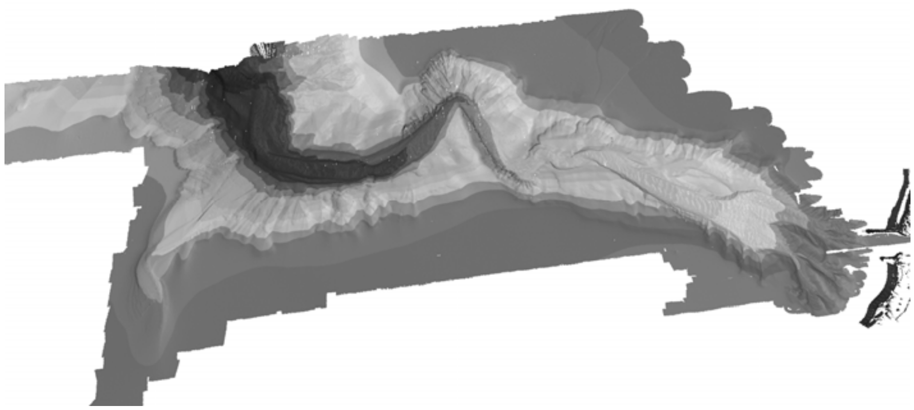
Detection of Geomorphic Change in the Monterey Submarine Canyon Head



A Capstone Project

Presented to the Faculty of Science and Environmental Policy

in the

College of Science, Media Arts, and Technology

at

California State University, Monterey Bay

in Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

by

Michelle Sandersfeld

May 2009

Abstract

Twice each year, multibeam data have been collected for the four kilometers of the canyon head nearest to shore by the Seafloor Mapping Lab at California State University Monterey Bay (CSUMB). The intention of this study is to add three more years of data to an ongoing time series begun in 2002 of bathymetric data of the Monterey Canyon to better understand patterns of geomorphic change. This study looks at previously unanalyzed data from 2005-2008. Although past research showed expansion in the canyon, it is still not understood if this is a long term pattern or part of an oscillation pattern. This project had multiple goals dealing with the geomorphic change of the Monterey Canyon between fall 2005 and fall 2008. The first goal was to quantify deposition and erosion in the canyon using raster subtraction. The second goal was to determine if the canyon lip is changing location using a Geographic Information System (GIS) technique of algorithmically determining the lip of the canyon and the previously used methods of hand drawn interpretations of the lip location. The final goal was to compare the two different methods used to determine the location of the canyon lip. The results of the raster subtraction indicate that the canyon is in a state of erosion with an annual net loss of 240,000 m^3 of substrate between fall 2005 and fall 2008. The rate of erosion has decreased since Smith et al. 2007 found the annual net rate of erosion to be 400,000 m^3 between fall 2002 and winter 2005. Both techniques of tracing the canyon lip statistically gave the same results. The study failed to reject the null hypothesis of no change occurring in the canyon lip. Comparison between current study and fall 2002 also failed to show significant change. These results indicate that in the scope of this time series study of the canyon lip is not moving monotonically toward Moss Landing Harbor but rather in a pattern of oscillation.

Introduction

Submarine canyons are found on most continental margins, both active and passive, worldwide (Chiang & Yu 2008, Kunze et al. 2002, de Stigter et al. 2007). Variations in continental margin and/or hydrodynamic conditions influence the transport, deposition, and accumulation of sediment in submarine canyons (Garcia et al. 2008). Submarine canyons play a large role in transporting sediment and organic matter to the deep ocean water (Kunze et al. 2002, Paull et al. 2003, Xu et al. 2004, Garcia et al. 2008, Green and Uken 2008). Redistribution of sediment to the open ocean happens through hydrodynamic processes such as turbidity currents, sand dune migration, and slope failures (Chiang & Yu 2008, Paull et al. 2005, Smith et al. 2005b, Smith et al. 2007, Sultan et al. 2007, Garcia et al. 2008, Xu et al. 2008). Research supports the idea that the volume of sediment transport is negatively correlated with the distance of the submarine canyon from the coast (de Stigter et al. 2007).

Submarine canyons located near shore undergo changes such as deposition and erosion due to interactions with coastal processes. When the head of a canyon is connected to the shore it becomes an active geomorphic feature (Greene et al. 2002). The connection of submarine canyons to the coast affects the sediment budget of the canyon (Smith et al. 2005b). Littoral drift and input from terrestrial systems such as rivers and sloughs, adds sediment to the sediment budget of a submarine canyon (Smith et al. 2005b, Smith et al. 2007). Sediment budgets refer to the amount of sediment added and subtracted from the submarine canyon system. For the sediment budget of the canyon to be balanced there would need to be an equal amount of sediment deposited and eroded from the system. If the budget becomes unbalanced it may lead to changes in the geomorphic feature. The geomorphic change follows one of two patterns: erosion or deposition. Deposition of sediment fills in the canyon and erosion causes the canyon to expand.

There is a documented connection between terrestrial and marine systems. Terrestrial anthropogenic activities can alter sediment supply in the watershed, which can result in marine sedimentation (Paull et al. 2006). These changes are difficult to quantify, especially when they occur over an extended timeframe (Paull et al. 2006). In the interactions between marine and terrestrial environments changes are not only made in the marine system but the coastal communities as well. Slope failures within submarine canyon heads pose a hazard to coastal development (Sultan et al. 2007). A deeper understanding of geomorphic changes within submarine canyons will improve the ability to predict the impacts marine and terrestrial systems will have on one another in the future.

The Monterey Canyon (Figure 1) is an example of an active canyon head connecting the

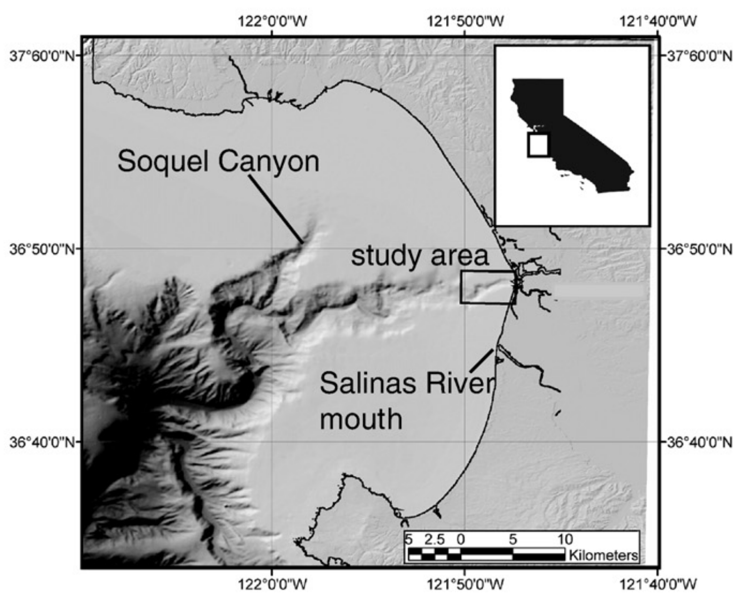


Figure 1: Monterey Canyon head found in Monterey Bay California. Image borrowed from Smith et al. (2007).

shoreline to the deep ocean across a short continental shelf. Although in the headward portion of the Monterey Canyon there is well documented evidence of canyon-axis “flushing events”, caused by turbidity currents and slumping, there is little known about the frequency of sediment transport, or the rate at which geomorphic change is occurring (Smith et al. 2005b).

