Vol. 357: 17–21, 2008
doi: 10.3354/meps07268

MARINE ECOLOGY PROGRESS SERIES
Mar Ecol Prog Ser

Published April 7

Abundance and distribution of seamounts in the Azores

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ABSTRACT: We characterized the seamount distribution of the economic exclusive zone (EEZ) of the Azores (Portugal) using 2 bathymetry datasets. Our algorithm showed that peaks and seamounts are common features in this region of the North Atlantic. The density obtained of 3.3 peaks of all sizes per 1000 km^2 is in the same order of magnitude as that obtained on the Mid-Atlantic Ridge by a few other studies. A total of 63 large and 398 small seamount-like features are mapped and described in the Azorean EEZ. Our distribution of seamounts predicts that about 57% of the potential Azores seamounts lie in the zone protected from deep-water trawling by European Commission Council Regulation No. 1568/2005.

KEY WORDS: Seamounts · Peaks · Locations · Characteristics · Azores · Trawl ban

INTRODUCTION

Despite the fact that seamounts are highly important for fisheries and biodiversity (Pitcher et al. 2007), their exact numbers and locations are poorly known. Only a few seamount location datasets are available in the literature (e.g. Fornari et al. 1987, Smith & Jordan 1988, Epp & Smoot 1989, Smith & Cann 1990, Wessel 2001). Recently, Kitchingman et al. (2007) have conducted a global analysis aiming to generate a spatial dataset of points across the world's oceans that indicate large peaked bathymetric anomalies with a high probability of being seamounts. In that study, 14287 potential large seamounts were identified in the world's oceans.

Seamounts are thought to be common topographic features in the economic exclusive zone (EEZ) of the Azores archipelago (an irregular area within 33.5° to 43° N, 21° to 35.5° W), given the rugged volcanic and tectonically active seafloor that characterizes the region. However, as in the rest of the world's oceans, their distribution has not yet been reasonably mapped. Seamounts are important areas for conservation and fisheries in the Azores (Santos et al. 1995), and knowledge of their locations is very important for choosing and implementing fisheries and for nature conservation management measures. Moreover, the importance of seamounts for some charismatic species, such as marine mammals, sea turtles, seabirds and large pelagic fishes, can only be fully understood with a good knowledge of the seamounts' locations and characteristics (Morato et al. 2008, this volume).

The main goal of the present paper was to infer potential seamount locations and thus generate an estimate of the number of seamounts in the Azores described herein according to location, depth of the summit, height, basal area, height to radius ratio, average slope and distance to nearest seamount. In a companion paper (Morato et al. 2008), this information is employed to quantify the abundance of a number of charismatic marine species in the vicinity of seamounts. Together, the 2 papers should contribute to the overall goal of better understanding the local distributions and abundance of marine organisms visiting seamounts and to infer their potential spatial dynamics, which has implications for conservation, management and monitoring.

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MATERIALS AND METHODS

In the present study, seamounts are defined as any topographically distinct seafloor feature that is at least 200 m higher than the surrounding seafloor, but which does not break the sea surface. We classify seamounts as being large or small, depending on whether the height exceeds 1000 m (regardless of depth). This height separation is useful in isolating large seamounts, the global distribution of which is well resolved by satellite altimetry, from small seamounts, the distribution of which can only be derived from less encompassing local acoustic mapping.

An automated methodology adapted from Kitchingman et al. (2007) was used to identify topographic structures with high probability of being seamounts. Two bathymetric datasets with different resolutions were used as the topographic bases.

The MOMAR (monitoring the Mid-Atlantic Ridge) mesoscale bathymetric map (Lourenço et al. 1998; www.ipgp.jussieu.fr/rech/lgm/MOMAR/Data/Plateau_bathy.grd) was the finest scale bathymetrical grid available for the Azores region at the date of the analysis (February 2006) and was used for the area constrained by the parallels 36° and 41° N and the meridians 24° and 32° W. This dataset is supplied at a 1 min cell resolution, thus allowing a reasonable scale at which to perform an analysis for large seamount-like features. The 'global seafloor topography from satellite altimetry and ship depth soundings' database (Smith & Sandwell 1997; http://topex.ucsd.edu/sandwell/sandwell.html) at a 2 min cell resolution was used as the bathymetry dataset for the remaining area. The version used still contained some artefacts, such as a spurious deep trough in the NE region of the study area.

