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# Where the continent ends

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## Abstract

The Earth's continents and islands are bordered by shallow ocean plains that are arguably the most environmentally, economically, and politically important parts of the sea. Yet in spite of this, they remain poorly defined and understood. A quantitative approach is employed here to map and analyze these plains, or shelves. The Earth's ocean bathymetry was used to determine the continent-ocean basin transition at ~1200 m and then parsed with a novel geospatial terrain classification concept/method borrowed from the field of image analysis: the geomorphic phonotype, or geomorphon. The technique is less subjective than visual interpretation and digitization and here illustrates that the ocean coastal plains are deeper, wider, and more steeply sloped than previously recognized. Their variable form is related to tectonics and latitude and ultimately affects function and habitat.

## 1 Introduction

ocean begins. Fundamentally, the Earth's surface consists of two distinct yet coupled physical realms: the land and sea. In between the two are often found shallow, variously submerged plains, commonly called shelves; these transitional environments are some of the most ecologically productive and economically vital parts of the global oceans. Understanding their extent and character can inform the myriad of processes and interactions that occur there. For example, research seeks to comprehend recently discovered cold-water coral communities living on the shelf at depths below the photic zone [ *Roberts et al* ., 2006]. Another area of current investigation are methane seeps—which are numerous on and along the outer ocean coastal plain [ *Gentz et al* ., 2014]—for their potential impacts on global climate. Here, though, we focus not on disciplinary matters, but on an overdue geomorphic investigation of these most prominent boundaries.

Continental and insular shelves reportedly occupy only about 8% of the global marine environment [ *Harris et al* ., 2014; *de Haas et al* ., 2002; *Hedberg* , 1970], but their importance to humankind far outweighs their relatively diminutive geographies. These areas are zones of high biologic productivity [ *Anderson and Anderson* , 2010; *Allen* , 2006; *Muller-Karger et al* ., 2005] supporting multibillion dollar commercial fisheries [ *Allen* , 2006]. They are large terrestrial sediment [ *Walsh and Nittrouer* , 2009; *Walsh et al* ., 2016] and nutrient repositories [ *Gautier et al* ., 2009; *Emery* , 1965] and, as a result, host a large amount of the world's offshore oil and gas reserves [ *Hedberg* , 1970; *Berner* , 1982; *Hedges and Keil* , 1995] and play a key role in carbon sequestration and concomitant climate regulation [ *Muller-Karger et al* ., 2005; *Anderson et al* ., 2010; *Chen and Borges* , 2009; *Frankignoulle and Borges* , 2001; *Fennel* , 2010]. Consequently, many coastal ocean nations find themselves embroiled in political deliberations relating to national and international boundaries, territorial rights, and sovereignties [ *Cook and Carleton* , 2000; *Higdon* , 2014; *International Hydrographic Organization (IHO)* , 2008; *MacNab* , 2004; *Hedberg* , 1976, 1981]. The importance of these areas is reflected in the large volume of scientific research conducted over the past half century. Remarkably, in spite of this research, arguments can and have been made that the morphology of the Moon and Mars [ *Smith et al* ., 2010; *Scholten et al* ., 2012; *Daubar et al* ., 2014] (and soon Jupiter) is better characterized than the seafloor adjacent to where billions of humans reside.

Many of our ideas about the ocean, particularly its gross geomorphology and geology, comes from the work of midtwentieth century investigators such as Francis Shepard who described the continental shelf as "…shallow platforms or terraces that surround most of the continents, and are terminated seaward by a relatively sharp break in slope" [ *Shepard* , 1973] and which "…are clearly related to the continents" [ *Shepard* , 1948]. Based on a survey of the contemporary data, he condensed his extensive observations into six summarizing statistics, three of which would, perhaps inadvertently, go on to influence subsequent generations of scientists (In fact, Shepard cautioned the reader as to the overall usefulness of such statistics in the face of the great variation seen in the data.). Shepard stated that the average width of the continental shelf was 42 nautical miles (77.8 km); the average depth at the shelf break was 72 fathoms (131.7 m); and the average slope was 0.07′ (0.0012°).