Previous CSU Monterey Bay studies (Astilla 2005, Smith et al. 2005b, Smith et al. 2007) have quantified the redistribution of sediment in the Monterey Canyon head via a series of high resolution bathymetric surveys. This time series indicates that the upper four kilometers of the Monterey Canyon is currently in a state of erosion (Smith et al. 2005b, Smith et al. 2007). The first project (Smith et al. 2005b) examined data from September 2002 to March 2003 finding an annual rate of erosion of 636,000 m^3 and deposition of 516,000m^3 of sediment annually. The annual net change found in the study was 120,000 m^3 of substrate eroded. These results support the assertion that the Monterey Canyon is an active sediment transport system (Smith et al. 2005b). The second project examined data from September 2002 to February 2005, finding that the Monterey Canyon head expanded by a volume of 1,000,000 m^3 ($\pm$700,000 m^3) through lateral erosion and vertical incision (Smith et al. 2007). Annual net change works out to be 413,000m^3 of substrate eroded from the Monterey Canyon.

Smith et al. (2007) also addressed changes in the lip of the Monterey Canyon (Figure 2). Between September 2002 and September 2003 the detected change in canyon lip position was

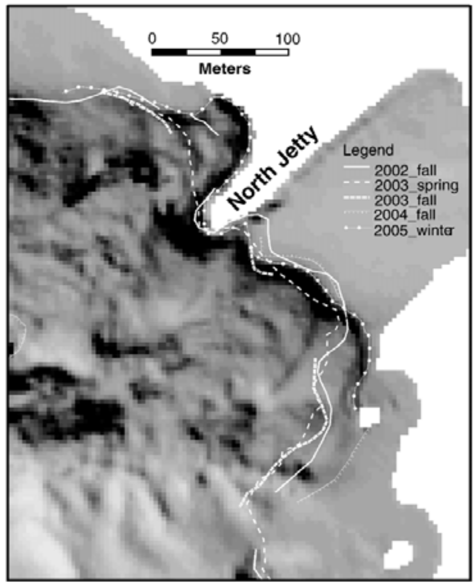


Figure 2: Work by Smith et al. 2007 noting the changes in the lip of the canyon between fall 2002 and winter 2005.

confined to a 3-4.5 meter wide swath (Smith et al. 2007). Between September 2003 and September 2004 the lip retreated 25 m shoreward at a section south of the southern jetty (Smith et al. 2007). The lip of the canyon to the north of the northern jetty was found to have retreated shoreward 50 m between March 2003 and winter 2005 (Smith et al. 2007). The third project compared data collected in March and September of 2003 which resulted in showing little sediment activity in the canyon head (Astilla 2005).

While two of the previous studies document expansion in the canyon, it remains unclear whether the demonstrated expansion is part of an oscillation pattern or a long term trend. Studies support the idea that the lip of the canyon goes though cycles of growth and failure (Smith et al. 2007). This could explain change in the lip seen over the short term; however it is the long term trends that will make a difference to the nearby community of Moss Landing. The occurrence of net erosion could pose a threat to the jetties on either side of the entrance to Moss Landing Harbor and buildings located along the shore just above the high water mark (Figure 3).

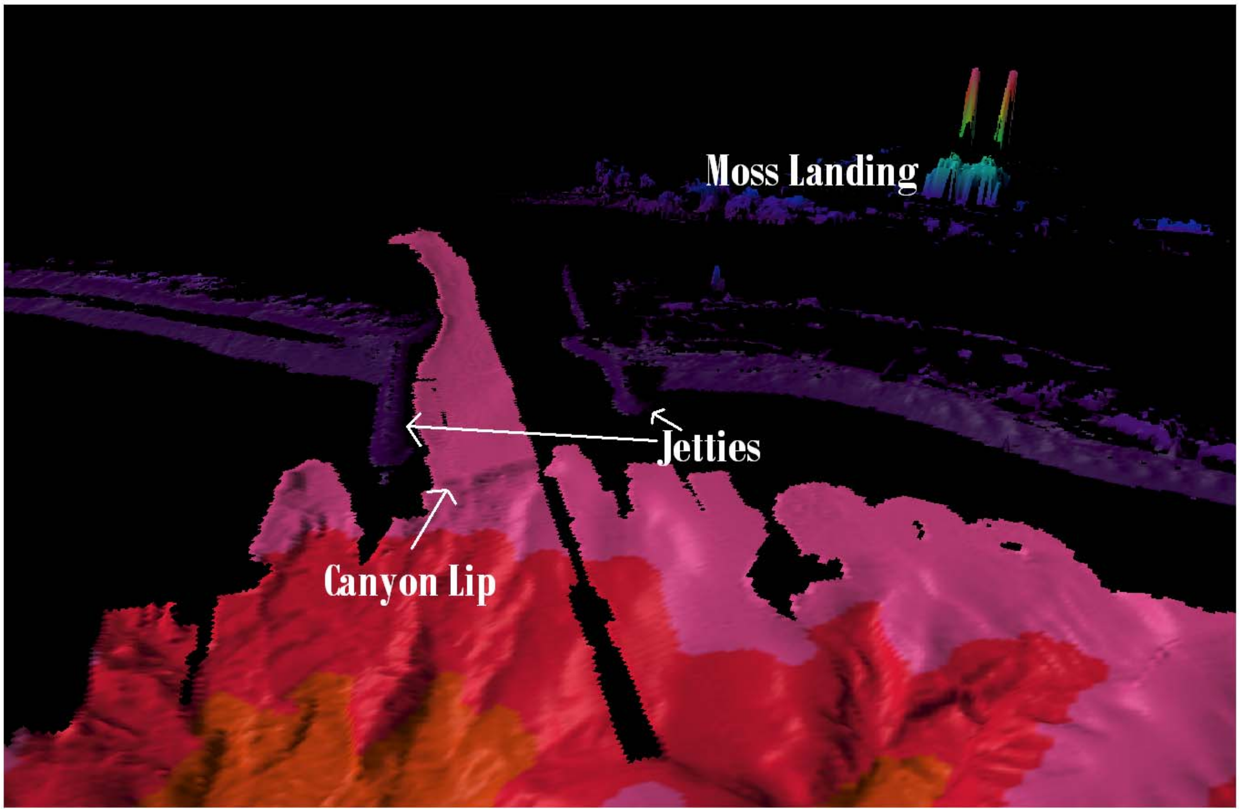


Figure 3: Proximity of the canyon lip to the jetties of Moss Landing Harbor in Fall 2008 bathymetric and LIDAR data, as shown in Fledermaus 3D software.

These threats could pose a negative impact on the economic welfare and security of the residents of Moss Landing, creating some choices for local policy makers. Understanding the basic science of the submarine canyon will help inform future policy decisions regarding coastal land use. In addition to restaurants and other commercial interest, this coastal strand is the home to the Monterey Bay Aquarium Research Institute (MBARI) and several facilities associated with Moss Landing Marine Labs. The long term pattern of the canyon head should also be considered in the planning of the proposed research pier that would extend out past the lip of the canyon.

This project used multibeam bathymetry data from fall 2005 to fall 2008, adding to the existing semi-annual time series begun in 2002 in order to better understand geomorphic change the Monterey Canyon. These analyses will focus on two distinct but related characteristics of the canyon head.

Doubling the length of the bathymetric time series used in previous research will help to further understand the geomorphic change and the time frame at which it is occurring in the Monterey Canyon head. The first area of the study concerns spatial and temporal patterns of sediment deposition and erosion in the Monterey Canyon between winter 2006 and fall 2008.

H_0: Monterey Canyon has not shown a pattern of net erosion or deposition and is in a steady state equilibrium.

H_1: The Monterey Canyon is in a state of erosion, causing widening and/or down cutting of the canyon.

H_2: The Monterey Canyon has been filling in though sediment deposition.

The second area of study concerns the lip of the canyon.

