

Article

# Volcanic Geomorphology: A Review of Worldwide Research

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**Abstract:** The purpose of this article is to provide an overview of academic research on volcanic geomorphology, through the use of bibliometric analysis and bibliographic visualization maps for the discernment of its growing interest by the academy in the last 30 years. It is sustained on the publications indexed in the Scopus database between 1956 and 2019, obtaining relevant information on scientific production, following the methodological structure of a rigorous bibliometric process, which ranges from the search for descriptors or keywords to the configuration of visualizations of tables and maps that allowed to consider the contributions by authors, institutions, journals and topics that have shaped the evolution of this field of study. The generations of bibliometric maps allowed understanding the intellectual structure of the field of study made up of 707 articles where the analysis of co-occurrence of author keywords showed six main lines of research that, combined with the co-citation maps, allowed understanding the breadth of intellectual structure. Extensive information is provided on the thematic that other investigations partially addressed or failed to capture their current status. Considering that the results allow us to identify areas of current interest and the potential of research in volcanic geomorphology.

**Keywords:** bibliometry; volcanic geomorphology; bibliometric map; co-citation; co-occurrence

## 1. Introduction

There is currently a wide interest and concern about the environment and how it works and evolves. The threats of climate change and the extinction of species are commonly highlighted; but what about changes in landscapes? [1]. There are still many unanswered questions about physical landscapes and anthropic events; how to conserve them and manage geological spaces in the best way is a great question [2]. That is why, geomorphology is the science that studies the origin and development of landforms, such as hills, valleys, caves, or volcanic spaces, that seek to explain the morphological processes on the surface, under monitoring and of those that shape the reliefs [3,4] characterized by

changes that occur in response to factors of tectonic and volcanic activity, changes in climate, but above all, anthropogenic activities through quantitative analysis [5]. However, researches could be directed mainly towards the reconstruction of old processes, such as changes in relief, understanding of current processes or the anticipation of future processes and changes.

In the field of geomorphology, the study of volcanism and volcanic deposits within the last decade has been one of the most prominent topics [6], defining volcanism as one of the endogenous processes associated with plate tectonics, capable of transforming, building and modeling the Earth's surface at local and regional scale [7]. Volcanism has been applied in various research issues, including the study of glaciers, tectonic evolutions, volcano-clastic deposits, among others [8,9]. This shows that it is an important issue whose sole purpose lies in promoting tourist attractions, due to their attractiveness [10], contributing to the development of the surrounding communities whose volcanic soils are very fertile, due to the rapid alteration that water generates in volcanic materials, and therefore, of great use for agricultural and agricultural activities [11].

Volcanic activity can be studied through the composition of the lava rocks, gas emission and associated seismic activity [12], evaluated through its geomorphological expression and the degree of water dissection that suffered by volcanic buildings and their associated deposits; observed in most of the continents where volcanic activity is not homogeneous in its distribution over the Earth's surface, but in a discrete way following more or less well-defined tectonic patterns [13]. That is why, 60% of volcanic activity is always located on the underwater ridges in the world's oceans, while 40% is located on the Pacific, Caribbean, and Mediterranean ring of fire belt [14]; where this distribution is related to the type and genesis of magma, which in turn is reflected in the type of volcanism observed and allows us to emphasize the importance of producing research in this area [15].

This extensive theoretical development, in which geological evidence of findings in different training environments has been provided, has allowed researchers to make publications for the conservation and protection of the geological landscape, which have served as a starting point for future research, inside and outside the scientific branch [16]; considering scientific research as the most effective way of transmitting knowledge obtained as a consequence of a series of factors, such as experimentation that can be measured through expressions of knowledge (e.g., papers, conference articles, or bibliometric articles) [17]. However, each of these documents they need to continue to follow an exhaustive production process because, it must comply with a referential style, in order to guarantee the order, methodology, scientific rigor and correct interpretation of information. That is why, some of them are of a particular nature, since they provide a systematic review related to the health hazards of volcanic gases [18], water contamination by the fall of volcanic ash [19], morphometric characterization of volcanic buildings [20], important topics, but there are no articles that cover in a general way the geomorphology of volcanic studies.

This justifies the need to synthesize the breadth of knowledge in the field of volcanology, through bibliometric analysis. This type of study organizes a specific area of knowledge, when studying patterns and structures [21]. In addition, they allow studying scientific productivity, its influence and relevance, as well as for inter-institutional cooperation, trends of scientific communities and classification of authors, institutions, magazines, most influential works, countries, etc. [22]. Bibliometric analysis is considered as a documentary method that has reached an important development during the last three decades [23,24].

Its fundamental objectives are, on the one hand, the study of the size, growth and distribution of scientific documents, and on the other, the investigation of the dynamic structure of the groups that consume these documents and the information they contain [25]. Its use has been generalized for various fields of knowledge related to geology, such as marine geohazard [26], coastal flooding [27], and megaclasts [28], as well as other areas of knowledge (e.g., management [29], environmental [30], and Health) [31].

