Trends in Publishing Muography Related Research: The Situation at the End of 2020

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Abstract

Cosmic-ray muography is a novel method for density characterization of gaseous, solid, and liquid materials in various dimensions and with numerous distinct technologies. The number of applications of muography is on a constant rise, as is also the number of authors, affiliations, journals, publishers, funding agencies, and countries that can be related to muography literature. We have applied the Web of Science global citation database to collect statistics of muography-related publications to draw a snapshot of where muography was at the end of 2020, how it got there, and where the current trends may get it in the future.

Keywords: muons, muography, muon radiography, muon tomography, applied geophysics, web of science
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1. INTRODUCTION

As a density-characterization method, the cosmic-ray muography is arguably experiencing more advancements and growth than before. This work builds on the foundations laid down by numerous earlier publications on muography. In this regard, the Theo Murphy meeting issue on "Cosmic-ray muography" in 2019 deserves a special mention as it is one of the earliest special issues dedicated to muography and, as such, provides a vital review snapshot of the development of muography at the time. The papers of the Theo Murphy meeting were published in the journal Philosophical Transactions of the Royal Society, Volume A377, Issue 2137. Our aim is to expand on the themes started in one of the papers in that issue [1].

One way to measure the development of an emerging research field is to apply the number of research papers as an indicator and a rough trend analysis tool. However, as sheer numbers of the publications alone do not adequately describe the research field, more sophisticated indicators are asked. Therefore, we have applied the research engine of the Web of Science (WoS) publisher-independent global citation database to collect statistics on muography-related publications. Nevertheless, we are well aware that our approach is far from being comprehensive compared with the state-of-the-art tools and techniques used in scientometric analysis and information science that utilizes, for instance, sophisticated algorithms and artificial intelligence to systematically review the development of a research field to serve science, technology, innovation policymaking, and innovation management [2, 3].

Examining the current trends is not meaningful if one does not have at least a rough understanding of the previous development. Therefore, we have included in this paper a brief overview of the applications and the underlying technologies that make muography possible and such a prolific research field. Indeed, there is a wide variety of applications in muography. These include engineering, border control, tunnel detection, cave mapping, architecture, archaeology, volcanology, mineral exploration, mining, rock mechanics, water exploration, and many monitoring applications. As an application and a discipline, muography is currently experiencing a shift from its pioneering stage to a transdisciplinary research field [4]. This is normal for a developing research field and necessary for any research that provides tools for applied research. Our WoS data analysis exposes the most researched applications in muography.

This work is a companion paper of Holma et al. [4], which focuses on outreaching and transdisciplinarity relating to muography and on thoughts and recommendations on how muography can be directed to its golden age.

2. METHODS

The database utilized was the WoS Core Collection (CC) which contains almost 1.9 billion cited references. According to its publisher, Clarivate, the Core Collection contains over 21,100 peer-reviewed, high-quality scholarly journals published worldwide in over 250 disciplines. Conference proceedings and book data are also available. In other words, as the WoS CC includes the world's

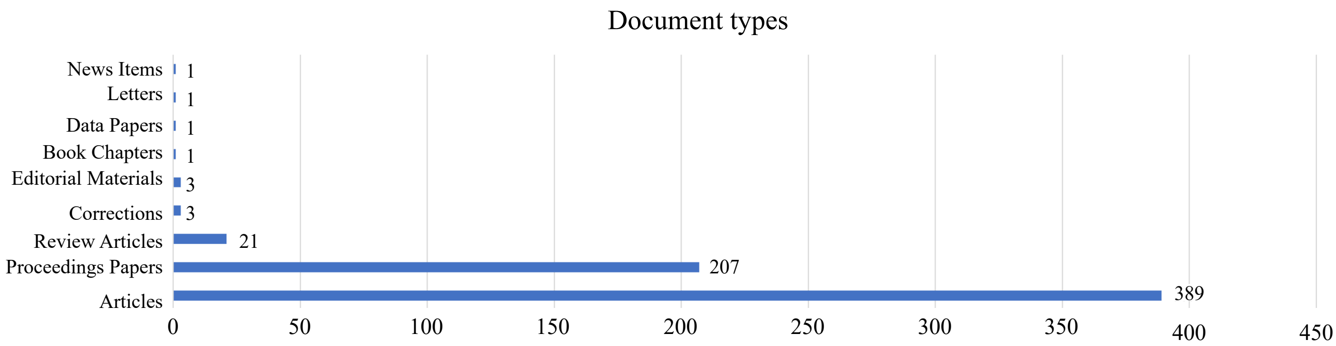

FIGURE 1: The 553 muography-related publications in the Web of Science Core Collection from 1975 to 2020, classified according to document type.

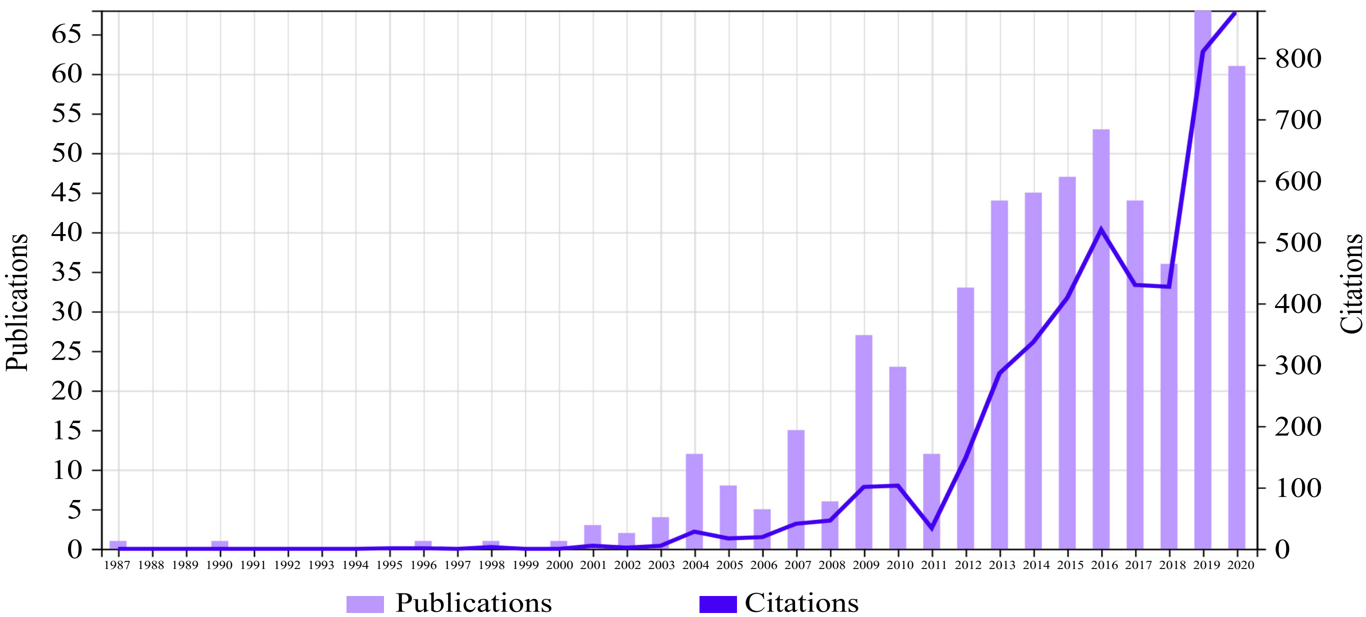

FIGURE 2: The 553 muography-related publications in the Web of Science Core Collection from 1975 to 2020, classified according to the publication year. The number of citations has expanded along with the expansion of the literature.

leading scholarly journals, books, and proceedings in the sciences, it forms an excellent research resource for studying relationships between complex and multifaceted phenomena. Note that CC is primarily a database for English-language publications.

The search was limited to the period between 1 January 1936 and 31 December 2020. One notes that 1936 is the year of the discovery of the muon by the American physicists Carl D. Anderson and Seth Neddermeyer. However, in this case, the WoS CC automatically sets the lower limit of the search to 1975. The search was limited to the end of 2020 as the records from 2021 may still change.

The Boolean operator "OR" was applied for data screening. The search terms were *muograph***, *muon radiograph***, *muon tomograph***, and *muon scattering tomograph***. The asterisk was used as a multiple-character wildcard allowing all suffix combinations with the parent term. Moreover, the searches were conducted by selecting the "All Fields" operator that searches all the searchable fields using one query. The operator includes searches, for example, for topics, authors, publication titles, publication years, affiliations, publishers, conferences, document types, funding agencies, and research subject categories (called WoS categories).

Note that the applied set of search parameters is hardly the only option to study muography publication trends. In addition, it is also true that there are many publications whose titles do not contain any of these word combinations. It is also worth noting that the word *muography* itself is a neologism first used in the paper of H. K. M. Tanaka [5] (also note that its meaning has broadened somewhat over the years). However, our search results support the general view that more and more muography-related literature has been published in the last ten years.

