



# Effects of Marine Channel Morphology on Sediment Depositional Characteristics

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## NONTECHNICAL SUMMARY

Understanding how the shape of marine channels controls the pattern of sediment deposited within them can help explain the relationship between seafloor channels and terrestrial rivers. Also, marine channels carry carbon and nitrogen, as well as other nutrients and pollutants, from the land to the deep ocean and are very important for understanding earth's chemical and physical cycles. This study used a seafloor sonar survey in combination with three sediment cores taken off the tip of the Baja Peninsula. The bathymetry from the survey was analyzed to determine how much each channel meandered (sinuosity), how steep the bottom of each channel was (slope), and how much area in the channel was available for flow. Cores were analyzed to determine the size of particles and how fast they are deposited within each channel. Differences in these characteristics were compared across the three channels studied. Sinuosity appears to be the direct control on sediment characteristics, and slope does not appear to have any effect.

## ABSTRACT

Terrestrial sediment is a main source of particulate matter for the ocean, and impacts many of earth's physical and chemical cycles, with significant impacts on the carbon and nitrogen cycles. An understanding of the relationship between channel morphology and sediment deposition characteristic will be useful to models of earth cycles important in understanding climate change, and to improve our comprehension of the similarities and differences between marine and terrestrial channels. This study combined several existing experimental techniques to understand what aspects of channel morphology and flow have the largest effect on sediment depositional characteristics on the floor of submarine channels. Specifically, this study evaluated channel morphology in terms of sinuosity, slope, and cross-sectional area; and addressed sediment depositional characteristics in terms of grain size and accumulation rate. The study area is tectonically unique, but few studies about local sedimentary processes on the shelf of the Baja Peninsula had been performed, where surveying and coring for this study took place. This study used multibeam, and singlebeam data from the R/V *Thomas G. Thompson* in conjunction with Pb-210 and grain size analysis of multicores taken in three channels within the study area. Of the metrics analyzed in this study, only slope was found to have little contribution to deposition patterns. Sinuosity appears to be the most important morphological characteristic, as high sinuosities result in high accumulation rates and low sand:mud ratios. Results indicate that cross-sectional area should not be calculated the same way for marine channels that is traditional in terrestrial channel analysis, as large-scale currents and overlying water blur the boundaries that channel steps provide to flow.

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Submarine canyons are well known as an important conduit for sediment transport from terrestrial to deep ocean reservoirs. Deposition rates in submarine canyons are controlled by many factors including channel morphology, flow rate, sea level, and surrounding bathymetry (Sisavath et al., 2011). With the rise in sea-level at the beginning of the Holocene, the dominant sedimentation process in submarine canyons on continental shelves has shifted from episodic gravity controlled mechanisms (turbidity currents, debris flows, and slumps) to continuous transport mechanisms (Carson, 1985). Numerous studies, including Liu et al. (2009), have observed enhanced accumulation rates in marine canyons relative to rates on the open continental slope. Understanding the spatial and temporal variability in accumulation rates and the factors that control them has many larger implications. These include effects on many of earth's physical and chemical cycles and an improved understanding of the anthropogenic influence on marine sediments deposited through fluvial systems (Nittrouer and Wright, 1994). The sediment deposited in submarine canyons traps terrestrial carbon in the deep ocean much faster than particulate organic carbon from the surface ocean sinking slowly to the seafloor (the dominant carbon source throughout the majority of the open ocean) (Covalt 2011).

Channel morphology can be quite complex and difficult to quantify. The large-scale bathymetric features (such as tectonic ridges and valleys) surrounding submarine channels are a major control on their shape (just as a terrestrial river's shape is controlled by the large-scale ridges and valleys around it), therefore multiple quantitative measurements are required to compare channels with morphological differences (Clark, Kenyon and Pickering, 1992). Despite the complicated tectonic processes of the area, studying three channels in the same region can help negate tectonic influences on shape. In a 1992 study by Clark, Kenyon and Pickering, methods for the quantitative analysis of submarine channel geometry were described in terms of specific numerical values. A full picture of channel shape can be composed through the combination of channel sinuosity for particular sections of the channel, down-channel changes in this sinuosity, channel meander wavelength, radius of curvature,

channel width, and channel depth. The focus of the 1992 study was submarine fan classification, so sediment on the channel bed and flow rate through the channel were not addressed.