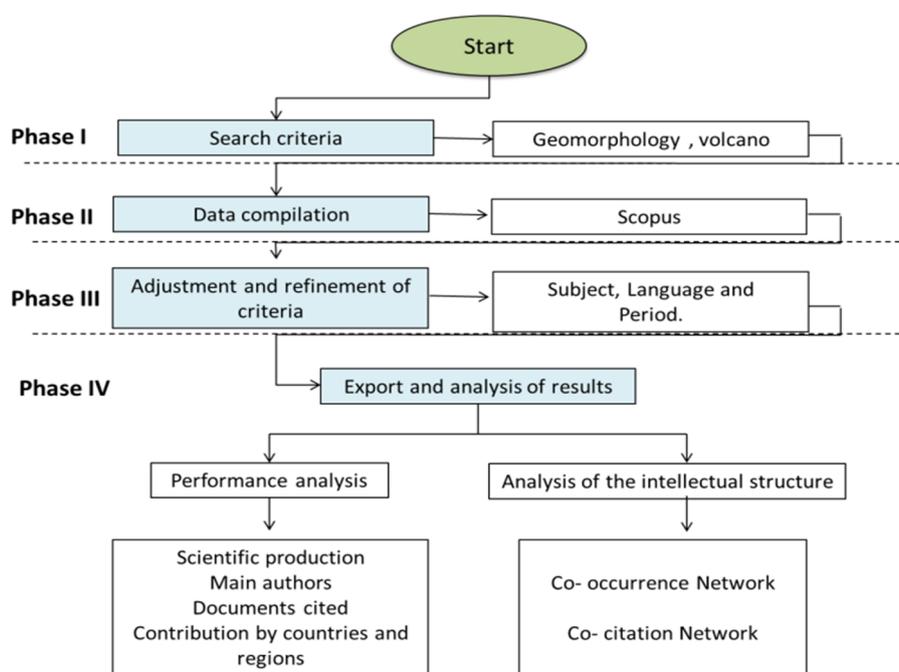
Due to the aforementioned, a question is raised capable of producing answers regarding the focus of the investigative process, but above all it allows us to know the course of geomorphology

and its relationship with geography, taking into account that worldwide this branch has been one of the first sub-disciplines to express interest in biophysical aspects for decades. Perhaps through this analysis, it is possible to know which journals and disciplines had the greatest impact on the research flow? Who are the most representative experts in the given field of research? How has the intellectual structure of the subject developed over time? Are international audit documents cited more? What are the subjects associated with this particular line of research?

Based on the above, two main objectives are considered, where the first seeks: To analyze the performance of scientific production related to published articles, researchers, main contributions and journals through a bibliometric analysis for the extraction of new knowledge and applications that contribute to the scientific development. The second is to reveal the intellectual structure of the study area, locating the central themes by co-occurrence and co-citation of cited authors and journals [32]; the purpose of which is to generate a bibliometric study about “volcanic geomorphology”, which seeks to contribute significantly to the advancement of research within the geological field. Identifies the scopes that have already been addressed within volcanology, and explore others that have not yet been promoted at the scientific level; but in addition, it seeks to promote trends in topics of great importance for the development of future research that stands out within the scientific branch [33,34].

## 2. Materials and Methods

Systematic literature reviews provide a rigorous and formal methodical procedure, which seeks to minimize bias and possible errors when selecting studies to know an area of knowledge [35,36]. Bibliometric studies are considered to contemplate a similar procedure as well [37]. The proposed methodology for bibliometric analysis has been structured, and comprises a sequence of four phases that allow the proposed developed analysis to be carried out: (1) Define the search criteria; keywords and time periods; (2) data compilation; (3) adjustment and refinement of criteria; (4) export and analysis of results in order to know the structure and evolution of geomorphology given its growing interest in academia (see Figure 1).



**Figure 1.** Scheme of the methodology applied in this study.

### 2.1. Defining Search Criteria

The words used as search parameters consider the terms geomorphology and volcano as referents of the study area [38], those that are in common use within the volcanological field [39]. The selection of these terms allowed the compilation of the base documents, for the proposed analyzes.

### 2.2. Data Compilation

The search was carried out in March 2020, which was based on the compilation of the information on “volcanic geomorphology” through the Scopus scientific database, considered as a viable alternative when selecting a database of peer-reviewed scientific literature [40] that analyzes the behavior of citations received by journals and generates indicators that evaluate the performance of journals, authors, research groups, universities, countries and even regions of the world [41,42].

