Evidence of modern erosional processes in submarine canyons north of Molokai, Hawaii

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Non-technical Summary

The largest canyons in the world occur not on land, but are carved into the sea floor. Rivers formed these submarine canyons during periods in the Earth's history when sea levels were low, and then were submerged as glaciers melted and sea levels rose. The research in this paper is focused on submarine canyons north of Molokai, Hawaii to determine if they continue to be eroded by underwater landslides and sediment flows, or if erosion halted when they were submerged. Key factors that create erosive sediment flows are the steepness of the canyon basins and the amount of sediment accumulating in them. I used sonar to created detailed high-resolution maps of the canyons to determine the canyon gradients and cores of sediment to determine the accumulation rate. All data were collected during a cruise aboard the *R/V Thomas G. Thompson* from 27 December 2010 – 4 January 2011. While I did not find definitive proof that erosion is active in the canyons, my findings suggest that this is likely. The mapping shows canyons that are similar in steepness to the Wilmington Canyons off the eastern coast of the US where erosion from sediment flows has been shown to be occurring. Additionally, I used radiometric dating of sediment grains to determine the accumulation rate in the Molokai canyons and found that it was also similar to the rates in the Wilmington Canyons. Given the similarity in environments, I concluded that erosion was likely to still be occurring in the Molokai canyons. Sediment flows of the type in this research carry carbon and other minerals to the deep ocean so are important in our understanding of the Earth's climate system and the chemical makeup of our oceans.

Abstract

Small stream environments play an important, yet understudied, role in the sediment transport and accompanying carbon and trace minerals from terrestrial sources to the deep ocean. In this paper I present data from such an environment in an examination of evidence for modern erosional processes and sediment transport in submarine canyons north of Molokai, HI. During a University of Washington research cruise aboard the *R/V Thomas G. Thompson* from 27 Dec 2010 – 4 Jan 2011, I performed swath bathymetry to create high-resolution maps and took a series of four box cores in these canyons. Mean canyon gradients determined from the bathymetry ranged from 3.7° to 6.8°. ^{210}Pb radiometric dating revealed a decrease in sediment accumulation rates occurred approximately 100 years ago, with modern rates ranging from 1.2 mm/yr – 1.3 mm/yr and earlier rates as high as 3.7 mm/yr. X-Radiography showed a finer-grained layer that may be the remnant of a turbidity flow occurring 208 years ago. Definitive evidence of active transport processes was not found but the findings show that the setting is consistent with canyon environments that have been previously shown to have modern active processes. Based on the seismic activity, canyon basin gradients, and sediment accumulation rates, I conclude that modern erosional processes are likely occurring. Additional research to get a broader set of cores from canyon channels and better constraints on supported ^{210}Pb levels would strengthen this conclusion.

Introduction

The Hawaiian Ridge, a region consisting of the Hawaiian Islands and extending northwest to the Kure Atoll, is a highly active area for submarine landslides. Earlier studies found that giant landslides (those that extend for more than 20 km) occurred on average every 32 km in the Hawaiian Ridge (Moore et al. 1994). These massive landslides are among the biggest in the world. The Wailau debris avalanche on the north side of Molokai Island, with an estimated age of 1400 ± 200 ka (Clague and Dalrymple 1987), is one such giant landslide (Fig. 1). A broad undersea terrace running east-west across the Wailau debris flow formed approximately 1170 ka (Moore et al. 1989) and extends roughly 15 km offshore before steepening sharply below 1300 m. Incised into this terrace are a series of major submarine canyons (Fig. 1). Seismic studies have shown that these canyons extend across the terrace and connect with terrestrial canyons but are filled with sediment near shore (Coulbourn et al. 1974). Earlier research found these massive submarine canyons were originally carved subaerially to near their current depths but continued erosion from landslides and turbidity currents have incised them further (Moore et al. 1989). Whether modern erosional processes remain active in these canyons, and to what extent, is unknown and is the focus of the research presented here.

