# Physiographic Classification of the Ocean Floor: A Multi-Scale Geomorphometric Approach

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## 1. Introduction

Physiography, in this paper, is the study and classification of the surface features of Earth. In the oceanic domain, the Physiographic Diagram of the North Atlantic by Heezen *et al*. (1959) forged our knowledge of the actual form of the ocean basins. Since then, much has been published about the morphology of continental margins, the geology of oceanic trenches and the continuity of the mid-oceanic ridge. In most of these studies, however, the pioneer work of Bruce Heezen and his colleagues proved to be precise, despite being grounded upon sparsely collected data and a lot of "scientific imagination".

Presently, the increasing availability of high-resolution and/or globally distributed Digital Elevation Models (DEMs), together with innumerous improvements in geomorphometry – the quantitative analysis of topography – stimulates objective classifications of the physiography of landscapes. In particular, the Smith and Sandwell (1997) global digital bathymetric database represents an invaluable contribution to ocean floor mapping. However, while classifications of topography of continental landscapes (Dikau *et al*. 1991, Brabyn 1997, Iwahashi and Pike 2007), or even of planetary landscapes (Miliaresis and Kokkas 2003, Stepinski and Bagaria 2009) are becoming common subjects of geomorphometry, submarine environments are rarely investigated through quantitative geomorphological techniques (Micallef *et al.* 2007), especially at physiographic scales. Also, the basic problem in geomorphometry – the fact that all measures vary with the scale of analysis (Evans 1972) - is seldom considered in submarine mapping efforts.

Therefore, the intention of this paper is to develop and test a geomorphometric classification procedure to be applied to the global Smith and Sandwell (1997) database. The geometric signature concept - "*a set of measures that describes the topographic form well enough to distinguish among topographically disparate landscapes*" (Pike 1988) - will be used to describe the ocean floor in a multi-scale approach and to classify topography in distinct physiographic domains. The main idea is to evaluate if there can be a "recipe" for the automated identification of physiographic provinces and how such classification correlates with the established knowledge.

## 2. Methodology

### 2.1 Study Areas

A test-DEM (Fig.1A) corresponding to a broad portion of the Northwest Atlantic Ocean (centred at 35°28'35.6"N and 122°3'9.2"E) was extracted from the Smith and

Sandwell (1997) database (2 arc minutes spatial resolution) and re-interpolated to a grid spacing of 3,700 meters in Mercator projection. This area was chosen for its wide range of physiographic features in diverse geological settings, representing an appropriate sample of the world's ocean floor. In a second phase, the methodology was applied to a much more extensive DEM, encompassing the entire ocean floor between the parallels 50° S and 50° N (Fig.1B).