A search strategy was used considering all the documents that contain the keywords in the titles, abstracts, and keywords. The terms were used combined with a series of Boolean operators and symbols that allow the refinement of the exploration and offer more adjusted results [43]. The search is presented as follows: (TITLE-ABS-KEY (“geomorphology”) AND TITLE-ABS-KEY (volcano\*)), descriptors that allow us to focus on the scope of volcanic geomorphology in a specific way, resulting in a total of 1001 documents found.

### 2.3. Adjustment and Refinement of Criteria

The data was refined by means of inclusion and exclusion criteria of the information. The “Earth and Planetary Sciences” area and the English language were selected for their frequent use in academia. Additionally, articles are selected (article, article in press), because the research papers are presented by one or more specialists and evaluated by peers [44]. Additionally, documents published until 2019 were considered. The resulting search equation applied is: (EXCLUDE (PUBYEAR, 2020)) AND (LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (SUBJAREA, “EART”)) AND (LIMIT-TO LANGUAGE, “English”). Through this process, 709 documents were obtained.

### 2.4. Export and Analysis of Data

The records obtained from Scopus were exported in CSV (comma-separated values) format, containing data on bibliographic information, abstract, keywords, among others, which are useful when studied through bibliometric analysis [45]. This downloaded information from bibliographic sources normally contains errors, requiring a data normalization process. The process consists of verifying the information to rule out erroneous or incomplete data [46]. This process can be done by combining Microsoft Excel and Vosviewer software. The first allows a manual review of the data of authors, journal titles or affiliations, which consolidates the data collection in 707 documents. This refined database makes it possible to consolidate the use of the second software for the review of the units of analysis prior to the construction of the bibliometric maps. In the co-occurrence map, it is necessary that some keywords be integrated into acronyms and single and plural forms and in the co-citation maps the names of the Journals and the author’s name should be standardized if necessary (thouret, j.-c. by thouret, jc)[47].

Vosviewer software was used to generate the bibliometric maps. This software allows the construction, exploration and graphic representation of easy-to-interpret two-dimensional maps [46,48], allowing to reveal the intellectual structure of the field of study using bibliometric networks recognized in the academic world, such as author co-occurrence maps, author co-citation and journal co-citation [49]. The Vosviewer has contributed notably in the development of bibliometric analyzes in various areas of knowledge in areas of earth science [50,51] management [52], and health [53].

### 3. Results

#### 3.1. Analysis of Scientific Production

The analysis of the results of the advanced search after cleaning the data of the geological term called “volcanic geomorphology”, indicates that the study of this line of research has resulted in a total of 707 documents produced from 1956 to 2019, the same ones that for analysis purposes we have divided into three time periods, such as introduction (1956–1998), growth (1999–2009), and maturity (2010–2019). Likewise, the analysis of productivity has been proposed of a field of study using Price’s law, which has served to evaluate the increase in production, adjusting to exponential growth [54]. Obtaining, as a result, the equation  $y = 2E-68e^{0.0792x}$ , where the value of  $R^2$  (coefficient of determination) is 0.86, revealing the quality of the representative power of the function, therefore, we can say that the research on “volcanic geomorphology”. It is in the phase of exponential growth, which guarantees that it is a growing research field (see Figure 2)

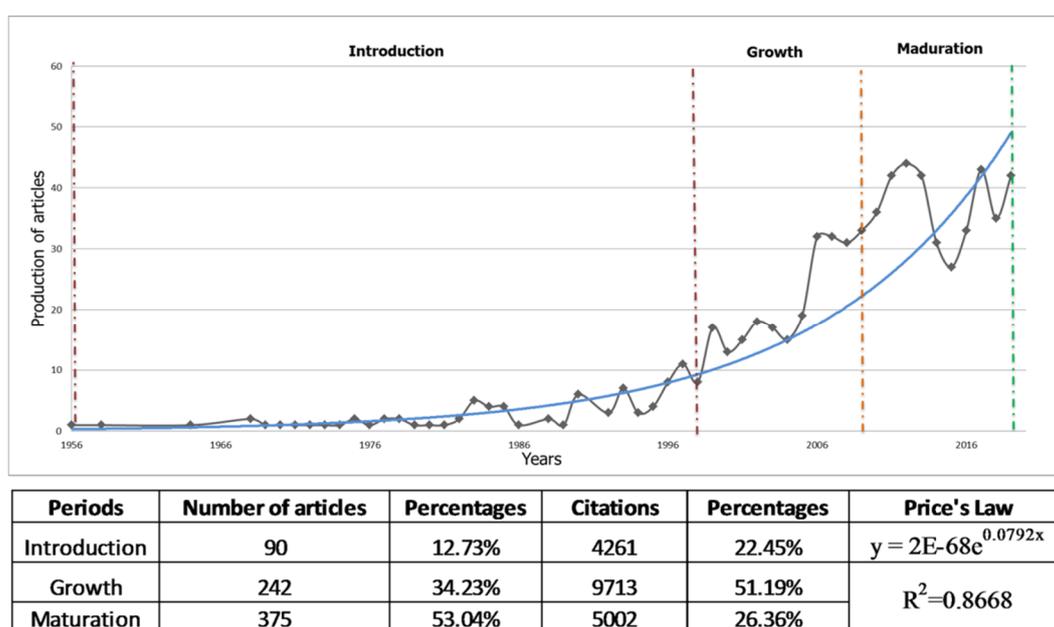


Figure 2. Scientific production table of volcanic geomorphology articles.

