geosciences

Review

Marine Geohazards: A Bibliometric-Based Review

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Abstract: Marine geohazard research has developed during recent decades, as human activities intensified towards deeper waters. Some recent disastrous events (e.g., the 2004 Indian Ocean and 2011 Japan tsunamis) highlighted geohazards socioeconomic impacts. Marine geohazards encompass an extensive list of features, processes, and events related to Marine Geology. In the scientific literature there are few systematic reviews concerning all of them. Using the search string 'geohazard*', this bibliometric-based review explored the scientific databases Web of Science and Scopus to analyze the evolution of peer-reviewed scientific publications and discuss trends and future challenges. The results revealed qualitative and quantitative aspects of 183 publications and indicated 12 categories of hazards, the categories more studied and the scientific advances. Interdisciplinary surveys focusing on the mapping and dating of past events, and the determination of triggers, frequencies, and current perspectives of occurrence (risk) are still scarce. Throughout the upcoming decade, the expansion and improvement of seafloor observatories' networks, early warning systems, and mitigation plans are the main challenges. Hazardous marine geological events may occur at any time and the scientific community, marine industry, and governmental agencies must cooperate to better understand and monitor the processes involved in order to mitigate the resulting unpredictable damages.

Keywords: marine geohazards; research evolution; scientific databases; trends; future challenges

1. Introduction

Geohazards are disasters induced by natural processes or human activity [1]. According to [2], marine geohazards include any feature or process that could harm, endanger, or affect seafloor facilities, risers, anchors, etc. Additionally, the facilities can be designed to avoid or withstand some geohazards. Marine geohazards can also be a local and/or regional site and soil conditions having a potential to develop into seafloor failure events, which cause losses of life or damage to health, environment, or field installations [3]. In this review, we will consider as a marine geohazard any and all features, processes, or geological events that affect the marine environment and are capable of damaging submerged and coastal infrastructures, causing the loss of human lives, including natural obstacles avoided during the planning phase of submarine pipeline and communication cable routes. Therefore, hurricanes, tropical storms, snowstorms, forest fires, typhoons, and floods represent natural disasters that do not fit into the concept of a geohazard used here.

Various geological processes and features can inflict hazards [4]. Some of them are well known due to their great destructive power. These include earthquakes, volcanoes, landslides, and associated tsunamis [5]. Others generally do not cause direct damage to societies but can affect engineered structures. These include pockmarks, mud volcanoes, and mobile bedforms [6–13]. Some manifest themselves on the surface of the seafloor, while others are concerned with processes that occur in the subsurface. This range of possibilities makes it uncommon for a single scientific peer-reviewed publication to investigate all categories of marine geohazards, except for a few conceptual or review articles [11,14,15].

Marine geohazard surveys have become increasingly relevant as exploration activities expand into deeper waters [4,16]. Some geohazards can generate damages to engineering structures, whose remediation is quite difficult, especially in very deep waters. Such difficulty justifies all efforts directed to geophysical surveys [17]. Generally, geohazard assessments are multi-disciplinary surveys, which involve expertise in geology, geophysics, sedimentology, geotechnics, fluid dynamics, and structural mechanics modeling [17,18]. To identify marine geohazards and the constraints on seabed infrastructure, the seafloor surface and subsurface data (bathymetry, seabed morphology, geology, geotechnical, and environmental assessments) must be combined [19,20].

In particular, for the marine industry, the geohazard surveys are essential for engineering the design, planning, and installation of infrastructures. Offshore drilling operations, especially those in deep water, are characteristically complex, expensive, and exhibit potentially challenging conditions [21]. At the beginning of the century, it was estimated that oil and gas companies spent around $20 billion annually on drilling and that nearly 15% of this amount was attributed to losses of material and days of work at sea [22]. Therefore, it is vital that drilling hazard preliminary assessments be performed with technical rigor, in the sense of identifying potential areas of shallow gas and any other geological limitations to drilling. Consequences of geohazards for drilling operations include loss of the rig from blowouts or punch-through, foundation scour, and shallow water flow.

The advancement of deep-water exploration activities, the uncertainties surrounding the consequences of climate change, the latest catastrophic events (e.g., the 2004 India Ocean and 2011 Japan tsunamis), and the human population densities in the world's coastal regions were responsible for the increased importance and awareness related to marine geohazard research. This context of the growing importance of marine geohazard surveys encouraged the use of bibliometric methods in order to register and analyze the evolution of peer-reviewed published scientific data related to this topic. These methods have been used to determine patterns of knowledge diffusion and scientific advances, based on the premise that scientific publications are the essential result of such activity [23]. In this way, the aims of this paper are to develop a bibliometric overview of this subject, discuss quantitative and qualitative aspects of peer-reviewed scientific publications related to marine geohazards and identify trends and future challenges. The purpose of this review is also to gather general information and important references concerning the diversity of marine geohazards in a single scientific publication.

2. Materials and Methods

Bibliometrics is the quantitative study of either physical published units, bibliographic units, or surrogates [24]. Therefore, bibliometric methods are used for providing quantitative analysis for written publications [25]. Currently, it is common to use scientific databases that allow searches across large collections of scientific publications in order to access these publications and to obtain further information about them [23,26–28]. These databases (for scientific articles) also offer the ability to download sets of articles that include information that is suitable for bibliometric analysis, such as references, the organizations the authors belong to, etc. Furthermore, bibliometric methods can be used to define trends within many areas and over extended periods of time [25,26].

A systematic review of peer-reviewed literature was undertaken to develop an overview of marine geohazards research based on scientific articles published in the Web of Science and Scopus. These databases are recognized for gathering a large collection of scientific publications and are, therefore, commonly explored in bibliometric analyses [29–32]. A systematic protocol was applied and allowed to answer the following questions: What was studied? By whom? Where? When? How? It is noteworthy that this review has a generalist character, i.e., is based on the search string 'geohazard*' to the detriment of all related features, processes, and events individually, e.g., 'Tsunami*', 'Submarine landslide*', etc.

The searches were performed on 05/26/2017 with the search string 'geohazard*' (title, keywords, abstract) and resulted in 570 and 816 results for the Web of Science and Scopus, respectively. The exclusion criteria were applied to papers related to terrestrial environments, articles that were not peer-reviewed (considered therefore as gray literature) and the duplicity (i.e., articles that appeared in the Web of Science and Scopus results simultaneously). Articles that could not be accessed were also eliminated from this analysis.

After the application of exclusion criteria, 183 peer-reviewed publications remained. This small number of publications allowed a detailed reading of each one, in order to extract the following data:

- Title of the Article;
- Year of Publication;
- Ocean;
- Geographic Scale;
- Depth Range;
- Type of Continental Margin;
- Number of Authors;
- Nationality of the First Author;
- Number of Institutions;
- Type of Institution of the First Author;
- Partnerships between Government, Academia, and Marine Industry;
- Perspective;
- Approach;
- Analysis, Instruments, and Techniques;
- Type of Marine Geohazard.

We do not present a complete overview of all case studies, but all of them were read by at least two co-authors and the collected data were grouped as Time and Space, Institutional Arrangement, Research Characteristics, and Geohazards, see Figure 1.

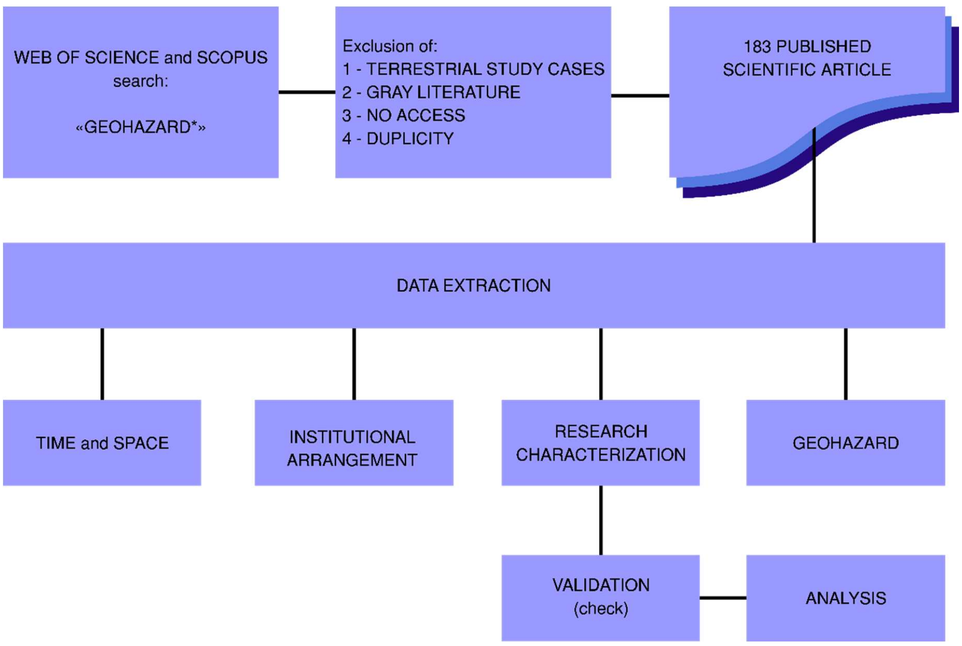

Figure 1. Methodological flowchart applied to the definition of the data set, extraction, and analysis of the information.

The data tabulated by pairs were crossed in order to check some disagreement between the co-authors and to guarantee a better quality of the obtained results. After this validation, the data were plotted and analyzed to identify trends and future challenges. Finally, it is worth mentioning that research on the evolution of marine geohazard was not restricted to the 183 articles rescued by the search protocol described here. This was because the concept of 'marine geohazard' is later than the first studies of events like submarine landslides, earthquakes, and tsunamis. Therefore, one limitation of this review was a partial inclusion of articles concerning marine geohazards. The definitions and protocols applied to each group of extracted data are described below.

2.1. Time and Space

The spatiotemporal distribution of the reviewed articles was investigated with regard to the number of publications per year, the country of the first author, the ocean studied, the type of continental margin analyzed, the geographical scale of the research, as well as the depth range involved. In order to determine the studied ocean, the 102 marine regions delimited by [33] and the Caspian Sea were grouped in 10 regions, see Figure 2.

