

Evolution of submarine terraces off Northern Moloka'i, HI

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Abstract

Submarine terraces off Northern Moloka'i, HI, have been understudied. Terraces are vital to our understanding of sea-level changes and terrestrial alterations. One study aimed to identify terraces and evaluate their evolution, and found three continuous terrace tracts. Bathymetric data, sub-bottom profiles, and Shipek grab samples were collected in this region during a cruise in late February 2023 on the R.V. Thompson. The data were processed and analyzed. Sixteen benches were identified, with most being formed by wave action but others due to faulting. While the primary goal of the study was to estimate the ages of terraces using sea-level curves, only two terraces could be aged. These ages being around 12.1 kyr and 13.5 kyr which is similar in age to corals dated offshore of Lanai, Most of the identified benches were unexpectedly deep and could not be aged. Terraces deeper than 200 m are speculated to have been deepened either by mass wasting events that moved former terraces down-slope or by volcanic loading that drove the subsidence of wave-cut terraces.

Plain Language Summary

Very little research has been done on submarine terraces off of Northern Moloka'i, HI. Only one study previously has been performed in this area. The purpose of this study was to identify terraces and also to age them. Sea floor profiles were collected in this region during a cruise in late February 2023 on the R.V. Thompson. Also collected were sub-bottom profiles, or strong sound pulses that allow the ability to see layering in the sediment. Sixteen submarine benches were identified with most being formed due to wave energy but others due to faulting because of landslides. Wave-cut terraces are steps formed by wave action. Due to not all the terraces being formed by wave action, "terrace" is not an appropriate term, but instead a more general term is used, "bench". While the primary goal of the study was to estimate the ages of

terraces using sea-level curves, only two terraces could be aged. These ages were 12.1 kyr and 13.5 kyr. Most of the identified benches were unexpectedly deep and could not be aged. This is speculated to be a cause of either landslides that moved the terraces deeper or volcanic loading, a process in which the lithosphere sinks, and causes relative sea-level rise. This is important because it is important to learn the past history of islands, especially relative sea-level.

Introduction

The configuration of paleo-sea-level reconstructions for specific areas is an essential clue into external Earth's past. Sea-level curves assist researchers in understanding the formation of the continental shelf/shoreline features and erosional processes. These reconstructions are produced using a variety of techniques, such as using $\delta^{18}\text{O}$ ratios. Sea-level evolution, grain sizes, and displaced shoreline features are also used in developing sea-level curves. Submarine terraces are beneficial to forming a sea-level curve because most are created and maintained by waves at the shoreline. Shallow, low stand terraces can be used as proxies for the sea-level position at the Last Glacial Maximum (Casalbore et al 2017). Preserved terraces that exist beneath the wave base indicate a sea-level that was once lower. Wave base constitutes the water depth at which 4% of the sea-level wave energy exists. Terraces can be eroded due to the movement of coarse sediment above wave base. As sea-level rises, shorelines are submerged, and terraces will be continuously eroded. If the sea-level rise is slow, the terraces will be completely destroyed because they are in contact with wave energy for an extended period of time. We see preserved submarine terraces off of Northern Moloka'i, Hawaii (Figure 1) and can infer sea-level rose quickly to move the terraces rapidly below the wave base. Submarine terraces that exist below modern wave base in an energetic wave environment offer the opportunity to determine the age of the terrace deposits using sea-level curves. Determining if

the waves have the capability to transport sediment and erode rock can be evidence that the terraces were formed by wave energy and therefore the sea-level rose rapidly. There is a complex interaction between sea-level rise, terrestrial and submarine mass wasting, subsidence, and tectonic activity. Sea-level rise and wave activity are the cause of most submarine terrace formation, but faulting because of landslide events can also create benches which can be confused with wave-cut terraces.