Other investigators, working subsequent to Shepard, have also described the shelf in similar terms as one that is characteristically flat to gently sloped with shallow (120 m to 200 m) average water depths, and highly variable widths [ *Hedberg* , 1970; *Hedges and Keil* , 1995; *Heezen and Wilson* , 1968; *Uchupi* , 1968; *Hayes* , 1964]. In more recent work, *Bouma et al* . [1982] posited an average shelf depth of 124 m and width of 75 km but did not cite a source. Still more recently, *Goff et al* . [2013] mapped shelf breaks along the U.S. Mid-Atlantic Bight, using isobath spacing to identify break positions. *Harris et al* . [2014] presented the first quantitative geomorphology of the global oceans, a mapping product that includes a representation of shelf geography. *Harris et al* . [2014], however, visually interpreted and manually digitized the shelf with guidance from bathymetric contours. Today, Notwithstanding the importance of the continental shelf, the descriptions, and statistics of those early investigators, many whose works are now a half-century or more old continue to be cited [ *Harris et al* ., **2014**; *De Haas et al* ., **2002**; *Anderson and Anderson* , **2010**; *Allen* , **2006**; *Chen and Borges* , **2009**; *Cook and Carleton* , **2000**; *Gao and Collins* , **2014**; *Helland-Hansen et al* ., **2012**; *Spalding et al* ., **2007**; *Pinet* , **2006**; *Hayden et al* ., **1984**] despite the wealth of new data. That these earlier findings persist could stand as testament to their veracity. On the other hand, a lack of sufficient global-scale data, and/or more robust analysis methodologies during much of this time period, may provide an equally likely explanation. That no one, to our knowledge, has yet reexamined the geomorphic structure of the land-ocean transition zone and reviewed the metrics employed to describe it using modern high-resolution data sets and newer geospatial classification and extraction methods was the motivation for this study.

This paper presents a new approach to mapping and analyzing the coastal ocean seafloor. Our objective is not, however, to present or propose a formal definition for what is a shelf but rather to show how a rigid interpretation is insightful. More specifically, we employ a quantitative methodology in lieu of subjective interpretation (1) to map the continent-ocean boundary and coastal ocean plains and (2) to use this new interpretation to evaluate some long-standing assumptions associated with this region (e.g., depth, slope, and width) and its variability.

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# 2 Approach

## 2.1 The Geomorphon

Considering that sea level is dynamic and ocean basins have complex tectonic and sedimentary histories, the boundary between land and sea can be defined in different ways [ *Hedberg* , **1970**]. For simplicity, this transition zone is hereafter referred to as the shelf. Geomorphically, the region is fundamentally constrained by the shoreline and seafloor slope and depth. With this in mind a quantitative, global geospatial analysis was undertaken. The approach used in our investigation is founded on an innovative concept/method in landform classification: the geomorphic phonotype, or geomorphon [ *Stepinski and Jasiewicz* , **2011**; *Jasiewicz and Stepinski* , **2013**].

Geomorphons derive from a subfield of computer image analysis research referred to as texture classification [ *Jasiewicz and Stepinski* , **2013**], where textures in an image are defined by intensity variations seen in adjacent and nearby pixels. By examining pixel variations, patterns emerge that reflect unique texture signatures or types. With geomorphons, elevation or depth values of a raster are used to define Earth surface textures or patterns (e.g., hills, slopes, peaks, valleys, and flats). The result is a continuous topographic model of an actual landscape. In the present study, regions across a bathymetric surface model were mapped as shelf when the geomorphon classifier assigned the flat archetype, and when additional depth and continuity constraints (as described below) were satisfied.

The geomorphon-based analysis (Digital Surface Models, DSMs) presented here utilized a set of three raster surface layers: bathymetry, slopes, and shelf geometry, derived from the Earth Topography 1 (ETOPO1) 1 arc sec Global Relief Bedrock Model bathymetry [ *Amante and Eakins* , **2009**]. The first is a continuous bathymetry data set mapping locations where water depths represent potential shelf area. Pixels are encoded as either floating point depth values or null values over locations where shelf is not possible. Similarly, a second raster surface characterizes the distribution of very low bottom slopes indicative of the near-planar shelf surface. Criteria established for possible shelf water depths and bottom slopes are described below. The final analysis product (layer) defines the shelf's geographic extent. The shelf is represented as a unary raster surface with

## 2.2 Shelf Depth

Shepard [via *Hedberg*, **1970**] and others have recognized that continental shelves may occur in relatively deep water (over 600 m), and for this reason, we used the global bathymetric data and not preconceived ideas or rules to define the potential depth limit. The depth domain was identified using natural breaks optimization [*North*, **2009**; *Fisher*, **1958**] on a 100,000 observation random sample taken from the ETOPO1 global bathymetry. Natural breaks produced the series of five nonoverlapping depth clusters seen superimposed over the depth-latitude scatter plot in Figure 1. Comparing the natural breaks results against the background data shows that the base of the shallowest depth class (i.e., 1,211 m) coincides well with a depth of reduced point density between a shallower and deeper region of higher data density (Figure 1). This suggests a valid cluster. The result was interpreted as sufficiently strong to warrant adoption of the 0 to 1211 m class to define the depth domain for the global shelf evaluation. Interestingly, the four remaining natural breaks clusters fail to clearly partition the distribution of depths in deeper waters. This duality in goodness of fit between the shallow and deeper clusters might be attributable to artifacts associated with the natural breaks optimization method. On the other hand, we believe, as suggested by *Shepard* [**1948**] and *Hedberg* [**1970**], that this reflects the clear separation of the oceanic coastal plain (i.e., the shelves associated with the continents) from the ocean basin area.

