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SEISMIC OCEANOGRAPHY METHOD: A PRISMA BASED SISTEMATIC REVIEW

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Abstract: Seismic Oceanography (SO) is an innovative method that uses seismic reflection data from surveys to study oceanographic features. We conducted a systematic review using the PRISMA method, retrieving 164 articles published between 2008 and 2023 from Web of Science and Scopus. Analyzing the data with Vosviewer and Bibliometrix software, we found that the SO methodology is expanding its applications and identified four sub-areas: 1) analyzing ocean background features, 2) mapping physical oceanographic features, 3) inverting and processing seismic data, and 4) studying interactions with the background. We traced the history of SO from its early studies in 1979 to recent works in 2023. Interestingly, the term "Seismic Oceanography" gained prominence after 2008, leading to the discovery of 15 additional articles through cross-referencing and citation analysis. Based on common processing techniques, we proposed a working guide with a flowchart for different types of seismic data, advanced processing, and relevant databases. This guide serves as a reference, offering professionals a historical perspective and practical guidance when applying the SO methodology. Our systematic review provides a comprehensive understanding of the current state of SO, identifies areas for further research, and introduces a valuable tool for professionals interested in utilizing the methodology.
Keywords: Seismic Oceanography; Data Processing; Oceanographic Features; Inversion of Seismic Data

INTRODUCTION

Seismic Oceanography (SO) is a relatively new methodology that utilizes seismic reflection methods to investigate oceanographic processes. To understand the application of seismic oceanography, it is first to discuss the seismic reflection method This geophysical technique has been widely used in oil and gas exploration since the 1920s, where it was initially investigated as a geophysical exploration technique due to the increasing demand for oil (Telford et al., 1990). The method utilizes seismology principles and controlled seismic energy sources such as dynamite, airguns, or seismic vibrators to estimate subsurface Earth properties from reflected seismic waves (Sheriff & Geldart, 1995; Yilmaz, 2001). The seismic reflection method has played a critical role in the offshore oil and gas exploration sector, especially during the 1970s, when it was extensively employed in marine environments (Ben-Menahem & Singh, 2012).

The low-frequency operation of the seismic reflection method, ranging from 10 Hz up to 100 Hz, enables indirect calculation of crust properties and image acquisition at scales ranging from tens of meters to tens of kilometers, making it useful for oil exploration surveys (Sheriff & Geldart, 1995; Telford et al., 1990). The seismic method's ability to determine subsurface geological characteristics such as the composition, density, and thickness of rock formations, the location and orientation of faults, and fluid-filled reservoirs has led to its numerous applications in fields such as mineral exploration, engineering site investigations, and earthquake studies. Overall, the seismic geophysical method remains a crucial tool for understanding the subsurface structure and properties of the Earth's crust (Yilmaz, 2001).

In simplified terms, the procedure of acquiring seismic data through reflection in the marine environment involves generating mechanical waves within the water column using compressed air cannons to minimize environmental impact (Dragoset, 2000; McCauley, Fewtrell, Duncan, Jenner, Jenner et al., 2000). The release of compressed air generates primary waves that propagate through the aqueous medium, creating a transient compression front (multiple wave front). These pulses of mechanical energy reach the sediment-water interface and interact with the solid medium through reflection and refraction, returning to the surface where hydrophones detect the reflected waves, depending on the angle of incidence, frequency used, density of intervals below the surface, and acoustic impedance of the media (Vermeer, 2012; Yilmaz, 2001).

The seismic reflection method uses measurements of transit times, acceleration, angle of arrival, and intensity of reflected pulses obtained from the detected waves to reconstruct the reflection points in the subsurface, producing time or depth images of the subsurface in both 2D and 3D (Dondurur, 2018; Vermeer, 2012).

Seismic oceanography (SO) emerges from this geophysical method, which involves processing seismic reflection data to investigate the propagation effects of seismic waves in response to heterogeneities that exist in the water column, such as physical and chemical variations of water masses (temperature, density, salinity). SO can interpret local and regional processes that may also be temporally variable (Biescas, Ruddick, Nedimovic, Sallarès, Bornstein et al., 2014; Holbrook & Fer, 2005). This new approach can generate data that can be converted into quantitative images or graphs, enabling the visualization and interpretation of thermohaline phenomena and background characteristics in the ocean (Bai et al., 2014; Huang et al., 2012; Pinheiro et al., 2010; Song et al., 2012).

The possibility of using seismic reflection data to visualize thermohaline structures was first discussed by Garrett and Munk (1979), Munk and Wunsch (1979), and Gonella and Michon (1988). However, Holbrook et al. (2003) laid the groundwork for Seismic Oceanography (SO) by validating features observed in seismic images against hydrographic data collected during various oceanographic studies. The term "Seismic Oceanography" was only established in 2008 in a special edition of "Geophysical Research Letters: Oceans" entitled "Seismic Oceanography: A New Tool to Understand the Ocean Structure" (Wood et al., 2008).

The reflections generated by contrasts in the physical properties of the water column are 100 to 1000 times weaker than those from the rocky strata found on the ocean floor and its subsurface. Hence, improving the signal-to-noise ratio in data processing is crucial to obtain images with high resolution, delineating areas with variations in the water column (Dong et al., 2013; Holbrook & Fer, 2005; Holbrook et al., 2009). However, studies using this approach must consider the resolution limits imposed by the physical laws that govern the seismic method (Ben-Menahem & Singh, 2012; Blacic & Holbrook, 2010), which affect how data are collected for exploratory purposes or reused for studying the physical conditions of the ocean environment (An et al., 2020; Biescas et al., 2010, 2014; Ha et al., 2015).

According to Yilmaz (2001), the resolution of a seismic image depends on the ability to distinguish between two closely spaced reflectors, either vertically or horizontally, regarding the rock layers. This resolution is affected by the frequency band of the signal and the total density of the medium through which the signal travels. Vertical resolution is a measure of the ability to identify two individual reflectors, which must be separated by a distance of at least 1/4 of the wavelength of the dominant signal, according to the Rayleigh criterion (Dragoset, 2000; Sheriff & Geldart, 1995). This criterion is defined by the equations $L = \lambda/4$ and $L = V/4f$, where L is the minimum distance to distinguish two events, λ is the wavelength, V is the speed of sound in the medium, and f is the dominant frequency of the seismic pulse (Evans, 1997; Hill & Rüger, 2019). Horizontal resolution refers to the method's ability to distinguish between two nearby events in the same horizontal plane (Evans, 1997; Sheriff & Geldart, 1995). This can be observed in Figure 1, where a spherical wavefront is shown reaching a plane reflector AA'. The radius of the R wavefront is approximately expressed by $R = (\lambda * Z / 2)$ ^ 1/2.

Thus, variations in the chemical and physical properties of seawater can affect the propagation velocity of seismic waves, and this effect can be transformed into 2D images representing oceanographic features. Besides internal waves, Seismic Oceanography (SO) can reveal a wide variety of oceanic phenomena such as water masses, eddies, sub-mesoscale vortices, turbulent thermohaline intrusions, and turbidity currents, as shown in Figure 2 (Fukao et al., 2019; Piété et al., 2013; Ruddick, 2018; Sallarès et al., 2009; Song et al., 2021). The literature demonstrates that it is possible to estimate geostrophic shear (White et al., 2011) and even the presence of vent bubbles (Chen et al., 2020; Li et al., 2017) using seismic reflection data. The quantitative nature of the data allows them to be combined with hydrographic data to produce high-resolution spatial models of temperature and salinity (Biescas et al., 2014).

The adoption of the SO method has also taken advantage of the large volume of seismic reflection data created by the industry over decades, which offers vast good quality material for analysis in many marine environments. The conventional reflection seismic data acquisition method used by the oil industry for exploration has characteristics such as: acquisition geometry, type of acoustic signal source and hydrophone arrangement, aspects also adopted for data generation for research in SO (Holbrook et al., 2003). However, this rich legacy of data has still been little explored.

