UiA University of Agder

Master

Do cold-water corals spatially correlate with submarine canyons in the Bay of Biscay?

A GIS study analysing the spatial distribution of cold-water corals along the seascape of the Bay of Biscay.

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Abstract

The seascape of the Bay of Biscay is a mysterious place. It is located to the west of France and the north of Spain and is often defined as well-differentiated geomorphological unit. The continental margin of the BoB is incised with many submarine canyons and is also thought to be a hotspot for cold-water corals. Unfortunately, it is an area under high anthropogenic pressure where intense fishing activity, bottom trawling especially, is causing major disturbances to benthic habitats such as cold-water corals. Cold-water corals have been well studied along the European margin and have more frequently been recorded in the northeast Atlantic than any other place in the world. They are often found along the heads of shelf-incised submarine canyons that offer suitable conditions for cold-water corals. This study is a Geographical Information Systems analysis with the objectives of (1) understanding the spatial distribution of cold-water corals along the seascape of the Bay of Biscay, (2) the spatial correlation between cold-water corals and submarine canyons, and (3) how well geomorphic features and benthic habitats are included in management measures of the region. Data includes the EMODnet bathymetry grid from 2018 with a resolution of 100 meters, a global cold-water coral dataset from WCMC and a global map of marine protected areas from protectedplanet.net. The results show that the majority of cold-water coral observations are located along the continental slope compared to the shelf and the abyss. In addition, the occurrence of CWCs is ~50% greater on continental slope areas outside of canyons compared to within canyons. Lastly, cold-water corals and submarine canyons are spatially well-covered by protected areas, but geomorphic features and benthic habitats are not properly included in the framework of the protected areas. This leaves them vulnerable to anthropogenic pressures. Further expansion of knowledge on geomorphic features and benthic habitats along the ocean floor is vital for successful conservation of the planet’s seascape.

Summary in Norwegian

Biscayabukta ligger vest for Frankrike og nord for Spania, og har en kontinentalsokkel som er rik på undervannskanjoner. Bukta er også antatt å være hjem til mange kaldtvannskoraller. Det er et område under høyt menneskeskapt trykk hvor intens fiskeaktivitet, spesielt bunntråling, forårsaker store forstyrrelser for bunnhabitater som kaldtvannskoraller. Kaldtvannskoraller blir ofte funnet innenfor de bratte veggene undervannskanjonene, spesielt langs toppen av kanjonen som er nærmest land. Dette studiet er en GIS-analyse av den romlige distribusjonen av kaldtvannskoraller langs sjøbunnen i Biscayabukten, i tillegg til å undersøke deres romlige sammenheng med undervannskanjoner. Analysen inneholder batymetri-data fra EMODnet fra 2018 med en oppløsning på 100 meter, et globalt kaldtvannskorall-datasett fra WCMC, samt et globalt kart over beskyttede havområder fra protectionplanet.net. Resultatene viser at flertallet av kaldtvannskorallobservasjonene finnes langs den kontinentale skråningen sammenlignet med sokkelen og avgrunnen. I tillegg viser studiet at forekomsten av CWC er ~50% større på kontinentale skråningsområder utenfor undervannskanjoner sammenlignet med innenfor undervannskanjoner. Kaldtvannskoraller og undervannskanjoner er godt dekket av beskyttede områder på et romlig nivå, men de er ikke inkludert godt nok i forvaltningsplanene til beskyttede områdene. Avslutningsvis er det viktig å utvide kunnskapen vår om undervannskanjoner og bunnhabitater for å oppnå vellykket bevaring av verdens havbunn.

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Preface

Writing this master's thesis has been a highly educational experience from the start until the end. I have been able to go into the depths of new topics and have developed my skills within GIS and general research. These are things I will bring with me in my further career, and I am very grateful to have had the chance to do this.

I want to thank Peter T. Harris and Miles MacMillan-Lawler, for their ideas, knowledge, inspiration and critical questions. Without them this thesis would not have been possible. A big thanks to Tove M. Gabrielsen, for maintaining the hard deadlines and keeping the rest of us in check. And to Ane T. Laugen, for her guidance and critical questions in the statistical analysis process.

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Arendal, May 28, 2020

Kaya Asdal

“With these surface waters, through a series of delicately adjusted, interlocking relationship, the life of all parts of the sea is linked. What happens to a diatom in the upper, sunlit strata of the sea may well determine what happens to a cod lying on a ledge of some rocky canyon a hundred fathoms below, or to a bed of multicolored, gorgeously plumed seaworms carpeting an underlying shoal. Or to a prawn creeping over the soft oozes of the sea floor in the blackness of mile-deep water.”

- Rachel Carson, The Sea Around Us

Abbreviations

BoB	Bay of Biscay, the Bay
CBD	Convention on Biological Diversity
CWC	Cold-water coral
DTM	Digital Terrain Model
EEZ	Exclusive Economic Zone
EMODnet	European Marine Observation and Data Network
EU	European Union
GIS	Geographical Information Systems
LME	Large Marine Ecosystem
MPA	Marine Protected Area
MSFD	EU Marine Strategy Framework Directive
NE	Northeast
NGO	Non-Governmental Organisation
OSPAR	The Convention for the Protection of the Marine Environment of the North-East Atlantic
ROV	Remotely Operated Vehicle
SDG	Sustainable Development Goal
VME	Vulnerable Marine Ecosystem

Chapter 1: Introduction

The seascape of the Bay of Biscay (BoB, the Bay) is a mysterious place. It is often defined as a well-differentiated geomorphological unit, that hosts many submarine canyons and is also thought to be a hotspot for cold-water corals (CWC). Unfortunately, it is an area under high anthropogenic pressure caused by intense fishing activities, marine litter and effects of climate change. These pressures highlight the importance of understanding the synergies along the BoB seascape, so that appropriate conservation measures can be applied that will help protect the geomorphic features, habitats and species located within the Bay.

Can better resolution bathymetric data help map submarine canyons in a more useful way compared to previously? What is the link between submarine canyons and CWCs in the BoB? Why is this interesting and why is it important to understand the relationship between CWCs and submarine canyons better? Is it even possible to study CWCs at such a large scale? Despite being a highly dynamic area in terms of human activities, very little is known about their effects on benthic habitats and geomorphic features. Is it an area in need of improved management strategies? This study aims to answer some of these questions through a geographic information systems (GIS) analysis of the Bay of Biscay.

1.1 Cold-Water Corals

Cold-water corals are azooxanthellate species, which means that they lack the iconic symbiotic algae that most tropical corals are associated with, and thus do not need sunlight to grow (Roberts *et al.*, 2009; Huvenne *et al.*, 2011). CWCs are cnidarian species that include stony corals, soft corals, black corals and calcifying lace corals (Lastras *et al.*, 2016). The Scleratinian white corals *Lophelia pertusa* (Linnaeus 1758; *L. pertusa*) and *Madrepoda oculata* (Linnaeus 1758; *M. oculate*) are the predominant reef-forming species in the northeast (NE) Atlantic, typically accompanied by the yellow *Dendrophyllia cornigera* (Lamarck 1816; *D. cornigera*; Lastras *et al.*, 2016). These corals are suspension feeders, preferring high energy hydrodynamic environments that prevent sediment deposition and promote hard substratum (Huvenne *et al.*, 2011; Lastras *et al.*, 2016).

CWCs have been observed at depths down to 5000 m on continental margins, seamounts and mid-ocean ridges. Here, they form meter-long structural habitats, mainly on steeper slopes such as cliffs, ledges or large boulders, but also on relatively level surfaces (Orejas *et al.*, 2009; Huvenne *et al.*, 2011; Lastras *et al.*, 2016). Their preferred temperature range is between 4 and 14°C (Huvenne *et al.*, 2011). Shelf-incising submarine canyons have been identified as a suitable CWC habitat due to the favourable conditions they offer (Reveillaud *et al.*, 2008; Orejas *et al.*, 2009; Harris and Whiteway, 2011; Huvenne *et al.*, 2011; Gori *et al.*, 2013; Lastras *et al.*, 2016). Unfortunately, ship-borne mapping and sampling techniques perform poorly in this heterogeneric terrain, which make such areas difficult to study (Huvenne *et al.*, 2011; Gori *et al.*, 2013; Hebbeln *et al.*, 2019).

CWCs have more frequently been recorded in the NE Atlantic than in any other region of the world (Reveillaud *et al.*, 2008). The presence of CWCs in the Bay of Biscay has been known since the late 19th century (Huvenne *et al.*, 2011; van den Beld *et al.*, 2017a). From the 2000s, CWC research increased due to the development of multibeam sonar bathymetric mapping, Remotely Operated Vehicles (ROV) and manned submersibles (Orejas *et al.*, 2009; van den Beld *et al.*, 2017a). These improvements in research techniques led to discoveries of CWCs in two of the most studied canyons in the BoB: the Avilés Canyon system on the Cantambrian margin and the Whittard Canyon on the Celtic margin (Fig. 3; van den Beld, 2017). The most common species of CWCs observed here are *L. pertusa* and *M. oculata* (Freiwald *et al.*, 2011; van den Beld, 2017). The canyons found within all the regions of the Bay of Biscay also host a range of other ecosystems such as anemone aggregations, sponge aggregations, cold seeps, hydrothermal vents and sea pen fields (Harris and Whiteway, 2011; van den Beld *et al.*, 2017a; Borja *et al.*, 2019).

CWCs act as structural habitats for many other species (Roberts *et al.*, 2009; van den Beld *et al.*, 2017a). They are long-lived and have slow growth rates, which makes them fragile and especially vulnerable to anthropogenic pressures (van den Beld *et al.*, 2017a). Once destroyed, many CWC habitats will not recover within the lifetime of humans and may cause a reduction of overall biodiversity in the area (Andrews *et al.*, 2006).

The Avilés Canyon is a structurally complex system consisting of three main canyons. In one of the three canyons, called La Gaviera Canyon, CWC reefs have been observed, mainly of the species *L. pertusa* and *M. oculata* (Sánchez *et al.*, 2014). The Whittard Canyon is another system that connects the shelf with the deep-sea Whittard channel (Huvenne *et al.*, 2011). The canyon itself is not connected to any terrestrial sources, so sediment input is therefore limited to shelf spill-over. CWCs have been found here between 880 and 3300 m deep, mainly on steeper slopes along the canyon walls (Huvenne *et al.*, 2011).

For the purpose of this study, CWCs have been divided into three subclasses of the phylum Cnidaria: (1) Hexacorallia (stony corals), (2) Octocorallia (soft corals), and (3) Hydroidolina (hydrocorals).

1.2 Submarine Canyons

Submarine canyons were first observed at the end of the 19th century at which point researchers struggled to comprehend the processes behind such large-scale seafloor features (Amblas *et al.*, 2017). The term *canyon* was originally applied to terrestrial valleys meaning "a deep and relatively narrow valley with high, steep slopes" (Shepard, 1972). Submarine canyons are the underwater equivalent, being similar in structure and appearance to their terrestrial cousins. They are incised into continental margins worldwide (Harris and Whiteway, 2011; Harris *et al.*, 2014), and play a fundamental role as conduits for sediment transfer from the continents to the depths of the abyss (Würts, 2012; Harris *et al.*, 2014).

Submarine canyons come in two categories: shelf-incising (type I) and blind (type II; Fig. 1). Shelf-incising canyons have heads (the top of the canyon) that intersect and cut across the continental shelf break/shelf edge (Fig. 1) and are on average over twice the mean size of blind canyons (Harris *et al.*, 2014; Bernardino *et al.*, 2019). In contrast to shelf-incising canyons, the heads of blind canyons do not intersect the shelf break and are instead completely confined to the continental slope (Harris and Whiteway, 2011; Amblas *et al.*, 2017; Bernardino *et al.*, 2019, Fig. 1). Due to the missing link to the shelf, blind canyons are less likely to transport organic matter from the continental shelf to the deep sea (Bernardino *et al.*, 2019).