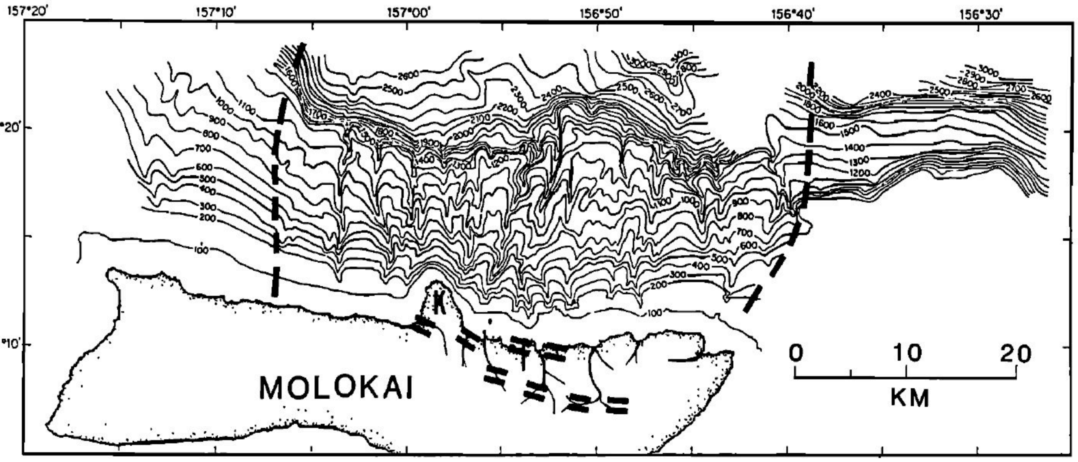

Figure 1. Bathymetry north of Molokai reprinted here from Moore et al. 1989. Heavy dashed lines indicate the margins of the Wailau debris avalance. Note that the terrestrial canyons are aligned with submarine canyons. Countour interval is 100 m.

While slope is the primary factor controlling frequency of subaerial landslides, sediment accumulation rate is the primary factor for submarine landslides and turbidity currents (McAdoo et al. 2000). Sediment input to these canyons has been previously reported as being low (Moore et al. 1989) which is no surprise given the lack of large river systems on Molokai Island. Smaller streams and erosional gulches do exist, however, which are likely depositing sediment onto the terrace and which may then be transported to the canyons. Canyon slopes in this region are some of the steepest in the world (Lipman et al. 1988l; McMurty et al. 1999) and could lead to active mass wasting even with low sediment accumulation rates. Further, the Hawaiian Islands are seismically active (Klein et al. 2001), which is a primary initiation mechanism for landslides and turbidity currents in many environments (Moore et al. 1989). It would be reasonable to assume that though accumulation is low, this high earthquake activity would trigger gravity flow events with lower sediment accumulation than would be required in environments with less seismicity.

Earlier studies suggest that though steep slopes and seismic activity are factors in triggering submarine landslides (Moore et al. 1989; Masson et al 2006), they may not be the primary factors. For instance, off the coast of Oregon, an area of high seismicity and steep slopes, fewer large landslides were found than expected when compared to areas where slopes were lower (McAdoo et al. 2000). This suggests that different regions have different processes beyond just slope that control slope failures. This was true only when considering regional slopes, however. Where local slopes were steep, as in the sidewalls of canyons, frequent landslides were found to have occurred (McAdoo et al. 2000).

Given the steep slopes of the canyon walls north of Molokai, this would indicate that landslides are likely to be occurring.

In order for turbidity currents to occur, an initiation process and sufficient gradient must be present (Piper and Normark 2009). The slopes in the Molokai canyons are steep enough to maintain flow. Initiation requires high-suspended sediment concentrations, which is often achieved via landslides (Piper and Normark 2009). The classic 1929 Grand Banks turbidity current is just such an example (Heezen and Ewing 1952). In this case, an earthquake triggered a landslide, which led to a turbidity current that was maintained by the steep valley walls (Piper et all 1999). This event occurred where sediment accumulation rates were high, unlike the canyons of Molokai. If sediment input is high enough to create landslides, however, it is likely, given that the other factors for turbidity currents are present that turbidity currents occur in these canyons as well.

In addition to providing insight into the geological history of Molokai Island and the Wailau debris avalanche, this research also furthers understanding of submarine gravity flows and the processes involved. Turbidity currents are the primary transport mechanism for clastic sediment to the deep sea (Piper and Normark 2009) so, along with landslides, play an important role in defining the depositional environment in the deep sea and transport carbon and trace minerals to the deep ocean. Despite their importance, these transport processes are poorly understood. This is especially true for high gradient, small stream environments like that of Molokai Island. With research historically focused primarily on large river systems, sediment flux to the ocean from small stream environments has been underestimated by as much as a factor of three (Milliman and

Syvitski 1992). This study, therefore, gives us insight into sediment transport in an important yet under represented research environment.

Methods

All data collection was performed as part of a University of Washington research cruise on 27 December 2010 – 4 January 2011 aboard the *R/V Thomas G. Thompson*. Bathymetric mapping of the canyons was done using the onboard Kongsberg Simrad EM302 30 KHz Multibeam Echosounder at a speed of 7 knots. Bathymetric analysis was performed using Caris and ArcGIS software packages. Mean canyon slopes were calculated from depth and canyon distance measurements using ArcGIS.

A series of four box cores were taken to obtain sediment that could then be analyzed to profile the sediment on the seafloor (Table 1). Each box core was sub-sampled using thin-walled PVC tubes (10 cm in diameter) that were dissected into 1 cm depth intervals for radiochemical and grain-size analysis. Additionally, plexiglass trays (2 cm thick, 12 cm wide) were inserted into each box core to obtain a vertical slab of undisturbed sediment for use in X-radiography. Samples were stored and brought back to the University of Washington sediment lab for further analysis.

