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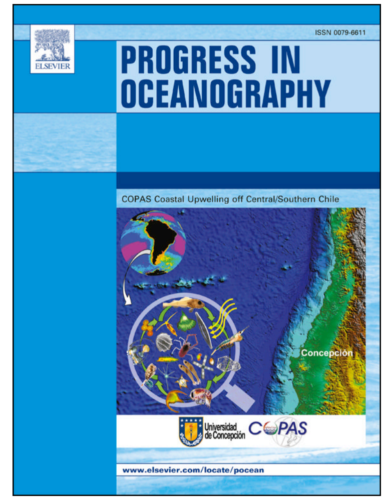

Canyons pride and prejudice: exploring the submarine canyon research landscape, a history of geographic and thematic bias

F.L. Matos, S.W. Ross, V.A.I. Huvenne, J.S. Davies, M.R. Cunha

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Canyons pride and prejudice: exploring the submarine canyon research landscape, a history of geographic and thematic bias

Matos FL [a], Ross SW [b], Huvenne VAI [c], Davies JS [d], Cunha MR [a]

[a] - Departamento de Biologia & Centro de Estudos do Ambiente e do Mar (CESAM), Universidade de Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal; [b] - Center for Marine Science, University of North Carolina Wilmington, North Carolina, USA; [c] - Marine Geoscience, National Oceanography Centre, University of Southampton Waterfront Campus, Southampton, UK; [d] - Marine Biology and Ecology Research Centre, Plymouth University, Plymouth, UK

Corresponding author: Matos FL, fmatos@ua.pt

Abstract

We mapped submarine canyon research using a scientometric approach to define and characterize its scientific landscape based on a comprehensive bibliographic dataset. The abundance of studies covering structural and functional aspects of submarine canyons allowed us to identify the existing knowledge clusters, historical trends, and emergent topics in canyon research. Our analysis documented a network of knowledge clusters of which four were particularly relevant: a strong cluster on “Geology & Geophysics”, well established since the beginnings of canyon research; a cluster on “Biology & Ecology” that gained strength primarily over the past two to three decades; a cluster on “Oceanographic Processes” which occupied a central position in the network and connected strongly to almost all the other clusters and especially to the fourth main cluster on “Modelling”. A smaller, but also well connected, cluster on “Biogeochemistry” related closely to “Biology & Ecology”, and three other small clusters (“Sedimentology”, “Sediments & Tidal Currents”, “Canyon Sampling”) bridged the main clusters. Finally, we identified three small, but specific satellite clusters (“Oil & Gas”, “Chemosynthetic Communities”, “Molecular & Symbionts”). The high-level structure of the knowledge network reflects a latent interdisciplinarity in canyon research. However, the evolution of the research lines over the past nine decades suggests that this pattern arose mostly in the new millennium. Emergent research topics in the last decade also reveal a concern regarding anthropogenic impacts and climate-driven processes. Our results also show a well implemented and international collaboration network, although research efforts have been mainly directed towards only a few canyon systems. A geographical and thematic bias also characterizes canyon research, with specific topics addressed preferentially in particular canyons by different leading research institutions. This spatial and thematic bias, together with the paucity of truly inter-disciplinary studies, may be the most important limitation to integrated knowledge and development in canyon research and hinders a global, more comprehensive understanding of canyon patterns and processes. The scientific landscape mapping and the complementary results are made available as an open and interactive platform that canyon stakeholders can use as a tool to identify knowledge gaps, to find key players in the global collaboration network and to facilitate planning of future research in submarine canyons.

Keywords: submarine canyons; research mapping; network analysis; textual analysis; knowledge clusters

1 Introduction

The scientific literature provides a critical instrument for research dissemination and, thus, an important source of scientific and technological information (Huang et al., 2011; Kahane et al., 2015). Research mapping based on bibliographic data (e.g., abstracts, affiliations) offers an intuitive and structured framework to explore and describe research areas, detect knowledge gaps and cutting-edge topics, and identify key players in different scientific fields (Boyack et al., 2005; Oldham et al., 2012; 2014b). A new methodology has been recently developed to reconstruct research dynamics over time (Chavalarias and Cointet, 2013). Mapping and historic reconstruction techniques both provide important information that can help direct and enhance research coverage, by reducing duplication of efforts and promoting synergies (Boyack, 2004; Oldham et al., 2014b).

Deep-sea scientific exploration has been hindered by costly and highly technology-dependent field work. To tackle these limitations requires strong institutional collaboration together with an extensive effort to seek research funding (Oldham et al., 2014a), as well as the adoption of multidisciplinary approaches integrated in well-designed strategies. Hence, future research agendas can benefit from detailed and visually explicit information on research trends and collaboration networks, particularly in stagnant or declining funding scenarios.

Submarine canyons are among the most iconic deep-sea ecosystems, with more than 9500 canyons catalogued worldwide along continental and island margins (Harris et al., 2014). The complexity of canyon systems and their influence on the surrounding environmental setting often requires scaling-up of proposed research to a regional level. Canyons influence water circulation (e.g., internal tides, currents), transport of sediments, nutrients and particulate matter (Liu et al., 2002; Allen and Durrieu de Madron, 2009; Puig et al., 2014), as well as ecosystem functioning and services, including an important role in carbon storage (Masson et al., 2010). They often enhance regional biodiversity (Cunha et al., 2011) and biomass of various organisms (De Leo et al., 2010; Kavanaugh et al., 2015), including many economically exploited species (Yoklavich et al., 2000; Company et al., 2012). Moreover, canyons act as natural traps and conduits for litter and contaminants (Castro-Jimenez et al., 2013; Pham et al., 2014) and are often exposed to the impacts of various anthropogenic activities, such as fisheries (Puig et al., 2012; Paradis et al., 2017) and hydrocarbon exploration (Harris et al., 2007) that may operate synergistically with natural disturbance (Almeida et al., 2017). Overall there is a high spatial and temporal variability within and between canyons, both in terms of physical environment and biological communities, which emphasizes the complexity, diversity and uniqueness of these systems (e.g., Tyler et al. 2009; Cunha et al., 2011; CSA Ocean Sciences Inc. et al., 2017). We are only beginning to understand the broad-scale physical and biological processes and patterns in submarine canyons, moving towards the integration of current fragmented knowledge in order to achieve a more comprehensive perspective on these important deep-sea features (Huvenne and Davies, 2014; Amaro et al., 2016).

The large volume of publications and ready access to their digital formats facilitates the scientometric analysis of their content through textual retrieval techniques, such as text mining and natural language processing (NLP). These methods offer powerful tools to organize, classify, label and retrieve novel data patterns. Textual data processing requires multiple steps: assembling a collection of texts on a particular subject (corpus) for computational processing, formatting the corpus, and selecting analysis methods to detect relationships among data elements (e.g., clustering methods, graphs and network algorithms) (Losiewicz et al., 2000). Co-word networks have been used for this purpose (e.g., Tancoigne et al., 2014; Ruiz-Martinez et al., 2015; Raimbault et al., 2016), combining the strengths of textual retrieval techniques with network analysis. Proximity measures that normalize the relationships and strengths in the network establish associations among nodes. Depending on the characteristics of nodes, the networks can be classified as homogeneous, if built from a single text field, or heterogeneous if built from distinct text fields (e.g., authors and affiliations) (Barbier et al., 2012). Despite some criticism of co-word analysis related to interpretation issues and language ambiguity (Leydesdorff and Hellsten, 2006), the structure of lexical co-occurrences allows the identification of relevant and directly interpretable commonalities between concepts, techniques, and research achievements (Rule et al., 2015; Raimbault et al., 2016). This approach has already produced important outcomes in different scientific fields contributing, for instance, to the development of research agendas (Tancoigne et al., 2014) and detecting the emergence of research lines (Raimbault et al., 2016).

This paper tackles some of the most pressing canyon research issues identified during past meetings of the International Network for submarine Canyon Investigation and Scientific Exchange (INCISE) (Huvenne and Davies, 2014), and provides evidence-based indicators to support planning of future research. We map the scientific landscape and overall trends of submarine canyons research based on the INCISE multidisciplinary literature database [dataset] (Ross et al., 2017). The analysis of the canyon research landscape addresses four specific objectives: (1) outlining the main knowledge clusters (and their relationships) in canyon research, (2) tracing canyon research evolution and detecting emergent research topics, (3) identifying the most well-studied submarine canyons and putative research biases, and (4) mapping the collaboration network of the canyons' scientific community.

2 Material and Methods

The epistemic analyses (analyses relating to knowledge) of the canyon research landscape were performed using the digital platform CorTexT (http://www.cortext.net). This tool offers a set of scripts developed to support the processing and analysis of large text corpora using information retrieval, natural language processing, scientometric methods and network analysis (Tancoigne et al., 2014). Complementary analyses and data visualization processing were carried out using R (Wickham, 2009; Gu et al., 2014; R Core Team, 2016; Chang et al., 2017).

2.1 Text corpus

The corpus was extracted from the INCISE database on the submarine canyon scientific literature [dataset] (Ross et al., 2017, last update August 2016). The foundation of this database was established during the 2nd INCISE meeting (Edinburgh, 2014) by the INCISE Working Group 2 and resulted from the recognized need for a comprehensive compilation of studies conducted in submarine canyons. The database was built with documents extracted from the scientific databases Scopus, ScienceDirect, the Thomson Reuters Web of Science and Google Scholar using the queries *"submarine canyon*"* and *submarine canyon** in the fields title, abstract and keywords. The documents retrieved were then checked individually and the ones not related with canyon research were excluded. Finally, the scientists from the entire INCISE community contributed their own canyon databases and references.

The selection of references for this study depended upon abstract availability. A total of 1968 references fulfilled this requirement, varying in type and scope, covering the period from 1929 to 2016 (Fig. 1). In addition to the abstract field, we populated the corpus with information regarding the research subject areas and categories, and author affiliations. The information on subject areas and category fields of the reference sources, retrieved from the SCImago Journal & Country Rank (SJR) classification, was available for 91.1% of the documents. The information on the author affiliations retrieved from Scopus was available for 79.1% of the documents.