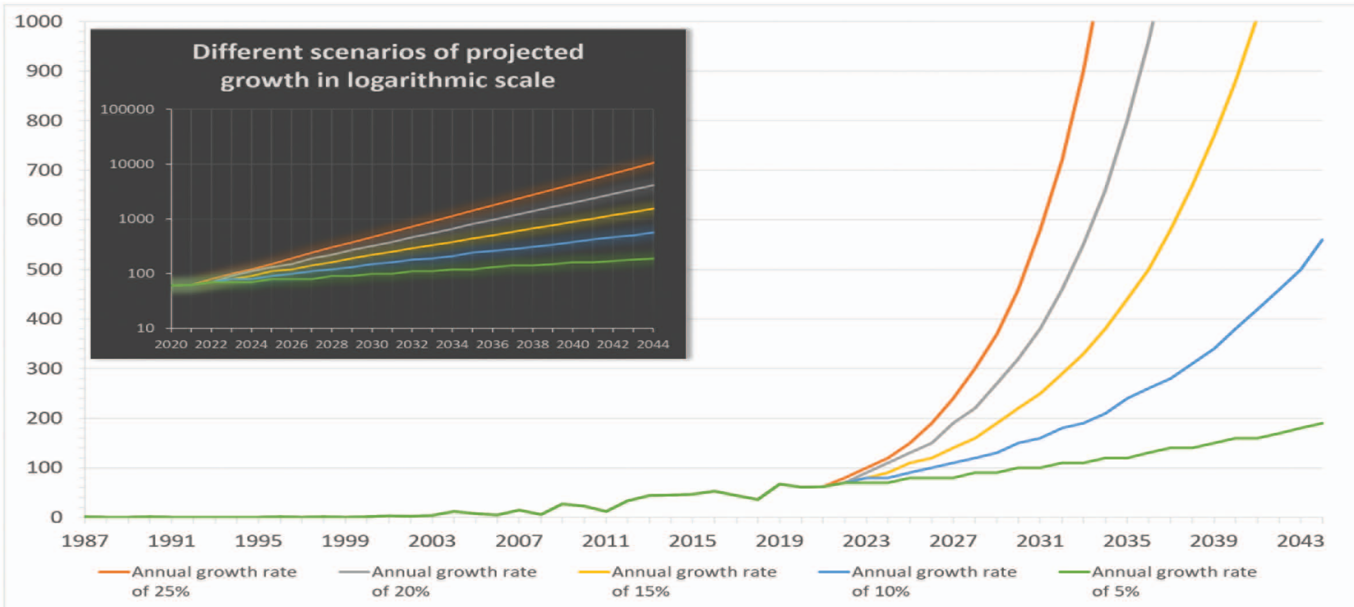

FIGURE 3: Five different hypothetical growth trends for the future of muography research. The current growth trend follows the annual growth rate of ∼26%, but it seems likely that the growth rate will slow down between an annual growth of 15% (yellow line) and 5% (green line). Inset shows the growth rates on a logarithmic scale. The vertical axis continues to an unimaginable 100,000 articles a year for clarity.

3. RESULTS

3.1. General Information

The WoS database search yielded 553 articles from the WoS Core Collection published between 1975 and 2020. From these, 389 are articles (62.0%), 207 are proceeding papers (33.0%), and 21 are review articles (3.3%) (Figure 1). There are also editorial materials, data papers, letters, news items, and some other classes, but only a few pieces of each. As the sum of these overpasses 553, some publications are categorized in more than one class.

A total of 268 from 553 WoS records are open access articles, that is, approximately 48%. The oldest found article is from 1987. This paper is a multidisciplinary geosciences publication [6]. Before 2021, the top ten peak years in publications have been 2019 (68 articles), 2020 (61), 2016 (53), 2015 (47), 2014 (45), 2013 (44), 2017 (44), 2018 (36), 2012 (33), and 2009 (27). More than one publication represents every year after 2000 (Figure 2). Of the 553 articles, 47.4% have been published between 2016 and 2020 (262 articles).

3.2. Citations and Growth Trends in Research

Figure 2 illustrates the development of citation numbers from 1975 to 2022. If self-citing articles are included, the search found altogether 1744 citing articles. Citing articles have cited one or more of the 553 items in the data. Muography-related publications have been cited in many nonmuography-related articles, but especially in research fields that focus on *Instruments Instrumentation* (23.1%), *Nuclear Science Technology* (19.8%), *Physics Particles Fields* (17.0%), *Physics Nuclear* (15.5%), *Physics Applied* (10.0%), *Engineering Electrical Electronic* (8.9%), *Physics Multidisciplinary* (8.4%), *Geosciences Multidisciplinary* (7.1%), *Materials Science Multidisciplinary* (6.3%), and *Geochemistry Geophysics* (5.9%).

The 553 muography-related articles have been cited 5490 times; this includes 804 citations from 2021 and 36 citations from 2022. These numbers are from January 23, 2022, which is the date the data was retrieved; one notes that although no articles more recent than December 31, 2020, were included in the search, it is a default in the Web of Science that all citations in the database citing the search results are contained in the citation report. However, the citation report feature is limited to a list of results of up to 10,000 records.

An average muography-related article has been cited 9.93 times, while the average per year citation number is 196.07. With these metrics, one may establish a baseline for understanding publication trends better, although comparing different disciplines makes little sense as various research fields' requirements, publication and funding opportunities, maturity, and citation traditions are often beyond comparing. In addition, a high number of publications usually result in a larger total number of citations. Nevertheless, to allow a simple comparison between muography and a couple of large overlapping research fields, we applied the search terms *physics multidisciplinary* (All Fields) and *geoscience* (All Fields) in the WoS. The "All Fields" operator was used in both searches. The data were delivered on March 20, 2022. The physics multidisciplinary and geoscience fields are much more prolific than muography, so we limited our search to only two publication years: 2015 and 2020.

In the *physics multidisciplinary* case, the search found 876 articles published in 2015. These articles have been cited 27.7 times on average. Because the publication year 2020 yielded 1,685 articles, this loosely defined research field is growing relatively rapidly

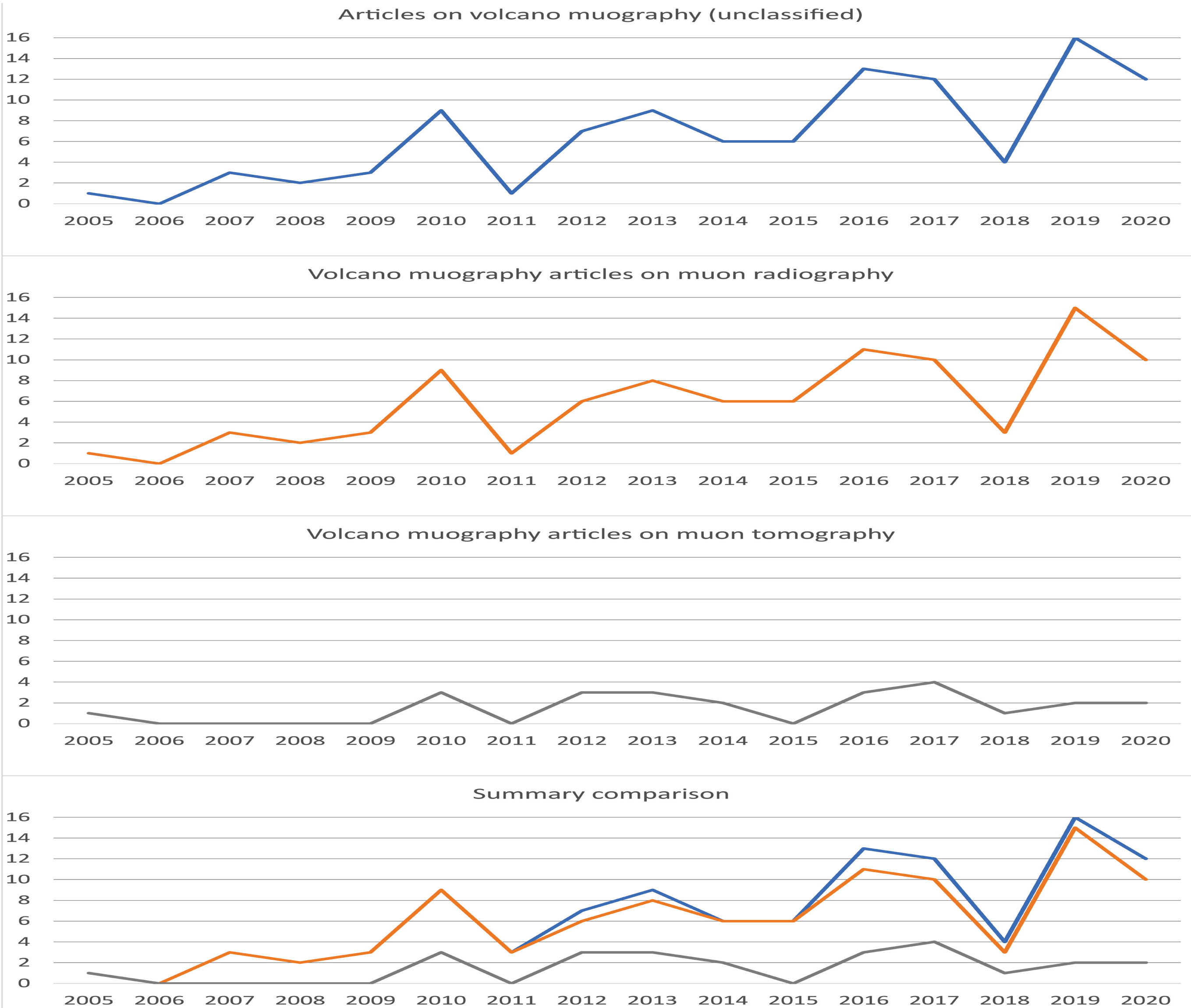

FIGURE 4: Comparisons of the numbers of muography articles on the volcano-imaging application published each year. From top to bottom, the images show the respective numbers of muography articles on the unclassified total, radiography, tomography and summary of the three.

(∼92% between 2015 and 2020). The 2020 articles have been cited no more than 7.4 times on average, undoubtedly because there has been less time to cite them. As another example, the search term geoscience yielded 4,628 and 5,127 articles published in 2015 and 2020, respectively. These numbers indicate a modest growth of ∼11% in six years. Our interpretation is that this shows the relative maturity of the field. Geoscience papers published in 2015 have been cited 17.48 times on average. The corresponding number is 5.1 for 2020.

Our original search terms for muography-related articles find 49 and 62 articles for 2015 and 2020, respectively. The average citation numbers per article are 7.8 for 2015 and 3.3 for 2020. Between these years, the number of muography-related articles has grown by 27%. Assuming muography continues to grow year after year with an annual rate of 25%, the articles published in this field would surpass the barriers of 100, 500, 1,000, 5,000, and 10,000 articles a year in 2023, 2030, 2033, 2040, and 2043, respectively. Of course, maintaining such a growth rate may prove challenging even for the next few years and probably close to impossible after that. This simple calculation is based on the 62 articles published in 2020.

