



Investigating changes in channel complexity across the coastal zone

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NONTECHNICAL SUMMARY

Submarine canyons are deep channels off the coast on the continental shelf. They allow matter to flow from land to the open ocean. The manner in which material flows through submarine canyons is dictated by characteristics of the terrestrial material, characteristics of the density of ocean water, the shape and network complexity of these channels. River channels on land control the timing, amount, and type of material that move through the submarine canyon systems. In the study area, at the last glacial maximum, when sea level was much lower, the submarine canyon and the river channels were a single channel network created by a combination of geologic structural and geomorphologic erosional processes. Now these systems are separated into two unique systems by a new shoreline, causing different material transportational processes in the submarine canyon channels from their original riverine channels. This study aims to identify changes in the shape of submarine canyons and river channels and determine whether structures created at the lowest sea level persist today, in light of processes occurring in both systems. By observing variations in spatial pattern metrics I was able to determine that similar types of processes are acting as the dominant force in control of the shape of channels in both the marine canyon system and the terrestrial riverine system.

ABSTRACT

Nearly half the world's population lives in a coastal watershed where all the anthropogenic input to the hydrologic network are transported downstream and onto the continental shelf. This connectivity then extends to the movement of terrestrial matter by submarine canyon channels. At the period of low stand during the last glacial maximum, a channel system was established by erosional processes in the coastal zone of Baja peninsula. Now, that single system has been split into a marine submarine canyon and terrestrial river channels with different morphological processes at work. Have these diverging processes altered the morphology of the original system? Do the two systems compare in terms of channel delineation and network complexity? I investigated the spatial patterns in channel morphology across a coastal zone on the Baja peninsula, and quantifying the similarity between river and submarine channel complexity through measurements of channel sinuosity, network slope gradient and order length. A negative linear relationship between sinuosity and slope gradient was observed in both systems, suggesting that the similar types of processes are acting as the dominant force in control of the spatial pattern.

From a systems perspective, the river of a coastal watershed provides the link for the transport of sediment, pollutants, and nutrients

from the terrestrial to marine ecosystems. Submarine canyon channels are the main transport mechanism from the shore, across the continental shelf, and to the ocean basins (Shepard, 1972). As

anthropogenic and natural forces alter coastal watersheds, riverine channels evolve and migrate. Associated submarine canyons undergo equally dynamic changes in channel morphology (Lin et al. 2002; Liu et al. 2004). Multiple studies, reviewing more than 20 coastal systems with broad spectrum of morphological river types, have established that terrestrial and submarine systems are linked (Clark et al. 1992; Popescuet al. 2004; Savoye et al. 2009).

The steep walled coastal watersheds of the Baja peninsula exhibit morphological characteristics that produce relatively rapid hydrological conductivity from the terrestrial to marine ecosystem. The rapid conductivity stemming from high magnitude rain fall events interspersed with long periods of drought. At the last glacial maximum when sea level was much lower in elevation, the terrestrial erosional processes of river building established the initial shape and pattern we currently see in submarine channel on the Baja continental shelf (Kuenen. 1953; Shepard. 1972; Lastras, et al. 2011). A rise of sea level split this single system into two parts: the terrestrial riverine system of high episodic flow and the marine canyon system of coastal dynamics. A quantitative connection across the coastal zone is likely more apparent in the Baja system than in contrasting systems that produce low peak flows and that have more even sediment deposition stream outflow over an annual or decadal cycle.

I investigated the changes in channel complexity across the coastal zone system of the tip of the Baja Peninsula. The study area is a complex network of channels of varying morphological characteristics. In order to effectively compare channels I utilized a quantitative characterization of channel connectivity, stream order, introduced by Arthur Strahler (Strahler. 1958), which provides a topological identity of channel order. Using Strahler stream order, structural variations in channels with similar topological position within the terrestrial and marine systems were compared. Then using data collected from the submarine canyon and terrestrial watershed, I derived channel sinuosity, slope gradient and order length of equal

order submarine canyon channels and river channels in the Baja system.