X-radiographs were performed using a Medical Corporation Model VR 1020 X-ray system and the variable exposure recorded on a Flashscan35 digital X-ray imaging subsystem. Images are presented here as X-ray negatives. Opaque (light gray) areas correspond to higher bulk density and coarser sediment. Relatively transparent (dark gray) areas correspond to lower bulk density and finer-grained sediment (Drexler and Nittrouer 2008). These images can be examined to get qualitative insight into sediment stratification and amount of bioturbation present.

Grain-size analysis was performed to determine weight percentage distributions of sand, silt, and clay for each depth interval. Samples were dispersed using a solution of 0.05% sodium metaphosphate and then wet-sieved at 63 μm to separate the sand (> 63 μm) fraction from silt (4 – 63 μm) and clay (< 4 μm) fractions. A Sedigraph 5100 at ¼ Φ intervals was used on the remaining mud to determine silt and clay fractions. Grain-size analysis was done on the top 1 cm of all four cores. More extensive analysis was done on cores 3 and 4 with grain-size analysis done on 1 cm bins every other cm for the full length of the core.

^{210}Pb radiometric dating was done on select samples using techniques established by Nittrouer et al (1979) and later refined by Drexler and Nittrouer (2008). 5 g samples of sediment were first homogenized, dried, and, and then spiked with a known activity of ^{209}Po. These spiked samples were digested first with 15.8N HNO_3 followed by 6N HCl. Po isotopes were then deposited on silver planchets and suspended in supernatent for approximately 23 hours. Following this, ^{209}Po and ^{210}Po activities were measured by alpha spectroscopy and ^{210}Pb activities were calculated by comparison with the measured amount of ^{210}Po. Supported ^{210}Pb activity in the environment is determined as the activity at depths where ^{210}Pb activity no longer decreases with an increase in depth. Excess ^{210}Pb is determined by subtracting this supported ^{210}Pb from the measured ^{210}Pb activities.

Accumulation rates (A) were calculated based on excess ^{210}Pb values using the relationship:

$$A = \frac{\lambda z}{\ln \frac{C_0}{C_z}}$$

where C_0 = activity of radio isotope in an upper level of the profile; C_z = activity of radio isotope at a distance z below level of C_0; and λ = decay constant of radio isotope = $0.693/t_{1/2}$ (Nittrouer et al 1984). By assuming a constant accumulation rate, the age (T) at a particular depth in the core by be determined by:

$$T = \frac{z}{A}$$

where z is the depth in the core and A is the accumulation rate.

Results

The terrace north of Molokai is incised by a series of slightly meandering canyons (Fig. 2). Mean slopes of the main canyons ranged from 3.7° to 6.8° (Table 2). The slopes at the oceanic edge of the terrace, approximately 15 km from the coast of Molokai, are significantly steeper and ranged from 17.5° up to 34.9°. The canyon walls are steep and appear intact with no indication of incised gulleys.

Significant systematic stratification and sediment layering are not evident in the X-radiographs at any of the stations (Fig. 3). Station 3, however, does show a 2 – 3 cm layer of finer grain sediment, as evidenced by the relatively dark layer, at a core depth of approximately 35 cm. Differences are apparent between cores 2 and 3, which were taken at shallower depths, versus deeper cores, 1 and 4. Bioturbation is evident in the shallower cores while mostly absent in the deeper cores, which appear to be denser and more consolidated.

The surface sediment at station 3, which is nearest to shore, had a clay percentage

Table 1. Coring locations and depths.

Station	Latitude (°N)	Longitude (°W)	Depth (m)
1	21.3140333	156.9073500	1620
2	21.2907167	156.8809833	1305
3	21.2705000	156.8826667	1177
4	21.3175000	156.9543333	1936