$H_{0:}$ The position of the Monterey Canyon lip has remained in steady state equilibrium, shifting back and forth without any net long term movement.

H_1: The lip of the Monterey Canyon head cut shoreward, migrating toward Moss Landing Harbor.

H_2: The position of the Monterey Canyon lip retreated seaward receding away from Moss Landing Harbor.

Methods

Site Description

The Monterey Submarine Canyon is found along the central coast of California in the Monterey Bay. The extents of the canyon start at the mouth of Moss Landing and extend to at least 90 km offshore (Smith el al. 2005b). The Monterey Canyon is crossed by both the San Gregorio and Monterey Bay faults, as well as being in close proximity to other major fault lines in the Pacific North American Plate (Smith et al. 2007). In the area studied, the top of the canyon ranges between 600m and 1600m across. The walls of the canyon are steep and have many scars from slumping. On the floor of the Monterey Canyon sand waves and terraces are found. The head of the Monterey Canyon is 700 m across, and is made up of four tributaries. The tributaries are about 300 m long and are split up into two northern and two southern. The northern two tributaries end at the mouth of the Moss Landing Harbor jetties (Figure 4).

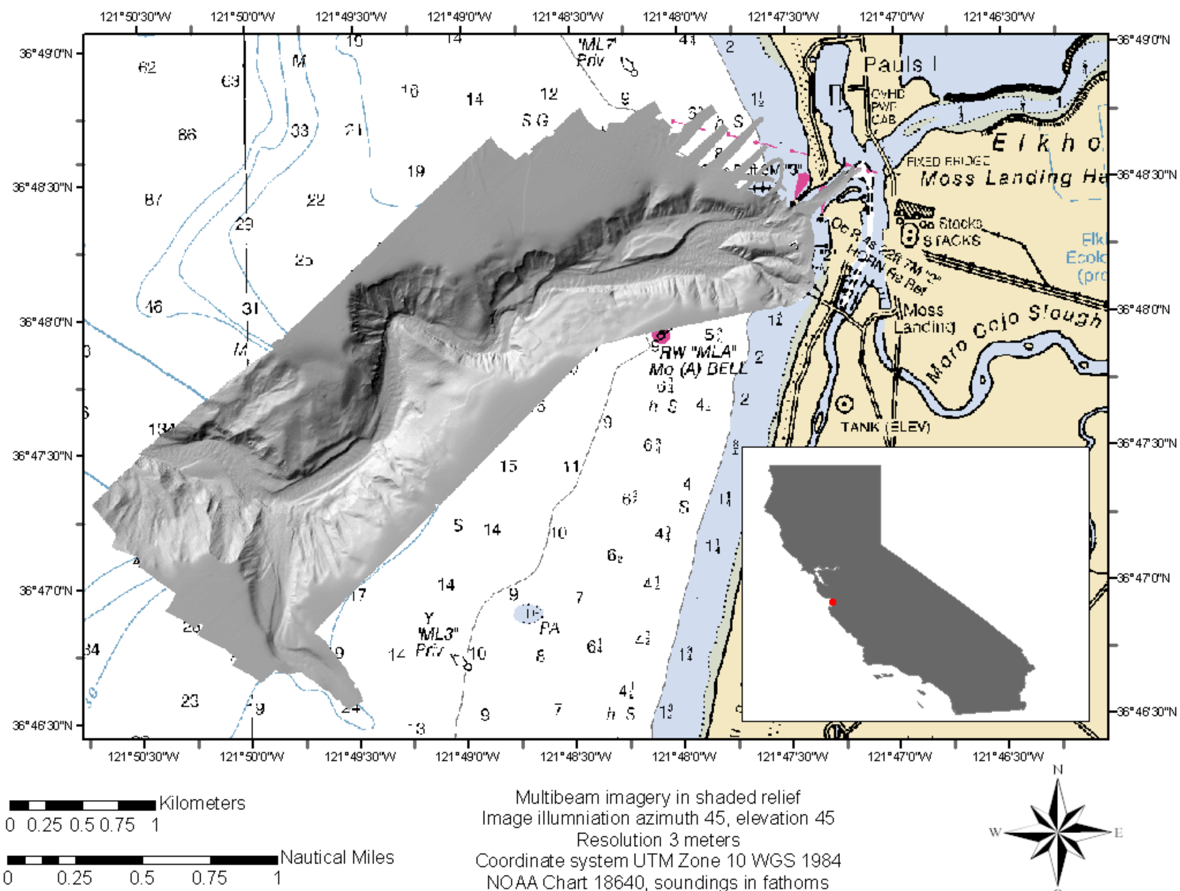


Figure 4: Image shows the head of the canyon meeting the two jetties of Moss Landing Harbor. Shaded relief images was created with the winter 2006 data.

Data Collection

Mulitibeam sonar is an active remote sensing process that uses acoustics to collect high resolution bathymetric data. Resulting images reveal detailed seafloor features and depth. For this investigation, high resolution mulitibeam data of the Monterey Canyon head were collected during one to two day surveys twice a year as follows: September 9, 2005 (fall 2005); February 21-23, 2006 (winter 2006); September 29-30, 2006 (fall 2006); May 1, 2007 (spring 2007); September 14, 2007 (fall 2007); March 19-20,2008 (spring 2008); and August 30 and September 2, 2008 (fall 2008). Prior to data collection, planned survey track lines were created using Hypack navigation software. These survey track lines were used aboard the *R/V Ven Tresca*, a 35 foot hydrographic research vessel, for the collection of full coverage data of the canyon. Two different sonar models were used in data collection. Prior to fall 2008, a pole mounted Reson SeaBat 8101, 244 KHz multibeam sonar was used. The Reson 8101 has 101 beams covering a 150 º swath angle and a maximum depth range of 300 meters. A dual frequency Reson 7125 multibeam sonar with a similar depth range was used in the fall 2008 survey. The 200KHz with 256 beams configuration was generally used for depth >100 meters, and the 400KHz, 512 beam setting was used for depths <100 meters.

The data were logged using Isis sonar data acquisition system. Vessel attitude (pitch, roll, yaw, heave) and position were recorded using an Applanix POS MV equipped with an auxiliary C-Nav 2050 GPS receiver. Sound velocity profiles (SVP) were taken periodically throughout the survey to record the changes in water column stratification for refraction correction done during post-processing. Prior to the fall 2008 data, tide files were created using the vertical position derived from post-processed L1 L2 GPS data obtained from the onboard C-Nav GPS receiver. For the fall 2008 data, smoothed best estimated trajectory (SBET) was used. SBETs were created from post-processing the POS M/V data in POSPAC 5 software, and provide a solution for attitude and position of the vessel based on a coupled kinematic GPS and internal solution. SBETs are used to correct for navigation and vertical fluctuations due to heave or tide, as they contain the horizontal and vertical offset of the vessel, based on the vessels relationship to a datum.

Processing Data

All of the data were processed at the CSUMB Seafloor Mapping Lab, using CARIS HIPS cleaning software. The raw data (.XTF – eXtented Triton Format) were brought into CARIS, where the soundings were SVP corrected for refraction. For data collected prior to fall 2008, heave and tide files were also applied. For the data collected in fall 2008, SBETs were applied. The data were then merged which gives the soundings real world positions. The data files were filtered and cleaned to reject any false soundings, often referred to as noise. Bathymetry Associated with Statistical Error (BASE) surface grids were exported from CARIS 9.2 as geotiffs with a resolution of three meters, as that provides the best coverage and resolution for the given depth. The cleaned XYZ data were exported from CARIS 9.2. AverageGridder was used to convert the XYZ file into a Digital Terrain Model (DTM)/Geo- referenced (Geo) file. Dmagic was then used to convert the DTM/Geo file into a Fledermaus shape (sd) file that was used in Fledermaus to visualize the data in 3D, checking for any remaining false soundings. Once data was cleaned Dmagic was used to change the DTM/Geo file to a ArcGIS ASCII grid file. This ASCII file was then brought into ArcMap and converted to a bathymetry DEM, which then was used to create slope and hillshade rasters for analysis.

