The relationship between current flow direction and sediment distribution within slope-confined submarine canyons off the north coast of Moloka'i, HI

Heather Maran

University of Washington

School of Oceanography, Box 357940

Seattle, WA 98195-7940

maranh@uw.edu

Abstract

Submarine canyons play an important role in transporting sediments from terrestrial sources to abyssal environments. Sediment can be transported along continental shelves and into submarine canyons through bottom currents and gravity flows. This study characterizes the variability of sediment deposition patterns within the intra-canyon and inter-canyon environments associated with submarine canyons along the north continental shelf and slope of Moloka'i Island, HI. Shallow seismic reflection and bathymetric surveys were conducted in order to visualize sediment deposition and morphologic patterns along the upper, middle, and lower courses of the canyons on the East Moloka'i Shelf and compared with a middle reach of the Central Moloka'i Shelf. The PacIOOS ROMS model was used to evaluate current direction and speed on both sides of the island and was compared with canyon sidewall slopes to differentiate possible current deposition from other sources that may not have representable patterns. Our results demonstrate that sediment is dominantly distributed along the intra-canyon environments and is not prevalent within the canyon axes. Canyon slope sidewalls off the Central Moloka'i Shelf are steeper with little differentiation compared to canyons on the East Moloka'i Shelf which have predominately steeper western sidewalls. Model data indicate a predominately NW current flow direction on the eastern shelf, which may contribute to shallower eastern slopes, while currents west of the Kalaupapa Peninsula exhibit eddy-like circulation, indicating a less consistent pattern. Submarine canyons off the north coast of Moloka'i are relatively understudied, so an understanding of their sediment deposition patterns plays a key role in evaluating sediment budgets in this region.

Plain Language Summary

This study looks at how sediment is distributed within and around submarine canyons off the north coast of Moloka'i, Hawaii. The research question in the larger context of this field is to understand the distribution of sediment within submarine canyons along the continental shelf and slope. In this paper we associate inter-canyon environments with regions that lie within the submarine canyons, while intra-canyon environments are those that are outside of the canyons and consist of flat lying areas connecting adjacent canyons. We sought to understand if the dominant current directions and speeds in this region have control over where the sediment gets moved and stored. This study found that sediment distribution patterns within and around submarine canyons are complex and not only related to the current flow but can be related to the complex shape of the canyons themselves and their proximity to stream sources. Currents in this region have variable directions and speeds so there is likely not a representative pattern associated with sediment transport from seabed current flow. It is important to understand the sediment budget in continental shelf environments so we can recognize areas that may contain high biodiversity and reconstruct the evolution of these marine environments. Studying sediment distribution in a complex system, such as off the north coast of Moloka'i requires integrating processes that occur through a range of marine environments.

Introduction

Submarine canyons are incisions into the continental shelf and slope along continental margins and play an important role in linking continental shelves to abyssal environments (Amblas et al., 2018). Sediment sources feeding continental shelves and slopes are derived from continents through erosion and transported into the continental margins by riverine input (Nittrouer et al., 2007). The supply of sediment onto continental shelves plays a role in determining how much sediment is made available for interaction with physical processes. Additional sources of sediment into submarine canyons include deposition from slope failures along the margin that can be then transported down slope (Manta et al., 2019). Methods of sediment transport within submarine canyons include rapid downcanyon transport via turbidity currents and transport via bottom currents that induce resuspension and settling (Manta et al., 2019). Sediment resuspension may occur when particles that are originally on the seafloor get disturbed from waves, tides, and nearbed currents, and become suspended in the water column until they are later transported and re-deposited (Salim et al., 2018). There is typically a threshold value (Fig. 1) that allows for resuspension of particles due to shear stresses on the seafloor and the shear stress can vary depending on the average current speed and depth of the water column (Salim et al., 2018). Characteristics of fluid and sediment that are also important for the threshold of grain motion include the fluid viscosity, grain-size distribution, how the particles sit on the seabed, and the cohesive properties of the sediment.

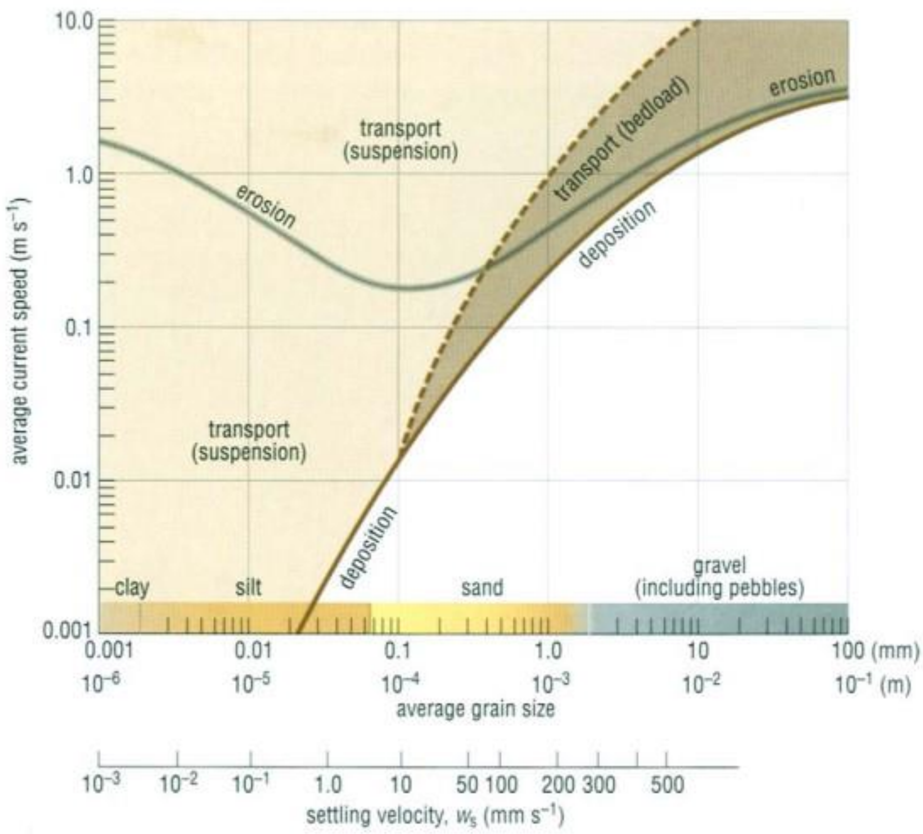


Figure 1. Threshold values for which grains of varying sizes can be transported, either in suspension or as bedload, or deposited. Grain sizes are classified into clay, silt, sand, or gravel. The blue curve represents the threshold of current speeds that can erode, or transport, particles at varying grain sizes. Figure obtained from The Open University (1999).

Moloka'i, the fifth largest island in the Hawaiian Islands, consists of two major subsections called East Moloka'i and West Moloka'i (Stearns & Macdonald, 1941). East Moloka'i is topographically dominated by the East Moloka'i Dome (Fig. 2). Between the two topographic features is a low-lying area, and in this study, we refer to this region as Central Moloka'i. Submarine canyons situated on the north coast of Moloka'i were eroded subaerially until they later subsided below sea level (Stearns & Macdonald, 1941). The region where submarine canyons are most common offshore of Moloka'i is along the north shore, particularly nearest the East Moloka'i Dome (Fig. 2). The continental shelf and slope of East Moloka'i is incised by eleven submarine canyons, whereas the West Moloka'i Shelf and slope is only incised by one (Mathewson, 1970). Canyon axes along the east shelf in particular are connected to smaller tributary canyons. Canyon heads along the eastern shelf are in close proximity to major fluvial systems that drain from the East Moloka'i Dome region.