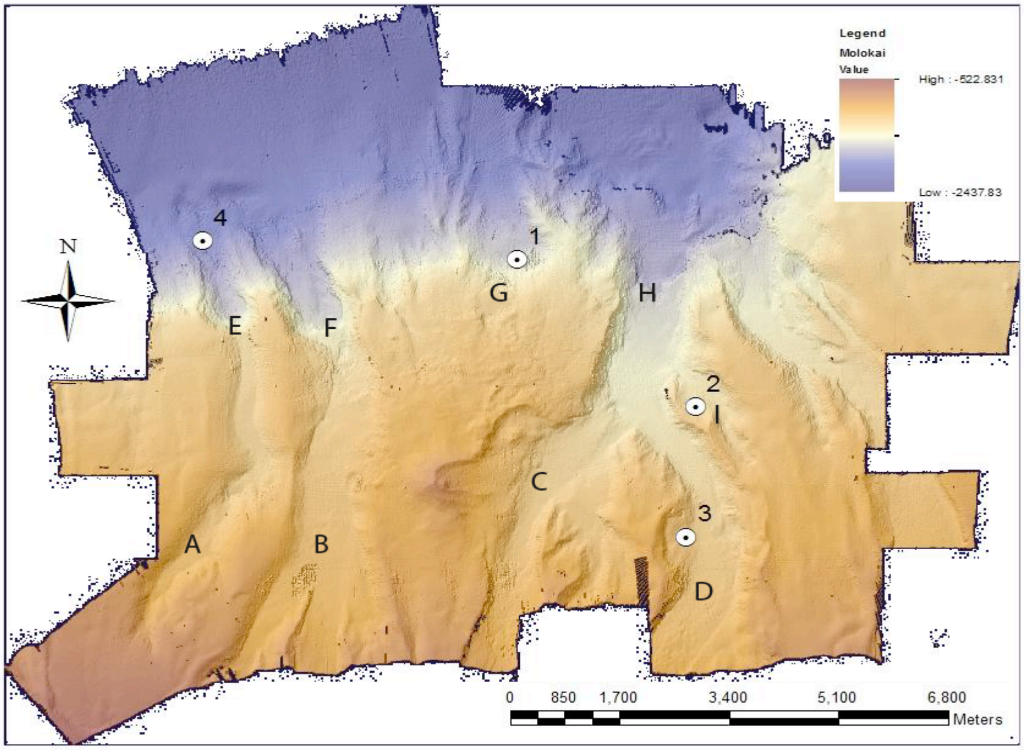

Figure 2. Bathymetry of canyons north of Molokai with 10 m resolution. Numbers 1 - 4 show the location of box core sites. Letters A – I indicate canyon basins referenced in gradient calculations (Table 1). Bathymetry processed in Caris by Megan Prescott.

Table 2. Canyon gradients.

Site	Near Shore Depth (m)	Offshore Depth (m)	Length (m)	Slope (°)
A	1017	1325	4769	3.7°
B	1039	1434	5023	4.5°
C	1151	1594	4686	5.4°
D	1048	1757	5988	6.8°
E	1332	1651	457	34.9°
F	1443	1639	395	26.4°
G	1296	1517	428	27.3°
H	1757	1594	516	17.5°
I	1163	1414	952	14.8

by weight of 64.57% with nearly equal amounts of sand and silt (Fig. 4). The cores furthest from shore, 1 and 4, show a decrease in clay, and have nearly equal amounts of sand, clay, and silt on the surface. Core 2, out of the main canyon channel, has significantly coarser surface sediment with 53.23% sand. Grain-size analysis was done every other cm for the full length of cores 3 and 4 (Fig. 5). Silt dominates both cores. Though relatively uniform in distribution with depth, core 3 shows a slight increase in sand with a corresponding decrease in silt deeper in the core. A small increase in percentage of silt is evident at the same depth as the apparent finer-grained layer visible in the X-radiograph (Fig. 5). Core 4 also has a relatively consistent sediment distribution with depth but does show a clear decrease in sand and increase in silt with depth. Full grain-size analysis of cores 1 and 2 are left for future research.