Analysis

Changes in the Monterey Canyon head between winter 2006 and fall 2008 (31 months) were determined and quantified using ArcMap 9.2.The study was restricted to the first four kilometers of the canyon nearest to shore. The walls of the canyon were masked out of the calculations so that only the canyon floor was included. Registration of the two digital elevation models (DEMs) was found to be inadequate upon visual inspection. Upon inspection of a primary raster subtraction of the two DEMs definite patterns of erosion opposite deposition were apparent, indicating there was a lateral shift. The distance and direction of the lateral shift was determined visually by measuring change in individual pixels in a well defined area. The horizontal misalignment was corrected by shifting the winter 2006 DEM 1.5 meters east and 2.6 meters north, to match the fall 2008 DEM. A vertical shift of 0.21 meters was found between the two DEMs. The 0.21 meter error was eliminated during the raster subtraction. The result of the raster subtraction showed the vertical differences found in each 3x3 m pixel. To reduce the chance of "noise" being included in the calculations, pixels showing a vertical change of $\pm$1m were excluded from the analysis. The total area of both deposition and erosion were derived by multiplying the number of pixels by the pixel area (9 m^2). This area was then multiplied by the mean vertical change resulting in total volumes of deposition and erosion. The volume deposited could then be added to the volume eroded determining the net change in the canyon over the 31 months of this research.

In order to quantify the changes found in the lip of the canyon there were biannual data collected between fall 2005 and fall 2008. The previous methods used in Smith et al. (2007) were to visually interpret and manually trace the position of the lip on a hill shade raster. The methods used in Smith et al. (2007) were improved in this study by using a slope raster in conjunction with a hillshade raster to visually determine the location of the break in slope, which coincides with the canyon lip, increasing the accuracy of the methods.

In an attempt to automate the process of determining the location of the canyon lip a new method was used. This was done in ArcMap 9.2 using the contour tool on each of the DEMs in the Spatial Analyst extension. The contour interval was set at 100 and the base contour was set to 4 degrees. For purposes of comparison to the Smith et al. study this method was also done for the fall 2002 data set.

In order to quantify the change in the canyon lip methods similar to those in Smith et al (2005a) were used (Figure 5). Ten randomly placed transects were drawn on the algorithmically derived canyon lip to quantify changes of the lip position over time. Transects were randomly placed in order to allow for results to be generalized so that they would apply to the canyon lip as a whole. Using fall 2005 as a baseline, changes in position of the canyon lip between years were measured along the transects. These changes in position were then compared using a one sample t-test in SPSS to determine if the changes were significantly different from zero, which would force us to reject the null hypothesis that the lip is in steady state equilibrium.

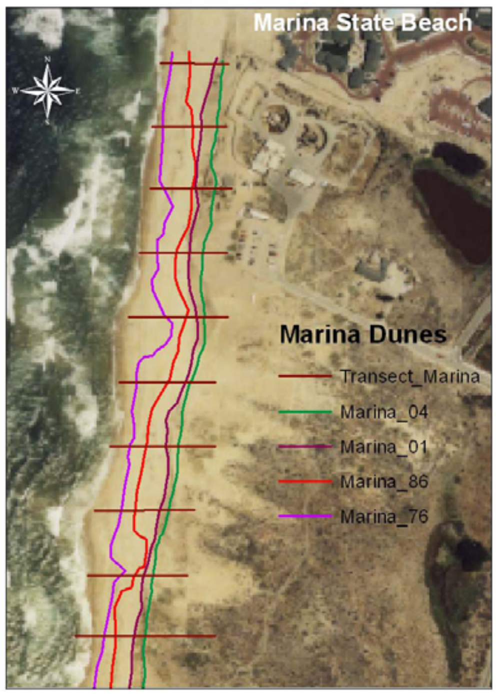


Figure 5: Shows transects drawn Marina Dunes by Smith et al. (2005a).

To verify that the algorithmically derived methods were appropriate for the classification of the canyon lip a comparison between those methods and the improved Smith et al. (2007) hand drawn interpretations was completed. Randomly placed transects were run across the lip to quantify changes. Distance between lip positions along the transects were measured using the fall 2005 data as the baseline and the mean change across years was calculated for each of the methods. After a square root transformation was completed on both sets of means to meet the assumptions of a parametric test, those means were then compared in SPSS using a t-test to determine if they were significantly different from each other based on a 95% confidence interval.

Results

Changes in sedimentation

Within the examined area, the canyon had a total substrate loss of 947,000 m^3 $\pm$ 294,000 which is an average of 360,000 m^3 eroded per year. Areas of deposition were less extensive than erosion totaling 326,000 m^3 $\pm$ 156,000. The average annual volume of deposition was 120,000m^3 of sediment. Overall the Monterey Canyon head had a net loss of 621,000 m^3 $\pm$ 450,000 which is an annual average net loss of 240,000 m^3. The head of the Monterey Canyon experienced large amounts of sediment movement between winter 2006 and fall 2008 (Figure 6)