How the citation numbers develop in the future is also interesting in the light of current scientometric research. For example, Chu and Evans [7] suggested that too many papers published each year in a field can lead to stagnation rather than advance. Their analyses propose that as the number of articles published per year in a scientific field grows large, the already well-cited papers draw most of the citations. Significantly, new articles are unlikely to ever become highly cited and proposing disruptive ideas becomes more difficult. While the current flow of muography-related articles shows an increasing trend (Figure 2), the publication

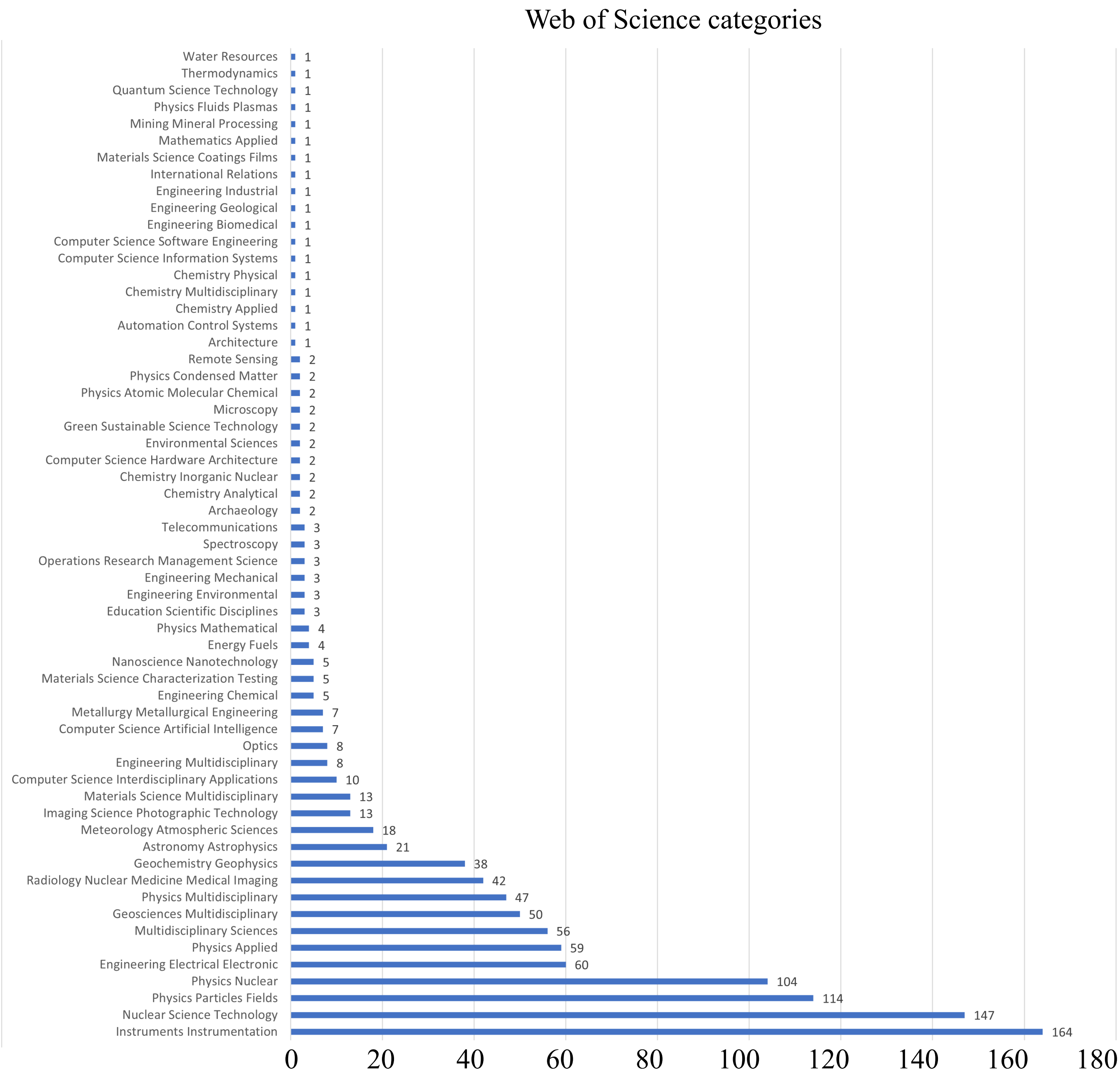

FIGURE 5: The 553 muography-related publications in the Web of Science Core Collection from 1975 to 2020, classified according to Web of Science categories. The Y-axis shows article counts.

numbers are still far, far below (<100) the level of concern related to the citation trends and stagnation of the research field. In the analysis of Chu and Evans [7], a large research field produces at least ∼10,000 papers a year.

One useful parameter in these comparisons is the so-called h-index, which shows how many articles are cited, as a minimum, by the given number of articles. The h-index for the 553 muography-related articles is 34, meaning that 34 papers have been cited a minimum of 34 times. The twenty so-far most cited articles are listed in Table 1. The h-index provides a focused snapshot of an individual's research performance or, more rarely, as in this case, the research field. The h-index is a metric for evaluating the cumulative impact of scholarly output and performance by measuring quantity with quality by comparing publications to citations. It also corrects for the disproportionate weight of highly cited publications or publications that have not yet been cited. However, the h-indices are not without shortcomings. First, comparisons of citation outputs between scientists of two different disciplines are not easy to accomplish since publication, and citation rates vary significantly from one field to another. It appears sensible that the same challenge is also valid between different disciplines. Second, the h-index is developed for comparing individuals [8]. For individuals, an h-index of 20 after 20 years of scientific activity is considered typical for a successful scientist. If the h-index is 40 after 20 years of scientific activity, the scientist has achieved an outstanding performance level, whereas values of 60 are reached

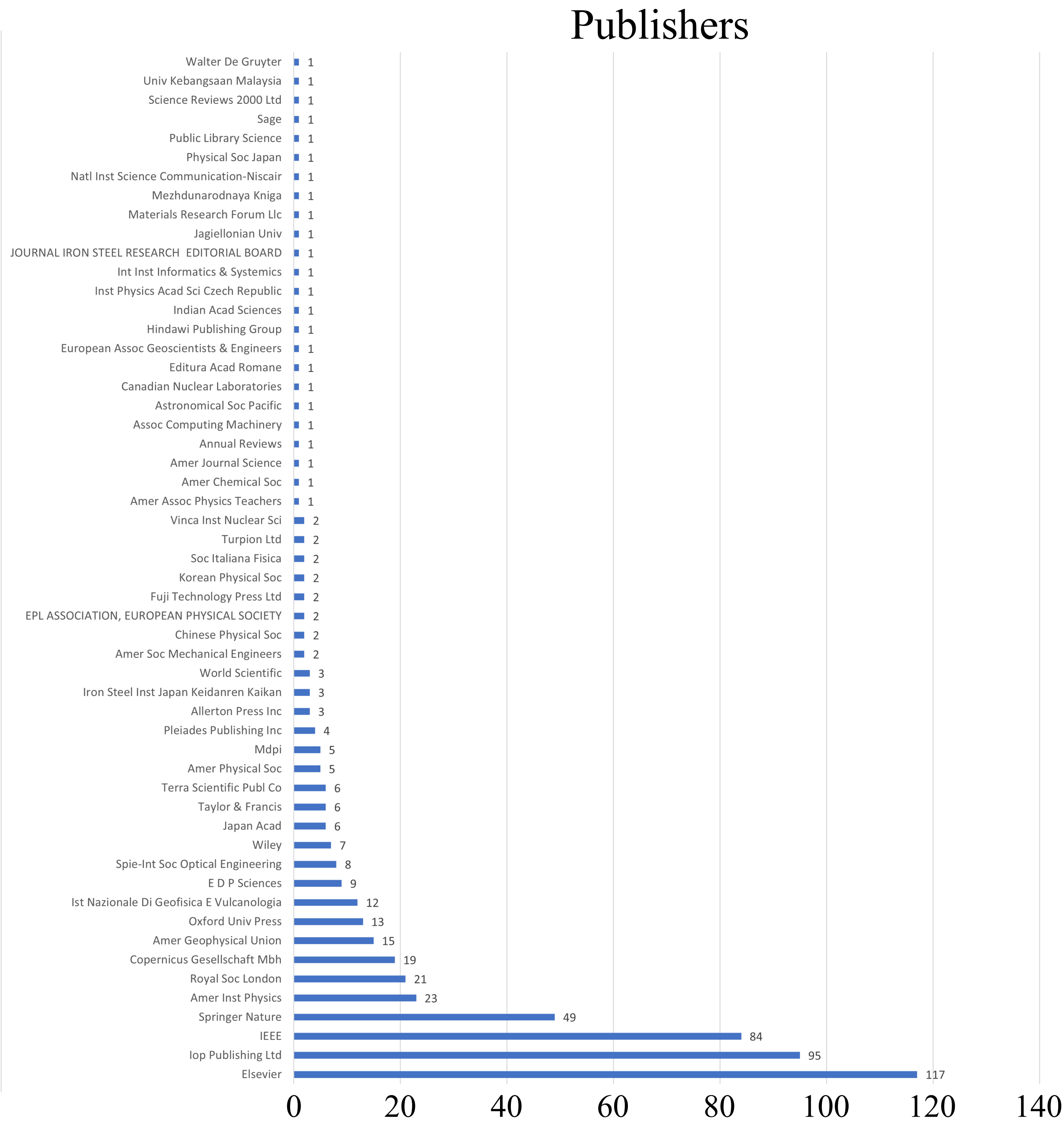

FIGURE 6: The 553 muography-related publications in the Web of Science Core Collection from 1975 to 2020, classified according to the publisher.

only by truly unique individuals [8]. We do not propose using the h-index of muography-related research to compare this value against the h-indices of other disciplines. Instead, we regard it as a value whose development may be interesting to follow as time goes by. It is also worth pointing out that not all researchers consider h-indices particularly effective attributes to describe research impacts.

We also examined those 553 articles in terms of content but only for one application: volcano imaging. We selected only papers related to volcanoes. This included further analysis only on papers that have titles or keywords terms linked to volcanoes, such as “volcanic”, “volcanism”, “volcano”, and “dome”. It was found that not all relevant articles contain keywords in the WoS database.