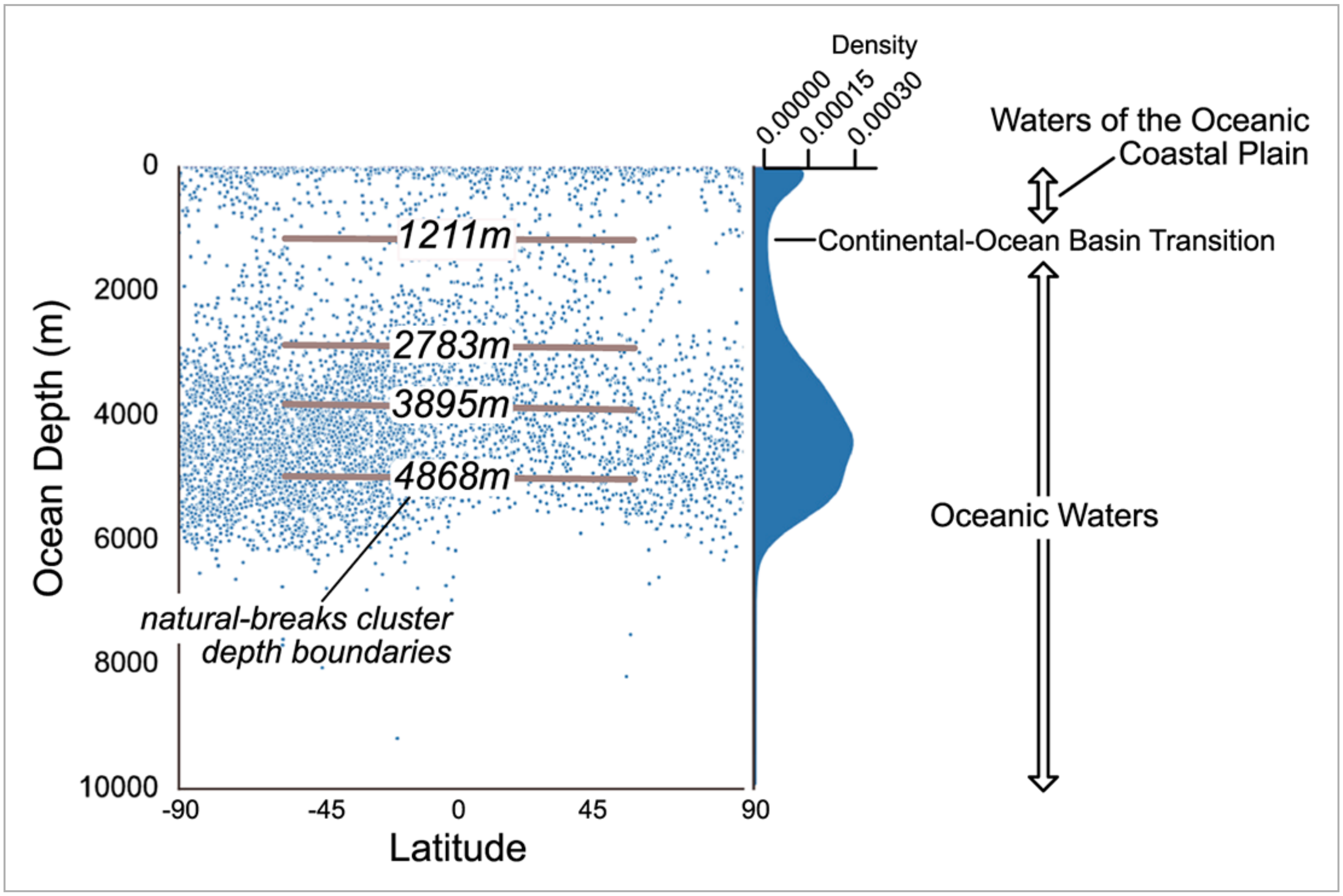

**Figure 1.**

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the four cluster depth boundaries produced from the Natural Breaks analysis. The shallowest of the four divisions (1211 m) lies between regions of higher data density in shallow and deeper waters; this break is interpreted to represent the continental-oceanic basin transition. The remaining cluster boundaries, however, do not as clearly partition the deeper abyssal waters.