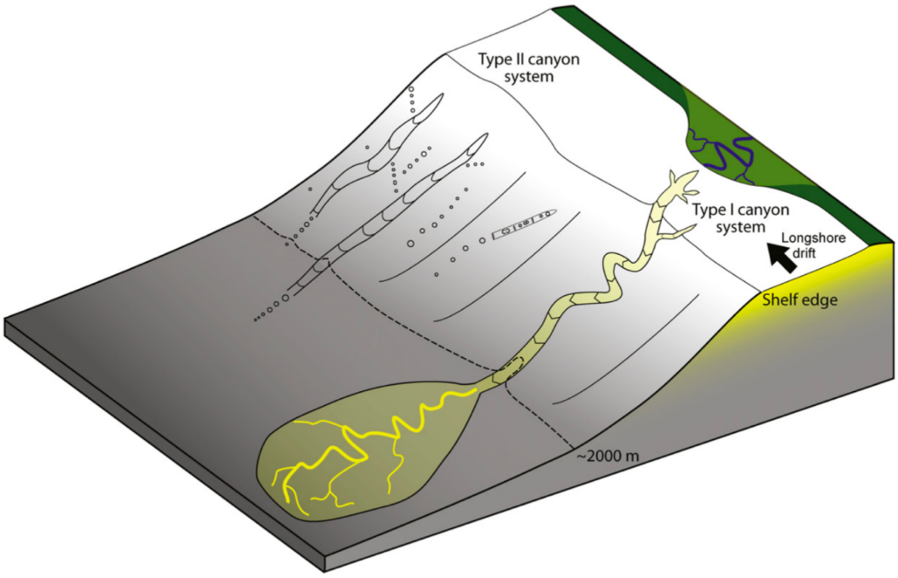

Figure 1: The difference between shelf-incising canyons (type I canyon system) and blind canyons (type II canyon system) along a continental margin. Reprinted with permission from from Zane Richard Jobe (Jobe *et al.*, 2011).

Canyons can vary in size, but to be able to distinguish larger canyons from smaller ones, Harris and Whiteway (2011) defined *large* canyons as "canyons that extend over a depth range of at least 1000 m and are incised at least 100 m into the continental slope at some point along their thalweg" (Harris and Whiteway, 2011). The line of lowest elevation along the length of the canyon is called a thalweg and may be bound by one or more terraces throughout the whole canyon (Amblas *et al.*, 2017). Small submarine valleys or gullies are commonly found both within and alongside submarine canyons and form part of their structure (Amblas *et al.*, 2017).

Globally, 9477 separate large submarine canyons have been identified (Harris *et al.*, 2014). One key distinction between the world's canyons is whether they are incised into an active continental margin, or a passive continental margin. Active continental margins are tectonically active and convergent, which means that they are located where a continental tectonic plate meets an oceanic plate. Passive margins on the other hand, are located where a continental plate abuts an oceanic plate without subduction (Nelson *et al.*, 2011).

Active continental margins are considered to have more tectonic activity such as earthquakes and volcanoes (Nelson *et al.*, 2011). In fact, there are 15% more canyons on active continental margins than passive margins (Harris and Whiteway, 2011). River-associated, shelf-incising canyons are more numerous on active continental margins compared to passive margins.

Additionally, the canyons along active margins are steeper, shorter, more dendritic and more closely spaced (Harris and Whiteway, 2011).

Submarine canyons are often found to be teeming with life, which is due to a range of hydrological processes. Accelerated currents, internal waves and shelf water cascading influence sediment accumulation within canyons and transport organic matter from the continental shelf into the deep sea (van den Beld *et al.*, 2017a). Internal waves cause enhanced mixing of water masses and nutrient release, resulting in increased primary production. This is further transported into the canyons where it is focused due to the oceanographic processes mentioned above (van den Beld *et al.*, 2017a).

1.3 Study Area

The Bay of Biscay is located in the NE Atlantic Ocean, to the west of France and the north of Spain (Fig. 2; van den Beld *et al.*, 2017b; Borja *et al.*, 2019). It is a passive margin formed by erosion and deposition processes (van den Beld, 2017). The abyssal plain of the Bay of Biscay represents around 50% of its total surface area and has a mean depth of 4800 m. The continental shelf on the southern part of the BoB is only between 12 to 30 km wide, while the northern part has a wide shelf of over 250 km (van den Beld *et al.*, 2017a; Borja *et al.*, 2019). The study site comprises the Exclusive Economic Zones (EEZ) of Spain and France, with a total area of 489539 km^2 (Fig. 2).

The continental slope of the Bay of Biscay contains approximately 135 submarine canyons, divided between the five margins (van den Beld *et al.*, 2017b). The Celtic margin has the widest shelf of more than 250 km (Fig. 3). It contains a range of canyons, most of which have heads containing cliffs formed by erosion (van den Beld, 2017). The Armorican margin can be divided into three zones: northern, central and southern. The northern Armorican margin is similar to the Celtic margin with a wide continental shelf (200 km) and many canyons. The central Armorican margin is characterised by an alternation of large and narrow canyons formed at different stages of development. Lastly, the southern Armorican margin contains less dendritic canyons compared to the northern and central margins (van den Beld, 2017).

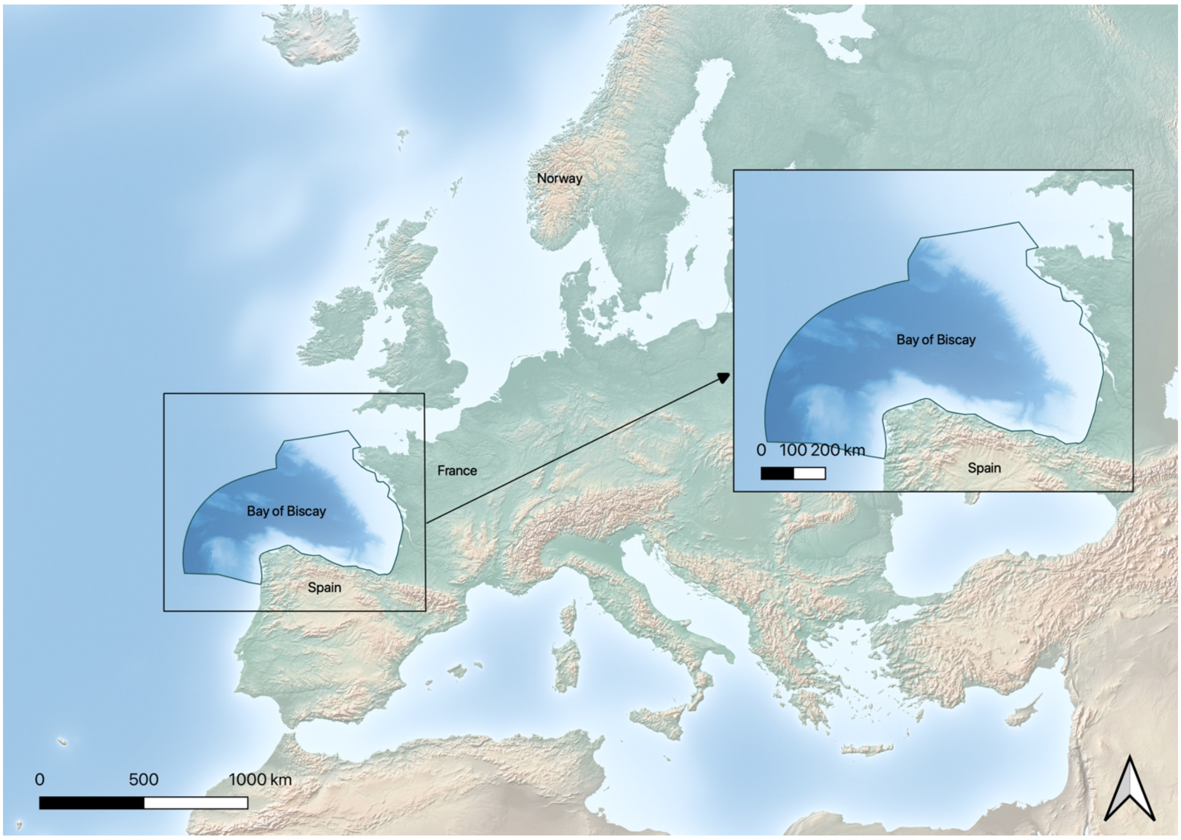

Figure 2: The study site includes the north Atlantic Exclusive Economic Zones of Spain and France, covering the entire Bay of Biscay.

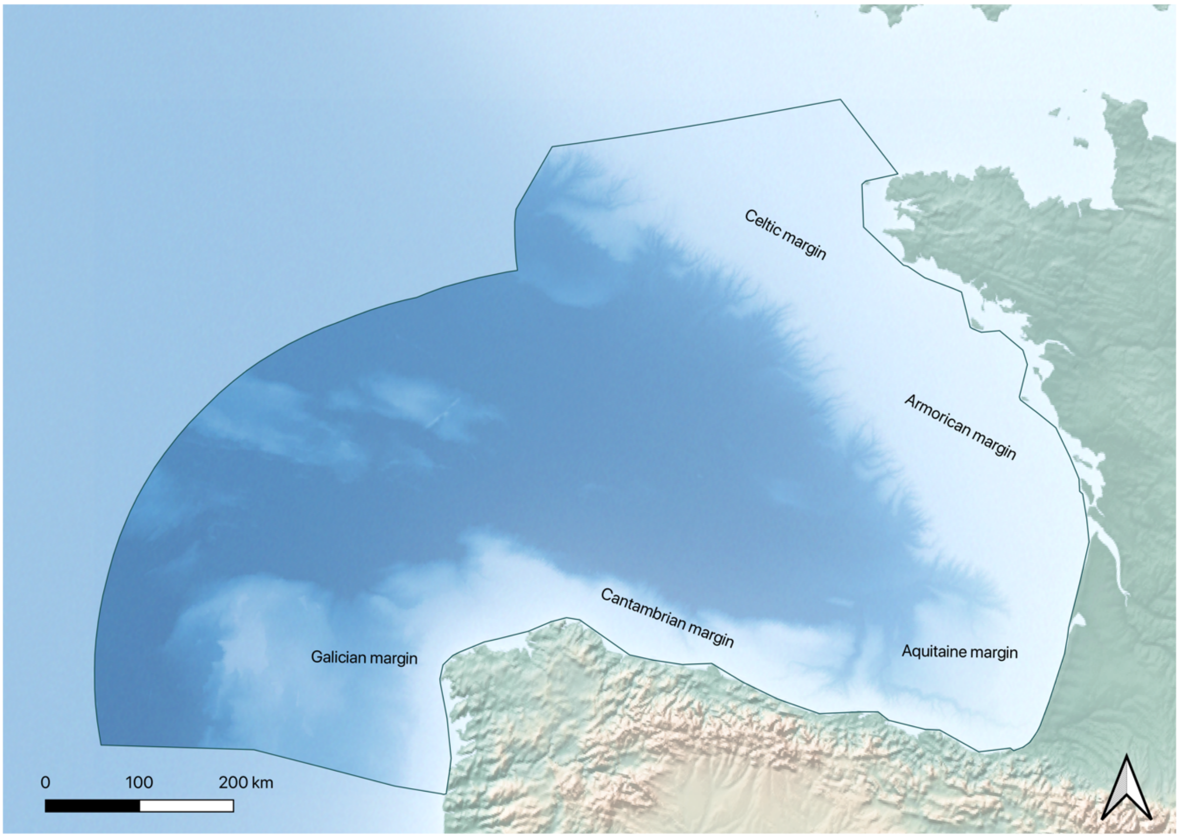

Figure 3: Bay of Biscay study site with its five margins: Celtic, Armorican, Aquitaine, Cantabrian and Galician.

The Aquitaine margin is the southernmost region off the coast of France, close to Spain (Fig. 3). It is also incised by canyons, but they are much less dendritic than the Celtic and Armorican canyons, and it is morphologically tectonic-dominated rather than canyon-dominated (van den Beld, 2017). The Cantabrian margin is the least studied of the Spanish margins. It ranges in depth from 40 to 250 m on the continental shelf to more than 4700 m on the abyssal plain (Gómez-Ballesteros *et al.*, 2014). It hosts the well-known Avilés Canyon System that contains four canyons, three of which fully cross the narrow margin from the shelf to the abyssal plain (Gómez-Ballesteros *et al.*, 2014). Both the Cantabrian and Galician margins are characterised by a narrow shelf allowing for strong continental input and high primary production caused by seasonal upwelling, they are also subject to a very high fishing pressure (Reveillaud *et al.*, 2008).

1.4 Anthropogenic Pressures

The Bay of Biscay is subject to a range of anthropogenic pressures including destructive fishing practices, maritime transport, marine litter and effects of climate change (Frank *et al.*, 2011; Amaro *et al.*, 2016; Fernandez-Arcaya *et al.*, 2017; van den Beld *et al.*, 2017b; Borja *et al.*, 2019). Combined with the high vulnerability of the deep ocean, this results in lasting effects on benthic habitats in the BoB (Gage *et al.*, 2005; Davies *et al.*, 2007).