In a second study by Carson et al. (1985), a study of how modern sediment is distributed along the Quinault Submarine Canyon off the coast of Washington focused on sediment accumulation rates and grain size distribution in combination with water column and flow characteristics throughout the basin. Using known current magnitudes and directions, Carson et al. compiled a sophisticated picture of circulation in the basin. They combined this picture with box cores analyzed for grain size and dated using excess Pb-210 methods. Mean accumulation rates were higher on the channel bed than on the channel walls.

A combination of the methods used in these two studies provides a thorough base for answering the question, "How does channel morphology and flow affect sediment depositional characteristics?" This project is inherently distinct from past studies in that it relates channel morphology to the characteristics of sediment distribution through a comparison of distinct channels within a localized area. Additionally, this study provides valuable information on sedimentation and channel morphology on the understudied shelf of the Baja peninsula. As an area of active tectonic processes (Michaud et al., 2004) and home to several watersheds providing a consistent source of terrestrial sediment, the tip of the Baja Peninsula provides the ideal location for a pilot study using this type of comprehensive analysis.

## METHODS

The data acquisition took place on board the R/V *Thomas G. Thomson*, March 21 and 22, 2012 on the continental shelf off the coast of the tip of the Baja Peninsula. This region is home to a channel system with three large channels of varying characteristics that are ideal for the study parameters. To understand both morphology and sediment deposition, the study combined a bathymetric multibeam survey of the channel system with multicores taken in the bottom of each channel.

The survey was conducted using the Kongsberg EM302 echosounder on board the *Thompson*. Four survey lines, covering an area of roughly 600km<sup>2</sup>, with a beam angle of 60° (resulting in a transect overlap of between 20 and 40%, depending on depth), were completed at a survey speed of 7 knots. Four sound velocity profiles (SVPs) were conducted during the survey to constrain the thermocline and allow downward extrapolation of the density gradient. The SVPs were determined from CTD data at the start of transects 1 and 4, and from expendable bathythermograph (XBT) data at the start of lines 2 and 3. Coring locations were determined from high-resolution survey results to accurately locate stations at the bottom of each channel. A consolidated area covering only the extent of the channels utilized in the study is shown in Fig. 1.

An eight-barrel multicorer was deployed at three locations with respective depths of 1724, 1374, and 1418 meters, and cable payout was matched with survey depth to ensure cores were precisely within the channels (Fig. 1). The two longest cores from each station were retained and sliced at 2 cm intervals. Core lengths varied between stations, with the longest core from the first deployment 34 cm long, the second deployment 44 cm long and the last deployment 10 cm long. Slicing shortens each core slightly, so only 4 sampling intervals were acquired from the third core.

Post-processing can be divided into two categories: channel morphology, derived from multibeam data, and sediment characteristics, acquired from analysis of the multicores.

#### *Channel Morphology*

The multibeam data from the shipboard survey was imported into CARIS's HIPS and SIPS, where a regional tide file and the appropriate SVPs were applied. Then a Combined Uncertainty and Bathymetry Estimator (CUBE) surface with a resolution of 10m was derived, further cleaned, and exported. This cleaned surface was then imported into ESRI's ArcGIS software to be analyzed for morphology metrics, using procedures from the Clark, Kenyon, and Pickering study.