## 2.3 Shelf Slope

Fitting geomorphons to a surface model relies on the choice of a user-defined surface flatness (limiting bottom slope) threshold [ *Jasiewicz and Stepinski* , **2015**]. In the presented analysis a limiting shelf slope threshold was identified and used to set the requisite flatness parameter [ *Jasiewicz and Stepinski* , **2013**]. The shelf slope domain from which the threshold was derived is based on results from a study by *Wright et al* . [**2001**], who present an association between sediment gravity flows and bottom slope. Wright et al. noted that at slopes less than about 0.012 rad (~0.69°), suspended sediment, without additional assistance from wave or current stresses, settles out of suspension. When, however, slopes exceed this critical threshold, gravity alone is sufficient to maintain sediment in autosuspension and compel continued transport downslope. The authors further suggested a link between this threshold and the continental shelf break. Experiments looking at the distribution of slopes within the 0 to 1211 m depth layer, clustered using natural breaks optimization, resulted in one of the five class breaks falling at 0.76°. This break value agrees quite well with *Wright et al* .'s [**2001**] 0.69° autosuspension threshold slope. Given this accord, we use this physical threshold as the limiting flatness threshold parameter (i.e., defining the flat geomorphon archetype) in the classification.

## 2.4 Shelf Continuity

The final shelf selection criterion used in these analyses was continuity: the requirement that ocean shelves must have unbroken geographic communication with its associated continental or insular landmass. By unbroken communication, we mean there is a benthic connection to the land. Conceptually, this criterion is satisfied when an unbroken path exists across the modeled shelf that connects the shoreline to the distal shelf edge (break). With continuity and the other criteria, the shelves as quantitatively defined here do include portions of what have traditionally been called plateaus [ *Harris et al* ., **2014**], as there is no objective way to disconnect them. One salient example is found along the southeastern U.S. coastline, where it is possible to connect the shoreline out to the edge of the Blake Plateau on a path across a continuous, uninterrupted surface that never exceeds 1211 m in depth or 0.69° slope (i.e., geomorphon “flatness”). Portions of the coastal ocean where the depth and slope flatness criteria are met, but fail the continuity criterion, are not included in the shelf model nor analysis results.

The geographic distribution of global shelves was mapped from the ETOPO1 data using the Geographic Resources Analysis and Support System (GRASS) [ *GRASS Development Team* , **2015**]. More specifically, the morphology was determined with the GRASS r.geomorphon command [ *Jasiewicz and Stepinski* , **2015**]. To evaluate the performance of the mapping, the shelf surface was compared visually with the ETOPO1-derived bathymetry profile for random locations around the Earth. If the predicted shelf break visually coincided with the estimated position of the break as interpreted from the underlying bathymetric profile, the fit was deemed good (Figure 2).