Marine litter, especially plastic waste, has been found to accumulate in structural habitats in the Bay, particularly among CWC aggregations (Amaro *et al.*, 2016; van den Beld *et al.*, 2017a). In addition, ghost fishing occurring as a result of lost fishing nets has caused rising concern in the area (Hareide *et al.*, 2005). Canyons have been observed to act as sinks for marine litter in the Bay of Biscay, with a mean litter density an order of magnitude greater than the highest densities measured from trawling on the continental shelf (van den Beld *et al.*, 2017a).

In addition, climate change is causing problems such as increased ocean temperatures and ocean acidification (Davies *et al.*, 2007; Frank *et al.*, 2011; García-Barón *et al.*, 2019). These anthropogenic changes may have major effects on CWCs, which are very fragile and susceptible to destruction (van den Beld *et al.*, 2017b). Combined with the slow recovery of such ecosystems, this will result in a detrimental reduction in biodiversity (Davies *et al.*, 2007; Fernandez-Arcaya *et al.*, 2017).

In the NE Atlantic, phytodetrital (organic matter) deposits during spring and summer deliver between 2 to 4% of the spring bloom surface production to the seafloor (Gooday, 2002). Maritime shipping alters this balance by polluting surface waters, thus affecting the nutrient balance that is transported through canyons into the deep sea (Amaro *et al.*, 2016; Borja *et al.*, 2019). CWCs are strongly linked with areas of high surface productivity (Rogers, 1999), and disruption of such patterns may therefore cause major changes to CWC communities found on the shelf, along the continental slope and in abyssal regions of the BoB (Ruhl and Smith, 2004).

Furthermore, many of the rich deep-sea habitats in the BoB, including CWC communities, have been negatively affected by destructive fishing practices such as bottom trawling (Huvenne *et al.*, 2011). Fishing is one of the key human activities in the BoB and also one of the main causes of habitat destruction in the region (van den Beld, 2017). The mean depth of fishing has increased by 32 m per decade since 1950s in the North Atlantic as fishermen seek unexploited areas (Morato *et al.*, 2006). This is perhaps the most acutely severe cause of deep-sea habitat destruction and reduces local diversity which can have subsequent effects for the wider biodiversity (Huvenne *et al.*, 2011).

Destructive fishing practices such as bottom trawling also influence canyons by altering their suspended particle matter concentrations (Fernandez-Arcaya *et al.*, 2017). This will ultimately affect the species and habitats located on the seafloor that are reliant on a balanced and stable suspended particle matter concentration (Amblas *et al.*, 2017). A study assessing the fishing activity across marine Natura 2000 sites found that Spain and France are among the countries with the highest fishing pressure, and that destructive fishing occurs within 22% of protected areas designated for reef protection in the EU (Smith, 2017).

1.5 Management

In the past, individual marine activities would be managed by relevant sectoral management bodies, with no coordination of management actions. This did not start evolving until the First World Conference on National Parks and an International Conference on Marine Parks and Reserves, followed by the appearance of various Non-Governmental Organisations (NGOs) in the 1960s-1980s (Carleton Ray, 2004). Following this, *conservation science* appeared from the mid-1980s that resulted in the development of Marine Protected Areas (MPAs) and debates between scientists, conservationists, managers and policy makers on how to proceed in the best manner possible (Carleton Ray, 2004). A key shift from the original efforts that focused on single species conservation was the more ecosystem-based approach to management. This means that rather than focusing on individual species, the emphasis lies on the uses and values of entire ecosystems instead (Gibson, 2005).

Management strategies have been developing since and there are now many tools at hand when planning and implementing marine protection measures (Gibson, 2005). In order to better manage human impacts on sensitive deep-sea ecosystems, there are a number of sector specific management tools used (Hebbeln *et al.*, 2019). For fisheries, Vulnerable Marine Ecosystems (VMEs) are often applied as a means to classify vital and vulnerable ecosystems. The deep-sea ecosystems in the Bay of Biscay, including CWC, anemone aggregations, sponge aggregations, cold seeps, hydrothermal vents and seapen fields, are classified as VMEs (Hebbeln *et al.*, 2019). The scientific classification *Large Marine Ecosystems* (LMEs) is often used to focus management actions and applies to selected areas of ocean based on high surface ocean primary production (Harris and Baker, 2012). They are usually larger than 200 000 km^2 and found adjacent to the continents in coastal waters (Fischer *et al.*, 2019).

There are two LMEs in the Bay of Biscay, though they are most often referred to as a single entity due to the similar biogeographical patterns they hold (de Groot, 2002). VMEs are biodiversity hotspots often found within LMEs that reflect the structural complexity of benthic habitats in addition to enhanced diversity and biomass (van den Beld *et al.*, 2017b). Declining ocean biodiversity and destruction of VMEs has caused rising concern globally, which has resulted in international agreements such as the Convention on Biological Diversity (CBD) (Fischer *et al.*, 2019).

In 2010, the Parties to the CBD created a Strategic Plan for Biodiversity 2011 that included twenty time-bound and measurable targets called the Aichi Targets (CBD, 2014; Fischer *et al.*, 2019). Aichi Target 11 states that by 2020:

> "… 10% of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well connected systems of protected areas

> and other effective area-based conservation measures, and integrated into the wider landscapes and seascapes" (CBD, 2016).

There has been progress in reaching the 10% target, but there is still a lack of areas of ecological importance set aside to be protected (Fischer *et al.*, 2019). The Aichi Targets have been emphasised by the United Nations 2030 Agenda Sustainable Development Goals (SDGs), where SDG-14 states: "Conserve and sustainably use the oceans, seas and marine resources for sustainable development," and SDG-14.5: "By 2020, conserve at least 10 per cent of coastal and marine areas, consistent with national and international law and based on the best available scientific information" (UN, 2018).

A 2019 study assessing the feature coverage and diversity within existing protected areas in LMEs and EEZs, found that only 27% of LMEs worldwide protected more than 10% of their marine geomorphic features and benthic habitats (Fischer *et al.*, 2019). Only 20% of EEZs had more than 10% of their geomorphic features and benthic habitats within MPAs (Fischer *et al.*, 2019). The Atlantic Ocean, which is very geomorphically diverse, had the smallest area of features within protected areas (Fischer *et al.*, 2019).

The Convention for the Protection of the Marine Environment of the North-East Atlantic was first initiated in Oslo in 1972 ("OS") and later extended in Paris in 1974 ("PAR"), hence the acronym OSPAR. It involves 15 governments which, along with the European Union (EU), cooperate to protect the marine environment of the NE Atlantic (OSPAR, 2019). OSPAR has listed threatened and declining habitats in the Bay of Biscay including coral gardens, deep-sea sponge aggregations and the CWC species *L. pertusa*, all of which are likely to be found in submarine canyons (ICES CIEM, 2018). There are several OSPAR MPAs in the Bay of Biscay (OSPAR Region IV: Bay of Biscay and Iberian Coast), but they have not been changed since 2016 and gaps still remain in the north-western coverage (Hennicke and Werner, 2018).

In terms of OSPAR habitat protection in Region IV, one deep-sea sponge aggregation, one *L. pertusa* reef and one coral garden have been identified and are under protection (Hennicke and Werner, 2018). Only 3 out of 8 habitats that are listed as threatened are covered in the region, which is the second lowest of all five OSPAR regions. Submarine canyons are not included in any of the listed features (Hennicke and Werner, 2018).

The collective EU-wide network of protected areas is called Natura 2000 and was established in 1992 (Kreft and Gungoroglu, 2019). The aim of Natura 2000 is to “conserve ecosystems (‘habitats’) and species of outstanding conservation importance by applying appropriate measures for their protection and restoration”, with the combination of the Habitats Directive and Birds Directive as the underlying legal framework (Kreft and Gungoroglu, 2019). There are 204 Natura 2000 sites in the Bay of Biscay and the Iberian Coast, which equals to 15.9 % of EU waters of the region (Fig. X2; EEA, 2018).

Habitats Directive has four annexes that list protected habitats and species within the framework. Annex I focuses on habitats among which reefs are listed as an ecosystem in need of protection (Johnston *et al.*, 2000). Submarine canyons can be found within many Natura 2000 sites. However, despite being increasingly acknowledged for their ecological importance, they are not properly represented in the network in terms of specific management measures (Würts, 2012). In the Bay of Biscay, the two largest Natura 2000 sites are located on the Celtic and Armorican margins. They cover the majority of the canyons on the Armorican margin, but are under the Birds Directive framework and thus do not offer any protection to benthic habitats (Würts, 2012).

The EU Marine Strategy Framework Directive (MSFD) aims to achieve Good Environmental Status in European waters by 2020 (Galparsoro *et al.*, 2014; García-Barón *et al.*, 2019). The Bay of Biscay and Iberian coast is represented in MSFD Article 4. Compared to the Habitats Directive, which aims specifically at certain habitats or species, MSFD focuses on applying an ecosystem-based approach to management of human activities generally within an area (Marine Strategy Framework Directive, 2012). In general, the Bay of Biscay is largely covered in MPAs. However, according to this literature review they offer very limited protection to benthic habitats thus leaving CWCs at risk.

1.7 Aims and Objectives

Is there a spatial relationship between submarine canyons and CWCs in the BoB? Why is this interesting and why is it important to understand this relationship better? Is it even possible to study CWCs at such a large scale? And is the BoB an area in need of improved management strategies? These are some of the questions this study aims to answer.

The objectives of are (1) to analyse the spatial distribution of cold-water corals along the seascape of the Bay of Biscay, (2) to analyse the spatial correlation between cold-water corals and submarine canyons, and (3) to understand how well geomorphic features and benthic habitats are included in management measures of the region. This will be done through a large-scale analysis conducted using GIS.

It is expected that there will be a spatial relationship between CWCs and submarine canyons, based on previous studies and the favourable conditions found within canyons. It is also expected that the majority of CWC observations will be located along the continental slope, compared to the shelf and the abyss. This is because the steep slopes along the continental slope will lead to less sediments accumulating, resulting in favourable conditions for the CWCs.

Further, depth and slope ranges of CWC observations will be analysed in order to ascertain if such variables can be used as a proxy for the occurrence of CWCs. Alongside this, another objective is to understand whether or not higher resolution data from 2018 (100 m resolution) will result in a more detailed classification of canyons as a geomorphic feature compared to lower resolution data from 2012 (1000 m).

Chapter 2: Methods

2.1 Datasets and Software

The study was based on a 2018 dataset from the European Marine Observation and Data Network (EMODnet). The bathymetric data in this dataset was from single and multibeam surveys that were integrated into the EMODnet Digital Terrain Model (DTM). The 2018 dataset was a new version with a higher resolution of 1/16 * arc minutes compared to the 2012 bathymetric data used by Harris *et al.* 2014 with 1/2 * arc minutes resolution in their global mapping of seafloor geomorphic features. Three tiles were downloaded, covering an area inclusive of the EEZs of Spain and France. The old bathymetric grid used by Harris *et al.* 2014, SRTM_v8, was included as a comparison.

In order to focus the study area to the EEZs of Spain and France exactly, version 9 of the world EEZ boundaries was downloaded from Marineregions.org. A point dataset showing the global distribution of CWC was downloaded from data.unep.wcmc.org, and lastly a shapefile containing the world's MPAs was downloaded from protectedplanet.net.

An open source GIS software called QGIS (version 3.4 followed by 3.10) was used for the data analysis of this study. Compared to other software such as ArcGIS, QGIS is free and it works on a Mac, which is why it was selected. For the statistical analysis, the programme R was used which is again, open source and user friendly for the Mac operative system.

2.2 QGIS

Spatial analysis was conducted in QGIS version 3.4/3.10.

The original 2012 bathymetric grid (STRM_v8) showed depth as negative values. The 2018 EMODnet layer had positive depth values and had to be inverted to allow for comparison of the two grids. This was done by using the QGIS raster calculator to multiply the depth values by -1. Three tiles were downloaded from EMODnet and each of them were inverted and then merged into one layer using the GDAL *merge* tool. Further, the EMODnet layer (three tiles merged into one layer) were compared to STRM_v8 by creating a layer showing the difference in depth between the 2012 and 2018 data. This was done using the raster calculator to subtract the STRM values from the EMODnet values and changing to a suitable colouring.

