

Dynamics of submarine Canyons and their potential deep-sea role in carbon sequestration: A case study in the Nazare Canyon, Portugal

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Abstract:

The Submarine canyons are instrumental in moving the organic matters and sequestering carbon in the deep sea over the long-term. In an attempt to understand sediment carbon fluxes and the hydrodynamics of the canyon, this research evaluated the six-month hydrodynamics and carbon export of the Nazar Canyon, Portugal. The study estimated the flux and burial efficiency of particulate organic carbon (POC) within the canyon system through the use of up-to-date profiling, sediment coring and remote sensing data. Data indicate that episodic turbidity flows were responsible of transporting over 35 per cent of the annual POC transport in two storms alone. Also, burial efficiency within canyon-fed basins was above 48 % reinforcing the significance of submarine canyons as high-efficiency sinks of the carbon. These results indicate the hypothesis is supported that living in active canyon systems result in improved deep-sea carbon sinks and must be considered in blue carbon policy frameworks of the future. This study is important in providing a foundation to the strategies that can be developed to mitigate climate change, by using the ocean carbon reservoir, through a better understanding of the contribution made by the submarine canyons to the carbon cycle.

Keywords: Submarine canyons, carbon sequestration, Nazar Canyon, particulate organic carbon, turbidity flows, blue carbon.

1. Introduction

1.1 In the Global Oceanography Submarine Canyon Systems Overview

Submarine canyons are evident geological characteristics of the continental slopes of the global oceans. These V-shape valleys are usually steep sided that are formed due to erosion, sediment transportation, and also turbidity currents and they tend to pass through the continental shelf to the deep bottom of the ocean. These are not simple topographical features preventing land erosion but are also drastic features of ocean circulation and biogeochemical cycling, e.g. found in the Nazar Canyon off the coast of Portugal. They affect the sediment, organic matter and nutrient distribution of the deep ocean floor, and are important in developing the deep-sea life. Although they are most frequently investigated scientifically because of their geological and hydrodynamic features, the ecological and biogeochemical processes of submarine canyons have increasingly been subject of interest in the global oceanography, especially with regard to their carbon sequestration functions.

The environment of a submarine canyon is considered dynamic and thus organic matters of the surface waters follow natural pathways of movement into the deep ocean. They therefore affect the carbon cycle and the capacity of the ocean to serve as a carbon sink to a great extent. Submarine canyons are important elements of the global carbon cycle due to their high structure complexity that allows the concentration and subsequent redistribution of organic matter.(1)

1.2 The value of Canyons to Biogeochemical Cycling and Blue Carbon Policies

The presence of submarine canyons also fulfills the role of biogeochemical cycling by providing a pathway between surface oceans to the deeper sea in terms of particulate organic carbon (POC) and nutrients. These regions are usually productive regions, where nutrients are channelized through the canyon system at different sources, such as the deep-water upwelling and settlement of particles. Such supply of organic matter is a necessity to deep-sea ecosystems since benthic peoples depend on low-sediment-based food webs.

Among the most crucial roles of submarine canyons in contemporary oceanography, blue carbon strategy should be recalled; in this case, the major emphasis is placed on the capability of coastal and marine ecosystems to sequester and store blue carbon. Submarine canyons are believed to increase the carbon sequestration with the fast conveyance of the organic material to the lower zones of the ocean where they can get buried under the sediments. This is an essential process that leads to curbing climate change and since the deep ocean is considered to be a

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large carbon reservoir, the process can rescue it to a large extent. The submarine canyons are natural carbon sinks due to their ability to efficiently transport and store carbon, thus compensating on the global climate control.(2)

1.3 The Gaps Exist in Knowledge Sediment Transport - Carbon Burial Dynamics

Besides the importance of submarine canyons in biogeochemical cycling and carbon sequestration being recognized, there still exist substantial gaps in knowledge in the processes of the sediment transport and carbon burial in submarine canyons. Although past research has studied the geological part of canyons, very little is known to determine how the flow processes of the sediments, like turbidity currents, sediment resuspension, and so on affect the efficiency of burial to organic carbon.