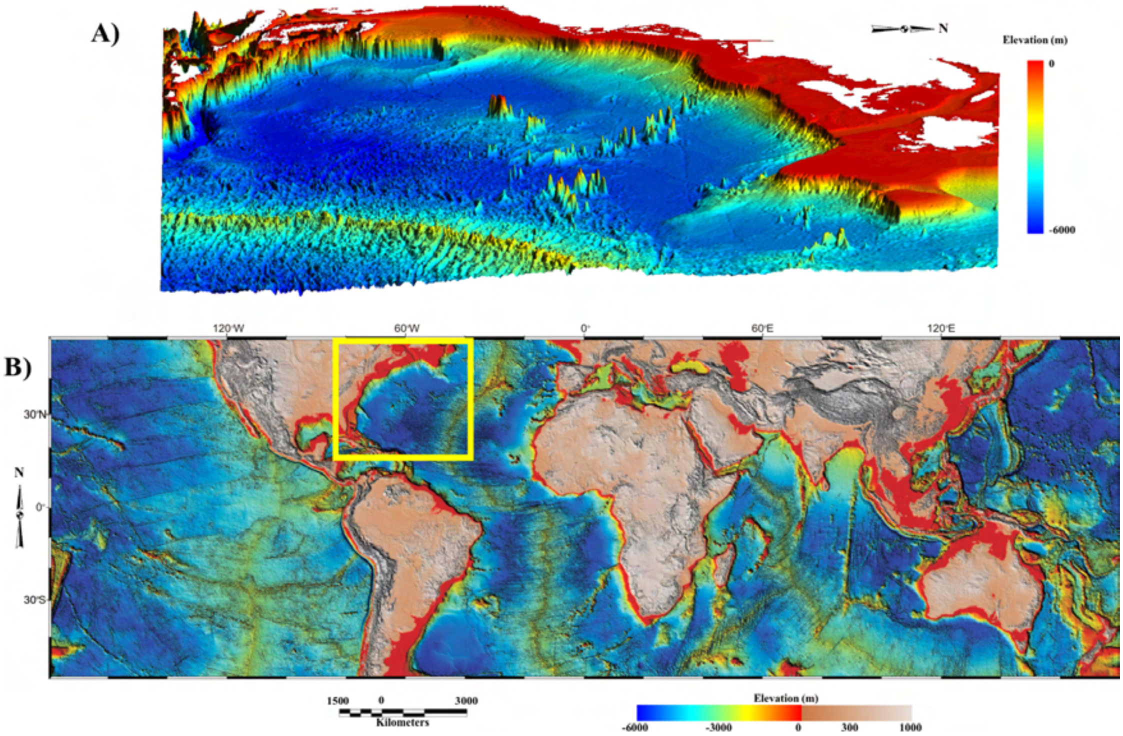


Figure 1. Oblique view of the test-DEM (A) and map of global DEM used in the application of the methodology (B - yellow box locates the test-DEM).

### 2.2 The Geometric Signature

In order to define appropriate variables, the *Landserf* software (©Wood, 1996–2008, http://www.soi.city.ac.uk/~jwo/landserf/landserf230/) was used for multi-scale surface parameterisation and feature extraction of the test-DEM. *Landserf* uses least squares regression to fit a quadratic surface through any arbitrary set of points, allowing surface measures to be taken for the same location over a range of spatial extents (Wood 1996).

In this way, the scale dependency of five terrain parameters (elevation, gradient, aspect, profile and plan curvature), as well as six surface features (pits, peaks, channels, ridges, passes and planes) were analysed by interactive probing through *Landserf*. A maximum spatial extent of analysis of 33x33 grid cells was considered to incorporate the majority of scale variations and, thus, used for the calculation of multi-scale variables.

These new variables summarized the behaviour of scale for each point on the surface by either (i) the mean of the surface characteristic over multiple scales to represent its central tendency or (ii) the standard deviation to represent its dispersion (Wood 1996).

This multi-scale approach yielded a three-part geometric signature (Fig.2A) – *multi-scale gradient* (mean of gradient), *roughness* (standard deviation of feature classification, *i.e.*, the scaled *entropy*) and *organization* (standard deviation of aspect) - as well as two auxiliary variables (Fig.2B) – *elevation* (scale independent) and *multi-scale profile curvature* (mean of profile curvature).