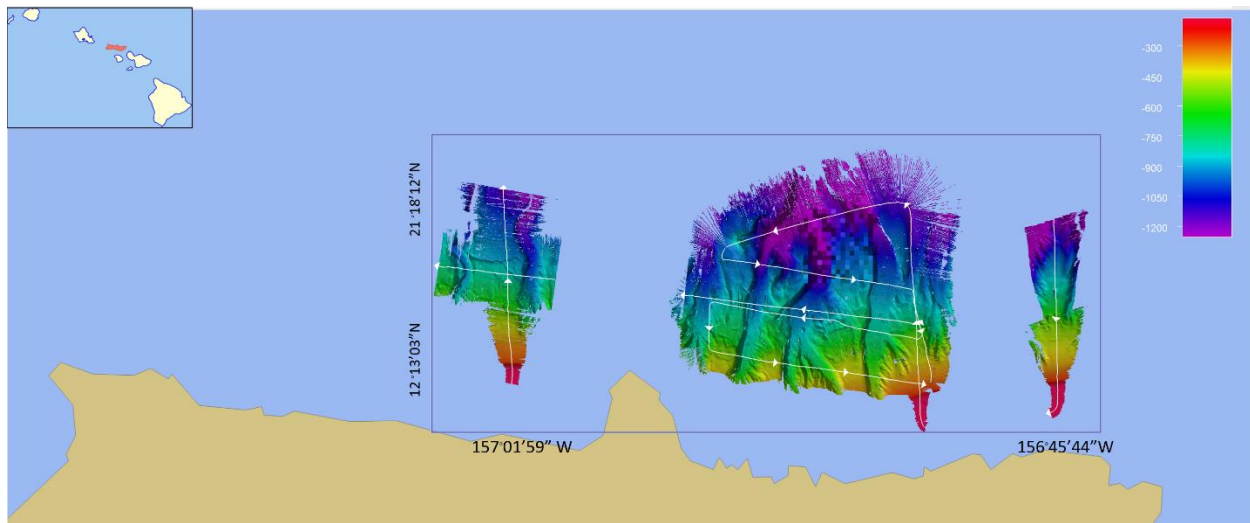


Figure 1. Northern Molokai, HI bathymetry with cruise track lines. Warmer colors indicate shallower water and cooler colors indicate deeper depths. Figure generated using bathymetric data collected from a Northern Moloka'i cruise processed with QPS Qimera.

Estimating the ages of submarine terraces and inferring the evolution of Moloka'i's canyons adds to our understanding of submarine canyons and terraces. Submarine terraces can be located at the head of submarine canyons, and they form with the evolution of sea-level. Terraces are often found by submarine canyons because for canyons to form there must be strong currents and abrasive material. The same conditions must be met to create wave-cut terraces. Terraces are mostly found in areas with an undeveloped continental shelf, such as volcanic island margins (Chiocci and Orlando, 1996). Terraces are formed mainly by the erosion of waves and over time

trend towards being broad with a gentle slope (Trenhaile, 2000, 2001). Previous studies have found terrace elevations correspond exactly to past sea-level (Quartau et al, 2010). This is not the case for all submarine terraces. Landslides and tectonic loading can transpose terraces deeper than expected (Faichney et al., 2010). Volcanic loading causes lithospheric subsidence. Other deep terraces can be attributed to deep in-place faulting (Keating 1998).

This study focuses on the geologic past of a volcanic island margin. Submarine terraces can be studied for sediment deposition rates for specific periods, past shoreline/wave processes, etc. There has been relatively little research on the Moloka'i terraces. Faichney et al. (2010) study identified and characterized Northern Moloka'i terraces (Figure 2). It was found that both deep and shallow terraces are linear with a northward tilt of 7 and 18 degrees (Faichney et al. 2010).