The main challenge for conducting research focused on SO is the processing of data, for which there are no established protocols based covering different data sources (Song et al., 2021). Processing involves the application of gain filters, analysis of acoustic signal contrasts, and low frequency filters, since the values of reflection coefficients in the water column are up to a thousand times lower than those produced by the rocky strata (Krahmann et al., 2008;Wood et al., 2008;Zheng and Yan, 2010;Kormann et al., 2011). Thus, SO has emerged as a promising new tool for studying the ocean on a large scale, since the extensive global archive of marine seismic data is a large and unexplored resource for probing the characteristics of ocean water bodies. There is a huge potential for using this data to identify marine structures thermohaline with unprecedented resolution, since these structures are the main generators of speed variation of the mechanical wave front through the water column(Yang et al., 2010;Huang et al., 2011;Biescas et al., 2014)

According to the context presented above, conduct a systematic review focusing on the advancement of SO knowledge today, to highlight the challenges still unresolved and future trends. This investigation summarizes the evidence related to a specific methodology, through applying explicit and systematized methods of search. Systematic reviews allow us to incorporate and relate a larger spectrum of results, rather than limiting the possible conclusions to reading only a few articles (Sarkis-Onofre et al., 2021). Other advantages include the possibility of evaluating the consistency and generalization of results between the locations where the methodology was applied and the mapped features, and specificities and variations already treated in

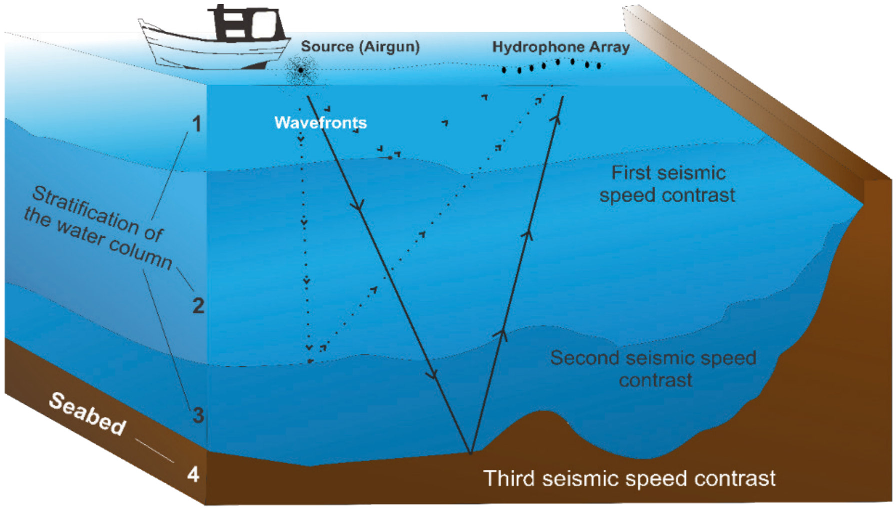

Figure1: Propagation of acoustic waves in the water column and its multiple reflections by the contrast of acoustic impedance of the medium.

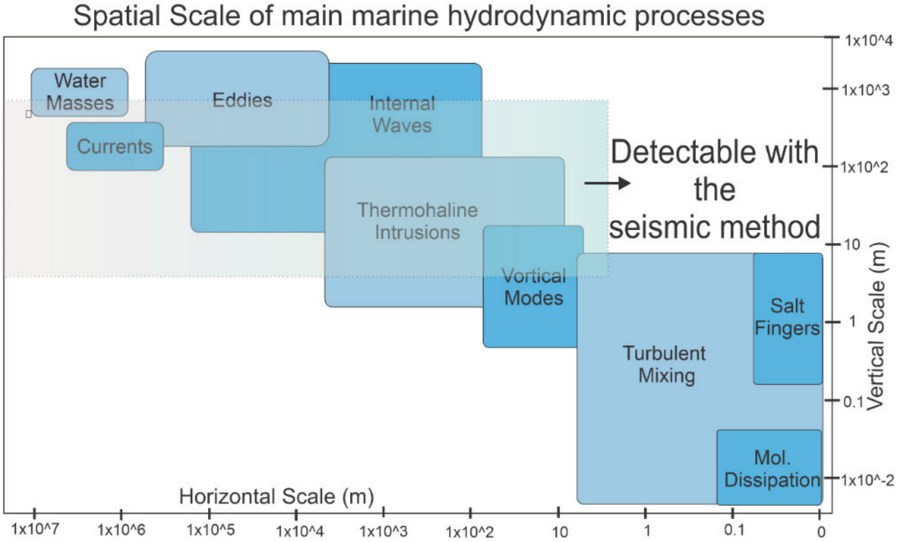

Figure2: Oceanographic features (scaled) detectable using Ruddick 2018's adapted seismic method considering high resolution seismic (single channel) and large-scale surveys.

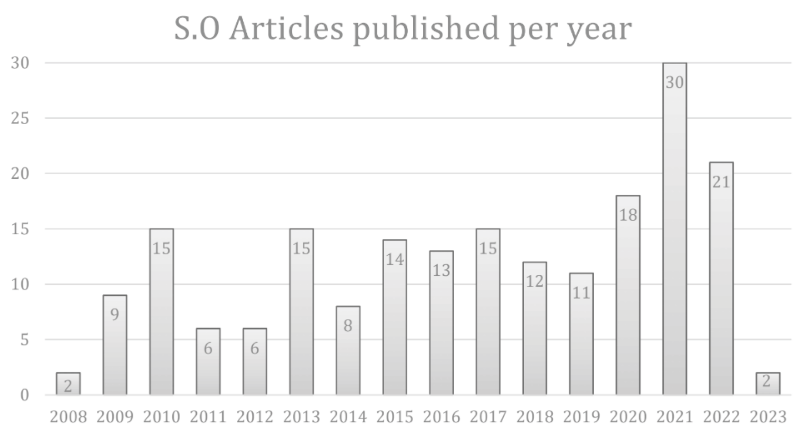

Figure3: Annual Evolution of Published Articles on "Seismic Oceanography".

relation to processing (Moher et al., 2015).

As a systematic review protocol, the present study adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, which is a set of minimum steps to be met, aiming to help authors to probe a large number of published papers. Developed within the medical sciences, the PRISMA protocol represents a tool that allows authors to produce transparent and complete communication on a topic. According to the protocol, the articles gathered on the subject will then be analyzed according to some predefined categories under the objectives of the systematic(Moher et al., 2009;Moher et al., 2015;Sarkis-Onofre et al., 2021).

In addition, an important aspect is highlighted, which is the analysis of the evolution of the scientific literature of the SO seeking its thematic relations. Therefore, some key questions have been established in this review, such as: 1)"What is the state of the art of Seismic Oceanography?", 2) " Which themes need better development, and what processing flow can be extracted from these studies?". 3) "How are the themes covered by the SO subdivided and how do they connect?". 4) "What are the potentials of this science and which areas could contribute to further development?" 5) "Is it possible to establish a processing or work flow as a general protocol?".

METHODOLOGY

This study employed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to obtain bibliometric data. The methodology, proposed by Moher et al. (2009), consists of four steps: identification, screening, eligibility, and inclusion. During the identification stage, the researchers searched the ISI Web of Science and SCOPUS databases using the term/keyword "Seismic Oceanography" in titles, keywords, and abstracts. The data collection took place in April 2023 and covered the period from 2008 to 2023.

In the screening stage, the researchers excluded documents that did not meet specific criteria. These criteria included documents without authors' names, book chapters, extended abstracts of symposia and congresses, and literature reviews. In the eligibility phase, the researchers evaluated the titles, keywords, and abstracts of the articles to determine if they aligned with the purpose of the research. Articles unrelated to the intended research, even if they used the words "Seismic" and "Oceanography," were excluded, particularly if they focused on terrestrial environments. During the final stage of the PRISMA methodology, duplicate articles were removed as both databases provided duplicate entries. Then the remaining 197 articles underwent further reading, and the metadata extraction and analysis process was initiated.