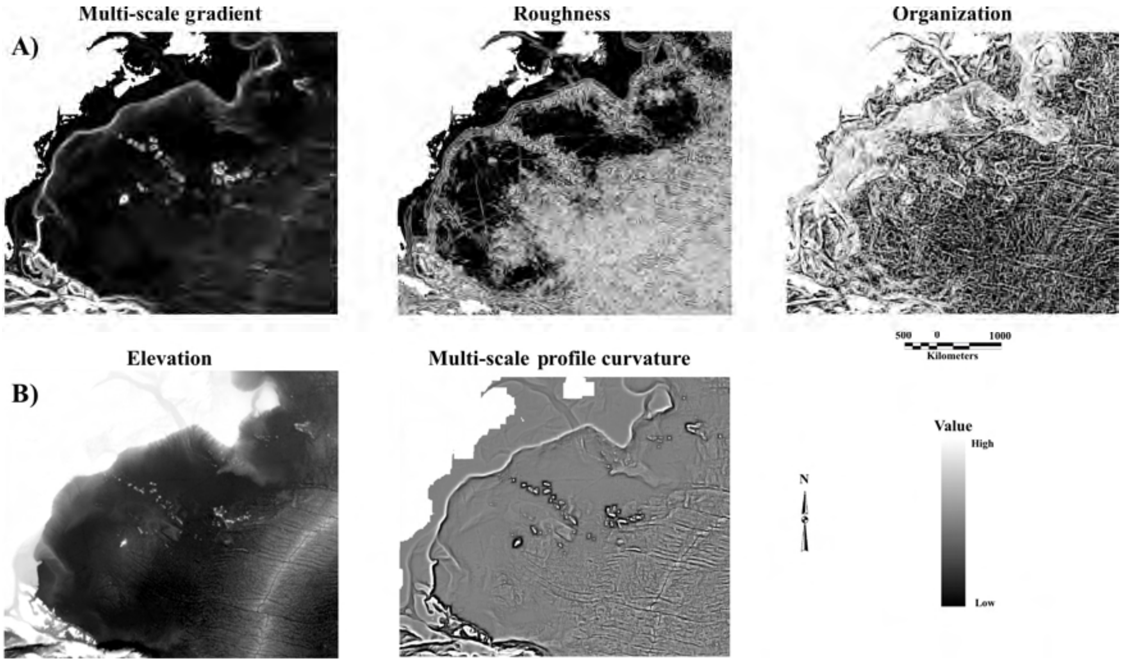


Figure 2. Greyscale images of the geometric signature (A) and auxiliary variables (B). Note the clear spatial independence of the three variables in (A).

### 2.3 The Classification Procedure

A classification procedure (Fig.3) was devised to combine the geometric signature with the auxiliary variables in four sequential stages. The two first stages were based on unsupervised techniques and the last two were supervised by the author's experience.

1) Initially, each attribute map was submitted to a statistical unsupervised classification algorithm (ISOCLASS) yielding morphometric classes defined by the inherent frequency distributions of each variable (Table 1). Visual and histogram analyses of the original maps indicated the optimal number of classes to be pre-set in the algorithm;

| Geometric signature | | | Auxiliary variables | |
|---|---|---|---|---|
| Gradient (tg α) | Roughness (0-1) | Organization (0-1) | Bathymetry (-m) | P. Curvature (+-) |
| flat (< 1:82) | smooth (< 0.210) | disorganized (0.55 – 0.77) | shallow (<1,588) | concave (-) |
| sloping (1:82 – 1:32) | rough (0.21 - 0.50) | organized (> 0.77) | intermediate (1,588 - 3,444) | convex (+) |
| steep (1:32 – 1:16) | very rough (> 0.50) | | deep (3,444 - 4,602) | |
| scarped (> 1:16) | | | abyssal (> 4,602) | |

Table 1. Morphometric classes of the selected variables.