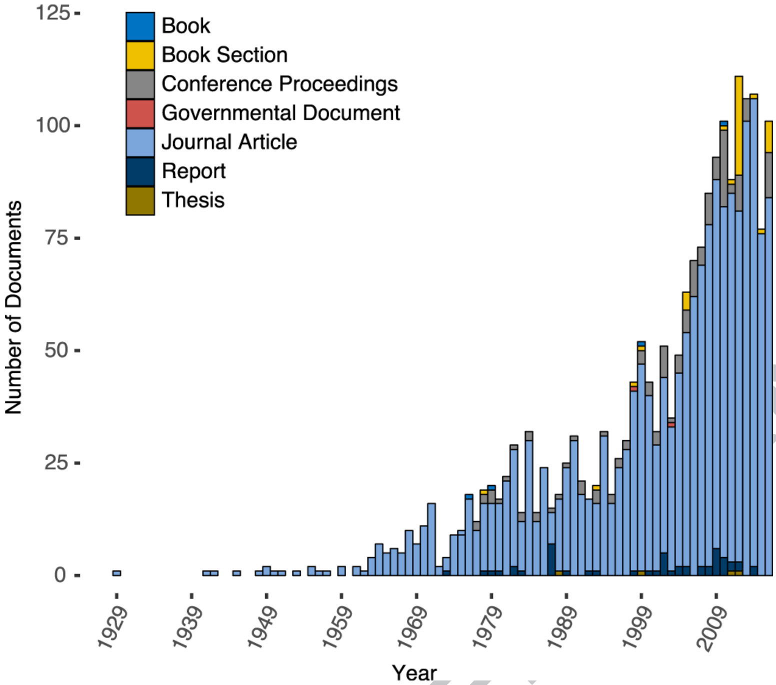

Figure 1 – Distribution of canyon related documents from 1929 to 2016, according to type. References composing the corpus were extracted from the INCISE canyons bibliographic database.

2.2 Extraction and systematization of terms

We built a preliminary list of 4500 lexical units (single- and multiword terms) from the abstracts and considered this list sufficiently explicit and informative for the analyses. We extracted terms using NLP methods, a process based on collocations of terms and sensitive to lexical variations (e.g., singular and plural forms) producing single lexical entities by root word. Terms such as measurement units, geographic references, dubious expressions and canyon names (treated independently) were removed. We classified the terms in the resulting list by research topic and reduced language ambiguity by sorting and merging all synonyms. After this process, we indexed the terms retained back to the abstracts allowing their detection and subsequent use in the analyses.

2.3 Mapping and network analyses

We built the networks using the most frequent entities (e.g., terms, canyon names, author affiliations) and their relationships. The links between entities were defined by a proximity measure based on the frequency of their co-occurrence. CorTexT divides proximity measures in two categories, direct (e.g., raw and chi-square) and indirect (e.g., distributional) depending on the transformation imposed on the data. The direct measures only consider co-occurrences between two elements not affecting the original statistics (for instance, the raw metric only considers the sum of all co-occurrences between two entities), while indirect measures ponder all co-occurrences in the network to determine a link between nodes (more information about these metrics available in: https://docs.cortext.net/metrics-definitions/). We applied the raw, distributional and chi-square metrics in order to construct collaboration networks (institutional affiliations and countries), homogenous networks (e.g., co-word mapping) and heterogeneous networks, respectively.

We estimated the *betweenness centrality* of terms which is a measure of centrality (Freeman, 1978) based on shortest paths between terms in a network. This measure allows us to identify the nodes that have the highest relevance to the information spread over the network.

2.3.1 Clustering

We determined the high-level structure (topical clustering) of the canyon research landscape using the Louvain community detection algorithm, which is capable of extracting cohesive groups from large networks (Blondel et al., 2008). We used a spatialization technique to optimize the arrangement of the nodes in a two-dimensional plot where spatial proximity represents the structural neighborhood of the clusters (Raimbault et al., 2016). The size of the nodes reflects the frequency of the terms, and the thickness of the links and distance between nodes encodes the frequency of the terms' co-occurrence. Depending on the network size and the number of links, we imposed a filter threshold and, for visual simplicity and readability, retained only a specified number of the most relevant connections. The resulting knowledge clusters encompass related nodes coded by color; the size of the circle drawn around each cluster is proportional to the number of documents containing the terms therein. Connections between nodes within a given cluster are stronger than connections between nodes of different clusters.

Every document entry in the corpus was matched against each cluster and labelled according to its content. This process allowed us to correlate the identified clusters with the most frequently-studied submarine canyons and with the research institutions through contingency matrices. These matrices were built considering the number of documents assigned to each variable and their correlation calculated against a null model assuming the independence of each distribution (Raimbault et al., 2016).

2.3.2 Research dynamics

We used a bottom-up reconstruction of the epistemic dynamics based on the tracking of terms over time to capture the evolution of scientific fields in canyon research (Chavalarias and Cointet, 2013). A river diagram illustrated the research dynamics following the methodology described in 2.3.1 using the top 100 terms. We divided the entire corpus (1929 - 2016) in 14 successive and regularly spaced time-slices of approximately 10 years each. Each time interval is partially overlapping with the previous one (four years) promoting a smoother flow of the existing research lines. We considered one decade as a reasonable time interval to capture research dynamics. Each period is composed of a group of vertical bars that correspond to distinct clusters in the network. This technique is sensitive to semantic changes (appearance and fading of terms), capturing the flow of concepts across time periods and recreating the dynamics of the research lines by the growth, forking, merging, or declining of thematic bars in a river plot. When relationships are detected between adjacent time periods, a stream flow connects the bars with a color intensity reflecting the degree of connection (see Chavalarias and Cointet, 2013, and Rule et al., 2015).

3 Results

Our analysis, namely the mapping of the research effort, the list of publications used, and the semantic and the collaboration networks, are available through an interactive online platform accessible at https://canyons-research-mapping.shinyapps.io/canyons-sci-landscape/ .

3.1 Corpus overview

The number of documents composing the corpus was low and irregularly distributed during the first half of the 20th century, but began to grow during the 1960s, and maintained a constant level until the mid-1990s when it started to steadily increase, with a considerable rise since 2004 (Fig. 1). Dominated by journal articles (88.5%), the corpus also includes conference proceedings, scientific reports, books, academic theses, governmental documents and maps. The information collected covers 814 clearly identified submarine canyon systems spread worldwide (Fig. 2). In some documents, the studied canyons were not formally designated and were not recognizable in the figures of publications, therefore their locations could not be mapped.

Most of the documents (67.9%) used in our analysis correspond to single canyon studies. Nevertheless, from the 814 listed canyons, eleven canyons account for a disproportionate research effort (about 48%). These most frequently studied canyons, with more than 50 associated publications each, are located along the North American and European continental margins and off Taiwan island: Monterey, Baltimore, Hudson, Gully, Nazaré, Lacaze-Duthiers, Cap de Creus, Blanes, Gaoping (Kaoping), La Jolla and Alaminos (ordered by decreasing number of publications).

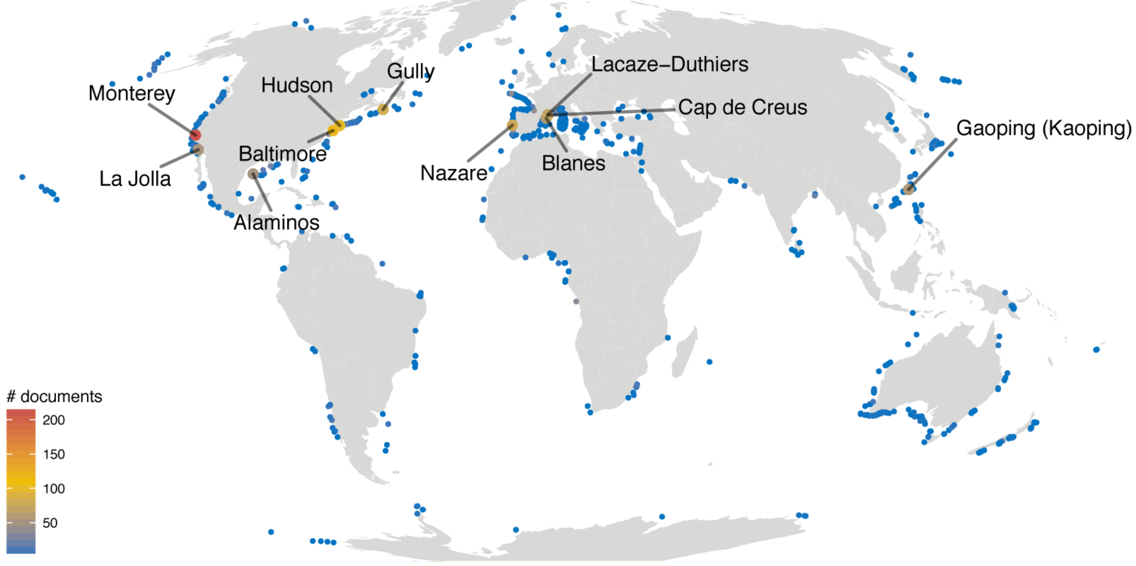

Figure 2 - Global distribution of the identified submarine canyons included in this study. The dots are colored according to the associated research effort (total number of documents). The eleven canyons linked to at least 50 publications are identified.

We identified a total of 105 subject categories corresponding to 23 major subject areas according to SJR. We included approximately 70% of the references in at least one of the subject categories (e.g., Geology, Oceanography) of the subject area “Earth and Planetary Sciences”, and ca. 34% in subject categories (e.g., Ecology, Evolution, Behavior and Systematics) of the subject area "Agricultural and Biological Sciences" (Fig. 3). Less common, although relevant, are disciplines associated with the multidisciplinary area of "Environmental Science" or related to areas such as "Engineering" and "Energy" focused largely on underwater technology, geotechnical studies, drilling, hydrocarbon exploration and environmental hazards. These results suggest a strong research investment in the study of canyon environmental settings, also noticeable in the most frequent terms identified in the abstracts (Fig. 4), which include "continental margin", "slope and shelf", "sea-level changes" and "fan systems".