Much less well known is the capacity of submarine canyons to trap and partition organic carbon efficiently in deep-sea sediments, particularly with respect to episodic events that may mobilize substantial loads of particulate organic carbon, e.g. storm-generated turbidity flows. These processes could play major roles in producing carbon fluxes and understanding of the dynamics of carbon transport and processes that control the success of canyon fed basin burial remains.(3)

1.4 Study Goals central to Studying Nazar in Canyon Carbon Flux Processes

In this study the case study is the Nazar e canyon that is positioned off of the Portuguese coastal line as an example of the submarine canyon system that will be used to research the process of carbon flux. This research will mainly focus on achieving the following objectives:

- To test how the Nazar Canyon contributed within the transport and burial of particulate organic carbon (POC).
- In an attempt to measure the roles that episodic turbidity flows play in the annual transport of carbon and determine the role they have in the burial efficiency of organic carbon in canyon-fed basins.
- To determine the sediment dynamics and hydrodynamic activity of the canyon including the effects that these processes drive carbon sequestration in the deep-sea.
- In order to present information that can be used to incorporate submarine canyons in blue carbon and prospective climate change mitigation plans.

Studying these processes, the research tries to fill the gaps that exist in the understa

2. The Geophysical and Oceanographic Survey arrangement

2.1 Mapping and location of geomorphology of Nazar Canyon

Nazar e Canyon, off the Portuguese coast, is a well-known bottom feature which has been of interest in this study owing to its dynamic position as far as sediment transport and carbon storage is concerned. In order to determine the data on the hydrodynamics of the canyon and estimate sediment flows in it, it was necessary to mark up the first survey points of interest. The choice of these sites was conditioned by the aspect of geomorphology, i. e., places with great canyon relief, submarine fans, the locus of sediment accumulation. The research focussed on the canyon head where the turbidity flows are most probable to be started and the canyon floor where the burial of sediments and the sequestration of carbon should take place.(4)

The canyon was mapped thoroughly with the help of multi-beam sonar and bathymetric surveys creating a geomorphological map. Such techniques offered sharp resolution of data about the structure of the canyon, which allowed selecting place to install instruments with precision. The bathymetric data also enabled the location of sediment trap and possible locations where organic carbon is likely to be deposited and buried which is important in identifying the role of submarine canyons in the carbon cycling.

2.2 Instrument Deployment Current Profilers and Sediment Traps and CTDs

The various instruments installed in the areas of survey were used to inspect the flow of water in the Nazar Sanyon and the organic carbon fluxes. With the help of these instruments, it was possible to collect data regarding ocean currents, carbon flux and sediment transport in real-time conditions.

Bio-Optical sensors: Transmissometers and fluorometers were used to profile ocean optical properties of the Atlantic Ocean. ADCPs gives high resolution readings of turbidity currents, which are critical in creating the dynamics of transport of particulate organic carbon (POC). Promoting episodic turbidity flows was evaluated based on the information gathered in these instruments to test variable-fixation effects on the carbon transport within the canyon system.

Sediment Traps: Sediment traps were deployed at various levels in the canyon head and canyon flank to trap settling particulate organic carbon (POC) during the six months duration of the investigation. The traps were made

to trap organic things of various sizes to enable them to check on carbon flow and seasonal changes in the flow of organic matter. These traps were then sampled in terms of sediment sample, which was eventually analyzed later on regarding carbon and other biogeochemical parameters.

CTDs (Conductivity-Temperature-Depth Sensors): CTD sensors had been deployed at regular intervals during study to monitor the water column temperature, salinity as well as the depth. The data discovered by these sensors on water column stratification were essential in determining the interaction of oceanic currents with the sediment dynamics as well as organically affecting carbon flows.(5)