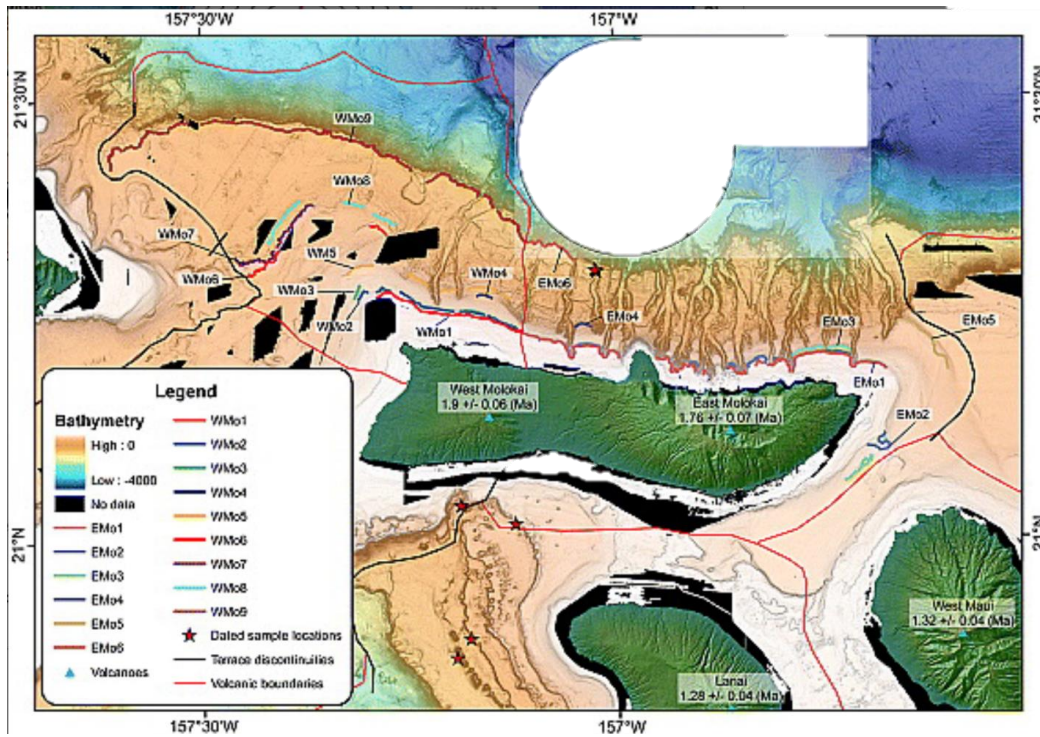


Figure 2. Map highlighting Molokai terraces and bathymetry. Different colors correspond to once continuous terraces. From Faichney et al. (2010).

This project considers the elevations of submarine benches and terraces off of Northern Moloka'i. Studies performed on the island of Hawaii have determined the island is subsiding and used terraces as evidence (Moore and Fornari, 1984). This study in part explores the subsidence of Moloka'i. The relative elevation of an extended coastal terrace offers information about the subsidence of the island. The island may be subsiding faster in an area where parts of a once connected terrace are deeper. It is also possible to estimate the ages of the terraces by plotting their elevation on a sea-level curve that corresponds to Moloka'i. Moloka'i is 1.8 million years old (Sinton et al, 2017), and the terraces can provide information during the time period of submergence. The ages can offer clues into the evolution of the heads of the canyon system such as the age of the canyon heads, and provides insight into past erosional processes. The project also calculates surface gravity wave base to evaluate the rate at which sea-level rose. Wave base corresponds to the water depth that wave energy can reach. Deeper than the wave base, there will be no wave erosion. If the wave base is as deep as terrace sediments, then the terraces are currently being modified by surface gravity waves. I hypothesize that Moloka'i is a high wave energy environment that can produce terraces which can be informative about relative sea-level history.

Methods

Data were collected via a research cruise on the R.V. Thomas G. Thompson offshore of Northern Molokai, HI. Three N-S transects of bathymetric and compressed high intensity radar pulse (CHIRP) (Figure 1) were taken. These locations were chosen by evaluating poorer

resolution bathymetric data from GeoMapApp and previous studies that have located submarine terraces in this area, Echosounder data was gathered to try and look into the layering of the sediment.

Data collection

Multibeam sonar data were collected using a Kongsberg Maritime EM 302, and the ship's onboard software. Sub-bottom profiling data were collected using Knudsen CHIRP 3260 and the software Sounder Sweep. The ship was traveling at approximately 6 kt during the transects. Two grab samples were collected at locations VV (21.21, -156.83) and NN(21.19, -156.82) using Shipek grab samplers.

Processing

Extensive cleaning of the bathymetric data occurred once the data was collected. The files were generated in the .all file format which contains all navigation data, including pitch and roll of the ship. QPS Qimera software was used to process the .all files and create a dynamic surface. Although the pitch/roll were included in the files, the data needed to be cleaned due to bad weather conditions at the time of sampling. Water column acoustic signals were also removed. The data was cleaned by excluding anomalous points that were generated due to the ships rocking, but do not exist in the real bathymetry.

CHIRP data was processed/viewed using MATLAB. To be able to view the CHIRP transects with the highest resolution, multiple parameters within the code needed to be changed. This also depended on the transect. A high pass bandwidth filter of 3000 with 0 phase was applied. By trial and error, the parameters which produced the highest quality figures

respectively were X.clip, x.scale, white and black amplitude, and log.frac, These parameters were essential in removing background noise and enhancing sediment layers.

Grain size analysis was performed on the grab samples. The samples had to be sieved due to their sandy nature. Sieve sizes ranging from -2 phi to 2 phi were used. The weights of the sieves were converted to grain size using an excel workbook from GRADISTAT version 9.1 (Blott 2020).

Terraces were identified using their bathymetric shape. Wave-cut terraces were defined by a plateau shape with a break in slope. Fault benches were identified also by their bathymetric profile shape. They were defined with a back stepping shape, meaning they have a divot, and then a rise in elevation.

Wave Base

Wave base was calculated using the average top 10% dominant wave period from 2016 and 2020 using record from Station 51210 in Kaneohe Bay, Oahu. There is no wave buoy off Molokai, and it assumed that the wave action between northern Oahu and Northern Moloka'i will be similar, and this Oahu buoy record will be sufficient. The wavelength and wave base formulas used were:

$$\lambda = \frac{T^2 g}{2\pi} \quad (1)$$

$$d = \frac{1}{2} \lambda \quad (1.1)$$

The max orbital velocity ($\tilde{u}_{b\max}$) threshold was found using the equations:

$$\lambda = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi d}{\lambda}\right) \quad (2)$$

$$\tilde{u}_{bmax} = \frac{H}{2} \frac{gT}{\lambda} \frac{1}{\cosh(2\pi d/\lambda)} \quad (2.1)$$

T is the wave period in seconds, Lambda is the wavelength in meters, H is the wave height in meters, and d is the water depth in meters.