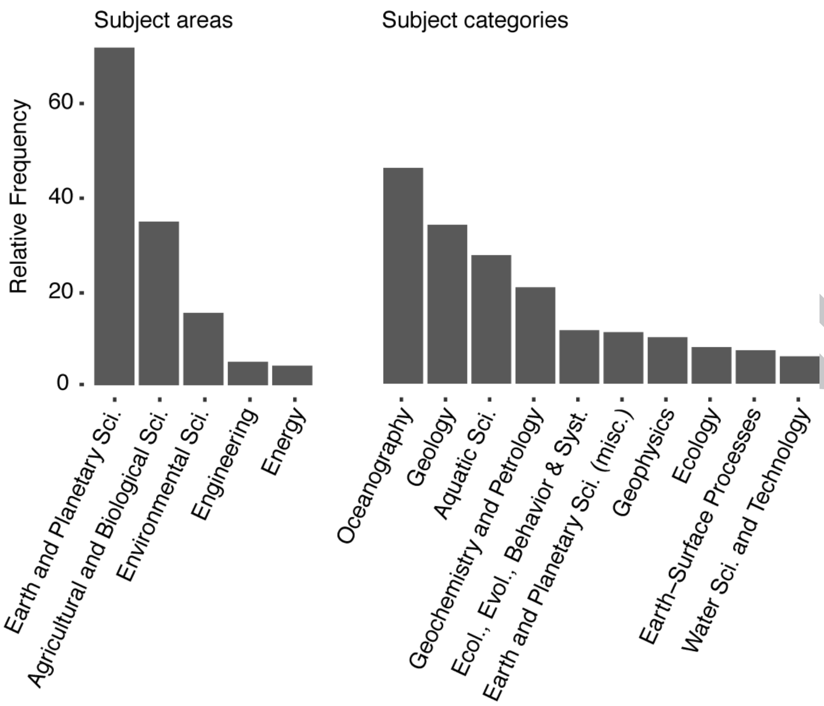

Figure 3 – The top 5 subject areas (left) and the 10 most frequent subject categories (right) in the full corpus according to the classification of the references' source in SCImago Journal & Country Rank (SJR). Sci. – Sciences; Ecol. – Ecology; Evol. – Evolution; Syst. – Systematics; Misc. – Miscellaneous.

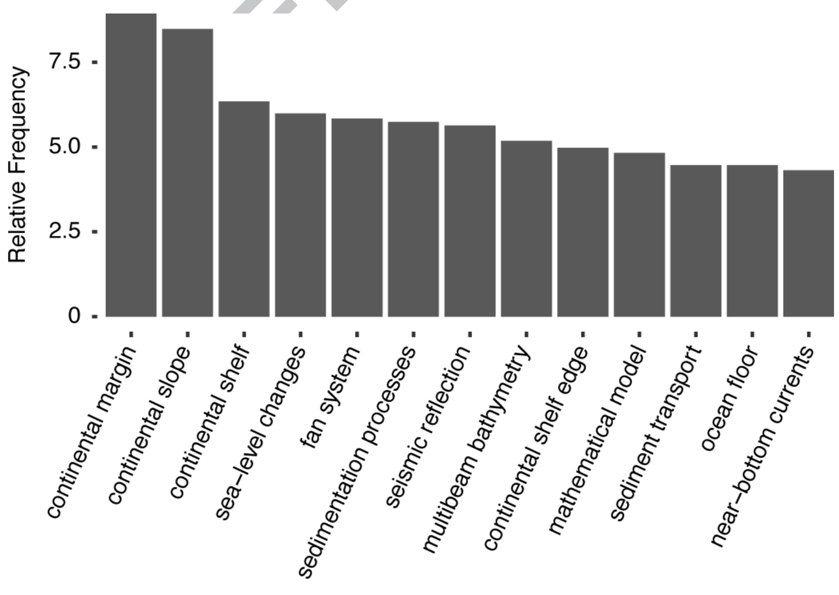

Figure 4 - The 15 most frequent terms occurring in the corpus.

3.2 Canyon research snapshot and retrospective overview

The synonymization process resulted in a list of 1084 terms which were indexed back to the abstracts for analysis. These terms, which are associated with one or more subject categories, constitute a varied and complex semantic landscape. We interpreted the semantic network considering its global structure and the internal organization of the clusters, namely, the position, connections and distance between nodes (Fig. 5).

Semantic co-word networks replicate the structure and relationships embedded in the corpus content. The labelling of clusters is based on their lexical content; however, since this is a static representation of the full corpus, it may not represent satisfactorily the whole context of the terms. This limitation may result in terms tagged under labels which would not usually be intuitive. An example is the inclusion of the term “marine sediments” under the category of “Biology & Ecology” (Fig. 5) mainly due the large number of publications in the last two decades related with infaunal studies. However, when considering a different period, for instance, the documents of the first three decades (results not shown), the same term appeared associated with knowledge clusters such as “Geology” and “Sediment Dynamics”. This shows that changes over time in the research topics associated to a given term are not retained by this static method. This limitation is overcome in the river diagram (Fig. 6) which we used to interpret the evolution of our understanding on canyons and the way it induced the direction of research lines.

Mapping of the abstract contents exposed 11 lexical domains that can be linked to distinct topics representative of the current knowledge clusters on submarine canyons (Fig. 5). The scientific fields detected confirm the trend already observed in the corpus overview (section 3.1), namely a research effort primarily directed to understanding the structural components of canyon systems. Despite the identification of distinct semantic units, the high-level structure of the network revealed an entangled connection pattern between knowledge clusters that reflects a latent interdisciplinarity in the canyon research spectrum. However, the evolution of the research lines suggests that this pattern has emerged only in recent years (Fig. 6).

The global picture from the river diagram conveys an absence of a semantic chain crossing the full-time span of our analysis, suggesting a lack of research continuity at least in the earliest years (1929-1960). Moreover, before the 1980s, canyon research was considerably fragmented with few publications covering rather disparate topics, which is expressed in the diagram by a high number of bars in each time interval and very few connections between successive time intervals. This pattern changes after the 1980-90s, with topic groups starting to be more cohesive, interconnected and comprehensively addressed in the literature (larger height of the bars) reflecting the growing deep-sea scientific community and knowledge buildup.

The largest knowledge cluster identified in the co-word network concerns the geological and geophysical characterization of canyons (“Geology & Geophysics”, Fig. 5). This is also one of the earliest topics arising in the canyon research historical record that we compiled (Fig. 6). This cluster is composed of terms related to the mostly geological survey and sampling of continental slopes and shelves (e.g., “seismic data”, “core samples”, “stratigraphic record”) and the search for relationships between the origin and evolution of submarine canyons with ocean eustasy (e.g., “sea-level changes”), tectonics (e.g., “tectonic activity”) and river systems (e.g., “river mouth”, “river inputs”). The role of these factors and of erosive processes (e.g., “mass-wasting processes”) on the canyons formation and evolution gave rise to new research lines dedicated to the study of “mass movements”, “turbidity flow”, “slope instability” and geo-hazards (e.g., “earthquakes”). In fact, these topics were recurrent along the history of canyon research in various branching systems of the river diagram (green, blue and yellow streams). Canyon research experienced an evident expansion between the 1960s and 1990s with the increasing effort on geophysical and geological surveys (e.g., the "Deep Sea Drilling Project", Fig. 6). These surveys deepened our understanding about the geological setting, geomorphology and sediment dynamics of canyons, highlighting the conduit effect of submarine canyons on materials transport and their deposition in fan systems.

Closely positioned and linked to the "Geology & Geophysics" cluster are three smaller clusters: "Sedimentology", "Sediments & Tidal Currents" and "Oil & Gas" (Fig. 5). The "Sedimentology" cluster is composed of terms related to sediment characteristics (e.g., "mineralogical composition", "grain size") and depositional structure (e.g., "physical stratification", "depositional features"), while the "Sediments & Tidal Currents" cluster is more focused on processes related to sediment transport and erosion (e.g., "downslope transport", "contour currents", "turbidite activity). The third group addresses aspects related to hydrocarbon exploration (e.g., "3D seismic", "Jurassic and Cretaceous periods", "deltaic deposits", "sedimentation basins"), essentially boosted during the 1960s and beginning of the 1990s by the investment in drilling programs and stratigraphic studies by academia, government agencies and private industry (stream system at the bottom of the river plot, Fig. 6).

The second largest research cluster is "Biology & Ecology". It covers a wide range of subjects including "trophic structure", "community composition", "spatial distribution" of emblematic organisms such as marine mammals (e.g., "whales") and "cold-water corals", but also commercially exploited species (e.g., "*Aristeus antennatus*"), their relationship with environmental factors, the effects of anthropogenic impacts (e.g., "fishing activities", "marine litter", "contaminants") as well as other conservation issues (e.g., "marine protected areas", identification and records of "Vulnerable Marine Ecosystems"). However, the research effort committed to these topics is traceable only in the last 30 years of the period covered by our analyses (Fig. 6), with some of these topics only addressed in the most recent years. Examples are the relation of species distributions to the canyon versus adjacent environments ("Community Composition & Adjacent Areas" bar, encompassing the period 2007-2016, Fig. 6), and the anthropogenic disturbance and conservation concerns ("ROV & fishing activities", same interval, Fig. 6). The technological developments and their growing application in oceanographic cruises, such as the use of remote operated vehicles (ROV) allowed recording and reporting of anthropogenic impacts in canyon ecosystems, namely, the documentation of fisheries, marine litter and contaminants impacts. Moreover, "ocean observatory systems" were also identified as one of the most important recent terms in canyon research associated with biological surveys.