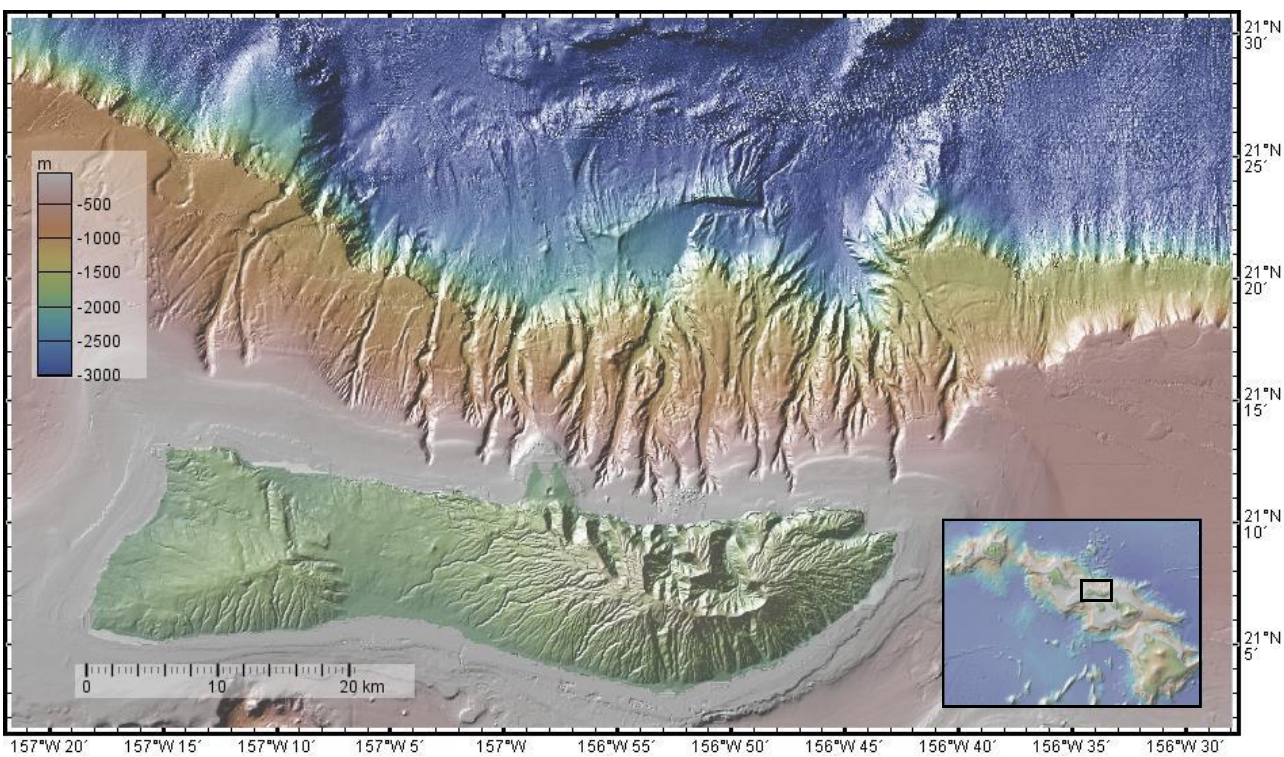


Figure 2. Bathymetric and shaded relief map of Moloka'i with inset map showing location among the Hawaiian Islands. The north coast is dominated by submarine canyons. The East Moloka'i Dome is a prominent geologic feature associated with East Moloka'i. West Moloka'i has low

topographic relief. Map made in GeoMapApp using SOEST main Hawaiian Islands multibeam bathymetry version 15, with 50 m resolution.

Submarine canyons are important environments for promoting biodiversity to a variety of species living in the benthic and subseafloor environments off the shores of the Hawaiian Islands (De Leo et al., 2014). Submarine canyons trap organic matter delivered from the continental shelf and slope, allowing benthic ecosystems to thrive in deep ocean environments. Previous research on the canyons off Moloka'i and neighboring O'ahu suggests they collect more organic-rich materials compared to the other Hawaiian Islands (De Leo et al., 2014). Sediment accumulation off the north coast of Moloka'i is mostly confined to the continental shelf and slope intra-canyon environments, and previous research suggests that submarine canyons along north Moloka'i transport sediment from the shelf to the abyssal environment through turbidity currents (Mathewson, 1970). Little research has been done to produce a detailed examination of the stratigraphy of the sediment comprising the submarine canyons along the north shore of Moloka'i. Therefore, the goal of this study is to provide a more complete understanding of sediment accumulation and deposition patterns within these canyons.

Morphology and sediment accumulation patterns are compared within the canyons nearest the East Moloka'i Dome vs those to the west of the Kalaupapa Peninsula (Fig. 3) to determine the role of the sediment source. The locations of streams that drain into the shelf environment (Fig. 3) are most prominent near the East Moloka'i Dome and are considered in the examination of sediment source patterns. Streams are a prominent source of sediment delivery to the shelf, so their locations can be potentially correlated with canyons that contain the thickest sediment deposits.

Various research methods allow for the study of sediment distribution and transport mechanisms along submarine canyons. Instrumented moorings with current meters collect in situ current and wave data that is utilized to study sediment movement within shelf and slope environments (Puig et al., 2014). Sediment coring allows for visualization of sediment deposition beneath the seafloor, and modern accumulation rates along different reaches of a canyon can be estimated using Pb-210 analysis on sedimentary layers (Puig et al., 2014). In addition to coring, a combination of multibeam echosounder data and seismic reflection imaging enables us to study sediment deposition patterns at and below the seafloor and allows us to interpret historic depositional events (Antobreh & Krastel, 2006). In this study, seismic reflection imaging is performed in tandem with multibeam bathymetric mapping in order to map sediment distribution across canyon axes indicated by sediment accumulation and canyon wall slope patterns.

This study focuses on understanding the distribution of sediment within intra-canyon areas as well as within the upper, middle, and lower course of the submarine canyons on the north Moloka'i coast. Sediment distribution patterns are analyzed using a combination of regional circulation model data, multibeam echosounder and seismic reflection data, and ArcGIS analyses. I hypothesize that sediment thickness will be greatest on the up-flow side of the current flow direction due to along isobath transport from intra-canyon areas into the inter-canyon areas. My null hypothesis is that there will be no sediment accumulation within the submarine canyons from the intra-canyon areas and along-isobath currents do not play a role in depositing sediment into canyons, resulting in more similar canyon slopes. Mapping out areas of significant sediment accumulation along these canyons could complement the array of work that has already been done to understand the benthic ecosystems along submarine canyons in the Hawaiian Islands. Evaluating sediment distribution patterns can allow us to study the characteristics and evolution of continental margins.