##### 3.1.1. Introduction (1956–1998): Birth of Volcanic Geomorphology

In this period, 90 scientific articles were produced, representing 12.73% of the total. Its last three years record a higher production, reaching a peak in 1997 with 11 items; where the document “The structure and geomorphology of the Dashgil mud volcano, Azerbaijan” is highlighted [55], the work of one of the most representative authors in the area. Additionally, in this period, the citations obtained were 4261 (22.45%), announcing the beginning of this area of research that expanded over time [56]. Other articles featured in this period cover topics, such as “[k]eys to analyze active lahars from Pinatubo on SAR ERS imagery” [57] and “[t]he effect of collapse structures on ground deformations in calderas” [58].

##### 3.1.2. Growth (1999–2009): Geomorphological Evolution

In this growth period, scientific production increased considerably in 242 articles (34.23%) and 9713 citations (51.19%). This demonstrated a growing interest in the subject of volcanic geomorphology in academic literature. In 2009 it reached the maximum production of the period with 33 articles; highlighting “LIDAR strip adjustment: Application to volcanic areas” [59], work that proposes a modality to analyze volcanic complexes through the adjustment of the Lidar strip. Other articles

featured in this period were: “The topography and morphology of low shields and associated landforms of plains volcanism in the Tharsis” [60] and “Geomorphic and geologic settings of the Phoenix Lander mission landing site” [61].

### 3.1.3. Maturation (2010–2019): Peak of Volcanic Geomorphology

Finally, in the maturation period, the scientific production reached a total of 375 articles, representing 53.04% of the total, where its peak was registered in 2012 with 44 publications. The featured article of the period is “Circular geomorphology and geological features in the Japanese islands” [62], generating interest in the scientific world by studying the geomorphology of circular islands on the Asian continent, and analysis of the seismic and volcanic risks of them. The period registers 5002 citations, which represent 26.36% of the total citations, showing the apogee of the topic and its breadth. Other articles featured in this period “Environmental changes across the Triassic-Jurassic boundary and coeval volcanism inferred from elemental geochemistry and mineralogy in the Kendlbachgraben section (Northern Calcareous Alps, Austria)” [63] and “Eruption of kimberlite magmas: Physical volcanology, geomorphology and age of the youngest kimberlitic volcanoes known on Earth (the Upper Pleistocene/Holocene Igwisi Hills volcanoes, Tanzania)” [64].

### 3.2. Contribution of the Main Authors

The 707 publications have been written by 1725 authors. Table 1 shows the 15 main authors with the highest production of articles in the study area, highlighting Németh Károly from Massey University Manawatu, Palmerston North (New Zealand), with 13 articles, among which “Volcanic structures and oral traditions of volcanism” are distinguished. of Western Samoa (SW Pacific) and their implications for hazard education” [65], “Reconstructing paleoenvironment, eruption mechanism and paleomorphology of the Pliocene Pula maar (Hungary)” [66] and “Facies architecture of an isolated long-lived, nested polygenetic silicic tuff ring erupted in a braided river system: The Los Loros volcano, Mendoza, Argentina” [67].

**Table 1.** Main authors considering the number of citations produced.

AU	AT	AF	CO	CI	HI
Németh K.	13	Massey University	New Zealand	125	3.4
Lahitte P.	9	Geoscience Paris Sud	France	24	13
Karátson D.	8	Eötvös Loránd University	Hungary	65	17
Favalli M.	7	Istituto Nazionale di Geofisica e Vulcanologia.	Italy	114	27
Quidelleur X.	7	Geoscience Paris Sud	France	99	6
Chiocci F.	6	Università degli Studi di Roma La Sapienza	Italy	40	26
Gomez C.	6	University of Canterbury	New Zealand	15	1
Bosman A.	5	Istituto Di Geologia Ambientale E Geoingegneria	Italy	24	16
Fornaciai A.	5	Istituto Nazionale di Geofisica e Vulcanologia	Italy	57	18
Martí J.	5	Institute of Earth Sciences' J	Spain	181	43
Melekestsev I.	5	Institute of Volcanology and Seismology	Russia	59	20
Palacios D.	5	Complutense University of Madrid	Spain	10	2.3
Acosta J.	4	Spanish Institute of Oceanography	Spain	93	21
Baker V.R.	4	The University of Arizona	United States	31	58
Carracedo J.C.	4	University of Las Palmas de Gran Canaria	Spain	11	31

Abbreviations: AU = Authors; AT = Articles; AF = Affiliations; CO = Country; CI = Citations; HI = H-Index.