The methodology followed 3 succeeding steps run on a cell-by-cell analysis over the bathymetric grids: (1) identifying all detectable peaks in the bathymetry dataset with the Environmental Systems Research Institute (ESRI) ArcGIS software flow direction and sink algorithms (www.esri.com), (2) isolating peaks with heights >200 m above surrounding seafloor and displaying an approximately circular or elliptical shape and (3) isolating large seamount-like features (height >1000 m). The datasets produced after Step 1 will be called the 'peaks dataset', while the dataset produced after Step 3 will be used as the 'Azores seamount dataset'. The dataset produced after Step 2 minus that produced after Step 3 will be called the 'small seamounts dataset'.

Steps 2 and 3 were preformed with an algorithm that scanned depths around each peak, along 8 radii of 20 km each at 45° intervals. The lowest and highest depths over the radii and the cells where those values were obtained were then recorded. A peak was considered to be a potential seamount when the following conditions were met:

(1) Each and all of the 8 radii included depths differing by at least 200 m. This helped eliminate all peaks of insignificant rises.

(2) No more than 1 of the 8 radii has the highest depth shallower than the depth of the peak and if the distance between these 2 cells is >10 km. This helped eliminate peaks that were part of a larger structure and peaks close to island slopes.

(3) If 2 radii included depths between 200 and 1000 m, with the shallowest point being closer to the peak than to the deepest point, and if the radii formed an angle of <135°. This condition was created to help separate ridges from seamounts.

(4) At least 5 of the 8 radii around a peak included depths with a difference of at least 1000 m, with the shallowest point being closer to the peak than to the deepest point.

(5) The average height of the peak above the surrounding seafloor is >1000 m.

Peaks that met all 5 conditions were considered large seamounts, while those that met only the first 3 conditions, but failed to meet the fourth and fifth were categorized as small seamounts. Several characteristics were gauged for the small and large seamounts detected: (1) location recorded as the latitude and longitude of the centroid of the detected peak or seamount; (2) summit depth (m) recorded as the depth of the cell where the peak was located and must be interpreted as the average depth of the cell, not the absolute minimum depth of the seamount; (3) seamount height (h in m) estimated as the average height of the 8 radii of the seamount, where each radius height was estimated as the difference between the summit and the deepest record; (4) basal area (a_b in km^2) approximated by the area of the octagon formed by the location of the deepest cell in each radius; (5) height to radius ratio (ξ_r); (6) the average slope (ϕ in degrees) estimated as the average steepness of the 8 radii of the seamount calculated by the slope algorithm of ArcGIS software; and (7) distance to nearest seamount (km).

Seamount size distribution is well characterized by a negative exponential model that considers the cumulative numbers of seamounts having heights greater than a certain value (Jordan et al. 1983, Smith & Jordan 1988). This distribution is expressed as $\nu(H) = \nu_o \cdot \exp(\beta, H)$, where $\nu(H)$ is the number of peaks per unit area with height greater than H, ν_o is the total number of peaks per unit area and β is the negative of the slope of a line fitting $\ln[\nu(H)]$ and H.

RESULTS

A total of 3177 peaks was identified yielding an average density of 3.3 peaks per 1000 km^2. Of these peaks, 1104 were found in the MOMAR Azores dataset (36° N, 24° W to 41° N, 32° W), whereas 2073 were found with the Smith & Sandwell (1997; S&S) dataset used to cover the rest of the EEZ.

The peaks dataset adequately identified topographic structures with heights >100 m (Fig. 1). The resolution of the bathymetry data seemed to be inadequate for peaks <100 m, leading to an underestimation of the counts. Thus, this data point was excluded from the fit. The exponential model adequately fitted the Azores peaks counts with $\nu_o = 4.31$ peaks per 1000 km^2 and $\beta = 2.89\ km^{-1}$, yielding a characteristic height (β^{-1}) of ~350 m. According to this exponential model there are about 4100 potential peaks in the Azores, where 1000 km^2 contain an average of ~4 peaks of all sizes.

Fig. 2 shows the location of 461 potential small and large seamount-like features in the Azores EEZ. Detailed tables of results for each seamount with location, depth of the summit and average slope are provided as supplementary information (see Appendix 1, available at http://www.int-res.com/articles/suppl/m357p017_app.pdf).