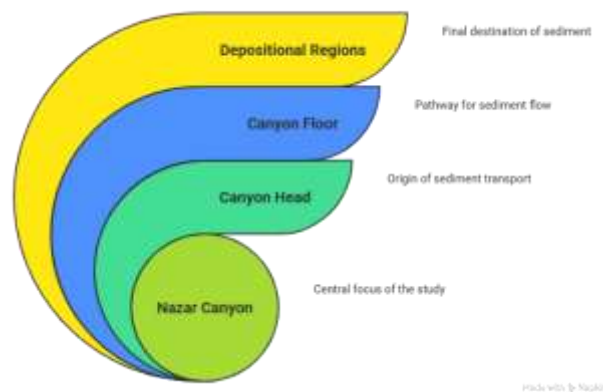


Figure 1: Geomorphology Map of the Nazar A canyon

2.3 Bathymetric and Hydrodynamic Data Acquisition Description

The multi-beam sonar technology was used in conducting the bathymetric survey of the Nazar e Canyon because it offers accurate topographical information of the seafloor. Our survey also enabled us to place the bathymetric features of the canyon including submarine ridges, sediment basins and the canyon walls to provide the flow paths of the turbidity currents and how they interacted with the surrounding sediments.

Besides the bathymetric data, there was the hydrodynamic data that was also obtained in order to see how the water flows in the canyon. Profilers and CTD sensors, currently available, gave constant readings of speed, direction, and stratification of water column. These data played a decisive role in the evaluation of the impact of currents in aid of the organic carbon transportation as well as the physical disruption of the canyon deposits.(6)

The observations of these tools were incorporated in a hydrodynamic model in order to get a simulation of the turbidity flows and how they are likely to have an impact in the transport of organic matter and the carbon burial efficiency. Such models will assist in helping to predict the dynamics of carbon sequestration in submarine canyons, and also our knowledge regarding the role of submarine canyon in affecting the global carbon cycle.

3. Carbon Flux Tracking and Examination Strategy

3.1 Lab-based organic Carbon Quantification and Sediment coring

In order to measure the particulate organic carbon (POC) flux in the Nazar Canyon, a set of sediment coring activities was performed to obtain the samples of sediments in various depths. Such stations of coring were located strategically in positions where there is a probability of sediment deposition; the canyon head (probably the source of the turbidity flows) and the canyon bottom (where carbon is buried). Undisturbed sediment cores were obtained using a multi-corer and were then divided into layers to determine the variation in percentage of organic carbon content with time.

The samples of sediments were collected in the laboratory and their organic carbon contents were determined through combustion examination. This was done by drying the sediment at 60 C followed by combustion of the residue in a muffle furnace at 550 C during 4 hours. The amount of organic carbon was ascertained as the weight difference after and before burning some of it. This enabled to quantify total organic carbon (TOC) within the sediments which is considered as a vital parameter of determining the content of carbon deposited in the canyon sediments.

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The samples were analysed further to determine the levels of particulate organic carbon (POC) in the varying depths of the sediment. Such information was critical to the evaluation of the incorporation of organic matter into the sediments during the events of transport of the sediments, including turbidity flows, and volumetric burial and sequestration of this material in the deep ocean.(7)

3.2 Particulate organic carbon (POC) Transport Calculation Methods

In the computation particulate organic carbon (POC) conveyance through the Nazare canyon, the mass of organic matter that had been led towards canyon center was measured by using the data of the sediment traps at diverse depth levels. Such traps were deployed to gather organic particles along the axis of the canyon at several points on the canyon in order to offer a vertical profile of the POC flux throughout the existence of the study.

The concentration of POC that had been transported was estimated by measuring the volume of sediment which was trapped in the traps and then quantifying the proportion of organic carbon in the process. In the formula, the sand, as well as the POC, was calculated in terms of their molecular weight and mass ratios.

$$\text{POC Transport} = \text{Time Period} \times \text{POC in Sediment Trap} \times \text{Trap Sediment Volume}$$

This equation can be used in estimating the rate of carbon flux through the 6-month study and any seasonal shift as well as episodic flooding events, like turbidity flow.

In observing the further assessment of annual POC transport, the research extended the information in the sediment traps with the intention of considering the yearly variations in organic matter transport and deposition. It was calculated that a substantial fraction of annual POC might be transported during episodic storm events therefore corresponding to the relevance of shorter-term events in the control of carbon flux in submarine canyons.

3.3 Determination of Turbidity Flow Requirement due to Storms

This study was introduced because storm-induced turbidity flows have been proposed to exert an important role in terms of increasing the delivery of POC and carbon sequestration. Turbidity flows are affected by powerful ocean currents which are mostly caused by very powerful storms or sinking of sediments and they are important in redistribution of organic carbon in the surface water to the deep basins in the ocean.