Methods

Data acquisition

The research cruise transect was designed to cross over submarine canyons both on the East Moloka'i Shelf and Central Moloka'i Shelf in order to differentiate sediment distribution between a shelf environment with high stream input to one with no stream input (Fig. 3). Additionally, three east-west trending transects were performed along the East Molokai Shelf and Slope in order to understand sediment deposition changes moving away from the continental shelf. Overall, eight submarine canyons were analyzed: four east of the Kalaupapa Peninsula, canyons 1-4 in Figure 3, and four west of the Kalaupapa Peninsula, canyons, 5-8 in Figure 3.

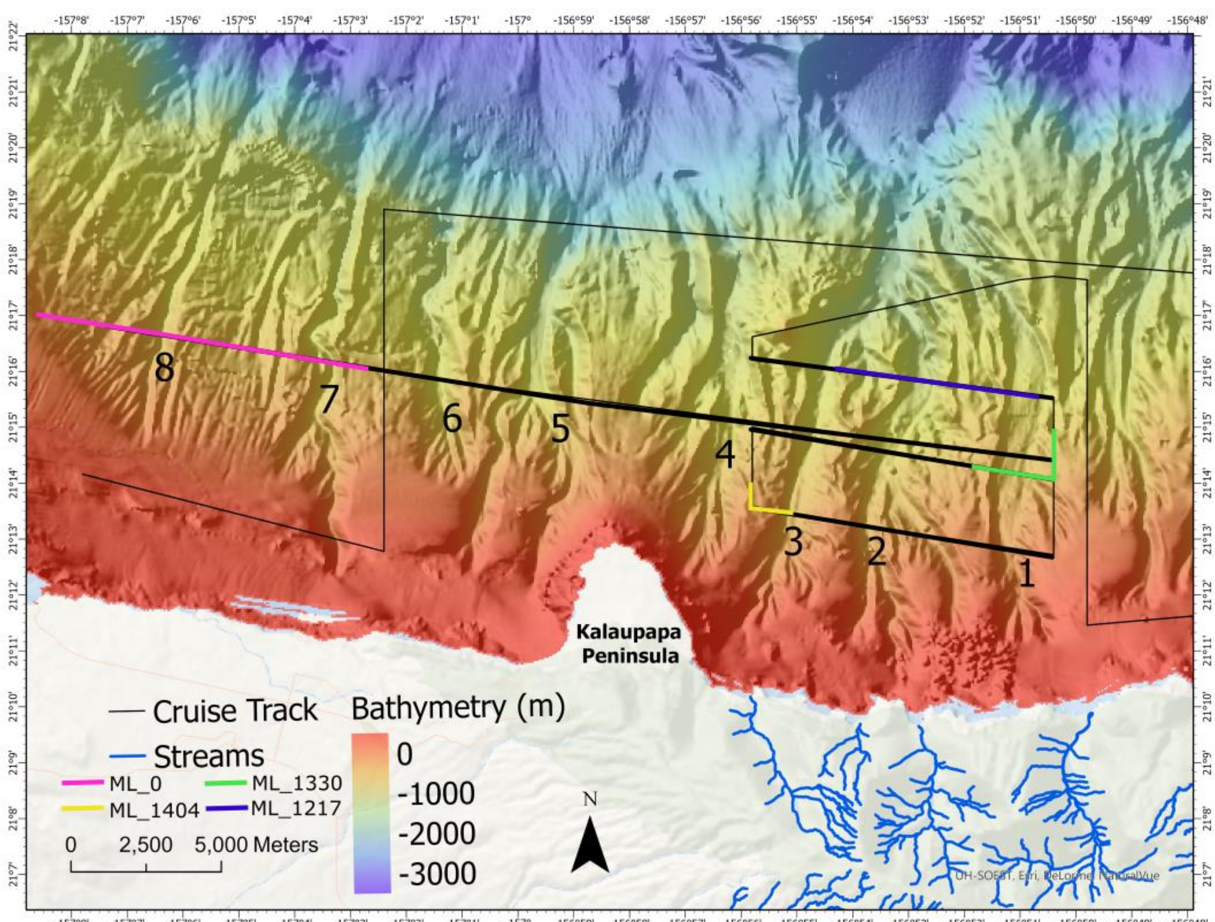


Figure 3. Map of the bathymetry off the north coast of Molokai with the cruise transect and locations of major streams. The bold transect represents areas used for analyses in this study, and colored lines indicate transects used for CHIRP analyses. Submarine canyons associated with this study are labelled 1-8. Map made in ArcGISPro using SOEST main Hawaiian Islands multibeam bathymetry with 50 m resolution.

In order to map the seafloor and visualize the morphology of the submarine canyons, multibeam bathymetry of the transects was created using a hull-mounted EM 302 multibeam echosounder with an approximate ship speed of 5 kts, or 2.6 m/s. A high-resolution bathymetric dataset was used for calculating the statistics of the morphologic features of the canyons such as the slope gradients of the sidewalls. Additionally, multibeam mapping allowed us to visualize slope failures that may be contributing to sediment supply so we can identify sediment sources that may not correspond with the along-isobath transport from the dominant current flow direction.

Seismic reflection profiles were collected coincident with the acquisition of the multibeam bathymetric data and analyzed to study sediment deposition patterns below the seabed within the submarine canyons. Shallow seismic reflection profiles were generated using a Knudsen Chirp 3260 echosounder with a frequency range of 3.5 kHz-210 kHz and an average ship speed of 5 kts, or 2.6 m/s. Basement rock is prominent in seismic reflection profiles as a high reflectivity layer compared to the sediment layers above it. In order to evaluate the thickness of sediment, the time it takes for the seismic wave to be emitted, reflect off the seabed reflectors, and return to the receiver is recorded and converted to depth by using estimated velocities of sound through seawater and seafloor sediment. Seismic stratification data allow us to investigate sediment distribution patterns across the axes of the submarine canyons and in the intra-canyon environments.

Model data from the Pacific Islands Ocean Observing System (PacIOOS) (http://pacioos.hawaii.edu/voyager/) was used to visualize current directions in order to hypothesize which side of the canyons accumulates more sediment. To assess the near bed dominant current direction in the model, a water depth of 500 m was used to generate the mean current direction using the Regional Ocean Modeling System (ROMS) within PacIOOS. Mean current speed and direction was produced for a location on the East Moloka'i Shelf (~ 21.35°N, 156.89°W) and the Central Moloka'i Shelf (~ 21.37°N, 157.16°W). The time period used in the ROMS model was the month of July 2022 which is during the time period of dominant trade winds. With an understanding of the most persistent nearbed current speeds and directions, we can understand if and where sediment may be transported from the intra-canyon environments. Two sediment grab samples taken at a location within the intra-canyon environment off the East Moloka'i Shelf indicated a dominant grain size of 0.42 mm and 0.38 mm, also classified as medium-grained sand (Baker, 2023). Currents greater than 0.2 m/s were used in analyses of current direction as a threshold value in which significant sediment resuspension may occur on the seabed for medium sand-sized particles based on the threshold of motion curve (Fig. 1).

A more complete multibeam dataset is provided by the University of Hawaii (http://www.soest.hawaii.edu/hmrg/multibeam/explorer.php) and is used in this study to provide additional coverage and data sources for the continental shelf along the north coast of Moloka'i. They provide additional data on backscatter that allow us to visualize the hardness of the seafloor to make inferences on large scale sediment deposition patterns.