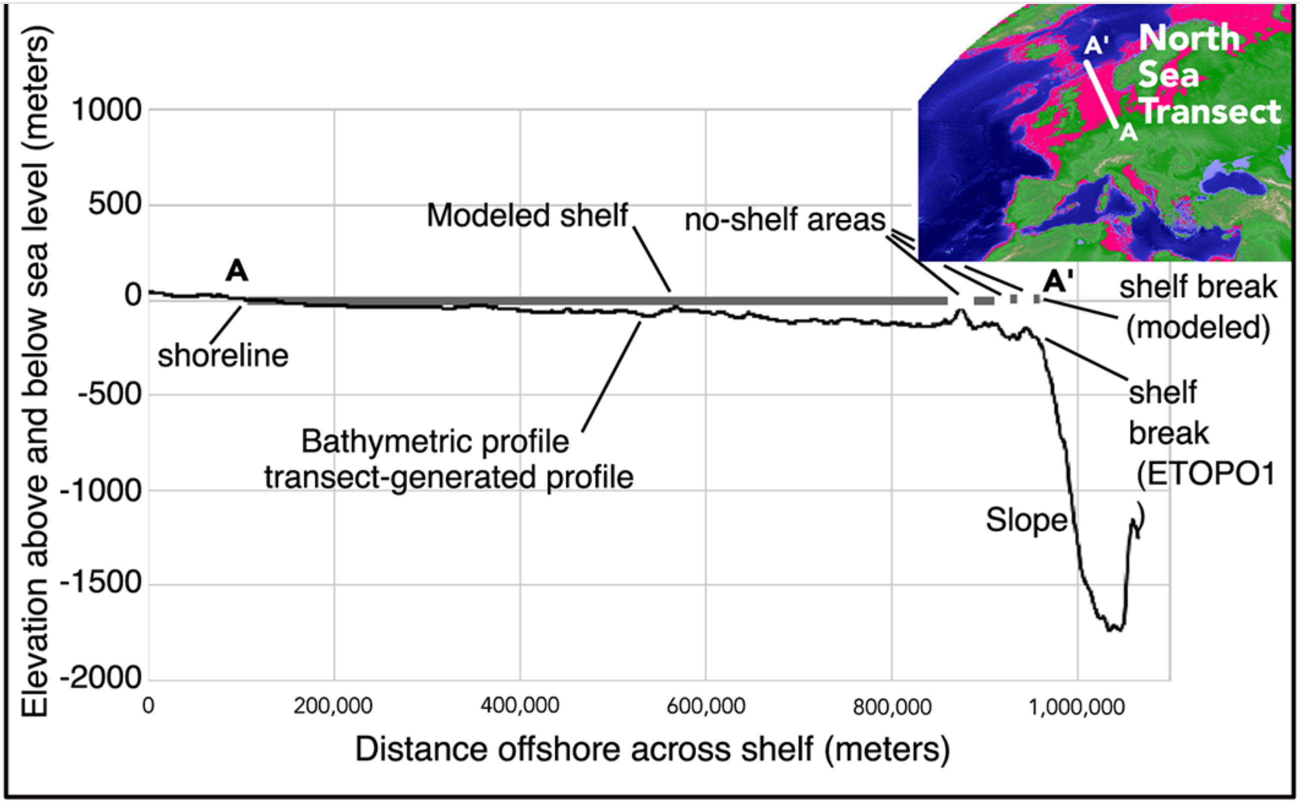

**Figure 2.**

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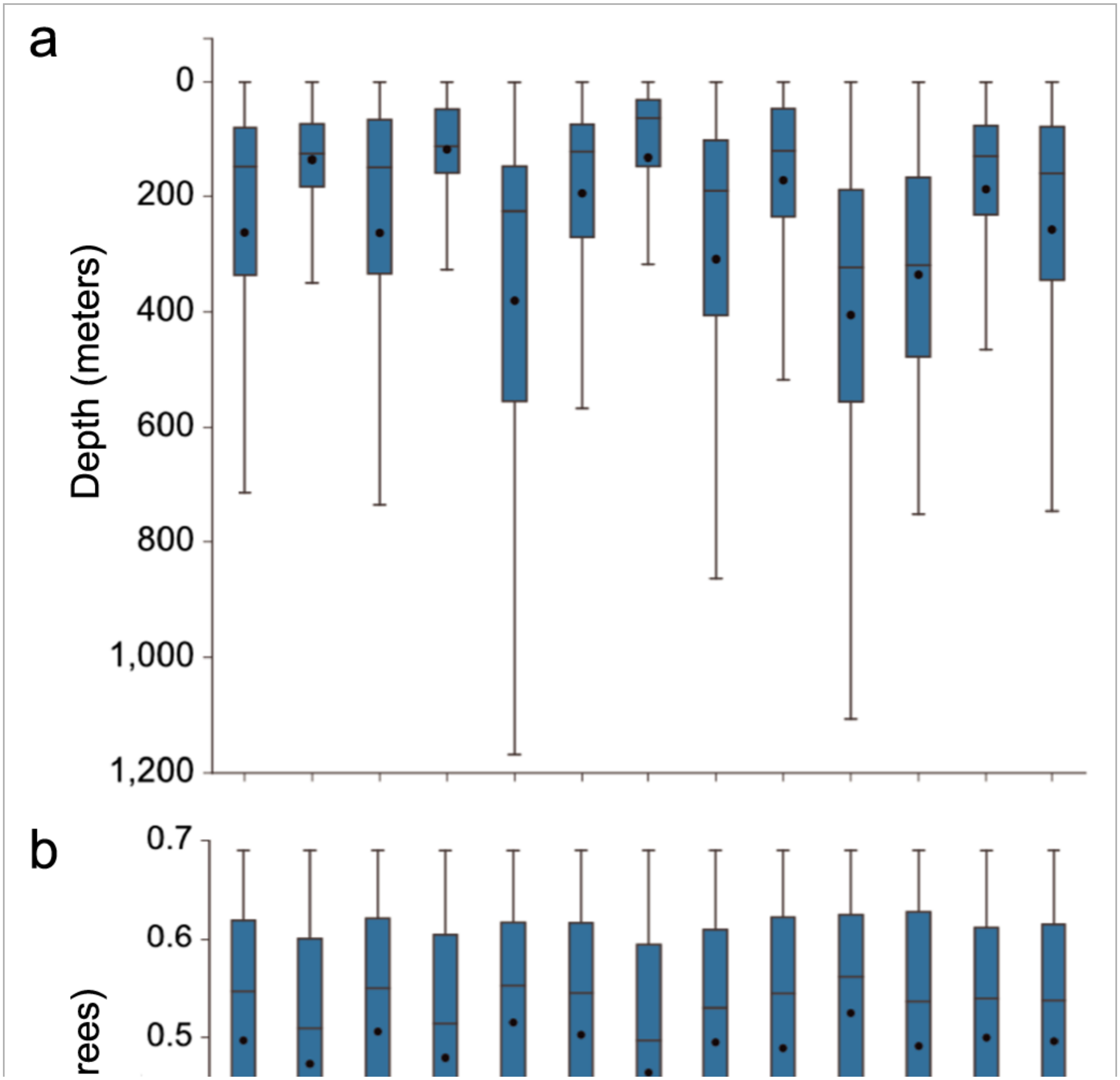
Example of the shelf analysis using a transect cast across the North Sea. The mapped "shelf" is depicted by the heavy horizontal line. Breaks in the shelf line, identified as regions of no-shelf in the illustration, represent areas along the profile where the sea bottom surface failed to meet one or more of the shelf definition criteria (e.g., canyons, depressions, ridges, and glacial scars). In this instance, bottom slopes exceeded the threshold in three locations near the distal end of the shelf.