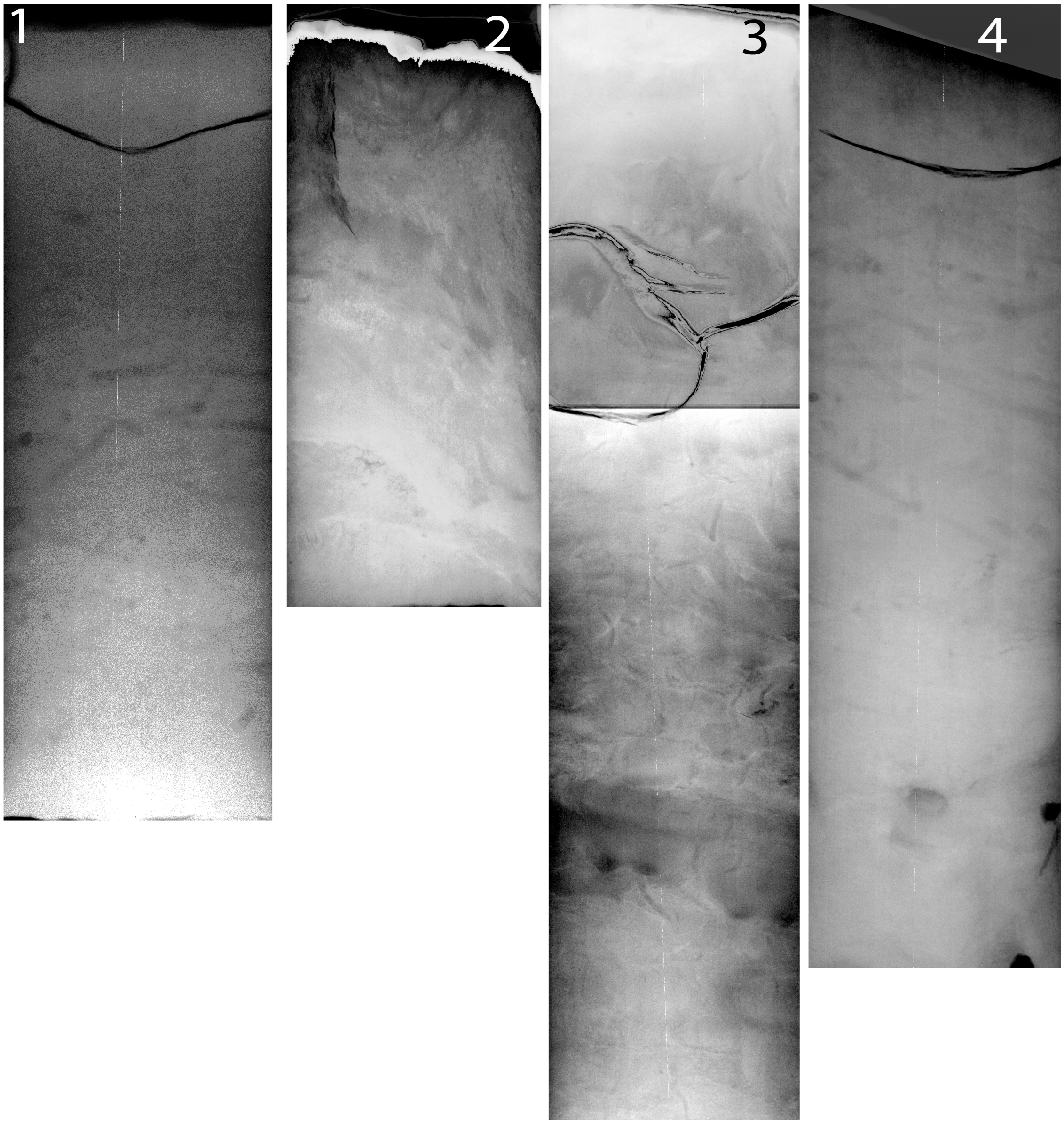

Figure 3. X-radiographs of cores taken at stations 1 – 4. Opaque (light gray) is indicative of higher bulk density and coarser sediment. Transparent (dark gray) is indicative of lower bulk density and finer sediments. The dark lines near the surface of cores 1 and 4. Note the apparent finer sediment layer at station 3. Note that the dark black lines in cores 1, 2, and 3 show cracking due to drying during transport and are not sedimentary structure.

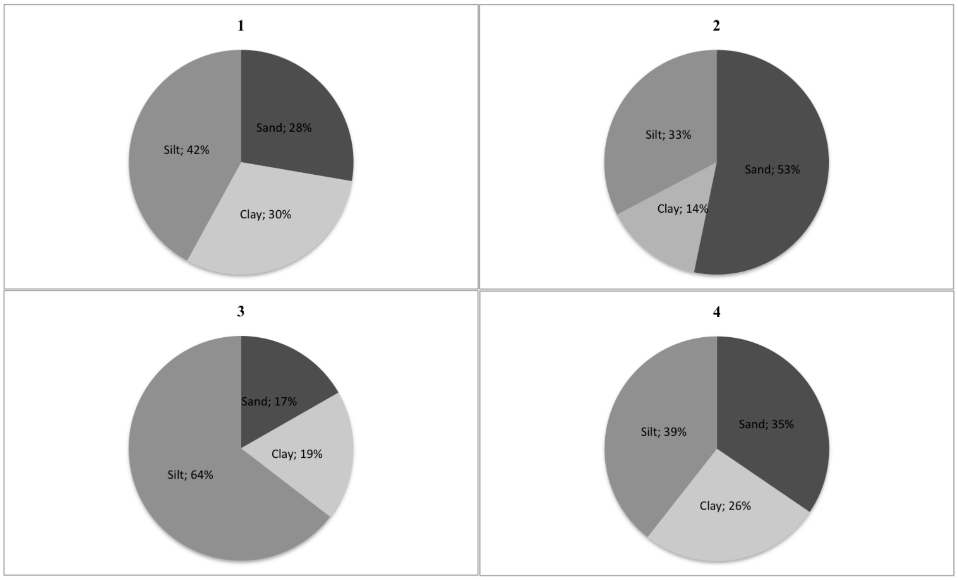

Figure 4. Surface sediment grain-size distribution by percentage weight. Numbers 1-4 correspond to coring sites in Fig. 2.