Results

Grain size analysis of VV categorized the sediment as slightly very fine gravelly medium sand with an average grain size of 377 microns, and a sorting of 366 microns (Table 1). The sample was 98% sand and 2% gravel. NN was categorized as poorly sorted coarse sand with an average grain size of 424 microns and a sorting of 267.8 microns. The sample was 100% sand.

Table 1. Grain size analysis of samples NN and VV. Sediment name, mean, sorting, and kurtosis are labeled. Chart from GRADISTAT version 9.1.

Method of Moments: Arithmetic	NN	VV
Sample type	Polymodal, Poorly Sorted	Unimodal, Moderately Sorted
Textural group	Sand	Slightly Gravelly Sand
Sediment name	Poorly Sorted Coarse Sand	Slightly Very Fine Gravelly Medium Sand
Mean (µm)	424.4	376.6
Sorting (µm)	267.8	365.6
Skewness (µm)	0.531	3.834
Kurtosis (µm)	3.391	19.93

The average period for the top 10% of dominant wave periods from 2016 and 2020 was 14.14s. Wavelength was calculated using this period to be 312.1m. The wave base is 156 m.

Terrace depths were calculated using the bathymetric data collected (Table 2) with the shallowest being 150 m and the deepest being 1042 m. Three transect profiles of the bathymetry were generated using points from QPS Qimera. The most terraces, seven, were identified on the western transect (Table 2), with the other transects having four identified terraces each. Backstepping was identified at five terrace locations.

Table 2. Depth and backstepping identified for each terrace. Numbers correspond to position. Backstepping considers whether the bench has a back tilt.

	Terrace	Western line	Middle line	Eastern Line
Depth (m)	1	150	164	158
	2	325	324	265
	3	533	643	-
	4	709	-	809
	5	750	852	852
	6	836	-	-
	7	881	-	-
	8	1042	-	-
Backstepping	1	N	N	N
	2	N	N	N
	3	N	N	-
	4	Y	-	Y
	5	Y	Y	N
	6	N	-	-
	7	Y	-	-
	8	N	-	-