The second place of production corresponds to the author Lahitte P., from Geoscience Paris Sud (France), with nine published articles. Highlights the work “DEM-based reconstruction of southern Basse-Terre volcanoes (Guadeloupe archipelago, FWI): Contribution to the Lesser Antilles Arc construction rates and magma production” [68]. Additionally, Table 1 presents the H-Index as an estimate of the impact of the contributions made by a researcher where Baker V.R. presents the highest H-Index (58), followed by Martí J. (43) and Németh K. (34).

### 3.3. Frequently Cited Documents

The use of document citation analysis evaluates its impact in a certain field of study [69]. Table 2 shows the first 15 documents with the most citations in the line of volcanic geomorphology research. The most cited publications are: First, the work by Massonnet D. from the Center National d'Etudes Spatiales (CNES) entitled "Radar interferometry and its application to changes in the Earth's Surface" (1998) with 1608 citations. The second most cited document is a study on continental collision zones, belonging to Chung S.L. (2003) of the National Taiwan University with 766 citations. Third place corresponds to Carr M.H. of the Geological Survey (United States) with 305 citations.

**Table 2.** Main documents with the most citations. [70–84]

AU	TI	CI
Massonnet, 1998 [70]	Radar interferometry and its application to changes in the earth's surface	1608
Chung, 2003 [71]	Adakites from continental collision zones: Melting of thickened lower crust beneath southern Tibet	766
Carr and III, 2010 [72]	Geologic history of Mars	305
Burr and Grier, 2002 [73]	Repeated aqueous flooding from the cerberus fossae: Evidence for very recently extant, deep groundwater on Mars	185
Heiken and Khan, 1988 [74]	Morphology and petrography of volcanic ashes	182
Gattacceca, 2007 [75]	Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications	182
Gulick, 1990 [76]	Origin and evolution of valleys on Martian volcanoes	160
Thomas, 2002 [77]	Precambrian evolution of the Sirwa Window, Anti-Atlas Orogen, Morocco	144
Pyle, 2006 [78]	Wide dispersal and deposition of distal tephra during the Pleistocene "Campanian Ignimbrite/Y5" eruption, Italy	144
Manville, 2009 [79]	Source to sink: A review of three decades of progress in the understanding of volcanoclastic processes, deposits, and hazards	142
Major, 2000 [80]	Sediment yield following severe volcanic disturbance - A two-decade perspective from Mount St. Helens	138
Ablay and Martí, 2000 [81]	Stratigraphy, structure, and volcanic evolution of the Pico Teidi-Pico Viejo formation, Tenerife, Canary Islands	129
Kurz, 1990 [82] Thouret, 1999 [83]	Cosmic ray exposure dating with in situ produced cosmogenic <sup>3</sup> He: results from young Hawaiian lava flows	129
Gulick, 2001 [84]	Volcanic geomorphology-an overview Origin of the valley networks on Mars: A hydrological perspective	128 124

Abbreviations: AU = Authors; TI = Title; CI = Citations.

### 3.4. Country and Region Contributions

The contribution of the different countries was established considering the affiliation of each of the authors of the articles. The study topic has been developed in 73 countries, but research has been concentrated in 15 countries, representing 20.55% of the total (see Table 3). Seven European countries, three Asian and American, and two countries in Oceania are ranked as the most productive. The fifteen main countries belong to the group of developed countries, showing a dominant position in volcanic geomorphology, demonstrating their economic capabilities and levels of research. The United States is the first country in the ranking with 217 documents and 6411 citations. The second place corresponds to Italy with 115 documents, but third in citations. The countries that occupy the third and fourth place with the highest production are France and the United Kingdom with 77 articles.

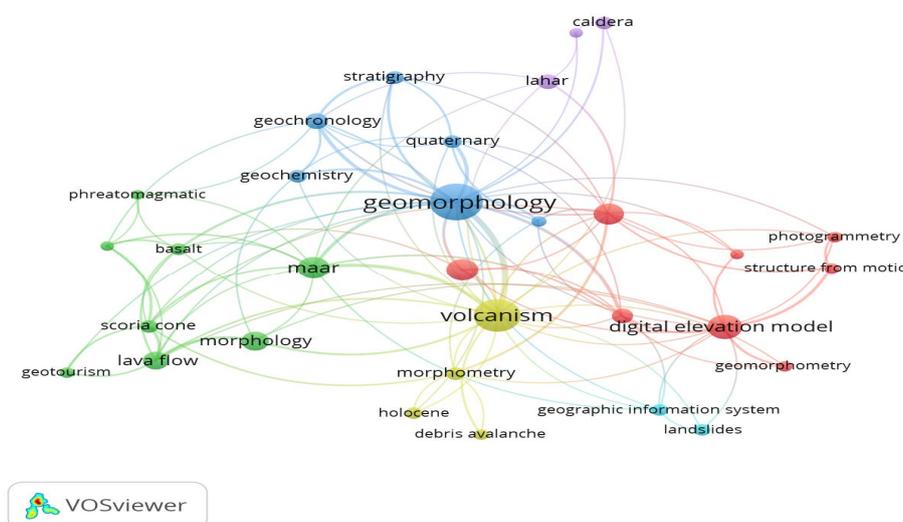
**Table 3.** Main documents with the most citations.