Data Processing & Analysis

Multibeam

After the raw multibeam bathymetry data was collected it was merged into a file format which includes the navigation files for the transects and the pitch and roll related to the ship's movement.

The pitch, or up and down motion, and roll, or side to side motion, is important to consider when processing multibeam data because we can remove the ships' movement and offsets that may create artifacts. The raw multibeam files were made into a comprehensive dataset using the QPS Qimera processing software to process the files and generate a dynamic surface. Outlier datapoints within the raw multibeam data may create artifacts that aren't representative of features on the seabed and were removed. Even though the pitch and roll were already incorporated into the dynamic surface we observed outlier data points that needed to be cleaned and removed. Gaps within the data were interpolated to provide a more complete dataset. A horizontal resolution of 25 m was used in the final analysis of the multibeam dataset. After the multibeam dataset was fully processed, bathymetric profiles were created over transects in order to visualize the side walls of the canyons and calculate the slope of both the east and west walls. There are multiple submarine tributaries present along the submarine canyons, so it is important when calculating the sidewall slope that the actual canyon sidewall is accounted for and not tributary morphology. In order to account for this, the multibeam bathymetry in Qimera was visualized in 3-D to discern areas that are either a part of the submarine canyon sidewall slope or a section of a submarine tributary.

CHIRP

The raw seismic reflection data was exported from the Sounder Suite software associated with the Knudsen software package as SEG-Y file formats and processed and plotted in MATLAB. Steps of deconvolution of the raw data included adding a high pass bandwidth filter set to 3000 Hz and a zero-phase wavelet filter order to produce a dataset that has a broad bandwidth zero-phase wavelet so that prominent strata reflectors stand out. We tested parameters of the scale, clip, and filter processing steps to see how it affected the quality of the seismic reflection profile images.

After processing, profiles were produced of the seismic reflection images and are used to visualize sediment deposition patterns along the transects. An image from the upper, middle, and lower course of the canyons along the East Moloka'i Shelf were then compared to a profile along the Central Moloka'i Shelf to compare and differentiate their sediment distribution patterns.

ArcGIS Pro

When the time does not allow for physical sampling of the seafloor sediments, backscatter analysis can provide information on the seafloor substrate composition (Valentine 2019). ArcGIS backscatter analysis was used to determine which areas around and within the canyon environments contain coarser sediment and which areas contain finer-grained sediments. Low backscatter values correspond to less dense sediment and a softer seafloor, typically consisting of mud, and high backscatter values correspond to harder seafloor composed of coarse-grained sediments (Smith, 2016). Backscatter analysis was used to understand depositional patterns of different sediment types and determine which areas may be prone to modern transport based on their hardness.

Results

Canyon Slope Analysis Using Multibeam Profiles

The slope of the sidewalls of the canyons were calculated using bathymetric profiles and ranged from 7° to 53° (Table 1). On average, the eastern slope of the eight submarine canyon sidewalls is less steep than the western sidewalls. There is a distinct difference observed when comparing the calculated slopes from the east or west of the Kalaupapa Peninsula. Slopes along the Central

Moloka'i Shelf show little changes in slope when comparing the east and west walls as compared to the slopes along the East Moloka'i Shelf.

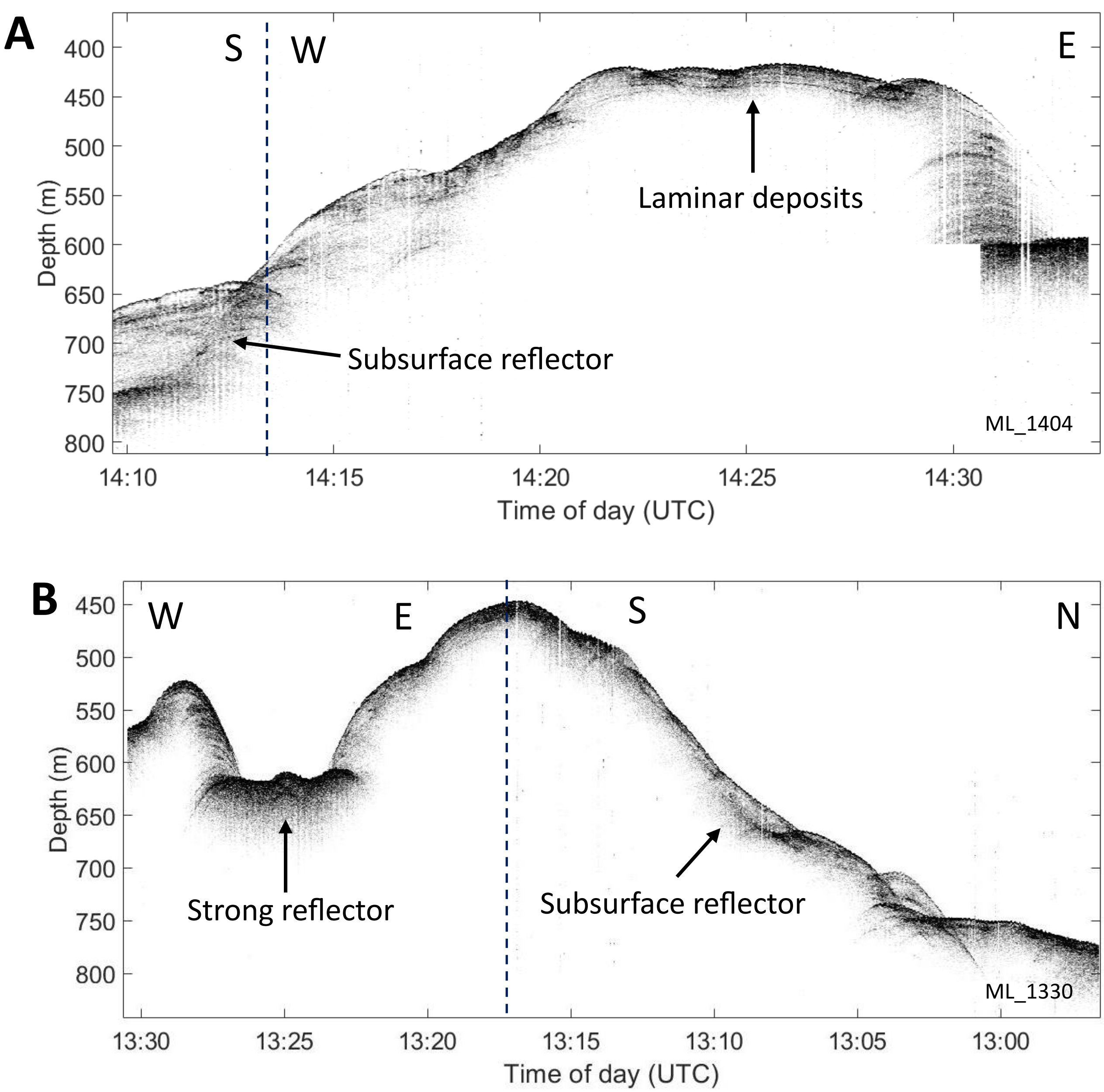
Table 1. Submarine canyon sidewall slopes separated by east and west walls. Four canyons are evaluated on the East Moloka'i slope and four on the Central Moloka'i slope. A positive change in slope indicates the east slope is shallower than the west slope, and negative values indicate the west slope is shallower than the east. Slopes calculated using multibeam bathymetry profiles in QPS Qimera.