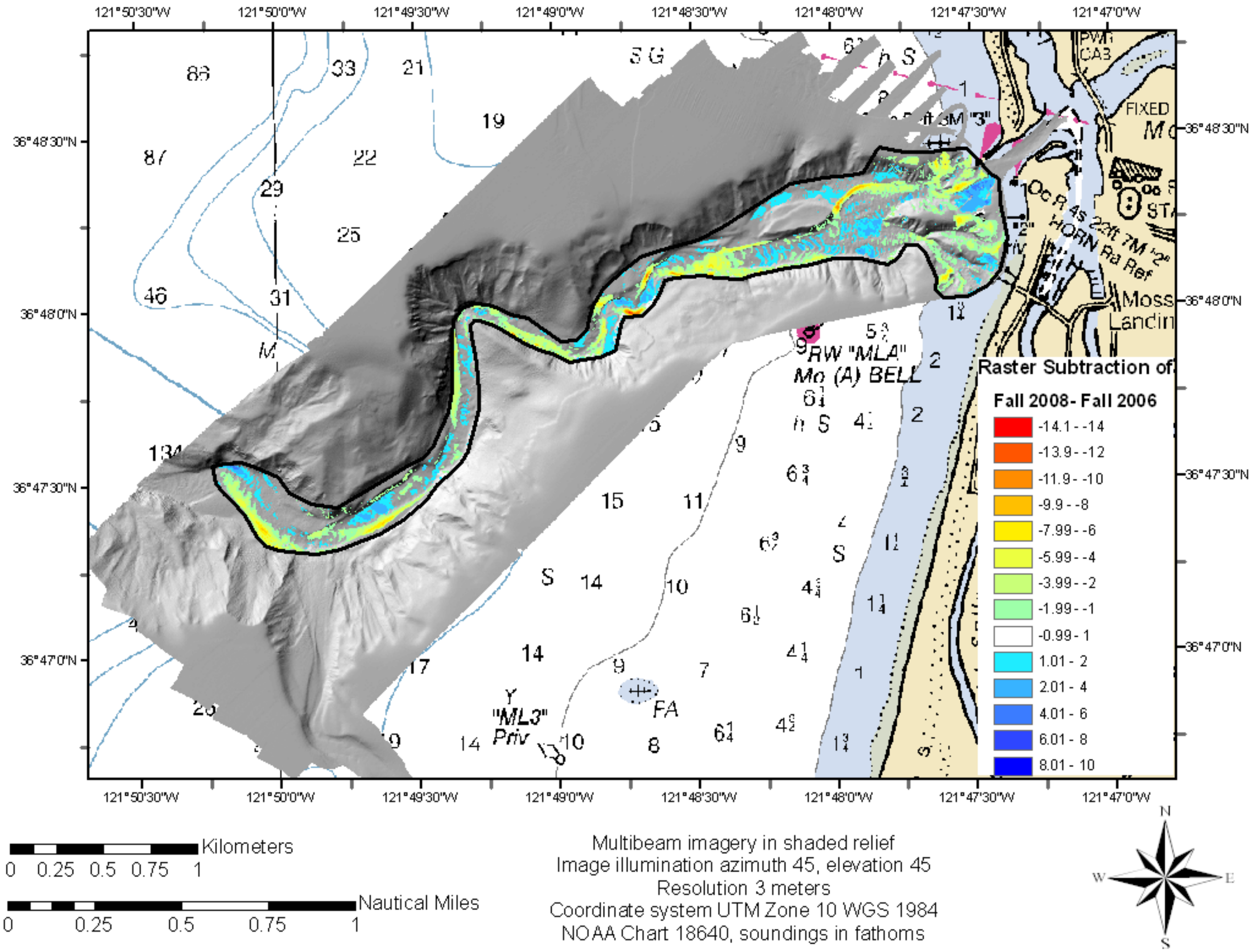


Figure 6: Areas of erosion and deposition between winter 2006 and fall 2008 shown in three meter bathymetric grids calculated using raster subtraction in ArcMap9.2. A vertical shift between the DEMs had to be accounted for by subtracting 0.21 in the raster subtraction. Boundary of analysis is bounded by outline. Erosion is noted by warm colors and deposition is shown in cool colors. Changes between -1 and 1 were excluded from this analysis. The raster subtraction is shown on the winter 2006 shaded relief.

Canyon Lip Position

Changes in the canyon lip were visually examined and revealed an oscillation pattern between the years, without a dramatic overall pattern of erosion or deposition found (Figure 7& 8). Greater variation between years is seen in transects at the head of the canyon in both data sets. Patterns in particular areas were found upon visual inspection of the computer generated lip. At the head of the southern tributary there appears to be a pattern of deposition though out the surveys. There also appears to be deposition in the most northern tributary, however with a greater number of holes in the more recent surveys of this area the pattern is not as clear. On the western side of the most southern tributary erosion is seen between the 2002 and the data set from this project, with the greatest amount of erosion seen between fall 2002 and fall 2005. Surveys after 2005 show an oscillation pattern of deposition and erosion. Areas of possible misinterpretation are also seen, such as areas with large jumps in the canyon lip that vary greatly from all other years. The center of the most shoreward section of the canyon lip also shows a likely location of misinterpretation, where the Spring 2008 data appears to suddenly show great deposition and then show a matching level of erosion in the following survey.

When statistically determining change in the lip of the canyon the computer generated lip data were analyzed. A one sample t-test failed to reject the null ($t_{0.05} = -0.551$, $p = 0.595$), showing there was not a statistically significant monotonic net change in the lip of the Monterey Canyon between fall 2002 and fall 2008.

Comparing methods of measuring the canyon lip

These results for both methods of interpreting the canyon lip were compared visually in graphs (Figure 9&10). Both graphs showed oscillation patterns which become larger in transects at the head of the canyon. A t-test comparing the means of the two methods showed no significant difference ($F_{0.05,1,18}$ =0.529, p-value = 0.476) (Figure 11).

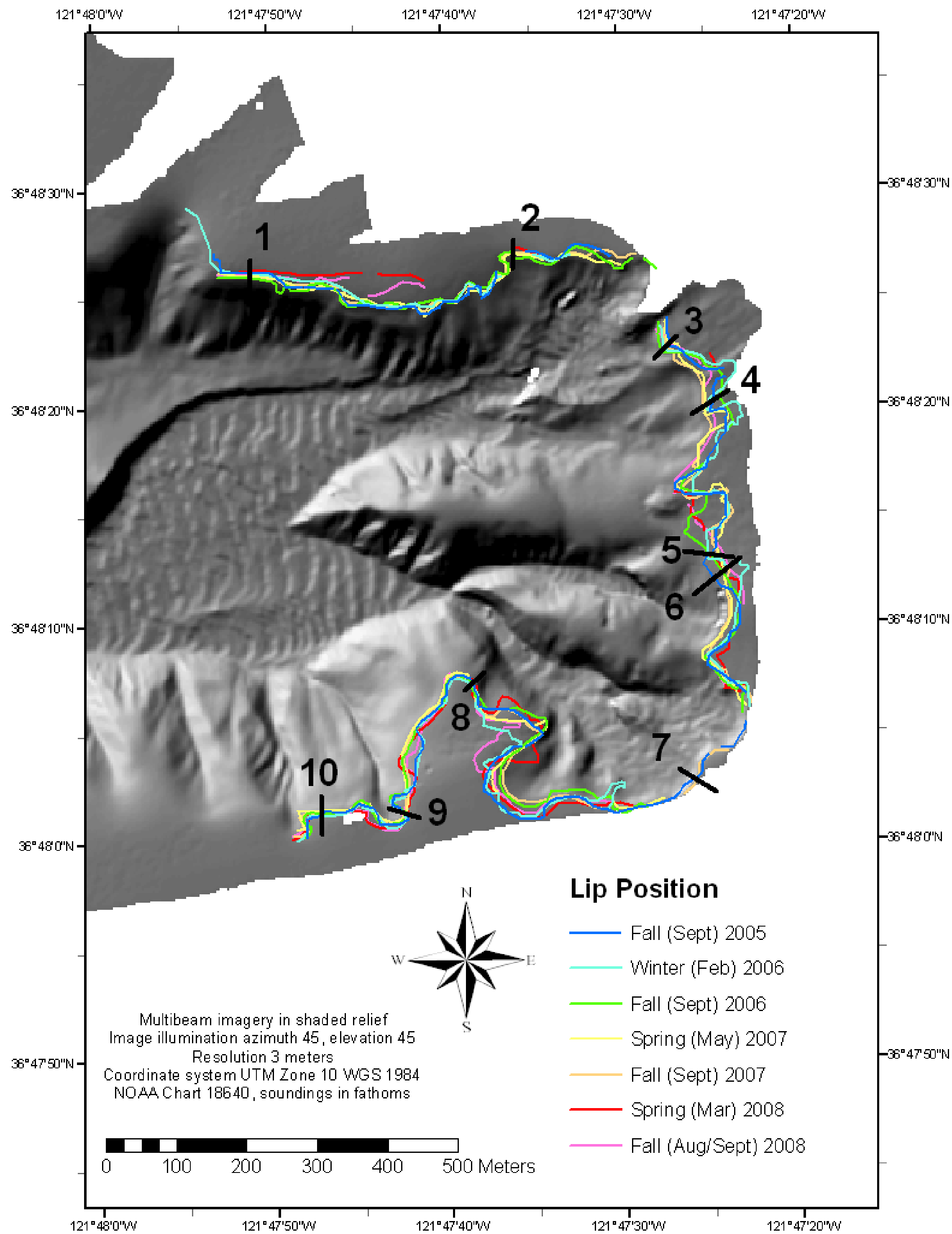


Figure 7: Image shows the changes in the position of the lip between fall 2005 and fall 2008 through the hand drawn interpretation method using ArcMap 9.2 hill shade and slope rasters. Outlined lips overlaid on shaded DEM of the head of Monterey Canyon collected winter 2006. Randomly placed transects were assigned numbers.