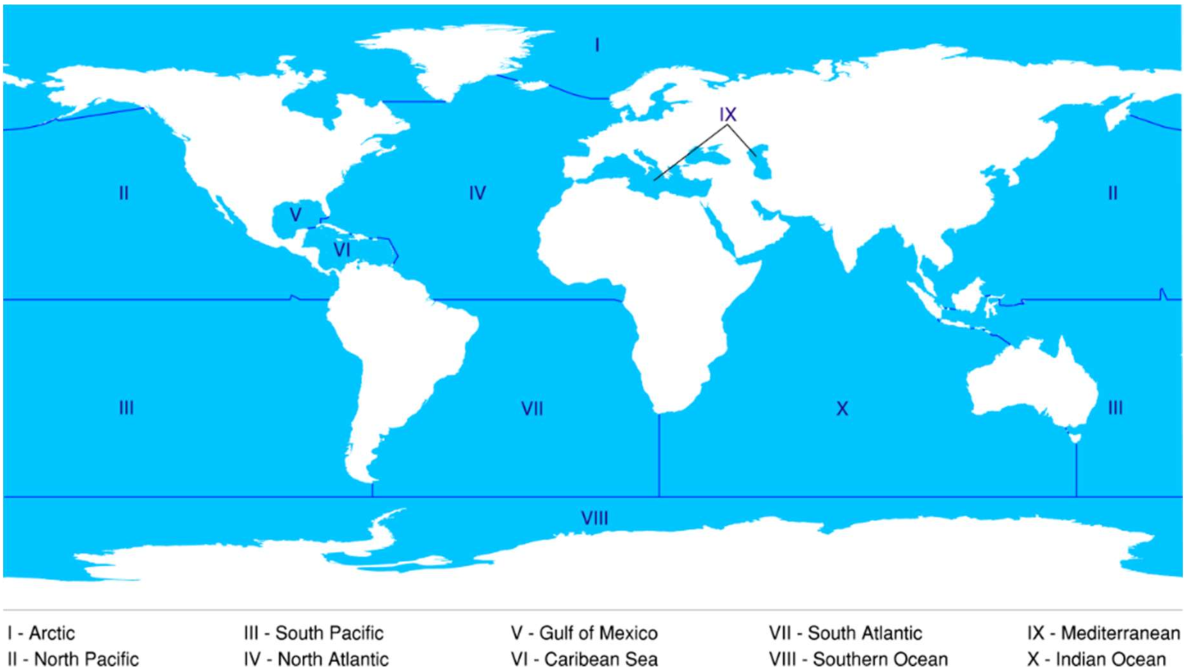

Figure 2. Ten marine regions delimited for analysis of the spatial distribution of marine geohazard surveys.

Additionally, regarding the spatial distribution of the marine geohazards studies, when possible, the information regarding the continental margin type (active, passive, or both) was registered. In the geographical scale, areas greater than 100 km^2 were considered a regional scale and smaller areas as a local scale. Regarding the depth range, depths up to 100 m were defined as shallow water, depths between 100 and 2500 m as intermediate waters, and depths greater than 2500 m as deep waters.

2.2. Institutional Arrangement

The analysis of institutional arrangements involved the determination of the number of authors and institutions involved in each article, as well as their nature (industry, government, or academia) and the occurrence of partnerships between these sectors. Co-authorship or any other type of support, such as specific software licenses, data collection, and analysis were characterized as a partnership.

2.3. Research Characterization

This characterization involved defining the research perspective as: Technical, Social, Economic, Environmental, or a combination of these. The protocol applied to do this included a standard, so articles that were related to tsunamis and earthquakes were compulsorily characterized as a Social perspective. Economic and Environmental perspectives were associated to peer-reviewed publications that mentioned any type of exploitation of energy or mineral resource, as well as if the article mentioned the conservation or protection of environmental resources or specific ecosystems, respectively.

Moreover, the publications were classified according to their approach as, conceptual, modeling, review, mapping, laboratory, geotechnical, geological dating, or a combination of these. According to the instruments and techniques involved, the classes were; i. Surface with acoustic methods (single and multibeam bathymetry, side scan sonar), ii. Subsurface with acoustic and other geophysical methods (2D and 3D seismic profiling, gravimetry, magnetometry, paleomagnetism, borehole), iii. Geological sampling (sediments, cores, wells, laboratory analysis, stratigraphy, dating), iv. Geotechnical: direct measurements (cone penetration tests), v. Reviews (concepts), or a combination of these.

2.4. Geohazards

The geohazards investigated in each peer-reviewed publication were registered and tabulated in order to evaluate their occurrence over the period in question. The frequency with which some marine geohazards were recorded in the articles analyzed was considered an indicator of the scientific effort focused to investigate a particular geological feature, process, or event. After registering them all, the geohazards cited in each article were grouped into distinct groups or categories according to their similarity. For example, outcrops, mounds, ridges, seamounts, and volcanic highs were classified as positive reliefs, in contrast, canyons, steep slope, channels, gullies, escarpments, and iceberg plow marks were defined as negative reliefs.

3. Results

3.1. Time and Space

The 183 peer-reviewed publications included in this analysis were published between 1982 and 2016, distributed irregularly with some discontinuities near the end of the 20th century. In each year, the minimum and maximum number of publications were 1 and 25, respectively. Viewing the publications frequency graph over the years, the occurrence of three distinct periods is evident, in which the trend in the volume of papers is shown to be increasing, see Figure 3.

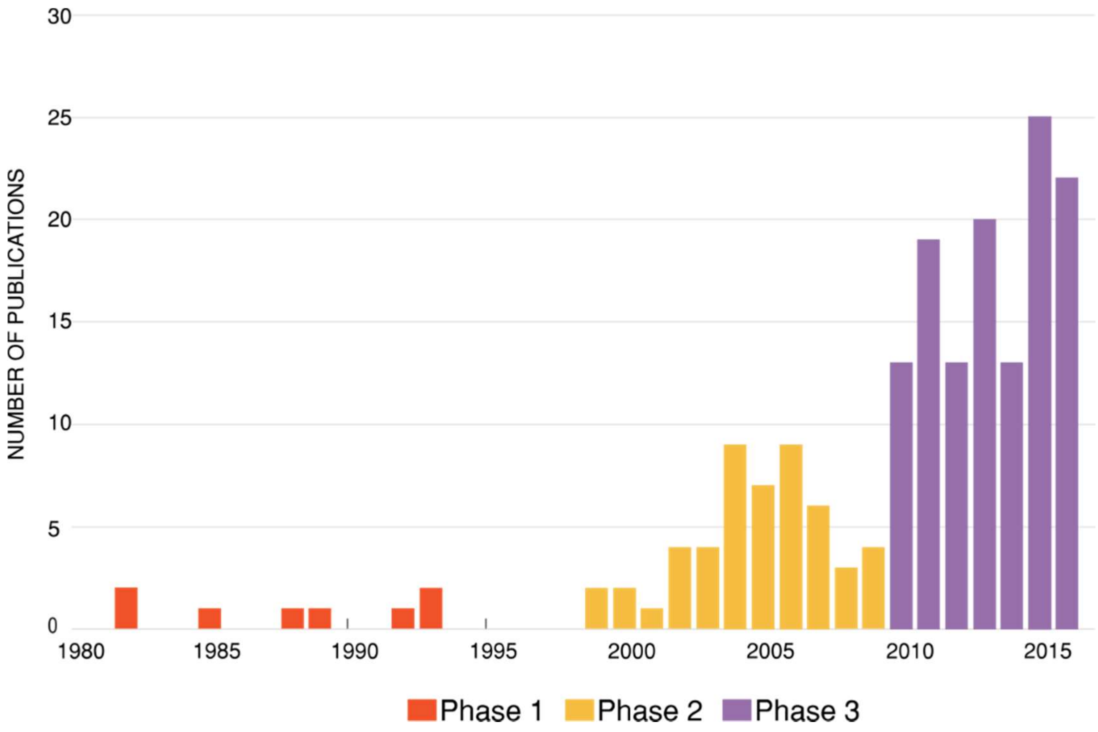

Figure 3. Number of peer-reviewed publications per year, between 1982 and 2016, indicating three distinct phases of scientific publications.

The country of the first author, contained in the address informed by the same, was attended by 24 different nationalities, among which the USA, UK, Norway, Italy, Germany, Canada, France, and Spain were the most productive, see Figure 4.

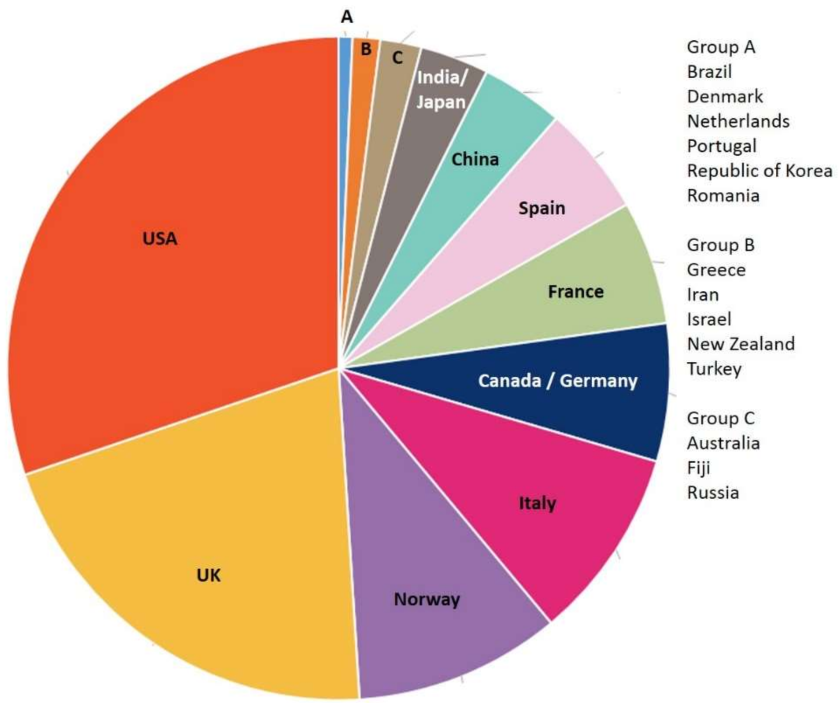

Figure 4. Number of peer-reviewed publications by country of the first author, between 1982 and 2016, indicating the predominance of USA, UK, Norway, Italy, Canada, Germany, France, and Spain.

The research was distributed across all 10 delimited regions and there was an emphasis on the number of surveys conducted in the Mediterranean (37), North Atlantic (31), Artic (22), North Pacific (21), and the Gulf of Mexico (17). Fewer scientific studies were found around Antarctica (1), the South Atlantic (4), and the Caribbean Sea (4), see Figure 5.

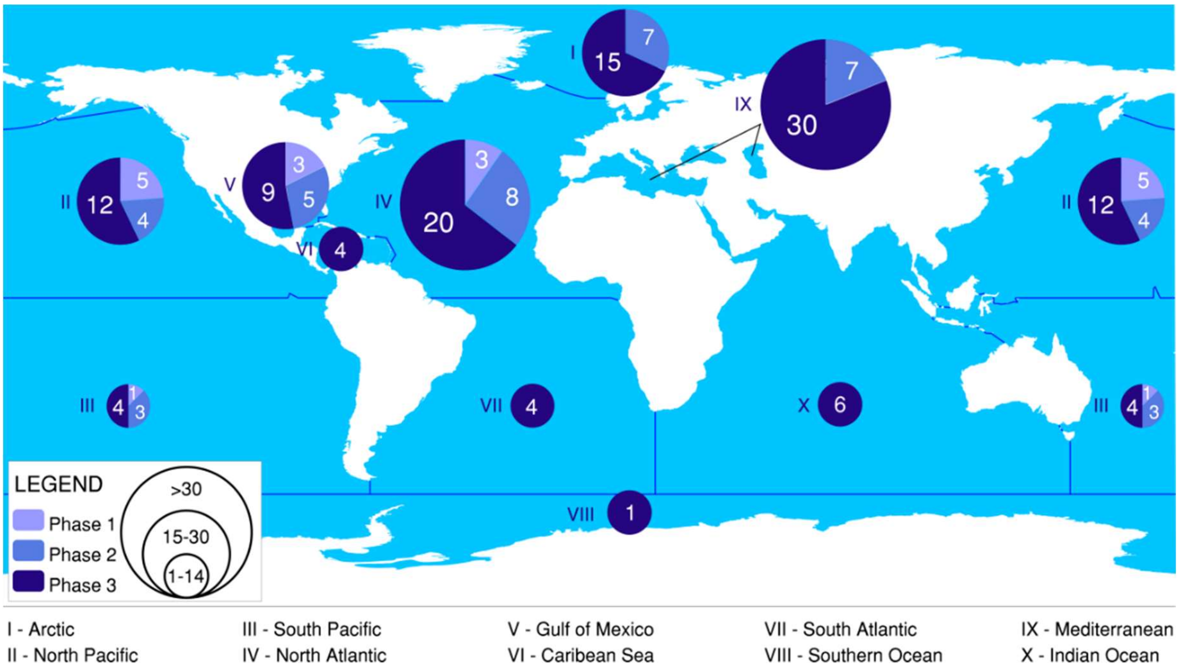

Figure 5. Number of peer-reviewed publications by oceans and seas between 1982 and 2016.