The research is focused on the structural elements of terrestrial watersheds and submarine canyons. The integrating element of those two systems is recognized to be the hydrologic channels (the rivers and submarine channels) that act as transport mechanisms through the coastal zone. This work investigates the structural complexity of these elements. The investigation addresses the research question: have the structural characteristics of channels, established during the low stand of sea level rise, persisted over time as the channel network transitioned to a coastal zone consisting of both a terrestrial river system and a marine canyon? Using spatial metrics I addressed four hypotheses: (1) as channel complexity as measured through the structural metric of sinuosity terrestrial systems will always be greater than marine systems, (2) order length in the terrestrial system is greater than order length in the marine system, (3) both the marine and terrestrial systems exhibit a similar relationship between slope gradient and channel order,

Evidence of intact submarine channel networks that are sustaining patterns established when terrestrial processes first initiated their connectivity suggest that the structural component of submarine channels control the processes of transport of material across the coastal zone and that physical alterations to either systems may disrupt that connectivity.

METHODS

Data acquisition

High-resolution bathymetric data (Fig. 1) were acquired of the seafloor submarine Canyon system off the East tip of the Baja Peninsula in March 2012 aboard the RV Thompson using the Kongsberg EM 302 multibeam sonar. The location was determined using existing bathymetry data from Smith and Sandwell (1997). The survey aimed at producing a 30 meter resolution gridded surface for comparison with a digital terrain model of the terrestrial watershed at the same resolution. The survey line swath overlap was set at approximately 35% and the beam angle to 65°.

The channel was surveyed at 7 knots. Real-time survey data was monitored using the Kongsberg SIS acquisition software to ensure that all required study-specific submarine channel features are being surveyed.

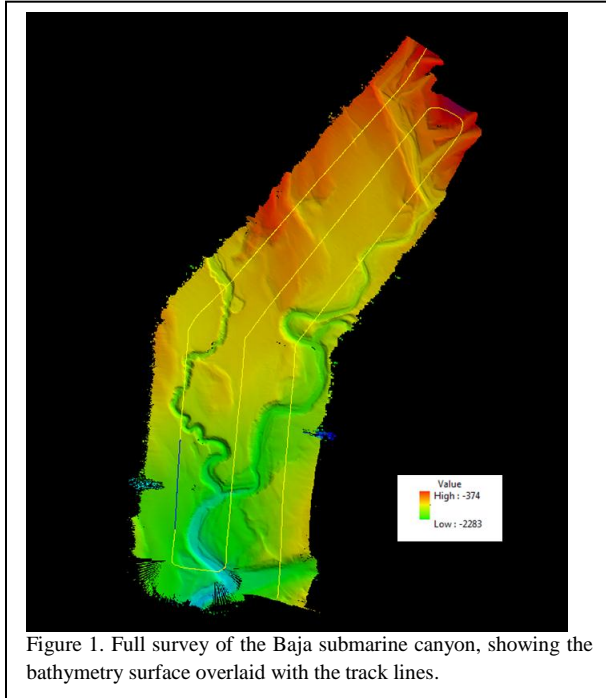


Figure 1. Full survey of the Baja submarine canyon, showing the bathymetry surface overlaid with the track lines.

A Digital Elevation Model (DEM) was derived from the Shuttle Radar Topography Mission (STRM) of the corresponding terrestrial watershed (Fig. 2). It contained a 30m resolution DEM.

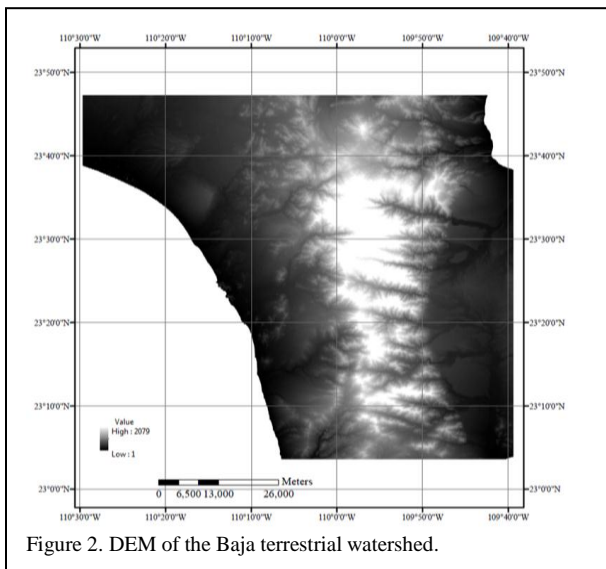


Figure 2. DEM of the Baja terrestrial watershed.