In order to study the differences in degrees of slope and to assign a slope value to each CWC, a new layer containing degrees of slope was created using the *raster analysis* tool and altering the colouring to match appropriate slope classes. To aid in the classification of the shelf, continental slope, canyons and abyss, contour lines were created on top of the bathymetric data to show the contours of the seafloor making it easier to accurately map the features. Using the raster *extraction contour* tool, contour lines of different intervals (100, 250, 500 meters) were set. In the end, polygons of the shelf, continental slope, canyons and abyss were created. This was done by creating new polygon layers using the contour lines and slope layer with a 1:300000 scale and 80% magnification.

CWC point data was inserted, but the points were multipoints meaning that they were connected to each other. This had to be changed in order to select only the points within the study area using the SAGA *vector point* tool and saving as a new layer. Further, the points outside of the study area were deleted, leaving only the CWC points within the study area. Depth values from the EMODnet layer and slope values from the slope layer created, were added to the CWC points using the SAGA *vector <-> raster* tool. The mean slope and depth values for each canyon were generated from the grids by using the SAGA *add raster values to features* tool.

Lastly, each CWC point was assigned a value to show whether they were located on the shelf, continental slope, abyss and inside or outside of a canyon using the canyon polygons previously classified and the vector research *select by location* tool. The selected points were given a value 1 using the raster calculator in a new column created in the attributes table with the points outside of the zone or feature given the value 0.

This process resulted in a CWC dataset with an attributes table containing slope values, depth values and whether they were located on the shelf, continental slope or abyss, and in/out of canyon. Some of this data was further used to conduct create plots in R.

2.3 R

R software version 3.6.2 (R Core Team, 2019) and the packages tidyverse and ggplot2 were used.

Tidyverse was used to tidy up the dataset and extract the parts of the CWC attributes table that were relevant to the study (Wickam *et al.*, 2019), and ggplot2 was used to create the different plots used in the study (Wickam, 2016).

Although the CWC dataset included 75 different species, the number of observations per species was very low for most of them, ranging from 1 to 359. This resulted in the study being based on the 3 subclasses: Hexacorallia (n=202), Hydroidolina (n=13) and Octocorallia (n=583).

Chapter 3: Results

3.1 Analysis Area

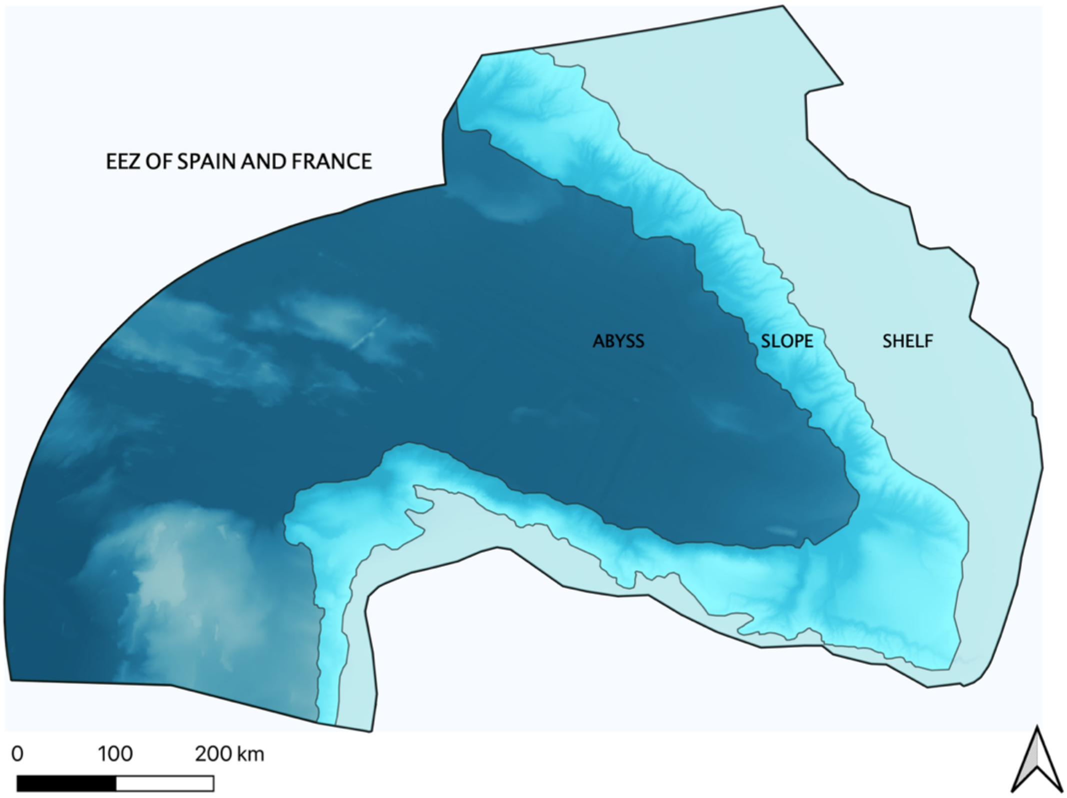

Figure 4: Study area including the EEZs of Spain and France along with classifications of the shelf, continental slope and abyssal floor.

Classification of the zones on along the seafloor (Fig. 4) show that the majority of the Bay of Biscay consists of the abyssal plain with a proportion of 55% (Tbl. 1). The shelf comprises 25,1% and the continental slope 19,9%.

Table 1: Area and proportions of shelf, continental slope and abyss within the study area.

Zone	Area (km^2)	Proportion (%)
Shelf	121229	25,1
Continental slope	96027	19,9
Abyss	265541	55
EEZ Spain & France	482797	100

3.2 Difference Between 2012 and 2018 Data

The new bathymetric data (EMODnet 2018) has a higher resolution and a different interpolation compared to the old data (STRM 2012), resulting in some differences in the dataset (Fig. 5). The largest differences are shown in dark blue and brown. Dark blue represents areas where the depth has increased by up to 500 m, and brown shows where the depth has decreased by up to 500 m. The majority of areas of both increased (dark blue) and decreased (brown) depth are located around and within canyons (Fig. 5).

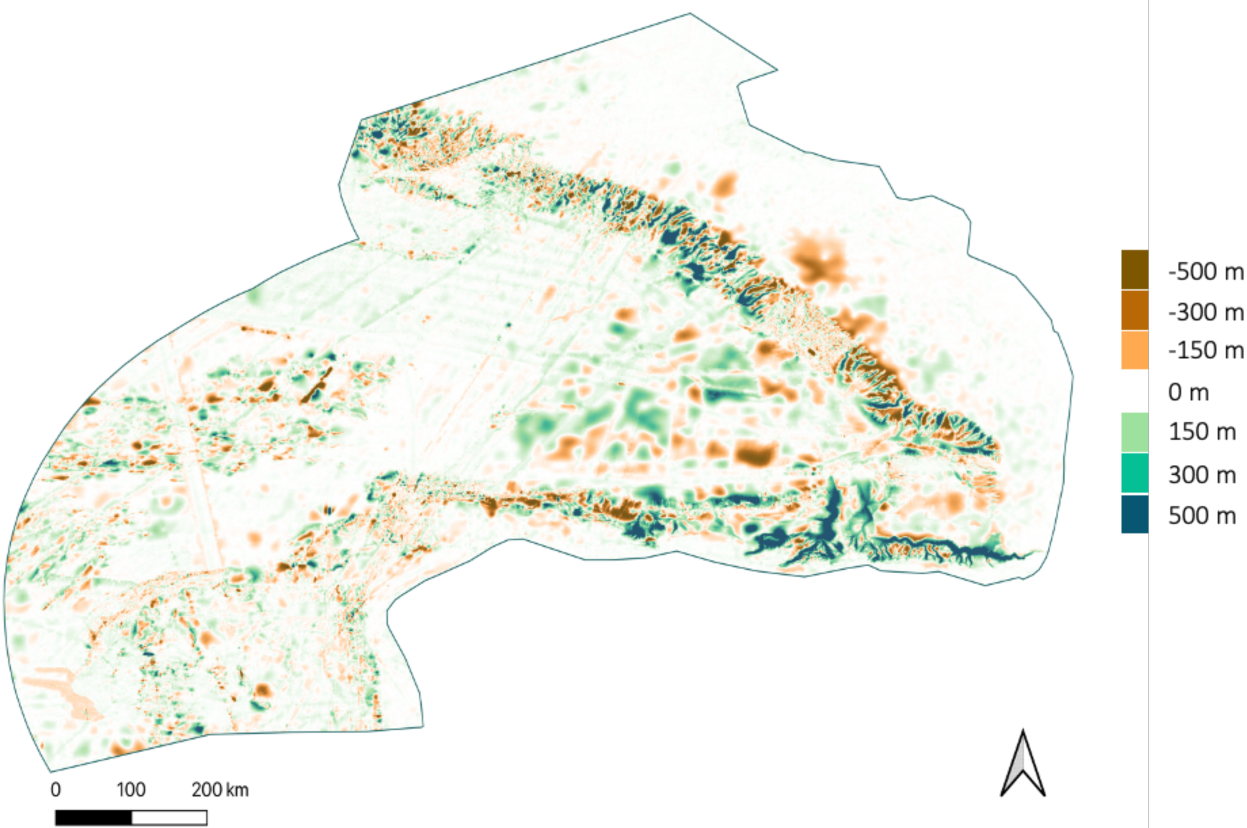

Figure 5: Map showing the differences in depth values between STRM 2012 and EMODnet 2018 bathymetric data. The dark brown shows where the depth has decreased, while the dark blue shows where it has increased in depth.

3.3 Submarine Canyons

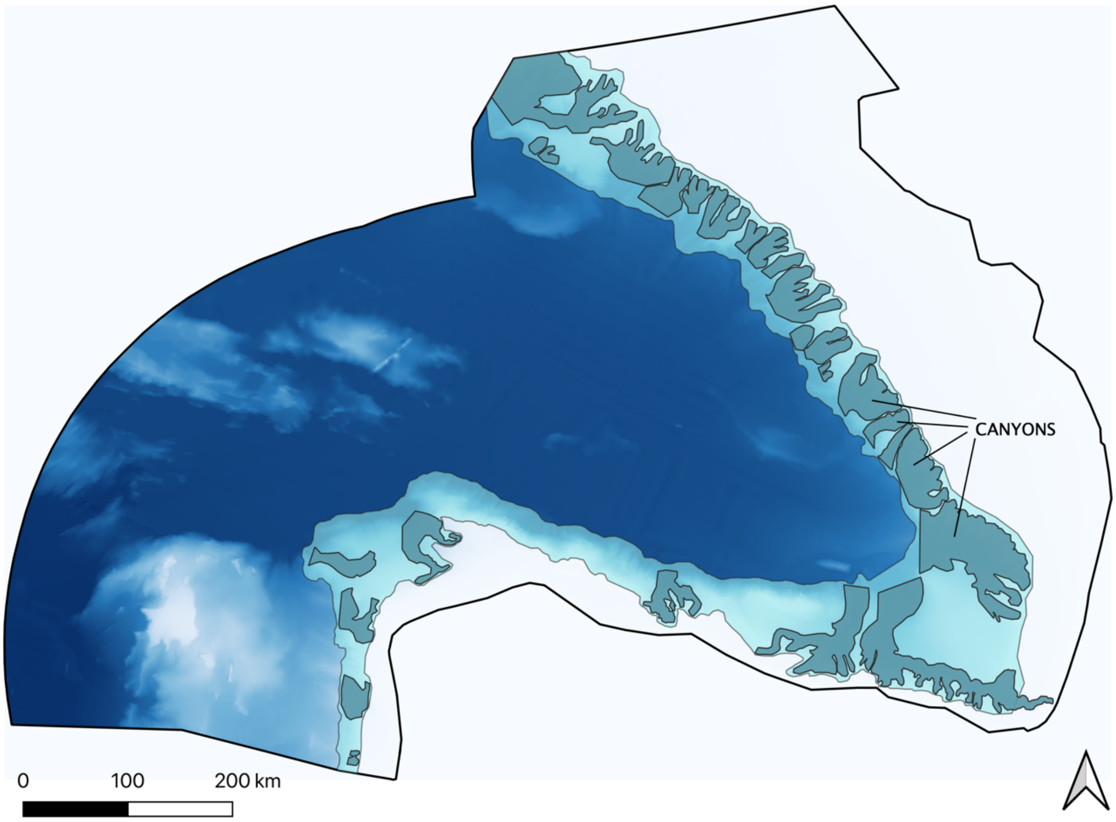

Figure 6: Study area with the continental slope classified and canyons mapped.

