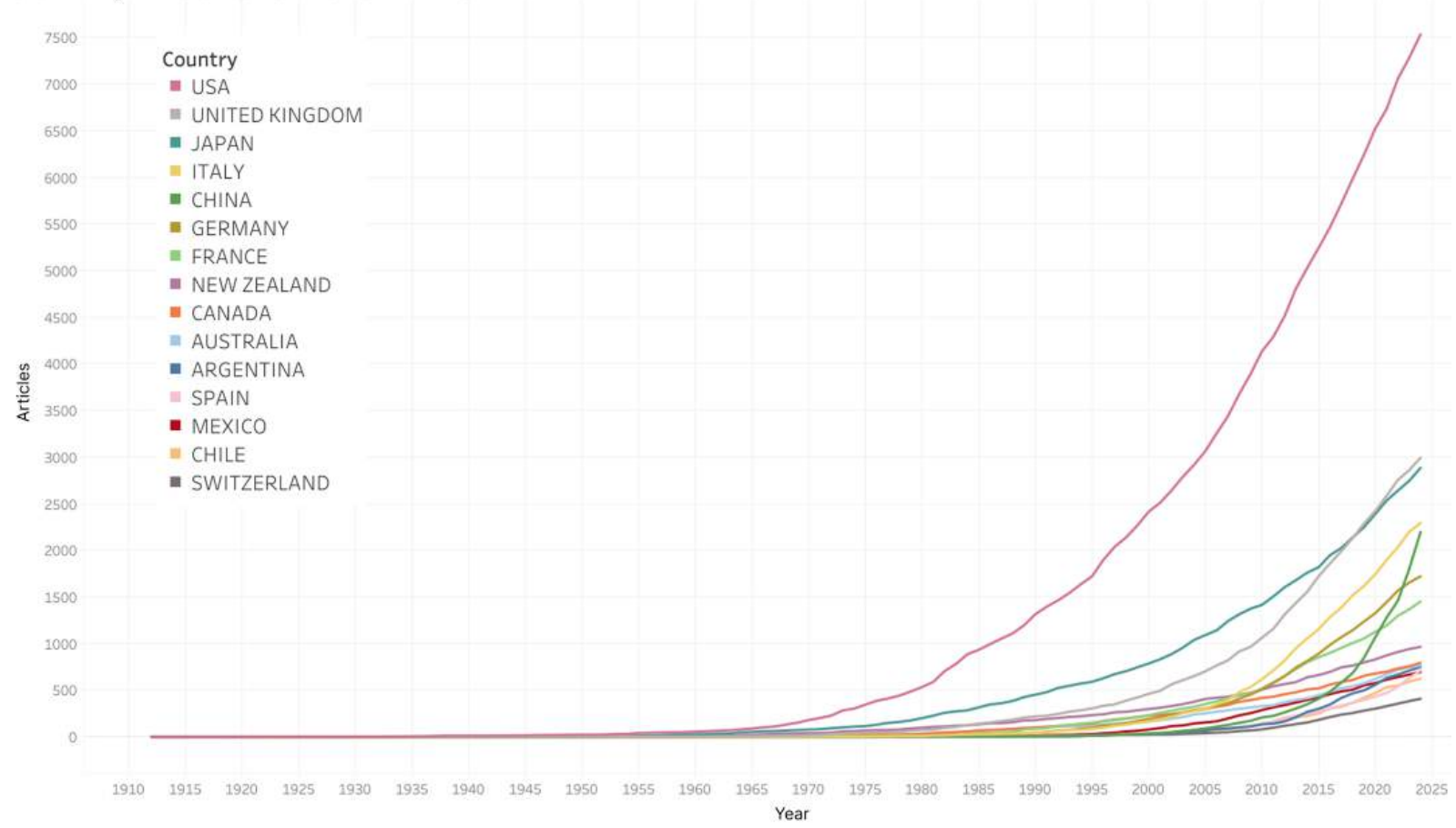
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Affiliations' Production over Time