Track line post-processing

The bathymetric data was post-processed in the University of Washington School Oceanography Spatial Analysis Lab. Data was input into CARIS Hydrographic Information and Sonar Image Processing System (HIPS and SIPS) ver7.1. Tidal corrections were applied using tidal data from Cabo San Lucas. A Combined Uncertainty and Bathymetry Estimation (CUBE) surface of 30m resolution was created using the Density & Locale parameter as a disambiguation method. The surface was exported to ESRI ArcGIS ver.10 for analysis.

Spatial Pattern Analyses

Channel derivations

The terrestrial and marine river and channel networks were derived from the digital elevation of the Baja watershed and the bathymetric surface of the associated submarine channels. The hydrological modeling tool set available within the ESRI ArcGIS ver10.1 analysis software was used to produce hydrologically corrected surfaces for the calculation of accumulated flow. The flow accumulation values assigned to each modeled grid cell was then used to identify channel and river networks and individual network segments.

Channels with similar basin area were derived from the terrestrial DEM. Four channels resulted from a flow accumulation threshold between 1.9×10^4 and 2×10^4 cells (Fig. 3). No marine channels were able to be derived solely from the flow accumulation model because the survey data did not completely cover the total drainage area of the submarine channel system. Therefore any channels derived from this method alone would be incomplete.

In both the terrestrial and marine data sets a set of channel networks were derived for comparison purposes using order of connectivity and delineation of segments between confluence evident in the flow accumulation model. Each network contained a main stem, the largest

channel of the system into which all tributary channels ultimately flow. Three tributary channels were derived in each system. These channels directly flow into the main channels and are terminated at their tributaries (Fig. 4).

Structural metrics

To quantify similarity in pattern between the submarine canyon channels and river channels structural metrics of sinuosity, slope gradient, and channel order length were computed. Sinuosity is a measure of the deviation of a path between two points from the shortest possible (Mueller, 1968). This ratio will range in values from a low of 1 (the channel shape is a straight line) and increase without limit as the shape of the channel become more complex. Slope gradient refers to the angle which any part of the earth's surface makes relative to the horizontal datum (Schroeder, 1987). This simple rise over run calculation is expressed in degrees with a vertical step in the change of elevation reflected as a 90 degree slope. The length of a specific order channel feature was derived via averaging values of channel lengths for a specific order channel.

$$\text{Sinuosity is given by: } \frac{\text{Actual path length}}{\text{Straight line length}} \quad (1)$$

$$\text{Slope gradient given by: } \frac{\text{elevation change}}{\text{real distance}} * 100 \quad (2)$$

Sinuosity, slope gradient, and order length were measure on all derived channels. Slope gradient was measured on only network channels.

RESULTS

The four channel segments identified by modeling the flow accumulation between 1.9×10^4 to 2.0×10^4 cells have a range in a sinuosity of 0.2111, with a low of 1.1043 and a high of 1.3154; with a standard deviation of 0.0638 (Fig. 3).

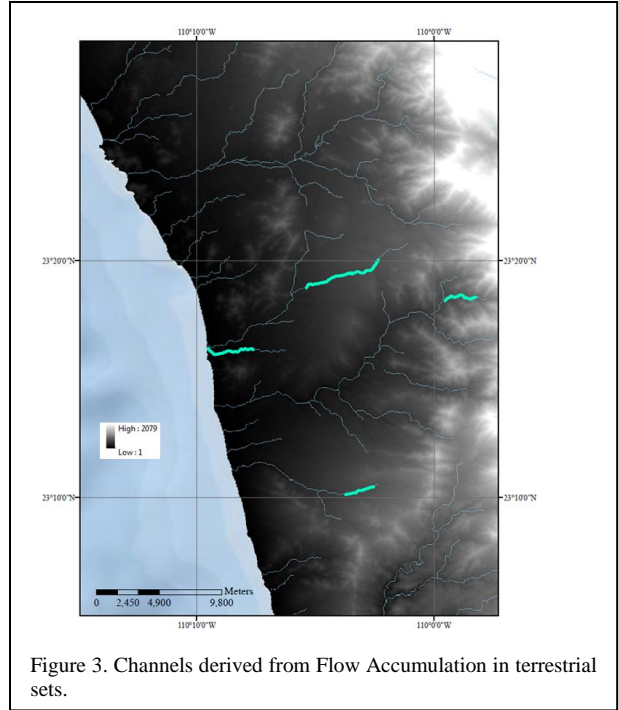


Figure 3. Channels derived from Flow Accumulation in terrestrial sets.