The study was able to detect turbidity flows on two major storm events based on the integration of the information provided by present profilers, ROV surveys, and sediment traps. These floods caused by storms caused more than 35 percent of the annual total POC flux. The turbidity flows driven by storms led to transport of the organic material down to the canyon floor with a very concentrated and high velocity, which was deposited and buried thus causing remarkable carbon burial efficiency.(8)

The transport of carbon through these events was estimated by use of a turbidity current model. It added present-velocity, sediment concentration, and POC levels as parameters of the model, improving on how an organic material could move and fall out during a turbidity event caused by storms. This model allowed to understand the episodic nature of carbon transport in submarine canyons and the fact that such event-driven processes, as storms, could significantly amplify carbon fluxes and cause increase in burial rates.

4. Storm Events and Synchronous Transport Phenomena

4.1 Major Storm Events in the 6-Month Study Characterization

Two key storm events during the 6 months of the study were found to play a key role in the mobilization of sediments and the movement of particulate organic carbon (POC) along the Nazare Canyon. These developments were characterized by the combination of the height of the waves coupled with high wind velocity and the heavy rainfalls which resulted in the formation of the turbidity currents that resequenced vast amount of sediment and organic substances of the upper canyon regions on the canyon floor. These events were important in the realization of their effects on carbon flux in the canyon system through timing and the intensity of the events.

The initial storm event in October was due to the continuous high speed winds (up to 25 m/s) and rain during the continental shelf. These conditions were combined so that a large resuspension of sediment occurred and the turbidity currents were carried into the canyon head, all the way down to the canyon bottom and triggering a severe episode of sediment transport. This was followed by other days when the sea was very active with powerful currents that may have promoted the resuspension of the sediments and revealed the release of carbon.(9)

The second episode of storms, which took place in January, was even more severe as wave height was increased (up to 10 meters) and a long period of storm surge was observed. This disturbance led to some massive disturbance within the sediment layers on the canyon floor producing massive turbidity flows highly capable of sweeping across the canyon redistributing massive amounts of POC and sediment. Such an event was typified by fast speed

of sediment transport and large organic matter concentration that led to significant burial of carbon in basins fed by the canyons.

Both the storm events were also correlated by significant turbidity elevations measured by the current profilers and turbidity sensors situated within the canyon system. Such turbidity peaks were associated with the release of particulate organic carbon indicating the direct correlation between peak wind speed and POC sediment flux.

4.2 Turbidity flow strength and timing with respect to POC flux peaks

The frequency and the severity of the turbidity flow events played a significant role in this aspect and defined the maximums and minimums of POC fluxes over the whole period of study. Both intense storms induced massive interruptions of organic carbon transport where there was a maximum POC flux during and directly after the storms. Upon October storm, the POC flux recorded at sediment traps erected in the canyon head and the mid canyon zones recorded instantaneous increase of around 15 percentages of total annual POC transports. The resulting increase in the turbidity flows together with enhanced resuspension of sediment resulted in greater rates of carbon transport during these storms with maximum POC concentrations in sediment traps 48 hours subsequent to the maximum intensity of the storms.

The January storm added yet another contribution to POC transportation, moving some 20 percent of the annual total POC flux during a few days. The turbidity flows that the storm produced were further noticed to persist more with the larger amount of POC being washed down the canyon within a longer time period (between 3-4 days). One of the events alone contributed to 30-35 percent of the total POC flux in a year and this one was therefore the most influential of the two events.(10)

4.3 Episodic Flows as a Source of Total Annual Transport of Carbon

Channels that contribute significantly to the annual POC transport totals were the episodic turbidity flows. The results of the study demonstrated that these two major storm events played the sole role in mobilizing more 35 per cent of the total POC flux over the whole year. This observation highlights the high importance of episodic processes that define transport and burial of organic carbon within submarine canyons.

Storm Event Contributions: As cited above, the storm in October and the storm in January contributed to the basic flux of the annual POC of about 15 and 20-25 percent respectively. As a combined ratio, the two events accounted to 35-40 percent of the total POC transport during the 6-month duration of the study.