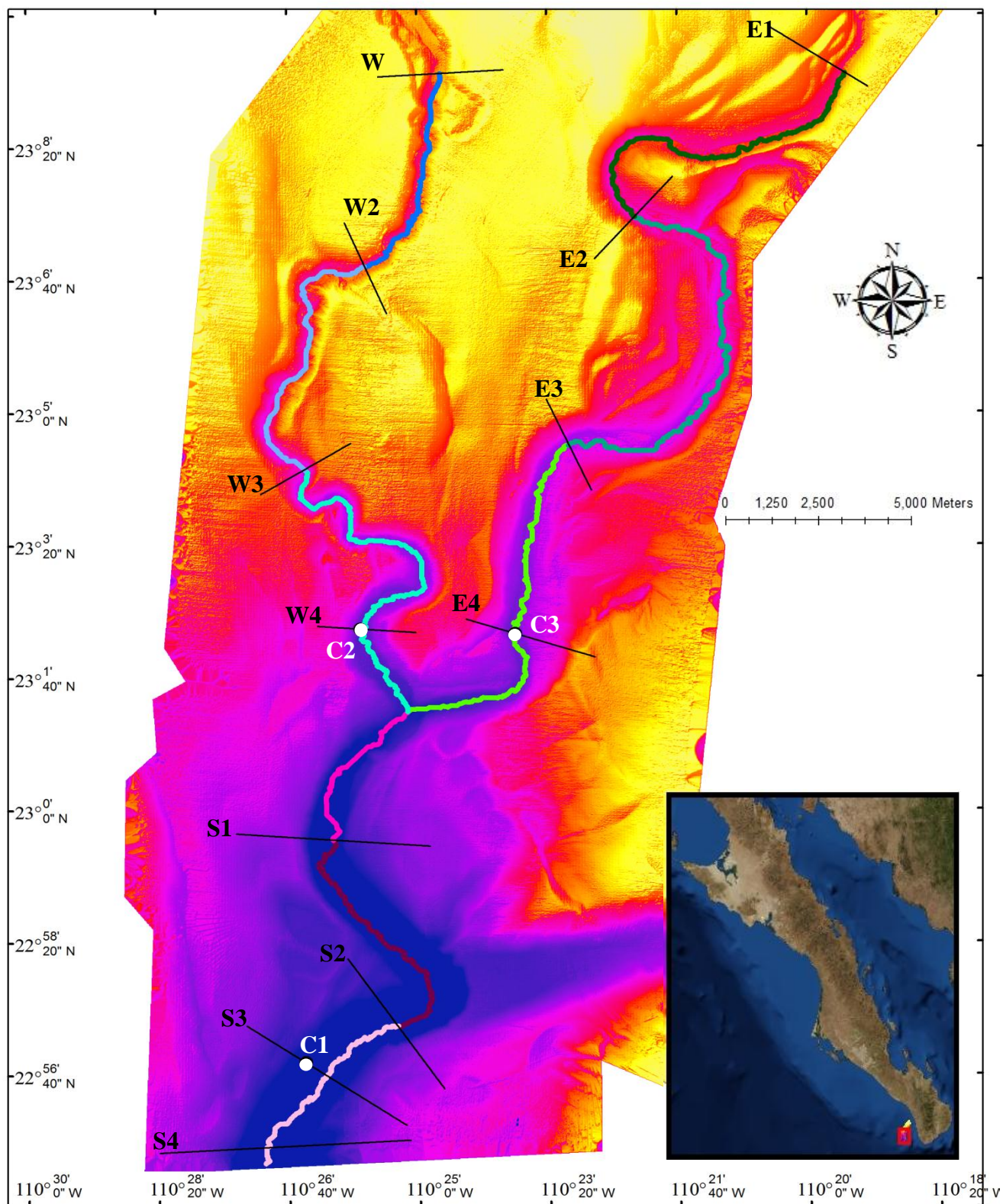
This study focused on three morphologic controls on sediment deposition within marine channels (sinuosity, slope, and cross-sectional

area). Sinuosity is a measure of how much the channel meanders, defined as the actual distance covered by the deepest points in the channel from the channel head to the channel foot, over the straight-line distance from the head to the foot. In this study, slope is defined as the ratio of vertical change to horizontal change from the head to the foot of the channel, rather than across the channel width. Cross-sectional area (CSA) is the channel width multiplied by the channel depth for a slice of the channel perpendicular to channel flow.

The extent of each channel analyzed was limited by ship-time. Collaboration with other scientist led to more coverage of shoreward channels than seaward, so the investigated length of each channel varies. The finalized study area covers three channels: a western and eastern channel closer to shore that combine to form a southern confluence channel (Fig.1). Each channel was subdivided into three roughly equal segments for statistical purposes. As the extent of the survey forced limitation on channel extent that are unrelated to channel confluences and natural lengths, using shorter segments as well as the entire channel length available helps to eliminate bias originating by arbitrary definitions of channel extents. For visual purposes, coring locations were overlaid on the surface

Defining the center of each channel was done with the flow accumulation function in ArcMap. This function determines the amount of surrounding cells that empty into each cell. As the function is cumulative, cells with very high flow accumulation values represent the bottom of large channels. The three channels in this study are very large in comparison to their neighbors, so clipping the cells with the highest flow accumulation resulted in a line representing the bottom of each study channel (Fig. 1).