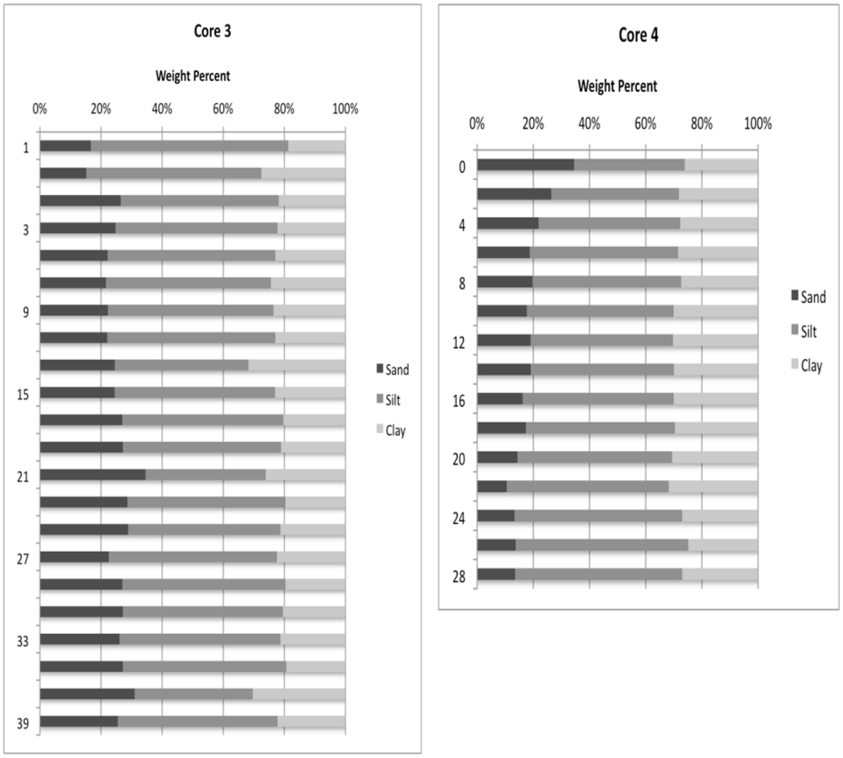

Figure 5. Grain-size analysis of cores 3 and 4.

^{210}Pb radiometric dating was done on cores 3 and 4 (Fig. 6). The core shallower and nearest to shore, core 3, had higher activity values, ranging from 92.67 dpm/g on the surface and decreasing to 0.15 dpm/g at a depth of 40.5 cm (Fig. 6). Activity was lower at the deeper, further offshore site with values of 45.5 dpm/g at the surface decreasing to 0.68 dpm/g at 26.5 cm.

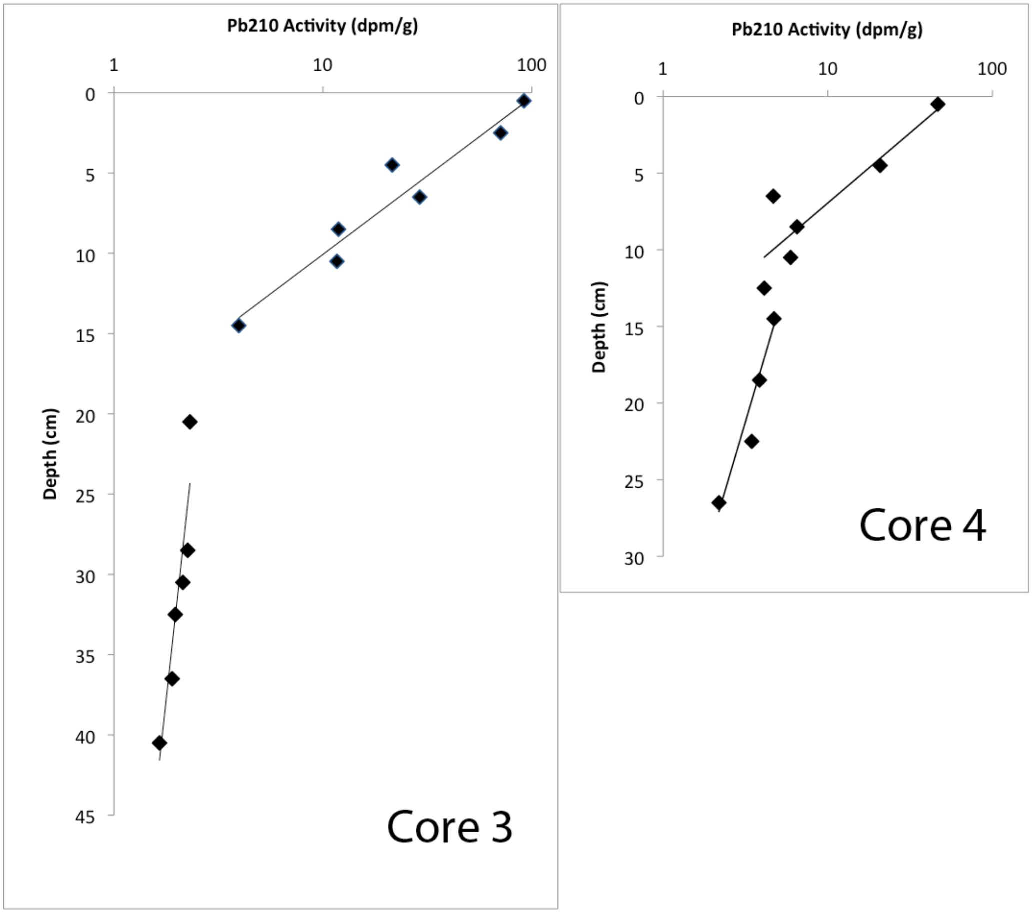

Figure 6. Total ^{210}Pb for cores 3 and 4. Lines are logarithmic regression lines.