Regarding the types of continental margins, there was no predominance of either type, see Figure 6A. Surveys of marine geohazards were conducted in both active and passive margins. In an active continental margin, the hazards studied were usually related to earthquakes, subsidence, and tsunamis, events associated with converging plates. However, passive margins showed an occurrence of other groups of geohazards that include landslides, pockmarks, and gas hydrates.

In only 40% of the articles, it was possible to extract information regarding the geographical scale of the research, 32% were classified as a regional scale (with survey areas greater than 100 km^2), and only 8% of the articles covered areas that were smaller than 100 km^2 (local scale), see Figure 6B. In relation to the depth range, this information was obtained directly from only 40.27% of the 183 articles analyzed here. However, the articles that involved surveys between 100 and 2500 m (intermediate waters) stood out with 31.22%. Meanwhile, shallow water surveys (0 to 100 m) and deep waters (>2500 m) corresponded to 16.74% and 11.76%, respectively, as shown in Figure 6C. Peer-reviewed publications with marine geohazard surveys at depths beyond 3000 m are scarce, probably due to the costs and technical complexities involved in operations of geophysical and geotechnical surveys, see Figure 6D.

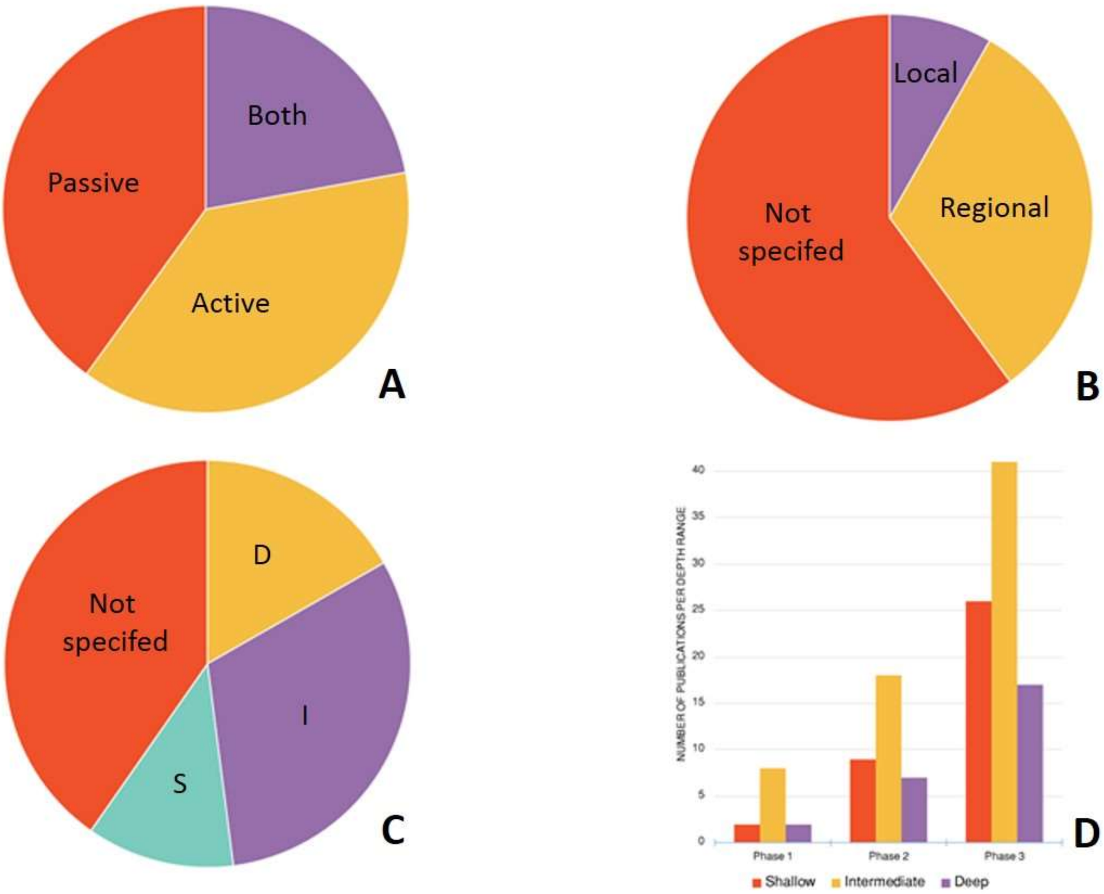

Figure 6. Qualitative and quantitative results of the spatio-temporal parameters. (**A**): Records of publications on different types of continental margins; (**B**): Records of publications on regional and local geographic scales; (**C**): Records of publications on shallow, intermediate, and deep waters; (**D**): Number of articles per depth range during three phases over the 35-year period analyzed.

The data indicated without doubt the growth, evolution, and territorial expansion related to the research on marine geohazards. The USA is the most productive country over the total period however there is an increase in the contributions of others countries, especially in recent decades. The increase in the participation of European countries is also remarkable. Marine geohazard surveys in the Mediterranean Sea were more frequent and this sea was the most studied, see Figures 5 and 7. For example, the publications by Italian authors revealed the impact of scientific efforts to recognize the geohazards along the Italian continental margin [34–41], one of the most seismically active regions in the central Mediterranean and the longest record of historical earthquakes in the world [41].

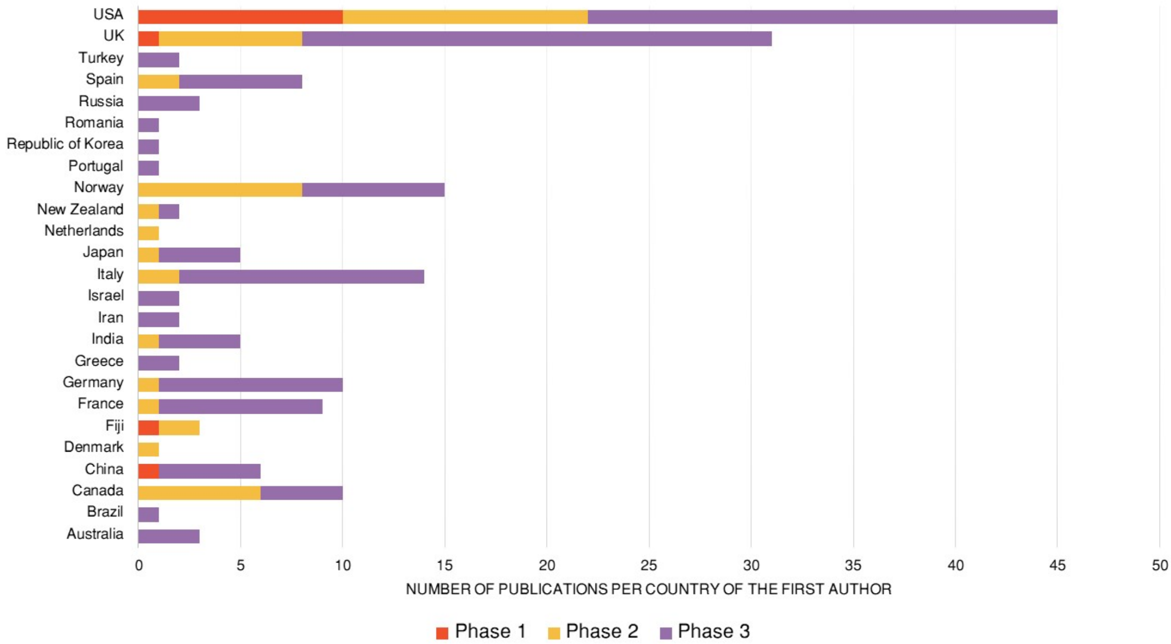

Figure 7. Number of articles per country of the first author during three phases over the 35-year period analyzed.

3.2. Institutional Arrangement

Regarding the composition of author's institutions, was assumed that the number and type of institutions in each publication was an indicative of efforts in a cooperation mode between industry, academia and government. The marine industry best practices require an imperative arrangement of interdisciplinary teams. Articles involving one, two, or three institutions were more common, 49.1%, 24.04%, and 10.38%, respectively, and articles with more institutions were scarce, see Figure 8A. Over the interval, the cooperation between institutions has become common, probably due the demand of integrated approach, common for marine geohazards surveys (Figure 8B). However, in relation to the number of authors, almost 50% of the publications had more than three authors, mainly in recent years (Figure 9). Regarding the type of institution associated with the first author, there was a predominance of academia (46.99%), followed by governmental institutions (33.33%), and to a lesser extent, by the industrial sector (16.97%) (Figure 10).

Finally, 44.8% of the articles did not involve a partnership between these sectors, while the partnership between two and three sectors was found in 43.16% and 12.02% of the articles, respectively, see Figure 11A. During the period analyzed, cooperation between academia, industry, and government became more common, see Figure 11B, probably as a way to overcome the difficulties imposed by the high operational costs inherent to these surveys. Since the 1990s, partnerships are consider fundamental in the development and progress of this area of research [3].