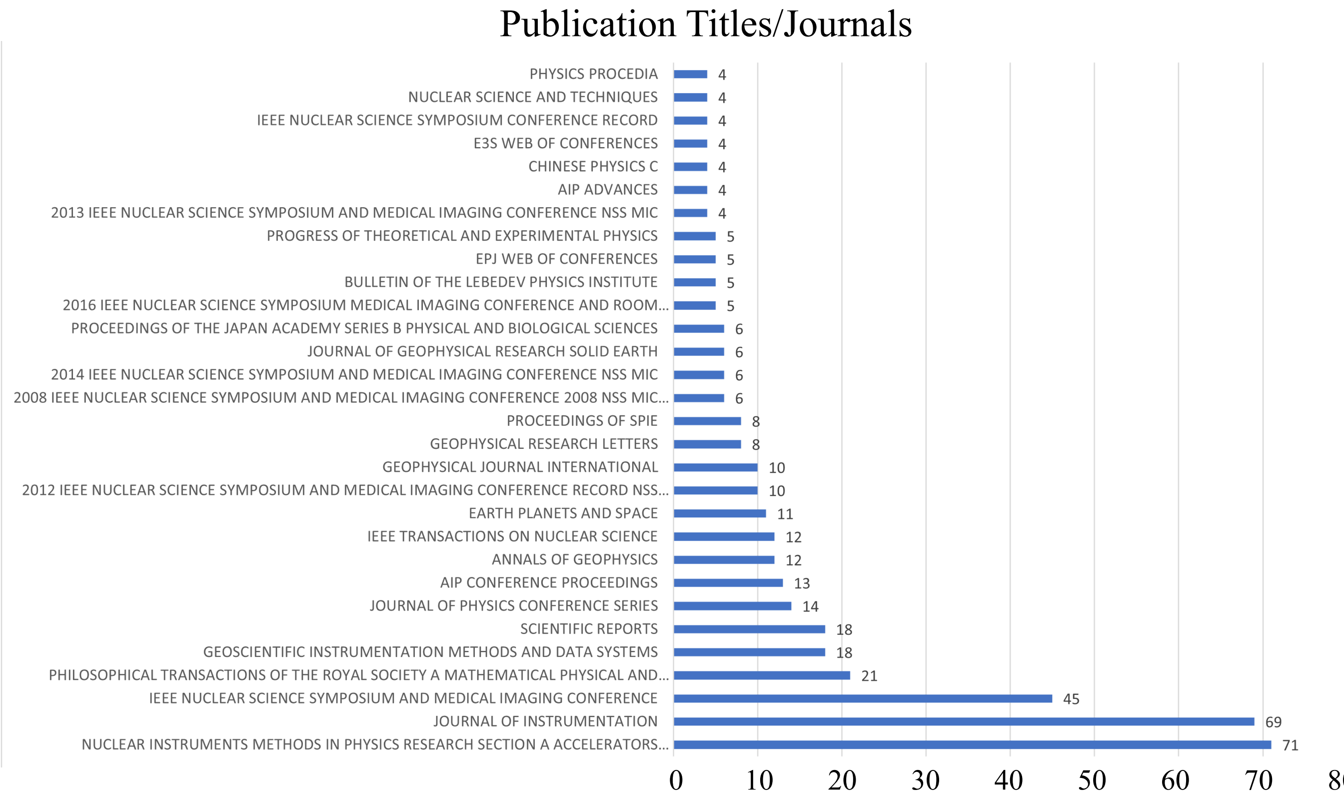

FIGURE 7: The 553 muography-related publications in the Web of Science Core Collection from 1975 to 2020, classified according to the publication title/journal name. Only those titles shown have published a minimum of four articles.

A relatively large number of additional articles were found manually from the database. In many cases, the actual paper had to be inspected to ensure whether it should be included. This part of our work was found to be relatively laborious and one that is hard, if not possible, to repeat with precisely the same results. In addition, deciding whether a particular paper should be included in the list of volcano muography articles is not straightforward. Indeed, the articles are dissimilar in content as some describe instruments, while others are more software and algorithm oriented or are review, concept, or actual deployment papers. Therefore, we chose to be relatively all-encompassing by including in the following analysis all articles that describe or discuss muographic volcano imaging more extensively than just a passing or two.

The above process yielded 104 articles. Muon radiography was discussed in 94 articles (∼90%). A majority of these have muon radiography as a primary and often the only topic. Twenty-four articles were engrossed in muon tomography (∼23%). Of the latter, nine articles are muon tomography-only publications, corresponding to ∼9% of all volcano-imaging articles. Fifteen articles can be held to have earned their place in both categories (∼14%). The oldest muon tomography article found is from 2005. However, due to the original search terms applied in the WoS database, inconsistencies in the data regarding the 553 articles, differences between the contents of the articles, differences in the used keywords between different articles, and discrepancies in the manual part of the search, it is likely that our examination was not comprehensive in finding all muon tomographic volcano-imaging articles out there. Those we found are listed in Table 2. A more complete result would need more vigilance in the manual screening of the articles. Figure 4 compares the development of muographic volcano imaging over time. Radiography applications have dominated the field earlier and still do so. However, tomography applications also seem to be on a slow rise.

3.3. Web of Science Categories

The WoS data on the 553 articles also comprises categorization data describing the nature of the research conducted. By using the categories of the WoS, the four most prominent research fields so far have been *Instruments Instrumentation* (164 articles), *Nuclear Science Technology* (147), *Physics Particles Fields* (114), and *Physics Nuclear* (104). After these four categories, there is a notable gap before *Engineering Electrical Electronic* (60), *Physics Applied* (59), *Multidisciplinary Sciences* (56), *Geosciences Multidisciplinary* (50), *Physics Multidisciplinary* (47), and *Radiology Nuclear Medicine Medical Imaging* (42) (Figure 5). The number of different WoS categories is 59. Note, however, that some publications are categorized in more than one class.

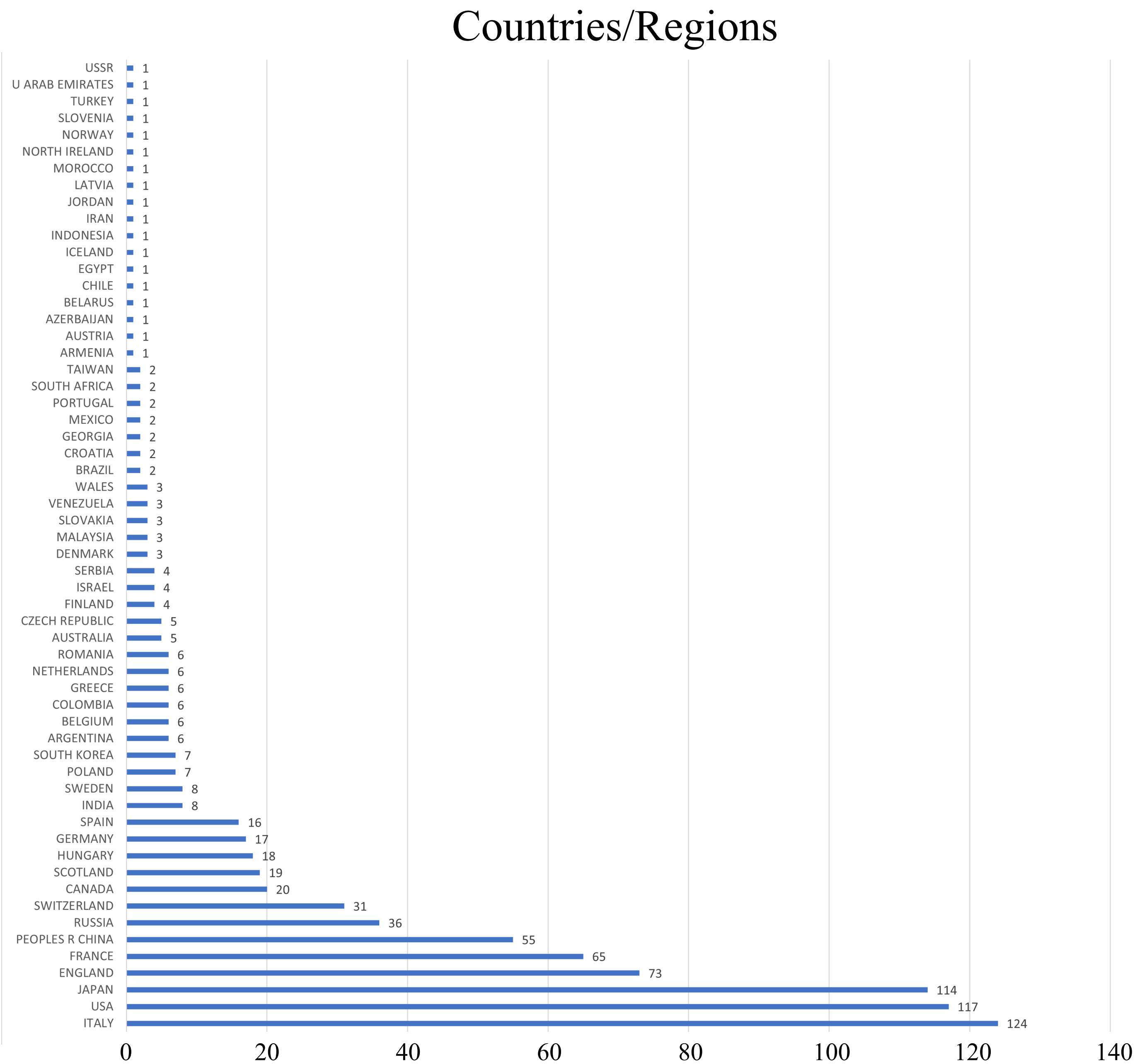

FIGURE 8: The 553 muography-related publications in the Web of Science Core Collection from 1975 to 2020, classified according to the publishing country/region.

3.4. Publishers and Journals

A total of 54 publishers have published on muography; the most prominent publisher is Elsevier (117 items, which corresponds to 21.2% of all articles), followed by IOP Publishing Ltd. (95 publications), IEEE (84), Springer Nature (49), and American Institute of Physics (23) (Figure 6).

The top ten most published journals are *Nuclear Instruments and Methods in Physics Research A: Accelerators, Spectrometers, Detectors and Associated Equipment* (71 articles), *Journal of Instrumentation* (69), *IEEE Nuclear Science Symposium and Medical Imaging Conference* (45), *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* (21), *Geoscientific Instrumentation Methods and Data Systems* (18), *Scientific Reports* (18), *Journal of Physics Conference Series* (14), *AIP Conference Proceedings* (13), *IEEE Transactions on Nuclear Science* (12), and *Annals of Geophysics* (12). Figure 7 shows those publication titles/journals that have been associated with at least 4 articles each. The 553 publications are spread in 212 publication/journal titles. Note, however, that some of these are noncontinuous conference titles.