The distribution of depths and slopes across the data were evaluated using sample points located along the geomorphon-modeled shelf breaks at 5 km intervals. Shelf widths were measured via 3045 approximately shore-normal transects with a nominal spacing of 100 km. The global shelf area was partitioned into 12 nonequal, nonoverlapping zones to characterize the continental shelves on a subglobal scale and enable comparisons between shelf morphologies around the world. The partitioning was based on continental and subcontinental geographies that in large measure paralleled the divisions defined by Shepard in his continental shelf "tour de monde" [ *Shepard* , **1948**, **1973**]. Our single departure from Shepard's groupings is in the Indian Ocean where it was decided to merge the shelves of Eastern Africa with those of Southern Asia. Doing this permitted the assessment of shelf differences and variability based on geography and, with some overlap, tectonic setting.

# 3 Results and Interpretation

## 3.1 The Global Shelf

with a large global standard deviation (±265 m), reveals a varied, highly skewed distribution of water depths across the world's continental shelves (e.g., global box plot shown in Figure 3a). The mean and median values depart from the average depth estimates of *Bouma et al*. [**1982**] (124 m), *Hedberg* [**1970**] (130 m), *Shepard* [**1948**, **1973**] (130 m), *Heezen and Wilson* [**1968**] (<200 m), and others. But our results align with early conclusions of *Shepard* [**1948**] and *Hayes* [**1964**] that highlight the large variability in shelf character, and with the global continent-ocean division at ~1200 m (Figure 1). The present results also suggest that the median, for its relative insensitivity to extreme values, may be a better measure of central tendency for shelf depth in lieu of the more commonly referenced arithmetic mean. Indeed, differences seen in the statistical results between those earlier and the findings presented here can be explained by the inclusion of the Blake Plateau and similar deep margin structures. But, we contend, if the morphology of these features is considered objectively, it fits that they are simply deeper sections of the submerged coastal ocean plain (i.e., shelves) and are geomorphologically not unlike those found in waters at higher latitudes (polar shelves), although their geological origin may differ. The natural breaks analysis and our continuity criterion both support this notion.