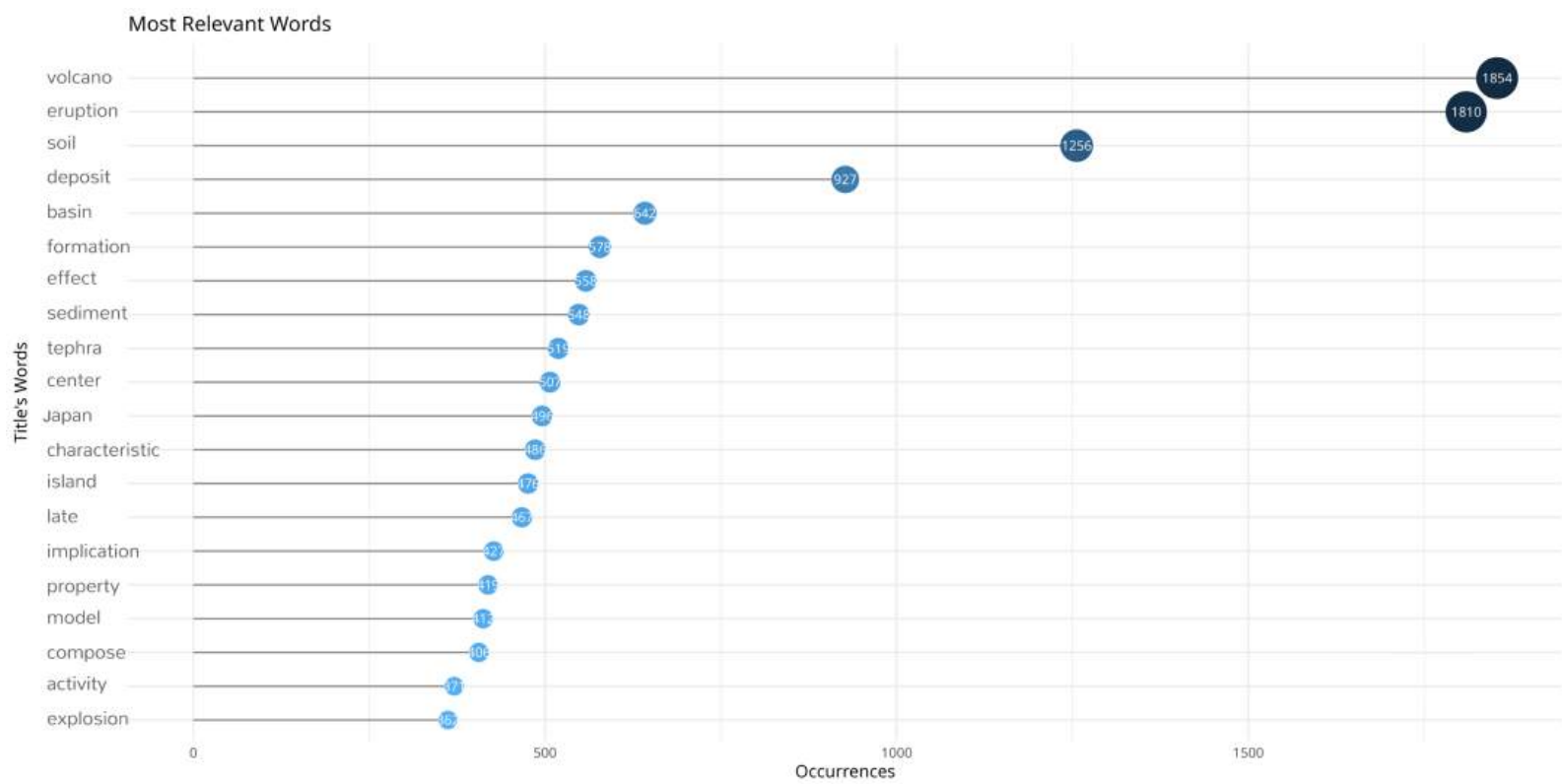


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Country Production over Time