Canyon number	East slope (%)	West slope (%)	Δ Slope
1 - Upper	24.6	47.0	22.4
2 - Upper	42.0	42.6	0.6
3- Upper	22.2	49.9	27.7
1- Middle	21.3	53.0	31.7
2- Middle	17.0	23.4	6.4
3- Middle	14.8	40.7	25.9
1 - Lower	7.0	45.3	38.2
2- Lower	25.8	40.2	14.5
3- Lower	40.6	23.0	-17.6
4	30.0	30.4	0.4
5	27.4	32.6	5.2
6	26.3	28.8	2.6
7	50.4	32.1	-18.3
8	40.8	39.3	-1.5
Average	**27.9**	**37.7**	

CHIRP Sediment Distribution

East Moloka'i Shelf:

Sediment deposits along the East Moloka'i Shelf most commonly occur in laminar layers along the intra-canyon environments as indicated by subsurface seismic reflectors (Fig. 4). At the base of the canyons within the thalweg, strong reflectors are present indicating a hard seabed and little to no sediment accumulation. Moving down the submarine canyons away from the shelf, sediment accumulation becomes less apparent. The N-S portion of the profiles in Figure 4 illustrates depositional features that are present within the intra-canyon environments as observed on the transect map in Figure 3. Multiples are present within certain profiles (Fig. 4.C) which are not subsurface features but instead form from a secondary reflection off a reflector making it more challenging to interpret features accurately.



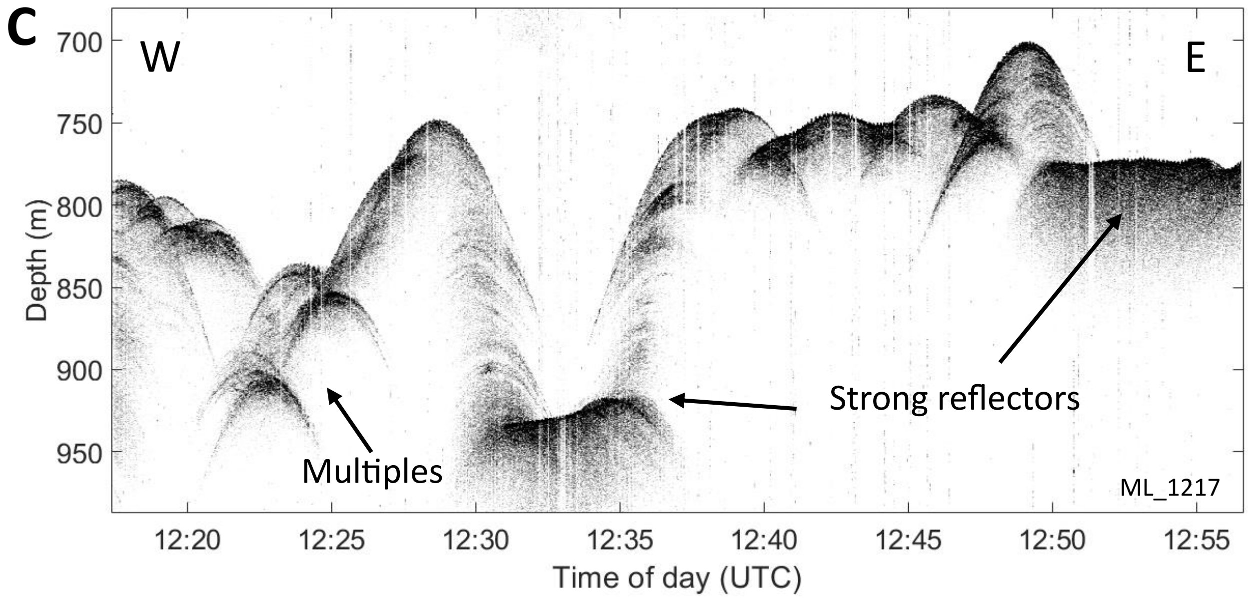


Figure 4. CHIRP seismic reflection profiles along the upper course, ML_1404 (A), middle course, ML_1330 (B), and lower course, ML1217 (C), of the canyons along the East Moloka'i Shelf as seen in Fig. 3. **A.** Laminar sediment deposits are present in the intra-canyon environment, and a subsurface reflector is present on the east slope of canyon 4. **B.** Strong reflector at the base of the canyon indicates a hard surface with no sediment deposition. A subsurface reflector is present in intra-canyon transect. **C.** Little to no subsurface reflectors are present along the intra-canyon environments, with strong reflectors present within the canyon axes. Multiples are present that do not indicate subsurface reflectors.

Central Moloka'i Shelf:

The canyon axes within canyons 7 and 8 contain strong reflectors, and subsurface reflectors are present predominately within the intra-canyon environments (Fig. 5). CHIRP profiles that were collected along the Central Moloka'i Shelf were not as high-resolution as some of the seismic reflection images collected along the Eastern Moloka'i Shelf. Multiples were also present in some of the profiles indicating repeated reflections that do not accurately represent a depositional reflector below the seafloor.