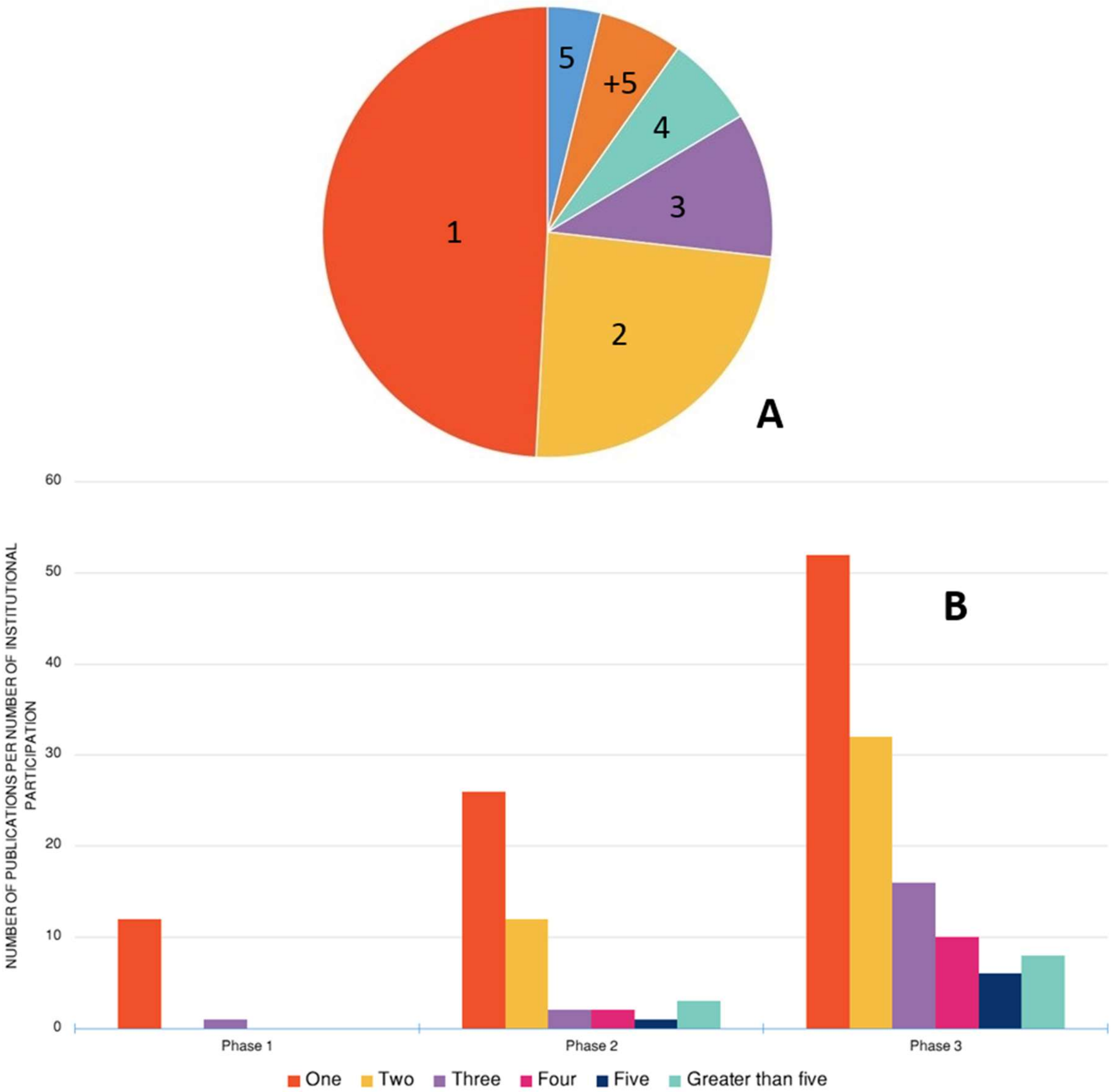

Figure 8. Qualitative and quantitative results of the institutional arrangements parameters. (**A**). Number of institutions in each peer-reviewed publications between 1982 and 2016. (**B**). Number of institutions in each phase over the 35-year period analyzed.

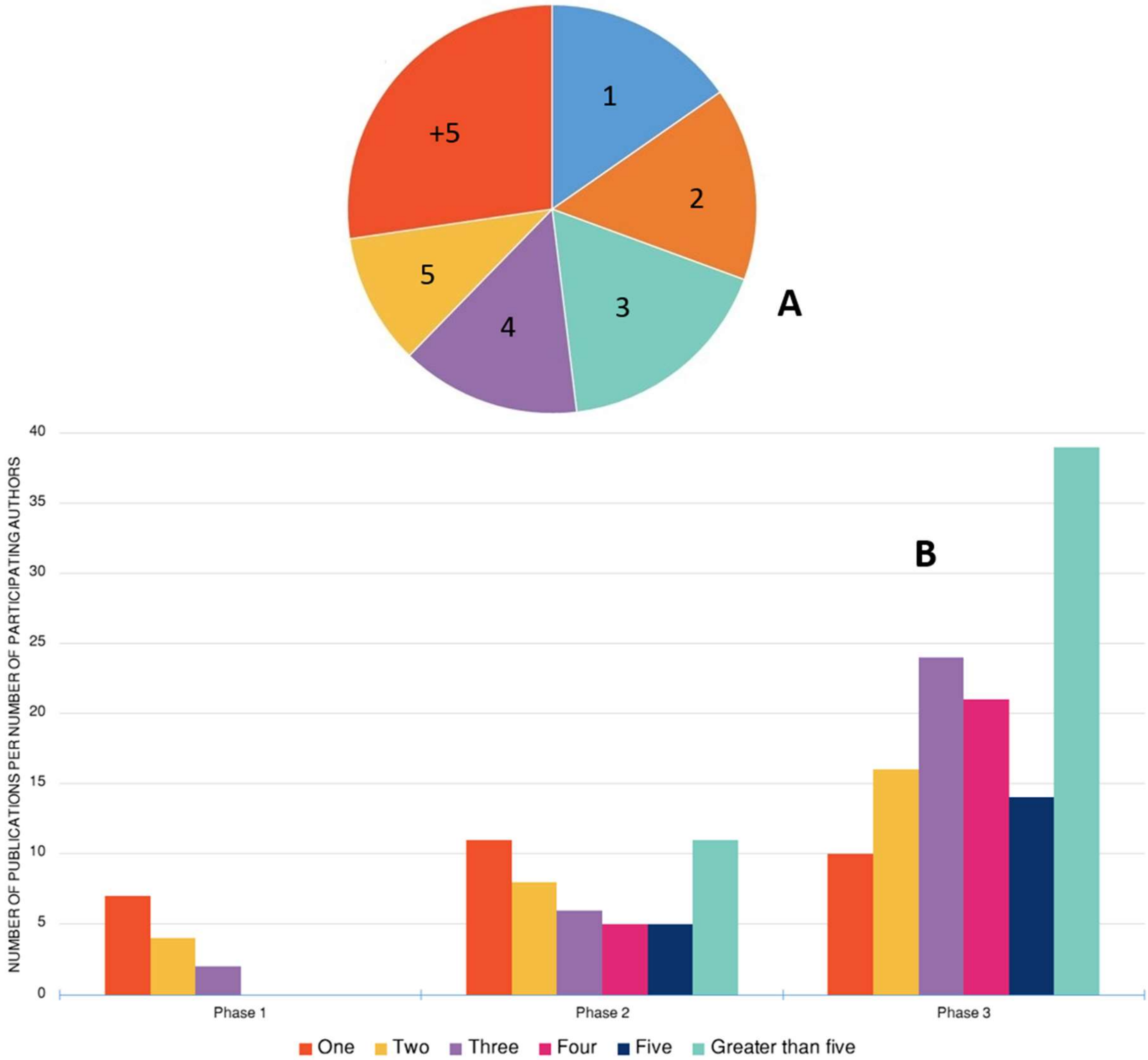

Figure 9. Qualitative and quantitative results of the institutional arrangements parameters. (**A**). Number of authors in each peer-reviewed publications between 1982 and 2016. (**B**). Number of authors in each phase over the 35-year period analyzed.

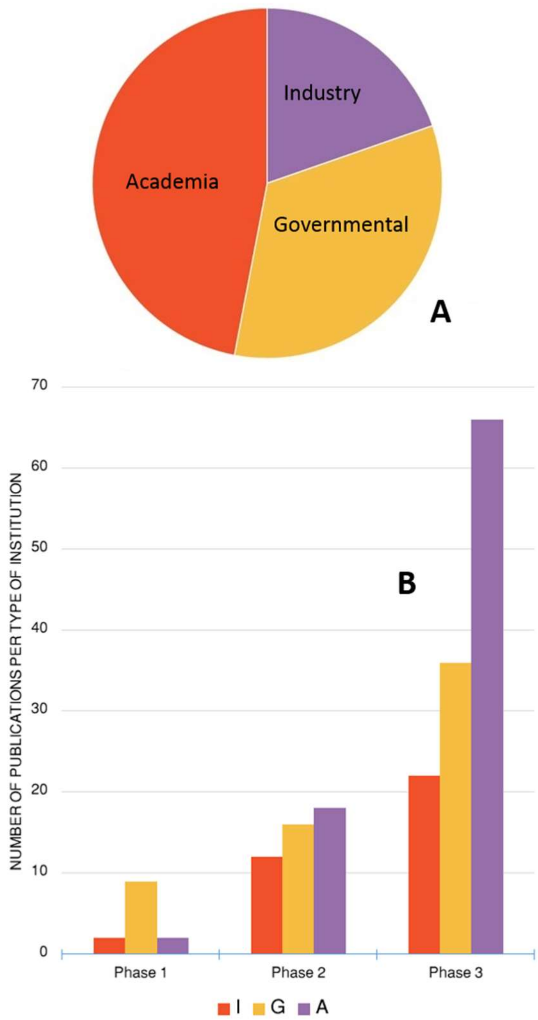

Figure 10. Qualitative and quantitative results of the institutional arrangements parameters. (**A**). Type of institution of the first author in each peer-reviewed publications between 1982 and 2016. (**B**). Number of each type of institution over the 35-year period analyzed.

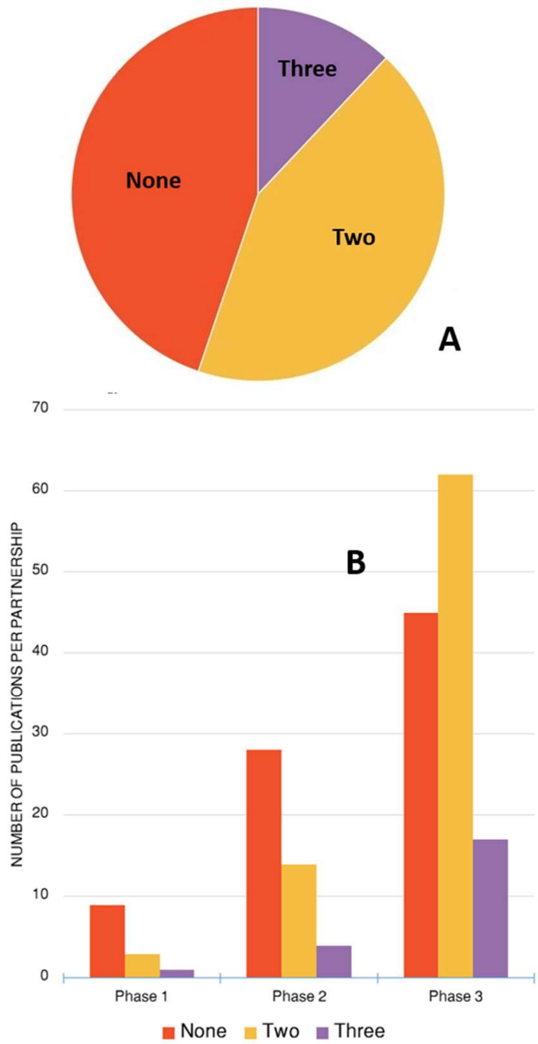

Figure 11. Qualitative and quantitative results of the institutional arrangements parameters. (**A**). Number of partnerships in each peer-reviewed publications between 1982 and 2016. (**B**). Number of partnerships over the 35-year period analyzed.

3.3. Research Characterization

In the analyzed articles, the technical and economic perspectives were highlighted to the detriment of the social and environmental perspectives, see Figure 12A. In relation to this approach, most articles that involved mapping, modeling, and review were registered; however, articles that utilized geotechnical measurements, conceptual, laboratory, and geological dating were rarer, see Figure 12B. Finally, with respect to the instruments and techniques, articles that involved geophysical techniques for subsurface and surface mapping, and geological sampling were predominant. The number of publications related to reviews, concepts and geotechnical aspects was smaller (Figure 12C).