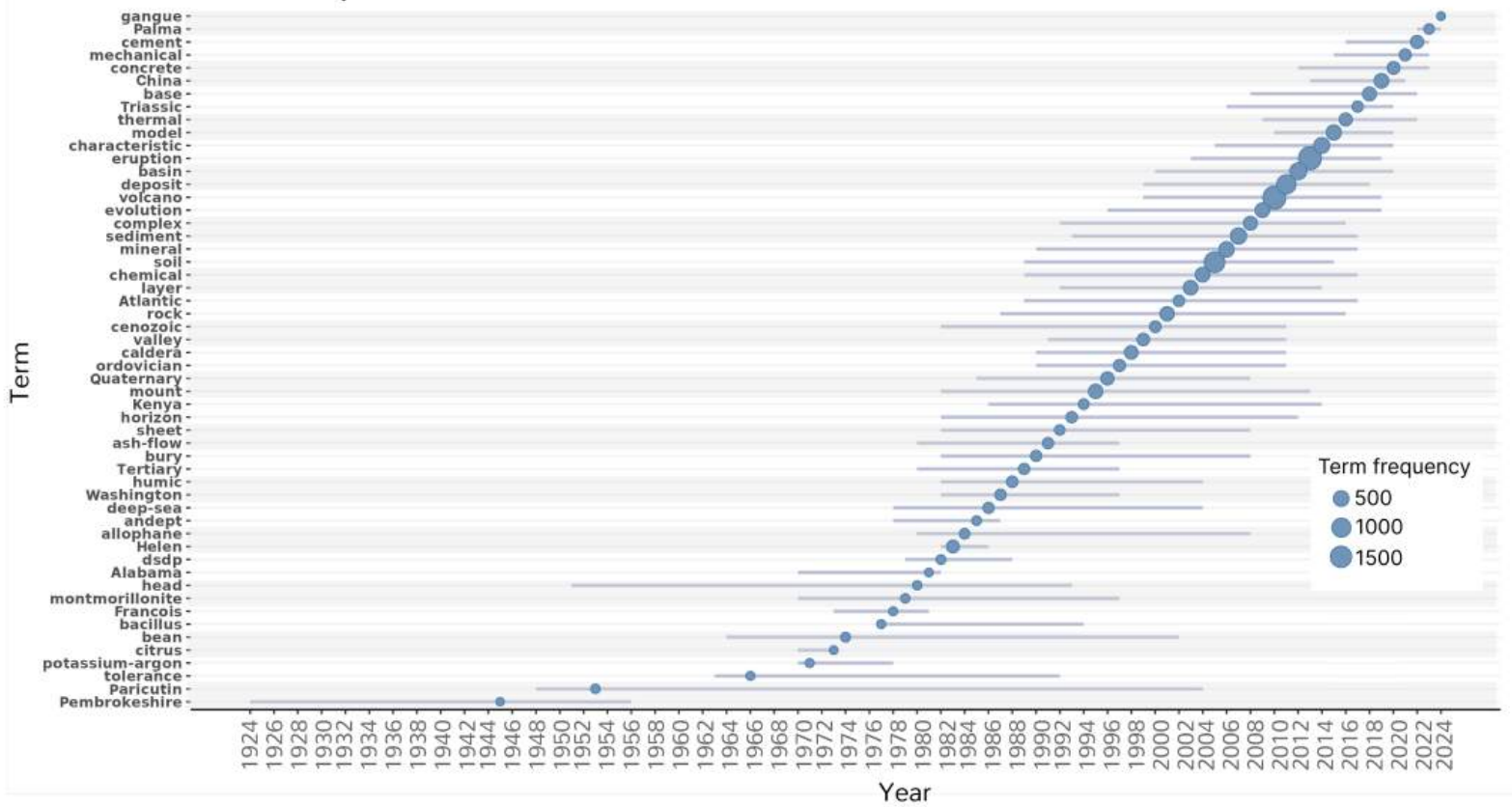


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