Strongly connected and closely positioned to the "Biology & Ecology" cluster are two smaller clusters (Fig. 5): one shaped by terms linked to "Canyon Sampling" (e.g., "canyon sites") and studies of "foraminiferal assemblages" which includes references to the environmental setting (e.g., "pore-water", "water-sediment interface") and "climate change", and the other, "Biogeochemistry", focused on the study of "organic matter", "primary productivity", "terrigenous inputs", and references to studies on meiofaunal assemblages. Both clusters are less represented in the corpus and therefore their detection in the historical evolution of canyon research is difficult (Fig. 6). More distant in the network are two very small satellite clusters of the "Biology & Ecology" and "Geology & Geophysics" main clusters, one regarding "Molecular & Symbionts" studies and the other linked to the occurrence of "Chemosynthetic Communities" in submarine canyons, both poorly represented in the literature until recently.

The next cluster, “Oceanographic Processes”, occupies a nearly central position in the network sharing several connections with the more peripheral clusters (Fig. 5). This highlights oceanography as a core research topic in submarine canyon research. The terms composing this cluster are related to currents (e.g., current flow”, “near-bottom currents”), oceanographic phenomena (e.g., “dense shelf water cascading”), environmental seasonality (e.g., “winter season”), and particle transport (e.g., "sediment transport”, “suspended load”, “active conduit”, “lateral transport”). Although references to oceanographic processes are frequent in the corpus (Fig. 5), they do not stand out throughout canyon research history until recently (Fig. 6). The three time-intervals depicted in the dark cyan stream of the river diagram (between the bars “suspended sediment & marine storms” and “dense shelf water cascading & cascading events”) indicate a strong research investment in the study of environmentally complex, climate-driven oceanographic events, highlighting the emerging relevance of these topics in the last decades.

The complex biogeochemical interactions (e.g., “nutrient fluxes”) and the interaction between canyon topography and oceanography (e.g., “circulation patterns”, “flow interactions”) started to be explored mainly after the 1990s essentially by modelling approaches (both numerical and laboratorial). The last cluster detected was a “Modelling” hub, positioned in the upper part of the co-word network (Fig. 5) and widely connected to several other clusters. It is composed of terms linked to ocean current patterns (e.g., “current system”, “circulation model”), tides (e.g., “internal tides”), waves and environmental variables. More recently, modelling approaches started to be used in biology studies, namely of species spatial distribution patterns (tracked in the river diagram for instance, in the “Whales & Mathematical Models” bar, Fig. 6).

The 10 terms with the highest betweenness centrality are the top staple nodes in the canyon research landscape and have a determinant influence on the network structure and connectivity between knowledge clusters. These are: “active margin”, “adjacent slope”, “seismic reflection”, “sediment budget”, “sediment dispersal”, “burial efficiency”, “accretionary wedge”, “organic carbon”, “seasonal variation” and “flow dynamics.”. The terms “seismic reflection” and “accretionary wedge” shared connections only within the “Geology & Geophysics” cluster. The nodes “sediment dispersal” (Geology & Geophysics), “adjacent slope” (Biology & Ecology) and “seasonal variation” (Modelling) are connected to “Oceanographic Processes” highlighting, once more, the centrality of this knowledge cluster in canyon research. The connection between “Geology & Geophysics” and “Oceanographic Processes” is further reinforced by the node “sediment budget”. “Flow dynamics” established preferential connections between “Geology & Geophysics” and “Modelling”. The nodes “sediment dispersal” and “flow dynamics” from “Geology & Geophysics” and “sediment budget” from “Oceanography Processes” are also linked to the cluster “Sedimentology”, therefore reinforcing the connection between these two main clusters. The cluster “Biogeochemistry” links to “Geology & Geophysics” by the nodes “surficial sediments” and “active margin” and to “Biology & Ecology” by the nodes “organic carbon” and “adjacent slope” thus acting as a bridging topic between these two main knowledge clusters.

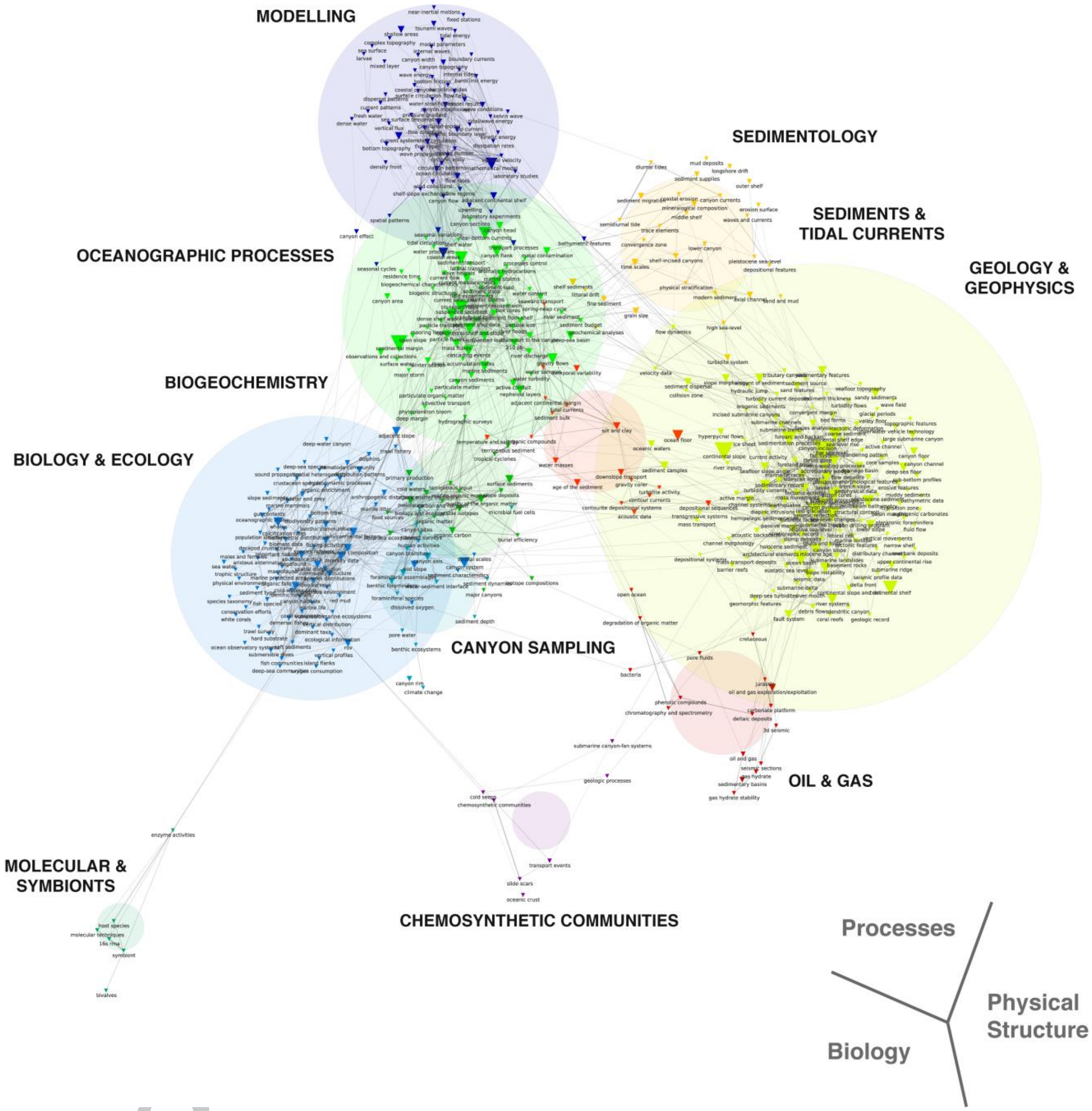

Figure 5 – Semantic network (measure: distributional, no filter applied to the edges) using the top 500 terms extracted from the abstracts. The 11 knowledge clusters are tagged according to their content and are globally divided in three categories (reading from the bottom-right, clockwise): canyons physical structure, biology and processes.