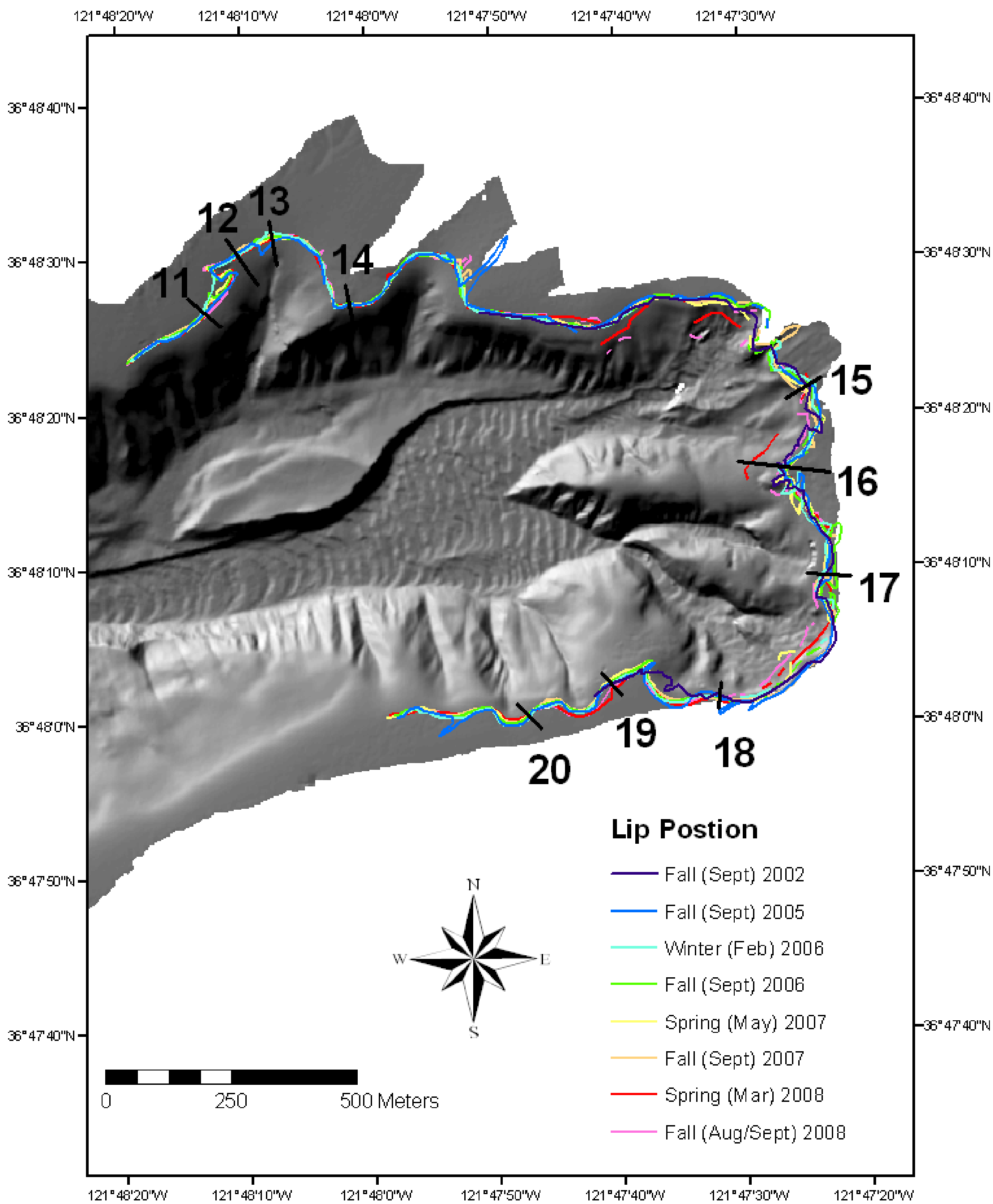


Figure 8: Position of the lip shown from fall 2005 to fall 2008 as derived using ArcMap 9.2 contour interval tool on each DEM to find break in slope at a four degree slope. Outlined lips overlaid on Monterey Canyon head shaded DEM collected winter 2006. Numbers were assigned to randomly placed transects.

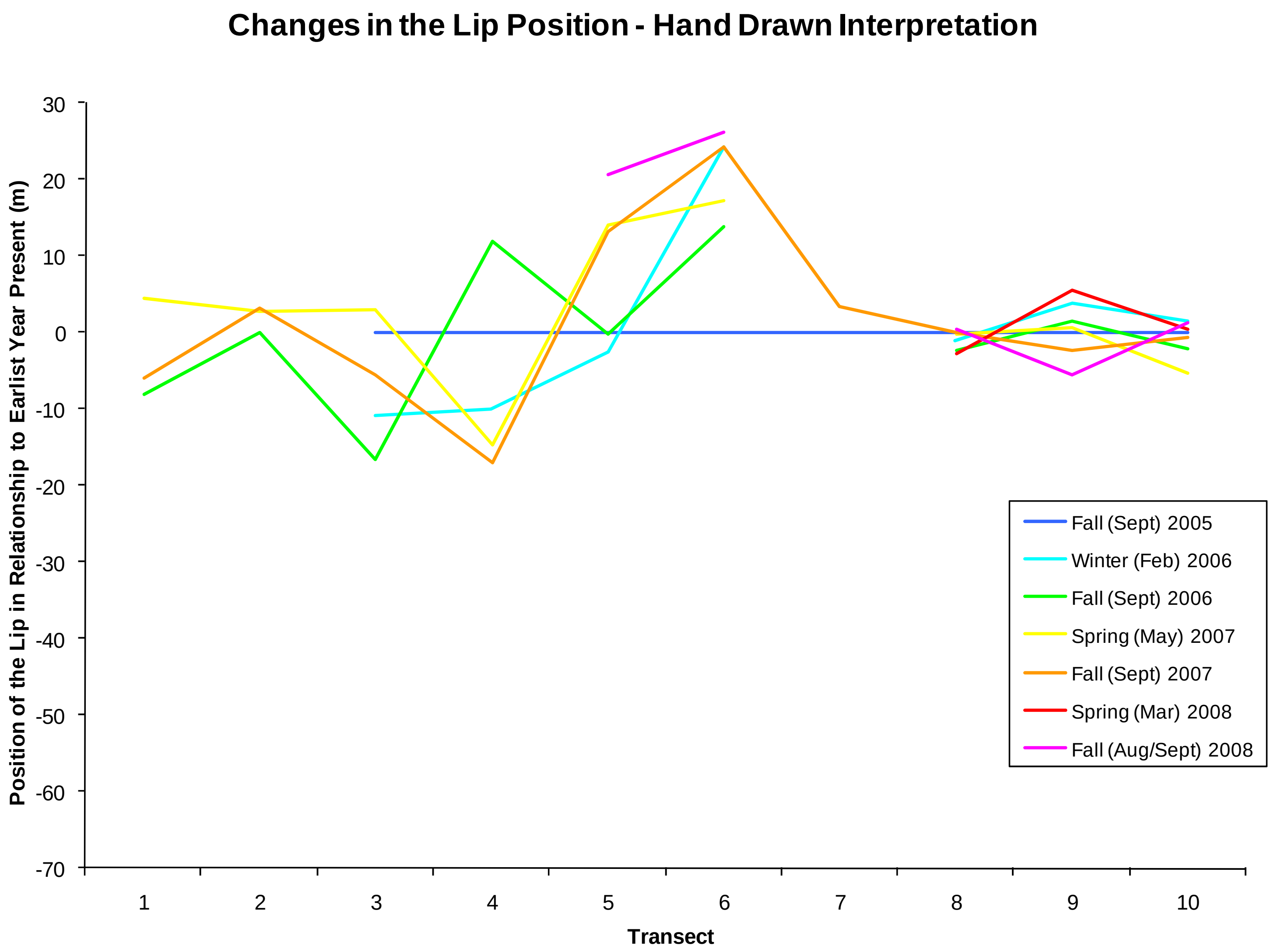


Figure 9: Graph shows changes in position of the Monterey Canyon lip over time as interpreted when drawn by hand using ArcMap 9.2 hillshade and slope rasters. Positive position values represent erosion and negative values represent deposition in the head of the canyon. Numbered transects represent randomly assigned transects shown in Figure 7. Gaps in the lines represent areas where no data was present for that survey.