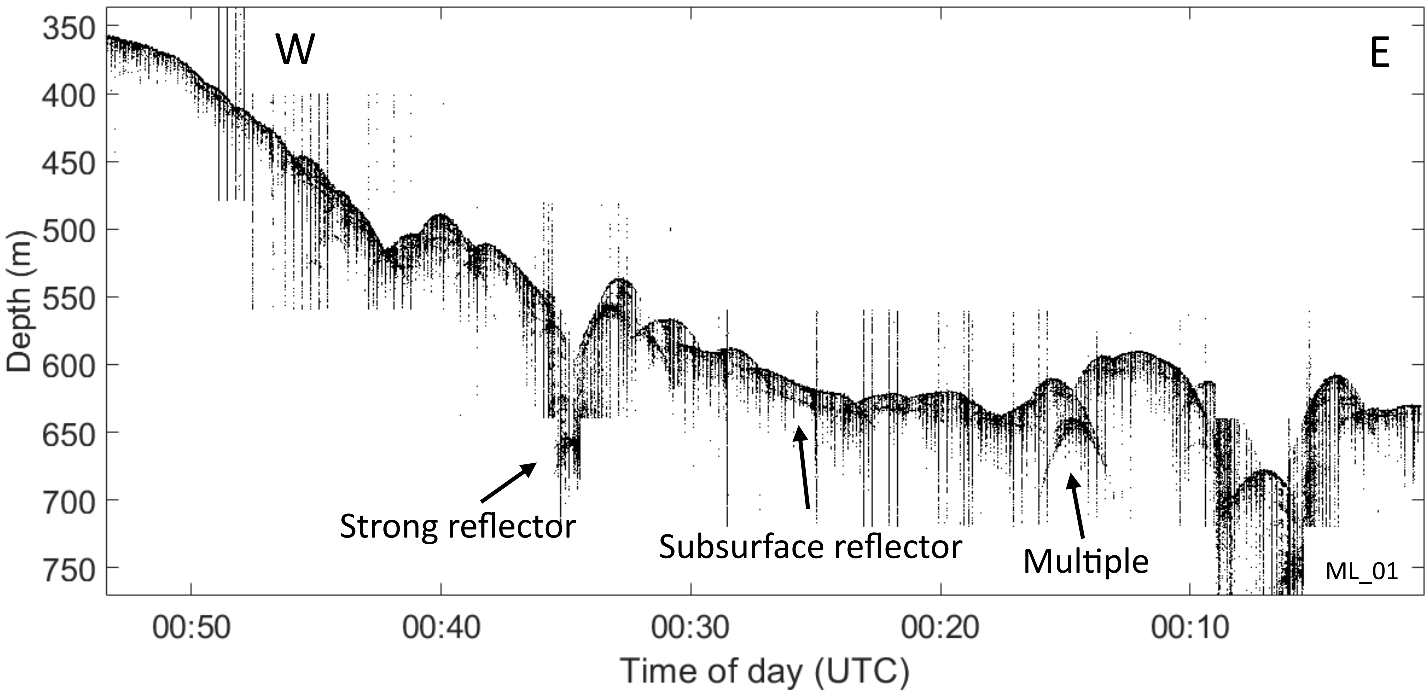


Figure 5. CHIRP seismic reflection profile ML_01 along the Central Moloka'i Shelf as seen in Figure 3. Sediment is mainly distributed along the intra-canyon environments indicated by subsurface reflectors. Strong reflector at the base of canyon 7 indicates little to no sediment.

Seabed Backscatter

Backscatter analysis indicates that the seafloor within the submarine canyons produces a higher backscatter value, which is related to a harder seabed (Fig. 6). The intra-canyon environments produce lower backscatter values which correspond to a softer seabed. Within the intra-canyon environments, low backscatter values are observed at the landward end of the continental shelf and increase seaward. Central Moloka'i canyons seem to have lower backscatter than the eastern canyons. Higher backscatter is observed in the intra-canyon environments along the lower course of the slope on the east side, with the central slope region having higher backscatter values that are more confined to the canyon perimeter.

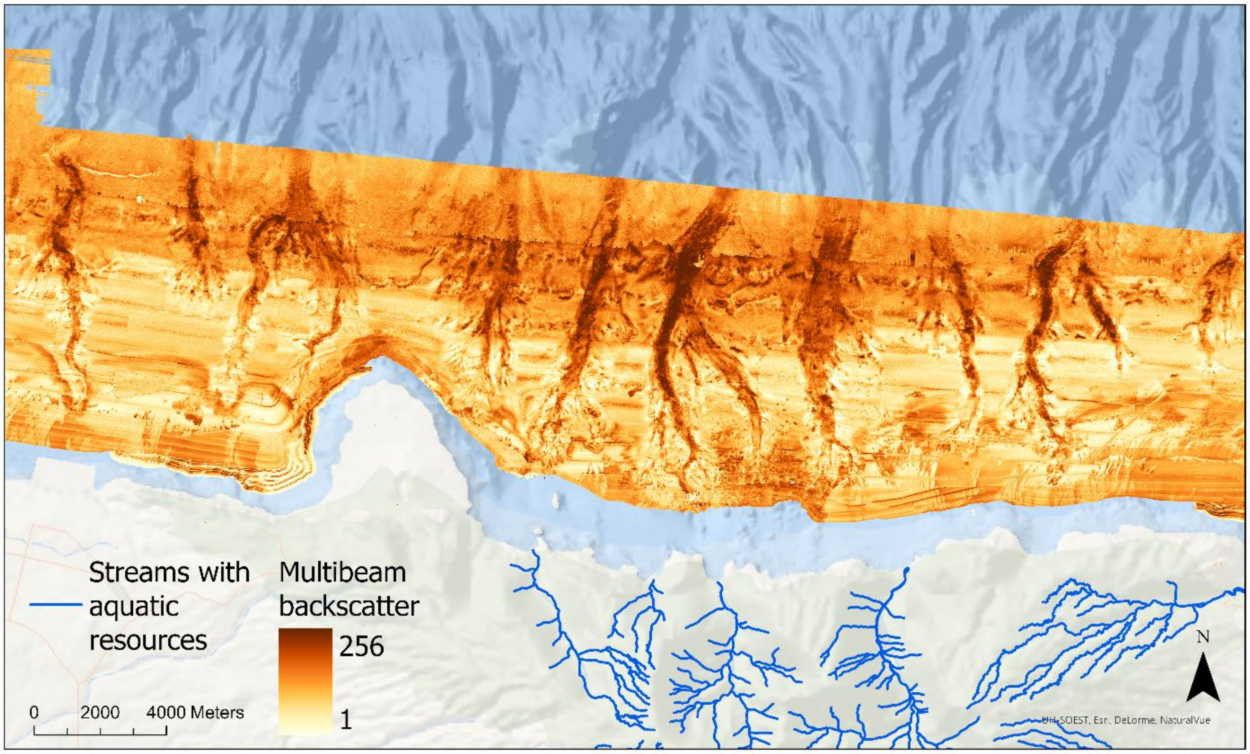


Figure 6. ArcGIS multibeam backscatter analysis with locations of streams with aquatic resources. Backscatter data is made available through the University of Hawaii at Manoa.

PacIOOS Nearbed Currents

Data produced from a location along the East Moloka'i Shelf, East of the Kalaupapa Peninsula, yielded a range of current speeds from 0.017-0.46 m/s (Fig. 7.C). Along the Central Moloka'i Shelf, west of the Kalaupapa Peninsula, a range of currents from 0.021-0.36 m/s were observed (Fig. 7.D). A current speed of 0.2 m/s was used to determine the dominant current direction within the East and Central Moloka'i Shelf region in order to represent the strongest currents that may be able to resuspend sediment along the seabed based on the threshold of grain motion curve (Fig. 1). Dominant current directions around the east shelf region trend toward the NW (Fig. 7.A). Currents around the central shelf region do not exhibit a dominant directionality and trend in almost every direction except for the S and SW (Fig. 7.B).