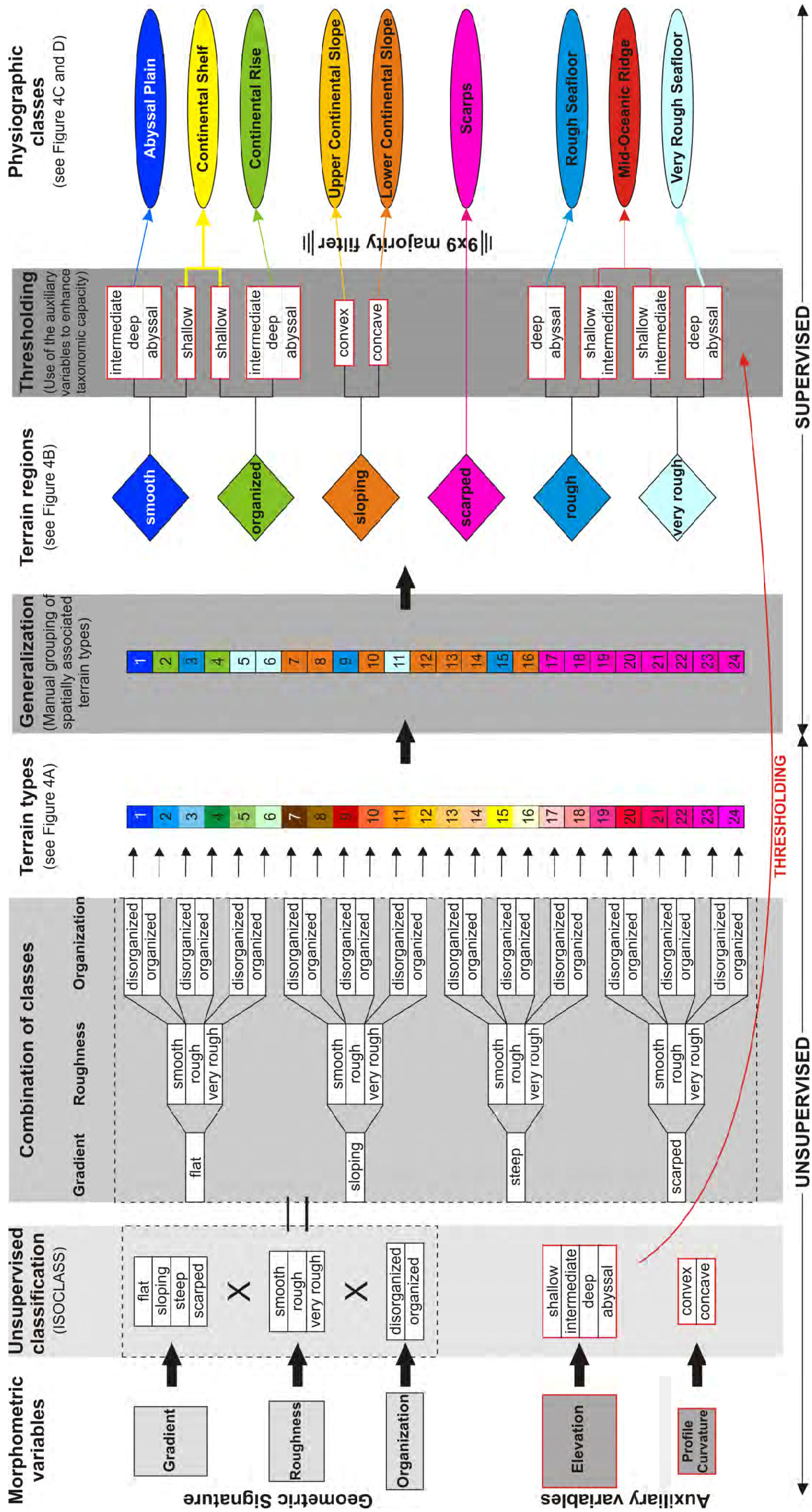


Figure 3. Flow chart of the classification procedure.

2) The resultant classes were then combined (4x3x2) to form 24 distinct terrain types (Figs.3 and 4A);

3) After that, manual grouping of spatially associated terrain types was used to generalize the classification into 6 terrain regions (Figs.3 and 4B);

4) Finally, the auxiliary variables were used as thresholds to enhance taxonomic capacity resulting in 9 physiographic classes (Figs.3, 4C and D). A 9x9 post-classification majority filter was used to consolidate scattered occurrences of classes.