Following the increased resolution and interpolation of depth values, the canyons were mapped (Fig. 6). The Celtic and Armorican margins host the majority of BoB canyons, with some large and dendritic ones on the Aquitaine margin and a few on the Cantambrian and Galician margins, the largest canyons are on the Aquitaine margin. The total proportion of canyons within the continental slope is 45,1% (Tbl. 2).

Table 2: Total area of all canyons and proportion of slope.

	Area (km^2)	Proportion of continental slope (%)
Total canyons	43298	45,1
Continental slope	96027	

The slope of the seafloor was examined to identify any trends (Fig. 7, Tbl. 3). The slope along the shelf ranges from 0° to 6°. The slope along the continental slope ranged from 0° to 35°, of which the majority of the steep slopes were located inside submarine canyons.

The slope within canyons ranged from 0° to 35° (Tbl. 3). On the slope values map, the darkest areas show the steepest slopes which mainly occur within the canyons (Fig. 7). It is apparent that along the Celtic, Armorican and Aquitaine margins it is the parts of the canyons located closest to the shelf edge that are the steepest, with the steepness decreasing toward the abyss (Fig. 8). Comparing slope with the depth of the canyons illustrates that the steepest parts of the canyons closest to the shelf are shallower compared to the more gently sloping sections located toward the abyss (Fig. 9).

Table 3: Slope and depth ranges in the different zones of the study area.

Zone	Slope range (°)	Depth range (m)
Shelf	0 – 6	0 – 1000
Continental slope	0 – 35	150 – 5050
Canyons	0 – 35	160 – 4600
Abyss	0 – 30	2100 – 5350

The shelf ranges from 0 m deep on the Armorican margin to 1000 m deep on the Cantambrian margin (Tbl. 3). The continental slope ranges from 150 m deep on the Celtic margin to 5050 m deep on the Galician margin. The abyssal floor ranges from 2100 m deep along the Galician margin to 5350 m deep on the abyssal floor.

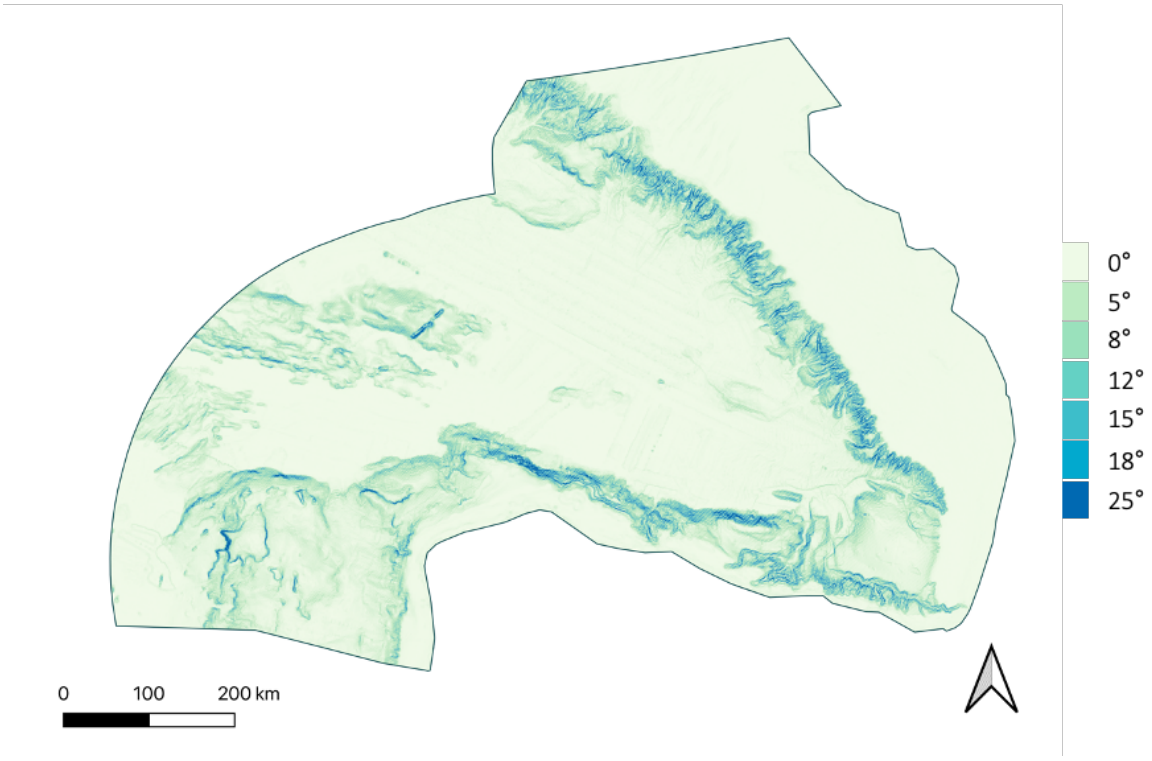

Figure 7: Visualisation of slope values in study area.

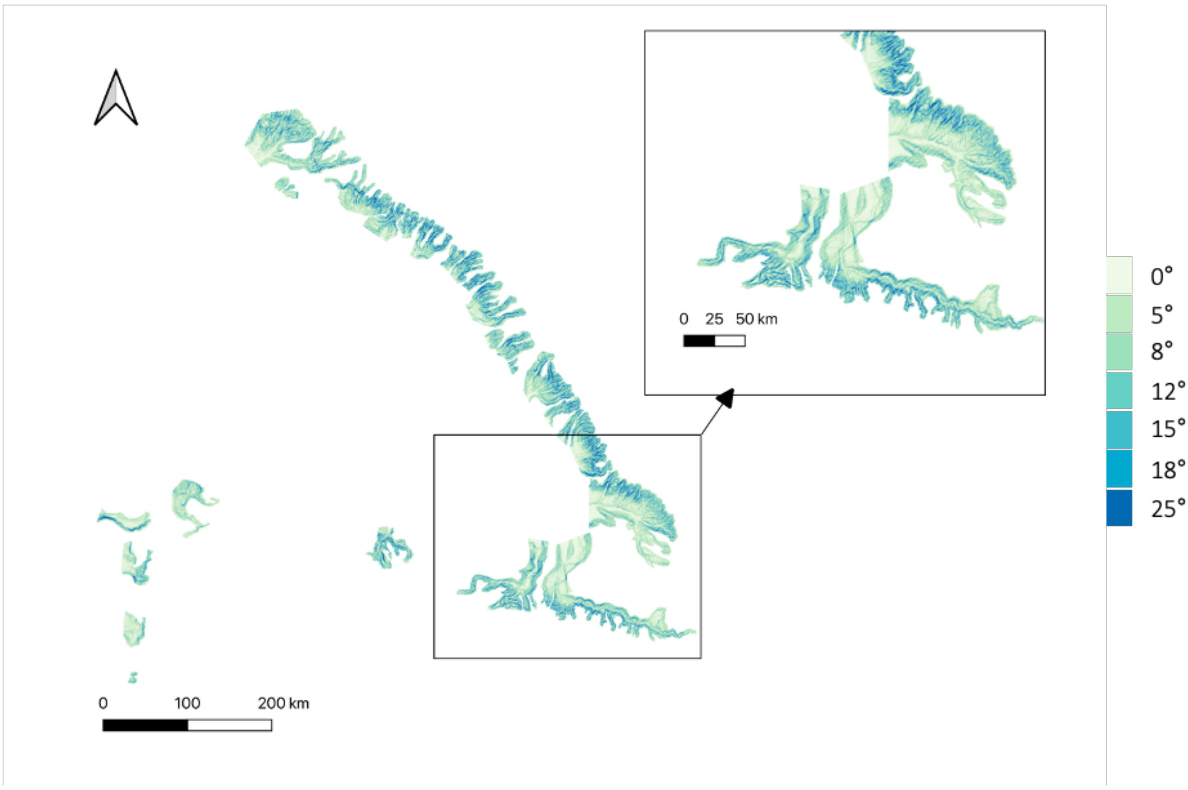

Figure 8: Visualisation of slope values within the canyons of the study area (measured in °).

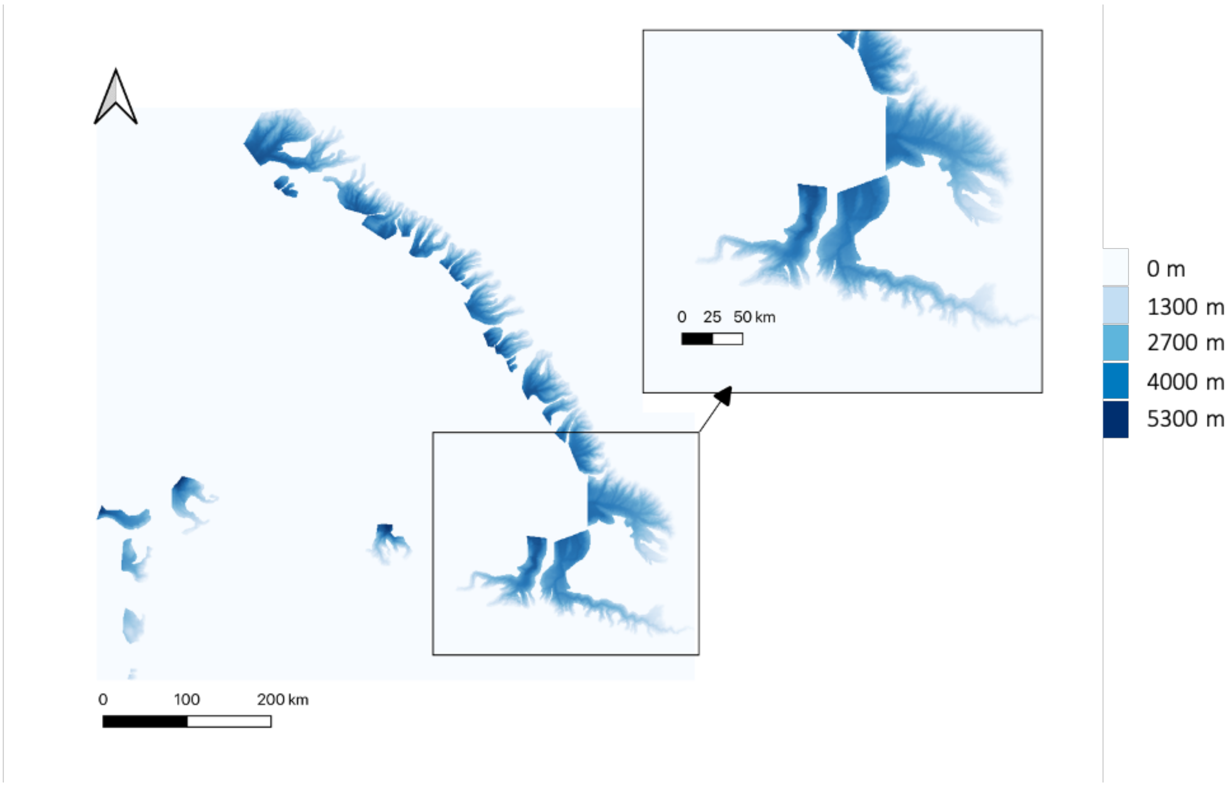

Figure 9: Visualisation of depth values within the canyons of the study area (measured in m).

3.4 Cold-Water Coral Distribution

The spatial distribution of CWCs in the Bay of Biscay are mainly focused around the continental slope (Fig. 10; Fig. 11). The highest densities are along the Celtic and Armorican margins, with fewer observations on the Aquitaine, Cantambrian and Galician margins. There are also some observations on the shelf and a few more on the abyssal plain. The Hexacorallia subclass of CWCs that includes soft corals are found all along the continental slope, but with higher densities on the Armorican and Cantambrian margins (Fig. 10). Some soft coral observations are also made on the abyssal plain. Octocorallia, stony corals, are clustered on the Celtic margin, with a few observations on the continental slope and spread out along the Armorican and Galician margins. The majority of these are located on the Cantambrian margin (Fig. 10).