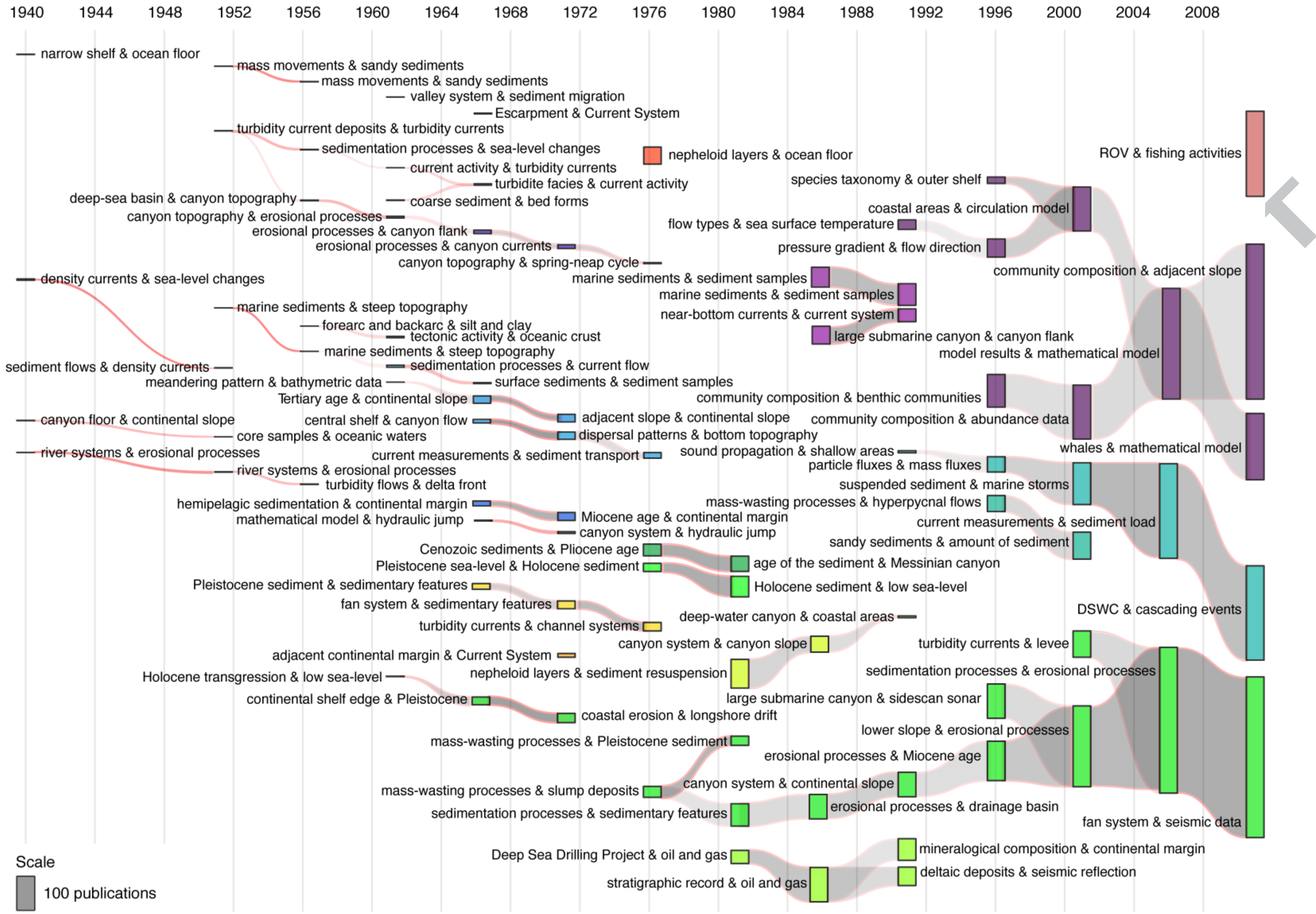

Figure 6 - River diagram illustrating canyon research dynamics over time (*x* axis) condensed in 14 time-snapshots of approximately 10 years each. Vertical bars represent the clusters detected in each time-period by the semantic network built with the 100 most frequent terms. Related clusters are connected between adjacent periods by a gray flow with a density reflecting the degree of connection. Vertical bars connected at any point in the timeframe share the same color and are considered as part of the same system. Different tones of the same color are indicative of clusters proximity. DSWC - Dense shelf water cascading.

3.3 Geographic and thematic research bias in canyon research

3.3.1 Research efforts in the most studied canyons

As previously mentioned (section 3.1) there is a strong imbalance in the observed number of publications in each canyon (11 canyons accounting for nearly half of the publication effort), which reflects a noticeable geographical bias in the allocation of research effort. Despite the considerable number of disciplinary fields explored in canyon research, there is some overlap in the explored subjects for the most frequently studied canyons (Fig. 7). The biases in the studies are typically in favor of either the physical structure and environmental processes or the biological component, a trend also observed in the contingency matrix relating the knowledge clusters with each canyon (Fig. 8).

In Figure 9 the geographical bias in canyon research is clearly depicted by the closer proximity of canyons from the same region, almost mirroring their geographical positions in a world map. The number of shared terms among the 11 canyons is rather low despite the multiple connection possibilities, which also reinforces the previous inference on thematic bias. The only exception, although affected by a geographical bias, was detected for the Mediterranean canyons, Cap de Creus and Lacaze-Duthiers. The work conducted so far in these two canyons was focused on shared research topics, predominantly related with “cold-water corals”, “dense shelf water cascading” and sedimentation processes. The geographically close Blanes Canyon, in turn, was studied mainly in terms of anthropogenic impacts (e.g., “fishing activities” and “marine litter”), “seasonal variations” and “fish communities”.

On the eastern margin of the Atlantic, the Nazaré Canyon is one of the most studied in terms of biodiversity patterns (e.g., “meiofauna”, “spatial distribution”, “organic matter” and “metal contamination”). On the opposite margin of the Atlantic, three canyons stand out with a high positive correlation to given knowledge clusters (Fig. 8): the Alaminos and Baltimore canyons are very frequently associated with terms related to “Oil & Gas” exploration and exploitation, while studies conducted in The Gully canyon are focused on “Biology & Ecology”, particularly with studies on marine mammals (“whales” and “dolphins”) and conservation (“marine protected areas”) (Figs. 8 and 9). The last canyon from the list in this region, Hudson Canyon, was mostly studied regarding fish and crustacean communities and water circulation.

Two of the most emblematic submarine canyons in terms of scientific surveys, Monterey and La Jolla submarine canyons, are both located in the USA margin of the north-east Pacific. Monterey Canyon is linked to the study of “chemosynthetic communities”, underwater technologies (e.g., “ROV”, “underwater vehicle technologies”), water circulation (e.g., “flow regime”, “upwelling”) and hydrodynamic modelling (e.g., “circulation model”, “mathematical model”) as well as the influences of near “coastal areas”, while the La Jolla studies were more focused on the sedimentary processes and features (e.g., “hemipelagic sedimentation”, “sedimentary features”) and “demersal fish”.

Lastly, in this list of the most studied canyons, the single example from the Asian margin is the Gaoping (Kaoping) Canyon, mostly described in terms of the river inputs (e.g., "river floods”, “river sediments”), sediments, hydrodynamics (e.g., “water circulation”) and tectonics related topics (e.g., "forearc and backarc”, “thrust zone”, Fig. 7).

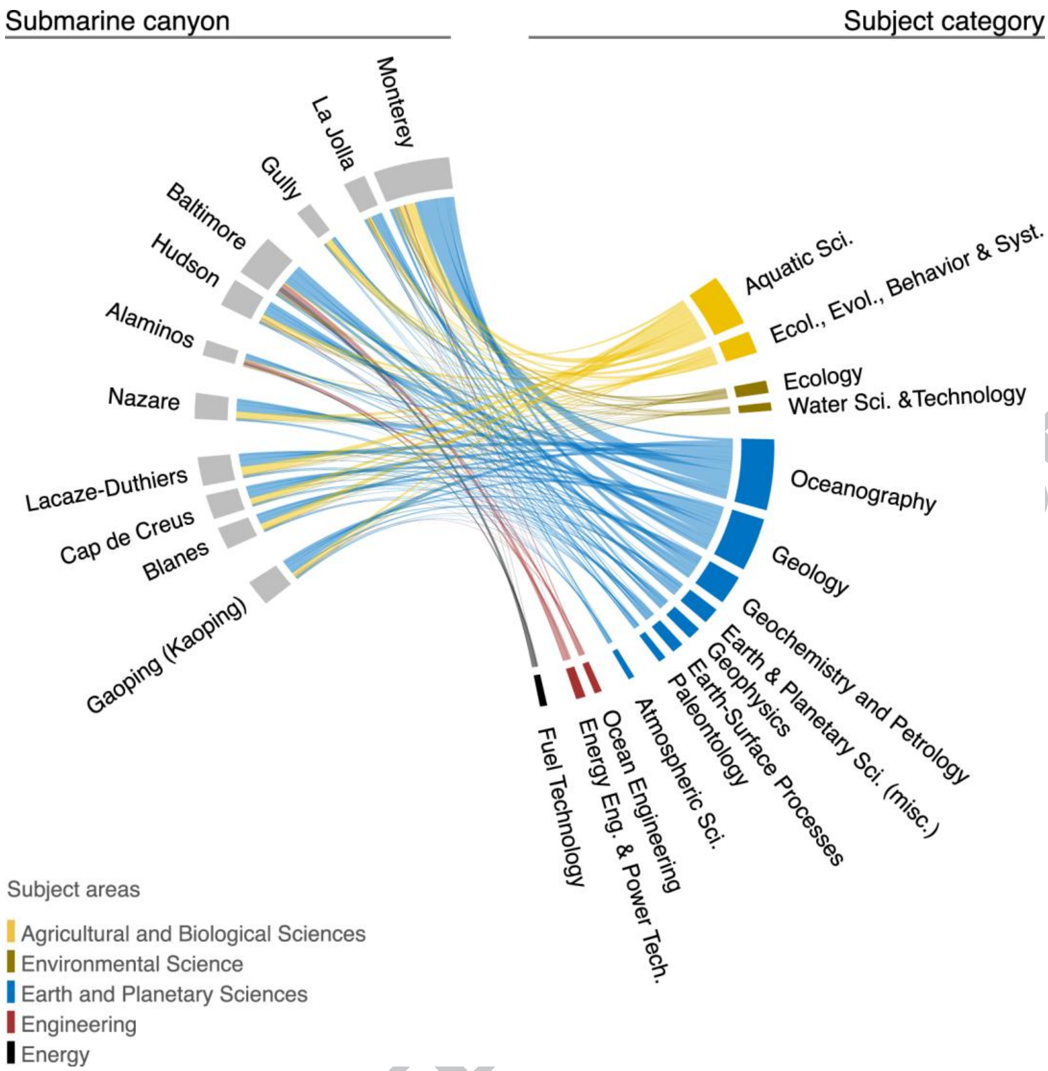

Figure 7 – Chord-diagram with the most well-studied submarine canyons in the corpus and related top 15 subject categories addressed. The arc length and the chord thickness are scaled to represent the number of documents associated to each entity while the colors correspond to the subject area where categories occur. Sci. – Sciences; Ecol. – Ecology; Evol. – Evolution; Syst. – Systematics; Misc. – Miscellaneous; Tech. – Technology.