To calculate channel sinuosity, the channel length of each segment and each channel was determined from the results of the flow accumulation function: a line was drawn through the center of all cells representing the channel bottoms, and the length of this line was calculated in ArcMap. These values were then divided by their corresponding straight-line distances, resulting in four sinuosity values for each channel. These values were then averaged to determine an overall channel sinuosity. The purpose of

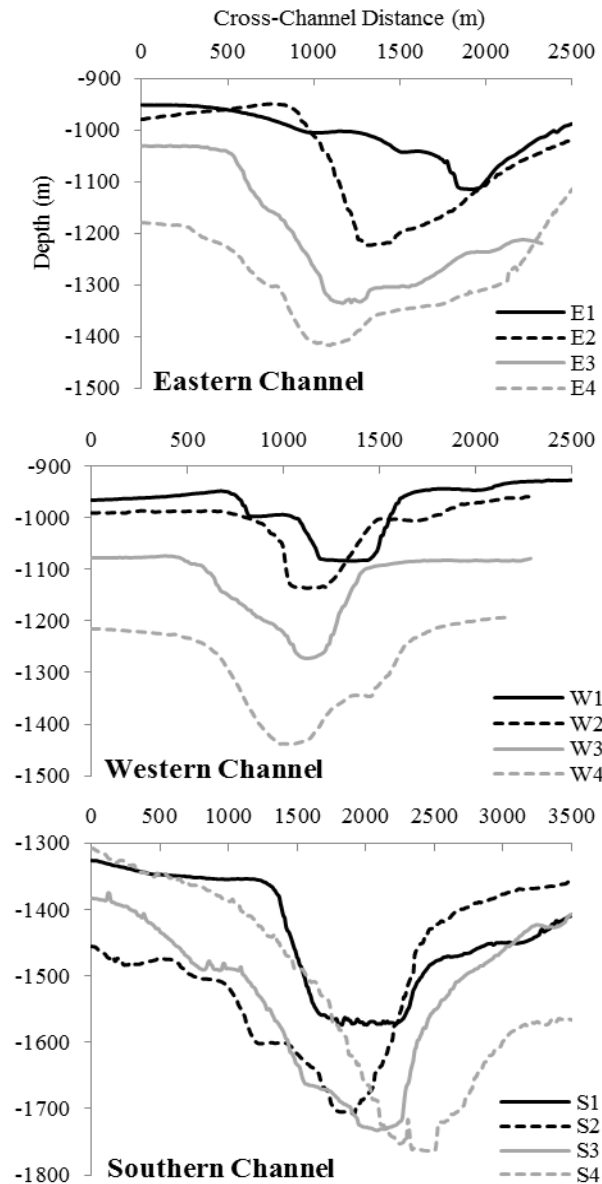


**Fig.1** Study area showing bathymetry from multibeam survey. Blues are the deepest, yellows the shallowest. Colored lines represent channel bottoms, determined from flow accumulation. The Western channel is blue, the Eastern is green, and the Southern is pink. Different shades represent segments of each main channel used in calculations. Black lines and letters represent profile locations and labels. White dots and letters represent core locations and labels.

averaging in smaller segments was to ensure that small-scale features were not overlooked.

Channel slope was determined simply by dividing the difference in elevation between the head and foot of each channel by the overall channel length (determined as described above). Values were then converted to degrees (Table 1).

The calculation for CSA of each channel began with extrapolating four cross-channel profiles of each channel (Fig. 1). These profile



**Fig. 2** Cross-Channel Profiles showing bathymetry. Labels correspond to Fig. 1, indicating profile location. Lower values represent profiles farther north along their channels. Profiles E4, W4, and S3 intersect the coring locations.

lines were drawn in ArcMap normal to the direction of flow, and extracted the depth at 10m intervals along the line. A table with distance along the profile line and bottom depth at each point was exported to Microsoft Excel, where all four profiles from each channel were plotted together (Fig. 2). An inspection of each profile reveal steps in each channel bed, possibly the result of changes in flow rate or sea level. For the purpose of this study, only the area of the bottom-most step was calculated, as it is assumed to be the active portion of the channel. A horizontal line was drawn from the top of the bottom-most step across the width of that portion of the channel, called the lid. The difference between the lid and the channel floor was calculated at 10m increments and multiplied by 10, to get  $m^2$  slices of area covering the channel (effectively step-wise integration). These slices were then summed for each profile and averaged, to get an overall CSA for each channel (Table 1).

