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Scaling response of a canyon-incised shelf break

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NONTECHNICAL SUMMARY

The continental shelf break is a global, large-scale geologic structure which separates continents from the deep sea. Along the shelf break many finer-scale features can be recognized, such as canyons and slope faces. As depth measurements are represented more frequently in space (finer resolution), and as the area of observation becomes smaller (smaller extent), even finer-scaled features of the seafloor are exposed. At the finest scales of observation, small universal variations such as fine ridges and valleys create a rough seafloor that is indistinguishable from seafloor elsewhere in the ocean. Using multibeam sonar data of the continental shelf break off the southwest coast of Baja, Mexico, I compared seafloor roughness between a canyon and slope face at different resolutions and distances from the line which separates the shelf and slope. Regions above the canyon and slope face were found to be very similar at all resolutions, while roughness within the canyon varied from that of the slope face. The inherent difference between the canyon and slope face was best observed at a 20-40 meter resolution at distances greater than 250 meters. As well as giving insight into structures which define the shelf break, results of this study can act as a guide for designing future studies on the continental shelf break.

ABSTRACT

The continental shelf break is a large-scale tectonic structure, but features occur along it at all scales. Which of these features are apparent depends on the representation of the depth data. Large-scale features such as canyons and incisions in the shelf break are seen at coarse resolutions over large extents. Smaller features such as ridges and valleys can either be widespread or unique to a region, but can only be seen using fine data resolutions. This study compares the scaling of features on a canyon-incised continental shelf break off the southwest coast of Baja, Mexico, using Kongsberg EM302 multibeam data represented at multiple resolutions. Analysis of the surface roughness over increasing distances from the line of separation between the shelf and break was conducted using ESRI ArcGIS ver. 10. The shelf and slope varied in their responses to scaling, emphasizing the inherent difference between the two regions. Zones adjacent along the break had similar responses on the shelf, but opposing responses on the slope. This opposing response at intermediate resolutions (20-40 meters) shows a fundamental difference between the canyon and the slope face. This difference should be taken into account when designing future studies investigating the geological dynamics of the continental shelf break.

The continental shelf break, which incorporates the edge of the shelf and top of the continental slope, designates the boundary between inshore waters and the deep ocean. It is the result of large-scale tectonic forces surrounding each continent, although its shape, depth and distance from shore vary (Vanney and Stanley 1983). As a prominent bathymetric feature, its morphology both affects and responds to ocean circulation patterns, sediment transport, and coastal up- and down-welling patterns (Allen 2004). These processes and their structural changes along the continental shelf break are important linkages in coastal nutrient cycling and marine ecology (Noda and Tuzino 2007; May et al. 1983; Young et al. 2001).

The Magdalena Escarpment is a section of the continental margin off the southwest coast of the Baja Peninsula, Mexico (Fig. 1). The margin between the Pacific Ocean and North America in the Baja Region was once an active convergent boundary, but has since become fused. The predominant tectonic influence in the region is from the Tosco-Abreojos Fault System (TAFS), a strike-slip fault which runs inshore of the shelf break (Michaud et al. 2007). Despite this nearby tectonic force, the Magdalena Escarpment exhibits the characteristics of a typical shelf break (Vanney and Stanley 1983). Large-scale canyon incisions in the shelf break are typically attributed to mass-wasting events or slope failures (Lastras et al. 2011; Noormets et al. 2009; May et al. 1983; Puga-Bernabéu et al. 2011) and act to funnel both depositional and erosional processes. Throughout the entire region, fine-scale ridges, slopes and depressions may or may not be related to the canyon-building process. The shelf break, canyon incisions, and numerous fine-scale ridges and depressions on the seafloor combine at multiple spatial scales to create a rough and complex bathymetric surface.