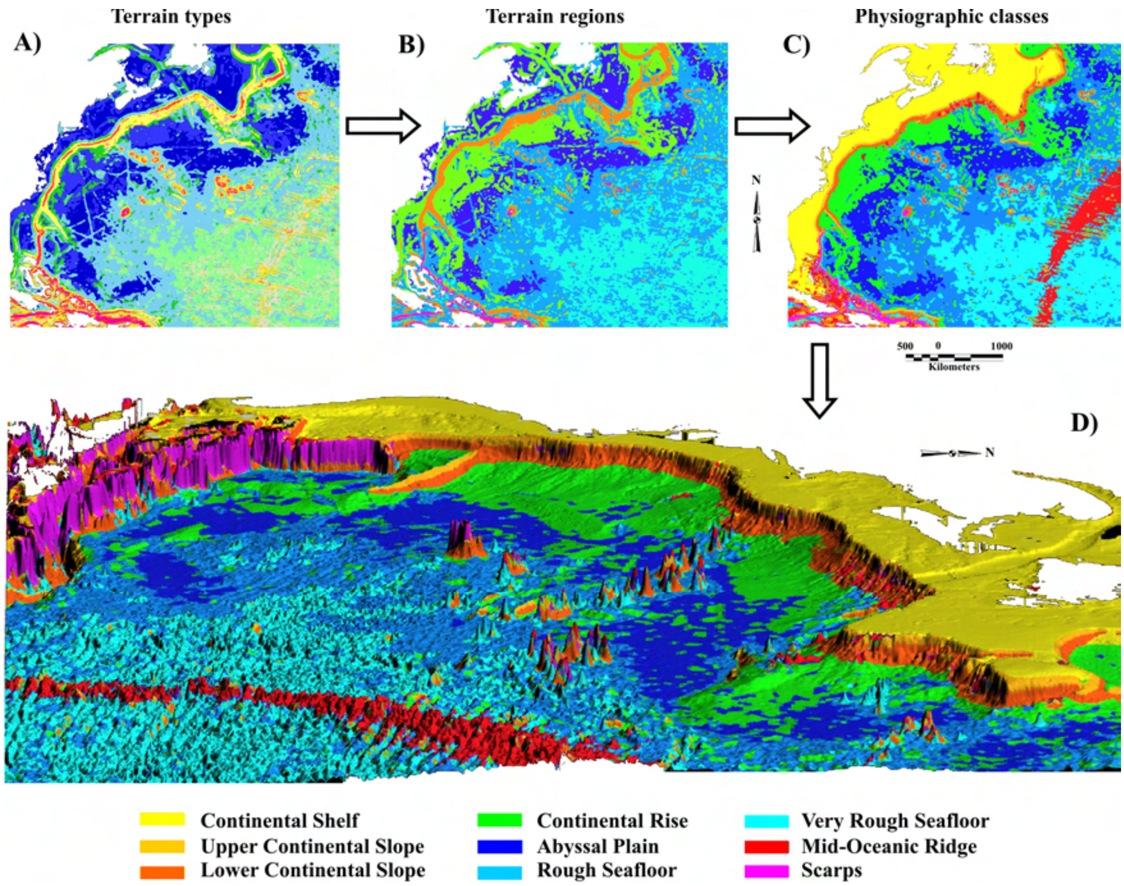


Figure 4. Classified maps of the test-DEM showing 24 terrain types (A), 6 terrain regions (B) and 9 physiographic classes (C). Oblique view of the classification draped over the test-DEM (D). See Fig.3 for colour-code of (A) and (B).

## 3. Results and Discussion

In order to assess the effectiveness of the classification achieved, the Physiographic Diagram of the North Atlantic (Heezen *et al*. 1959) was directly overlaid to the classified map (Fig.5). Clear similarities can be seen with respect to the spatial distribution of the continental slope, continental rise and abyssal plains, although no traditionally accepted thresholds (*e.g.* gradient of 1:40 for continental slopes and 1:1000 for abyssal plains) were used in their classification. The concentration of scarps in the southwest portion of the map indicated the association of this class with the landward slopes of trenches. Some individual seamounts were also classified as scarps.

The physiographic classes *rough seafloor* and *very rough seafloor* were defined mainly by the use of entropy as a roughness parameter but were not directly equivalent to known physiographic provinces. They are more related to distinct textures of the ocean floor where abyssal hills, the mid-oceanic ridge and its fracture zones are included. A depth threshold was necessary to individualize the mid-oceanic ridge as well as to distinguish the continental shelf among smooth and organized terrain.