#### *Sediment Characteristics*

Multicore slices were split in two: one half was reserved for excess Pb-210 and the other for grain size. The top 8 cm of each core were analyzed, to maximize the data from the shortest core. Subsamples at 6 cm intervals (starting with the 10-12cm interval) were analyzed from the two longer cores.

The resultant 24 Pb-210 subsamples were dried and then ground with an agate mortar to reduce the coarse fragments (Cheevaporn and Mekkongpai, 1996). Dried and ground samples were analyzed with traditional Pb-210 methods at the University of Washington. Assuming a constant flux of Pb-210 to the sediments, the Pb-210 excess activity found through alpha spectrometry was plotted against depth. Calculating the slope of a line-of-best-fit through these points yielded the accumulation rate for each core.

On board ship, grain size subsamples were wet-sieved through a 62.5 micron filter using a .05 sodium metaphosphate solution to separate sand particles ( $>62.5 \mu m$ ) from silts ( $<62.5 \mu m$  and  $>4 \mu m$ ) and clays ( $<4 \mu m$ ). The wet sand portion was placed in a pre-weighed aluminum tray and dried, then weighed to determine the sand fraction. The wet silt and clay portion were stored in the cold room for approximately a month until the ship

returned to the University of Washington, then sonicated in the Sediment Analysis Lab before being run through a Micromeritics 5120 Sedigraph (McIntyre and Eleftheriou, 2005). The mud fraction was then dried and the ratio of sand to mud was calculated from their respective weights. Grain size analysis shows the differences in grain size between sample locations both spatially and temporally (inferring age from the Pb-210 analysis). This data, in combination with the metrics of channel morphology and sediment accumulation rates, provides a thorough picture of how channel morphology effects sediment accumulation rate and grain size in submarine canyons on the shelf of the Baja peninsula.

## RESULTS

### *Channel Morphology*

Three distinct channels were defined within the final study area: a Western channel with a length of 23854m, an Eastern channel with a 32064m length, and a southern channel with a 17732m length. The southern channel analysis extent was significantly shorter than the other two due to limitations in the survey. The Western channel was shallowest, followed by the Eastern channel. Those two combined to form the southern channel, with this confluence point serving as the

endpoint of the Western and Eastern channels, and the starting point of the southern channel.

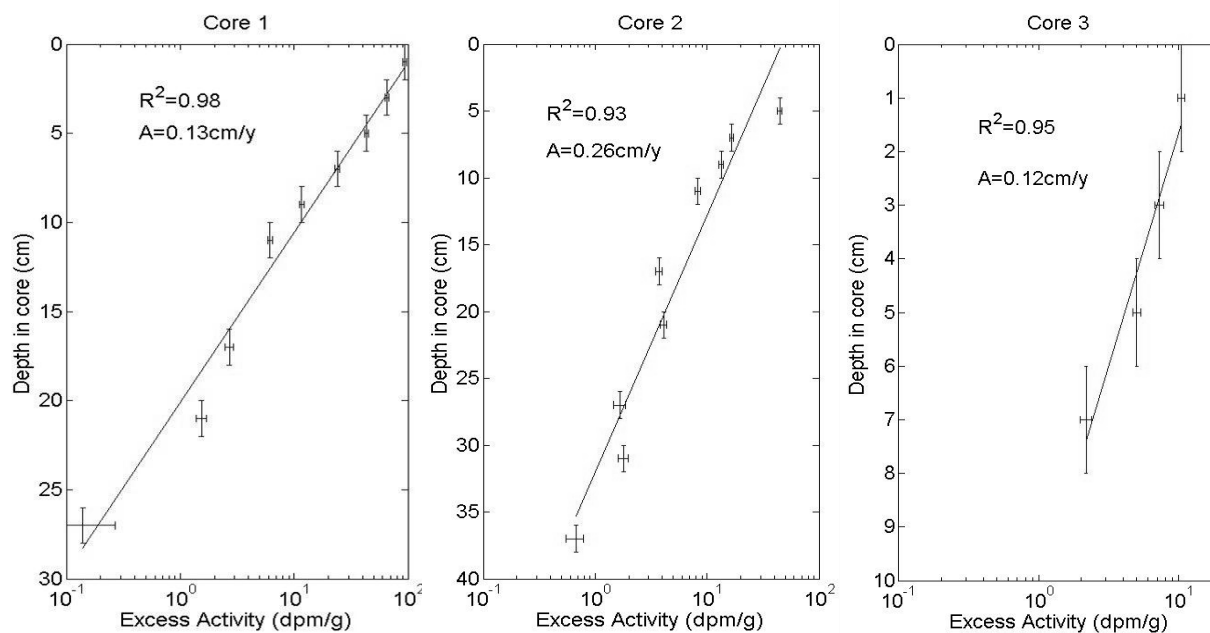
Sinuosity ratios are unit-less, and vary for each channel, with the Western channel's at .685, the Eastern's at .574 and the Southern's the largest at .708. To help explain the relationship between channels, it is important to mention that two of the three segment of the Western channel had sinuosity values of .83 and .84, the highest ratios seen in any of the channels.