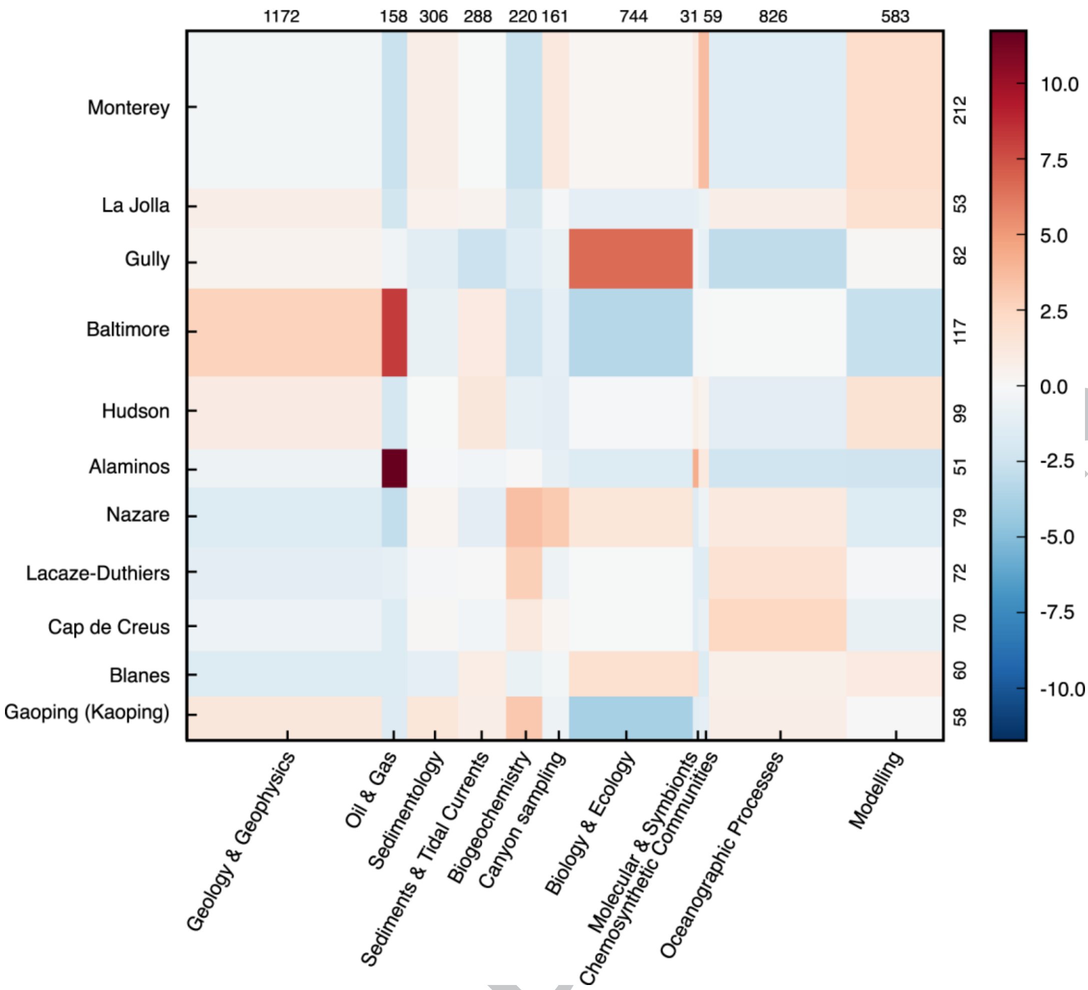

Figure 8 - Contingency matrix showing the correlation degree (chi-square score) between the top 11 submarine canyons and the topical clusters identified in the semantic network. The size of each cell is proportional to the number of documents. The color scale encodes how submarine canyons are positively correlated (red), not correlated (white) or negatively correlated (blue) with the topical clusters.

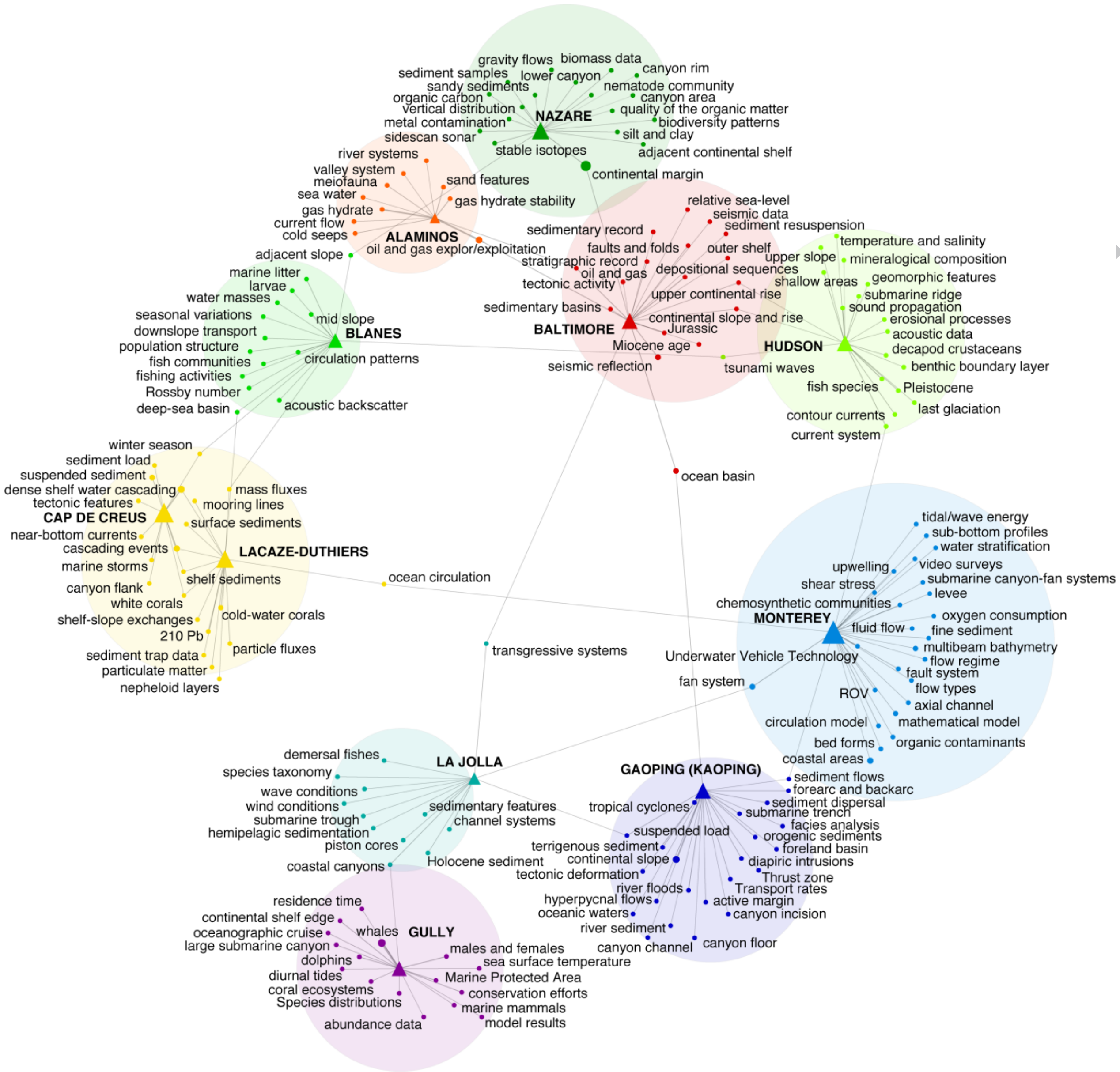

Figure 9 - The top 11 submarine canyons (triangles) and the top 300 most common terms in the abstracts (dots). Network built using the distributional proximity measure; no filter was applied.

3.3.2 International networking

International collaboration is strongly implemented in canyon research (Fig. 10), and the leading institutions were identified by the top 100 authors collaboration network (Fig. 11). The ten most prominent institutions were (by decreasing order, Fig. 12) the ICM-CSIC (Spain), US Geological Survey (USA), MBARI (USA), University of Barcelona (Spain), NOCS (UK), Scripps Institution of Oceanography (USA), IFREMER (France), Woods Hole Oceanographic Institution (USA), NIOZ (Netherlands) and University of Washington (USA). Although academia and governmental agencies were the main players in the canyon research arena, we also identified private companies operating primarily in the energy sector and geophysical studies (e.g., Chevron Energy Technology Company, AOA Geophysics Inc.) among the 100 most relevant contributors to canyon research.

We tagged the groups detected in the collaboration network with the five most relevant abstract terms in order to highlight the main research topics carried out by each one. The results suggest that the research networking tends to concentrate on specific subjects, also demonstrated by the high correlation of some institutions with the main knowledge clusters. Examples are the correlation of the US Geological Survey with "Geology & Geophysics" and "Oil & Gas", the University of Washington with "modelling hub", and the NIOZ with "Biogeochemistry". Some cross-disciplinary collaboration revealed by the links between clusters was also observed between institutions (Fig. 11 and 12).