The range in sinuosity for channels of equal low accumulation was 0.2111 and the standard deviation was 0.0638. The slope gradient has a much larger range and standard deviation, 2.9782 and 0.4529 respectively (Table 1).

Channels derived from flow accumulation		
	Sinuosity	Slope Gradient
Channel 1	1.2624	1.4513
Channel 2	1.2183	2.9872
Channel 3	1.3154	4.4295
Channel 4	1.1043	4.1537

Table 1. Sinuosity and slope gradients derived from terrestrial channels, marked in blue on Figure 3.

Four channels in both the marine and terrestrial system were derived based on network connectivity and stream order (Fig. 4).

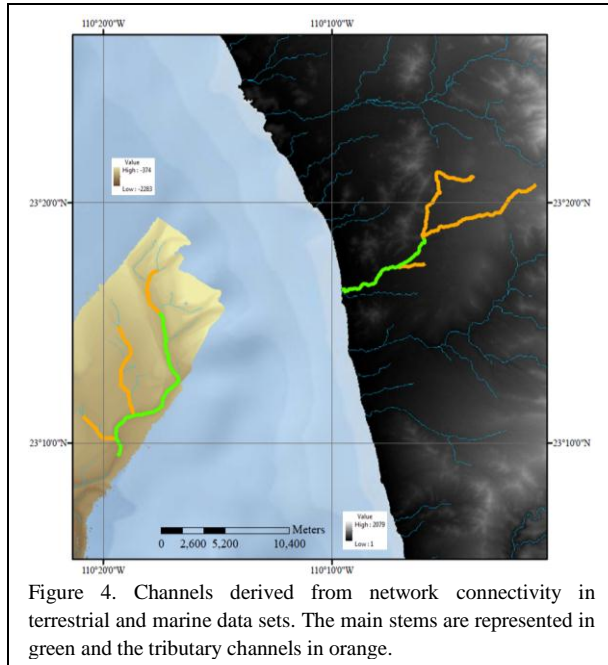


Figure 4. Channels derived from network connectivity in terrestrial and marine data sets. The main stems are represented in green and the tributary channels in orange.

main stem; while the average secondary channel sinuosity in both systems was nearly the same. The range in sinuosity values of terrestrial channels was 32% larger than the range of the marine (0.50 versus 0.32); indicating greater variation (Table 2).

In both systems the slope gradient of the main stem is lower than that of the secondary channels. Similar to sinuosity, the slope gradient of the terrestrial secondary channels was great than that of the marine channels, 21% greater. The average slope gradient of the marine was larger (Table 2).

The order length of the main stem in the marine system was significantly longer than in the terrestrial system, 1.7 times greater. The length of a terrestrial secondary order channel features were higher than the length of a marine secondary order channel features. The range of the terrestrial system secondary channels was 10963m versus a range of 4975m in the marine; the range is twice as large in the terrestrial system (Table 2).

Sinuosity, slope gradient, and order length were computed for all derived channels (Table 2).

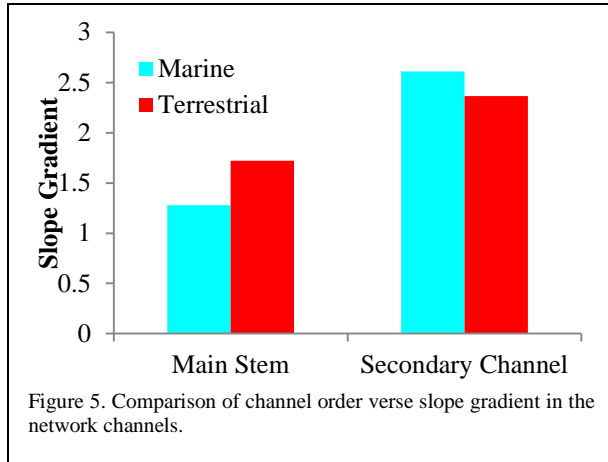
The computed sinuosity of the terrestrial main stem was significantly lower than the marine