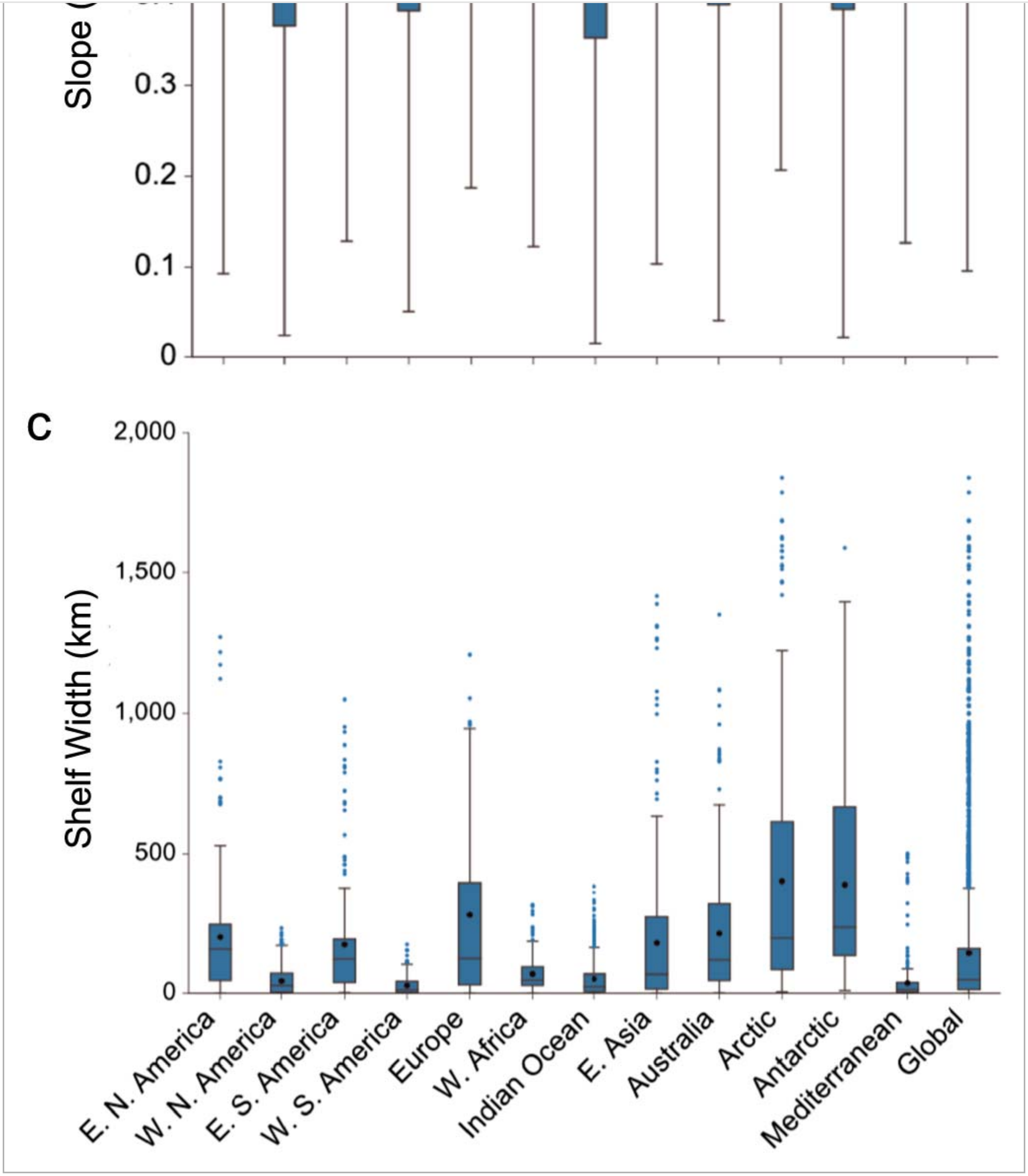


**Figure 3.**

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Box plots of (a) shelf depth, (b) slope, and (c) width indicating medians and interquartile variability. Each was measured at or out to the model-defined shelf break. Arithmetic means are also denoted by

The data reveal that shelf slopes (global box plot appearing in Figure 3b), in contrast to depths, display much less variability across all shelves. The global mean slope was measured at 0.50° (median = 0.54°; standard deviation = 0.15°). This consistency can be explained in part by the constraint placed on slope, where the maximum shelf break slope was held at 0.69°. Nevertheless, the mean and median slopes are each greater than reported by previous investigators [ *Hedberg* , **1970**; *Hedges and Keil* , **1995**; *Shepard* , **1948**, **1973**; *Heezen and Wilson* , **1968**; *Hayes* , **1964**]. They are necessarily less than the 0.69° model threshold, but the fact that 0.69° is not within one standard deviation of the measured mean lends credence to the argument that the slope limit does not exert a strong influence on the mapping. Thus, the calculated mean slope (0.50°) and standard deviation (0.15°) accurately reflect the slope of the shelf around the globe. Transect shelf-width analysis reveals that shelf width, like depth, exhibits much variability (Figure 3c). The calculated global mean width is 143 km, a value twice that reported by *Shepard* [**1948**] at 75 km. The standard deviation is, however, very large at 242 km.

## 3.2 The Regional Shelves

Based on the 12 nonoverlapping regional subdivisions, the deepest shelves (mean = 405 m; median = 323 m) occur over the glacially influenced Arctic Ocean, followed by Europe (mean = 381 m; median = 226 m), and Antarctica (mean = 336 m; median = 319 m) (Figures 3a and 4). The Arctic and European shelves are also the steepest in slope (mean = 0.53°, median = 0.56 and mean = 0.52°, median = 0.55°, respectively). The similarities seen between Europe and the Arctic are not surprising considering the proximity of the two regions. Interestingly, the shallowest shelves are areas of convergent or “active” margins (e.g., west coasts of North and South America, Southern Asia along the Indian Ocean, and the Mediterranean Sea), and this likely reflects the recent tectonic history of these areas. Also, this suggests that not only their width but also their shallowness may encourage shelf sediment remobilization and transport to the deep sea due to episodic wave-current reworking [ *Wiberg et al* ., **1996**]. Trailing-edge (i.e., “passive”) margins exhibit shelf depths that overlap or sit in between convergent and glacial margins (Figure 4). The only regional anomaly observed is that of West Africa, a passive margin with a shelf that plots in the vicinity of the convergent-margin group (Figure 4). Other investigators have also discussed the unusual character of these narrower and deeper African shelves as falling intermediate between tectonically active and passive margin classification [ *O'Grady et al* ., **2000**].