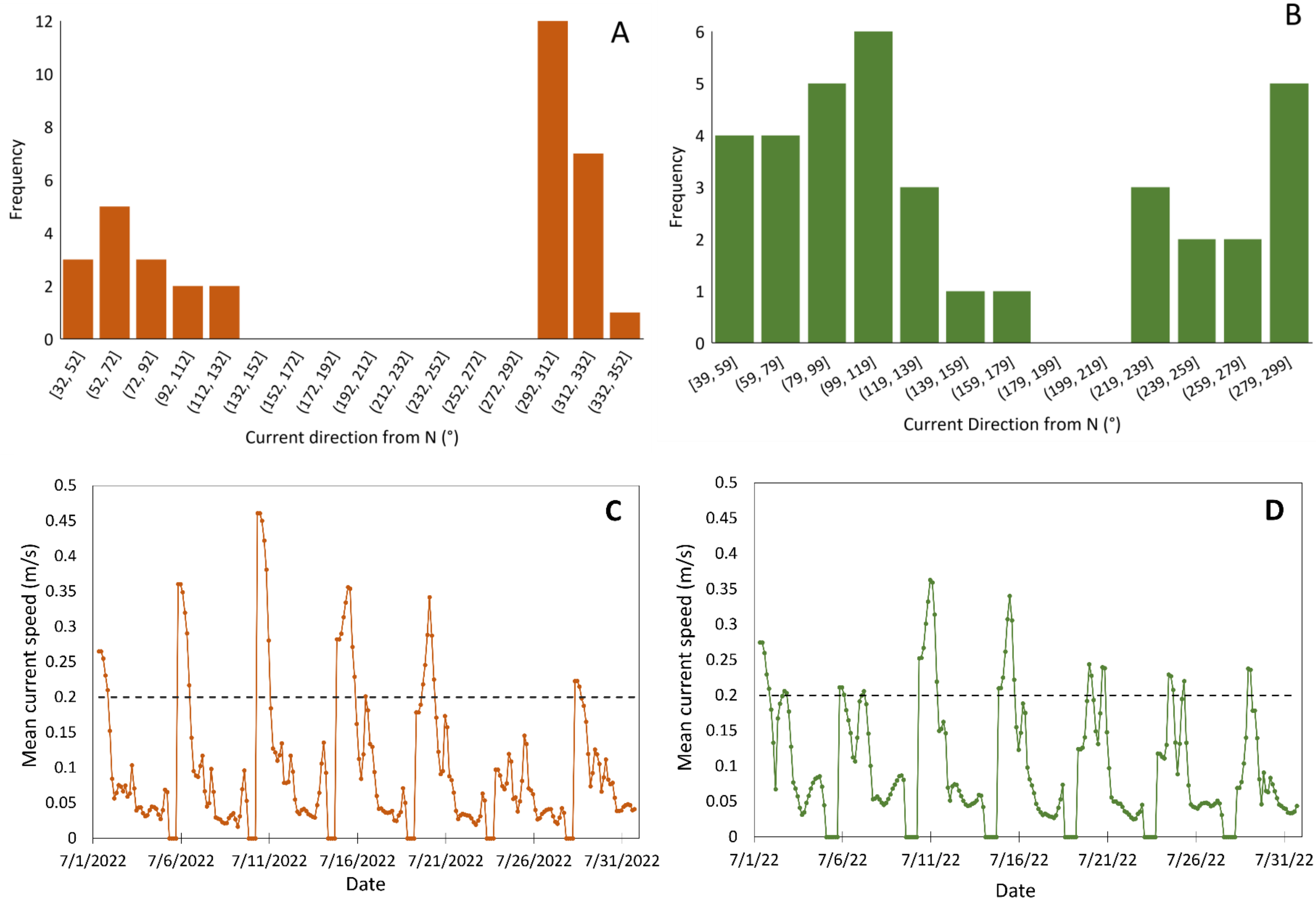


Figure 7. PacIOOS ROMS model data for July 2022 off the north coast of Moloka'i, HI at a water depth of 500 m. **A.** Current direction distribution at speeds greater than 0.2 m/s off the East Moloka'i Shelf, with a dominant directionality of 292-312° indicating flow toward the NW. **B.** Current direction distribution at speeds greater than 0.2 m/s off the Central Moloka'i Shelf indicating no apparent dominant current direction; flows are toward the NE, SE, SW, and NW. **C.** Mean current speed in m/s for July 2022 off the East Moloka'i Shelf. The 0.2 m/s threshold used to calculate directions for plot A is represented by the dashed line. **D.** Mean current speed in m/s for July 2022 off the Central Moloka'i Shelf. The 0.2 m/s threshold used to calculate directions for plot B is represented by the dashed line.

Discussion

The morphology of the fluvially connected canyons along the East Moloka'i Shelf contain complex characteristics with variations in canyon sidewall slopes and several tributaries and channels that may influence sediment transport patterns. Off the coast of Moloka'i, sediment deposits are not common along the thalweg of the canyons and are predominately associated with the intra-canyon environments (Fig. 4). Sediment deposition may be happening within the canyon axes, but the canyons may be swept clean and acting as transport mechanisms before we can map it. Some studies suggest that sediment transport in submarine canyons is driven by gravity flows, such as turbidity currents, while others suggest that bottom currents also play a significant role. The backscatter distribution inferred hard sediments within the canyons and softer sediments in the intra-canyon regions (Fig. 6). These patterns correlate to patterns we observed in the seismic reflection images; strong reflectors present at the bottom of the canyons indicate no deposition compared to reflectors in the intra-canyon environments which show signs of a depositional history (Fig. 4). Sediment deposition becomes less apparent as you move away from the shelf and move into the slope environments (Fig. 4). When comparing the seismic reflection images from the upper, middle, and lower courses of the canyons, sediment accumulation is most common along the upper course and is rarely present along the lower course (Fig. 4). Understanding that sediment is deposited predominately within the intra-canyon environments, we can use the modelled current directions to predict where the sediment may be moving given an appropriate nearbed current speed that can initiate grain motion on the seafloor. Once grains are set in motion, they can be transported and deposited within deeper environments that contain weaker nearbed currents not capable of eroding sediment, such as within submarine canyons. With an understanding of the direction that nearbed currents are flowing, we can estimate where sediment on the seabed may be transported and thus deposited within the shelf environment. Over the month of July 2022 currents are predominately trending to the NW, which is the same direction as the easterly trade winds (Fig. 7.A). As observed in Table 1, shallower slopes of the eastern sidewalls of the canyons, and steeper slopes on the west, may be due to increased sediment deposition that could be decreasing the slope steepness over time. On average there are more tributaries present along the eastern sides of the canyons (Fig. 3) which may be contributing to shallower slopes through introduction of more sediment sources that aren't confined to the intra-canyon environments. The high abundance of streams that drain from the East Moloka'i Dome (Fig. 3) may be contributing to increased sediment input into the shelf environments that can either be transported NW by nearbed currents, or through tributaries that dominate the eastern slope regions.

Similar to the East Moloka'i Shelf, sediment distribution along the Central Moloka'i Shelf is mostly confined to the intra-canyon environments with little to no sediment deposition within the inter-canyon environments. However, the morphology, current directions, and sediment source inputs vary when compared to the systems observed along the East Moloka'i Shelf. The slopes of the canyon sidewalls are less differentiated between each other when compared to the east shelf region. On average the eastern sidewalls are slightly less steep compared to the western sidewalls, but the magnitudes are remarkably smaller than those observed on the East Moloka'i Shelf. A variety of physical processes could be responsible for these differences. Little to no streams drain onto the Central Moloka'i Shelf which may account for some of these morphology differences. Additionally, if currents are predominately heading toward the NNW along the eastern shelf, they could come into contact with the peninsula. When this occurs the wave and current energy is dissipated and dispersed in differing directions resulting in multiple eddies around the west side of the island that could slow down transport of sediments or move it offshore where it gets more broadly dispersed. According to Storlazzi et al. (2012), nearbed current speeds and directions vary greatly in observations of Pelekane and Kawaihae Bays in Hawaii. Given this, we can expect that this may be true for the north coast of Moloka'i, and the model output may be producing representative magnitudes. Current direction variability can also be influenced by contact with the local bottom topography. Based on the information about current directions in this region and slope characteristics we can infer that the Central Moloka'i Shelf receives less sediment input and is less morphologically diverse than the East Moloka'i Shelf.

