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Seafloor Characteristics in the Azores Region (North Atlantic)

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Current European legislation such as the Marine Strategy Framework Directive (MSFD; 2008/56/EC) has highlighted the need for accurate maps on the geomorphology of Europe's maritime territory. Such information is notably essential for the production of habitat maps and cumulative impact assessments of human activities (Halpern et al., 2008) necessary for marine spatial planning initiatives (Gilliland and Laffoley, 2008) and assessments of the representativity/sufficiency of marine protected areas networks like Natura 2000. Broadscale satellite bathymetry presently allows the identification of all prominent geomorphic structures present on the seafloor with a high grade of accuracy. However, these datasets and maps still need to be more widely disseminated in the scientific community.

In this contribution, we provide an inventory of some important datasets related to the physical characteristics of the seafloor surrounding the Azores Archipelago. The objective is to ensure that our compilation is readily available for any researchers interested in developing species distribution models, or for the management and conservation of natural resources in the region.

In total, we produced and compiled 18 layers of seabed characteristics for the Azores region (**Table 1**), deposited at Pangaea, Data Publisher for Earth and Environmental Science (Perán Miñarro et al., 2016).

The Azores area is located in the North Atlantic Ocean between 28°00′ N – 49°00′ N, and 17°00′ W – 41°00′ W with an extension of approximately 8,051,544 km^2 that includes the Exclusive Economic Zone (EEZ) along with the Portugal's claimed extended continental shelf area around the archipelago (**Figure 1**).

Several seafloor geomorphic variables were produced through the different geoprocessing tools: Slope, Aspect, Northness, Eastness, Vector Ruggedness Measure (VRM), Plan Curvature, Profile Curvature, Total Curvature, Surface-area, Surface-ratio, Hillshading, MDOW-Hillshade (Multidirectional Oblique-Weighed) and broad/fine scale Bathymetric Position Index (BPI). All these bathymetric derivatives (**Table 1**) were based on the Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution (SRTM30_PLUS; Becker et al., 2009) and computed in ArcGIS using a combination of two geoprocessing add-ons; Benthic Terrain Modeler (Wright et al., 2005) and Digital Elevation Model Surface Tools (Jenness, 2004).

Using SRTM30_PLUS (**Figure 1A**), we also provide a layer that delimits the depth-based biological zones proposed by Howell (2010). Four different biological zones were mapped: sublittoral (0.05% of the seafloor in our study area), upper slope (0.29%), upper bathyal (0.42%), mid bathyal (2.95%), lower bathyal (9.94%), and abyssal (86.28%).

The diversity of the different geomorphologic structures present in the study area (**Figure 1B**) was obtained through the recently completed digital Global Seafloor Geomorphic Features Map (GSFM; Harris et al., 2014).

In their study, Harris et al. (2014) present seafloor geomorphology as a hierarchy of base layers for the shelf, slope, abyss and hadal zones, which are further divided into classification layers and discrete feature layers, sometimes overlaying each other. The Azores area considered

TABLE 1 | Layers on the characteristics of the seafloor in the Azores.