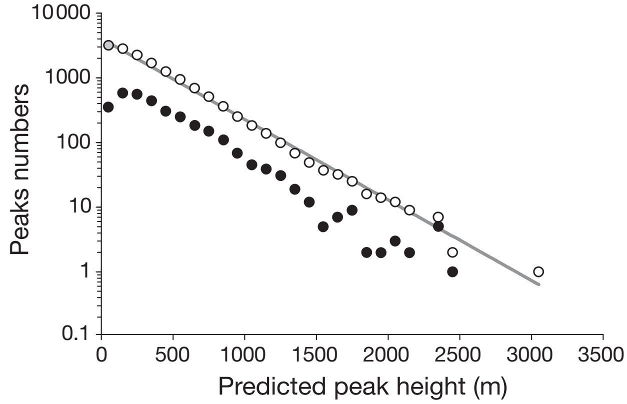

Fig. 1. Height (h) frequency distribution of all identified peaks. Solid circles are actual counts; open circles are cumulative counts. The grey circle data point was excluded from the exponential model fit. The relationship can be expressed as $N = 4041.8 \cdot e^{-2.89h}$, with h in km; $r^2 = 0.99$. If the number of peaks y is expressed by unit area (km^{-2}) with a height greater than H, $\nu(H) = 4.31 \cdot e^{-2.89h}$

Our methodology identified a total of 398 small features, which represents only 12% of the 3177 identified peaks. This discrepancy shows that our methodology successfully eliminated insignificant rises, peaks belonging to larger structures, or peaks that are part of