The surface roughness of the seafloor is a physical expression of the processes which form repeated or continuous patterns in bathymetric features. The pattern of these features may be observed at multiple scales, yet as the scale of observation changes new feature and new processes are exposed. Because the seafloor is not directly observable other than through the use of remotely sensed data (i.e. sonar-derived bathymetric soundings or images from submarine or remotely operated vehicles), remote sensing and spatial analysis are preferred methods for analyzing large regions of the seafloor. This remotely sensed data must be represented at a scale to emphasize the desired features. At fine resolution (high frequency of data points) and over very small spatial extents (where observations and analyses are restricted to local windows of data), fine scale features appear to dominate the seafloor. However, when relying on coarse resolution data over large spatial extents, large-scale features dominate our understanding of the morphology of the seafloor. Because data representation fundamentally changes the interpretation of the surface features, determining the optimal resolution at which to sample the data and the extent over which analyses should be made is a critical step in studying geomorphological processes.

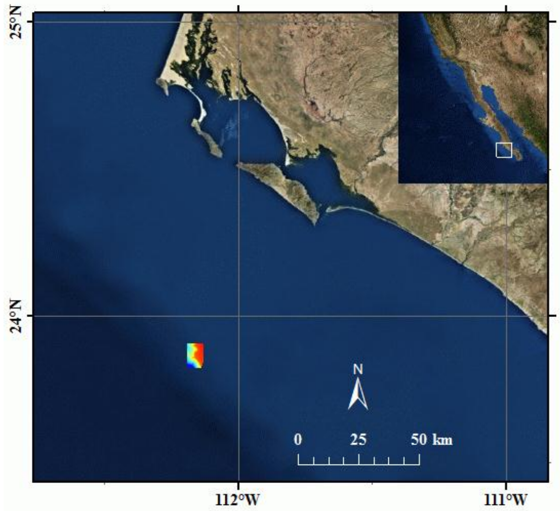

Figure 1. Map of the Magdalena Escarpment and the survey site off the southwest coast of the Baja Peninsula.

This study investigates variation in the scaling response of seafloor roughness associated with multiple scaled features found along the Magdalena Escarpment. Values of surface roughness for the shelf and slope surrounding incised and non-incised features (hereafter referred to as a canyon and face, respectively) are compared across multiple resolutions and extents of bathymetric data. Three specific hypotheses regarding seafloor roughness across multiple spatial scales in the shelf-slope region are tested: (1) the continental shelf break is visible as a continuous line of inflection at all scales; (2) seafloor roughness depends upon the scale of observation; and (3) adjacent zones along the continental shelf slope break exhibit uniform variation in surface structure across all spatial scales.

METHODS

Data acquisition

A bathymetric survey of the Magdalena Escarpment (Fig. 2) was conducted on March 21, 2012, using a Kongsberg EM302 multibeam echosounder and Seafloor Information System (SIS) acquisition software onboard the *R/V Thomas G. Thompson*. The survey was conducted at a speed of 5.0 – 6.2 knots and included 9 lines and 2 crossing calibration lines. One sound velocity profile (SVP) was applied at the beginning, with an expendable bathythermograph (XBT) SVP applied after 4 hours. The beam angle was set to 65° except where an unexpected data gap required a greater coverage, at which point the angle was changed to 75°. The track lines were imported to CARIS Hydrographic Information and Sonar Image Processing Systems (HIPS/SIPS) for post-processing. A tidal correction was applied based upon data from Puerto San Carlos, the nearest port. The corrected bathymetric data was cropped to the study region and cleaned visually for outliers – extreme high or low soundings – and aberrant soundings along NADIR. Cleaning was aimed towards removing obviously abnormal soundings while retaining the natural variation in the data. Bathymetry with Associated Statistical Error (BASE) surfaces were created at 19 resolutions between 5 and 50m, at intervals of 2-3 meters.

Defining the analysis regions

Within the shelf-slope region, the shelf break is defined as the point of maximum inflection in the slope of the seafloor, or the greatest change in the local gradient of slope. An inflection index was created based upon the absolute difference in maximum slope between opposing directions in the gridded BASE surfaces. The sum of all slope differences resulted in points of high and low inflection. In this way, the shelf break is represented as a continuous line of maximum inflection (LMI). The LMI was manually digitized from the 25m resolution BASE surface, which provided the most constrained but continuous expression of maximum inflection (Figure 3).