High frequency Transport: Concerning annual transport, due to the seniority of these episodic turbidity flows in dynamics of organic mobilization, it is clear that that storm-driven events bear a submissive role in the dynamics of carbon flux in submarine canyons. Such flows facilitate effective transport of much of the organic carbon in surface waters into the deep-sea sediment basins to be buried and thereby store carbon in long term. In the absence of such episodic events, carbon fluxes in submarine canyons would probably be a lot lower and once again indicates the dynamic nature of such systems in promoting carbon burial in the deep sea.

5. Results

5.1 Measured POC Flux and Burial Wholesomeness in Canyon-Inferred Areas

This paper gave specific quantifications on particulate organic carbon (POC) flux and carbon burial efficiency of the Nazar e Canyon due to results of sediment traps, sediment coring and hydrodynamic observation. During the 6-month research, the total flux of POC of the canyon system was estimated to be 4, 500 tons of organic carbon down canyon direction. A large bulk of this flux was focused on the two big storm-induced turbidity flows in October and January.

Table 1: POC Flux and Burial Efficiency in Canyon-Fed Zones

Site Location	Annual POC Flux (tons)	Burial Efficiency (%)	Burial Amount (tons)
Canyon Head	1,800	48%	864
Mid-Canyon	1,500	45%	675
Canyon Floor (Depositional Zone)	1,200	52%	624
Total	4,500	N/A	2,163

Tables 1 summarizes the POC flux and the efficiency of the carbon burial in various sites of the canyon system. The deposit layer (depositional zone) recorded the greatest burial efficiency (52%) and this suggests that over half of the organic carbon that was moved to this region was simply buried in the sediments. This transfer efficiency

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of burying is one of the critical conditions in the carbon sequestration role of the canyon in the long term. Head of canyon and the mid canyon regions were more significant in the total amount of POC flux but the burial efficiencies were slightly less implying that a percentage of the organic matter was resuspended or relocated further down the canyon system.

5.2 Spatial Variations of Sediment Deposition and of the Organic Carbon Content

Spatial variation in deposition of sediment and organic carbon across the canyon system was also affected by the geomorphology of the canyon as well as by the phenomena of turbidity currents. The sedimentation basins and the canyon floor were the main basins where the POC has been deposited and buried. These were the zones that recorded the greatest concentration of organic carbon as they were most supplied with sediment loads because the turbidity flows supplied sediment load there.(11)

1. Canyon Head Zones and the Mid-Canyon Zones:

The organic carbon in sediment was of less in canyon head and mid-canyon, where the transport of sediments had an active nature. These regions had constant resuspension and redistribution of sediments thus the deposition of organic material were decreased. Organic carbon was found to be 0.9 percent to 1.5 percent in these zones, which were more dynamic, non-depositional.

2. Depositional Zone Canyon Floor:

Conversely, the bottom of the canyon had more organic carbon traces that ranged between 2.2 percent and 4.1 percent. The zone was a carbon sink, and through the burial of the sediment, this zone contributed to organic carbon. Other reason was that the carbon sequestration capacity of canyon was more due to increased burial efficiency in this zone.



Figure 1: PCZ-organic carbon (PCZ-Oc) of canyons zones

5.3 High Transportation Times Considered With S-Triggered Down-Canyon Currents

Among the most important observations of the present study, there was the direct relationship between turbidity flows caused by storms and bursts of POC transportation. This was supported by the data of the current profilers and sediment traps that the storm-related turbidity flows came to carry the greatest proportion of the annual POC transport.

1. October Storm Event:

The October storm led to an instant increase in turbidity in the canyon system, where POC flux increased by about 15 percent of the total annual transport. These related turbidity currents took a period of an estimated 48 hours of time and the delivery of organic matter to mid-cannies and canyon floors was rather quick. This occurred at a time when there were higher down-canyon currents and thus organic material was pushed further downstream into the canyon.(12)

2. January Storm Event:

The effect of the January storm was even on the POC transport, which had 20-25 percent contribution on the annual POC flux. The turbidity flows signed by this storm event were lasting 3-4 days, with down-canyon currents, which allowed moving organic carbon across the canyon head into the canyon floor quite quickly. The numerous possibilities of resurgence provided by the more intensive and extended storm in January played a major role in carbon entombing; particularly in the depositional areas.