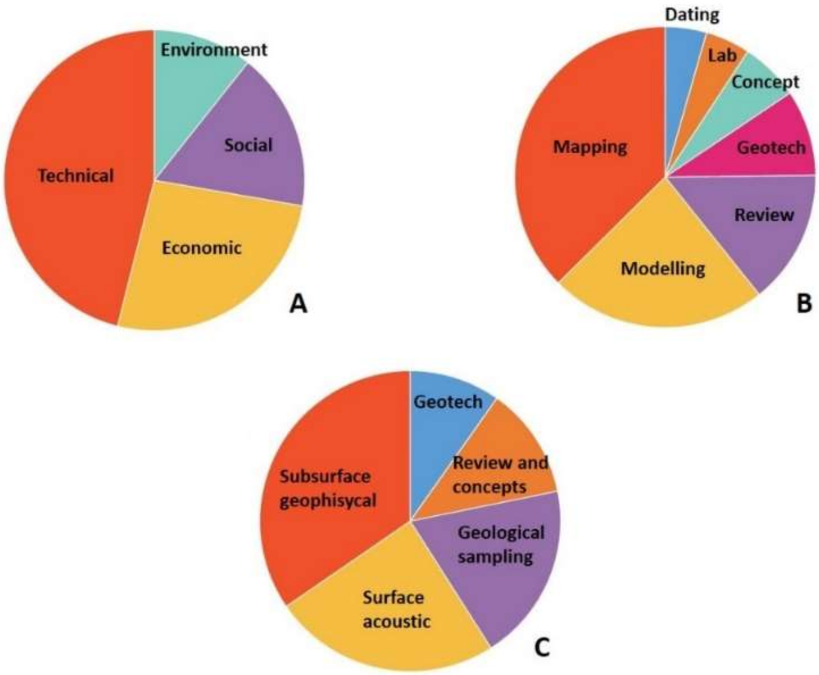

Figure 12. Qualitative and quantitative results of the research characterizations parameters. (**A**): Number of each perspective in peer-reviewed publications between 1982 and 2016. (**B**): Number of each approach in peer-reviewed publication between 1982 and 2016. (**C**): Number of each of the instruments and techniques in peer-reviewed publication between 1982 and 2016.

Regarding the perspectives, most of the analyzed publications presented technical and economic ones. In the first phase, many articles discussed the economical use of gas hydrates [42–47]. Only in the third phase did the number of articles concerning tsunamis, earthquakes, climate change, and marine conservation increased [48,49] (Figure 13). Marine geohazards have always existed; however, only with the advent of acoustic mapping systems they were recognized, systematically mapped, and studied. Therefore, over a long period, scientific papers presented approaches focused on mapping (Figure 14). Throughout the most recent decades, the number of articles concerning the development of mathematical models, geotechnical measurements, data collection in laboratories, and dating has become gradually more representative, which indicates the tendency for maturation of the discussions in this subject area. Throughout the 35-year period covered in this analysis, it is obvious that equipment and techniques have undergone improvement, and today it is possible to investigate marine geohazards with greater accuracy, precision, and resolution. However, during the 1990s, the number of articles that involved the seafloor surface and subsurface mapping were predominant, and there was ample use of acoustic methods for multi-beam bathymetry and high seismic resolution, see Figure 15. Geological sampling and geotechnical measurements were rare [46,47,50,51]. During the second and third phases, this scenario evolved in the sense that geological sampling, geotechnical measurements, and reviews became more common.

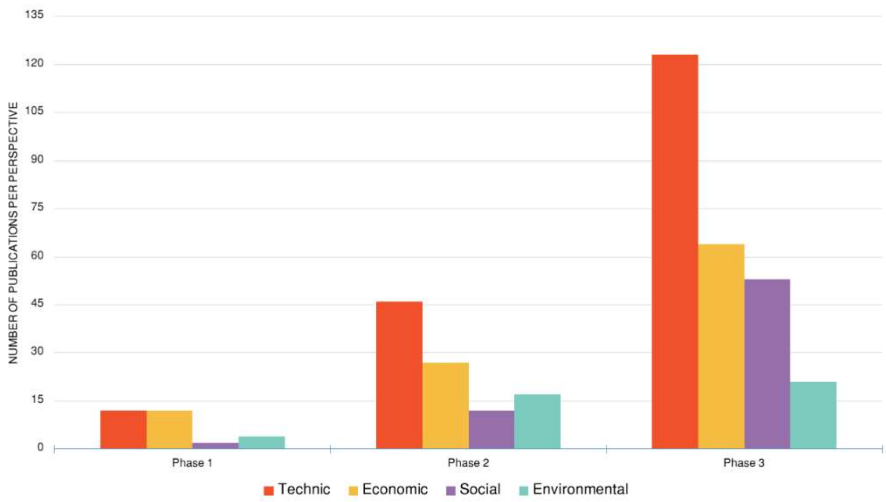

Figure 13. The number of each perspective in peer-reviewed publications between 1982 and 2016.

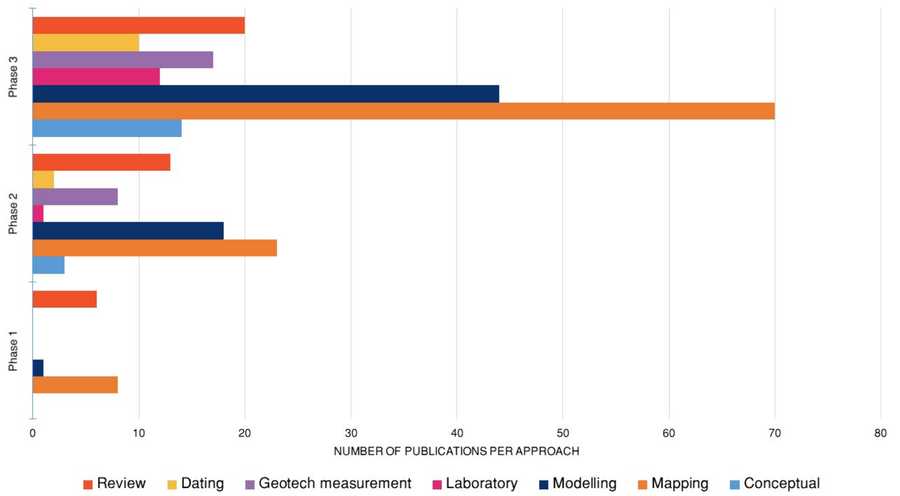

Figure 14. The number of each approach in peer-reviewed publications between 1982 and 2016.

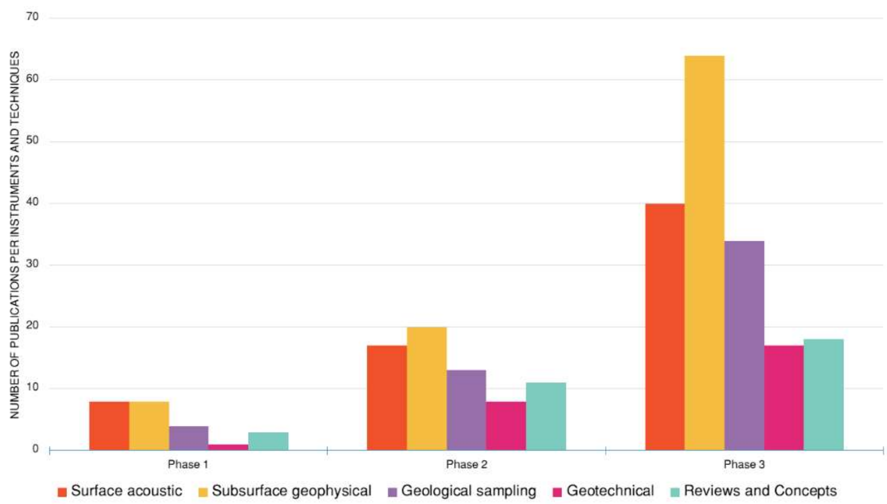

Figure 15. The number of each instrument and technique in peer-reviewed publications between 1982 and 2016.

3.4. Geohazards

There were 676 records of marine geohazards cited on the 183 peer-reviewed publications retrieved, which were expressed in a wide variety of geological features, processes, and events. According to their nature and in a generic way, the identified geohazards were grouped into 12 categories, see Table 1 and Figures 16–18.

Table 1. Categories of geohazards defined after the grouping of features, process, and related events with a similar nature.

Marine Geohazard Categories	Geological Feature, Process or Event
Slope failure	Creep, slumps, debris flow, mud flows, turbidity currents, landslides, slope failure, scars, scarps, slide blocks, slope instability
Fluids seepage	Pockmarks, gas chimney, mud volcanoes, shallow gas, charged sediments, gas hydrate, overpressured sands, shallow-water flows, seeps, free gas accumulations, fluid flow
Earthquake	Earthquakes
Tsunami	Tsunamis
Volcanism	Submarine eruptions, submarine volcanoes, flank collapse, volcanic tremor
Subsidence	Vanished islands, subsidence
Bedforms	Sediment waves, mudwaves, sandwaves, boulder fields, mobile sediments
Positive reliefs	Outcrops, mounds, ridges, seamounts, volcanic highs
Negative reliefs	Canyons, steep slope, channels, gullies, escarpments, iceberg plough marks
Diapirs	Salt bodies, diapirs, mud diapirism
Faulting	Faults
Erosion	Cliff erosion, beach erosion, submarine erosion

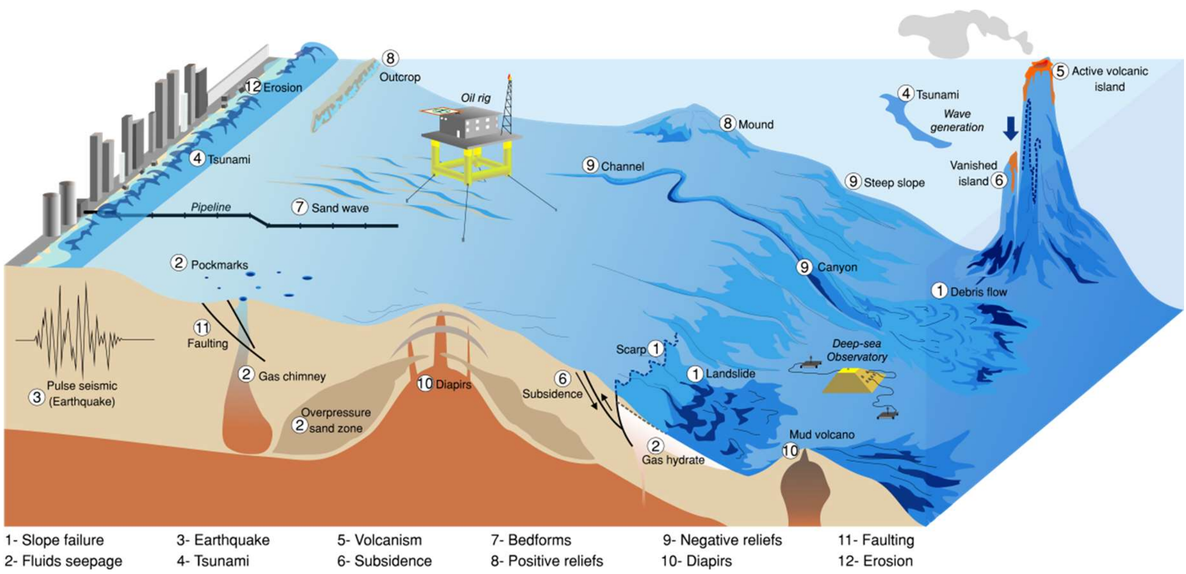

Figure 16. Categories of marine geohazards defined after the grouping of features, process, and related events with similar nature.