DATA EXTRACTION AND ANALYSIS

The present study employed Vosviewer (Van Eck & Waltman, 2010) and Bibliometrix (Aria & Cuccurullo, 2017) to analyze a database of 197 articles on Seismic Oceanography. The database, exported in the "bib" format, included article titles, keywords, author names, citation information, and complete reference lists. After applying the methodology, a scientometric analysis was conducted, involving thoroughly reading the selected studies to gain a comprehensive understanding of the research. This approach helped identify articles not initially indexed due to the absence of the term "Seismic oceanography" in their metadata. These articles were separately analyzed to explore the origins and consolidation of Seismic Oceanography.

The study created a thematic evolution and thematic map covering the period from 2008 to 2023. The thematic map was generated with specific criteria, including a 250-word limit, a minimum cluster frequency of 5, using the weight index as a word-occurrence weighted index, a minimum weight index of 0.1, and one label per cluster. And a conceptual structure map and a topic dendrogram were produced through multiple correspondence analysis (MCA) between keywords and plus keywords. To manage the analysis, the number of terms was limited to 50, and the number of clusters was determined automatically using Bibliometrix correspondence analyses.

RESULTS

The findings of the analysis conducted on the selected articles are presented in Table 1. During the analyzed period from 2008 to 2023, 197 articles were revealed. These articles were by 682 individuals and published in 76 journals. In terms of keywords, the articles contained 520 unique terms, and they collectively cited 7,999 references.

MAIN INFORMATION ABOUT DATA	
Timespan	2008:2023
Journals	76
Documents	197
References	7999
Author's Keywords	520
Keywords Plus	1316
Authors	682

Table 1: Main information in the analyzed database.

An analysis was conducted to examine the annual evolution of published articles (Figure 3). The objective of this analysis was to identify the trend in researchers' interest in the subject of SO. The results, depicted in Figure 3, illustrate the number of publications over the surveyed years.

According to Figure 3, the number of articles addressing the theme "Seismic Oceanography" has experienced a high rate of change since 2008, gradually decreasing over the years. Overall, there has been an average growth trend of 19.38%. The average number of annual publications is 10 articles per year, with the lowest value recorded in 2008 (only 2 articles) and the highest in 2021 (30 articles).

Based on the analysis of Figure 3, there has been a significant increase in the number of publications and interest in Seismic Oceanography in recent years. It was necessary to examine the journals with the highest number of publications on this subject, and the countries of origin of the first authors. By analyzing the primary journals where the publications are concentrated, we can determine the general objectives of the articles and the broad areas of activity in which the studies are conducted, such as Geological Oceanography, Coastal Oceanography, Geophysics, or Geology.

Table 2 presents the top 10 journals, along with their respective numbers of articles on the subject, in descending order. The journal with the highest number of articles published is "Acta Geophysica Sinica," based in China. The articles in this journal primarily focus on data processing in the oil industry and its application in case studies, with 26 articles. The second highest number of publications (20 articles) is found in the Journal of Geophysical Research: Oceans, which emphasizes studies on oceanographic processes and their interactions. The third journal, with 16 publications, is "Geophysical Research Letters," which focuses on applied geophysics and methodologies for processing geophysical data.

Information regarding the countries of origin for the first corresponding authors of the Seismic Oceanography (SO) articles is presented in Table 3. This analysis was conducted to examine the connection between the countries of the corresponding authors and the areas where oceanographic features

Sources	Articles
ACTA GEOPHYSICA SINICA	28
JOURNAL OF GEOPHYSICAL RESEARCH: OCEANS	23
GEOPHYSICAL RESEARCH LETTERS	14
FRONTIERS IN MARINE SCIENCE	10
OCEAN SCIENCE	8
CONTINENTAL SHELF RESEARCH	7
GEOPHYSICAL JOURNAL INTERNATIONAL	4
JOURNAL OF OCEAN UNIVERSITY OF CHINA	4
MARINE GEOLOGY	4

Table 2: 10 journals where articles related to SO were published most

are extensively mapped, and to identify regions with a significant lack of mapping in these areas.

Country	Freq	Country	Freq
CHINA	68	AUSTRALIA	2
UK	18	NORWAY	2
USA	18	BRAZIL	1
ITALY	15	CHILE	1
SPAIN	15	POLAND	1
FRANCE	8	SAUDI ARABIA	1
GERMANY	8	SWITZERLAND	1
SOUTH KOREA	8	CROATIA	1
JAPAN	8	INDIA	1
PORTUGAL	7	ISRAEL	1
CANADA	4	NORWAY	1
NETHERLANDS	3	IRELAND	1
NEW ZEALAND	3	Total	197

Table 3: Links of the corresponding authors of all articles

Table 3 illustrates the prevalence of corresponding authors with affiliations in China and other Asian countries, with 58 articles originating from China and an additional 13 articles from various Asian countries, resulting in 71 articles. European countries contribute significantly with 64 articles, with the United Kingdom being the largest contributor with 18 articles. In the Americas, the United States takes the lead with 18 submitted articles, followed by six articles from other countries in the American continent.

An examination was conducted to identify the most frequently cited authors worldwide in the database. This information offers valuable insights into the foundational research within the realm of Seismic Oceanography (SO), as highly cited authors often represent the cornerstone of a particular field of research. Figure 4 displays the top 10 authors with the highest number of citations in the reference lists, shedding light on their influential contributions.

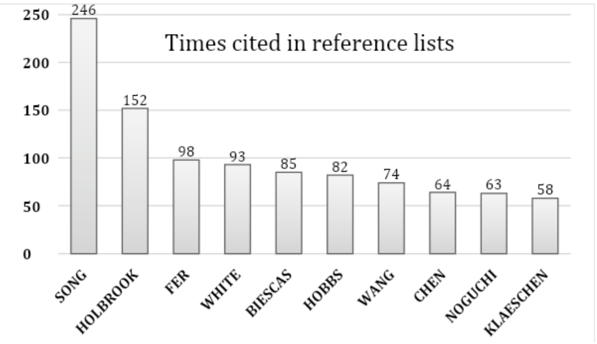

Figure 4: 10 main authors with the highest number of citations within the articles of SO. The total was 1015.

The most cited author in Seismic Oceanography (SO) is Song, accounting for approximately 24% of the total citations with 246 mentions. Holbrook secures second place with 152 citations, followed by Fer, White, and Biescas with 98, 93, and 85 citations respectively. To gain insights into the changing interests over time, the trend topic was analyzed by combining the authors' chosen keywords and the Keywords Plus from WoS and Scopus. This analysis revealed the evolution and utilization of methodologies related to SO during the studied period. The main subjects researched each year can be categorized into three groups: processing, mapped oceanographic features, and study locations (Fig. 5).

In recent years, particularly since 2019, there has been a growing and diverse interest in seismic processing, evident by the appearance of keywords such as "Pre-Stack Migration," "Inverse Problems," "Maximum Amplitude," "Markov Chain," and "Seismic Response." Although "Image Resolution" was prominent mainly in the early 2010s, the higher frequency of these terms signifies the significance of seismic data processing in SO.