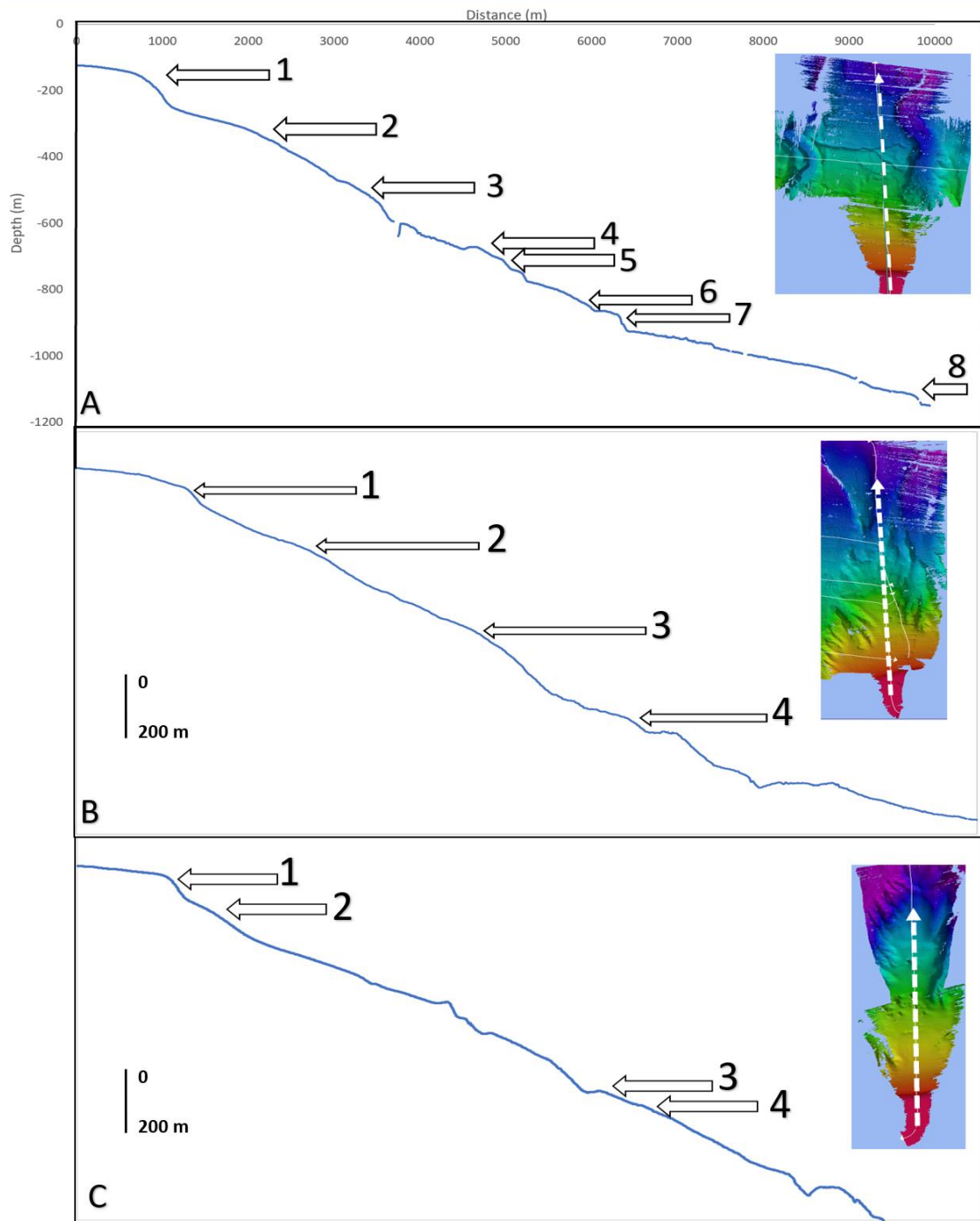


Figure 3. Bathymetric profiles of three transects. A) the eastern transect of Molokai. B) the middle transect, and C) the western transect. All profiles have the same y and x axes. Arrows are pointing to submarine terraces, and numbers correspond to Table 2. Profiles made using QPS Qimera and Excel.

CHIRP tracts did capture terraces (Figure 4), but due to low resolution, no sediment layers could be observed on the terraces. Sediment layering was observed on the intra-canyon environments (Maran 2023). Generally, there is sediment deposition, but nothing could be observed over the terraces.