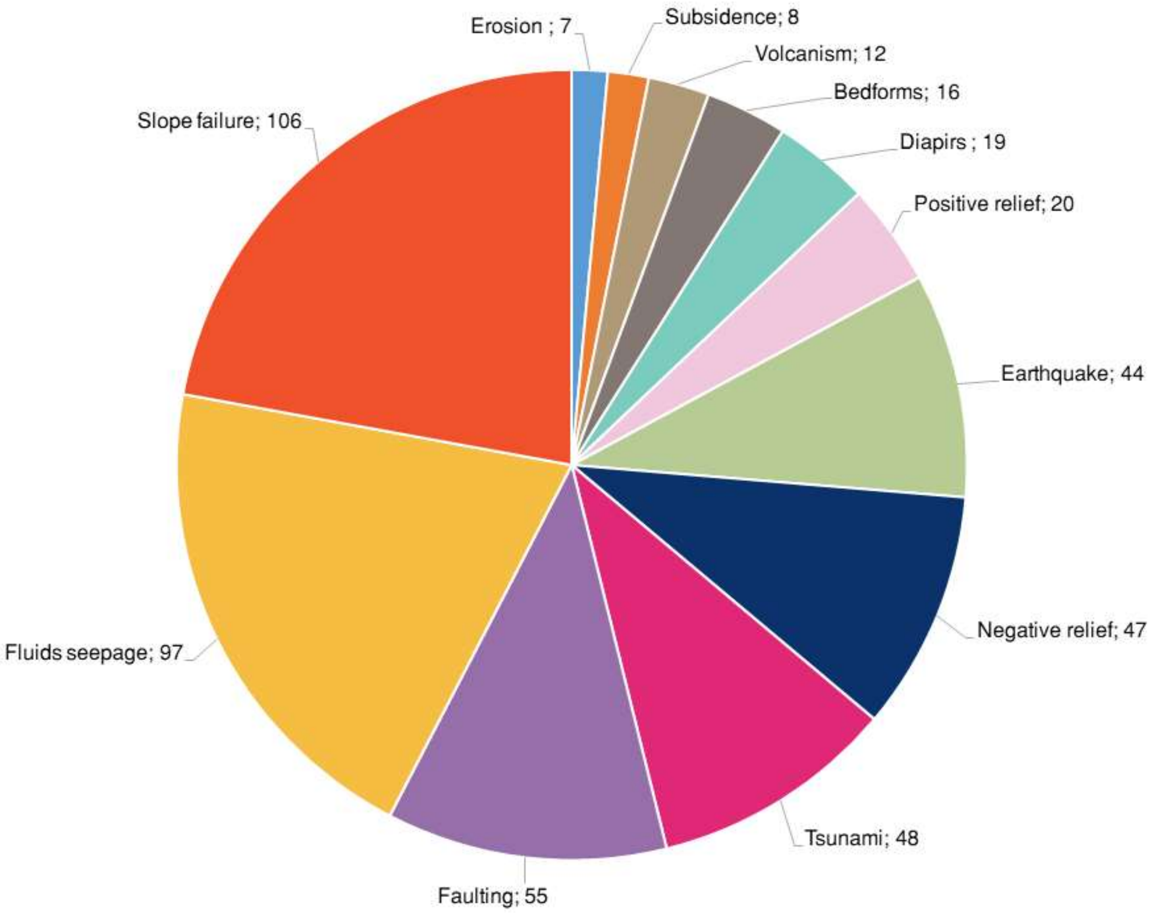

Figure 17. Number of publications between 1982 and 2016 for each category of marine geohazard.

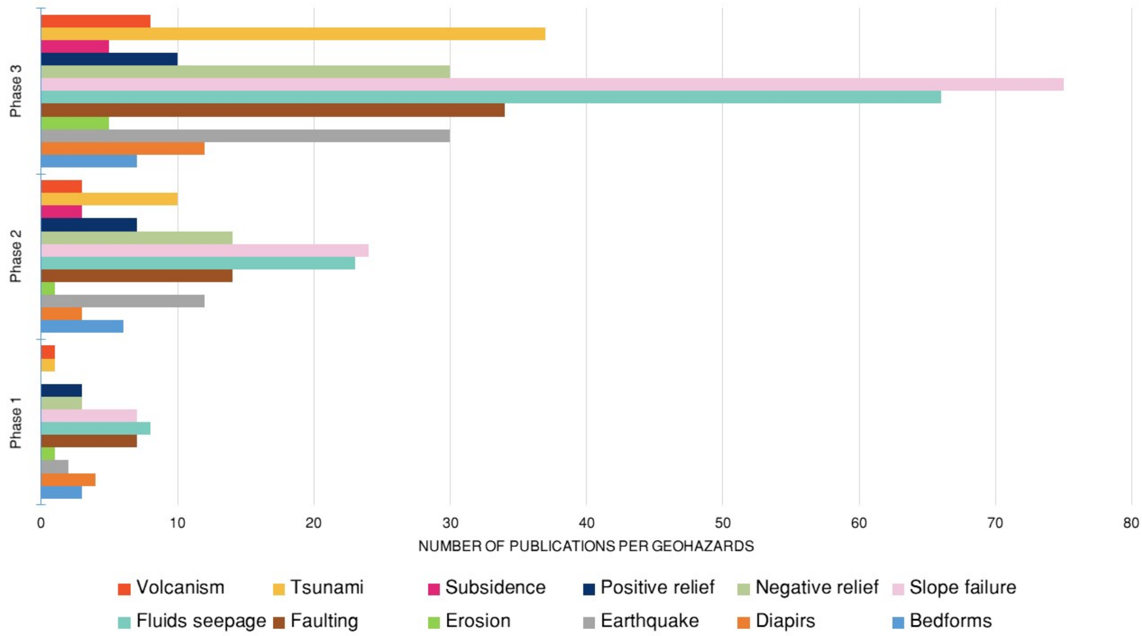

Figure 18. Number of publications per marine geohazard category during the distinct phases over the 35-year period analyzed.

The importance of the oil and gas industry in boosting scientific research that was related to marine geohazards is evident, primarily during the first phase, when most articles involved the study of fluids seepage, slope failure, faulting, and diapirs, as shown in Figure 16. To a lesser extent, these articles involved the investigation of bedforms, positive, and negative reliefs. The occurrence of studies on earthquakes, tsunamis, volcanism, and erosion was rare. By the second and third phases, diversification was the rule, with an emphasis on investigations on slope failure, fluid seepage, tsunami, faulting, negative reliefs, and earthquakes.

The categories are described below. Being in common, the interaction between more than one, that is, in some cases, a category described here is the trigger of another one, in a causal relation. Tsunamis, for example, can be generated by earthquakes, flank collapse of volcanic islands, as well as by slope failures. On the other hand, slope failures can occur due to earthquakes, volcanism, and fluids seepage. Earthquakes can trigger tsunamis and fluid seepage and tsunamis can lead to severe erosion in coastal areas.

3.4.1. Slope Failure

The original discovery of slope failures and turbidity currents in the deep ocean was made in the 1950s through an analysis of the breaks in transoceanic communications cables [52]. This geohazard was the most studied among the peer-reviewed publications and was cited in 22.23% of them, which is indicative of its widespread occurrence along continental margins and its socioeconomic impacts. For example, at present, a global fiber-optic cable network transmits more than 95% of communications and is subject to severe damage due to the occurrence of submarine landslides [52]. According to [52], the main factors that contribute to the initiation of submarine landslides are i. Rapid sedimentation rates, ii. Gas and gas hydrates, iii. Erosion, iv. Groundwater seepage, v. Tectonic activity, vi. Earthquakes, vii. Storm-waves, viii. Volcanic activity and ix. Human activity.

Since the early 1980s, national and international projects were related to the study of slope failures [53–55]. Due to their easy identification, their wide occurrence along the continental margins is increasingly evident [54]. Slope failures represent a major threat, not only to the marine industry but also to the marine environment and coastal facilities [1]. They can lead to substrata instability and produce catastrophic losses in deep-water drilling and deep-sea cable and pipeline construction [4,17,56–59]. Moreover, submarine landslides can generate devastating tsunamis [60–64].

Compared to subaerial landslides, the submarine failures generally occur with higher velocities, greater volume, and longer run-out distances [15,64,65]. These events play an important role in the evolution of continental margins as they represent an efficient mechanism of sediment transport from coastal to deep-sea [53,66]. The great scale of some continental slope landslides may be due to the long and continuous slopes found on these margins and due to extensive weak horizons in the layer-cake stratigraphy [64]. However, submarine landslides are not restricted to areas of steep slopes and may occur on surfaces with a slope of less than 2° [67–69].

3.4.2. Fluids Seepage

Seabed fluid flow is the second most investigated category of geohazard in the analyzed publications (20.25%) and is known by humans for centuries [70]. Generally, such processes include the leakage of water, light hydrocarbons (in particular methane), and/or sediments. The use of acoustic techniques to detect gas emissions escaping through the seabed into the water column has dramatically increased in recent decades [71], and several pieces of seismo-morphological evidence are recognized to support fluid flow [72]. Evidence of this marine geohazard includes surface features, such as pockmarks, carbonate mounds, and mud volcanoes, and also subsurface features, such as gas chimney, gassy sediments and gas hydrate, and even by acoustic 'plumes', 'flames', and 'clouds' in the water column [70,71,73].

Pockmarks are depressions on the seabed with underlying fluid conduits such as gas chimneys and faults [74]. King et al. [75] used the first acoustic mapping system and published the first scientific paper related to pockmarks. Pockmark dimensions range from a few meters to 300 m or more in diameter and from 1 m to 80 m in depth [76]. Pockmarks are common, both in shallow and deep water, in deltas, estuaries, and even in some lakes [77]. The occurrence of pockmarks is an indication of shallow fluid flow activity, which constitutes a potential geohazard to hydrocarbon exploration and production activities [7,9,12]. According to [13], the presence of pockmarks should be taken into consideration when installing the anchors of drilling vessels and offshore platforms because pockmarks may indicate the presence of gas and may contain hard carbonate skins.

Another feature related to fluid seepage is mud volcanoes, which are geological structures formed due to the emission of argillaceous material on the Earth's surface or the seafloor [78,79]. Submarine mud volcanoes occur in both active and passive margins [6,8,10] and are related to the upward migration of over-pressured fluids, which cause liquefaction of mud-rich units, and episodic extrusions of solids, liquids, and gases [80,81]. There are large variations in the size and geometries, as well as the sources, of fluids and sediments expelled by mud volcanoes [78,82]. Mud volcanoes can have discrete eruptive events or periods of eruption that expel massive amounts of fine-grained sediments in periods that last for hours or centuries [79]. These events are potential geohazards for deep-marine infrastructures [10], as they may affect drilling operations, ring installations, and pipeline routings [4,8].

Pockmarks and mud volcanoes are the superficial expression of seabed fluid flow and are related to chimneys and geological faults [83]. However, there are situations in which the gas contained in the subsurface does not find trajectories for escape, which sets a dangerous scenario, especially for drilling operations. Usually, shallow gas is a term used to characterize the gas buried in shallow sediments [84,85]. Shallow water flow is a term used by the offshore oil and gas industry to define the flow of sand and water mixtures into wells and blowouts of water that is driven by high pressure after drilling hits over-pressured sand layers. According to [86], shallow gas identification and assessment is one of the most important tasks in a geohazard evaluation. Gas in the shallow subsurface can undermine an offshore structure, or cause a gas blowout that can result in property and investment losses and loss of life.

Another important feature that is related to fluid seepage is gas hydrates, which are an ice-like crystalline compound that is formed by gas and water molecules under low temperatures and high pressure [87]. Based in scientific ocean drilling, research on coring and downhole logging operations, carried out by the Deep Sea Drilling Project (DSDP), Ocean Drilling Project (ODP), International Ocean Drilling Project (IODP), government agencies, and several consortia, has significantly improved our understanding of how methane hydrates occur in nature [88].