Network Channels		Sinuosity	Slope Gradient	Order Length
Terrestrial	Main Stem	1.2913	1.7201	9359.7
	Channel A	1.1048	2.8289	2226.9
	Channel B	1.2007	2.7792	11190
	Channel C	1.6020	1.4875	9747.4
	Average	1.3025	2.3652	7221.4
Marine	Main Stem	1.4241	1.2774	16268
	Channel A	1.1451	3.1565	3398.4
	Channel B	1.2124	2.5799	8373.7
	Channel C	1.4802	2.0993	4669.9
	Average	1.2792	2.6119	5480.7

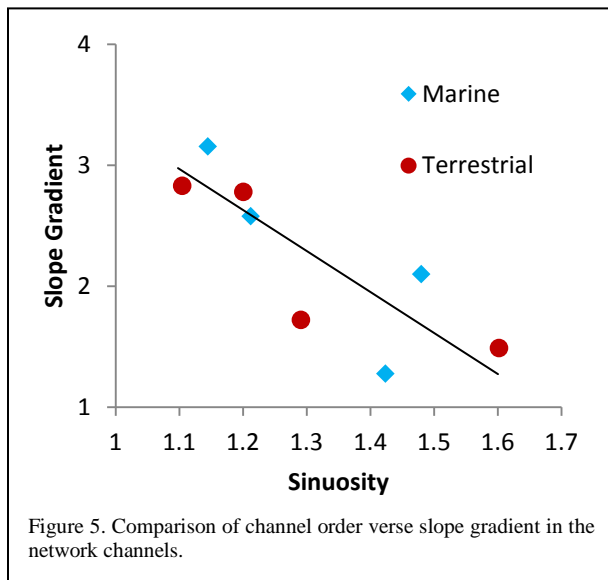
Table 2. Sinuosity and slope gradient of network connectivity channel segments of the terrestrial and marine systems.

In both systems the second order channels have the same relationship to the main stream, which is a higher order channel. These channels

have a high slope gradient than the main stem channels (Fig. 5).



In a comparison of sinuosity to slope gradient both the terrestrial and marine channels show a similar negatively linear relationship (Fig. 6). There is a clear trend, with increasing slope gradient there is decrease sinuosity, with a R2 value of 0.68.



DISCUSSION

Terrestrial river channels were not found have higher values of sinuosity then submarine channels of the same network order. The sinuosities of the terrestrial main stem were lower than that of the marine main stem and the sinuosities of the secondary channels were nearly equal. During the last glacial maximum, at low stand, these systems were not separate, but a single system which was created by erosional processes acting upon the underlying geology of the Baja Peninsula. At that time only terrestrial processes

were acting on the channels. During that time period, a single system of channels of the same order would possess the similar morphological characteristics. When the sea level rose to its current stand the network was split into separate marine and terrestrial systems. Illustrated in the network channel data (Table 2), the main stem channels have a sinuosity higher than the average secondary channels. Since the marine main stem was most likely a higher order, downstream continuation of the terrestrial channels, its higher sinuosity could be explained by the formation of the entire system. As some point in the past all of the water flowing through both systems ended up flowing through that main channel, causing a high sinuosity, which is still seen today. The secondary channels of both systems are very similar which indicates that erosional processes that created these channels have had very little effect on the morphology of the channels since their creation. Furthermore the similarity in sinuosity of the second order channels indicates that marine processes, such as biogenic sedimentation and currents (Kuenen. 1952; Liu et al. 2002), have had little effect on the morphology of the marine channels.

The terrestrial channel segments identified by a range in the modeled flow accumulation threshold illustrate that regardless of accumulated flow a measure of neither the sinuosity nor the slope gradient are similar; nor does appear to be a correlation between their sinuosities and slope gradients (Table 1). This suggests that similar flow accumulation is not an indicator of similar sinuosity or slope gradient, and that flow accumulation is a poor indicator of shape complexity. The morphology of a channel depends on its place in the network connectivity of the system not solely on the accumulated flow.