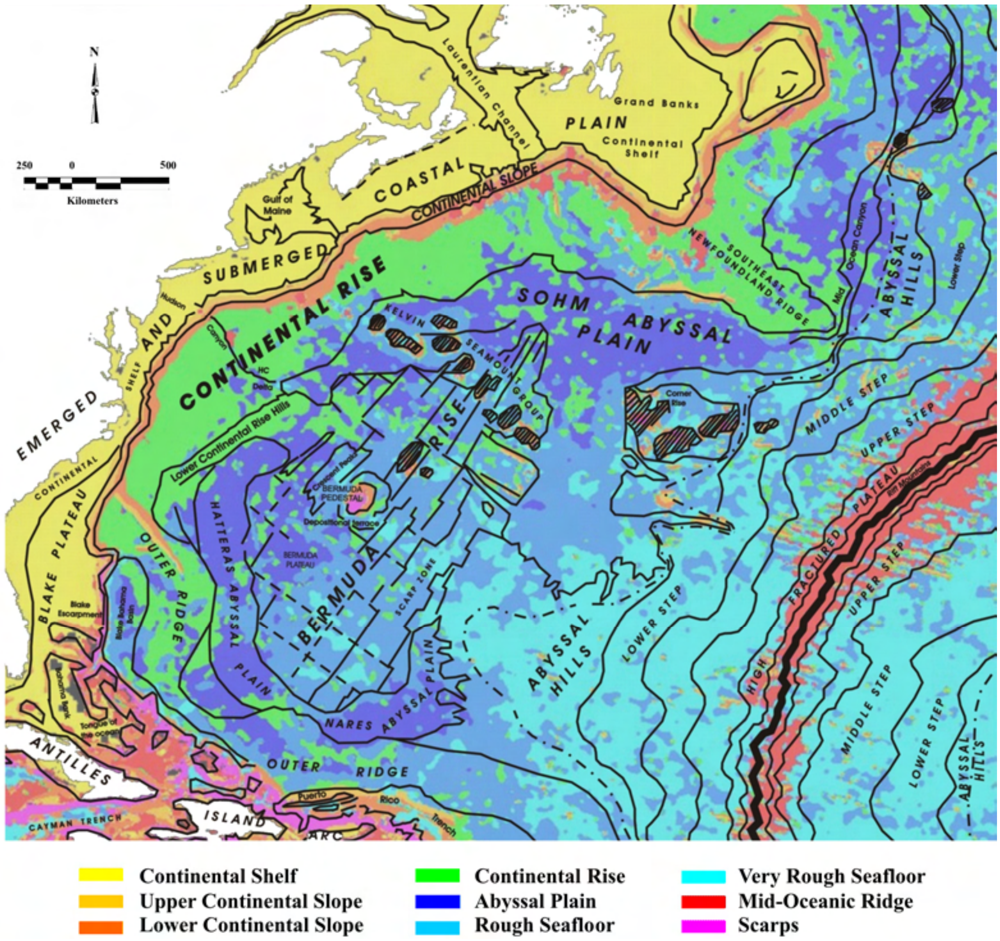


Figure 5. Visual comparison between the Physiographic Diagram of the North Atlantic (Heezen *et al*. 1959) and the present study.

The application of the classification scheme to the global DEM (Fig.6) allowed further evaluation of the methodology Continental rises and scarps concentrated, respectively, in the Atlantic and Pacific oceans differentiating passive from active margins (Fig.6C). The central portion of the mid-oceanic ridge was identified in every ocean giving a desirable structure for the classification. Different textures of the deep ocean were identified both regionally (Fig.6A and D) and locally (Fig.6B).

The selective use of auxiliary variables avoided over-segmentation of the surfaces in meaningless classes while still enhancing taxonomic capacity. The elevation parameter was not included in the geometric signature due to the directional trend of the ocean basins (down from the shoreline to the deep ocean and back up to the mid-oceanic ridge crest), which tend to create "natural" broad regions with high pattern coherence but low geomorphological content. Profile curvature was also excluded from the geometric signature for its statistical correlation with gradient and for producing local convex and concave features with limited significance for a physiographic assessment.