Four spatial regions form the basis for comparison of structural variation across multiple spatial scales: the canyon shelf, canyon slope, face shelf and face slope. The canyon and face are recognizable features along the shelf break that are visually evident in the bathymetric data and the shape of the LMI. The limits of the canyon and face were projected downslope from the LMI along ridges visible in the bathymetric data to form the boundaries of the slope regions. The continuation of these lines upslope from the LMI formed the limits for the shelf regions. Analysis zones that extended 100, 250, 500, 750 and 1000 meters from the LMI were created in all regions, with additional extents of 1250 and 1500 meters along the slope of both the canyon and face (Figure 3).

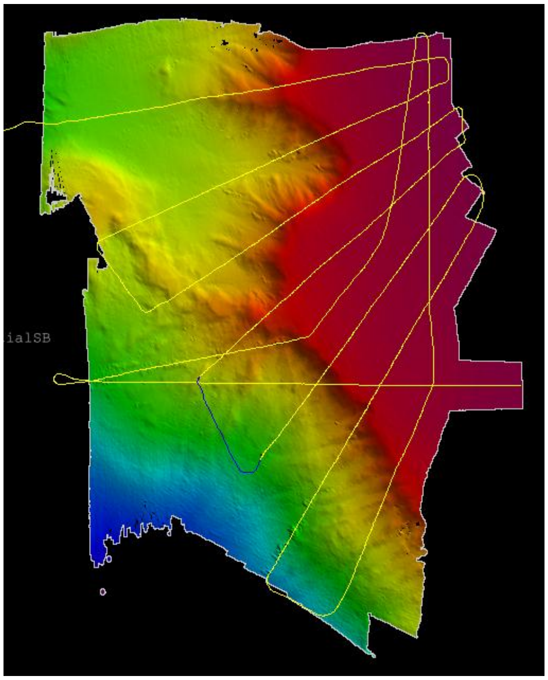

Figure 2. The full bathymetric survey of the Magdalena Escarpment at 15 meter resolution, showing track lines and uncleaned bathymetry. Line 1 starts at top left (NW corner). Turns, line ends and the final east-west transect were not used in the analysis.

Sinuosity and Roughness

The spatial pattern metrics, sinuosity and surface roughness, were derived to compare the complexity of features forming the shelf-slope break and the Line of Maximum Inflection (LMI).

The sinuosity of the entire LMI and its respective regions (canyon and face) is defined as a ratio between the actual length and the straight-path length of the line. A straight line will have a sinuosity of 1; any curvature of the feature will result in a greater value of sinuosity. The roughness of a region of the seafloor is characterized through the 3-dimensional (modeled) surface area and the 2-dimensional Euclidean (planar) area of the polygon which defines its boundaries. The percent difference in surface area between the surface and its bounding polygon can be used as a metric of surface roughness. Surface area and roughness measurements were made in all four regions, at all 19 resolutions, and across all extents (5 for the shelves, 7 for the slopes).

RESULTS

Line of Maximum Inflection (LMI)

Below 10 m resolution, the inflection method did not result in a clear bounding line, but for resolutions >15m a clear LMI appeared between the shelf and slope (Fig. 3). The location of the LMI did not vary greatly over the various resolutions, though it was more solidly visible at greater resolutions. The sinuosity of the LMI and its respective segments corresponds well with the visual separation of the analysis regions; the canyon had the greatest sinuosity (1.84) and the face had the least (1.08), while the entire LMI had an intermediate sinuosity (1.56; Table 1).