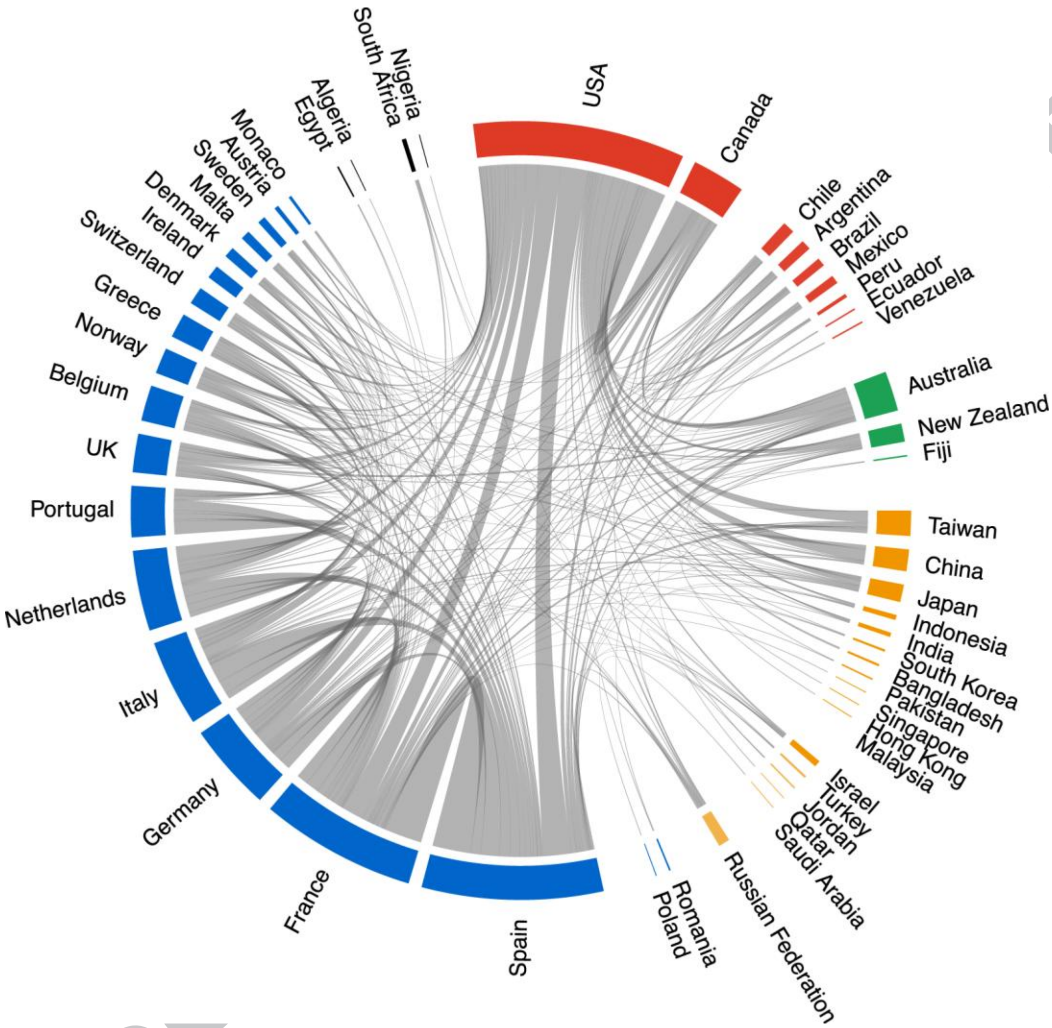

Figure 10 – Chord diagram of the international collaboration network at the country level, grouped by geographical region. When multiple institutions of the same country were present in the same reference, the country contribution was only counted once. The arc length is scaled to represent the total number of collaborations endorsed (an indicative measure of the countries investment in canyons research) while chord thickness between bands encodes the collaboration frequency between countries detected in the corpus.

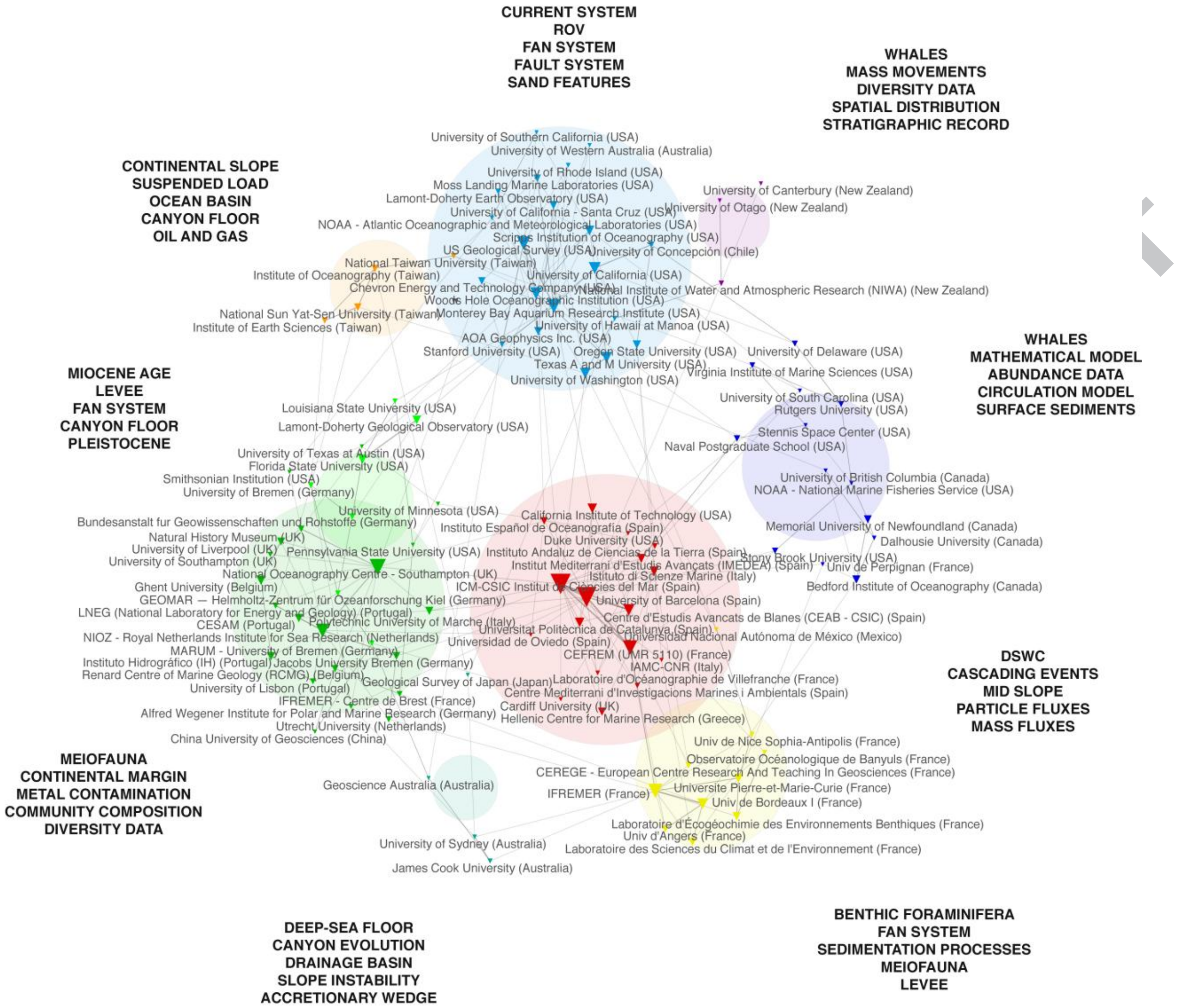

Figure 11 - Institutional collaboration network (top 100 authors affiliation from a total of 1092 institutions (measure: raw, threshold: top-3 neighbors). The clusters are tagged with the top 5 related abstract terms (chi-square metric). DSWC - Dense shelf water cascading.

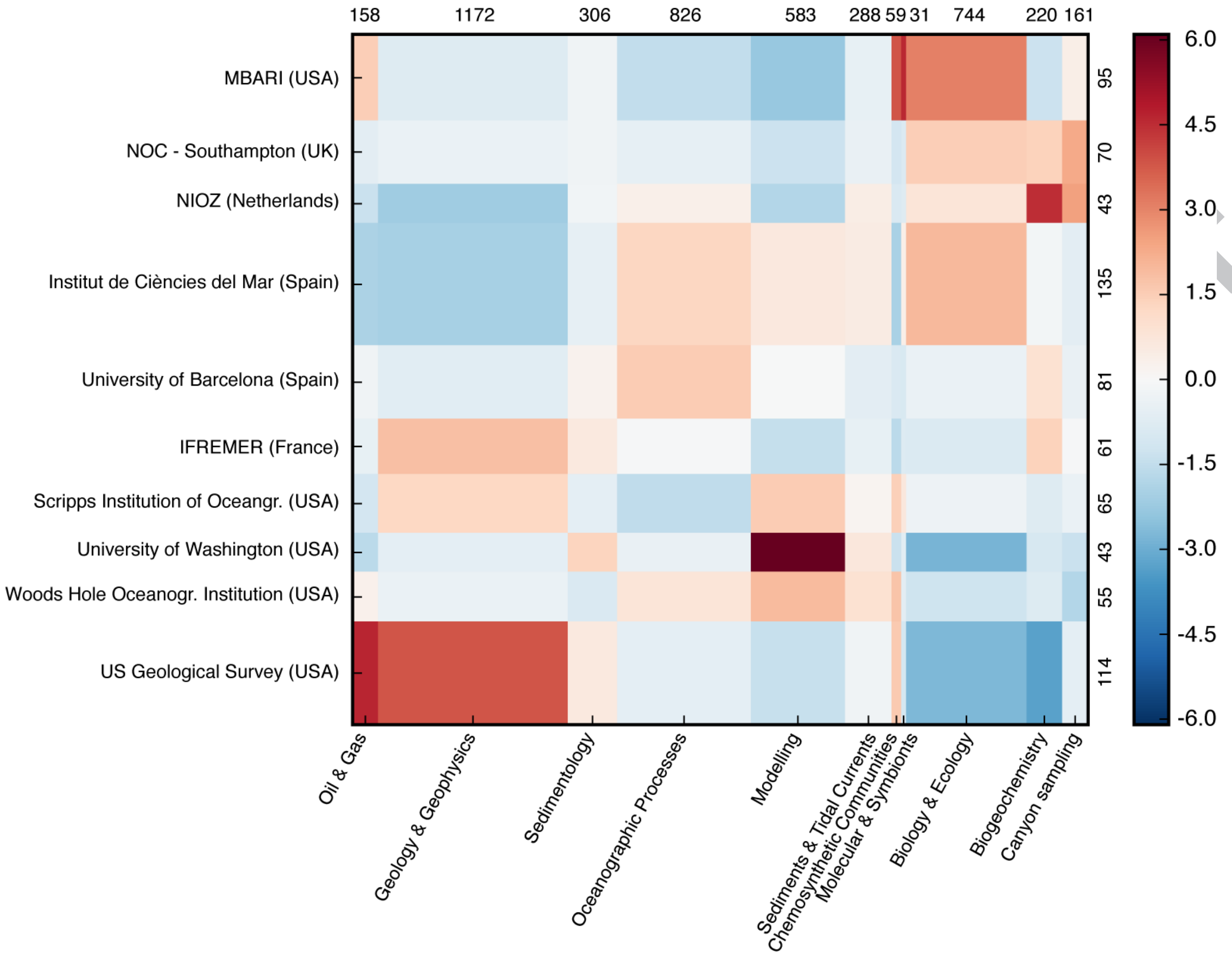

Figure 12 - Contingency matrix (chi-square measure) between knowledge clusters detected in the semantic network and the top10 institutions.