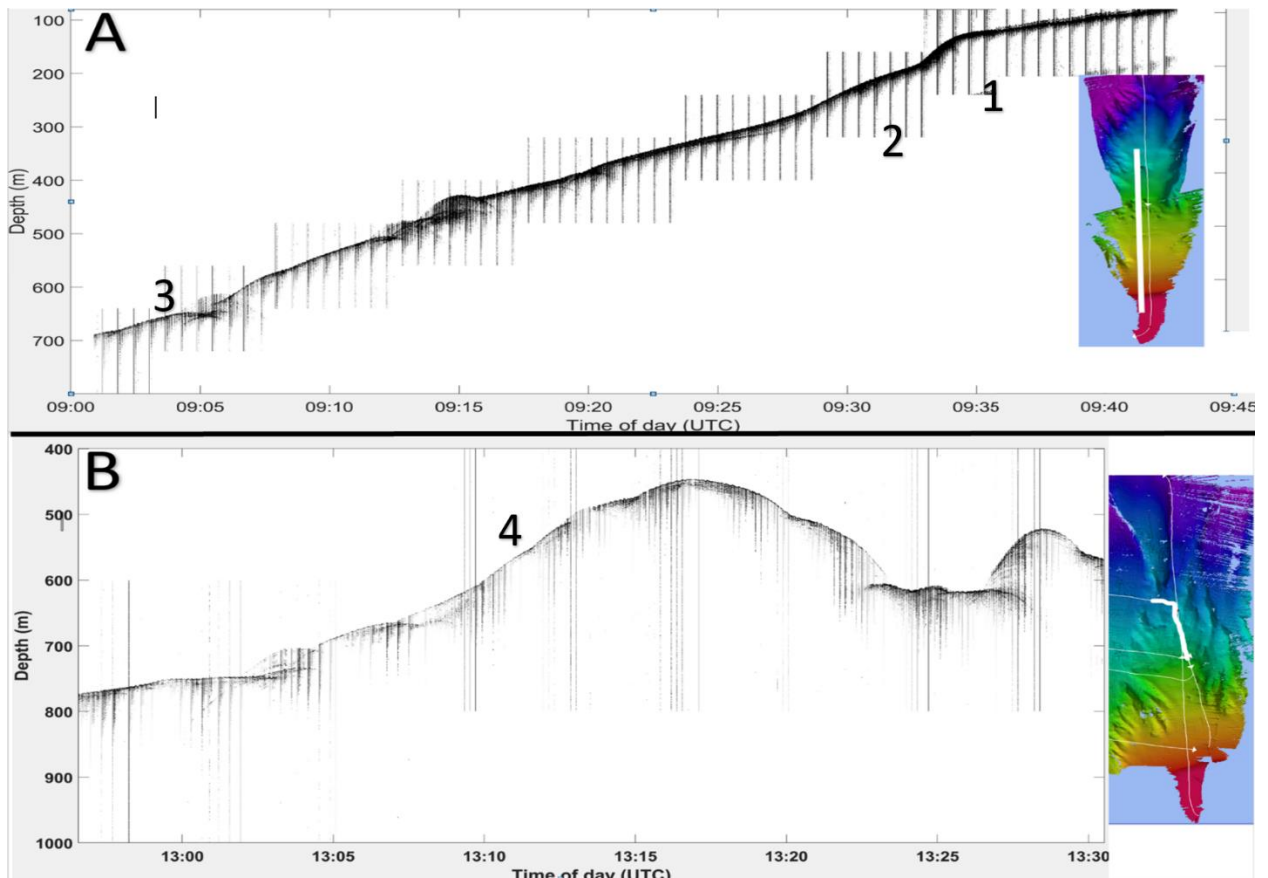


Figure 4. Sub-bottom profiles of two tracts A) the eastern transect of Molokai and B) the middle transect. Both are time of day vs depth, indicating when the CHIRP was collected. Terraces labeled with numbers according to Table 1. No identifiable sediment layers on the terraces were found due to poor resolution. Profile images were generated using MATLAB.

Discussion

Sixteen submarine benches were identified, out of these there appear to be three formerly continuous terraces. All three transects have an identifiable terrace around the same depth. The

two shallower terrace tracts were previously established by Faichney et al. (2010). More terraces were identified in this study compared to the previous study which could be attributed to the higher resolution bathymetric data used in this study. The exception is benches formed by faults, which are discussed later.

An attempt to age the terraces using a sea-level curve by Webster et al. (2016) resulted in only two terraces being estimated (Figure 5). The terraces are thought to be created below eustatic sea-level but match the depths of Lanai terrace coral deposits from Webster et al. (2016.) Assuming terraces formed at relative constant stands of sea-level, estimated ages of the terraces presently at 150 m and 164 m deep are 12,100 and 13,500 yrs respectively. Two other terraces were shallow enough to be able to be plotted, but did not have similar depths to coral deposits and these terrace ages could not be estimated. These shallow terraces are relatively young, and only one falls above wave base today, which indicates that sea-level must have risen quickly in the last 13,500 years. The evidence that supports this includes the clear plateau shape of the

shallow terraces, and that they have not been destroyed by wave energy.