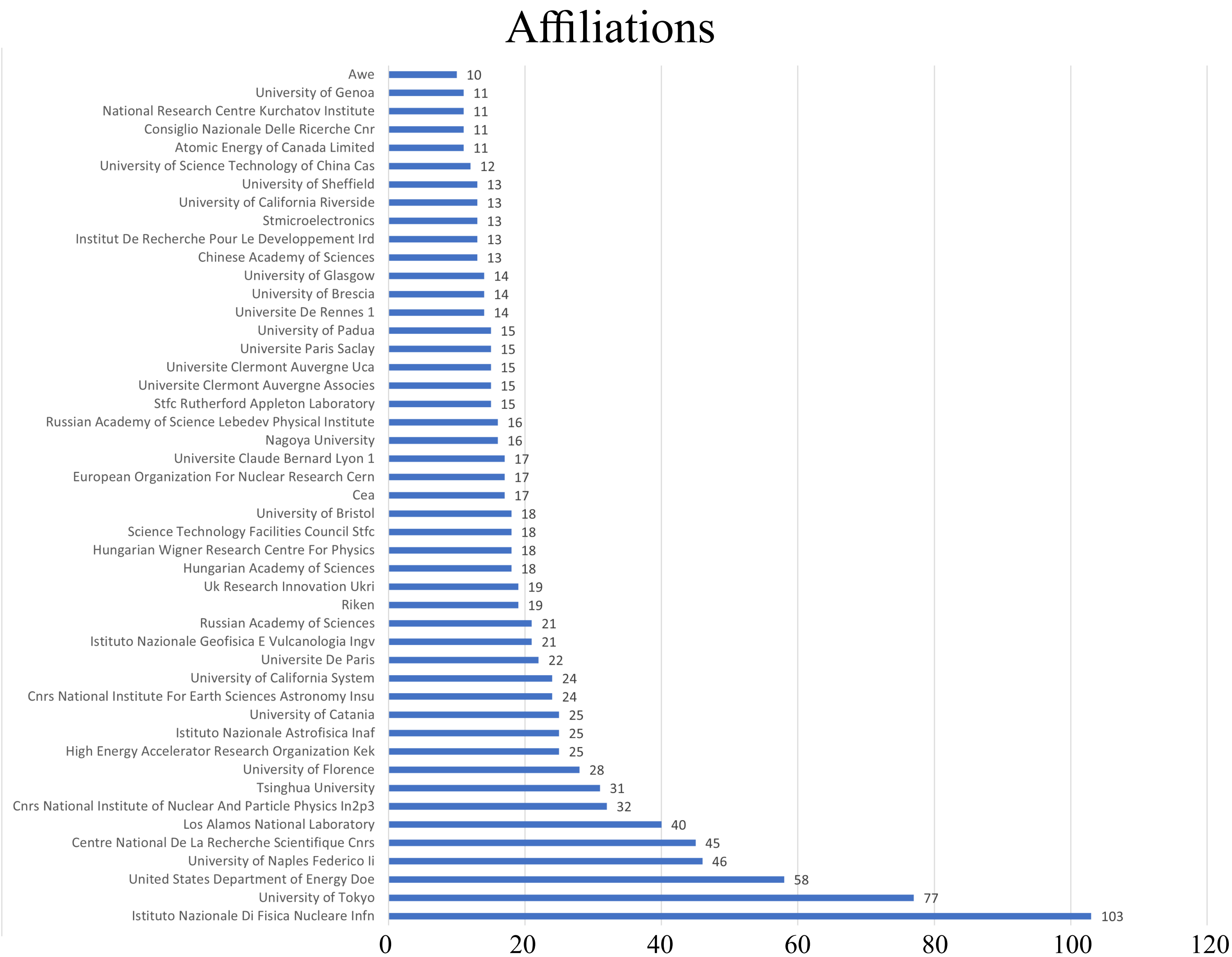

FIGURE 9: The 553 muography-related publications in the Web of Science Core Collection from 1975 to 2020, classified according to the specific affiliation. Only those affiliations shown have published a minimum of ten articles.

3.5. *Authors and Affiliations*

The most published author is, by far, H. K. M. Tanaka (64 articles). The second most published author is F. Riggi (27). A total of 75 authors have published a minimum of 10 articles, while 190 authors have published at least 6 articles. In addition, 524 authors have participated in at least 3 articles. 4775 separate authors have published at least once.

When it comes to publishing muography-related science, the top list of most prolific countries is dominated by Italy (124 cases), the USA (117), and Japan (114). The total number of countries or regions that have published muography-related articles is 58. Thirteen countries/regions have published more than 10 articles (Figure 8).

The *Istituto Nazionale di Fisica Nucleare* (INFN) from Italy is the most frequent affiliation (103 articles, which corresponds to 18.6% of all articles) (Figure 9). The *University of Tokyo* (77) is the second most used affiliation. The total number of different affiliations is 709. However, 9 records (1.6%) do not contain affiliation data. The number of affiliations that have published at least 10 articles is 47. A total of 96 affiliations have published at least 5 articles.

3.6. *Review Papers*

Review papers are often a good starting point for the newcomers, and they play a major influence on scientific communication and moving a research area forward. Hence, it is worth examining data on the 21 review papers in more detail (Table 3). H. K. M. Tanaka has published most (5 articles). Most of the review papers have been published in *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* (7 articles). Review papers are dominated by the WoS categories *Multidisciplinary Sciences* (9 articles), *Instruments Instrumentation* (4), *Nuclear Science Technology* (4), *Physics Nuclear* (3), and *Physics Particles Fields* (3). The University of Tokyo leads as an affiliation of the muography review papers (6 articles). Based on Table 3, the number of review papers has increased in frequency in the last few years.

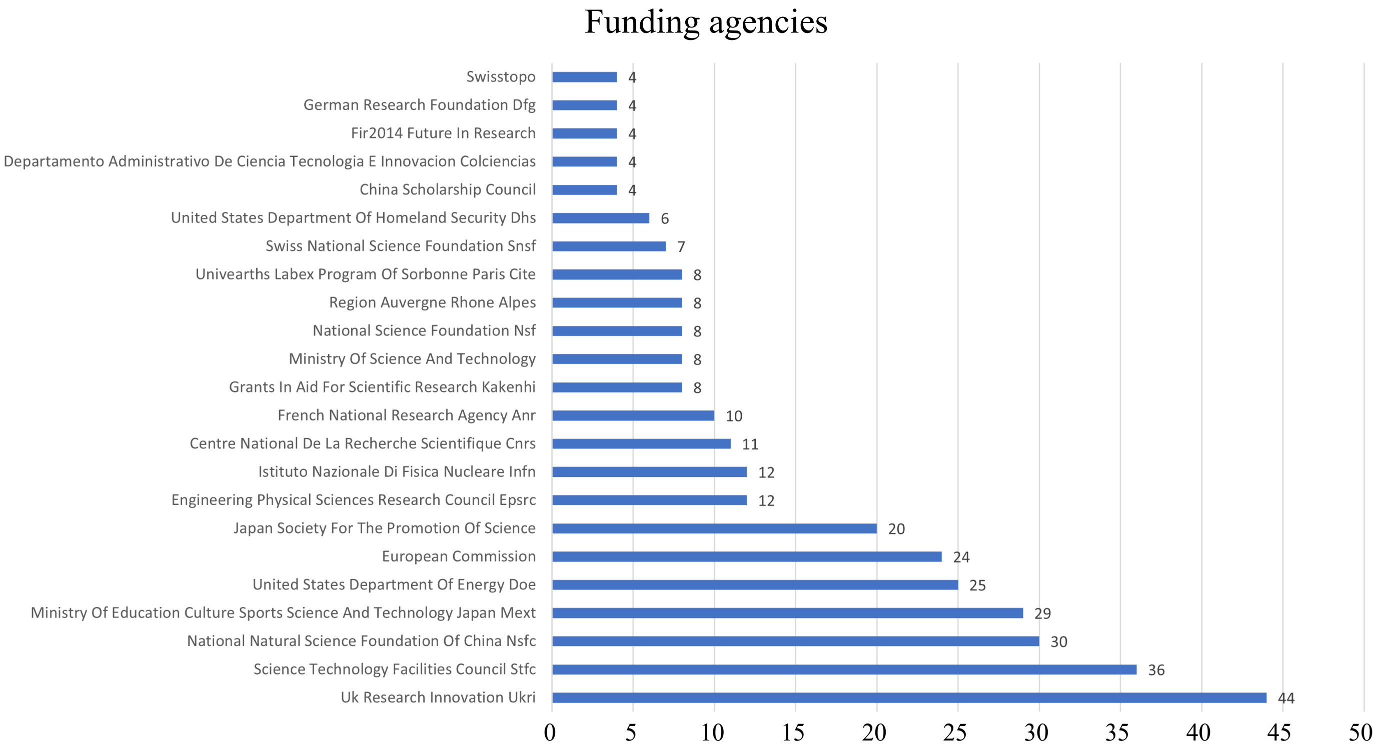

FIGURE 10: The agencies that have funded muography research between 1975 and 2020, based on the Web of Science Core Collection data. Only those financing agencies shown of have names that have been acknowledged at least in four articles. This data does not contain information on the actual size of the funding.

3.7. *Funding Agencies*

The top ten funding agencies for the research are *UK Research Innovation* (UKRI) (44 cases), *Science Technology Facilities Council* (STFC) (36), *National Natural Science Foundation of China* (NSFC) (30), *Ministry of Education Culture Sports Science and Technology Japan* (MEXT) (29), *United States Department of Energy* (DOE) (25), *European Commission* (EC) (24), *Japan Society for the Promotion of Science* (20), *Engineering Physical Sciences Research Council* (EPSRC) (12), *Istituto Nazionale di Fisica Nucleare* (INFN) (12), and *Centre National De La Recherche Scientifique* (CNRS) (11). The data contain the name of 426 different agencies that have funded muography research, but as many as 269 records (48.6%) do not include data in the field being analyzed. Figure 10 depicts the names of the agencies that have funded at least four research articles each.

4. DISCUSSION

It is worth acknowledging that muography-related information that is not formally published as peer-review articles in scholarly journals does not end up in the WoS. These publications typically include conference works, reports, theses, and guidelines produced by governments, universities, and private companies. Works falling to the large grey literature category may be considered unpublished as academic literature, but one may still find information worth reading within this group. Many nonacademic research organizations may be more oriented toward publishing primarily grey literature due to time and resource limitations and, perhaps, better input/output ratio. Hence, the reader interested in getting the broadest possible understanding of the current state of muography should not forget to take notice of these types of information sources, including published materials in magazines, newspapers, blogs, and other social media platforms.