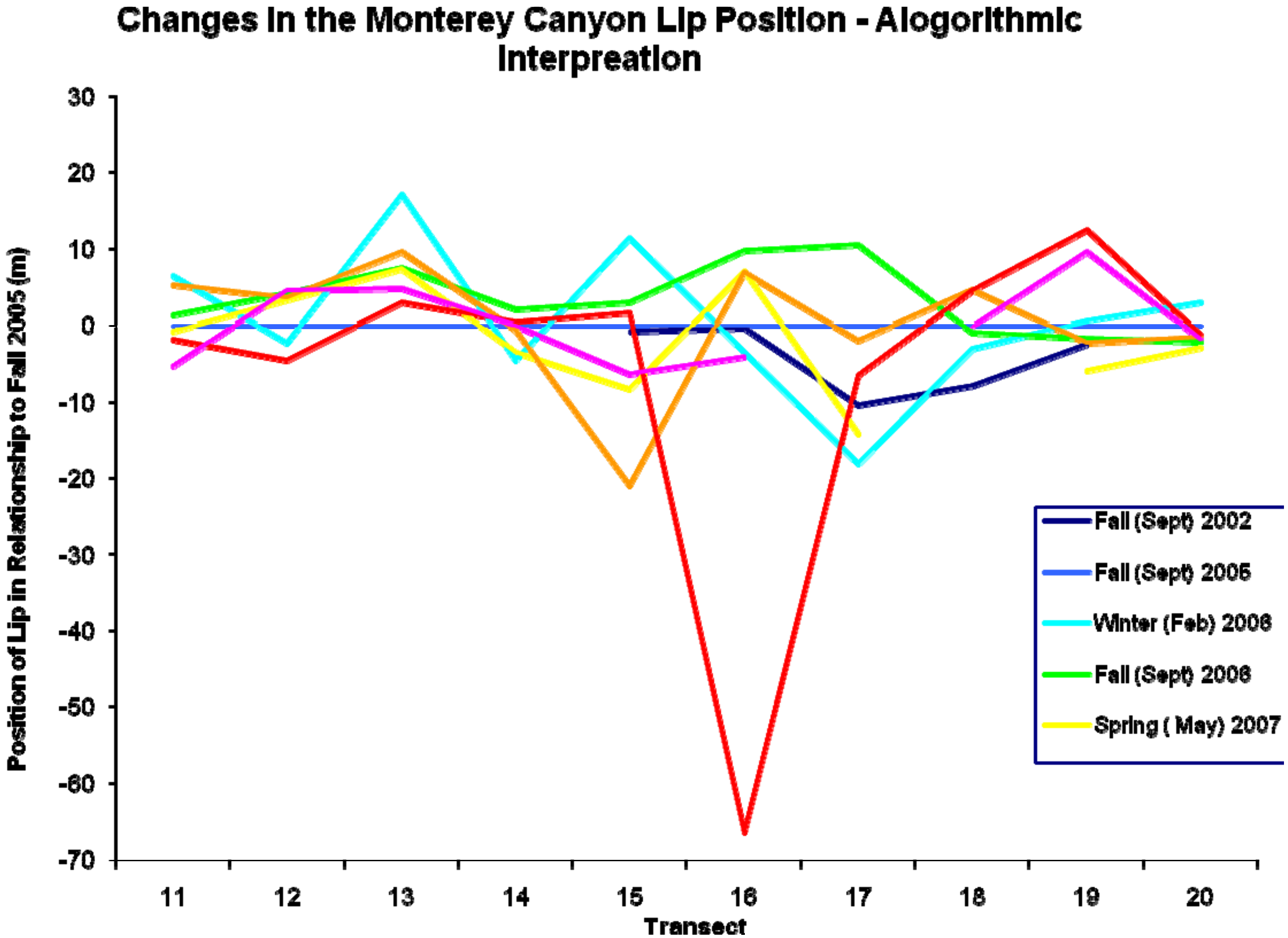


Figure 10: Shows the changes in lip position of the Monterey Canyon as determined by ArcMap 9.2 at 4 degree slope. Negative position values represent deposition in the canyon and positive values represent erosion out away from the canyon. Transects numbers are representative of randomly placed transects across the computer generated lips. No data present is represented by the unconnected lines.

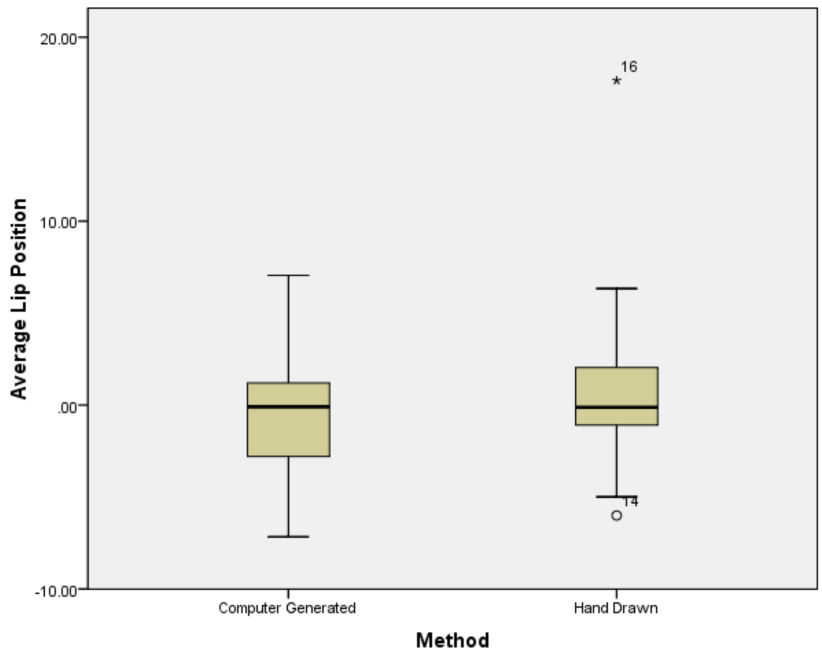


Figure 11: A box plot created in SPSS comparing the means of the two methods used. The box plot shows that the means of the two methods give comparable results with each other.

Discussion

Changes in sedimentation

The Monterey Canyon experienced a large amount of sediment movement, both through erosion and deposition, between winter 2006 and fall 2008. These results support previous research that the Monterey Canyon is an active sediment transport system currently in a state of erosion. The rate at which erosion is occurring in the canyon appears to be decreasing. In the study by Smith et al. (2007) the net rate of change was calculated to be 400,000 m^3 of substrate eroded annually. In comparison to this study that found a net annual rate of erosion to be 240,000 m^3, which is a difference of 150,000 m^3. A canyon in an oscillation pattern of deposition and erosion would have a net change of zero. As this is not the case either the canyon is not in a state of oscillation or it is in a pattern is longer term this study could detect. While areas of deposition are found in the canyon head, areas of erosion are more widespread. Patterns of erosion are apparent down the canyon appearing to be caused by currents.