Though all three channels were relatively glacia (gently sloped), the Western channel was the steepest, with a slope of  $-1.06^\circ$ , followed by the Southern channel at  $-.76^\circ$  and the Eastern channel at  $-.74^\circ$ . CSA varied greatly between channels, with the Eastern channel's by far the smallest at  $8073\text{m}^2$ . The Western and Southern channels were closer in value, with respective CSAs of  $25082$  and  $31555\text{m}^2$ .

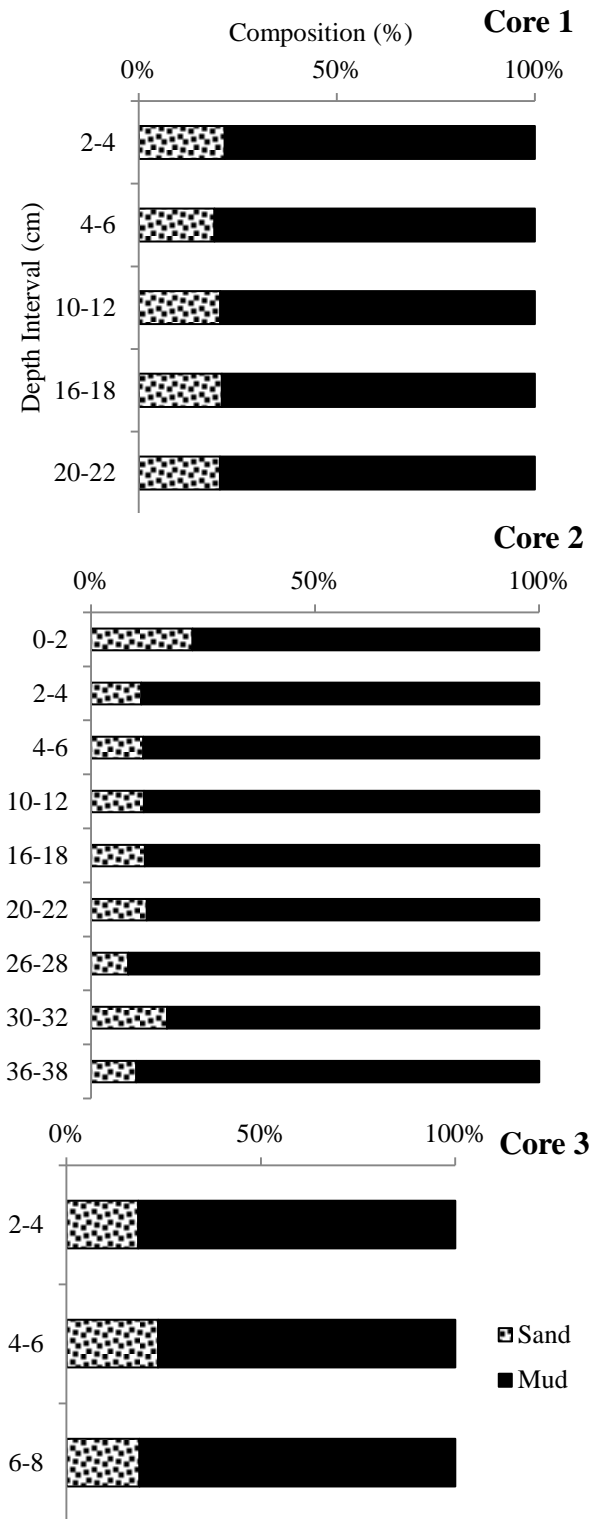
### *Sediment Characteristics*

Coring locations are visible in Fig. 1, with core 1 corresponding to the Southern channel, core 2 to the Western channel, and core 3 to the Eastern channel.