Although our parameter set used in the search failed to find older publications than Bondarenko et al. (1987) [6], it is well known that several earlier publications exist. Indeed, these pioneering works noted the possibility of using cosmic-ray muons' attenuation on material characterization. However, it is interesting to note that many early works targeted rocks as a medium of interest [9, 10, 11]. This also holds true for the early archaeological works applying muography for pyramid scanning [12]. The link between muography and rocks is easy to understand as we live on a rocky surface, even though the Earth is mainly covered by water. It is also understandable because geological landforms are often prominent in size and, hence, within the optimal size category for muography. Also, the broad spectrum of different geological subdisciplines and geophysical techniques to study their challenges prove that there is no shortage of need for new approaches in earth sciences.

The close connection between geoscience and muography has continued to flourish with the introduction of the many new application related to earth materials (not only rocks but also sediments), such as those related to volcanoes [5, 13, 14, 15], mineral exploration and mining operations [16, 17, 18], geoengineering [16, 17, 19], and in many, many other types of geoscience research

TABLE 1: The 20 most cited muography-related papers published between 1975 and 2020, based on the Web of Science Core Collection and its Citation Report at the end of January 16, 2022.

Year	Authors	Article Title	Source Title	Vol.	Issue	DOI	Total Citations	Average per Year
2003	Borozdin, K.N. et al.	Surveillance: Radiographic imaging with cosmic-ray muons	Nature	422	6929	10.1038/422277a	225	11.25
2004	Schultz, L.J. et al.	Image reconstruction and material Z discrimination via cosmic ray muon radiography	Nucl. Instrum. Methods Phys. Res. A	519	3	10.1016/j.nima.2003.11.035	140	7.37
2007	Tanaka, H.K.M. et al.	High resolution imaging in the inhomogeneous crust with cosmic-ray muon radiography: The density structure below the volcanic crater floor of Mt. Asama, Japan	Earth Planet. Sci. Lett.	263	1-2	10.1016/j.epsl.2007.09.001	131	8.19
2017	Morishima, K. et al.	Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons	Nature	552	7685	10.1038/nature24647	119	19.83
2007	Schultz, L.J. et al.	Statistical reconstruction for cosmic ray muon tomography	IEEE Trans. Image Process.	16	8	10.1109/TIP.2007.901239	109	6.81
2012	Lesparre, N. et al.	Density muon radiography of La Soufriere of Guadeloupe volcano: comparison with geological, electrical resistivity and gravity data	Geophys. J. Int.	190	2	10.1111/j.1365-246X.2012.05546.x	89	8.09
2014	Tanaka, H.K.M. et al.	Radiographic visualization of magma dynamics in an erupting volcano	Nat. Commun.	5		10.1038/ncomms4381	86	9.56
2009	Pesente, S. et al.	First results on material identification and imaging with a large-volume muon tomography prototype	Nucl. Instrum. Methods Phys. Res. A	604	3	10.1016/j.nima.2009.03.017	83	5.93
2010	Lesparre, N. et al.	Geophysical muon imaging: feasibility and limits	Geophys. J. Int.	183	3	10.1111/j.1365-246X.2010.04790.x	81	6.23
2003	Priedhorsky, W.C. et al.	Detection of high-Z objects using multiple scattering of cosmic ray muons	Rev. Sci. Instrum.	74	10	10.1063/1.1606536	73	3.65
2016	Negoita, F. et al.	LASER DRIVEN NUCLEAR PHYSICS AT ELI-NP	Rom. Rep. Phys.	68			67	9.57
2012	Marteau, J. et al.	Muons tomography applied to geosciences and volcanology	Nucl. Instrum. Methods Phys. Res. A	695		10.1016/j.nima.2011.11.061	64	5.82
2013	Carloganu, C. et al.	Towards a muon radiography of the Puy de Dome	Geosci. Instrum. Methods Data Syst.	2	1	10.5194/gi-2-55-2013	63	6.3
2009	Tanaka, H.K.M. et al.	Cosmic-ray muon imaging of magma in a conduit: Degassing process of Satsuma-Iwojima Volcano, Japan	Geophys. Res. Lett.	36		10.1029/2008GL036451	61	4.36
2007	Tanaka, H.K.M. et al.	Imaging the conduit size of the dome with cosmic-ray muons: The structure beneath Showa-Shinzan Lava Dome, Japan	Geophys. Res. Lett.	34	22	10.1029/2007GL031389	61	3.81
2012	Tremsin, A.S. et al.	High-Resolution Strain Mapping Through Time-of-Flight Neutron Transmission Diffraction with a Microchannel Plate Neutron Counting Detector	Strain	48	4	10.1111/j.1475-1305.2011.00823.x	60	5.45
2007	Tanaka, H.K.M. et al.	Development of an emulsion imaging system for cosmic-ray muon radiography to explore the internal structure of a volcano, Mt. Asama	Nucl. Instrum. Methods Phys. Res. A	575	3	10.1016/j.nima.2007.02.104	59	3.69
2005	Tanaka, H.K.M. et al.	Radiographic measurements of the internal structure of Mt. West Iwate with near-horizontal cosmic-ray muons and future developments	Nucl. Instrum. Methods Phys. Res. A	555	1-2	10.1016/j.nima.2005.08.099	58	3.22
2011	Gnanvo, K. et al.	Imaging of high-Z material for nuclear contraband detection with a minimal prototype of a muon tomography station based on GEM detectors	Nucl. Instrum. Methods Phys. Res. A	652	1	10.1016/j.nima.2011.01.163	52	4.33
2012	Borozdin, K. et al.	Cosmic Ray Radiography of the Damaged Cores of the Fukushima Reactors	Phys. Rev. Lett.	109	15	10.1103/PhysRevLett.109.152501	43	3.91

challenges [20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30]. In all of its varied forms, the connection between muography and subsurface research has recently culminated in the first-ever book solely dedicated to muography. The book's content and title (Muography: Exploring Earth's Subsurface with Elementary Particles) are a testimony to the demand to get a new density-sensitive, noninvasive method to applied geophysics. Note, however, that as the book is published in 2022, none of its publications is included in our WoS data. Nonetheless, many of the references herein are from this book.

As demonstrated by Figure 5, geoscience-associated publications are currently only a small part of the spectrum of application-oriented publications. Indeed, many publications describe the application of muography in as varied applications as border control and cargo tomography [31, 32, 33], imaging of spent nuclear waste and nuclear reactors [34, 35, 36, 37], and archaeology and architecture [12, 38, 39, 40, 41, 42]. Authors participating in research topics pointed out above are typically a mix of muography old-timers and end-users, such as civil engineers, geologists, mining engineers, archaeologists, and entrepreneurs of various backgrounds. It can be anticipated that the number of these types of research will expand in the future in both quantity and multidisciplinarity.

TABLE 2: The 24 muon tomography articles related to volcano-imaging published between 1975 and 2020, based on the Web of Science Core Collection and its Citation Report at the end of January 16, 2022. All but nine articles can also be classified as muon radiography papers. The WoS categories are explained in the next section. Continues to the next page.

Year	Authors	Article Title	Source Title	Vol.	Issue	DOI	Muon radiogr.	Muon tomogr.	WoS Categories
2005	Tanaka, H.K.M. et al.	Radiographic measurements of the internal structure of Mt. West Iwate with near-horizontal cosmic-ray muons and future developments	Nucl. Instrum. Method:	555	1-2	10.1016/j.nima.2005.08.099	x	x	Instruments & Instrumentation; Nuclear Science & Technology; Physics, Nuclear; Physics, Particles & Fields
2010	Tanaka, H.K.M. et al.	Three-dimensional computational axial tomography scan of a volcano with cosmic ray muon radiography	J. Geophys. Res.-Solic	116		10.1029/2010JB007677	x	x	Geochemistry & Geophysics
2010	Lesparre, N. et al.	Geophysical muon imaging: feasibility and limits	Geophys. J. Int.	183	3	10.1111/j.1365-246X.2010.04790.x	x	x	Geochemistry & Geophysics
2010	Gibert, D. et al.	Muon tomography: Plans for observations in the Lesser Antilles	Earth Planets Space	62	2	10.5047/eps.2009.07.003	x	x	Geosciences, Multidisciplinary
2012	Fehr, F.	Density imaging of volcanos with atmospheric muons	J. Phys. Conf. Ser.	375		10.1088/1742-6596/375/1/052019	x	x	Astronomy & Astrophysics; Physics, Applied; Physics, Particles & Fields
2012	Lesparre, N. et al.	Density muon radiography of La Soufriere of Guadeloupe volcano: comparison with geological, electrical resistivity and gravity data	Geophys. J. Int.	190	2	10.1111/j.1365-246X.2012.05546.x	x	x	Geochemistry & Geophysics
2012	Marteau, J. et al.	Muons tomography applied to geosciences and volcanology	Nucl. Instrum. Methods Phys. Res. A	695		10.1016/j.nima.2011.11.061		x	Instruments & Instrumentation; Nuclear Science & Technology; Physics, Nuclear; Physics, Particles & Fields
2013	Bene, S. et al.	Air shower simulation for background estimation in muon tomography of volcanoes	Geosci. Instrum. Methods Data Syst.	2	1	10.5194/gi-2-11-2013		x	Geosciences, Multidisciplinary; Meteorology & Atmospheric Sciences
2013	Portal, A. et al.	Inner structure of the Puy de Dome volcano: cross-comparison of geophysical models (ERT, gravimetry, muon imaging)	Geosci. Instrum. Methods Data Syst.	2	1	10.5194/gi-2-47-2013	x	x	Geosciences, Multidisciplinary; Meteorology & Atmospheric Sciences
2013	Jourde, K. et al.	Experimental detection of upward going cosmic particles and consequences for correction of density radiography of volcanoes	Geophys. Res. Lett.	40	24	10.1002/2013GL058357	x	x	Geosciences, Multidisciplinary
2014	Carbone, D. et al.	An experiment of muon radiography at Mt Etna (Italy)	Geophys. J. Int.	196	2	10.1093/gji/ggt403	x	x	Geochemistry & Geophysics
2014	Marteau, J. et al.	Implementation of sub-nanosecond time-to-digital convertor in field-programmable gate array: applications to time-of-flight analysis in muon radiography	Meas. Sci. Technol.	25	3	10.1088/0957-0233/25/3/035101	x	x	Engineering, Multidisciplinary; Instruments & Instrumentation
2016	Bouteille, S. et al.	A Micromegas-based telescope for muon tomography: The WatTo experiment	Nucl. Instrum. Methods Phys. Res. A	834		10.1016/j.nima.2016.08.002		x	Instruments & Instrumentation; Nuclear Science & Technology; Physics, Nuclear; Physics, Particles & Fields
2016	Bouteille, S. et al.	Large resistive 2D Micromegas with genetic multiplexing and some imaging applications	Nucl. Instrum. Methods Phys. Res. A	834		10.1016/j.nima.2016.08.006		x	Instruments & Instrumentation; Nuclear Science & Technology; Physics, Nuclear; Physics, Particles & Fields
2016	Nishiyama, R. et al.	Monte Carlo simulation for background study of geophysical inspection with cosmic-ray muons	Geophys. J. Int.	206	2	10.1093/gji/ggw191	x	x	Geochemistry & Geophysics
2017	Nishiyama, R. et al.	3D Density Modeling with Gravity and Muon-Radiographic Observations in Showa-Shinzan Lava Dome, Usu, Japan	Pure Appl. Geophys.	174	3	10.1007/s00024-016-1430-9	x	x	Geochemistry & Geophysics
2017	Rosas-Carbajal, M. et al.	Three-dimensional density structure of La Soufriere de Guadeloupe lava dome from simultaneous muon radiographies and gravity data	Geophys. Res. Lett.	44	13	10.1002/2017GL074285	x	x	Geosciences, Multidisciplinary