Table 1. Lengths and straight-path lengths of regions of the line of maximum inflection (LMI). Sinuosity is derived by the ratio (actual length / straight length)

Region	Actual length	Straight length	Sinuosity
LMI	14618.8	9357.49	1.56
LMI canyon	4344.43	2359.11	1.84
LMI face	3579.54	3318.75	1.08

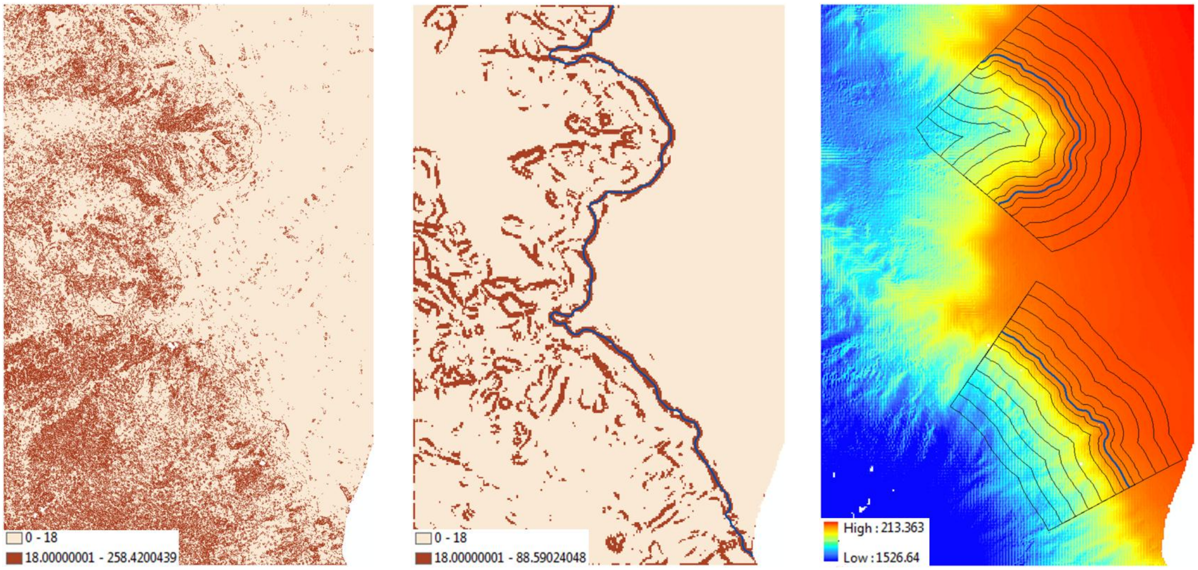

Figure 3. Index of the line of maximum inflection (LMI) at 5m (left) and 25 m (center) resolutions, derived using the sum of the absolute difference in slope of opposite compass directions. Cream = low inflection; red = high inflection. Units are combined degrees of rise. The manually-digitized LMI is shown as a blue line (center). Analysis regions are superimposed on depth (m) at right. Each region extends from the LMI to its maximum distance (100, 250, 500, 750 and 1000 m for slopes and shelves, plus 1250 and 1500 m on the slopes).

Roughness

The slopes and shelves exhibited different scaling responses in roughness. The slopes had a greater surface roughness than the shelves, in both regions of study. The shelf typically exhibited a roughness of 0.5-4.5 % increase in area, whereas the slopes both had an increase of 3-10%. The overlap in roughness occurred at low distances from the LMI (100m extent). The roughness of the shelves decreased exponentially from the LMI (R^2 from 0.91-0.98). The slopes increased in roughness from the LMI to a distance of 250-500m before decreasing in a similar fashion for most data resolutions (Fig 4.)

Surface roughness is variable at low extents (100 & 250 m from the LMI) across all resolutions in all analysis regions. At extents above 500m the variation with resolution decreases, and the pattern of roughness by resolution in each region remains relatively constant. Between the slopes, the face has a greater roughness except at 25 m resolution, when the incision slope has a large peak in roughness and the face slope has a corresponding low (Fig 5). The shelves have very similar roughness up to a resolution of 20 m, but between 20 and 30 m their relative values fluctuate greatly. From 30 – 40 m the separation of roughness between the slopes remains large, whereas the shelves exhibit similar roughness. At resolutions larger than 42m, roughness again becomes similar for the two slopes and two shelves.