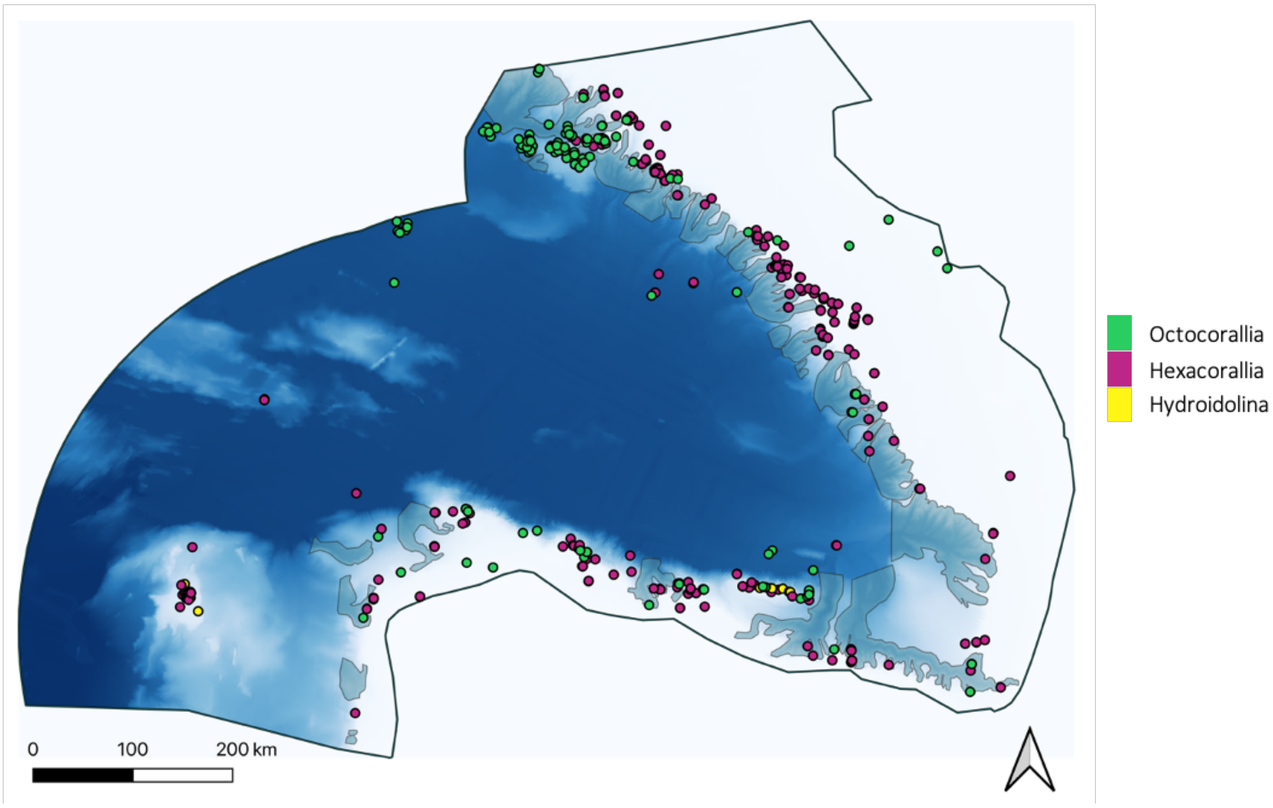

Figure 10: Distribution of cold-water corals within the study area. Colour-coded by subclass: Octocorallia (hard corals; green), Hexacorallia (soft corals; pink) and Hydroidolina (hydrocorals; yellow).

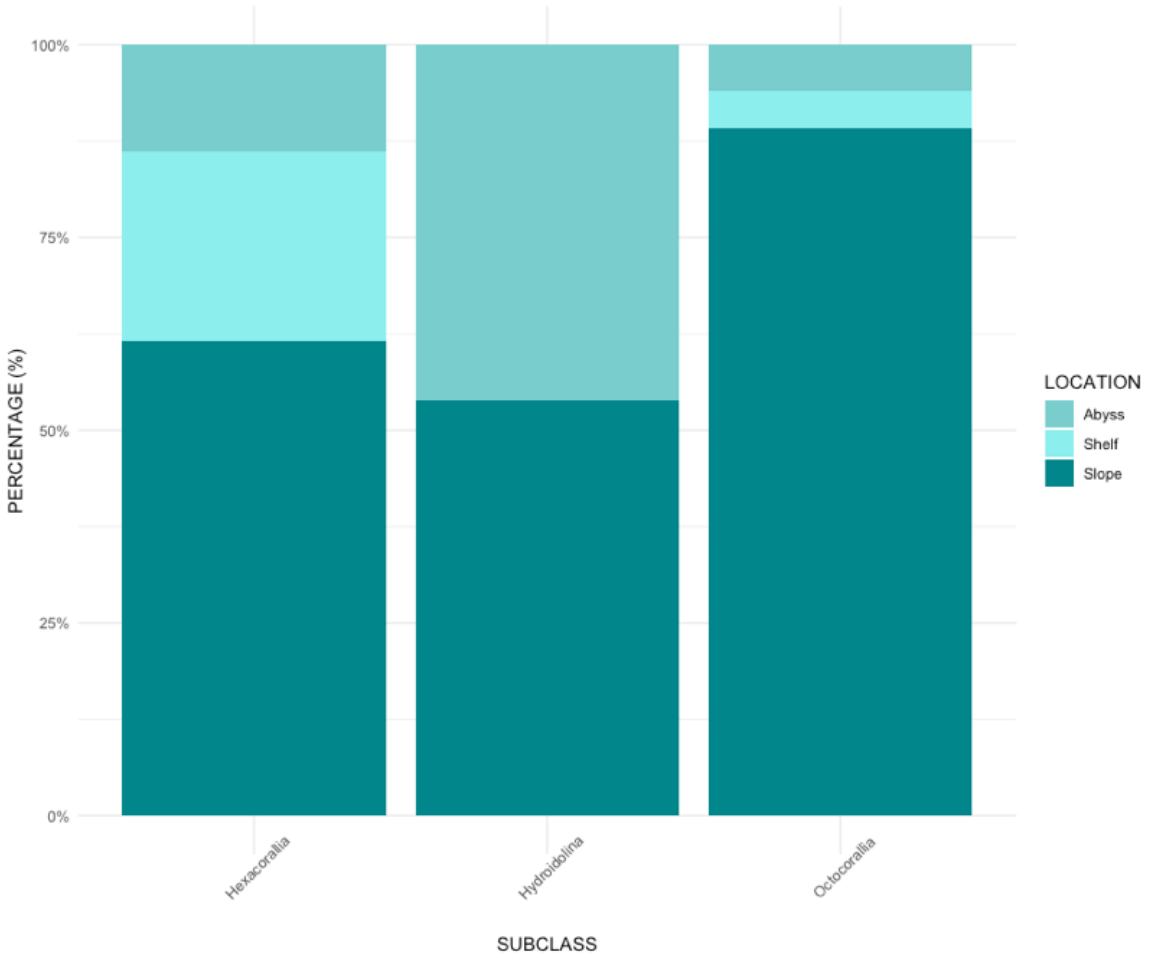

Figure 11: The proportion of corals located on the shelf, continental slope and abyss within the study area. Divided into subclasses of Hexacorallia (soft corals), Hydroidolina (hydrocorals) and Octocorallia (hard corals). The majority of corals are located on the continental slope. Hexacorallia and Octocorallia also have a proportion located on the shelf. Hydroidolina has just over 50% of observations located on the continental slope and the remaining on the abyssal floor.

All three subclasses of CWCs are mainly located on the continental slope (Fig. 11). Hexacorallia have over 60% of observations on the continental slope, approximately 30% on the shelf and 10% on the abyssal plain. Hydroidolina are located approximately 50% on the continental slope and 50% on the abyss. Octocorallia have approximately 90% of observations located on the continental slope, and 5% on the shelf and abyss (Fig. 11).

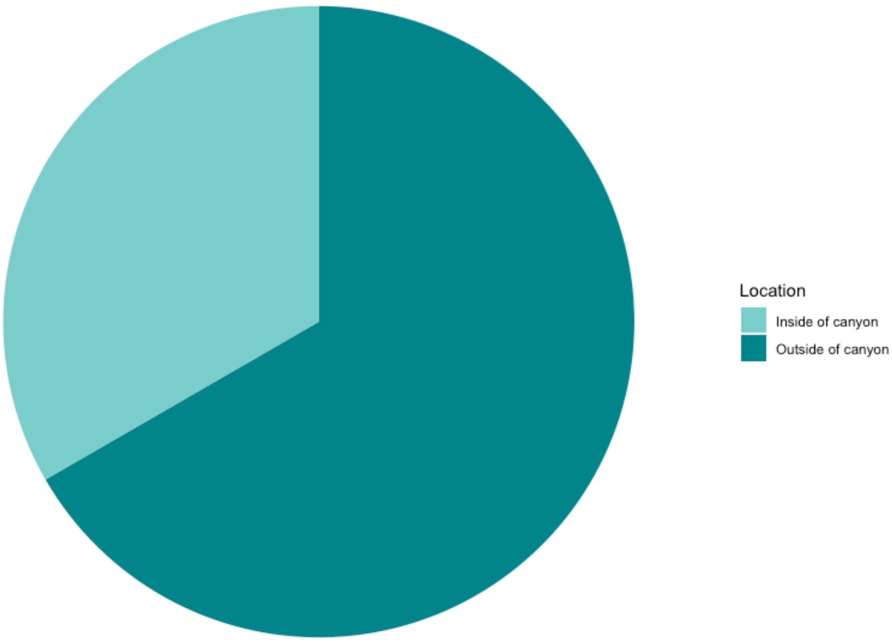

Figure 12: The proportion of cold-water coral observations inside and outside of canyons within the study area of the Bay of Biscay. 26% of the corals were observed within canyons (n=221), and the majority - 74% - were located outside of submarine canyons (n=624).

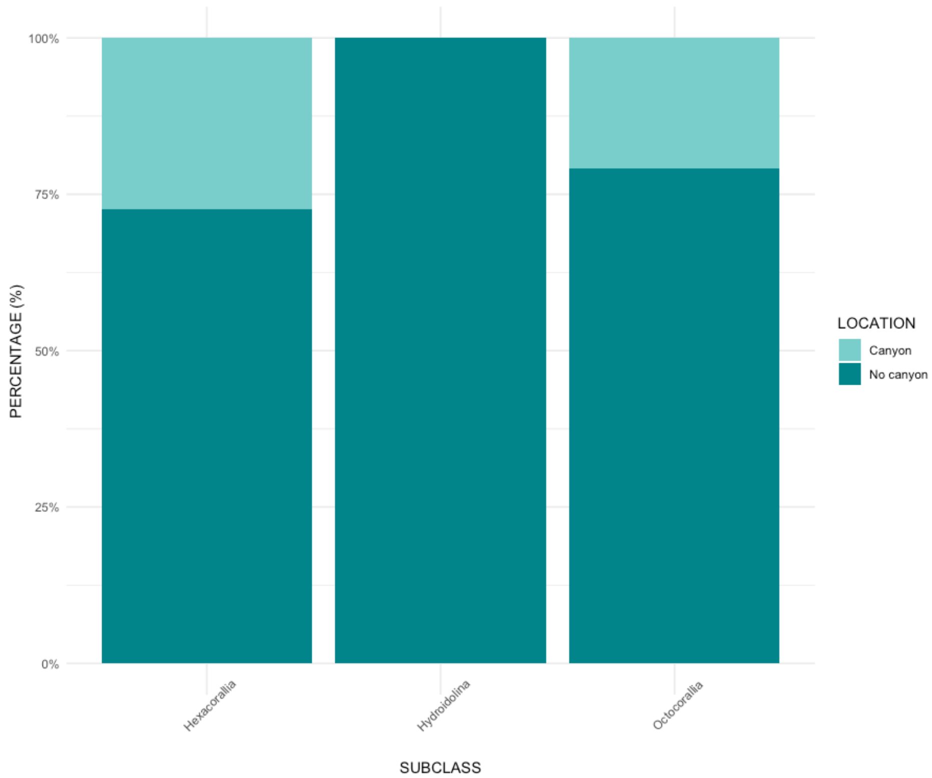

Figure 13: The proportion of the cold-water corals observed on the continental slope inside and outside of submarine canyons. Divided into subclasses of Hexacorallia (soft corals), Hydroidolina (hydrocorals) and Octocorallia (hard corals).

Across all three subclasses, 74% of observations are located outside of submarine canyons (n = 624) and only 26% within canyons (Fig. 13; n = 221). The distribution of observations within and outside of canyons show similar traits for Hexacorallia and Octocorallia: the vast majority outside of canyons and a smaller percentage within canyons. Hydroidolina are 100% located outside of canyons, but with only 13 observations these will not be further discussed in detail (Fig. 13).