To determine values for excess ^{210}Pb, the supported ^{210}Pb level must first be determined. It is debatable whether the cores were long enough to have reached supported ^{210}Pb. Though there is a clear decrease in the amount of change in activity, there is still change occurring with increased depth (Fig. 6). With an assumption, however, that the core was long enough, the average of the deepest samples are used as supported ^{210}Pb activity. Using this approach, supported ^{210}Pb is 1.98 dpm/g for core 3, which results in an accumulation rate of 1.1 mm/yr (Table 3). This would mean the fine-grained layer was deposited 316 years ago. With the same assumption, core 4 would have a supported level of 3.16 dpm/g and an accumulation rate that is slightly greater at 1.3 mm/yr. With the assumption, however, that the cores were not deep enough to reach

Table 3. Total ^{210}Pb from cores 3 and 4.

Core	Depth (cm)	Total 210-Pb Activity (dpm/g)
3	0.5	91.73660766
	2.5	70.95116652
	4.5	21.47342568
	6.5	29.05853899
	8.5	11.87546218
	10.5	11.67226974
	14.5	3.957777024
	20.5	2.30922786
	28.5	2.253433767
	30.5	2.135617598
	32.5	1.965260885
	36.5	1.898663378
	40.5	1.650888388
4	0.50	46.6530
	4.50	20.8111
	6.50	4.6696
	8.50	6.5070
	10.50	5.9458
	12.50	4.1141
	14.50	4.7169
	18.50	3.8506
	22.50	3.4551
	26.50	2.1843

supported ^{210}Pb levels, I use an arbitrary supported level of 1.5 dpm/g based on typical values in other environments (personal communication from C. A. Nittrouer 2011). In this case, there is a change in accumulation rate in both cores (Fig 6). For core 3, the near surface average accumulation rate would be 1.2 mm/yr in shallower depths, 3.7 mm/yr deeper in the core, and have an overall mean of 1.9 mm/yr. For core 4, the shallow rate would be 1.3 mm/yr, a deeper rate of 2.4 mm/yr, and the overall mean would be 1.9 mm/yr. Based on rates, the date of the change in the accumulation rate occurred 120 years ago in core 3 and 96 years ago in core 4.

Discussion

Submarine canyons are typically thought to actively transport sediment during periods of low sea level and be inactive during sea level highstands as we have today (Sanford et al 1990). However, continuing sediment input from longshore transport or proximity to river sources, tectonic setting, and basin gradient have been shown to support active modern sediment transport in some submarine canyons (Kolla and Macurda 1988). With the limited number of box cores taken in this study, I did not find definitive evidence of modern turbidity currents or landslides in the Molokai canyons. Given their geomorphology, sediment accumulation rates, and proximity to sediment sources, however, the environment is consistent with canyons where modern sediment transport is occurring. As such, it is likely that these canyons are also active.

X-Radiography

While definitive evidence of gravity flows was not found in the sediment record, the X-radiograph of core 3 did show a layer of relatively finer-grained sediment (Fig. 3). The grain-size analysis did not show a significant change in grain size correlating with the layer seen in the X-radiography. This is likely a result of the sampling method used. The layer is 2 – 3 cm in depth so with a sampling bin size of 1 cm it is likely that the sample taken of that layer contained sediment above or below it which would have muted any change in grain size. The layer is also not fully horizontal which would further increase the likelihood of samples containing significant amounts of sediment outside the layer.

Even without collaboration in the grain-size analysis, the X-radiography does clearly show a layer in core 3 and may be an indication of a turbidity flow. Turbidity currents sort sediment vertically in the sediment record with coarser grains deposited by the head of the current and progressively finer-grained sediment as the body of the flow passes over a particular location (Kneller and Buckee 2000). The sediment record on the flank of a confined canyon, where the depth is shallower than at the thalwag where the turbidity flow would be concentrated, would only reflect the higher, finer-grained portion of the flow. One possible explanation of the layer in core 3 is that the core was taken on the flank of the canyon so we only see the fine-grained sediment layer resulting from a turbidity current. A definitive determination is not possible from the data on hand and other explanations for a finer-grained layer do exist (eg: a large flood event on Molokai). If this layer is not the result of a turbidity flow, however, it is still indicative of a large pulse of sediment, which, by increasing sediment influx, would make gravity flows more likely.