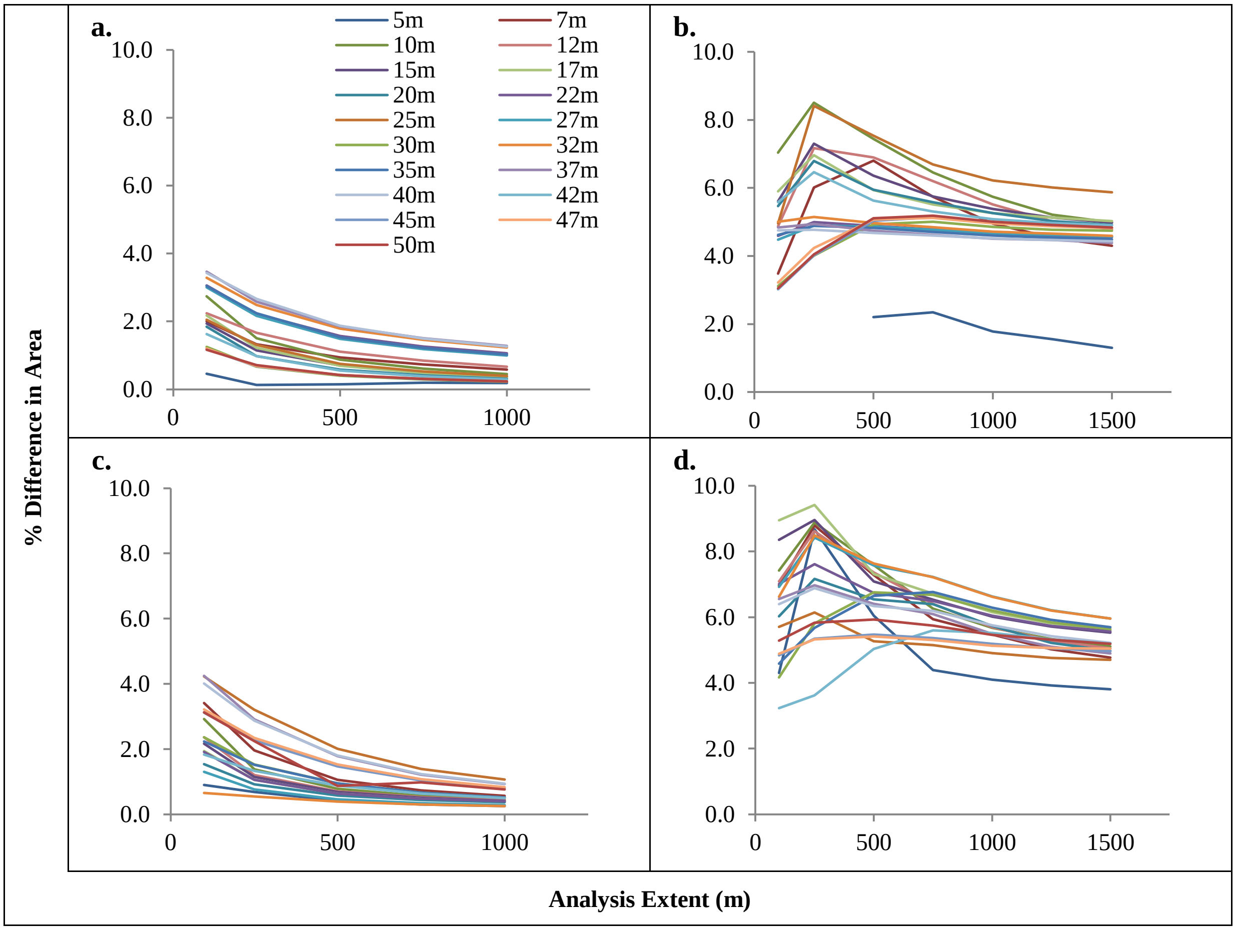

Figure 4. Roughness as measured by the percent difference in area between the surface and planar analysis extent in the four analysis regions: a) canyon shelf; b) canyon slope; c) face shelf; and d) face slope. Note the difference in horizontal axes; the slopes contain additional extents of 1250 and 1500 m. The difference in response between shelves and slopes can be seen in (b) and (d) as the increase in roughness from 100-500 m.