The trend analysis (Fig. 5) highlights a shift in research focus related to the most studied oceanographic features and the refinement of their nomenclature. Before 2014, the

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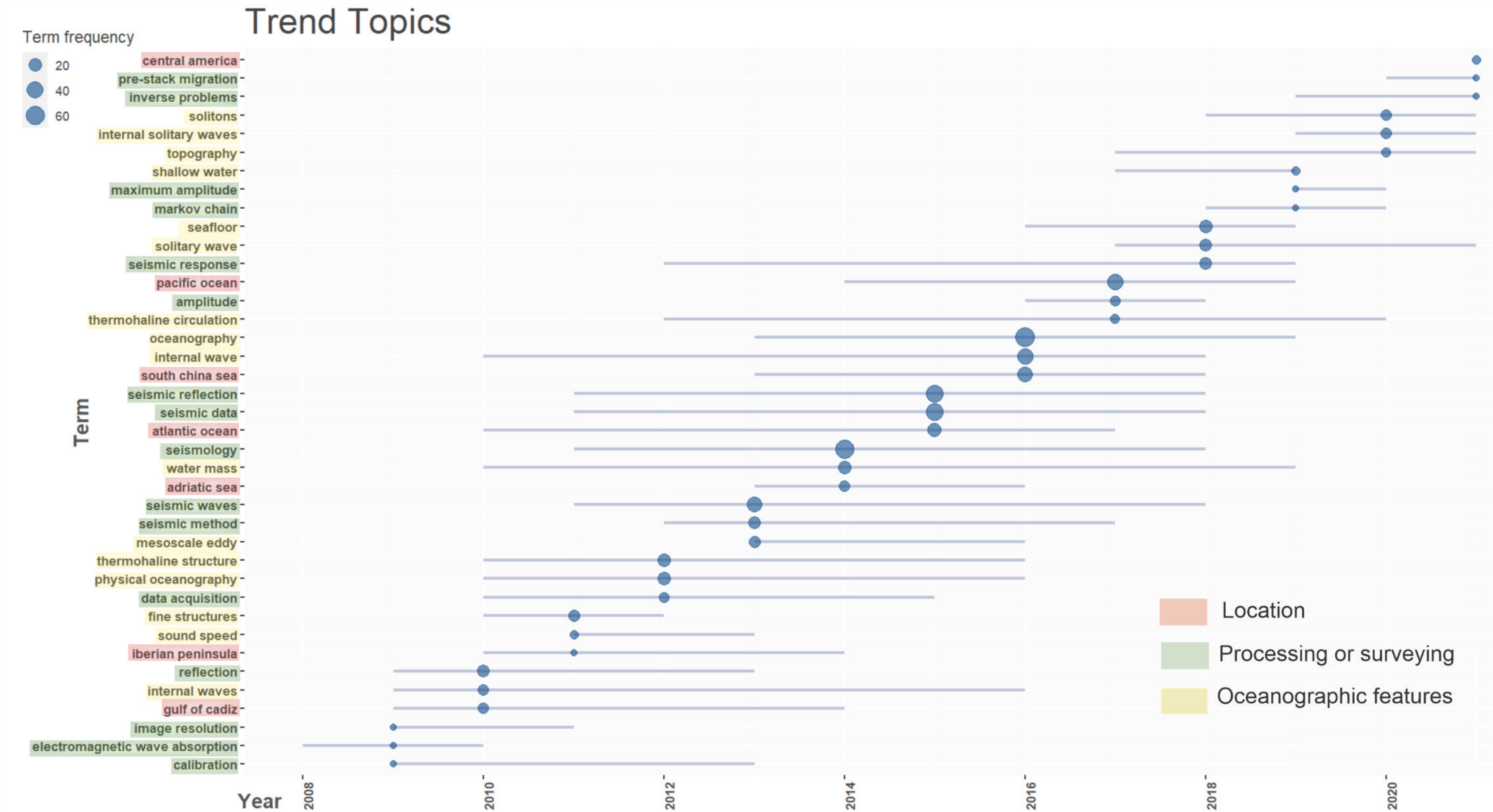

Figure 5: Main Trends of the topics studied in SO (the lines represent the years in which the term had its peak of use, which is highlighted by a bubble in the line, this being when the use was more frequent. The size of the bubbles represents the frequency of use for each term; the larger the bubble, the higher the frequency of use.

commonly used terms were “Water Mass,” “Mesoscale Eddy,” “Thermohaline Structure,” and “Fine Structures.” However, subsequent terms include “Solitons,” “Internal Solitary Waves,” “Solitary Wave,” “Thermohaline Circulation,” and “Internal Wave.” And the study locations exhibit interesting trends. Research initially focused on the Gulf of Cadiz in 2009 and the Iberian Peninsula in 2010. In 2013, the term “Adriatic Sea” became prominent, while the “South China Sea” emerged as the most studied area in 2016. There is also an increasing interest in studies conducted in Central America starting in 2021.

While the topics provide information about a term from a temporal variation (fig. 5), thematic evolution allows us to understand how the main terms in a period correlate with other main terms in another distinct period (fig. 6). The image of thematic evolution was constructed based on the analysis of Trend Topics, considering as breaking points the years 2014 and 2019, in which the largest number of trends was closed and/or started. Thus, for this analysis, three-time intervals were generated: the first from 2008 to 2013, the second from 2014 to 2018, and the third from 2019 to 2023. (fig. 6)

The thematic evolution in Seismic Oceanography (SO) exhibited similarities with the trend topics. From 2008 to 2013, the main terms observed were internal waves, reflection, Atlantic Ocean, wave propagation, internal wave, Mediterranean Sea, and ocean temperature. In the period spanning 2014 to 2018, there was a shift in research focus from the Atlantic Ocean to the Pacific Ocean, with an emphasis on internal wave studies. Wave propagation investigations progressed to explore the influence of salinity on propagation effects. And the study of sea surface temperature using seismic data emerged as a notable thematic evolution during this period.

The most diverse thematic evolution occurred between 2019 and 2023, highlighting the potentialities of seismic oceanography (Figure 6). During this period, water mass studies were conducted in the Atlantic and Mediterranean deep waters. Significant advancements were made in seafloor mapping using seismic data, particularly in the Pacific and Mediterranean Oceans. The Northern South China Sea also garnered attention from SO researchers. Other evolving topics included the Pacific Ocean, topography, seawater, Atlantic Ocean, and Japan.

In the thematic map in figure7, the main themes are displayed, and their relevance within the SO, for the entire time studied. In the upper to left quadrant are terms considered niche (with high relevance and low development), the upper right quadrant represents the motor themes (considered the main and best developed). The lower left quadrant represents the themes on the rise or in decline (lower interest and development) and the lower left quadrant the themes considered as the basis of SO.

The basic themes (fig 7) are the themes well developed within the literature studied. They are the theoretical basis of most other studies within our sample universe, so they end up not having as much relevance to be more studied than all other terms. The themes that fit this item are: South China Sea, Internal Solitary waves, Seismic Oceanography, Internal Waves, Diapycnal mixing, turbulence, pockmark, bottom current, cold seep.

The motor terms have high relevance and self-development within the studies used, and these themes nowadays are the points of greatest interest for researchers in this area of knowledge. The terms engines found are: Northern South China Sea, Internal Solitary Waves, Eddy, Mediterranean, inversion, mixing, full waveform inversion, Mediterranean Undercurrent. (fig. 7)

Niche themes (fig.7) are those themes with a high relevance, however, low development and, coincidentally for this sample universe, all terms of this niche are directly linked to the processing aspect of seismic data. What they are: Inverse Theory, Numerical Approximations and Analysis, and Seismic Tomography.

Themes with low relevance and low development fit those researchers have an interest that may be on the rise or decline. The terms on the rise and decline are: Distortion of Seismic imaging, Mesoscale eddies, Bottom currents, and Oceanographic Processes (fig 7).

Basic themes have remained on axes: in the lower part with low relevance and medium development are the terms: Water masses, Adriatic Sea, Southern Adriatic Sea; and with medium relevance and low development, is the term Glider (fig 7).

The multivariate correspondence analysis conceptual map (figure8) allows you to understand the correlations between the key words within the field of study, and how they are subdivided. Groups are calculated and designed so what compose it have an interconnection stronger than the words outside it. In addition, the proximity between the terms corresponds to how often they occur in the same article within the database. Subjects are close to each other due to a large proportion of articles dealing with these; therefore, they present a high correlation; their distance also reflects the aspect that a small fraction of articles treated them, jointly, or that they have no correlation.

In figure8 the first green cluster is linked to terms related to background features such as "Bottom Current"; "Mud Volcano"; "Fluid Flow" and "Pockmark". The second cluster in blue has, mostly, terms linked to features close to the bottom but already related to the water column and the place where they were inferred as: "Cold Seep"; "Eddy"; "Seismic Facies"; Gas Plume and South China Sea. The purple cluster probably has terms linked to pioneering studies of seismic oceanography such as" "Salinity"; "Temperature"; "Amplitude", "Mediterranean Undercurrent", "Mixing" and "Thermohaline Fine Structure".