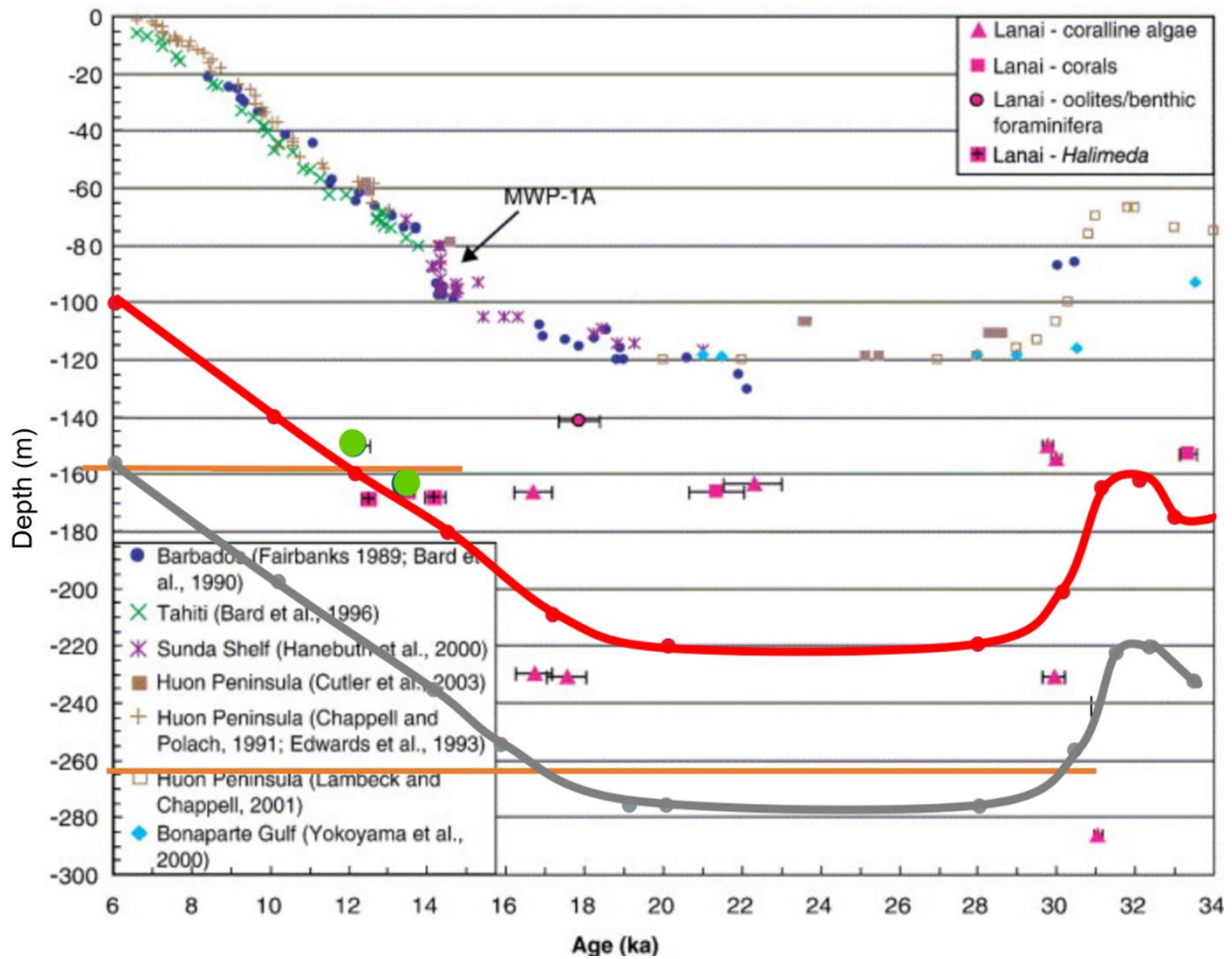


Figure 5. Eustatic sea-level curve from Webster et al. (2006) with identified terraces plotted in green and orange. Green terraces correspond to a previous coral deposit. Orange lines indicate terrace depth but did not match with a coral deposit. The grey line is wave base below eustatic sea-level. The red line is the maximum wave velocity threshold.

Most submarine terraces are formed due to wave energy which leaves them with a plateau shape and a thin sediment layer (Tyler et al. 2009). Terraces are potentially formed when the wave base is strong enough to reach the bottom and there is a period of steady eustatic sea-level, which is then followed by a quick rise in sea-level. The wave base was calculated to be 156 m based on the strongest 10% of waves (eq 1.1). This wave base is currently impacting only the shallowest terrace identified. The rest are unaffected by wave energy today. Sediment from

station VV had an average size of 0.424 mm, using a Hjulstom curve, this means it takes a flow velocity (\tilde{u}_{bmax}) of 11.2 cm/s to erode the sediment. The \tilde{u}_{bmax} was interpolated to find the threshold of around 100 m below sea-level (eq 2.1). The \tilde{u}_{bmax} and wave base findings imply that Northern Molokai is an energetic wave environment that is capable of eroding at least medium-sized sand. The majority of terraces that were identified are theorized to have been formed due to wave activity due to their shape and the assumption that wave base does not change over time.

Some terraces do not have the classic plateau shape, but instead appear to be backstepped. Primarily, these types of benches are formed due to faulting activity. Islands are prone to landslides (Fairbridge 1950) and 1.2-1.6 mya a major landslide occurred on northern Molokai when half of the volcano slumped. A consequence of landslides is that faults may form in the blocks that slid. These faults can create a faux terrace but with a dip before the bench. Five benches have been identified as faults due to their appearance as back-stepping. All of the fault-formed benches are below 700 m in depth. In fact, 5 out of the 8 identified terraces below 700 m are identified as fault-formed. Although CHIRP data does not show clear sedimentary structure throughout the profiles which intersected the benches, there is evidence of both sedimentation and landsliding in the record. More detailed CHIRP data would be needed to confirm the origin of each bench identified. Without this, the shape of the bench is the only identifier of fault-formed benches. Previous work done by Keating (1994) on Oahu has identified stepped benches that formed due to mass wasting events. Fault-formed benches may be a reason why more benches were recognized than in Faichney et al. (2010) as that paper only recognized wave-cut terraces.

The shallower terraces are at depths that are expected if they were formed by wave activity. They can be plotted above waves base on an eustatic sea-level curve. The medium and deep terraces are much deeper than any appropriate sea-level curve. A subsidence rate cannot be estimated with the data collected, but other studies have estimated Molokai's subsidence rate to be around 0.8 m/kyr (Faichney et al. 2010). Webster et al. (2006) estimated the subsidence rate of Lanai to be less than .4 m/kyr. These rates would mean that the 12.1 kyr terrace would have subsided anywhere from 4-8 meters. The shallower terrace depths are consistent with either of these subsidence rates. These subsidence rates do not account for how deep the other terraces are. Some deeper terraces can be explained due to the faulting and were formed in place very deep, but other terraces appear to be wave cut. Either a landslide moved the terraces down or the terraces have shifted down due to volcanic loading. Faichney et al. (2010) found that many terraces were tilted north which indicates that they have been subsiding. They attributed the unexpected deep depths to volcanic loading which caused lithospheric subsidence, which slides the terraces deeper.