Rank	Country	Number of Articles	Citations
1	United States	217	6411
2	Italy	115	2895
3	France	77	3556
4	United kingdom	77	1927
5	Germany	61	1282
6	Spain	49	1046
7	New Zealand	43	1139
8	Australia	38	944
9	Japan	33	694
10	Mexico	30	544
11	Canada	26	659
12	China	21	1072
13	Russian Federation	21	455
14	Hungary	19	487
15	Switzerland	17	330

### 3.5. Analysis of the Structure of the Field of Volcanic Geomorphology

#### 3.5.1. Author Keyword Co-Occurrence Network

It is a content analysis technique that uses author keywords to construct semantic visual maps that reveal the cognitive structure of the investigated area [45,85]. For this purpose, the VOSviewer software was used to prepare the bibliometric map using co-occurrence data and its association strength [22], managing to represent and analyze the information as an alternative to traditional techniques of multidimensional representation and network visualization by combining visualization and clustering techniques favoring analysis [86]. A total of 1266 keywords provided by the author were extracted from the information base. These words co-occurred at least five times. The network shows 31 keywords that make up six clusters (Figure 3), in which the relationships between words are represented by graphs that were connected by means of nodes and links. The nodes represent the keywords, and their size is related to the number of times the keyword appears in the documents, that is, a larger size reflects a higher frequency of appearance (and vice versa). The links (edges) indicate the relationships between a pair of nodes and the strength of this relationship is observed in the width of the link, where a greater it implies a greater relationship [46].



**Figure 3.** Co-occurrence bibliometric map of author keywords.

The most developed research area is Cluster 3 (blue) called “Geomorphology and tectonism” (see Table S1). A cluster consisting of six nodes with 117 co-occurrences, where his research focuses on knowing the determined age of geomorphological structures [87] and its tectonic implications [88], having as keywords “geomorphology”, “geochronology” and “stratigraphy”. Cluster 1 “Topographical methods” consists of eight nodes and 112 co-occurrences, a cluster that highlights topographic, tectonic and volcanic detection methods through photogrammetry [89], and remote sensors [90], with prominent keywords, such as “digital elevation model”, and “photogrammetry”.

Others, smaller clusters are: Cluster 2 (green) “Volcanic Products”, made up of eight nodes and 92 co-occurrences, showing studies related to the types of geological materials [91] that have arisen as a product of volcanic processes [14]; where the keywords that stand out are: “maar”, “lava flow”, “scoria cone”. Cluster 4 (yellow) “Volcanism” consists of four nodes and presents 75 co-occurrences. In this cluster, the studies are focused on volcanism [92], knowledge and detection of land relief modifications [93] and the conformation of new geological structures through geotechnical processes [94]; where the most representative keywords of the cluster are “volcanism” and “morphometry”. Cluster 5 (purple) “Pyroclastic flows” consists of two nodes and 25 co-occurrences, represents studies related to volcanic flows that arise in an eruption [95] and of structures that make up the land relief as a result of geological processes [96].

Featured keywords include “lahar” and “caldera”. Finally, Cluster 6 (light blue) “Mass movements” comprises two nodes and 14 co-occurrences, comprising flow-like mass studies [97] and especially modeling tools for large amounts of data linked to a spatial reference [98]. The relevant cluster keywords are “landslides” and “geographic information system” (see Table S1).

### 3.5.2. Co-citation Network of Cited Authors

This map allows us to study the intellectual structure of the scientific discipline using the authors of the reference works as the unit of analysis, which allows us to reflect the fields of research with the greatest impact [45,49,99]. In the construction of the map, the Vosviewer software and the similarity measurement were used to match the data, called the association force and the fractional counting method [22] 36,748 reference authors were established, determining as a parameter that the minimum number of author citations is at least 20 citations, obtaining 700 authors, who are represented by nodes, exposed in eight clusters (see Figure 4).