Sum MPAs areas	**227861 km^2**
Sum MPAs dissolved (overlapping areas excluded)	109591 km^2
Sum BoB area	489539 km^2
Sum canyons area	43298 km^2
Sum canyons within MPA area	23184 km^2
Number of CWC observations	798
Number of CWC inside canyons	221
Number of CWC outside canyons	624
Number of CWC within MPA area	518
Number of CWC observations/km^2 inside canyons	5,10 x 10^{-3}
Number of CWC observations/km^2 outside canyons, on continental slope	11,83 x 10^{-3}
% of canyons within MPA	53,6 %
% of (dissolved) MPA cover within BoB	22,4 %
% of CWC within MPA	64,9 %

Table 4: Summary statistics.

If CWCs were randomly distributed along the slope both inside and outside of canyons, the rate of CWC observations per km^2 inside of canyons would be the same as the rate of observations of CWC per km^2 on the continental slope outside of canyons. There are 5.10 x 10^{-3} CWC observations per km^2 inside of canyons and 11.8 x 10^{-3} CWC observations per km^2 on the continental slope outside of canyons (Tbl. 4). The results of this study thus show that the occurrence of CWCs is ~50% greater on the continental slope areas outside of canyons compared to inside of canyons.

3.5 Cold-Water Coral Depth and Slope Ranges

Plotting the number of CWC located within each 100 m depth bin (Fig. 14) shows a trimodal frequency distribution with modal peaks at 300 m, 900 m and 2100 m. The majority of observations are located between 0 and 2400 m depth, with two sets of observations at further depths – one group between 2600 and 3600 m deep and one between 4100 and 5000 m deep. The depth within canyons ranges from 150 to 4900 m and the slope ranges from 3° to 30°.

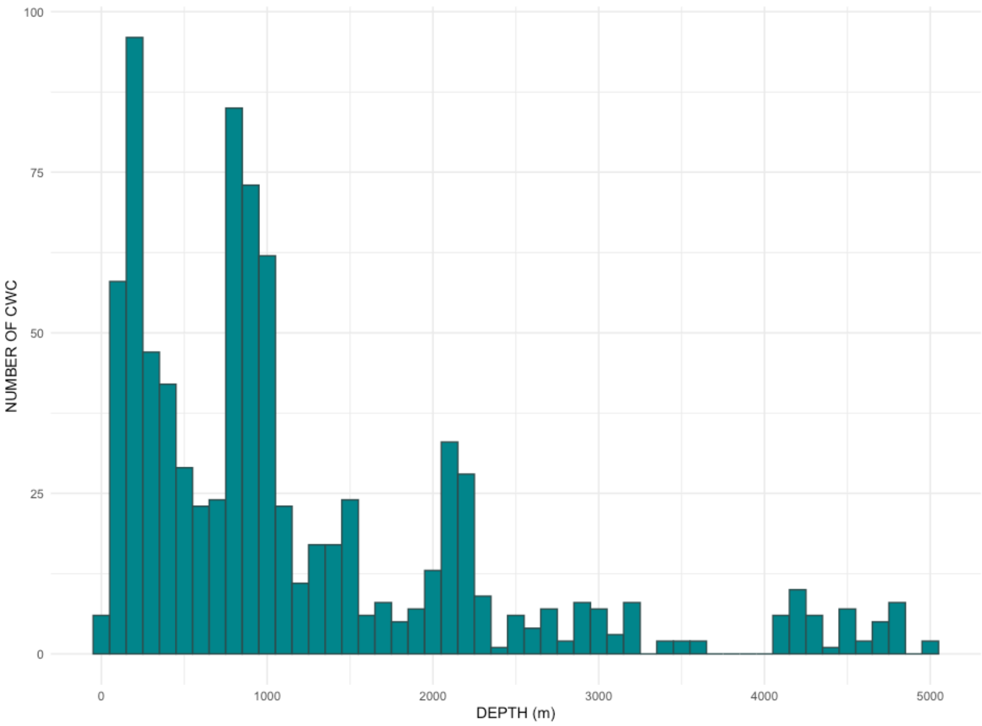

Figure 14: The number of cold-water coral observations found within each depth bin (=100m). The plot is trimodal, with the majority of observations located between 0 and 2400 m depth. The peaks are located at 300 m, 900 m and 2100 m. The deepest observations are located within the 5000 m to 5100 m depth range, and the shallowest at 0 to 100 m.

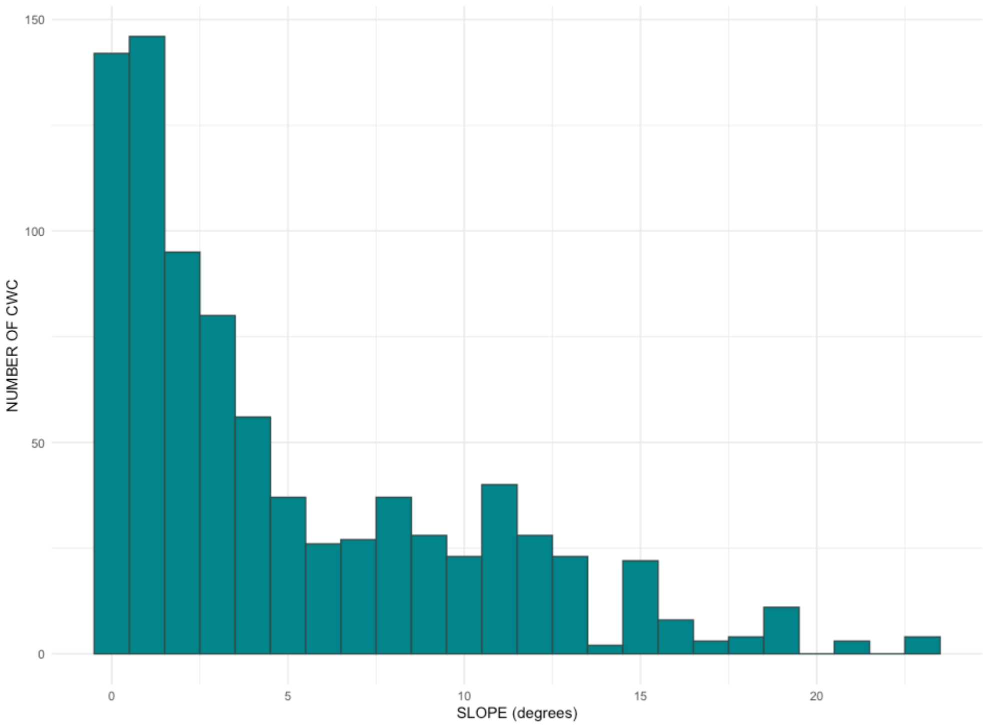

Figure 15: The number of cold-water coral observations within each slope range (=1°). The histogram exhibits a positive skewness with a modal peak at 2°.

Plotting the number of CWC observations against slope (binned at 1 degree; Fig. 15) shows the data are positively skewed with two modal peaks, one at 2° and one at 11°. The majority of observations are located on slopes ranging from 0° to 5°, with a large group located on slopes of between 6° and 13°.

3.6 Existing Protected Areas in the Bay of Biscay

The total area of all MPAs (Fig. 16) located within BoB is 227861 km^2 (Tbl. 4). Once dissolved (overlapping areas excluded), the area is 109591 km^2 and covers 22,4% of the Bay, 53,6% of the canyons and 64,9% of observed CWCs. Along the Celtic and Armorican margins, most of the canyons are within protected areas, the two large canyons on the Aquitaine margin are not (Fig. 16). There are also some smaller MPAs on the Cantambrian and Galician margins where one canyon on the eastern Cantambrian is located within an MPA. But the remaining few canyons located on these two margins are not located within MPAs.

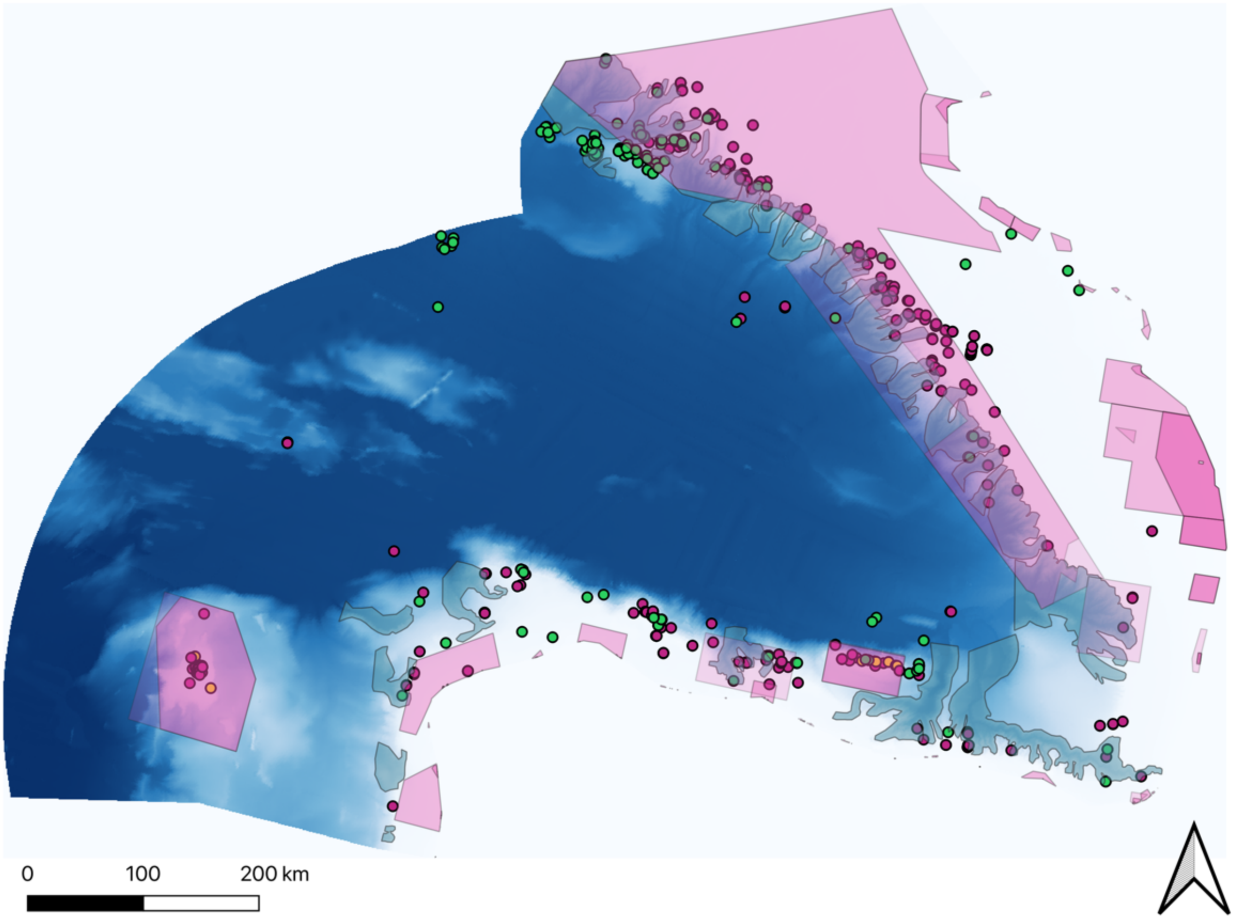

Figure 16: Bay of Biscay with protected areas (pink), classified canyons (blue) and CWC observations (green, pink and yellow dots).

Chapter 4: Discussion

The Bay of Biscay is indeed a mysterious place. With its numerous submarine canyons and array of CWCs, it is a vast area full of relationships yet to be understood. The intense anthropogenic pressures that are faced by the BoB highlight the need for comprehensive management strategies that aim at conserving geomorphic features and benthic habitats. This study focused on understanding where CWCs are distributed along the seascape of the BoB and how they spatially correlate with submarine canyons. Another objective was assessing if the improved bathymetric data from 2018 would be useful in re-mapping submarine canyons, with the collective objective of highlighting whether or not these features are properly included in management strategies in the region.

The bathymetric data from 2018 with a 100 m resolution interpolates the depth values at 100 times the resolution of the 2012 data with 1000 m resolution (Fig. 5). This higher resolution reveals a clearer picture of the geomorphology of the area than the 2012 bathymetry did. The high interpolation of the 2018 dataset also allows for a more detailed slope analysis. This results in a good overview of how the angle of slope varies along the dataset. High resolution slope and depth data make it easier to understand how these factors vary throughout the study area, particularly along the continental slope which is especially interesting due to the many submarine canyons located here (Fig. 6). In combination with the improved depth and slope data, the increased resolution provides for a more detailed mapping of the size and extent of the submarine canyons which allows for a better understanding of the distribution of canyons in the BoB (Fig. 6).