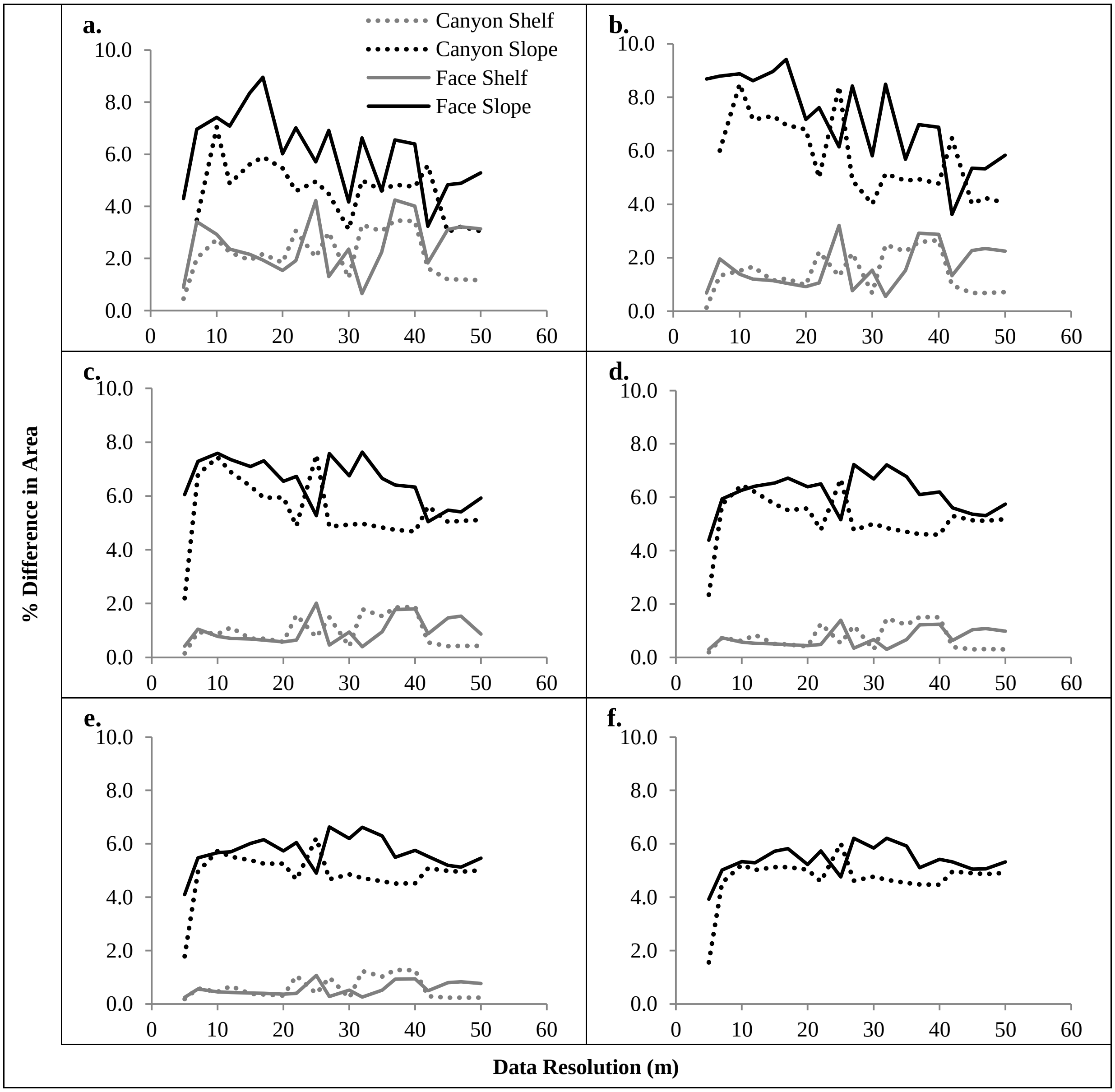

Figure 5. Roughness as derived by the percent difference in area between the surface and the bounding polygon, for extents of a) 100 b) 250; c) 500; d) 750; e) 1000; and f) 1250 meters. 1500 m extent is not shown, as it does not differ greatly from the 1250 m. The shelf regions are not distinguishable in their scaling responses, whereas the slopes have opposing responses between resolutions of 20 and 40 meters.