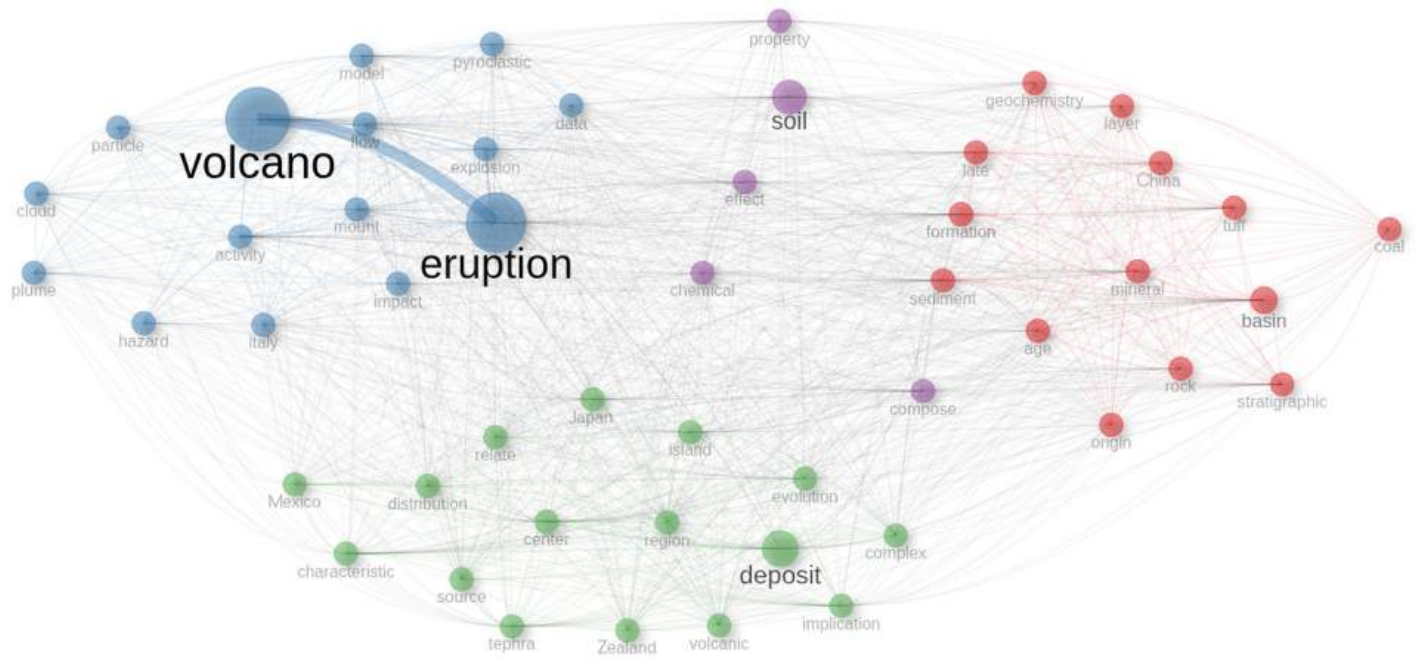