^{210}Pb Dating

To interpret the ^{210}Pb data we must first address the ambiguity introduced by lack of a clear supported level for ^{210}Pb in these canyons. The simplest interpretation would be to assume that the box cores were long enough to have reached supported levels. The data, however, show a continued consistent decrease in activity even in the deepest samples (Table 3). This indicates that excess ^{210}Pb is still decaying at these depths and that we have not reached supported levels (Nittrouer et al 1979). The difference in the rate of change of activity, therefore, indicates not that supported level was reached, but instead points to a change in sediment accumulation rate. A gradual increase in rate over time would not be surprising given anthropogenic impacts on terrestrial erosion seen in many environments. The reason for an abrupt decrease in the rate, as seen here, is less clear. Such a rapid and sustained decrease in sediment flux to the canyons would have to be the result of a decrease in sediment influx from longshore transport or a decrease in sediment from river input. No mechanism exists to explain a change in longshore transport. The likeliest explanation, therefore, is a decrease in sediment influx from rivers. While determining a definitive cause for a change in sediment influx is beyond the scope of this study, I examine the impact of tectonics as one possibility.

Rivers are extremely sensitive to tectonic tilting and may undergo avulsion in response to lateral tilting (Holbrook and Schumm 1999). A magnitude 6.8 earthquake struck Lanai in 1871 causing severe damage on Molokai (http://earthquake.usgs.gov/earthquakes/states/events/1871_02_20.php) and could have altered the sediment transport regime of rivers flowing onto the terrace. The lag of 20 years for core 3 and 44 years for core 4 between this earthquake and the change in sediment rate in the canyons could be explained as the time it takes for river sediment to be transported across the terrace. River sediment is likely stored temporarily on the terrace and transported to the canyons via resuspension from wave energy and longshore transport. It is not unreasonable that it would take decades for sediment in temporary storage on the terrace to be depleted, thereby delaying the impact on accumulation rates in the canyons. Further research into the accumulation rate changes with tectonics as the cause would be compelling.

Even if my interpretation of the ^{210}Pb data is incorrect, it would have little impact on the overall question of whether these canyons are actively eroding. The difference in the timing of the finer-grain event discussed above is just 108 years between the two interpretations of supported ^{210}Pb levels. In geological terms, this is insignificant.

Comparison to other canyons

The bathymetry reveals geomorphology that is consistent with known active canyons. As a point of comparison, I consider the Wilmington Canyon area off the east coast of the US, which have been shown to have active modern turbidity currents (Sanford et al 1990). The tectonic setting for these canyons is fundamentally different than that at Molokia. The east coast is a passive margin with low seismicity while Molokai is a high gradient hot spot area with high seismicity. In addition, the Wilmington Canyon walls are heavily incised by erosive gulleys carved by mass wasting (McGregor et al 1982) while the Molokai Canyons do not have incised gulleys and show no indication of eroding canyon walls. In spite of these differences, the canyon basin gradients and sediment accumulation rates, two critical components to gravity flows, are similar.

Mean basin gradients in straight, non-meandering canyons in the Wilmington Canyon area range from 5° – 10° (Stubblefied et al. 1982). Meandering canyons in the Wilmington Canyon area were much lower at 1° and less. This is similar to the Molokai canyons we explored with gradients ranging from 3.7° to 6.8°. Sediment accumulation rates in Wilmington Canyon ranged from over 6 mm/yr to under 0.3 mm/yr compared with a range at Molokai of 3.7 mm/yr to 1.2 mm/yr.

Similarities between the Molokai canyons and the Wilmington Canyon area does not lead to a conclusion that the Molokai canyons must also have active gravity flows. It is suggestive, however, that the gradient and accumulation rates make the Molokai canyons consistent with a setting where modern gravity flows would be expected.

Conclusions

The primary findings of this project are:

- No definitive proof of modern erosional processes were found but data show that the canyon gradients and sediment accumulation rates is consistent with the Wilmington Canyon area which has been shown to be active.
- The submarine terrace is incised by a series of canyons with gradients ranging from 3.7° to 6.8°.
- Based on ^{210}Pb data, a decrease in sediment accumulation rates occurred approximately 100 years ago. Current accumulation rates range from 1.2 – 1.3 mm/yr. Before the decrease they were as high as 3.7 mm/yr.
- A finer-grained event was observed approximated 208 years ago in one core. Though

no definitive proof exists, it is consistent with a sedimentary record taken from a core on the flank of a turbidity flow.

Future research in this area should include:

- Longer cores to better constrain supported ^{210}Pb levels in order to improve dating data.
- Additional cores focused more precisely in the thalwag of the steepest canyons.
- Studies of the streams feeding into these canyons to measure sediment load and to look for evidence of a change that could have caused the decrease in sediment flux as found in this study.

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