The Pb-210 analysis yielded statistically spectacular results, even for the shortest core (Fig. 3). None of the cores showed a distinct mixed layer, with best fit lines starting at the first depth interval (0-2cm)



**Fig. 3** Pb-210 results for each core. Slope of line of best fit (black line) is the accumulation rate. Vertical error bars indicate range of depth covered by sample (2cm slices).  $R^2$  values and accumulation rates (A) shown.



**Fig. 4** Sand to mud ratios for each core (separate panels) and each depth sampled.

and producing  $R^2$  values extremely close to 1. The first core returned the best  $R^2$  value, at .98, closely followed by the 3rd core, with .95. Though core 2

had the lowest  $R^2$  value, at .93, it also returned the highest accumulation rate: double that of the other two cores at .26cm/yr. Cores 1 and 3 showed similar accumulation rates of .13 and .12cm/yr, respectively.

Grain size analysis of the month-old mud fraction yielded unusual results. A typical grain size profile will show 25-5% of the mud sample finer than the Sedigraph can detect, resulting in an informative and widely distributed particle size curve. Instead, all three cores from this study produced grain size profiles with 85-90% of each sample smaller than  $1\mu\text{m}$ . As this means only a few particle sizes actually contained a portion of the sample, Sedigraph results were not informative enough to be included in the final analysis. Instead, the ratio of dried sand to mud in each sample interval was used as a broad indicator of grain size distribution both spatially (between cores) and temporally (between depths) (Fig. 4).

Due to initial core lengths, Core 2 had the most samples analyzed for grain size, and Core 3 the least. Over those analyzed, Core 2 showed the most variation in sand:mud ratio with depth, with more sand in the surface layer than anywhere else in the core. Core All three cores showed well-sorted behavior, with little variation between depth intervals. Thus it is safe to take an average of the ratios at each depth to determine the overall sand:mud value for each core. The Eastern and Southern channels yielded very similar results, with respective ratios of .254 and .259. The Western channel was muddier, with a ratio of .152.

## DISCUSSION

The variability within each characteristics evaluated in this study provides a good base for understanding the relationship between channel morphology and sediment deposition. Before venturing further in this discussion, it is important to understand some of the error sources in the data, namely in the grain size results. Samples run through the Sedigraph yielded very atypical results. The explanation for these particle distributions became clear when samples were placed in a  $60^\circ$  oven to dry. A white

Channel	Length (m)	Sinuosity	CSA (m <sup>2</sup> )
West	23854	0.685	25082
East	32064	0.574	8073
South	17732	0.708	31555

Slope (°)	Core	Accumulation Rate (cm/yr)	Sand:Mud
-1.06	2	0.26	0.152
-0.74	3	0.12	0.254
-0.76	1	0.13	0.259

**Table 1** Summary of channel metrics (first 5 columns) and core analyses (last 3 columns). Table wraps, with lower 4 rows corresponding to upper four.

substance began to precipitate from the samples, and grew to a volume larger than the mud itself. The substance turned out to be sulfide oxidizing bacteria (personal communication with Dr. John Baross, University of Washington), who appear to enjoy warm environments. The presence of biological material confused the Sedigraph and introduced some error into the mud weights of each sample, and thus the sand:mud ratios. However, as the bacteria were using the sediment as a source of their biomass, and as their distribution was relatively constant between all the samples, their existence should not change the overall ratios reported above. In future studies, however, samples should be frozen to below -20°C before any analysis is performed to prevent any biological processes from contaminating the sample and introducing error.

Most of the results for the marine channels studied correlate well with typical terrestrial channel behavior (with the exception of CSA's influence). Though the South channel has the highest average sinuosity, this is due to large-scale meanders in a wide channel with a high CSA. The West channel has the highest sinuosity for two thirds of its length, with values above .8. The sand:mud ratio for this channel is lower than the other two channels, indication that small-scale meanders in the channel are slowing the current and allowing the deposition of smaller particles, resulting in a higher fraction of mud in the sample. This is also consistent with the accumulation rate, as the slower current results in a higher accumulation rate in this channel than in either of the others. These results are validated in Pyles et

al.'s (2010) analysis of sedimentation flow processes in sinuous submarine channels.