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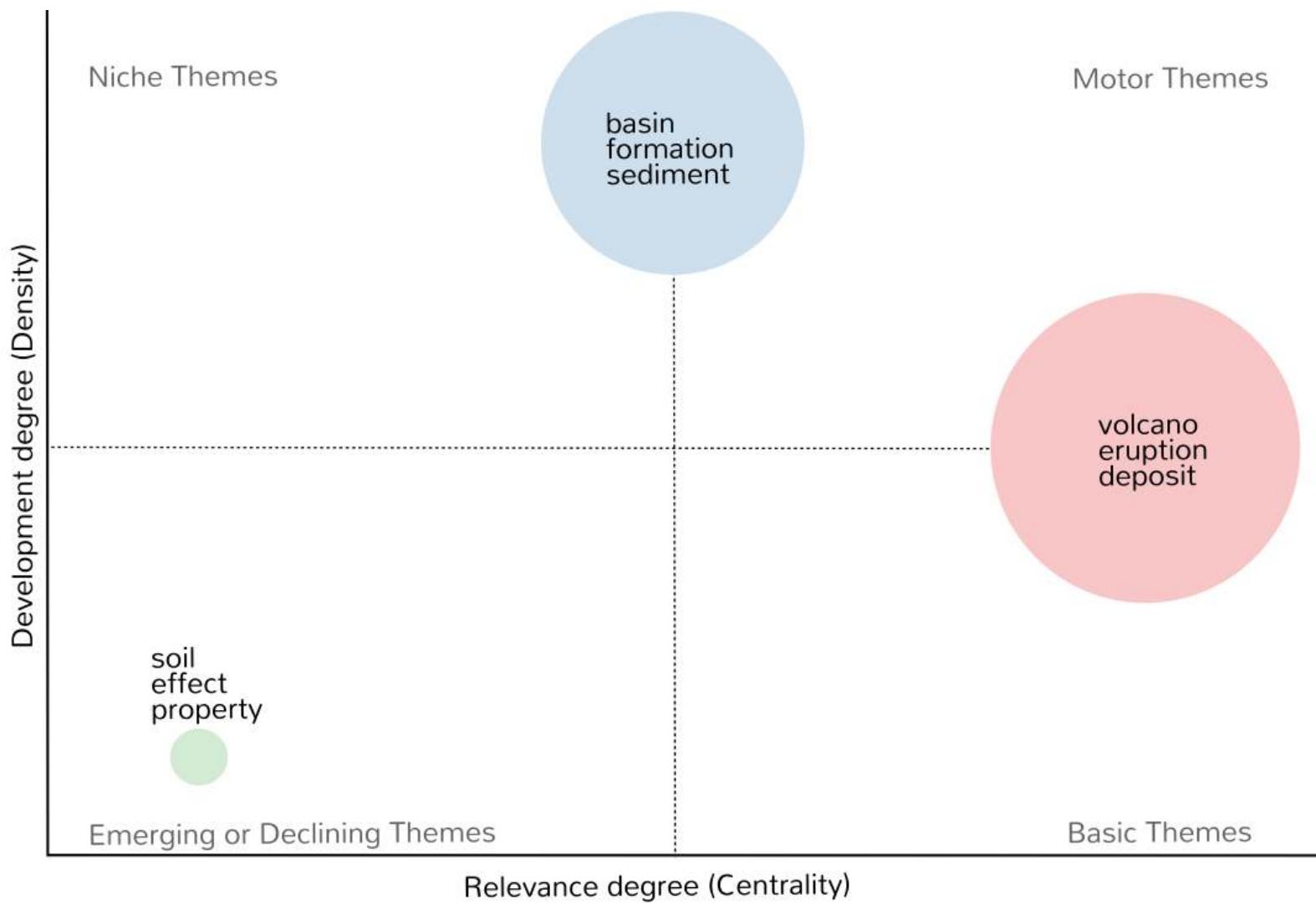
Trend Topics