The red group is the core term grouping of the SO search field. This grouping has as limits on the X+ axis the term "Thermohaline Intrusions" and X- "Thermocline" and in Y+ the terms "Thermohaline Structure" and Y- "Distortion of Seismic Imaging". The cluster in yellow contains terms linked to the processing SO es group is close to red and is being strongly attracted by it, the terms of the yellow cluster are: "Numerical Approximations and Analysis"; "Inverse Theory"; Seismic Tomography.

Another form of representation of the results of the MCA analysis is topic dendrogram (fig. 9). This tree diagram displays the groups formed by thematic correspondence analysis, defined along the horizontal axis that shows the hierarchical relationships between themes. Themes within the same cluster can be worked more together than other terms belonging to the same grouping, such as figure 9 "Pockmark" and "Fluid Flow" have a similar hierarchical level and a higher correlation with each other than with the term "Mud Volcano", for example.

Because the initial research linked to a key term, "Seismic Oceanography", the articles obtained in WoS and Scopus do not encompass the entire history of SO. Therefore, the analysis of the references also allowed to locate 15 articles dealing with Seismic Oceanography, but in which the term was not used in any part of the article (Table 4).

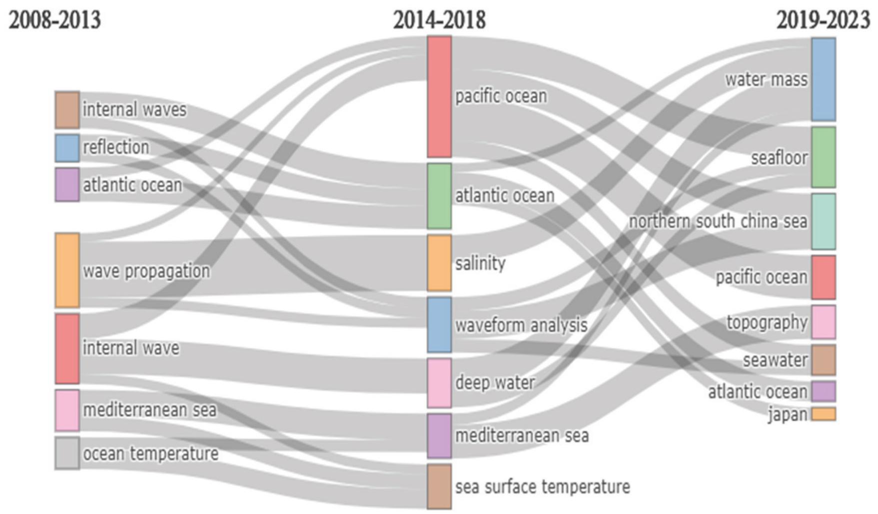

Figure 6: Thematic evolution for the analyzed period. In the image the color bars are merely for distinction of occurrence of a term. The size of the bar indicates the normalized proportion of the term between all periods, the links from one term to the other indicate the thematic evolution of this term and may have more than one branch, we have no longer have a branch connection shows a discontinuation of research interest in this subject.

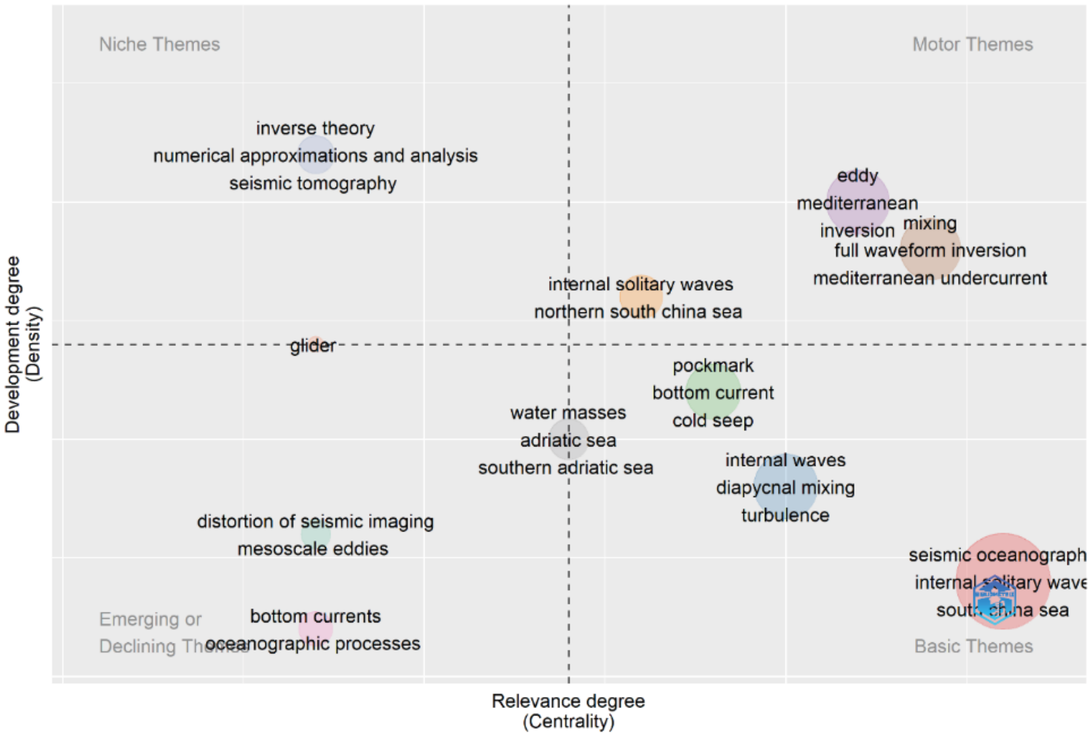

Figure 7: Thematic map of the subjects dealt with in the SO. Plotted on a Cartesian axis where X is development of a term and Y indicates the relevance of this term.

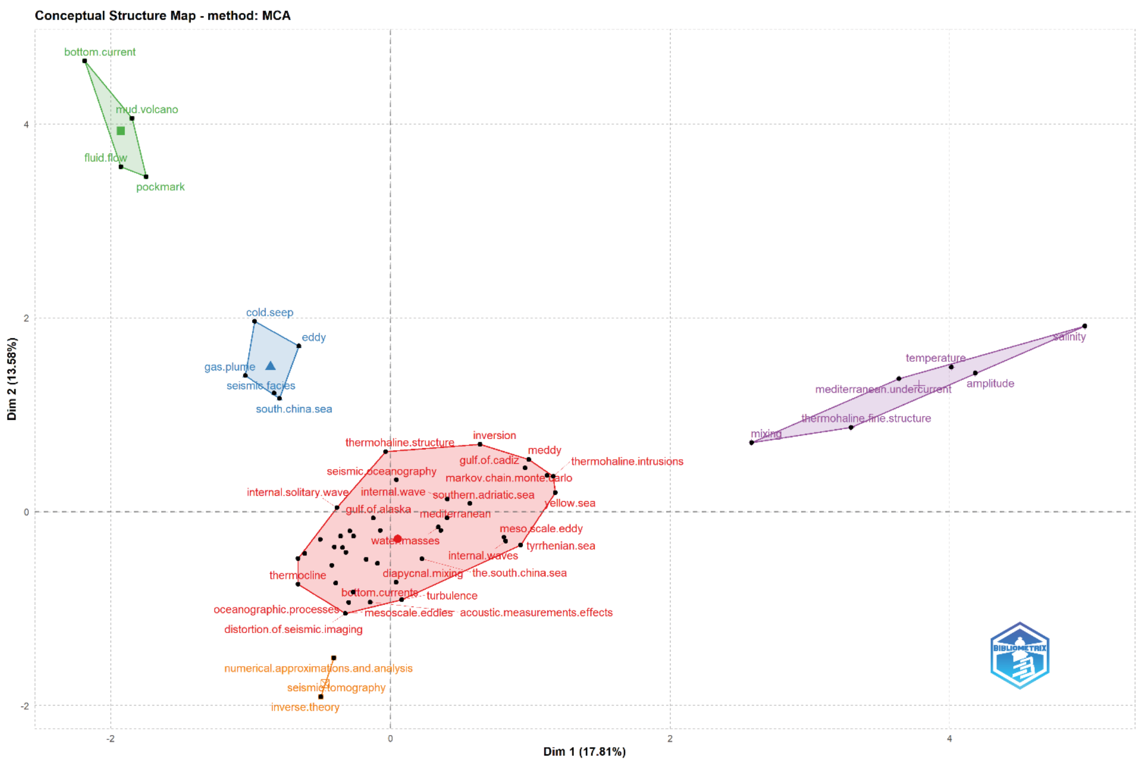

Figure 8: Conceptual structure map, showing the 5 clusters defined. The proximity of the point of origin (0.0) shows the highest index of thematic correlation among all articles, therefore, it represents the center of the research field.