Note: Continues to the next page.

TABLE 2: Continued.

Note: Continues from the previous page.

Year	Authors	Article Title	Source Title	Vol.	Issue	DOI	Muon radiogr.	Muon tomogr.	WoS Categories
2017	Marteau, J. et al.	DIAPHANE: muon tomography applied to volcanoes, civil engineering, archaelogy	J. Instrum.	12		10.1088/1748-0221/12/02/C02008		x	Instruments & Instrumentation
2017	Lesparre, N. et al.	3-D density imaging with muon flux measurements from underground galleries	Geophys. J. Int.	208	3	10.1093/gji/ggw482	x	x	Geochemistry & Geophysics
2018	Nagahara, S. & Miyamoto, S.	Feasibility of three-dimensional density tomography using dozens of muon radiographies and filtered back projection for volcanos	Geosci. Instrum. Methods Data Syst.	7	4	10.5194/gi-7-307-2018		x	Geosciences, Multidisciplinary; Meteorology & Atmospheric Sciences
2019	Lelievre, P.G. et al.	Joint inversion methods with relative density offset correction for muon tomography and gravity data, with application to volcano imaging	Geophys. J. Int.	218	3	10.1093/gji/ggz251		x	Geochemistry & Geophysics
2019	Barnoud, A. et al.	Bayesian joint muographic and gravimetric inversion applied to volcanoes	Geophys. J. Int.	218	3	10.1093/gji/ggz300	x	x	Geochemistry & Geophysics
2020	Riggi, F. et al.	Investigation of the cosmic ray angular distribution and the East-West effect near the top of Etna volcano with the MEV telescope	Eur. Phys. J. Plus	135	3	10.1140/epjp/s13360-020-00287-x		x	Physics, Multidisciplinary
2020	Vesga-Ramirez, A. et al.	Muon Tomography sites for Colombian volcanoes	Ann. Geophys.	63	6	10.4401/ag-8353		x	Geochemistry & Geophysics

While the bulk of the earlier literature focused on applications, more and more papers from 2010 onwards have had a more technical approach. Publications of this kind concentrate on detector designs [43, 44, 45, 46, 47], software codes and simulation toolkits [48, 49, 50, 51], algorithms [52, 53, 54], and comparison studies [55, 56, 57]. It can be anticipated that this type of research continues for many years to come as continuous development of tools and methodologies is an essential part of the development of muography. Authors participating in this research are typically physicists, mechanical engineers, and software experts.

Regarding science and technology in general, the volume of papers has expanded drastically over the years as the speed at which the researchers can publish their work has increased, and the number of publishing possibilities has grown significantly [58]. Also, policy measures aim to increase the number of scientists, research funding, and scientific output, leading to an increasing number of published papers [7]. These trends also affect muography. Yet, it must be emphasized that interest in commercialization leads to fewer publications, as publishing of results makes it impossible to file a patent. This may result in delays in the publication of muography results; i.e., the number of publications on muography may underestimate the activity of the field.

Due to the space limit, we will leave it to the reader to find other interesting trends in the presented data.

5. CONCLUDING REMARKS

We conclude the following:

(i) The number of muography papers is on an increasing trend.

(ii) Based on the publication titles, the term *muography* is clearly stabilizing.

(iii) Applications of muography are spreading out into different fields of research and practical functions.

  (a) The first wave has been dominated by applications such as border control and volcanoes, and it may not be too far-fetched to say that these have reached, at least compared to succeeding applications, an early-stage maturity (i.e., recognition outside the developers and first end-users).

  (b) The second wave applications (e.g., civil engineering, caves, mining) are gaining momentum.

  (c) The third wave applications are under piloting (e.g., oceanography).

  (d) More and more future applications are proposed in the literature (e.g., planetary research).

We propose that muography publications can be disruptive compared to prior literature: for example, a publication describing a new muography application published in a journal that has not published muography-related papers before may face more attention than the run-of-the-mill article in that journal. However, such publications may even go unnoticed if they are too heavily technically oriented or not written in a language familiar to the new target audience. Nevertheless, if the publications address their audience correctly, some may accumulate surprising attention and citation impact over the long run.

Cross-pollination between different disciplines will likely continue as muography develops from multidisciplinary research to a genuinely transdisciplinary field. Finally, based on our Web of Science analysis, it is easy to conclude that the research on

TABLE 3: The 21 muography-related review papers published between 1975 and 2020, based on the Web of Science Core Collection and its categories classification scheme.

Year	Authors	Article Title	Source Title	Vol.	Issue	DOI
2012	Okubo, S.& Tanaka, H.K.M.	Imaging the density profile of a volcano interior with cosmic-ray muon radiography combined with classical gravimetry	Meas. Sci. Technol.	23	4	10.1088/0957-0233/23/4/042001
2013	Morris, C.L. et al.	Charged particle radiography	Rep. Prog. Phys.	76	4	10.1088/0034-4885/76/4/046301
2014	Tanaka, H.K.M.	Particle Geophysics	Annu. Rev. Earth Planet. Sci.	42		10.1146/annurev-earth-060313-054632
2015	Parker, H.M.O. & Joyce, M.J.	The use of ionising radiation to image nuclear fuel: A review	Prog. Nucl. Energy	85		10.1016/j.pnucene.2015.06.006
2016	Checchia, P.	Review of possible applications of cosmic muon tomography	J. Instrum.	11		10.1088/1748-0221/11/12/C12072
2016	Nagamine, K.	Radiography with cosmic-ray and compact accelerator muons; Exploring inner-structure of large-scale objects and landforms	Proc. Jpn. Acad. Ser. B	92	8	10.2183/pjab.92.265
2017	Alexandrov, A.B. et al.	Muon radiography method for fundamental and applied research	Physics-Uspekhi	60	12	10.3367/UFNe.2017.07.038188
2019	Schouten, D.	Muon geotomography: selected case studies	Philos. Trans. Royal Soc. A	377	2137	10.1098/rsta.2018.0061
2019	Checchia, P. et al.	INFN muon tomography demonstrator: past and recent results with an eye to near-future activities	Philos. Trans. Royal Soc. A	377	2137	10.1098/rsta.2018.0065
2019	Yang, G.L. et al.	Novel muon imaging techniques	Philos. Trans. Royal Soc. A	377	2137	10.1098/rsta.2018.0062
2019	Gomez, H.	Muon tomography using micromegas detectors: From Archaeology to nuclear safety applications	Nucl. Instrum. Methods Phys. Res. A	936		10.1016/j.nima.2018.10.011
2019	Kaiser, R.	Muography: overview and future directions	Philos. Trans. Royal Soc. A	377	2137	10.1098/rsta.2018.0049
2019	Hussein, E.M.A.	Imaging with naturally occurring radiation	Appl. Radiat. Isot.	145		10.1016/j.apradiso.2018.12.006
2019	Tanaka, H.K.M. & Oláh, L.	Overview of muographers	Philos. Trans. Royal Soc. A	377	2137	10.1098/rsta.2018.0143
2019	Tanaka, H.K.M.	Japanese volcanoes visualized with muography	Philos. Trans. Royal Soc. A	377	2137	10.1098/rsta.2018.0142
2019	Khuntia, P.	Novel magnetism and spin dynamics of strongly correlated electron systems: Microscopic insights	J. Magn. Magn. Mater.	489		10.1016/j.jmmm.2019.165435
2019	Oláh, L. et al.	MWPC-based Muographic Observation System for remote monitoring of active volcanoes	Nucl. Instrum. Methods Phys. Res. A	936		10.1016/j.nima.2018.11.004
2019	Hillier, A.D. et al.	Muons at ISIS	Philos. Trans. Royal Soc. A	377	2137	10.1098/rsta.2018.0064
2020	Bonomi, G. et al.	Applications of cosmic-ray muons	Prog. Part. Nucl. Phys.	112		10.1016/j.ppnp.2020.103768
2020	Okubo, S.	Advances in gravity analyses for studying volcanoes and earthquakes	Proc. Jpn. Acad. Ser. B	96	2	10.2183/pjab.96.005
2020	Wang, B. et al.	Non-destructive testing and evaluation of composite materials/structures: A state-of-the-art review	Adv. Mech. Eng.	12	4	10.1177/1687814020913761

muography encompasses substantial portions of human activity. This demonstrates that muography is a multidisciplinary research field with many exciting possibilities and, most likely, a bright future. Therefore, we anticipate that the proportion of application-oriented publications will increase in the future.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] R. Kaiser, Muography: overview and future directions, Philos. Trans. Royal Soc. A 377, 20180049 (2019), doi:10.1098/rsta.2018.0049.