Conclusion

Studying the evolution of marine terraces off of Northern Molokai improves our understanding of both the wave environment, and past sea-level changes along with tectonic processes. There has been little previous work done on the terraces of Northern Molokai. Two tracts of terraces had been previously identified. In this study, sixteen terraces were identified, and depths were charted. It was found that five of these have profiles that can be best explained as being formed by faulting due to landslides. The other terraces were classic wave-cut terraces. The shallowest two terraces are estimated to be 12.1 kyr and 13.5 kyrs. Most of the terraces were too deep to age. This was unexpected and was theorized that this was due to volcanic loading

sliding the terraces down or large land sliding the moved the terraces down relative to sea-level. Future studies should continue to age and identify these terraces with high resolution CHIRP data and radiocarbon dating.

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References

- Blott, S. 2020. Version 9.1 GRADISTAT. Kenneth Pye Associates Ltd.
- Casalbore, D., Falese, F., Martorelli, E., Romagnoli, C., and Chiocci, F. 2017. “Submarine Depositional Terraces in the Tyrrhenian Sea as a Proxy for Paleo-Sea-level Reconstruction: Problems and Perspective.” *Quaternary International*, vol. 439, pp. 169–180., <https://doi.org/10.1016/j.quaint.2016.02.027>.
- Chiocci, F. L., and L. Orlando. 1996. Lowstand terraces on Tyrrhenian Sea steep continental slopes. *Marine Geology* 134: 127–143. doi:10.1016/0025-3227(96)00023-0
- Faichney, I. D., J. M. Webster, D. A. Clague, J. B. Paduan, and P. D. Fullagar. 2010. Unraveling the tilting history of the submerged reefs surrounding Oahu and the Maui-Nui Complex, Hawaii. *Geochemistry, Geophysics, Geosystems* 11. doi:10.1029/2010gc003044
- Keating, B. H. 1994. Analysis of Seismic Profiles, Drowned Reefs and Terraces around the Hawaiian Island Chain. Hawaii Institute of Geophysics and Planetology, Honolulu, HI. Sheet, 8.
- Maran, Heather. 2023. The relationship between current flow direction and sediment distribution within slope-confined submarine canyons off of the north coast of Moloka’i, HI. University of Washington,
- Moore, J.G. and Fornari, D.J. 1984. Drowned reefs as indicators of the rate of subsidence of the Island of Hawaii. *Journal of Geology*, 92, 753– 759.

- Quartau, R., A. S. Trenhaile, N. C. Mitchell, and F. Tempera. 2010. Development of volcanic insular shelves: Insights from observations and modelling of Faial Island in the Azores Archipelago. *Marine Geology* 275: 66–83. doi:10.1016/j.margeo.2010.04.008
- Sinton, J. M., D. E. Eason, and R. A. Duncan. 2017. Volcanic evolution of moloka‘i, hawai‘i: Implications for the shield to postshield transition in Hawaiian volcanoes. *Journal of Volcanology and Geothermal Research* 340: 30–51. doi:10.1016/j.jvolgeores.2017.04.011
- Trenhaile, A.S., 2001. Modelling the Quaternary evolution of shore platforms and erosional continental shelves. *Earth Surface Processes and Landforms* 26, 1103–1128.
- Trenhaile, A.S., 2000. Modeling the development of wave-cut platforms. *Marine Geology* 166, 163–178
- Tyler, P., Amaro, T., Arzola, R., Cunha, M. R., De Stigter, H., Gooday, A., Huvenne, V., Ingels, J., Kiriakoulakis, K., Lastras, G., Masson, D., Oliveira, A., Pattenden, A., Vanreusel, A., Van Weering, T., Vitorino, J., Witte, U., & Wolff, G. 2009. Europe’s Grand Canyon Nazaré Submarine Canyon. *Oceanography*, 22(1), 46–57.
[Http://Www.Jstor.Org/Stable/24860922](http://www.jstor.org/stable/24860922)
- Webster, Jody M. 2006. “Drowned Coralline Algal Dominated Deposits off Lanai, Hawaii; Carbonate Accretion and Vertical Tectonics over the Last 30 Ka.” *Marine Geology*, vol. 225, no. 1-4, Jan., pp. 223–246., <https://doi.org/10.1016/j.margeo.2005.08.002>.