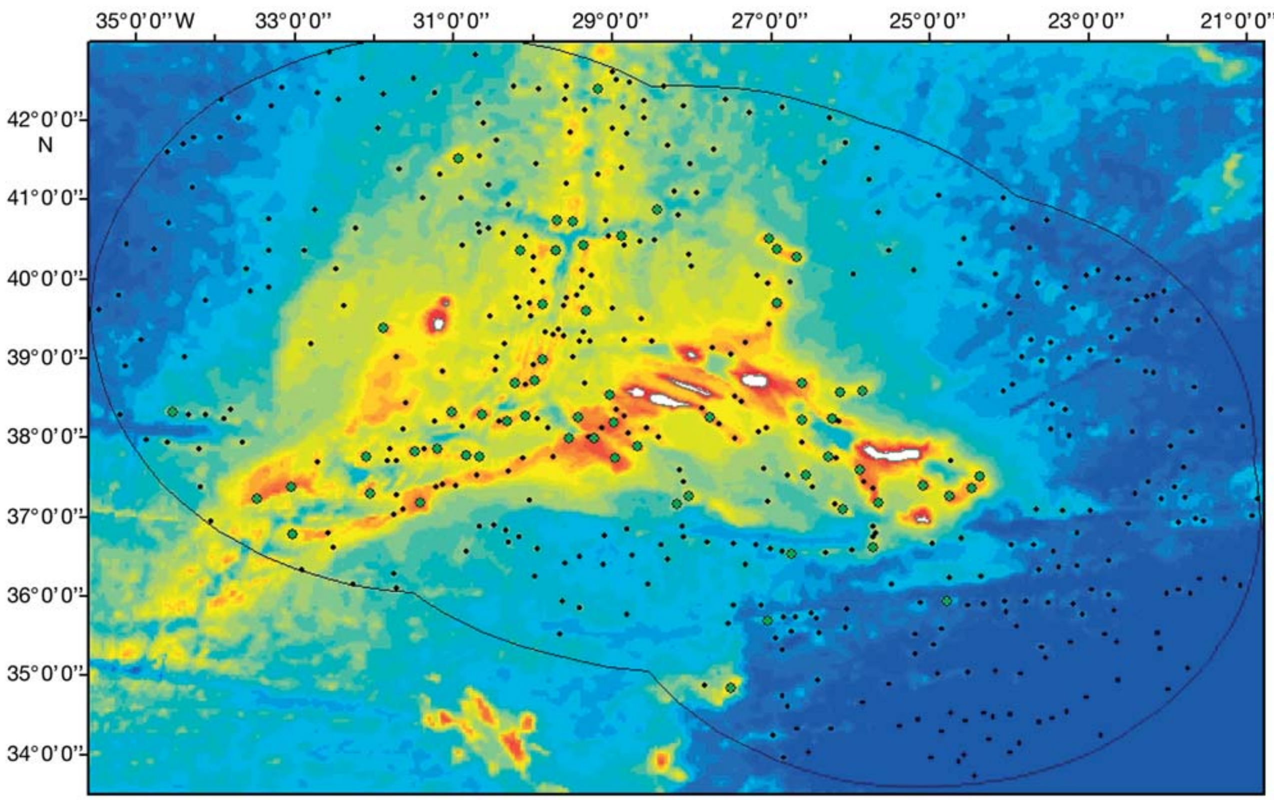

Fig. 2. Distribution of seamounts in the Azores economic exclusive zone (black line). Green circles show large seamounts; black dots show small seamount-like features. Scale goes from dark blue (deep water; about 5000 m) to dark red (shallow water). Islands shown in white

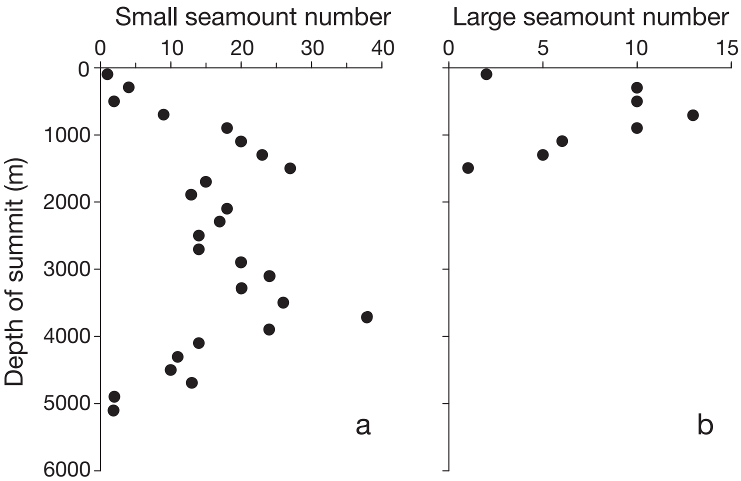

Fig. 3. Depth of the summit frequency distribution of (a) small and (b) large seamount-like features

ridges or island slopes. We have also detected 63 large potential seamounts, which only represent 2% of the identified peaks. The mean abundance of small and large seamounts in the Azores EEZ is 0.42 and 0.07 per 1000 km^2, respectively.

Most of the seamounts in the Azores have deep summits (Fig. 3), with a strong predominance of summit depths of 800 to 1500 m. Only 4 large seamounts have a mean summit depth shallower than 250 m, while 14 lie in the depth range from 250 to 500 m. The other 45 large seamounts have their summits deeper than 500 m. Small seamount-like features show a similar pattern, with only 6 shallower than 500 m.

Regarding seamount characteristics, our results show that small seamounts had a mean height of 612 m (SD = 210), while the mean height for large seamounts was 1267 m (SD = 272). Shapes of seamounts as characterized by the basal radius (r_b), by the height to radius ratio (ξ_r) and by the slope (ϕ) show marked differences between small and large seamount-like features. Small seamount-like features showed a mean r_b of 9.4 km (SD = 2.0), while large seamounts showed a mean r_b = 11.2 km (SD = 1.8). Accordingly, basal area is smaller on small seamounts (a_b = 742 km^2; SD = 213) than on large seamounts (a_b = 961 km^2; SD = 171). The mean height to radius ratio increased from ξ_r = 0.07 (SD = 0.027) on small seamounts to ξ_r = 0.12 (SD = 0.030) on large seamounts. Average slope angles ranged from ϕ = 0.73 to 9.27. The sample mean slope angle was ϕ = 2.90 for small seamounts and ϕ = 5.23 for large seamounts. The slope angle and summit height relationship is presented in Fig. 4.