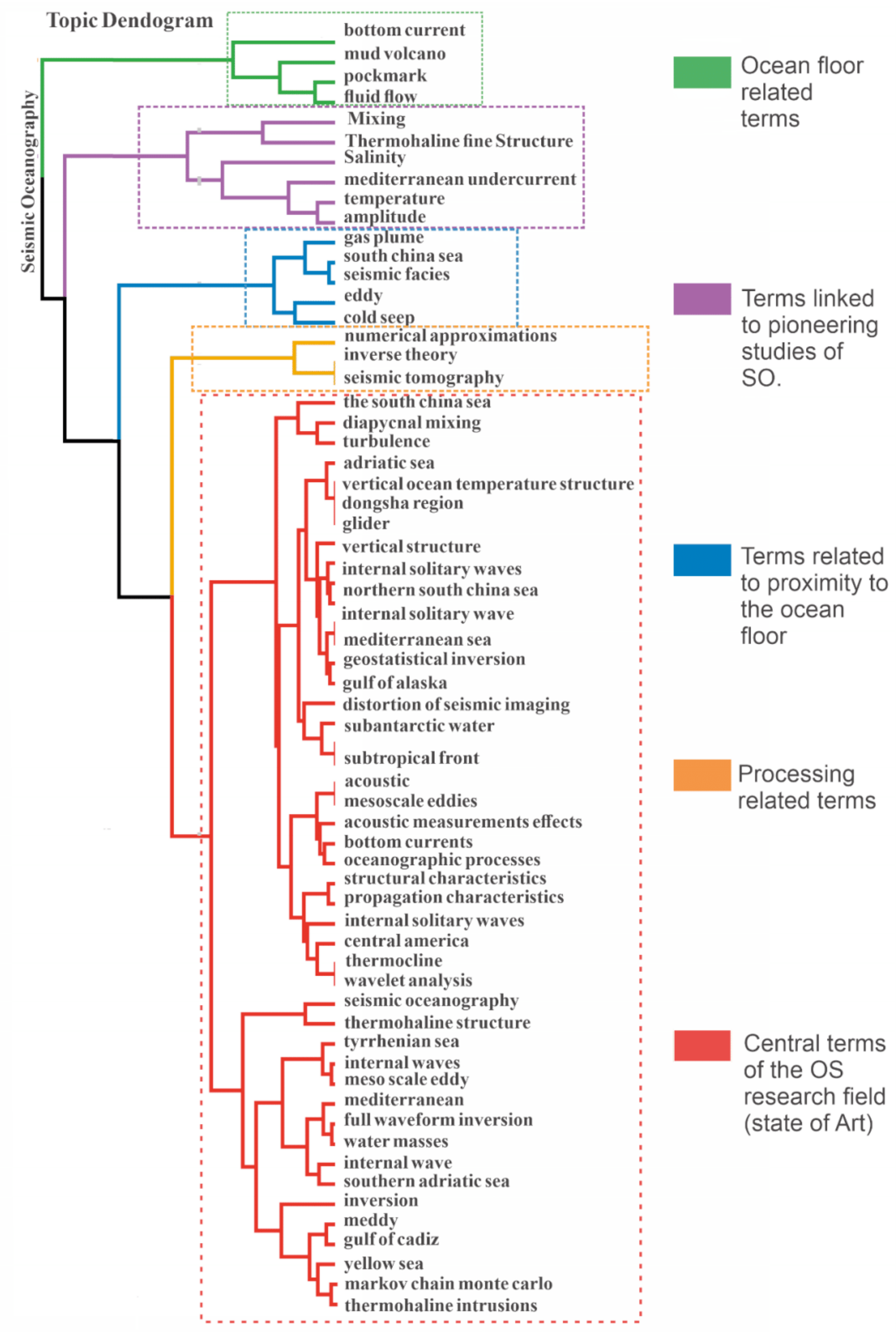

Figure 9Dendrogram of topics showing the subdivision of subjects treated in Seismic Oceanography

AUTHORS	YEAR	TITLE
Garrett, C., & Munk, W.	1979	Internal waves in the ocean.
Munk, W., & Wunsch, C.	1979	Ocean acoustic tomography: A scheme for large scale monitoring.
Gonella, J., & Michon, D.	1988	Deep internal waves measured by seismic-reflection within the eastern Atlantic water mass
Phillips, J., & Dean, D.	1991	Multichannel acoustic reflection profiling of ocean watermass temperature/salinity interfaces
Holbrook, W. S., Páramo, P., Pearse, S., & Schmitt, R. W.	2003	Thermohaline fine structure in an oceanographic front from seismic reflection profiling
Ruddick, B.	2003	Sounding out ocean fine structure
Holbrook, W. S., Fer, I., Pearse, S., Nandi, P, Brown, H. E., Nealon, J., & Páramo, P.	2004	Internal tides and breaking waves imaged on the Norwegian continental slope
Nandi, P., Holbrook, W. S., Pearse, S., Páramo, P., & Schmitt, R. W.	2004	Seismic reflection imaging of water mass boundaries in the Norwegian Sea.
Rainville, L., & Pinkel, R.	2004	Observations of energetic high-wavenumber internal waves in the Kuroshio
Holbrook, W. S., & Fer, I.	2005	Ocean internal wave spectra inferred from seismic reflection transects
Páramo, P., & Holbrook, W.S.	2005	Temperature contrasts in the water column inferred from amplitude versus offset analysis of acoustic reflections.
Schmitt, R., Nandi, P., Ross, T., Lavery, A., & Holbrook, W. P	2005	Acoustic detection of thermohaline staircases in the ocean and laboratory
Tsuji, T., Noguchi, T., Niino, H., Matsuoka, T., Nakamura, Y., Tokuyama, H., Bangs, N.	2005	Two-dimensional mapping of fine structures in the Kuroshio Current using seismic reflection data.
Nakamura, Y., Noguchi, T., Tsuji, T., Itoh, S., Niino, H., & Matsuoka, T.	2006	Simultaneous seismic reflection and physical oceanographic observations of oceanic fine structure in the Kuroshio extension front
Hardy, R., Jones, S., & Hobbs, R.	2007	Imaging the water column using seismic reflection data

Table 4: List of articles that started the discussion on the potential use of seismic data for water column analysis, but did not use the term "Seismic Oceanography" found through the analysis of citations of the articles in the analyzed database.

DISCUSSION

Although HOLBROOK (2003) is considered a precursor of using seismic data for studies of physical aspects of the water column, this study was not the first to discuss the potentials of wave analysis generated by the seismic reflection method in the water column, for studies for studies of physical aspects of it. On the one hand Holbrook was the first to discuss and propose a basic methodology for developing Seismic Oceanography. However, Holbrook did not initiate the observation and questioning of the seismic reflection method for oceanographic studies, it was also not from it that the "Seismic Oceanography" gained this name and began to be admitted as a subarea that integrates marine geophysics and physical oceanography.

Through the crossing of references and analysis of the articles selected by the PRISMA method, it was verified that some articles that dealt with themes that could be linked to Seismic Oceanography were not indexed in the research in WoS or in Scopus, being treated here as pioneer studies. With the search and analysis of these non-indexed articles, the division of SO can be proposed into three periods: Pioneer Studies (1979-2002), Seismic Reflections in water (2003-2007) and Seismic Oceanography (2008-2023).