The lower accumulation rates in the Eastern and Southern channels are indicative of wider, shallower channels (Covault 2011). Though the Eastern channel has the smallest CSA in the lowest part of the channel, it is the widest and shallowest of the three overall. As the Eastern channel is similar the Southern channel, with a slightly lower sinuosity, the CSA may not be a good representation of where channel flow occurs in a marine environment. Using the lowest step in the channel as an indicator of the present flow is typical of terrestrial systems, but may not be fully representative in marine systems, as the presence of water throughout the entire channel could reduce the force boundaries presented by channel steps. Also, the predominant bottom current in this region is the California Undercurrent, which flows along the coast of Baja in a North-West direction, so they would intersect the Eastern and Southern channels first (Spencer, 2012). This could contribute to the lower sediment accumulation rates in these channels, as particles could be re-suspended in the Undercurrent, transported and deposited farther to the northwest. This could also help explain the nearly double accumulation rate in the Western channel, as the increased sinuosity could account for some of the deposition, while a channel with a large cross-sectional area could disrupt the Undercurrent and result in a slow in large-scale flow that would contribute to particle loss from suspension. Nittrouer and Wright 's conclusions (1994) support this mechanism, as they found that most particulate transport along continental shelves occurs close the seabed, and is influenced by hydrodynamic forces from currents and surface gravity waves.

Another contributing factor to the differences in accumulation rate could be geographic location, as the Western channel has a more direct connection shore than the Eastern channel (apparent from portion of survey closer to shore). Thus the flow through the Western channel could still contain more sediment load in the study area than the Easter channel. Though indicated by accumulation rates, the sand:mud ratios do not support this conclusion, as larger particles should be deposited earlier on in the channel. Thus the expected sand:mud distribution

would show a higher sand fraction in the channel with a more direct connection to the terrestrial ecosystem (Wheatcroft and Butman 1997). This contradiction could be explained by the source of material to each channel. Though not covered by this study, the terrestrial channels that feed the marine channels of interest could meander through different terrain, incorporating different particle sizes in each channel. Future studies should include an analysis of direct terrestrial input as a means of mitigating this contradiction.

Slope values appear counterintuitive to terrestrial rational, as steeper slopes usually indicate faster flow and thus lower accumulation rates and higher sand:mud ratios. The results of this study reveal the inverse relationship. This is probably due to the fact that all three slopes are very shallow, and vary by only  $\sim 25^\circ$  between channels. Thus slope does not appear to be a control on sediment deposition in this channel system.

The goal of this study was to establish a relationship between channel morphology and sediment depositional characteristics. This relationship can be useful on many levels and throughout many disciplines. First, a thorough knowledge of this relationship will eliminate the need for extensive bottom samples in future studies: a time consuming, expensive, and often dangerous procedure. Instead, high-resolution multibeam and singlebeam data of the channel in question can be analyzed for the same metrics used in this study and sediment characteristics can be inferred from these results, with only a few bottom samples necessary for calibration. Second, the distinctions in behavior between terrestrial and marine channels indicated by the results can be applied to future studies where a thorough understanding of this relationship is paramount to designing a study. For example, the fact the small changes in slope do not appear to contribute to sediment distribution could be very useful in determine where to sample. Third, understanding deposition rates in marine channels will help to constrain models of many chemical and physical cycles, in addition to bettering our understanding of anthropogenic effects. These anthropogenic effects include how changes in channel morphology caused by human processes will affect the natural cycles, how anthropogenic

pollutants will be distributed within the continental shelf environment, and what fraction of those pollutants reach the deep sea through marine channels.

## CONCLUSIONS

Results of this study indicate that the relationship between marine channel morphology and sediment deposition is complex and many-faceted. Of the metrics analyzed in this study, only slope was found to have little contribution to deposition patterns. Sinuosity appears to be the most important morphological characteristic, as high sinuosities result in high accumulation rates and low sand:mud ratios. Cross-sectional area should not be calculated the same way for marine channels that is traditional in terrestrial channel analysis, as large-scale currents and overlying water blur the boundaries that channel steps provide to flow.

As relationship distinctions are hard to constrain in a system as complex as a marine channel network with only three constituents available for interpretation, future studies should incorporate more than one core in each channel. A higher spatial distribution of samples both in terms of the number of channels and the number of cores per channel will provide a larger range of metric and analysis values, which would help strengthen confidence in the relationships described in this study.

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