4 Discussion

The investments in submarine canyon research over the last 87 years have resulted in the development of a series of research fields, which is illustrated by a steady increase of research publications, especially in the past two decades. Although peer reviewed journal articles are the main vector for disseminating scientific results, topics regarding technology and resource assessment can be underestimated in this study because they are published in more difficult to access technical reports or other document types only for internal use within an organization. The early years are also less represented in the corpus, partly an artifact resulting from the absence of older works in digital format, but also a consequence of early difficulties imposed by greater technological and operational limitations. Furthermore, we only considered abstracts written in English, and therefore, some governmental and institutional documents written in other languages were possibly excluded. Despite these limitations, we believe that the main trends in canyon research were captured by our analyses, particularly in the most recent years where the number of documents was considerably high. As observed by Huvenne and Davies (2014) and corroborated by our results, the research effort committed to submarine canyons is unevenly distributed, not only geographically (11 canyons dominating the efforts) but also thematically. In general, most canyons are almost completely unknown. Of the 9500 canyons listed in Harris et al. (2014), we identified studies conducted in less than a tenth of those.

This preference towards particular canyons may be due to practical reasons like the ease of access and consequently reduced costs, a common caveat in deep-sea research (Oldham et al., 2014a), or scientific reasons because biologically productive or geologically unique canyons have long been recognized as the most relevant. This geographical and thematic bias coincides with the location of the leading research institutions and the expertise or fields of interest of their scientific teams, further enhanced by the scientific funding frameworks and amount of investment by each country or region. Moreover, once a specific canyon has been studied to a certain level, the accumulation of background data makes it easier and more attractive to continue further detailed studies or to conduct long-term time-series, a phenomenon described as the *Matthew effect* (Perc, 2014). The disproportionate efforts towards the study of some canyons may be a necessary step for research development. Continuous and multidisciplinary studies in some pilot systems optimize limited resources, allow understanding more factors and variables, identify new directions for future research and increase the robustness of the interpretation of new studies.

The most determinant traits of submarine canyon research are captured in the 11 knowledge clusters identified by the semantic network analysis. However, a sustained investment in canyon research will probably result in the development of fields still poorly explored (e.g., biogeochemistry, molecular studies), or the rise of new research lines. In fact, emergent topics (e.g., conservation and ecosystems services) requiring multidisciplinary approaches and/or the integration of social sciences, virtually absent in today's canyon research, will probably gain momentum in view of the growing societal concerns that drive present-day research funding.

The early interests leading the scientific exploration of submarine canyons and the prominent nature of physical processes operating therein resulted in a predominance of geological and geophysical studies. The most cited works in the corpus appear to be seminal in canyon research and, therefore, determined the evolution of different research lines. Landmark publications, concerning sediment sampling (Ericson et al., 1961), their transport (Gardner, 1989) and deposition (Curray and Moore, 1971; Damuth and Kumar, 1975), turbidity currents (Komar, 1971) and landslides (McAdoo et al., 2000), marked the stride of canyon research in geology, geophysics and sedimentology. Technological improvements in sampling methodologies (e.g., remote sensing, core sampling, ROVs) and, later, the economic interest associated with exploration for hydrocarbons likely contributed to maintaining the effort towards these knowledge clusters. The study of present-day processes with, for instance, moored instruments, instrumented tripods, or multibeam systems, revealed a significant dynamism in some submarine canyons shifting the paradigm about canyons' activity (e.g., Canals et al., 2006; Palanques et al., 2006) and attracting new disciplines. Many topics related to oceanography and biology started to be explored only more recently, also benefiting from technological developments in sampling (e.g., remote sensing, underwater vehicles, multi-parameter observatories) and modelling (e.g., computers' processing capacity, data access, big data). However, the links between "Modelling" and "Biology & Ecology" in the network are weaker or indirect reflecting the low number of studies already using modelling approaches to ecological problems. On the other hand, the close links between "Modelling" and "Oceanographic Processes", and to some extent also "Geology & Geophysics", reflect the development of fields such as operational oceanography dedicated to the systematic and long-term measurement of the oceans and forecasting. Ever more national or regional data portals provide useful forecasts and data products from operational oceanography based on a swift interpretation of ocean data and their dissemination to the public, governmental institutions and industry.

Oceanography arises as a central cluster, well embedded in the canyon research landscape and connected by the nodes with highest betweenness centrality. The evolution of oceanography in canyon research is not completely independent from other research lines, and it is difficult to track along the historical record. This might be because it shares many connections with other knowledge clusters, and it has been used as a fundamental tool to better understand complex interdisciplinary problems rather than being studied for its own merit. In the study of oceanographic processes, the work of Millot (1990) on dense water formation coincided with the origin of a stream system in the river plot (cyan bars, Fig. 6) focused on transport mechanisms of water and sediments. More recently, the works by Palanques et al. (2006) and Canals et al. (2006) highlighted the importance of climate driven extreme events (dense shelf water cascading) and the concern regarding global change which was reflected in a two-fold increase in publications.

Biological research in canyon ecosystems derived initially (mostly during the 1990s) from opportunistic sampling of infaunal (macrofauna and meiofauna) and foraminiferal assemblages in campaigns focused on characterization of the seabed. A strong relationship with the "Biogeochemistry" knowledge cluster is reflected by the importance of the nodes "organic carbon" and "burial efficiency". Pioneer studies were focused on community composition and structure. In one of the most cited canyon biology papers, Vetter and Dayton (1998) bring to the fore the importance of organic matter enrichment and its influence on benthic communities. Canyons as hotspots of biomass and productivity remained a central topic in canyon research as demonstrated by the often cited works of Schmiedl et al. (2000), Croll et al. (2005) and De Leo et al. (2010). Many studies (e.g., Ross et al., 2015; Demopoulos et al., 2017) tested for a possible *canyon effect* by comparing the biological assemblages of canyons and the "adjacent slopes" (a node with central importance in the network) in relation to their respective environmental settings. During the past decade, this knowledge cluster evolved continually with biology topics becoming greatly diversified and more interconnected with other disciplines through the study of biological processes (e.g., population connectivity, Perez-Portela et al., 2016) and the use of multi-disciplinary data retrieved from observatory networks (Matabos et al., 2014). The implementation of the ecosystem principles approach in deep-sea research (Jobstvogt et al., 2014) and the growing concerns regarding conservation and management issues, anthropogenic impacts and climate change (Fernandez-Arcaya et al., 2017), projected biology as a current hot topic in canyon research.

In the earliest periods of canyon research history, the lack of continuity in research lines, and their diversity despite the low number of studies, are consistent with the initially worldwide spatially fragmented research on canyons. However, we cannot ignore that this low number of studies may reduce the probability of terms co-occurrence. Furthermore, the distinctive nature of the canyons investigated (active vs. inactive canyons, size, topography), as well as the different scientific interests and research priorities of the teams involved, may have also contributed to this initial lack of connectedness. This pattern further developed into a thematic and geographical bias in canyon research with a preference of the canyon scientific community to address specific questions and specific canyons. These findings uncover a strong limitation, locally and regionally, to our interdisciplinary understanding of submarine canyons. Besides, since patterns captured from a single canyon may not be universally transposable to other canyons (Huvenne and Davies, 2014), this fragmented view hinders knowledge integration and prevents a comprehensive assessment of the patterns and processes that shape these outstanding geomorphological features and their associated ecosystems. Still, the international collaboration within the scientific community is becoming more deeply implemented in the current landscape, actively contributing to the research topic diversification, fundamental to the understanding of canyon systems (e.g., Amaro et al., 2016). In fact, the evolution pattern described here for canyon research follows some of the theoretical principles of scientific progress - the paradigm shifts, the knowledge spreading and the reinforcement of scientific collaboration increase the interdisciplinarity while developing and consolidating research lines (Chavalarias and Cointet, 2013; Salatino et al., 2017).

We now understand better the geological evolution and the structural and functional components of several canyon systems. However, the historical imbalance among disciplines, the lack of standardized approaches and paucity of robust inter-disciplinary research have hindered further advances in other topics, such as understanding functional interactions between the biota and canyon environment, or perceiving patterns of spatial and temporal variability within and between canyons. Progress in intrinsically cross-disciplinary fields like biogeochemistry, ecology and conservation as well as the growing utilization of modelling and molecular techniques, may help counteract these limitations. Moreover, the implementation of multidisciplinary ocean observatory networks and other concerted initiatives at the international level that use a standardized set of sensors and equipment to collect data on essential ocean variables (Lindstrom et al., 2012) are important steps towards the integration of knowledge at large temporal and spatial scales.

5 Conclusion

The geological and geophysical characterization, including processes involved in canyon formation and evolution, represent the main research topics addressed in submarine canyon research over the last 87 years. This emphasis is likely to persist with the worldwide increase in studies conducted in canyons and the technological advances in environmental surveys and habitat mapping. Even so, the historical disparity between the number of studies focused on the physical environment and on the biological component is starting to decrease.

The triad “canyons - research topics - leading institutions” typifies the canyon research landscape and is translated into regionalization and thematic bias: specific topics have been consistently addressed in the same submarine canyon by a given leading institution, typically based geographically close to that canyon. The lack of coherence in the set of traits and essential variables covered in different canyons hinders knowledge integration and a comprehensive assessment of submarine canyons’ physical and biological structure and functioning. However, continuous and multidisciplinary studies in some canyon model systems may have ensured the necessary background knowledge for the development of future research directions. Our results, based on an extensive and multidisciplinary set of submarine canyon publications, revealed that synergies between knowledge clusters have developed only recently. The investment in fields that are interdisciplinary by nature, technological advances and a strong international collaboration network should enable future comparative studies at regional and global levels and contribute to successfully addressing conservation issues and complex emergent research topics, such as the effects of anthropogenic impacts and climate change on submarine canyons.

This work depicts the status and historical trends of canyon research; the results are available through an open access, interactive online platform, offering the scientific community and stakeholders an informative tool to identify knowledge gaps, find key players in the global collaboration network and facilitate planning of future research in submarine canyons.

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- Eleven knowledge clusters were identified in canyon scientific research landscape
- Geology & Geophysics and Biology & Ecology are the most frequently published topics
- Concerns with human impacts and climate-driven processes emerged in the past decade
- Canyon research is led by a well implemented international collaboration network
- A spatial and thematic bias in canyon research limits knowledge integration