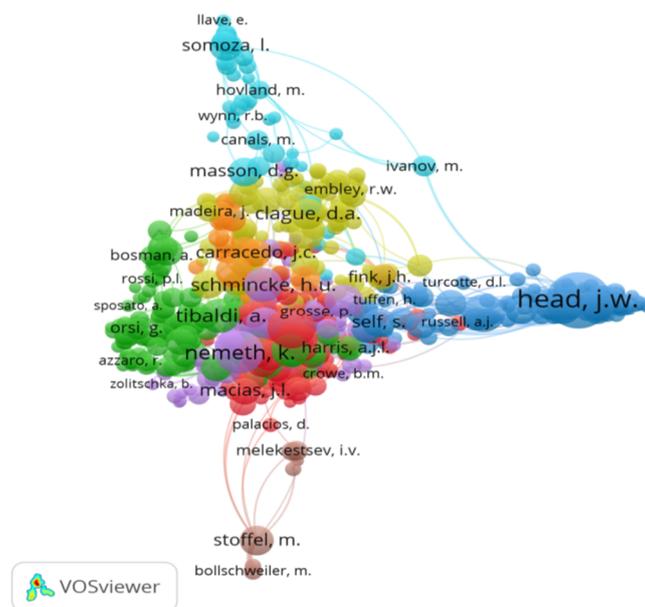


Figure 4. Co-citation bibliometric map of cited authors.

Cluster 3 (blue) “Geological deposits” with 111 authors and 29,432 citations. The cluster is focused on studying deposits from landslides of underwater structures; where the most outstanding researchers in this scientific area are Head, J.W.; Fassett, C.I. and Blewett, D.T. of the Department of Geological Sciences, Brown University. Cluster 5 (purple) consists of 82 authors and 29,183 citations, this research front deal with the morphology and origin of craters, where researchers search for the origin of certain volcanic processes for the formation of structures. The prominent authors of the cluster are: Németh, K. from Massey University, Schmincke, H.U. from GEOMAR Helmholtz Zentru für Ozeanforschung Kiel.

Cluster 1 (red) “Processes and geological effects” made up of 173 authors with 28,887 co-citations whose central theme of the cluster focuses on the evolution of the quaternary landscape through the use of high-resolution remote detection to determine the perception of certain structures, dynamic effects and geological consequences. The featured author is Sparks, R.S., and the University of Cambridge. Cluster 2 (green) “Petrology of volcanic fields” represented by 140 authors with 28,029 citations. The Cluster that mentions the structure and petrology of the various volcanic fields in order to control the intrusion of sheets or other objects within them. The most outstanding researchers were: Tibaldi, A. from the University of Milano—Bicocca and Acocella, V. from Università degli Studi Roma Tre.

Cluster 7 (orange) consists of 31 authors with 27,172 citations, where the topics are related to central eruptions and stratovolcano flanks. The outstanding author of the cluster is Marti, J., Ablay, G.J. of the Institute of Earth Sciences “Jaume Almera”, Spain. Cluster 4 (yellow) “Geology of the sea” with 104 authors and 26,965 citations, exhibits a research area that falls under the analysis of eruptions of underwater structures whose purpose is to know new perspectives on the displacement of the flow of underwater lava from of high resolution mappings, having Clague, D.A., Reynolds, J.R. and Moore, J.G. of Monterey Bay Aquarium Research Institut as the main exponents.

Cluster 8 (brown) “Geological phenomena” is the last one with 8 and 26,603 citations where their studies reveal the relationships between earthquakes, hurricanes and landslides. The main researchers are: Stoffel, M. and Bollschweiler, M. from the Department of Geosciences, Geography, and the University of Friborg. Finally, Cluster 6 consists of 47 authors and 26,061 citations where the thematic area that stands out is geophysics and the researchers that stand out from the cluster are Masson, D.G. of the Institute of Ocean Sciences, Fisheries and Oceans Canada and Somoza of the University of Coruña, Spain (see Table S2).

### 3.5.3. Co-citation Network of Scientific Journals

This analysis visualizes the shared citations of the references of the journals [100] For this purpose, the Vosviewer software was used to generate the co-citation network, showing those journals that are cited at least 20 times, obtaining 122 journals that are related in six clusters (Figure 5), where the nodes with the largest size correspond to the journal with the highest number of citations received.

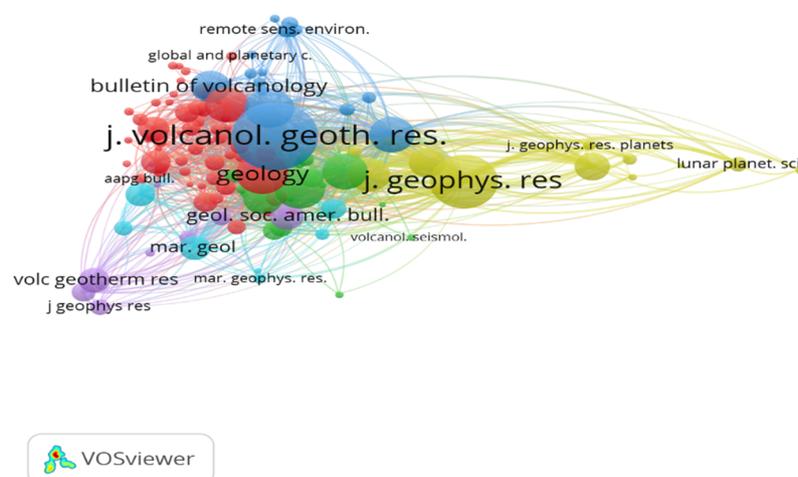


Figure 5. Bibliometric map of co-citation of journals.