DISCUSSION

Line of Maximum Inflection (LMI)

Defining the location of the interface between shelf and slope is a key aspect of interpreting the scaling response of the seafloor surrounding the break. Many conceptualize the shelf-slope break as a sudden increase in slope at some distance away from shore. Often a common depth contour is referenced as the line of break where continental shelf processes transition to continental slope processes, but the depth contour varies with region (Emery 1981). Each of these approaches fails to account for the multi-scale response of the seafloor itself. Instead, I derived a line of maximum inflection (LMI), which incorporates the frequency and magnitude of change in the bathymetry at multiple scales in order to represent the multi-scaled boundary between the shelf and slope.

Along the Magdalena Escarpment, the LMI existed at resolutions coarser than 10 m as a semi-continuous line which became more contiguous with coarser resolutions, but at finer resolutions there was no clear line of inflection. While the variation in inflection was greater on the slope than on the shelf (figure 3), there was no clear delineation between the two regions. This suggests that the dominant process which forms the large-scale shelf break – which we understand to be tectonics – acts over scales greater than 10 meters. Indeed, the dominant scale for tectonics is likely greater even than the coarsest scale investigated in this study. Below a 10m resolution, widespread fine-scale processes such as hemi-pelagic or pelagic sedimentation, benthic turbation and bottom sediment resuspension (Hargrave 1985) produce similar smoothed surfaces. At mid scales these fine-scale surfaces are lost to larger features, and geological processes such as landslides, slope failure and other mass wasting define the shelf break.

Canyon and face

As expected, the LMI differentiates the shape complexities of a canyon and slope face along the shelf break. The sinuosity in the LMI at the canyon is greater than that at the slope face. Thus, the shape of the LMI is determined by the features surrounding it. Processes which create sinuosity along the LMI, such as slope failures and canyons, tend to be self-sustaining due to their concentration of across-shelf currents and eddies (Allen 2004). Faces, on the other hand, tend to remain linear due to a lack of foci to concentrate erosional processes. This is not to say that they remain so indefinitely. Canyons, like other geomorphic and sedimentary structures, are dynamic and their formation processes can be accelerated, maintained or aborted depending on the depositional and erosional characteristics of the region (Farre et al. 1983). The change in seafloor structure over time is indicative of temporal scaling, which is a similar topic to spatial scaling. In this study, however, the canyon is taken to be a constant, non-transient feature.

Zones adjacent to each other along the LMI are more similar than those zones which are adjacent across the LMI. The shelves both have an exponential decrease in roughness from the LMI, whereas the slopes increase in roughness near the LMI and then decrease with greater distance (figure 3). The high roughness which surrounds the LMI on both sides – although the slope regions peak farther away – is indicative of the boundary nature of the shelf break. The inflection represents the interface of processes which commonly affect only the shelf or slope – such as boundary current sedimentation or wave-bottom interactions (Karl et al. 1983). Therefore, it is unsurprising that there is greater similarity between adjacent zones along the shelf break then across the shelf break. The magnitude of the difference between the shelf and slope cannot be quantified as I have derived it; the absolute values of roughness are not slope-normalized, which means that the slope regions will have an inherently larger value. Despite this lack of a quantitative difference, however, I maintain a qualitative observation that the scaling responses of regions on the shelf are different from those on the slope.

While the two shelf regions have similar responses, the two slope regions have differing responses to changes in resolution. Near-linear responses occur in both slope regions at resolutions from 7-20m, but at coarser resolutions the roughness varies greatly. While the slope face has a low roughness at 25 m surrounded by high roughness values at coarser and finer resolutions, the canyon slope has a corresponding high value surrounded by low roughness. As with the shelf and slope, the magnitude of these differences cannot be quantified. The defining points in the graph at 500m extent, however, represent a 36% and 35% deviation in roughness from the general trend of the canyon and face, respectively. As each of these points can be taken as significant in the trend of their respective responses, and as they are opposite in relative magnitude, they can be considered unique responses. Given the difference in large-scale morphology between the canyon and the face, represented by the change in sinuosity along the LMI, differences in scaling response can be interpreted as differences in processes which create and maintain these coarser-scale features.