I found that order length in the marine system is greater than order length in the terrestrial (Table 2). In a comparison of the terrestrial and marine main stem network channels the marine channel is more than twice the length of its terrestrial counterpart. In the past, at low stand, when the two networks were just one network the marine main stem and the terrestrial main stem were most likely linked into a single long channel. The main stem of the marine system was a continuation of the terrestrial main stem. Now at

current sea level stand, the two systems are not a directly connected and the lengths of the marine and terrestrial main stems are a byproduct of the amount of sea level rise not a geological process.

The secondary network channels have the opposite relationship. The terrestrial secondary channels are longer than the marine secondary channels (Table 2). This is most likely a consequence of difference in environment. The processes that created the channels are no longer occurring in the marine environment. They have been separated from the episodic gravitational erosion and matter flow since the period of low stand, while these processes are still influencing the terrestrial channels (Leopold et al. 1957). The continual erosion of the terrestrial channels would increase the length of a terrestrial secondary order channel features causing them to have a higher length in comparison to the marine secondary order channels.

The marine and terrestrial systems exhibit similar relationships between slope gradient and channel order (Fig. 5). In both the marine and the terrestrial systems the slope gradient decreases with increasing channel order. This difference is greater in the marine system. In both systems the slope gradient of the secondary channels is higher than the slope gradient of the main stems. In typical watershed morphology, the lowest order channels will always have the highest slope gradient because they exist highest up in the watershed. As elevation increases the slope becomes steeper and the kinetic energy and carrying capacity of water flow becomes higher (Leopold et al. 1957; Shepard. 1972; Zhandaev. 1991). The lower order channels by definition exist at higher elevation because as water flows down slope the channels converge, creating channels of higher order. The most extreme of which is the main stem, which will have the lowest slope gradient. In both the marine and terrestrial systems this pattern can be seen. Not only because the channels were formed by the same processes but also because erosion and matter are still moving through both.

In channels derived based upon network connectivity sinuosity and slope gradient have a negative linear relationship. The steeper the path a channel takes the closer the sinuosity approaches

one, a straight line, therefore a relationship in which increasing sinuosity is paired with a decreasing slope gradient is expected.

In the past these systems were a single network. Both the marine and terrestrial data showed similar trends in comparisons of sinuosity verses slope gradient and slope gradient verse channel order. This would indicate that the systems were formed by the same processes. Comparison of sinuosity of the main stems showed evidence that the marine main stem was once a continuation of the terrestrial main stem. There is ample evidence that these systems were once a large system and that current processes have done very little to change their morphology since the last low stand. A connection in the past could mean this connection still exists between the two systems. If the systems are still connected then changes to the terrestrial channels would result in changes to the marine channels. For example, damming of a terrestrial channel could change the morphology of the marine channels by stopping the matter flow into that system. If the morphology of the marine channel is changed then the flow of matter through it would be changed as well. Therefore anthropogenic matter that normally would flow through the submarine canyon, off the continental into the open ocean would possibly not do so. A connection between the systems also would mean that monitoring the terrestrial system would be a proxy for monitoring the marine system. Changes across this zone would be traceable by evaluating a single part of the network.

Future work in the connectivity of terrestrial and submarine channels should insure that the complete drainage basin of the submarine channel network is surveyed. With a complete survey of the basin and channel a more accurate flow direction and flow accumulation model could be created. More accuracy in the flow model would lead to better channel derivations, better estimates of accumulated flow into each cell and better estimates total basin area. This in turn would lead to a better comparison against the terrestrial data set, which is complete. If it were possible it would be best to also map closer to the shoreline. The more information that can be gleaned about the connection between the mouth of the terrestrial river channel and the incision

point of the canyon the better. The magnitude of distance between the incision point and the mouth of the river would be an indication of the amount of time that has passed since the two systems were a single system. More information about the close to shore morphology would also be an asset in identification of which terrestrial system or systems were connected to the submarine canyon system.

CONCLUSIONS

In this study sinuosity, slope gradient, and order length of submarine canyon channels and terrestrial river channels were compared. The same negative linear relationship between sinuosity and slope gradient was found in both systems. Similarity between the metrics indicates that the two systems were once connected and that the current processes that are acting on them have not significantly changed their morphology. This suggests that quantifying the changes in channel complexity across the coastal zone will provide means to monitor anthropogenic impacts upon submarine canyons.

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