Gas hydrates are considered a potential energy source and a source of methane, a greenhouse gas that affects climate changes and marine geohazards [51,89,90]. The risk posed by gas hydrates is related to their dissociation ("melting"). Theoretical and laboratory evidence suggests that dissociation of gas hydrates will result in increased fluid pressure, dilation of the sediments, and the development of gas bubbles, all of which will substantially weaken the sediments and could be responsible for the triggering of submarine slopes failure [89]. However, more work is needed to create a better understanding of the impact of hydrates on safety and seafloor stability, as well as to provide data that can be used by scientists to study climate change, geohazards, and to assess the feasibility of methane hydrates as a potential future energy resource [88]. In deep-water oil and gas exploration and development, gas hydrates are an important risk to drilling wells and platform stability. Gas hydrates in shallow sediments can trap fluids and destabilize slopes, posing a potential risk to industrial well drilling operations and installations [74,91].

3.4.3. Earthquake

An earthquake is a sudden movement of the Earth crust, caused by an abrupt release of strain that has accumulated over a long period. This marine geohazard was investigated in 9.2% of the analyzed dataset. Earthquakes are geological events that were recognized even in ancient times, in all cultures. According to [92], the earliest register of an earthquake was in the 23rd century B.C. in China. The hazard from earthquakes is primarily due to large (typically a magnitude of 6.5 or greater) earthquakes [93]. Earthquakes are among the most damaging events caused by the Earth and pose a serious threat to lives and property for urban areas near major active faults on land, or subduction zones offshore [94].

Earthquakes and their related hazards are predicted to have claimed >2.5 million lives during the 21st century [95], and their predictions represent a scientific problem worldwide [96]. This marine geohazard deserves its prominence because, depending on the magnitude and depth of an earthquake, it can trigger slope failures [97], tsunamis [98], and gas seepage [7,99].

The Sumatra-Andaman earthquake on 26 December 2004 occurred at a depth of 30 km and lasted for about 10 min, which generated one of the most devastating tsunamis in recorded history. More than 283,000 people have been killed in the coastal regions of 13 Indian Ocean countries [100].

The 2011 earthquake, off the Pacific Coast of Tohoku (2011 Tohoku-oki), was also one of the largest earthquakes in recorded history and had a moment magnitude (Mw) greater than 9 [101]. The earthquake generated a large and destructive tsunami that hit the Pacific coast of NE Japan and caused extensive damage. In addition, earthquakes can generate local damage such as cable breaks [97,102] and, in the case of tsunamis, impact distant regions on another margin of an ocean basin.

3.4.4. Tsunami

This marine geohazard was investigated in 10% of the articles reviewed and mainly in those published after 2010. Tsunamis occur infrequently compared to many other natural hazards [98]. The converging margins around the world are major areas that generate the most devastating earthquakes and tsunamis [103]. Earthquakes [100,101] caused the most destructive tsunamis in recent history, however, in some parts of the globe the major causes of catastrophic tsunamis were non-seismic and included landslides, volcanic activity, atmospheric disturbances, and meteorite impacts [98].

Massive submarine landslides register on active and passive continental margins, and tsunamis that occurred without an earthquake event stimulated investigations concerning slope failures as a potential contributor to tsunami generation [63,104–109]. However, there is still much controversy regarding the tsunamis triggers, as earthquakes and fault ruptures that are not very intense can generate submarine landslides that can generate tsunamis [98,110–114].

3.4.5. Volcanism

Discussed in 2.5% of the dataset analyzed, this category of marine geohazard is related to submarine eruptions and volcanic island flank collapse. Shallow seamounts and volcanic islands may eventually be subject to underwater eruptions as the volcanic edifice evolves [115–117]. Explosive activity at seamounts may begin at abyssal depths, but it is most pronounced at eruption depths that are shallower than 700 m [115]. During this process of growth, destructive periods also occur, which are related to the eventual collapse of the flanks in the volcanic edifice [118]. The cause of these collapses is due to the continuous accumulation of volcanic material that at some point renders the slope unstable [119,120].

This dynamic is responsible for the common occurrence of features that are related to landslides along volcanic islands, such as Hawaii [121–123], Réunion Island [124], Canary Islands [125], and Cape Verde Islands [126,127]. According to [115], collapse features are most prominent in the largest seamounts and islands with well-established and long-lived magmatic plumbing systems. Such events result in catastrophic tsunamis that may have run-ups that reach inland to localities up to 400 m above sea level, which constitutes a major ocean-basin-wide natural hazard [120,128].

A key question regarding tsunami generation is whether volcanic island landslides occur in a single stage or multiple stages [118]. If gaps in time of even a few minutes separate discrete stages of failure, then the tsunami magnitude is reduced greatly [124]. Models simulate the resulting tsunami generation and propagation [129–134].

3.4.6. Subsidence

This category of marine geohazard was mentioned in only 4.3% of the analyzed articles and was related to two different geological processes. One of them is the characteristic subsidence of converging continental margins that is responsible for the long-range phenomenon known as vanished islands, which is common in the Pacific Ocean [135,136]. Another process is the subsidence of coastal areas (such as the deltas) exposed to a high sedimentation rate [137]. The impact of this geohazard is slow and gradual, generally with a reduced potential for material damage and loss of life.

3.4.7. Bedforms

Discussed in 3.3% of the analyzed articles, this category of marine geohazard is related to environments exposed to hydrodynamic forcing (wind-driven, tidal, and thermohaline currents), capable of generating mobile bedforms [138,139]. Mobile bedforms are of critical engineering importance in the placement of submarine pipelines and cables [140]. According to [141], the presence of mobile bedforms implies specific challenges because the stability of a marine pipeline, which is exposed to lateral currents, is one of the major concerns of the pipeline engineer. These challenges also include the potential exposure, or undermining, of buried foundations, the development of free-spans beneath pipelines, and excessive burial of thermally sensitive power cables [142–144].

3.4.8. Positive Reliefs

This category of geohazard was quoted in 10.9% of the scientific articles and is represented by positive topographic features such as reefs, outcrops, beachrocks, mounds, and ridges. These features represent natural obstacles that should be avoided in engineering projects that involve the definition of pipelines routes, telecommunications cables, or any other infrastructure to be installed next to the seafloor [141,145].

3.4.9. Negative Reliefs

This group of marine geohazard is related to channels, canyons, gullies, and steep slopes, and was discussed in 9.8% of the articles reviewed. Some topographic features pose risks to pipelines and submarine cables and the cable route should, as much as possible, avoid them [146]. Negative reliefs, especially on the continental slope, are considered conduits for sediment transport, and evolve through geological time, channelizing sediment gravity flows that are derived primarily from the canyon head or canyon flanks failures [147]. Therefore, submarine canyons and channels are commonly associated with slope failures [148–150], sediment gravity flows [151,152], and mobile bedforms [153].

3.4.10. Diapirs

Mentioned in 10.3% of the articles analyzed, salt and mud diapirs are intrusions of sedimentary rocks into the overlying sedimentary sequence that usually imply deformations in the seafloor [154]. Several salt provinces are located on passive continental margins (e.g., the Gulf of Mexico, numerous West African margins, the margin offshore Brazil, and the margin offshore Nova Scotia) [155].

The loading of the overlying sediment is responsible for the deformation of the salt flow and its direction toward the surface (through the sedimentary layers) as fingers of salt (diapirs). Salt diapirs may generate outcrops (salt domes) on the surface of the seafloor, which, in turn, may interfere with the stability of engineering structures. However, in addition to these positive reliefs, salt tectonics are also responsible for the formation of structural lows, which is caused by salt or shale evacuation: mini-basins [156]. The relief that is related to salt diapirism processes is, therefore, irregular and prone to deformations, which imposes challenges to the installation of engineering structures.

Another risk associated with salt diapirs is associated with drilling operations, since evaporitic rocks present great mobility when submitted to large deviatoric tensions and elevated temperatures, which can lead to (during the drilling phase) well closing, drill column entrapment, and the creation of mechanical stops, and caves by salt dissolution by drilling fluid [157].

Mud diapirs/volcanos are also related to this group and are commonly produced by the release of high-pressure fluids [11], which can seriously reduce sediment shear strength and cause shallow sediment deformations that affect seabed installations and trigger submarine slope failure [74].

3.4.11. Faulting

Discussed in 11.5% of the analyzed articles, this group of marine geohazard is related to tectonic events, which can trigger earthquakes and tsunamis [158]. Active faults are susceptible to ground surface ruptures that can compromise pipelines and submarine cables [159,160]. Seabed forms that indicate pre-existing seabed instability, surface displacements, or fluid escapes are conditions that pose a significant risk to oil and gas exploration and development can result in construction and operational problems if not properly investigated, assessed, and mitigated [161]. Therefore, active failures have been mapped and investigated to determine the level of their activity (recurrence times, displacements, slip rates) in the context of seismic hazard assessments [114,162–168].

Some ground surface ruptures may be due to halokinesis, which are called salt-influenced faults [169–171]. According to [172], these faults, in the context of the oil and gas industry, (1) pose significant difficulties during borehole drilling, (2) increase local risks in terms of local slope stability, and (3) may generate fluid-migration paths that potentially contribute to the escape of hydrocarbons in evolving reservoir units to growing diapirs. Under these circumstances, it is also common that failures are associated with fluid seepage [83,86,99,173–175]. Sub-surface fault zones may provide preferential conduits for gas migration, or may be hydraulically active during (or shortly after) earthquakes [99].

3.4.12. Erosion

Discussed in only 1.5% of the analyzed articles, this group of marine geohazard was related to: (1) coastal cliff and sandy shore erosion and retreat [15,176–180], (2) the processes of evolving canyons, slumps, and submarine landslides [13,181,182], and (3) coastal areas subject to possible tsunamis [183–185]. Tsunamis, beyond their obvious role in the tsunami hazard, can cause significant changes in the coastal morphology and/or the coastline and, therefore, have implications in the processes of erosion, transportation, and coastal sedimentation, which leads to modifications in the erosion hazard and morphology of the coastal zone [184].

4. Discussion

In the period between 1982 and 2016, the main trend in marine geohazard research was the gradual increase in the number of articles that resulted from cooperation between authors and institutions, and a partnership between industry, academia, and government agencies. The few peer-reviewed articles during the period prior to the 1990s are probably related to the reduced number of institutions and researchers interested in publishing and/or reviewing scientific papers concerning the topic. A marine geohazard is a relatively recent term which emerged as an initiative to bring together several features, processes, and events in a single concept, although earthquakes, tsunamis, and submarine landslides have been the subject of studies prior to its popularization.

This systematic review evidenced a territorial expansion, evolution, and improvement of the techniques and equipment related to research on marine geohazards. The state-of-art consolidation also included the awareness of the scientific community, industry, and decision makers concerning the importance of this topic. In this scenario, national and international initiatives have emerged in arrangements based on the cooperation to study and monitoring of marine geohazards [15,186]. No doubt, this strategy fostered the sharing of knowledge and made it possible to investigate geohazards in different geological settings [1]. Another aspect of the evolution of research on marine geohazards was the diversification of approaches, instruments, techniques, and analysis that occurred over the decades.