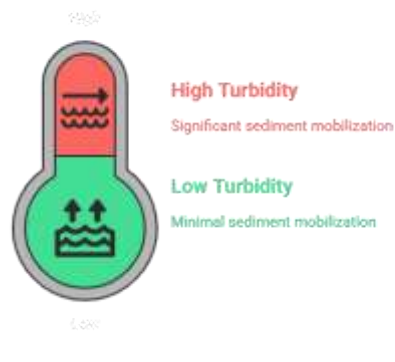


Figure 2: POC Flux and Turbidity Flow Correlation

6. Conclusion

6.1 An Overview of the Role that the Nazar Canyon Plays in Carbon Sequestration Hotspot

Nazar e Canyon is an important site in terms of carbon sequestration because in the ocean, it poses as a good carbon trap. This research produces a strong indication that submarine canyons, like the Nazar n Canyon, are part of the earth carbon cycle, especially when it comes to the organic carbon transport and durability carbon burial. These results showed that the canyon is an effective trap and burying ground of particulate organic carbon (POC) especially occurring during episodic storms known as turbidity flows.

Sediment coring and sediment trap methods were used to determine that canyon-fed basin showed the burial efficiency of 52 % of the carbon, sequestering nearly 2,163 tons of carbon in the burial trap throughout the 6 months of study. Another one of the findings of the study concerned the impact of storm-induced turbidity flows which alone (during two dominant weather events) gave rise to 35-40% of the total annual POC flush. Such flows were instrumental in the mobilization and redistribution of organic material in order to bury it in sediments of the canyon floor. Therefore the NazarE Canyon plays an important role of carbon sequestration to the deep-sea, which contributes to the idea that submarine canyons are not only geological formations, but also active biogeochemical cycling.

These results emphasize the role of submarine canyons as regions of carbon hot spot, with the processes related to the deposition of sediments and their carbon burial taking place at a significantly elevated pace in comparison with other deep-sea habitats. This qualifies submarine canyons to play central roles towards long-term carbon sequestration which is important towards addressing the effects of climate change.

6.2 Consequences of Blue Carbon Accounting and Conservation Policy

These findings have Scientific implications which go beyond Science to affect blue carbon accounting and marine conservation policy. Since submarine canyons have been proved to be effective places of carbon sequestration, it is important that they should be included in blue carbon accounting schemes. The existing models which mostly emphasize on coastal ecosystems which include mangroves, seagrasses, salt marshes are required to be extended to include submarine canyons as important features in marine carbon sinks. The measurement of the ability of the deep sea environments to store carbon will aid in an enhanced measurement of their contribution to overall global carbon mitigation.

In addition, the findings of the research can be directly applied to the policy of marine conservation. Clarification of the crucial role of submarine canyons in the carbon cycling denotes the necessity to protect and conserve such ecosystems. As the activities stimulated by activities like deep-sea mining, fishing, and ocean pollution continue to strike, the Nazar Canyon, and any other such canyons regimes, ought to be designated as marine protected areas (and established within the tight conservation guidelines to preserve their viability in carbon storing). Understanding of their carbon sequestration processes further will be important in revising global carbon budgets and improved climate change mitigation measures.

6.3 Recommendation to Include the Processes of Submarine Canyons in Global Carbon Models

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This has been a very strong result of this study in terms of providing evidence that submarine canyon processes should be incorporated in global carbon models. After considering the fact that submarine canyons are involved in major transport and burial of organic carbon, the role played by submarine canyons in oceanic carbon burial should be improved by calculating the amount of carbon buried and included into climate models. Scientists and policymakers can employ more effective strategies to improve the global capacity of the ocean in terms of the carbon sinks by increasing the accuracy of the carbon flux estimations and by realizing the importance of episodic turbidity flows.

A better understanding of the future distribution of carbon sequestration under various climate change scenarios can also be made through the use of submarine canyons in global carbon models. With the further acknowledgment of the importance of deep-sea systems, such as submarine canyons to the carbon cycling around the globe, they are the topic that needs to be studied, monitored, and preserved in research in the future.

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Conflicts of interest

The authors have no conflicts of interest to declare

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