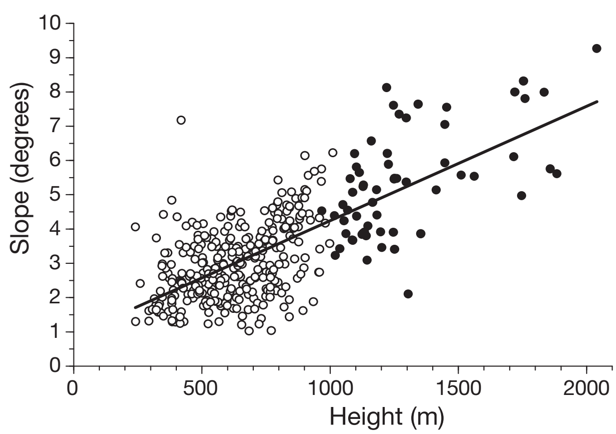

Fig. 4. Slope angle (ϕ) and seamount height (h) linear relationship for small (○) and large (●) seamount-like features. For all seamounts the relationship can be expressed as $\phi = 0.003h + 0.86$; $r^2 = 0.53$

DISCUSSION

This work is the first attempt to identify the seamounts in the Azorean EEZ. This information is very important to better understand the functioning of seamount ecosystems. For example, Morato et al. (2008), in a companion paper, used this information to help estimate the abundance of many organisms such as tuna, seabirds, marine mammals and sea turtles that are thought to visit seamounts. Information on seamount location is essential for testing hypotheses related to seamount-induced primary production enhancement, assessing genetic isolation of associated populations, employing metapopulation dynamic models, or simply for planning surveys and monitoring programs that can assess the impacts of fisheries on seamount community structure and function.

It must be emphasized, however, that there are some potential sources of uncertainty in this study. First, the bathymetry of the Azores EEZ is not perfectly known and most of its seafloor remains to be surveyed by shipborne acoustic methods. Both bathymetry datasets used (Smith & Sandwell 1997, Lourenço et al. 1999) may lack resolution and thus preclude the identification of a significant number of small seamount-like features. For this reason, our references to seamounts should be interpreted as potential seamounts. A better but very costly solution would be to perform extensive multi-beam surveys that would provide not only excellent bathymetric data for mapping seamounts and estimating depths, areas and slopes, but also backscatter data for mapping the nature of the seafloor.

Our approach showed that peaks and seamounts are common features in the Azorean EEZ. A comparison with other topographical studies of the Mid-Atlantic

Ridge show that our average density of 3.3 peaks of all sizes per 1000 km^2 is in the same order of magnitude as that obtained by Batiza et al. (1989), but is an order of magnitude lower than that obtained by Smith & Cann (1990) and by Jaroslow et al. (2000). The discrepancies observed in relation to the latter studies are probably due to the fact that they focused only on the immediate vicinity of the ridge, an area with exceptionally rugged topography (Smith & Cann 1990).

In the present study, we were able to map and describe 63 large and 398 small seamount-like features in the whole EEZ of the Azores. The total area where seamounts are found is 356 700 km^2, representing about 37 % of the EEZ area, a much larger area than previously thought. However, most of the summits are in waters deeper than 1000 m. Etnoyer (2005) presents some evidence that small features with deep peaks predicted by some bathymetry datasets can actually be large seamounts with shallower summits. Therefore, our estimates of seamount abundance may perhaps be biased by underestimating seamount heights and overestimating depth of summits. For that reason, the large-seamount abundance in the Azores may be even higher than presented here. Also, the depth of the summits may be shallower than we have estimated.

Notwithstanding the overall distribution suggesting that a large proportion of the seamounts occurs in chains along the Mid-Atlantic Ridge, isolated seamounts are also present in the Azores region. This group of seamounts showed such a wide range of sizes (heights), depths of summits, slopes and areas that it is difficult to make generalisations about them. This diversity suggests that seamounts provide a variety of environmental conditions that can suit different biological assemblages (Morato et al. 2008). Recently, the EU Regulation 1568/2005 (European Commission 2005) banned deep-water trawling in a large area of the Azorean EEZ. According to our distribution of seamounts, this regulation protects 58 large and 207 small seamounts. Thus, 57 % of the potential Azores seamounts are protected against deep-water trawling.

Acknowledgements. T.M. and F.T. acknowledge support from the 'Fundação para a Ciência e Tecnologia (FCT)', POCI 2010 and European Social Fund through grants BD4773/2001, BPD/27007/2006 and BD12885/2003, respectively. We are grateful to R. Medeiros for his committed assistance in the production of GIS material. We thank the 3 anonymous referees for their comments, which greatly improved the manuscript. IMAR-DOP/UAÇ (Research Unit No. 531 and part of the Associated Laboratory No. 9) is funded annually by FCT.

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Editorial responsibility: Konstantinos Stergiou, Thessaloniki, Greece

Submitted: September 19, 2006; Accepted: September 29, 2007
Proofs received from author(s): February 27, 2008