Layer	Description	Source	Processing tool
Bathymetry	Seafloor depth	SRTM30_PLUS	–
Slope	Maximum seafloor depth gradient	SRTM30_PLUS	DEM Tools
Aspect	Direction of maximum slope	SRTM30_PLUS	DEM Tools
Northness	Orientation of the slope (cosine of aspect)	SRTM30_PLUS	Benthic Terrain Modeler
Eastness	Orientation of the slope (sine of aspect)	SRTM30_PLUS	Benthic Terrain Modeler
Vector Ruggedness Measure (VRM)	Index reflecting the variability of slope and aspect in a single measure	SRTM30_PLUS	Benthic Terrain Modeler
Plan Curvature	Variable representing the concave, convex or linear profile of the substrate perpendicularly to the slope. A positive value indicates the surface is sidewardly convex at that cell, while negative values indicate the surface is sidewardly concave. A value of zero indicates the surface is flat across-slope. PlC emphasizes convergence and divergence of along-slope flows	SRTM30_PLUS	DEM Tools
Profile Curvature	Profile curvature is extracted along to the direction of the maximum slope. A negative value on a given cell indicates that the surface is upwardly concave. Instead, positive values indicate surfaces that are upwardly convex. A value of zero indicates that the surface is linear (i.e., slope does not change along-slope). PrC emphasizes the ridges, valleys and terraces on a surface. It is also an indicator of the acceleration and deceleration of gravitational flows, which influences erosion and deposition processes	SRTM30_PLUS	DEM Tools
Total Curvature	Total curvature or general curvature is the second derivative of the surface (or the slope-of-the-slope). It is extracted on a cell-by-cell basis taking into account its eight surrounding neighbors. It considers both plan and profile curvature together, permitting a more accurate understanding of flow patterns across a surface	SRTM30_PLUS	DEM Tools
Surface-area ratio	Seafloor topographic roughness/irregularity index calculated by dividing the surface area value of a gridcell (taking into account its slope gradient) by its planimetric area	SRTM30_PLUS	DEM Tools
Bathymetric Position Index (BPI) (Broad-scale)	The BPI is a measure of where a referenced location is relative to the locations surrounding it. The BPI is derived from an input bathymetric data set and itself is a modification of the topographic position index algorithm that is used in terrestrial environment. The Broad-scale BPI (inner radius of 25 and outer radius of 250) identifies larger features within the seafloor	SRTM30_PLUS	Benthic Terrain Modeler
Bathymetric Position Index (BPI) (Fine-scale)	The BPI is a measure of where a referenced location is relative to the locations surrounding it. The BPI is derived from an input bathymetric data set and itself is a modification of the topographic position index algorithm that is used in terrestrial environment The Fine-scale BPI (inner radius of 5 and outer radius of 25) identifies smaller features within the seafloor	SRTM30_PLUS	Benthic Terrain Modeler
Hillshading	Sun-illuminated relief representation computed using a single illumination angle	SRTM30_PLUS	DEM Tools
MDOW-Hillshade (Multidirectional Oblique-Weighled)	Advanced sun-illuminated relief representation computed using illumination simulations from multiple angles	SRTM30_PLUS	DEM Tools
Classified depth zones	Depth zones segmentation using Howell (2010) thresholds (littoral, upper slope, upper bathyal, mid bathyal, lower bathyal, abyssal)	SRTM30_PLUS	–
Geomorphic features	Delimitation of the different geomorphic structures present in the region (abyss, basin, canyon, escarpment, plateau, ridge, rift-valley, rise, shelf, through)	Harris et al., 2014	–
Substrate type	Seafloor substrate type	Multiple (see text)	–
Sediment thickness	Sediment thickness of the seafloor	Divins (2003)	–