The United Nations Convention on the Law of the Sea (UNCLOS) was of great importance to leverage the development of research on marine geohazards. After its rectification, deep, towed sonar systems and multi-beam echosounders were used for the successful mapping of topographic features that were never before mapped [187,188]. In 1969, the GLORIA (Geological Long-Range Inclined Asdic) system was developed by the British Institute of Oceanographic Sciences (IOS) and was, at that time, the only available mapping system applied to seafloor characterization. It was responsible for mapping some regions of the USA continental margin. This effort produced maps with a scale of 1: 500,000 and revealed the occurrence of, i. Submarine fans and their distributary channel system, ii. Large bedforms fields, iii. Submarine volcanoes, iv. Fracture zones, v. Salt diapirs, vi. Submarine landslides, vii. Submarine canyons, viii. The Puerto Rico Trench, ix. Fluid lava flows, and x. Volcanoes flank collapse.

Advances and improvements in data acquisition, recording, and replay system, which included simple image-processing techniques, were fundamental to guarantee the detection of objects or patterns in a digital image for either visual interpretation or digital classification [188–190]. The development of the Towed Ocean Bottom Instrument (TOBI) was another advance in terms of resolution of the acoustic images, which was used to map geohazards [191–194].

The development and enhancement of multi-beam echosounders were responsible for registers of new morphological and textural seabed attributes that led to the discovery of new geological features and processes [195]. In May of 1977, the first non-military version of a multi-beam, wide swath, deep ocean, and bathymetric sonar was put in service and some years later a shallow water version was offered to the market [187]. This technology replaced the mono-beam echo sounders and allowed seafloor mapping with resolution, spatial coverage, and unprecedented precision, which consolidated the multi-beam as one of the main geophysical tools to investigate the seafloor morphology [196,197].

Side scan sonar systems and echosounders are, therefore, widely used hydroacoustic tools for surface characterization. However, this data should be complemented with subsurface data in order to identify marine geohazards that include faults, gas chimney, salt diapirs, shallow gas, and gas hydrates. In this sense, in the last three decades, there has been an evolution of seismic equipment, processing, and interpretation tools. According to [86], these geophysical tools evolved as the needs of the industry evolved. The development of swept frequency (chirp) sub-bottom profiling systems, 3D seismic, and high-resolution 2D and 3D seismic systems was responsible for an increase in the number of the tools available to analyze the seabed and subsurface.

3D seismic acquisition systems have a good resolution, which turned them into a tool for regional reconnaissance as well as a tool for field development during the 1990s. This has resulted in nearly complete coverage for areas under active exploration [198]. The 3D seismic data processing has since evolved to facilitate the detection of the presence of gas in the subsurface [86,199–201]. Chimney detection indicates the location of the origin of hydrocarbons, how they migrated into a prospect, and how they spilled or leaked from this prospect and created shallow gas pockets, mud volcanoes, and pockmarks near and on the seabed [202,203]. Studies [204,205] present the advantages and disadvantages of using 2D and 3D seismic systems in conventional and high-resolution (HRS) modes. It is evident that the investment in development and the improvement of these technologies is justified by the damages caused by accidents and the loss of wells that were caused by blowouts and shallow water flows.

Still, in relation to the hydroacoustic tools, a relatively recent trend is the development of Autonomous Underwater Vehicles (AUVs) for geophysical surveys [206,207]. Currently, AUV surveys are the most efficient way to map the details of seabed conditions in deep water [208]. AUVs are multi-sensor instruments which can include multi-beam echosounder, side-scan sonar, and subbottom profiler systems, however, still cameras, lidar scanners, magnetometers, and geochemical (CO2, CH4, PAH, and dissolved oxygen), temperature, and salinity sensors could still be added. More recently, several 4D AUV surveys have been carried out [208–210], which allows the analysis for the evolution of geohazards over short periods (years).

The hydroacoustic tools discussed here are examples of indirect sampling methods. However, it is necessary to point out that direct sampling amplifies the scientific questions that can be answered because they allow the determination of geologic structures and biostratigraphy, measure physical properties, and up to date past events, like submarine slides and tsunamis [19,211]. In this context, the Integrated Ocean Drilling Program (IODP) has contributed greatly through the provision of dedicated vessels for scientific ocean drilling and collecting core data around the world [212–215].

Another important set of equipment and techniques used by the marine industry are the geotechnical investigations carried out on the surface of the sea floor and through drilling operations [20]. Samples and geotechnical data provide the ground-truth and essential parameters for hydro-mechanical modeling and engineering applications. Geotechnical investigations that combine laboratory and in situ tests allow for a reliable and comprehensive analysis of sediment strength, deformation, and flow properties as well as a pore pressure regime [11,216]. The characterization of soil conditions (type, layering, undrained shear strength in clayey soils, and relative density and internal friction angle of sandy layers) is essential for the design of offshore structure foundations [20].

It is evident that studies involving a hydroacoustic surface and subsurface mapping, coring, dating, and geotechnical measurements have a greater potential in answering a larger number of scientific questions. This reinforces the importance and strategical aspect of interdisciplinary approaches in marine surveys, since the understanding that some geological processes may create hazardous conditions, the geomechanical explanation for observed instabilities, the dating of these events, and the evaluation of present and near future conditions are key elements in geohazard investigations [3]. However, the scientific literature still illustrates a fragmented picture, probably due to the operational costs involved. In the industrial context, integrated surveys are already recognized as a standard; however, such results are generally not submitted for peer-reviewed scientific publication.

The marine industry was largely responsible for technical advances and science propagation, which justifies the significant number of articles that have a technical and economic perspective. More recently, there is a trend towards studies with social perspectives and networks of seafloor observatories for continuous geohazards monitoring [35,54,217–219]. Therefore, direct monitoring represents a complementary manner, alongside conventional techniques in which environmental conditions call for deployment and provide enhanced confidence regarding geohazard assessments [139]. The technology involved in seafloor observatories is developing and should generate continuous data that will complement knowledge that concerns geohazards episodic events that are (in general) recorded in response to cable breaks [53,97,220,221].

The establishment of a global network of seafloor observatories will provide powerful means to understand the ocean and its complex physical, biological, chemical, and geological systems. In addition, these observatories will offer new opportunities to study multiple, interrelated scientific processes over time scales that range from seconds to decades, such as: (a) episodic processes; (b) processes with periods between months to several years; and (c) global and long-term processes [222]. Clearly distributed according to the potential for earthquakes, tsunamis, and volcanic eruptions, scientific publications that concern seafloor observatories in the following regions were allocated to the countries in Table 2.

Table 2. Main seafloor observatories initiatives registered in scientific publications.

Country/Region	Project	References
Japan	Dense Ocean floor Network system for Earthquakes and Tsunamis, DONET	[223–227]
USA	Monterey Accelerated Research System, MARS and Ocean Observatories Initiative, OOI	[220,228]
Canada	North-East Pacific Time-Series Undersea Networked Experiments, NEPTUNE and Victoria Experimental Network Under the Sea, VENUS	[229,230]
European Union	European Multidisciplinary Seafloor and water-column Observatory, EMSO	[35,217,231,232]
Taiwan	Marine Cable Hosted Observatory, MACHO	[233]

Unlike the observatories in the terrestrial environment, the number of marine observatories is still small due to the specific technical challenges and high operational and logistical costs that require cooperative efforts and cost sharing to be overcome [217]. Despite this, according to [54], seafloor observatories will be fundamental in the near future to increase scientific knowledge regarding, i. Seismicity, ii. Gas hydrate stability, iii. Seabed fluid flow, iv. Submarine landslides and fluid flow along the seabed, and v. Geohazard early warning. It is worth mentioning that the IODP program greatly contributes to the installation and retrieval of borehole geophysical observatories, whose technology has played a vital role in the evolution of the seafloor observatory concept [234].

In general, one of the objectives of the seafloor observatory is real-time detection of seismic activity in the sense of feeding earthquake early warning (EEW) systems [94,231,235]. EEW is an area practical tool for mitigating earthquake hazards and are capable of estimating the occurrence time, location, and magnitude of an earthquake and of issuing warnings before strong ground-shaking begins in a specific location [96]. EEWs are also developed for the early prediction of tsunamis that are caused by earthquakes, including tsunamis caused by submarine landslides [225]. With timely information, people and manufacturing facilities are able to take the necessary precautions to reduce the seismic hazards caused by large earthquakes [96]. According to [94], even a few seconds of lead-time can be enough for pre-programmed emergency measures in critical infrastructures, facilities, or at a personal level.

It is noteworthy that after the catastrophic events in the Indian Ocean [100] and Japan [101,217], the impacts generated by marine geohazards were widely diffused by conveyed images in diverse media. According to [236], between 2000 and 2015, there was a tendency to increase the number of industrial accidents related to the occurrence of tsunamis. Before 2011 (when there was the nuclear accident in the Fukushima Daiichi plant) only a few articles mentioned tsunamis as the potential causes of industrial accidents. However, in just five years, 19 articles studied tsunamis as a cause of the occurrence of NATECH events, i.e., natural events that affect industrial plants and can cause leakage of hazardous substances causing severe technological accidents [236]. Some of these studies dealt with the occurrence of tsunamis in a more detailed way, such as those by [237–241].

The motivation for this systematic review arose because only a few publications with a broad approach describe all categories of marine geohazards, their concepts, generalities, and specificities. In this context, the efforts gathered here are intended to establish an alternative source of information directed to the general public in order to disseminate the term 'marine geohazard' as a concept related to a diversity of features, processes, and events. However, the paper is not without limitations, since it covers only a part of the research published on the topic, as it excludes other languages and other types of publications. Despite their methodological limitations, bibliometric studies are useful tools for assessing the social and scientific relevance of a given discipline or field.

Undoubtedly, the current reach of news, reports, and videos related to geological events such as tsunamis, volcanic eruptions, submarine landslides, and earthquakes reinforce the negative potential of marine geohazards. This has put this scientific topic in newspaper headlines around the world and has encouraged the creation of funds, programs, and international consortia focused on marine geohazards research. Therefore, this field of research is promising. However, this future should require joint multi-sectoral efforts for the definition of integrated and interdisciplinary survey protocols.

5. Conclusions

Research on marine geohazards encompasses diverse geological features, processes, and events. Some are recognized as being responsible for natural disasters with significant destructive power, while others have only been revealed in the last decades of the twentieth century due to initiatives in mapping the continental margins. The advent of surface and subsurface mapping technologies, and their popularization among the marine industry, government agencies and, more recently, academic institutions, have revealed a number of marine geohazards that were hitherto unknown to science.

The efforts employed here allowed the definition of 12 categories of marine geohazards which were studied in 183 articles that composed the set of scientific publications analyzed in this work. In general, such geohazards are widely distributed in the seas and oceans and some categories are clearly more studied than others. Over the last few decades, research has evolved toward spatial expansion, diversification of complementary methods and tools, and the establishment of partnerships between the industrial, governmental, and academic sectors.

The current state of research is in a stage of consolidation of the evidence of past events and geological processes that, if they occurred today, would present risks to infrastructures and to human life. However, the continuous monitoring of the seafloor conditions is considered the main challenge for the future. Efforts related to the implementation of a network of seafloor observatories will increase our understanding of the geological processes and the resulting instabilities, which, in turn, will permit an increasingly accurate assessment of the present and near-future seafloor conditions. There is no doubt that events that are considered marine geohazards will occur in the future, and this leaves the scientific community, industry, and governmental agencies with the arduous and exhausting mission of determining the natural processes involved and to develop methods to mitigate their unpredictable damages.

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