The expectation was that CWCs would more frequently be observed along the continental slope compared to the shelf and the abyss due to the steep slopes and range in depth occurring along the continental slope. The results did support this hypothesis with more than 60% of all CWC observations located along the continental slope of the Bay (Fig. 11). Based on literature, another hypothesis for this study was that CWCs would be located within submarine canyons due to their steep slopes, suitable depth range and hydrological processes located and occurring within canyons, particularly in shelf-incising canyons (Lastras *et al.*, 2016).

However, the results of the study show the opposite of this, where the majority of CWC observations (74%) are located outside of canyon boundaries rather than within (Fig. 12). In addition, by dividing CWC observations by km^2, the results showed that if randomly distributed, there are twice as many CWC observations located outside of canyons on the continental slope compared to inside of canyons (Tbl. 4). This discrepancy may be caused by many contributing factors.

One reason could be that the benthic habitats within the canyons are so damaged by bottom trawling that there are only a few remnant CWCs left within them. This is a serious problem as CWC communities are slow growing and take many years to recover from disturbance (van den Beld *et al.*, 2017a). One of the most prominent human activities in the Bay of Biscay is fishing, and bottom trawling is a commonly applied method in the region (Huvenne *et al.*, 2011). Bottom trawling is classed as one of the most destructive fishing methods, particularly for seafloor habitats (Huvenne *et al.*, 2011; van den Beld, 2017), and has been shown to be a key factor in seascape evolution overall (Puig *et al.*, 2012). Bottom trawling gear scrapes the seafloor and will damage any CWC within its reach (Puig *et al.*, 2012), this has already been documented within canyons along the Celtic margin in the BoB (Huvenne *et al.*, 2011).

Another effect of bottom trawling on the outer shelf is that it mobilises shelf sediments that are transported down-slope through canyons (Puig *et al.*, 2012). It may be that this heavy increase in sediment flux is damaging to CWCs, which can cause them to disappear from the canyons (Davies *et al.*, 2007). Sediment resuspension caused by bottom trawling is a known problem in the BoB (Mengual *et al.*, 2016). This type of resuspension increases with depth due to rapid decay of wave effect and is heightened during the fishing season. CWCs in the Bay of Biscay prefer to be located where hydrodynamics prevent high sedimentation rates (Lastras *et al.*, 2016), meaning that increased sediment flux caused by bottom trawling will contribute to the disturbance and possible destruction of deep-sea habitats like CWC (Mengual *et al.*, 2016).

Further, the validity of the WCMC CWC dataset is important to discuss as it is vital to the conclusions of this study. First of all, there is no absence data, which reduces the usefulness of the dataset. It includes where CWCs were observed, but not where samples were taken but no observations of CWCs were found. In order to fully understand what conditions CWCs prefer to be associated with, it is important to have access to absence data in addition to their observed locations. Predictive habitat mapping models also generally perform better when absence data are included, as this reduces the likelihood of overestimation of suitable habitats (Robert *et al.*, 2016).

In addition to the lack of absence data, there are no specifications about the extent of each of the CWC data points in the dataset. Each data point may represent one coral or, as most of the data collection occurred using bottom trawling, it may represent a trawl track where many corals were collected. The latter raises further questions about the length of the trawl track, and whether the coordinates for the data point correspond to the start, end or centre point of the track. Confidence in the results of this study would be increased if the CWC data had been collected in a more structured way, using a specific method for the entire dataset and also including absence data. In addition to bottom trawl data, more recent studies of CWCs have used smaller-scale techniques such as ROVs which allows for a much more detailed analysis (Lastras *et al.*, 2016; van den Beld *et al.*, 2017b).

Although the improved data resolution helps better classify submarine canyons, the weaknesses of the CWC dataset make it difficult to understand the true spatial relationship between CWCs and canyons. Nevertheless, it is still possible to analyse where the CWCs are located and thus what depth and angles of slope they prefer according to the dataset in hand. The expectation based on the literature review was that they would prefer steep slopes, but in fact, the majority of the CWC observations in this study are located on gentle slopes between 1° and 5° (Fig. 14).

One reason for this could be that canyons may not be suitable CWC habitat due to the erosive effects of turbidity currents and impacts of sediment depositing over CWCs (Clark *et al.*, 2015). As mentioned above, these processes may be increased by bottom trawling resulting in steep slopes both in canyons and along the continental slope being unfavourable to CWCs due to the conditions that arise with increased trawling pressure (Clark *et al.*, 2015). However, according to studies on CWCs located within canyons, this seems highly unlikely (Lastras *et al.*, 2016). It has been shown that turbidity currents as well as sediment-laden waters found in shelf-incising canyons enhance hydrodynamics and food arrival. This provides favouring conditions for CWCs (Lastras *et al.*, 2016).

Regarding depth range of CWCs, the results of this study show that they are mainly located in depths above 2000 m (Fig. 15). This may mean that the preferred depth range of CWCs in the BoB is between 0 and 2000 m deep, but it can also mean that depths above 2000 m are easier to sample. Adding to the issues with the WCMC CWC dataset, the accessibility of the deepest parts of the study area might be a limiting factor. If this is the case, it would result in a dataset consisting of CWC observations at much shallower depths than their actual range allows for. Studies have after all, shown that CWCs have been observed down to 5000 m deep (Huvenne *et al.*, 2011). The abyssal plain of the BoB has a mean depth of 4800 m and a max depth of over 5000 m. This, in combination with the preferable conditions provided by shelf-incising canyons, suggests that CWCs could also be located deeper than 2000 m in the Bay of Biscay.

The majority (624) of CWC observations are from the continental slope outside of canyons (11.8×10^{-3} CWC observations per km^2), with 221 CWC observations from within submarine canyons (5.1×10^{-3} CWC observations per km^2; Tbl. 4). The depth and slope ranges of CWC occurrences within submarine canyons are similar to those for the continental slope outside of canyons, which does not explain the low rate of occurrence of CWCs within canyons. While this does not prove there is an anthropogenic explanation for the relative absence of CWCs within canyons, the prevalence of bottom-trawl fisheries in this area is likely to contribute to the observed patterns.

The fact that most of the CWCs were sampled using bottom trawling may be one of the reasons why fewer samples were observed within canyons, simply due to the likely challenges of using bottom trawl gear in heterogenous canyon terrain (Gori *et al.*, 2013). On the other hand, it could be possible that the lack of CWC observations within canyons are because canyons previously have been targeted fishing grounds resulting in complete destruction of the CWC communities that used to be located there. However, no evidence has been found regarding this in the Bay of Biscay.

Several papers that have used smaller-scale methods to look more closely into CWC communities in canyons have identified many large patches within the geomorphic feature (Huvenne *et al.*, 2011; Puig *et al.*, 2012). The use of small-scale sampling methods would be highly beneficial when studying continental slopes in general, particularly in areas such as the Bay of Biscay where submarine canyons are abundant (van den Beld *et al.*, 2017a). Canyon terrain is highly heterogenous, which makes them very difficult to study without the right technology (Gori *et al.*, 2013). Bottom trawling is a large-scale sampling method which can be useful in many cases but might not be the most appropriate method for studies that focus on identifying CWC communities within canyons. Small-scale technology would take longer to sample large areas, but in turn would produce a much more detailed set of data (van den Beld *et al.*, 2017a).

However, methods such as mapping via video imagery captured by ROVs or towed cameras are very small scale (1-10 m) and do not match the scale of the bathymetric data (100 m grid) in this study. In order to do more overarching studies of the spatial correlation between geomorphic features and CWCs or similar ecosystems, there is a need for improved bathymetric data that matches the small-scale results produced by ROVs and similar techniques.

This study has identified many areas that could be beneficial for improved management strategies of the region. The majority of current MPAs in Europe lack protection measures aimed at geomorphic features and benthic habitats such as CWCs (Smith, 2017), which may partially be due to the difficulties of locating such seafloor features. By using higher resolution bathymetric data to map geomorphic features combined with smaller-scale research techniques to study seafloor habitats, one can better understand where they are most likely to occur. This can further be included in improved management measures that are aimed at protecting those features specifically, which may additionally help to better protect the range of both commercial and non-commercial species found within them (Freiwald *et al.*, 2011).

A study focusing on evaluating the effectiveness of MPAs in the EU found that reefs are the most at-risk habitats when it comes to fishing efforts, even ones located within protected areas (Smith, 2017). This means that in addition to more protected areas being required, it is also vital that the framework around those protected areas specifically include measures aimed at protecting benthic habitats.

The anthropogenic pressures of marine litter, ghost fishing, maritime shipping and commercial fishing (bottom trawling especially) on benthic habitats can all be reduced if management strategies target such activities with the aim of protecting benthic habitats specifically. The effects of climate change are harder to reduce with protected areas and require a more overarching approach.

Aichi Target 11 states that 10% of coastal and marine areas should be under protection by 2020 (CBD, 2016), emphasised by UN SDG 14 (UN, 2018). To date, 46% of the countries worldwide are on track to reach the target, 37% are moving at an insufficient rate, 10% are exceeding the target, 2% are showing no progress and 1% moving away from the target. Spain is currently moving at an insufficient rate, while France is exceeding the target (CBD, 2020).

Two of the MPAs located on the Celtic and Armorican margins are large and cover much of the continental slope and thus canyons. Unfortunately, they are both special protection areas under the Birds Directive and do not offer any protection for benthic habitats (Marine Strategy Framework Directive, 2012). This leaves benthic habitats such as CWCs highly vulnerable despite being located within protected areas. Bottom trawl fishing causes irreversible (over human lifespans) effects that destroy slow-growing CWC communities, which is one of the key reasons why the Bay flourishes in marine life to start with (Andrews *et al.*, 2006). Improved management strategies are therefore required in order to protect CWCs and consequently other marine life dependant on this ecosystem to continue flourishing in the future.

Luckily, legislation better recognises the differences in seabed habitats today compared to early years of conservation science (Galparsoro *et al.*, 2014). Combining this with better mapping of canyons and CWC communities, improved management strategies can be developed that will help conserve the geomorphic features and ecosystems much better than the current state of management measures in the Bay of Biscay.

The Natura 2000 network of MPAs does include many submarine canyons and benthic habitats despite not acknowledging them very well in their framework (Birds Directive; IUCN, 2012). This means that with a more comprehensive framework that better includes the protection of the geomorphic features and benthic habitats, they can be much better conserved in the future than what they currently are.

Overall, this study has identified the need for better protection measures focussing on benthic habitats and geomorphic features. To aid this, further research should include mapping CWCs using high resolution methods, or alternatively broad-scale methods that have the technology to map ecosystems at the level of detail required. Predictive habitat mapping is a tool that can be used to predict where original CWC communities may have been present, before fishing pressure and other factors became as destructive as they are today. This would aid in the understanding of how human impacts really have made alterations to the Bay of Biscay seascape ecology.

Chapter 5: Conclusions

The 2018 version of the EMODnet 100 m resolution bathymetry grid was used to produce a new map of submarine canyons in the Bay of Biscay for comparison with existing data on the occurrence of CWCs and maps of marine conservation zones. The research question was: *Do cold-water corals spatially correlate with submarine canyons in the Bay of Biscay?* Based on a literature review, it was expected that CWCs would correlate with the steepest slopes of canyon walls. Instead, this study found that the occurrence of CWCs is ~50% greater on continental slope areas outside of canyons.

Furthermore, the CWCs were more commonly observed on slopes of 1° to 5° rather than on the steepest slopes observed in the data. It is not clear if the current map of CWC distribution is biased due to the impact of bottom trawl fishing practices which are known to have removed CWCs from the seafloor in other locations.

This study has been fruitful in terms of understanding where research is currently lacking in the Bay of Biscay. Future studies should focus on using the new bathymetric data and interpreted map of submarine canyons as a tool for better understanding the occurrence of benthic habitats like CWCs. This can further be used to better understand the relationships between geomorphic features and parameters (seafloor gradient, rugosity, TPI, etc.) and the occurrence of benthic habitats.

The final conclusion is that improved conservation measures for CWCs and submarine canyons in the Bay of Biscay are needed. Although MPAs are present, it is unclear how they protect geomorphic features or benthic habitats, which are currently exposed to major disturbances and destructive practices like bottom-trawl fishing. Further research is required in order to understand biophysical controls on the occurrence of CWCs in the BoB and to implement the necessary conservation measures required for a healthy and sustainable future of the Bay of Biscay.

Expanding our knowledge on geomorphic features and benthic habitats along the ocean floor is vital for successful conservation of the planet's seascape.

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