[2] S. Saha and S. Kar, Special Issue on Machine Learning in Scientometrics, J. Scientometr. Res. 8, 1 (2019), doi:10.5530/jscires.8.2.20.
[3] Y. Lin et al., New directions in science emerge from disconnection and discord, J. Informetr. 16, 101234 (2022), doi:10.1016/j.joi.2021.101234.
[4] M. Holma et al., Muography, outreaching and transdisciplinarity: Toward the golden age of muography, JAIS (2022), doi:10.31526/JAIS.2022.258.
[5] H. K. M. Tanaka et al., Detecting a mass change inside a volcano by cosmic-ray muon radiography (muography): First results from measurements at Asama volcano, Japan, Geophys. Res. Lett. 36, L17302 (2009), doi:10.1029/2009GL039448.
[6] V. M. Bondarenko et al., Muon Tomography of a Rock Terrain, Izvestiya Akademii Nauk SSSR Fizika Zemli 5, 103–108 (1987).
[7] J. S. G. Chu and J. A. Evans, Slowed canonical progress in large fields of science, PNAS USA 118(41), e2021636118 (2021), doi:10.1073/pnas.2021636118.
[8] J. E. Hirsch, An index to quantify an individual's scientific research output, PNAS USA 102(46), 16569–16572 (2005), doi:10.1073/pnas.0507655102.
[9] E. P. George, Cosmic rays measure overburden of tunnel, Commonw. Eng. 43, 455–457 (1955).
[10] L. Malmqvist et al., In-situ density determination by means of underground cosmic-ray intensity measurements a theoretical study, Geoexploration 16, 251–336 (1978).
[11] L. Malmqvist et al., Theoretical studies of in-situ rock density determination using cosmic-ray muon intensity measurements with application in mining geophysics, Geophysics 44, 1549–1569 (1979).
[12] L. W. Alvarez et al., Search for Hidden Chambers in the Pyramids, Science 167, 832–839 (1970), doi:10.1126/science.167.3919.832.
[13] H. K. M. Tanaka et al., Radiographic visualization of magma dynamics in an erupting volcano, Nat. Commun. 5, 3381 (2014), doi:10.1038/ncomms4381.
[14] S. Miyamoto and S. Nagahara, Tomographic Imaging of Volcano Structures with Cosmic-ray Muons, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch02.
[15] G. Leone et al., Muography as a new complementary tool in monitoring volcanic hazard: implications for early warning systems, Proc. R. Soc. A: Math., Phys. Eng. Sci. 447, 2255 (2021), doi:10.1098/rspa.2021.0320.
[16] Z.-X. Zhang et al., Muography and its potential applications to mining and rock engineering, Rock Mech. Rock Eng. 53, 4893–4907 (2020), doi:10.1007/s00603-020-02199-9.
[17] M. Holma et al., Future Prospects of Muography for Geological Research and Geotechnical and Mining Engineering, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch15.
[18] D. Schouten et al., Muon Tomography for Underground Resources, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch16.
[19] G. Saracino et al., Applications of muon absorption radiography to the fields of archaeology and civil engineering, Philos. Trans. Royal Soc. A 377, 20180057 (2019), doi:10.1098/rsta.2018.0057.
[20] R. Nishiyama et al., Bedrock sculpting under an active alpine glacier revealed from cosmic-ray muon radiography, Sci. Rep. 9, 6970 (2019), doi:10.1038/s41598-019-43527-6.
[21] P. Scampoli et al., Exploration of Hidden Topography Beneath Alpine Glaciers with Muography, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch13.
[22] H. K. M. Tanaka et al., First results of undersea muography with the Tokyo-Bay Seafloor Hyper-Kilometric Submarine Deep Detector, Sci Rep 11, 19485 (2021), doi:10.1038/s41598-021-98559-8.
[23] M. Holma et al., Studying bedrock fracture and weathering patterns with cosmic-ray induced muon particles, EGU General Assembly 2021 (2021), EGU21-9886, doi:10.5194/egusphere-egu21-9886.
[24] M. Holma et al., An introduction to principles of muography in continental scientific boreholes, Institute of Seismology, University of Helsinki, Report S-71, 39–42.
[25] M. Holma and P. Kuusiniemi, Cosmic-ray based geothermal exploration - A short introduction to muography, Institute of Seismology, University of Helsinki, Report S-71, 35–38.
[26] M. Holma et al., Imaging faults, shear zones and folds with cosmic-ray induced atmospheric muons: an introduction to muography for structural geologists and mining industry, 16th Biennial Meeting SGA 2022, Rotorua, New Zealand (2022).
[27] I. Lázaro Roche et al., Water resource management: The multi-technique approach of the low background noise underground research laboratory and its muon detection projects, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch10.
[28] G. Hamar et al., Exploration of Underground Cave Systems with Muography, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch11.
[29] G. Saracino et al., Detection and 3D Reconstruction of Cavities Inside Mount Echia, Naples, Italy, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch12.
[30] L. F. Thompson et al., Muography, a Key Technology for Monitoring Carbon Geostorage, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch14.
[31] K. N. Borozdin et al., Radiographic imaging with cosmic-ray muons, Nature 422, 277 (2003), doi:10.1038/422277a.
[32] L. Schultz et al., Cosmic Ray Muon Radiography for Contraband Detection, Proceeding of AccApp'03, San Diego, CA (2003).
[33] K. Gnanvo et al., Imaging of high-Z material for nuclear contraband detection with a minimal prototype of a Muon Tomography station based on GEM detectors, IEEE Nuclear Science Symposium & Medical Imaging Conference, Knoxwille, TN, USA, 30 October–6 November 2010 (2010), doi:10.1109/NSSMIC.2010.5873822.
[34] R. D'Alessandro et al., Muography applied to nuclear waste storage sites. Ann. Geophys. 60(1), S0106 (2017), doi:10.4401/ag-7381.
[35] D. Mahon et al., First-of-a-kind muography for nuclear waste characterization. Philos. Trans. Royal Soc. A 377, 20180048 (2019), doi:10.1098/rsta.2018.0048.
[36] D. Poulson et al., Application of muon tomography to fuel cask monitoring. Philos. Trans. Royal Soc. A 377, 20180052 (2019), doi:10.1098/rsta.2018.0052.
[37] H. Fujii et al., Imaging the Inner Structure of a Nuclear Reactor by Cosmic Muon Radiography, PTEP 2019(5), 053C01 (2019), doi:10.1093/ptep/ptz040.
[38] M. Menichelli et al., A scintillating fibres tracker detector for archaeological applications, Nucl. Instrum. Methods Phys. Res. A 572, 262–265 (2007), doi:10.1016/j.nima.2006.10.317.
[39] K. Morishima et al., Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons, Nature 552(7685), 386–390 (2017), doi:10.1038/nature24647.
[40] G. Bonomi et al., Cosmic ray tracking to monitor the stability of historical buildings: a feasibility study, Meas. Sci. Technol. 30, 045901 (2019), doi:10.1088/1361-6501/ab00d7.

[41] H. K. M. Tanaka et al., Muography as a new tool to study the historic earthquakes recorded in ancient burial mounds, Geosci. Instrum. Method. Data Syst. 9, 357–364. (2020), doi:10.5194/gi-9-357-2020.
[42] S. Vanini et al., Cultural heritage investigations using cosmic muons, Comptes Rendus Physique 19(7), 533–542 (2018), doi:10.1016/j.crhy.2018.08.002.
[43] J. Marteau et al., Development of Scintillator-Based Muon Detectors for Muography, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch17.
[44] A. Giammanco et al., Resistive Plate Chambers in Muography, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch18.
[45] D. Varga et al., Development of Multi-Wire Proportional Chamber-Based Trackers for Muography, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch19.
[46] S. Bouteille & S. Procureur, Development of Micro-Pattern Gaseous Detectors for Muography, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch20.
[47] K. Morishima et al., Development of Nuclear Emulsions for Muography, Geophysical Monograph Series 270, Wiley (2022), doi:10.1002/9781119722748.ch21.
[48] V. A. Kudryavtsev, Muon simulation codes MUSIC and MUSUN for underground physics, Comput. Phys. Commun. 180, 339–346 (2009), doi:10.1016/j.cpc.2008.10.013.
[49] T. T. Böhlen et al., The FLUKA Code: Developments and Challenges for High Energy and Medical Applications, Nucl. Data Sheets 120, 211–214 (2014), doi:10.1016/j.nds.2014.07.049.
[50] J. Allison et al., Recent Developments in Geant4, Nucl. Instrum. Methods Phys. Res. A 835, 186–225 (2016), doi:10.1016/j.nima.2016.06.125.
[51] R. Engel et al., Towards A Next Generation of CORSIKA: A Framework for the Simulation of Particle Cascades in Astroparticle Physics, Comput. Softw. Big Sci. 3(1) (2018), doi:10.1007/s41781-018-0013-0.
[52] L. Bonechi et al., Tests of a novel imaging algorithm to localize hidden objects or cavities with muon radiography, Philos. Trans. Royal Soc. A 377, 20180063 (2019), doi:10.1098/rsta.2018.0063.
[53] S. Vanini et al., Muography of different structures using muon scattering and absorption algorithms, Philos. Trans. Royal Soc. A 377, 20180051 (2019), doi:10.1098/rsta.2018.0051.
[54] W. Zeng et al., Principle study of image reconstruction algorithms in muon tomography, Journal of Instrumentation 15, T02005, (2020), doi:10.1088/1748-0221/15/02/t02005.
[55] N. Lesparre et al., Density muon radiography of La Soufrière of Guadeloupe volcano: comparison with geological, electrical resistivity and gravity data, Geophys. J. Int. 190, 1008–1019 (2012), doi:10.1111/j.1365-246X.2012.05546.x.
[56] K. Cosburn et al., Joint inversion of gravity with cosmic ray muon data at a well-characterized site for shallow subsurface density prediction, Geophysics Journal International, 217, 1988–2002 (2019), doi:10.1093/gji/ggz127.
[57] Y. Le Gonidec et al., Abrupt changes of hydrothermal activity in a lava dome detected by combined seismic and muon monitoring, Sci. Rep. 9, 3079 (2019), doi:10.1038/s41598-019-39606-3.
[58] M. Fire and C. Guestrin, Over-optimization of academic publishing metrics: observing Goodhart's Law in action, Gigascience 8, 1–20 (2019), doi:10.1093/gigascience/giz053.