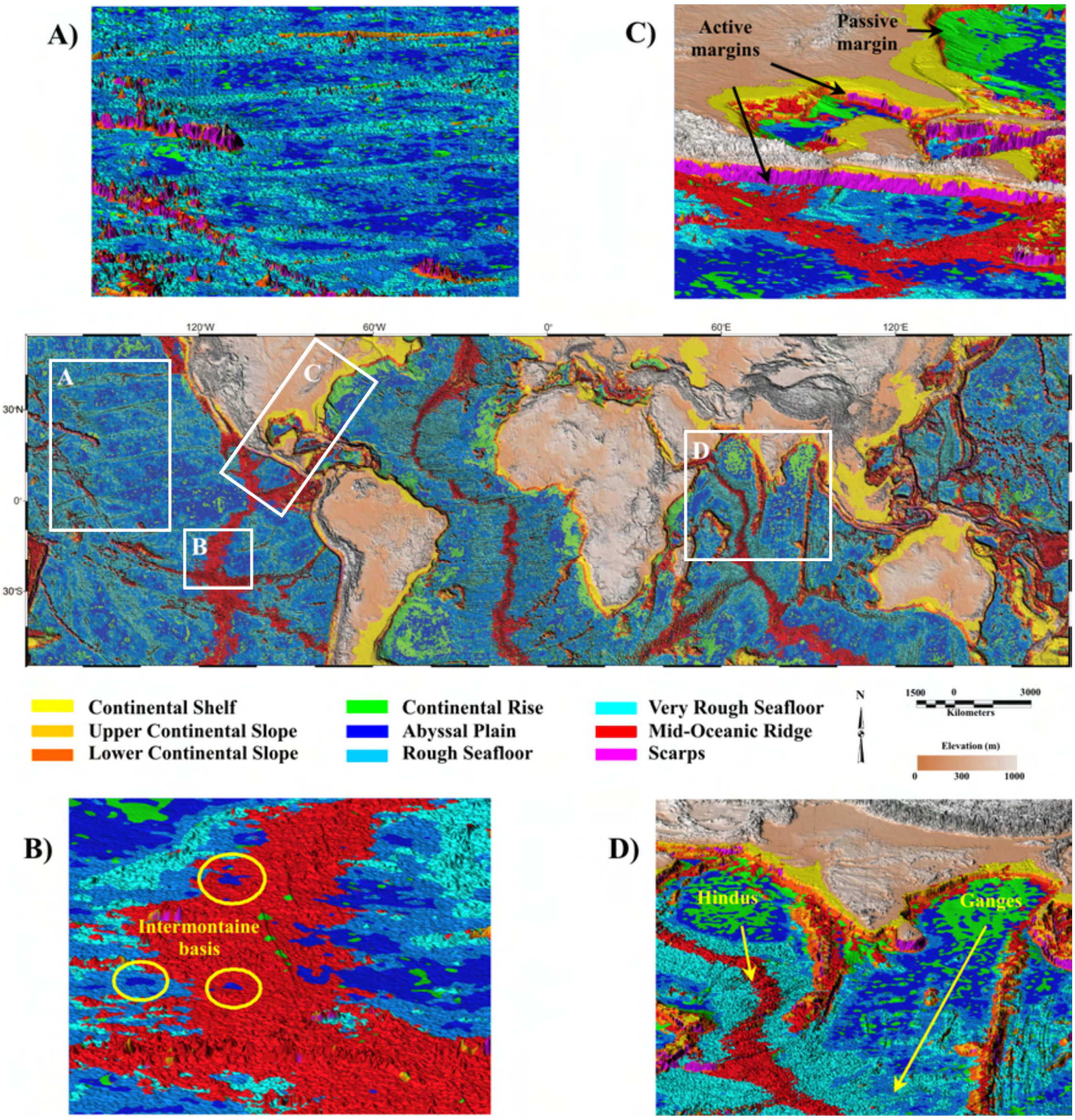


Figure 6. Global physiographic map. A) Regional pattern of rough and very rough seafloor intertwined with abyssal plains in the Pacific Ocean; B) Local intermontaine basins identified among the flanks of the mid-oceanic ridge; C) Clear differentiation between passive and active margins; D) Characterization of abrupt (Hindus Fan) and gradational (Ganges Fan) regional changes in relief.

## 4. Conclusions

Important geometric properties of physiographic provinces were captured by the morphometric variables used, thus allowing the consistent identification of physiographic classes through a semi-automated classification procedure. The global physiographic map showed that classes usually formed large spatial assemblages coherent with certain physiographic provinces. However, some isolated occurrences of classes were not related to a physiographic province *per se*, but to local geomorphological characteristics.

The multi-scale description attempted to cope with the influence of scale in geomorphometry but was oversimplified by a fixed limit size of analysis and by collapsing the scale variation dimension in one simple measure. More sophisticated approaches like Schmidt and Andrew (2005) that identifies dominant scales may be a good alternative for the method to better reflect the inherent *scale tendency* of the data.

While different geometric signatures should be tested to enhance taxonomic capacity, it is hard to believe that the spatial arrangement of the classes alone will define all the physiographic provinces. Not only the use of auxiliary variables proved to be essential, but it also indicated that each physiographic province may have its own unique set of descriptors, which should be investigated in further development of the method. This objective reassessment of the physiography of the ocean floor, far from contradicting the established knowledge, may represent a path for new discoveries and, without doubt, many new questions.

## Acknowledgements

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