The submarine canyons situated on the north continental shelf and slope of Moloka'i experience similar depositional patterns and morphological features that can be observed along other continental margins. Within most submarine canyons there are tributaries which connect to the main canyon that contribute to the drainage and transport processes. Aiello (2020) produced bathymetric profiles across submarine canyon axes and found that the submarine canyons off Naples Bay experiences asymmetrical slopes accompanied by laminar deposits along the intra-canyon environments with an input of sediment accompanied by riverine input feeding the continental slopes with sediment.

Results from this study are consistent with Mathewson (1970) and support my null hypothesis that submarine canyons off the north coast of Molokai are not depositional systems given the lack of sediment accumulated within the canyons themselves. Instead, most sediment is deposited in the intra-canyon environments and potentially on the upflow sidewalls, with little to no sediment accumulating within the axes of the canyons. The continental shelves off East and Central Moloka'i have varying complex depositional systems that are strongly influenced by the morphology of the canyons and their proximity to sediment sources.

Future Work

The deposits that we are visualizing in the shallow seismic reflection images may not be an accurate representation of the full range of deposits in the subsurface. In order to estimate and compare the thickness of sediment deposits in this region we would need to use higher resolution seismic reflection imaging that can penetrate deeper into the subsurface. In addition, this project could be improved in the future by performing Pb-210 analysis within layers in box cores to estimate sediment accumulation rates in the intra-canyon environments compared to the inter-canyon environments. With all of these seabed tools, we can infer which areas are receiving more sediment deposition compared to others on a range of timescales. Additionally, the PacIOOS ROMS model data for a depth of 500 m may not accurately represent the current flow direction and magnitude at the depth suitable for sediment transport in this region. Moored buoys with current meters would allow us to understand the current dynamics of this region in order to better differentiate between the east and west shelf environments.

Conclusions

The morphology of the submarine canyons off the coast of Moloka'i is complex and varies along the canyon's channels. There are multiple factors that can influence the transportation and distribution of sediment off the shelf and into the inter and intra canyon environments. These are associated with current speed and direction, the morphology of the canyons, proximity to a sediment source, and location near a peninsula that contributes to changing current patterns. Currents may be influenced by the local bottom topography associated with the submarine canyons and interaction with headland morphology that can change their magnitude and directionality. This study suggests that there is not one mechanism for sediment transport within the canyons and multiple factors are involved. Future research of the sediment budget off the coast of Moloka’i will improve our understanding of the mechanisms driving sediment transport and deposition in these canyon environments and put together an understanding of the erosional and depositional history of this continental margin.

Acknowledgements

I would like to thank Andrea Ogston and Maleen Kidiwela for their support with all aspects of putting my research ideas into fruition and with their help on data processing and interpretation, the crew of the R/V Thompson for getting us to our research destination and helping with data collection, and the School of Oceanography for supporting this research and giving us the opportunity.

References

Aiello, G., Iorio, M., Molisso, F., & Sacchi, M. (2020). Integrated Morpho-Bathymetric, Seismic-Stratigraphic, and Sedimentological Data on the Dohrn Canyon (Naples Bay, Southern Tyrrhenian Sea): Relationships with Volcanism and Tectonics. *Geosciences*. 10: 319. doi:10.3390/geosciences10080319

Amblas, D., Ceramicola, S., Gerber, T. P., Canals, M., Chiocci, F. L., Dowdeswell J. A., Harris, P. T., Huvenne, V. A. I., Lai, S. Y. J., Lastras, G., Iacono, C. L., Micallef, A., Mountjoy, J. J., Paull, C. K., Puig, P., & Sanchez-Vidal, A. (2018). Submarine Canyons and Gullies. In Micallef, A., Krastel, S., and Savini, A. [eds], *Submarine Geomorphology, Springer Geology*. 251-270. doi:10.1007/978-3-319-57852-1_14

Antobreh, A. A., & Krastel, S. (2006). Morphology, seismic characteristics and development of Cap Timiris Canyon, offshore Mauritania: A newly discovered canyon preserved-off a major aird climatic region. *Marine and Petroleum Geology*. 23(1): 37-59.

Baker, A. (2023). Evolution of submarine terraces off Northern Molokai, HI. The University of Washington.

De Leo, F. C., Vetter, E. W., Smith, C. R., Rowden, A. A., & McGranaghan, M. (2014). Spatial scale-dependent habitat heterogeneity influences submarine canyon macrofaunal abundance and diversity off the Main and Northwest Hawaiian Islands. *Deep-Sea Research II*, 104, 267-290. doi:10.1016/j.dsr2.2013.06015

Manta, K., Rousakis, G., Anastasakis, G., Lykousis, V., Sakelarious. D., & Panagiotopoulos, I. P. (2019). Sediment transport mechanisms from the slopes and canyons to the deep basins south of the Crete Islands (southeast Mediterranean). *Geo-Marine Letters*, 39, 295-312.

Mathewson, C. C. (1970). Submarine canyons and the shelf along the north coast of Molokai Island, Hawaiian Ridge. *Pac Sci.,* 24, 235-244.

Nittrouer, C.A., Austin, J. A., Field, M. E., Kravitz, J. H., Syvitski, J. P. M, & Wiberg, P. L. (2007). Continental Margin Sedimentation: From Sediment Transport to Sequence Stratigraphy. *International Association of Sedimentologists*.

Puig, P., Palanques, A., & Martín, J. (2014). Contemporary Sediment-Transport Processes in Submarine Canyons. *The Annual Review of Marine Science*, 6:53-77. doi:10.1146/annurev-marine-010213-135037

Salim, S., Pattiaratchi, C., Tinoco, R. O., & Jayaratne, R. (2018). Sediment resuspension due to near-bed turbulent effects: A deep sea case study on the northwest continental slope of Western Australia. *Journal of Geophysical Research: Oceans,* 123, 7102-7119. https://doi.org/10.1029/2018JC013819

Smith, J. R. (2016). Multibeam Backscatter and Bathymetry Sythesis for the Main Hawaiian Islands Final Technical Report July 2016. *SOEST*.

Stearns, H. T., & Macdonald, G. A. (1947). Geology and Ground-water Resources of the Island of Molokai, Hawaii. Geological survey, United States Department of the Interior.

Storlazzi, C. D., Field, M. E., Presto, M. K., Swarzenski, P. W., Logan, J. B., Reiss, T. E., Elfers, T. C., Cochran, S. A., Torresan, M. E., & Chezar, H. (2012). Coastal Circulation and Sediment Dynamics in Pelekane and Kawaihae Bays, Hawaii – measurements of waves, currents, temperature, salinity, turbidity, and geochronology. *U.S. Geological Survey,* Open-File Report 2012-1264, 102.

The Open University. (1999). Waves, Tides, and Shallow Water Processes. (Edition 2). Butterworth-Heinemann, Oxford (pp. 102-103).

Valentine, P. C. (2019). Sediment classification and the characterization, identification, and mapping of geologic substrates for the glaciated Gulf of Maine seabed and other terrains, providing a physical framework for ecological research and seabed management: U.S. Geological Survey Scientific Investigations Report 2019-5073, 37.