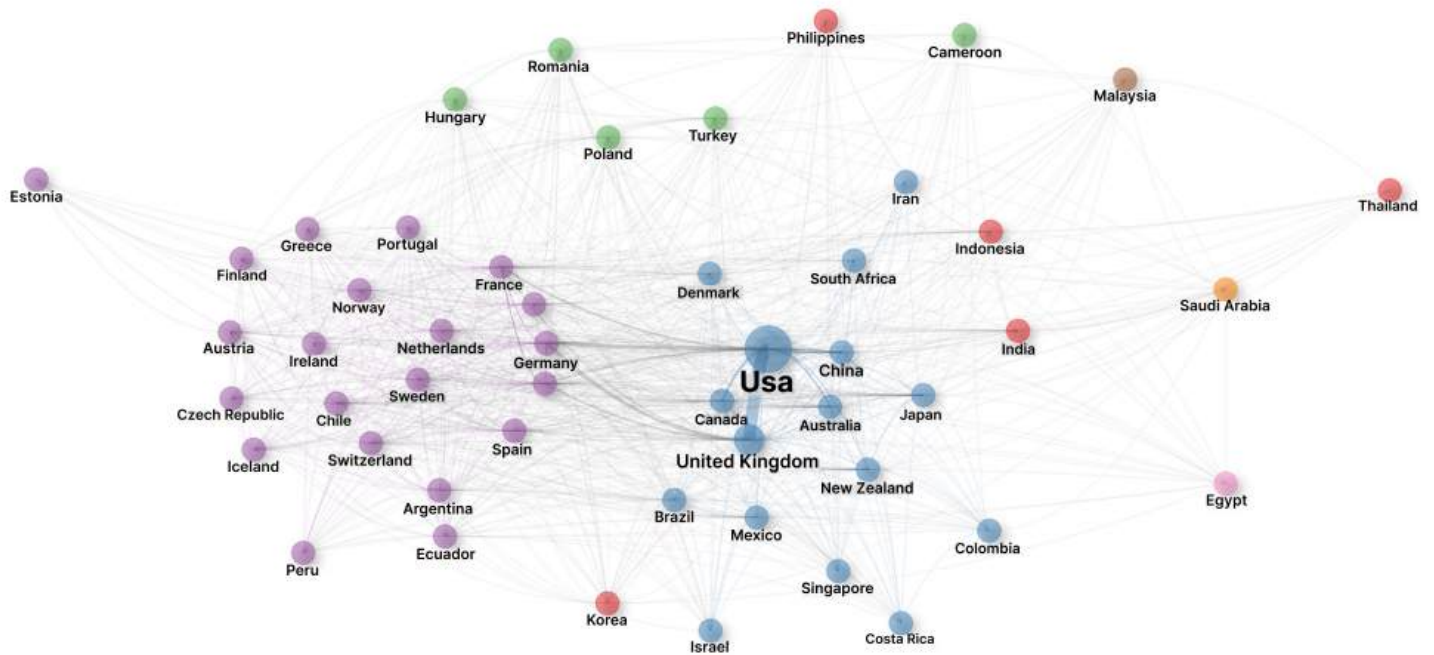
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Terms – temporal distribution

Q1 AND Q3 SEPARATED BY SEVERAL DECADES

Wide temporal distribution, indicating that they have maintained their relevance for a long time.

- **SOIL** (1989–2015): 26 YEARS.
- **ROCK** (1987–2016): 29 YEARS.
- **MINERAL** (1990–2017): 27 YEARS.
- **SEDIMENT** (1993–2017): 24 YEARS.

CLOSE Q1 AND Q3

Narrow temporal distribution, suggesting that their use was more concentrated in a specific period.

- **POTASSIUM-ARGON** (1970–1978): 8 YEARS.
- **CITRUS** (1970–1973): 3 YEARS.
- **BACILLUS** (1977–1994): 17 YEARS.
- **FRANCOIS** (1973–1981): 8 YEARS.

Q3 IN 2023 OR 2024

Most recent terms suggest emerging research areas

- **CONCRETE, CEMENT, MECHANICAL** (2023), **GANGUE** (2024): USE OF VOLCANIC ASH IN CONSTRUCTION MATERIALS OR INDUSTRIAL APPLICATIONS.
- **PALMA** (2024): RELATED TO THE ERUPTION OF THE VOLCANO IN LA PALMA (SPAIN) IN 2021.

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