Comprising from 1979 to 2002 the pioneering studies dated 1979 (Garrett and Munk, 1979;Munk and Wunsch, 1979) are marked by observations of oceanographic features in seismic sections, in data collected by the oil industry, without specific processing being carried out for such images to be (Garrett and Munk, 1979;Munk and Wunsch, 1979;Gonella and Michon, 1988;Phillips and Dean, 1991)) Professionals in the prospecting industry dealt with the information in the water column only as a processing obstacle, a noise to be filtered. Almost in an accidental way, the authors before Holbrook, came across data processed as images related to oceanographic features where only noise was observed(Munk and Wunsch, 1979;Phillips and Dean, 1991))

But this period was important for the marine seismic data acquisition industry, with the advance of large-scale surveys and with increasingly sophisticated technologies around the globe, processing and filtering techniques of the effects generated by the water column were widely discussed and developed (Telford et al., 1990;Yilmaz, 2001). These techniques would later be adapted by researchers interested in SO, such as Holbrook et al. (2003);Ruddick (2003);Nandi et al. (2004). However now in a way to highlight the seismic signals obtained in the water column, such as using a filter "passes band".

From 2003 (Holbrook et al., 2003) to 2007 (Hardy et al., 2007) established the basis of what would later be called Seismic Oceanography. Considered among the articles studied (Song et al., 2021), the article that shows how the precursor of the SO Holbrook et al. (2003), in which the authors demonstrated the remarkable sensitivity of the seismic wave reflex, in an experiment used to study reflections in relation to the variation of sea temperature, developed over 172 km in the Norwegian Sea.

Holbrook et al. (2003) reported that the images of thermohaline structures resulting from SO have a lateral resolution greater than other oceanographic conventional methods. This justifies the original survey in the SO are made in a smaller spacing between measurements. In addition, the increase in horizontal resolution is two orders of magnitude compared to conventional methods using CTD (Conductivity, Temperature and Depth) and XBT (expendable Bathythermograph) profilers. Thus, seismic reflection has emerged as a new tool to study the ocean on a large scale, since the extensive world archive of marine seismic data constitutes a great and unexplored resource for probing structures in the water column, thus helping oceanographers to visualize and identify the structures in the water column with unprecedented resolution. (Ruddick, 2003;Holbrook et al., 2004;Nandi et al., 2004;Rainville and Pinkel, 2004;Holbrook and Fer, 2005;Páramo and Holbrook, 2005;Schmitt et al., 2005;Tsuji et al., 2005;Nakamura et al., 2006;Hardy et al., 2007)

From Holbrook et al. (2003) several authors have sought ways of processing to improve the visualization of oceanographic features in seismic sections, and seeking to validate these results through other methods of studies of oceanographic features already consolidated, such as CTD and ADCP for example(Holbrook and Fer, 2005;Páramo and Holbrook, 2005;Schmitt et al., 2005;Tsuji et al., 2005). Tests were also carried out based on acquiring unique seismic surveys for developing SO studies, which increased the progress produced with the availability of use of old data (legacy data) produced by the oil industry, for example. (Nandi et al., 2004;Holbrook and Fer, 2005;Schmitt et al., 2005;Tsuji et al., 2005)

SEISMIC OCEANOGRAPHY (CONSOLIDATED)

The period between 2008 and 2023 corresponded to the database used because they were linked to the term "Seismic Oceanography" thus obtaining information about the state of the art of it. This term began to be established in a project coordinated by the University of Durham (United Kingdom) the so-called "Geophysical Oceanography - a new tool to understand the thermal structure and dynamics of oceans" starting in 2006 and finalizing in 2009 (CORDIS, 2009). Besides the United Kingdom, this project was supported by universities and research centers from other countries such as Spain, Italy, Portugal, France and Germany (Biescas et al., 2008;Kormann et al., 2008;Krahmann et al., 2008;Wood et al., 2008). This influenced the journals where articles related to "Seismic Oceanography" (Table 2) were most published, in the links of the main authors of these articles (Table 3) and in the most cited authors (figure4).

The project "Geophysical Oceanography" (GO) resulted in a special edition of the journal "Geophysical Research Letters: Oceans" where the term Seismic Oceanography came to be used in all works that used data from seismic surveys of reflection for physical oceanographic studies (Fortin and Holbrook, 2009;Geli et al., 2009;Hobbs et al., 2009;Holbrook et al., 2009;Klaeschen et al., 2009;Kormann et al., 2009;Krahmann et al., 2009;Sallarès et al., 2009).

Publications have an average publication growth rate of 19.38% from 2008 to 2023 (fig. 3), therefore different periods there were production peaks. Due to the results of the GO project expeditions, SO had its first peak of publications in 2009 and 2010 since it began to be discussed as a potential methodology in 2003 (fig. 3 and Table 4). Another "Boom" of publications was the most productive period of all, in the years 2020 and 2021 (fig.3) with 48 papers published mainly using data from previous seismic surveys(Bakhtiari Rad and Macelloni, 2020;Chen et al., 2020;Fan et al., 2020;Gunn et al., 2020;Kuang et al., 2021;Yang et al., 2021). Such a factor

Many articles come from Chinese researchers as seen in Table 3 and figures 3 and 4. Probably to make this methodology more accessible to Chinese researchers, many articles were published in Mandarin and English, however, with the same different content and DOI. (Song et al., 2010;Yang et al., 2010;Huang et al., 2012;Huang et al., 2013;Jiang-Xin et al., 2016;Jiang-Xin et al., 2017;Jun et al., 2019)

As seen in figure4 and Tables 2 and 3, there is a predominance of researchers and journals where SO is published in the northern hemisphere. This directly reflects in the places where the studies were conducted. Observing the topics of bias (fig. 5) it is verified the tendency of the studies to be carried out in the southern hemisphere only from the year 2021 (Fan et al., 2021;Yang et al., 2021).

Observing the trends in the trend topics (fig. 5) and crossing with the information of thematic evolutions (fig. 6), we highlight the increase in the diversity of themes as the SO methodology has been evolving since 2008. Studies using the methodology proposed Holbrook et al. (2003) focused on topics such as mapping thermohaline structures in the water column (Fortin et al., 2017;Jiang-Xin et al., 2017;Fan et al., 2020). However, these proposals for the SO diversified, which allowed the mapping of background features to be mapped, thus removing information about the topography and the interaction of water with the bottom. (Fortin et al., 2017;Chen et al., 2018;Jia et al., 2019;Chen et al., 2020). The mapping of background features is a promising tool to be further explored in the OR, since investigation of processes of water interactions with background morphology can be of great use to the sciences of the sea, especially in regions where bathymetric information is scarcer.

Processing techniques are of fundamental importance to SO since the seismic data of reflection began to be worked by Holbrook et al. (2003). This is observed in the term "full waveform inversion" as the motor theme in the thematic map (fig 7). Initially contrast techniques (Buffett et al., 2009;Fer et al., 2010;Eakin et al., 2011;Yamashita et al., 2011) were the most applied, followed by filtering (Mirshak et al., 2010;Song et al., 2010;Bai et al., 2015;Ker et al., 2015). Although it is a basis for this methodology, when the thematic map (fig. 7) is observed SO data processing are niche themes (with few researchers working in this area) such as "Inverse Theory", "Numerical Approximations and Analysis", "Seismic Tomography", there are also processing topics in emerging or declining themes (with few papers published in this area) such as "Distortion of Seismic Imaging" (fig. 7).

GENERAL WORKFLOW FOR SO STUDIES

The observation of the metadata referring to the articles from 2008 to 2023, and in all the articles that defined the processing of seismic reflection data since Holbrook et al. (2003), shows a lack of standardization of the steps necessary for the visualization of seismic reflections within the water column (Nakamura et al., 2006;Hardy et al., 2007;Hobbs et al., 2009;Kormann et al., 2009;Krahmann et al., 2009;Eakin et al., 2011;Yamashita et al., 2011;Huang et al., 2012;Rice et al., 2013;Meléndez et al., 2014;Buffett et al., 2017;Moon et al., 2017;Jun et al., 2019;Sun et al., 2019;Bakhtiari Rad and Macelloni, 2020).