This suggests that a process, or more likely a suite of processes, are occurring within the canyon but do not interact with the face, or vice versa. This inherent difference between the canyon and slope is best seen at resolutions between 20 and 40 meters.

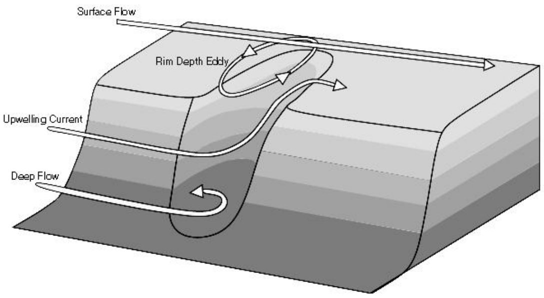

Figure 6. Currents along the continental shelf break interact with canyon features, upwelling onto the shelf and forming eddies at the canyon rim. Source: Allen 2004.

The shelf pattern of roughness decreasing with distance from the LMI is indicative of a process which acts strongest on the shelf-slope interface but disperses with distance from the inflection point. In connection with the differences between the four regions, this suggests that interaction between the process and the LMI defines the large-scale feature of the canyon or face, and its effect decreases upslope. A similar trend is seen at the face slope, although its decrease is not as great as on the shelves. This agrees with a study by May et al. (1983), which found that erosional and depositional processes along the shelf break are focused at the heads of canyons and where the change in seafloor gradient is greatest. The canyon on the Magdalena Escarpment, however, exhibits a constant roughness down-slope over the extent of the study region at the indicated resolutions (22-40m, not shown). This pattern suggests either that the incision-building process acts over the entire incision region, not just at the head of it, or that its effects extend much farther from the LMI than those of the face-building process. Large shelf-break canyons have been shown to create circular current flows within their rim (Allen 2004), which would have the effect of stabilizing a canyon by acting over its whole (figure 6). In the absence of a directed input at the head of the canyon such as a fluvial channel, it is possible that the canyon in this study is maintained by up- and down-welling currents and their associated eddies.

This study was designed to determine the spatial scaling response of features within the shelf break region, in an effort to better assist in the study of those features and the processes that form them. The findings of this research have implications for research in shelf-break canyons, shelf-slope interaction, and bathymetric survey planning and data acquisition. Further work on this region could be to normalize the roughness values for the respective gradient of the regions in order to facilitate direct comparisons between the shelves and slopes, or conduct point-rugosity (roughness) measurements which will indicate how the seafloor variation changes throughout the regions. Studying the possible effect of the Tosco-Abreojos Fault System or correlating the findings to sedimentation patterns will help characterize this site for comparison with other shelf break segments. Additional research directions within this field include investigating the global or regional variability of these findings, cross-examining these results with systems that differ in upwelling or down-welling regimes, alongshore transport, sedimentation rate or the tectonic activity of the continental boundary.

CONCLUSIONS

Understanding the scaling response of different features along the continental shelf break is essential for studying the geomorphology of the region. Representation of data affects our interpretation of it, and changing resolution and extent of observation allows new features to become apparent. At fine scales (resolution <10 m), the magnitude of fine-scale variation within the shelf break masks the presence of a coarse-scale line of maximum inflection (LMI) which is apparent in coarser resolutions. This LMI acts as a boundary between the shelf and slope, resulting in different scaling responses in the two regions. These two regions can then be further split into four separate zones by the coarse-scale canyon feature on the shelf break and its adjacent linear face.

Adjacent zones along the continental shelf have similar responses to scaling, indicating that the same processes act over them regardless of their location along the shelf break or their position in relation to canyon features. The canyon slope and the linear face slope have opposing responses of roughness at resolutions between 20 and 40 meters, which define the scale of inherent difference between the two regions. Results of this study have implications for studying processes along the shelf break, including the formation and continuation of canyon incisions, as well as bathymetric surveys and analyses of seafloor features.

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