There were several restrictions on the raster subtraction analysis. These restrictions were described in Smith et al. (2007) and are summarized here. The first constraint was that the study only included the first four kilometers nearest to shore. The second constraint was the analysis was restricted to the floor and head of the canyon, excluding the canyon walls. Even with great caution taken in registering the rasters small horizontal errors are still present. These offset errors cause depth errors that are minimal in areas such as the canyon floor that are relatively flat, but become too great to be acceptable on the steep, tall canyon walls. The final constraint was all pixels exhibiting vertical change of <1 m were excluded from the calculations. This constraint can have two possible implications on the analysis. Firstly this can result in underestimates in the calculations of change in bathymetric and sediment volume if there are large areas of the survey with less than one meter of deposition or erosion. The second implication is the possibility of creating an overestimate of net erosion. This overestimate of erosion would happen if erosion created scours that were greater than one meter in depth and the removed substrate was relocated within the study site over a larger area and deposited in less than a meter thickness (Smith et al. 2007).

Canyon lip position

According to the data studied, the Monterey Canyon lip appears to be in an oscillation pattern with the exception of a few outliers. When determining the location of the lip it became rather apparent that some areas of the lip were more defined then others. The transects that were in areas of a poorly defined lip in Figure 7 were transects 4, 5, 6, and in Figure 8 it was transects 15, 16, 17. In areas where the lip is not well defined there is greater uncertainty in the interpretation of the lip location, causing an increase in the error of both methods. The outliers are found in these poorly defined areas of the lip. The oscillation does support the idea that has been proposed about growth and failure cycles in the canyon lip (Smith et al. 2005b, Smith et al. 2007)

The null hypothesis, that the Monterey Canyon is in a steady stat equilibrium failed to be rejected, meaning that there is a possibility of the canyon lip having no net change. This research does not support idea that the canyon lip is eroding into Moss Landing Harbor. The oscillation pattern shown in this study does not pose a threat to Moss Landing Harbor in the near future.

Comparing methods of measuring canyon lip

Two methods were compared to examine the canyon lip, a hand drawn technique and a computer generated technique. The two methods were shown to be statistically similar. As expected, both of the methods showed more variation in the areas where there was not a sharp break in slope. Future use of the computer generated technique would have several benefits. Using this technique would be more time efficient and would allow for more repeatability, eliminating any differences in individual interpretation. Variations in interpretation between individuals were not accounted for in this study, as all of the hand drawn interpretations of lip position were completed by a single individual. Further research could be done with the older datasets in the time series to algorithmically create lips and compare them with the previous work done. Since the previous research was done by another individual these results could give a clue to repeatability of hand drawn interpretations between individuals.

Future Research

With the proximity of Monterey Canyon lip to Moss Landing Harbor, research of this dynamic system should be continued. In future surveys, I would recommend that effort be put into obtaining data of the entire lip, eliminating holes such as the ones found in datasets used in this research, creating a more complete understanding of the system. Local research should be conducted to better understand the relationship between Monterey Canyon and Elkhorn Slough. Research is currently being conducted in the Elkhorn Slough to support policy decisions about handling the substantial erosion in the slough that has continued to take place since Moss Landing Harbor was built in 1946. If the Elkhorn Slough was no longer a source of sediment, the question that arises is what impact will this have on the dynamics of the Monterey Canyon system? A change in the dynamics of the slough could require another study be done on the Monterey Canyon to ensure that the change in the slough does not decrease sediment input to the canyon enough that the canyon lip erodes out further into Moss Landing Harbor.

Acknowledgments:

I would like to thank everyone who has helped me though out this capstone. I would like to thank my advisors for their help and support. Thank you, Dr. Rikk Kvitek for giving me this great opportunity to complete this research and for the patience and help along the way. Thank you, Dr. Doug Smith for the continued enthusiasm and support with this research. Thank you Krystle Gomez for helping me come up with solutions to my small road bumps along the way, such as the idea of using the slope raster in hand drawn interpretations of the canyon lip. I would also like to thank all of my coworkers at the Seafloor Mapping Lab who have given their support in different aspects of this capstone along the way.

Literature Cited:

Astilla J. 2005. A model of deposition and erosion in the Monterey Canyon Head during a pre-storm season using serial multibeam bathymetry surveys [Bachelors]. Seaside (CA): California State University Monterey Bay. 27 p. Available from : Seafloor Mapping Lab, California State University Monterey Bay.

Chiang CS, Yu HS. 2008. Evidence of hyperpycnal flows at the head of the meandering Kaoping Canyon off SW Taiwan. Geo-Marine Letters 28:161-169

De Stigter HC, Boer W, de Jesus Mendes PA, Jesus CC, Thomsen L, van den Bergh GD, van Weering TCE. 2007. Recent seiment transport and deposition in the Nazare Canyon, Portuguese continental margin. Marine Geology 246:144-146

Garcia R, van Oevelen D, Soetaert K, Thomsen L, De Stigter HC, Epping E. 2008. Deposition rates, mixing intensity and organic content in two contrasting submarine canyons. Progress in Oceanography 76:192-215

Greene HG, Maher NM, Paull CK. 2002. Physiography of Monterey Bay National Marine Sanctuary and implications about continental margin development. Marine Geology 181:55-82

Green A, Uken R. 2008. Submarine landsliding and canyon evolution on the northern KwaZula-Natal continental shelf, South Africa, SW Indian Ocean. Marine Geology 254:152-170

Hutson L. 2005. Getting to the bottom of things. Materials World 13(11):4

Kunze E, Rosenfeld LK, Carter GS, Gregg MC. 2002. Internal Waves in the Monterey Canyon. American Meteorological Society 32:1890-1913

Paull CK, Ussler III W, Greene HG, Keaten R, Mitts P, Barry J. 2003. Caught in the act: the 20 December 2001 gravity flow event in Monterey Canyon. Geo-Marine Letters 22:227-232

Paull CK, Ussler III W, Greene HG, Barry J, Keaten R. 2005. Bioerosion by chemosynthetic biological communities on holocene submarine slide scars. Geo-Marine Letters 25:11-19

Paull CK, Ussler III W, Mittls PJ, Caress DW, West GJ. 2006. Discordant 14C-stratigraphies in upper Monterey Canyon: A signal of anthropogenic disturbance. Marine Geology 233:21-36

Smith DP, Gref K, Hofmann A, Turrini-Smith L. 2005a. Are "Stable Shorelines" and "Broad Beaches" Mutually Exclusive Management Goals Along Southern Monterey Bay? : The Watershed Institute, California State University Monterey Bay, Publication No. WI-2005-09: 46

Smith DP, Ruiz G, Kvitek R, Iampietro PJ. 2005b. Semiannual patterns of erosion and deposition in upper Monterey Canyon from serial multibeam bathymetry. Geological Society of America Bulletin 117(9/10):1123-1133

Smith DP, Kvitek R, Iampietro PJ, Wong K. 2007. Twenty-nine months of geomorphic change in upper Monterey Canyon (2002-2005). Marine Geology 236:79-94

Sultan N, Gaudin M, Berne S, Canals M, Urgeles R, Lafuerza S, 2007. Analysis of slope failures in submarine canyon heads: An example from the Gulf of Lions. Journal of Geophysical Research 112

Xu JP, Nobel MA, Rosenfeld LK. 2004. In-situ measurements of velocity structure within turbidity currents. American Geophysical Union 31(9)

Xu JP, Wong FL, Kvitek R, Smith DP, Paull CK. 2008. Sandwave migration in Monterey Submarine Canyon, Central California. Marine Geology 248: 193-212