Due to this lack of standardization of SO data processing, a basic flowchart is being proposed in this work, based on the information obtained from the SO literature and from the basic literature of Geophysics (Telford et al., 1990;Sheriff and Geldart, 1995;Evans, 1997;Dragoset, 2000;McCauley et al., 2000;Yilmaz, 2001;Yilmaz et al., 2001;Barão et al., 2018;Dondurur, 2018;Hill and Rüger, 2019;An et al., 2020;Bakhtiari Rad and Macelloni, 2020;Chen et al., 2020;Jun et al., 2020;Song et al., 2021). From this proposed flowchart (fig. 10), professionals of the marine sciences could have a basis to start their work with the SO.

The Flowchart below is a generic organization for the beginning of work with seismic oceanography. Itis divided into 4 columns, according to the need and/or focus of the work to be done. The first column (Raw 2D Seismic Data) should be used when the seismic reflection data obtained is unprocessed (raw). But the second column (stacked data) is for seismic data already preprocessed (stacked). Pre-processed (stacked) data deserve attention in this flowchart, since it is a very common way of being provided by companies that have carried out seismic surveys, or that hold legacy data from the oil industry. The third column (Seismic Derived Information) shows information that can be obtained by inversion of seismic data, and information on speed, temperature and salinity can be obtained. The fourth column (Oceanographic Data) points to a free public database that can corroborate the integration and calibration of the processing of seismic reflection data.

SUMMARY, ONGOING WORK, AND FUTURE CHALLENGES

A systematic review was conducted focusing on Seismic Oceanography, analyzing the evolution of the scientific literature of the SO seeking its thematic relations. Some key questions were answered in this review and will guide the conclusions, such as: 1)"What is the state of the art of Seismic Oceanography?". 2) "Which themes need better development?". 3) "How are the topics covered by the SO subdivided?". 4) "What are the potentials of this science and which areas could contribute to further development?" 5) "Is it possible to establish a processing flow as a general protocol?".

Sequentially the conclusions for these questions are:

1) Occasionally it is related the "state of the art" of a particular science with the most modern and technological available for this science. Scientific advancement and computational processing capacity, neural networks, 3d surveys, development of new processing techniques draw the limit of what is most modern within seismic oceanography.

Although counter intuitive define only this side as the state of the art is not coherent, since it has been proven that the SO comes s and diversifying and exploring new subareas (fig. 5 and fig. 6) and each of these subareas is "the state of the art of Seismic Oceanography" (fig. 9 and fig.8). A good example, of a subarea with great potential, using legacy data from the oil industry to obtain historical information on temperature and salinity, especially in places with scarcity of set type of data, because they have had some interest from the oil industry.

2) Within the themes of seismic oceanography, the themes that need to be explored the most are those related to data processing, such as Inverse Theory, Numerical Approximations and Analysis, Seismic Tomography, Distortion of seismic imaging, Mesoscale eddies, Bottom currents. (fig. 7)

3) All themes addressed by the SO can be grouped into 4 sub-areas according to the final objective that the methodology is applied (fig. 8 and fig. 9) namely: 1st analysis of ocean background features with seismic data; 2nd mapping of physical oceanographic features in water (which originated SO); 3rd processing, inversion, and optimization of seismic data collection; 4th interactions of physical oceanographic features with the background.

4) The thematic map of the subjects dealt with in the SO (fig. 7) statistically represents the subjects that need further development in the quadrants to the left of the central axis (x negative), and most are linked to processing, inversion, and optimization of the collection of seismic reflection data. This is also verifiable in reading the articles.

The greatest potential of SO is linked to its origin as a methodology, because it has a large lateral resolution to map oceanographic features in relation to traditional methods

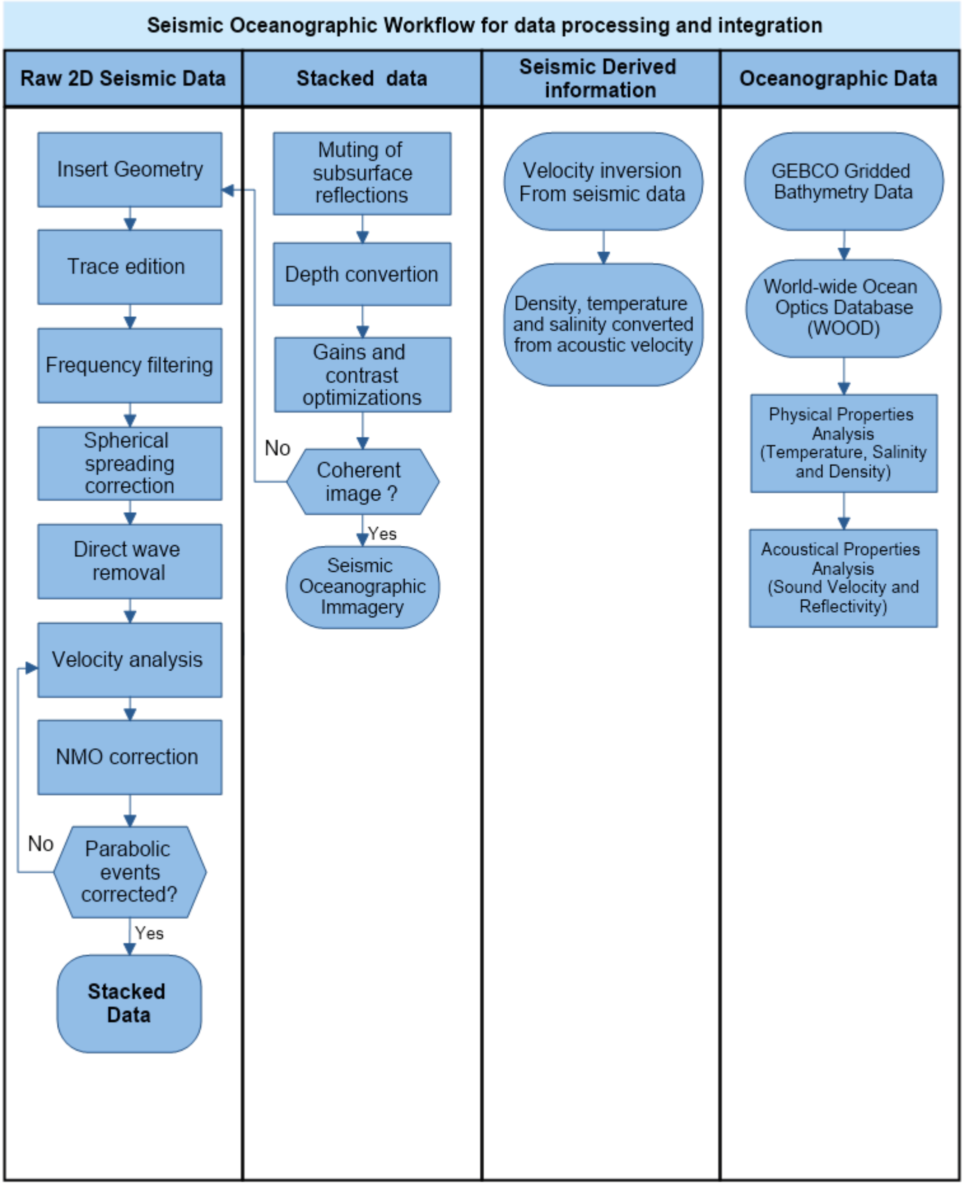

figure 10: Workflow proposed through the analysis of the processing of seismic oceanography works.

related to Physical Oceanography, such as CTD. But new branches of SO offer great potential to be explored, such as: mapping background geological features thus refining geological knowledge of the region. Or, the inversion of seismic reflection data to obtain information on temperature and salinity, with the potential to build historical series with these legacy data from the oil industry.

5) Due to the specificities that each seismic data of reflection has, and different objectives when using these data, it is very complex to establish a processing flow as a fixed protocol for SO. However, it is possible to propose an organization chart so beginners in the SO can perform their work (fig.10). In this proposed basic working protocol, a processing flow common to two types of data can be verified, besides auxiliary information that can corroborate the studies of professionals of professionals who will work with the SO.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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