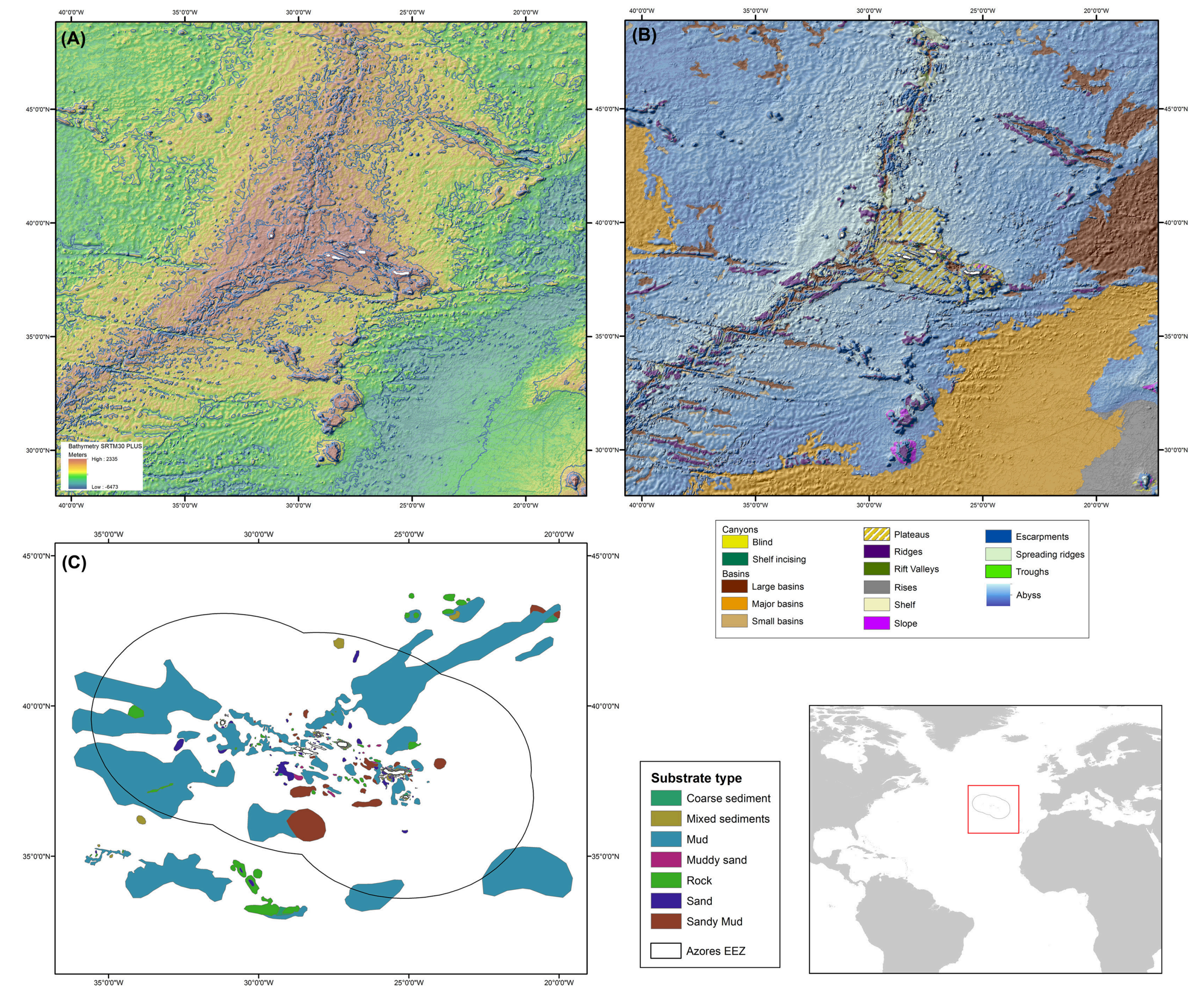

FIGURE 1 | (A) Bathymetry of the study area (SRTM30_PLUS) for which all the derivatives were based on; **(B)** geomorphologic structures of the seafloor based on Harris et al. (2014); **(C)** seabed substrate type.

in this study encompasses the following layers: the base layer abyss (representing 99.1% of the study area and subdivided into abyssal plains, abyssal hills and abyssal mountains) and the following discrete feature layers: basin (22.72%), canyon (0.14), escarpment (7.35%), plateau (2.91%), ridge (3.95%), rift-valley (0.63%), spreading ridges (3.4%), shelf (0.04%) and through (0.54%).

Seabed substrate type (**Figure 1C**) were based on different sources: multibeam backscatter and seismic surveys, point data digitized from up-to-date and historical nautical charts for the Azores and data provided by the World Seabed Data Browser, the Lamont-Doherty Earth Observatory and National Geophysical Data Center (NGDC). Since most of the information was available as sample point data, a geologic interpretation of seafloor type around the Azores was undertaken (collaboration with IEO researchers: José Luis Sanz Alonso and Dulce Mata Chacón) using the seafloor point data and bathymetry information. This approach was later complemented by statistical modeling (Multinomial regression models) using other terrain variables (e.g., Bathymetry, Slope, Eastness, Northness, Rugossity) to cover the uninterpreted areas left by the expert (Mata Chacón et al., 2013; Vasquez et al., 2015). The expert geological interpretation of seabed sampled points was given priority in the final mosaic of the substrate types for the Azores region. The output resulted in the compilation of the highest resolution seabed substrate data available: an interpreted and modeled substrate layer with a 250 m resolution. The area covered by the seabed substrate layer is more limited than the total area considered in this study.

A specific analysis of the sediment thickness characteristics of the Azores area was undertaken using the "Total Sediment Thickness of the World's Oceans and Marginal Seas, Version 2" (Whittaker et al., 2013), an updated dataset from the original global National Geophysical Data Centre (NGDC) sediment grid (Divins, 2003). The new total sediment thickness grid can be found at the National Geophysical Data Center's website (https://www.ngdc.noaa.gov/mgg/sedthick/index.html).

The compilation of the seabed characteristics for the Azores and surrounding areas in North Atlantic is part of a larger effort to assemble as much data on the environmental characteristics of this region (e.g., Amorim et al., in press), to improve our knowledge and facilitate the development of future integrated studies.

AUTHOR CONTRIBUTIONS

TM, CP, FC, and FT designed the study. PA, ADP, and FT collected and processed most of the data through GIS software. TM, CP, PA, and ADP performed most of the analyses. PA, ADP, CP, FC, FT, and TM wrote the paper.

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