Table S3 shows a diverse and complex co-citation group for journals: Cluster 1 (red) “Earth geological processes” consists of the Geology journals; Geomorphology; Geological Society of America Bulletin and Sedimentology, where the most relevant is “Geology” with H-index 189 considered as the representative journal of the study area for its number of co-citations; In Cluster 2 (green) “Earth and science” shows the journals Earth and Planetary Science Letters (EPSL), Bulletin Volcanology, Tectonophysics and Geophysics; as the most representative; the most relevant of this group is “Earth and Planetary Science Letters (EPSL)” with 215 H-index. Cluster 3 (blue) “Volcanic processes” are made up of the journals Volcanology and Geothermal Research, Journals Geophysics Research and Remote Sensing of Environment as the most representative; where “Journal of Volcanology and Geothermal Research” presents the highest H-index (105). Cluster 4 (yellow) “Geological Nature” presenting the journals Nature, Journal Geophysical Research, Science and Icarus; where the “Journal Geophysical Research” shows the highest H-index of the group.

In Cluster 5 (purple) “Structures and Geopatrmony” with journals (such as the Geological Society of America Bulletin, Geoheritage, and Geological Magazine) highlights “Geological Society of America Bulletin” with 134 H-index. Finally, in Cluster 6 (light blue) “Marine Geology” with a notable presence from the journals Marine Geology, Oceanography, Eos, Transactions American Geophysical Union and Marine Geophysical Research. In this cluster, the highest H-Index corresponds to “Marine Geology” (117).

#### 4. Conclusions

This article exhibits a review of the intellectual structure on volcanic geomorphology during the period 1956–2019. Bibliometric analysis was used as a method of evaluating scientific production, helping to understand the intellectual structure and promoting the discovery of new topics. The analysis of scientific production reflects an exponential growth according to the mathematical adjustment of the trend curve without reaching the saturation point described by Price, where an initial period of 1956–1998 is identified with a production of 90 scientific articles, a second period from 1999 to 2009 (242 publications), showing increasing interest from the academy; and a third period 2010–2019 (375 publications) evidencing the consolidation of the scientific field.

The growing interest in the field of volcanic geomorphology is evident, considering the contribution of 707 scientific articles written by 1725 authors, from 73 countries. This international contribution has a strong responsibility on the part of developed countries, such as the United States, Italy, France, the United Kingdom, and Germany. The authors of this subject with the highest production come from European institutions; the presence of researchers from American institutions also stands out, demonstrating the expansion of information.

For the analysis of the journals, the most important were considered, the Journal of Volcanology and Geothermal Research presents the highest number of contributions (106), followed by Geomorphology (64). Analysis of bibliometric maps revealed connections, such as co-occurrence bibliometric mapping of keywords shows topics related to geomorphology, geochronology, volcanism, morphometry, indicating that most subject areas were based on analyzes of geomorphological structures, age, and volcanism. Secondly, the authors co-citation bibliometric mapping, demonstrating that the intellectual structure is related to geological processes and effects. Being Head, J.

The analysis of co-citation of journals allowed to know the different conceptual approaches that are structured in topics related to volcanic processes, geo-heritage and marine geology. Finally, the use of bibliometric analysis allows us to identify an intellectual structure and its tendency in journals on the topics of geology, geophysics, geomorphology, remote sensors, and marine geology. This research has limitations: (i) Not using more academic fields; (ii) considering a single type of document (articles); (iii) the use of a single database (Scopus) instead of considering other databases that are frequently used in the academic world like Web of Science. Later studies may choose to identify the intellectual structure from another perspective. However, the rigorous methodology used the selection of a reliable and comprehensive academic database, as well as a careful selection of keywords based on theory and

the extensive analysis carried out is considered as an important study that serves as a reference point for future research in the area of volcanic geomorphology.

**Supplementary Materials:** The following are available online at <http://www.mdpi.com/2076-3263/10/9/347/s1>, Table S1: Detail of the Keywords with the highest Co. occurrence, Table S2: Detail of the authors with the highest Co. citation, Table S3: Detail of the journals with the highest number of Citation.

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## Abbreviations

The following abbreviations are used in this manuscript:

CSV Comma-Separated Values  
CNES Center National d'Etudes Spatiales

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