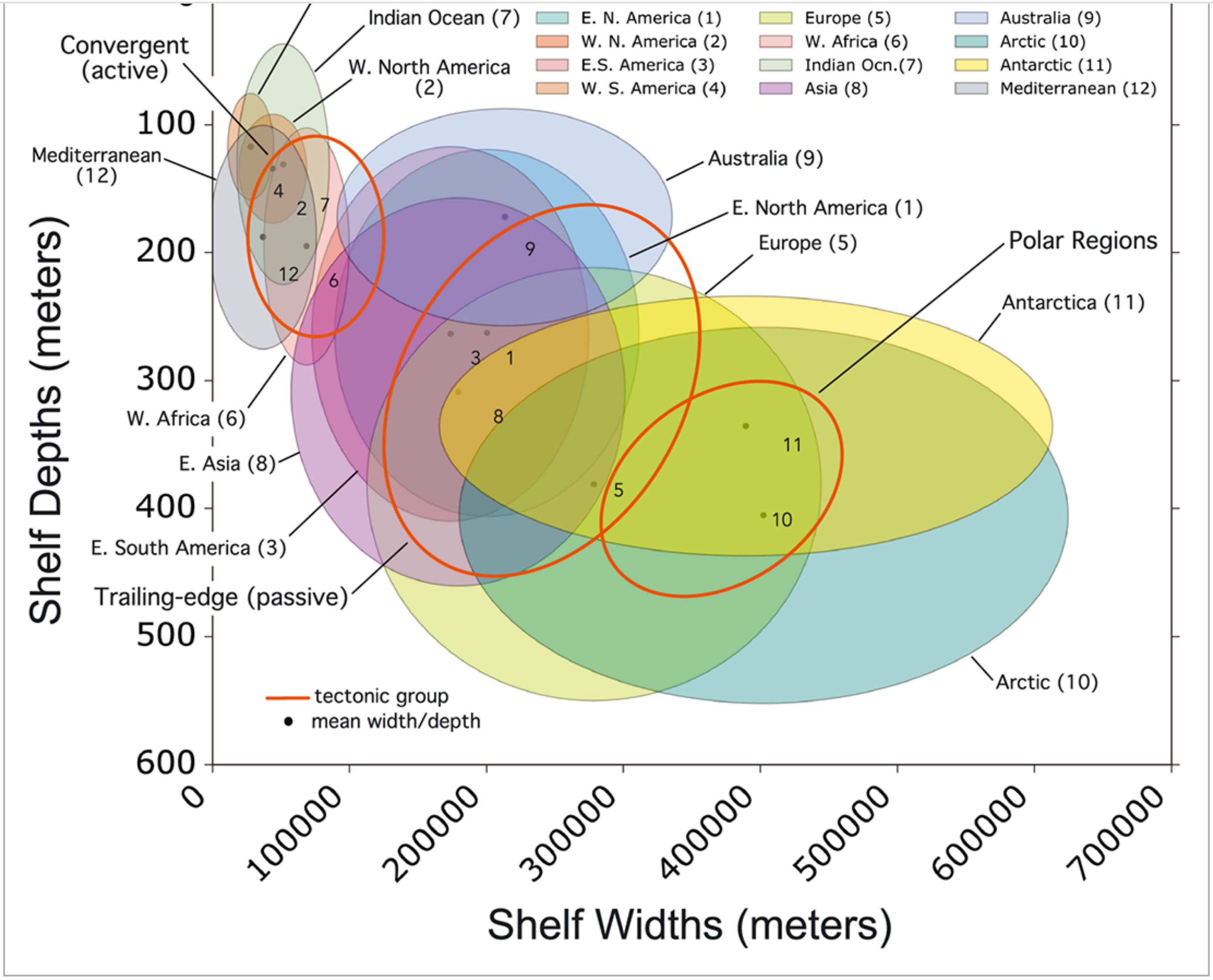

**Figure 4.**

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Shelf widths and depths by region. Bubble plots indicate mean shelf widths and depths (at the model-defined shelf break) for each of the 12 nonoverlapping geographic regions. The three ellipses show three manually identified data regions: convergent, trailing edge, and glaciated shelves.

Shelf width is hypothesized to have a critical control on sediment and carbon export to the slope [ *Milliman and Syvitski* , **1992**; *Walsh and Nittrouer* , **1999**], and this may have major ramifications for global elemental budgets [e.g., *Blair and Aller* , **2012**]. The narrowest regional mean shelf was measured at just under 28 km along South America's Western Coast, while the widest exceeded 400 km (436 km) adjacent to the Arctic Continent. In fact, not only are the Arctic and Antarctic shelves the deepest (mean = 405 m and mean = 336 m, respectively), they are the widest by a large amount (Figures 3c and 4). Shelves near the poles (e.g., Barents and East Siberian Seas in the Arctic and Ross and Weddell Seas along the Antarctic) are almost twice as wide, on average (mean = 402 km and 389 km for the Arctic and Antarctic, respectively), as those found along temperate zone passive margins (mean = 200 km for North America's eastern coast), and 3 to 4 times wider than tectonically active margins. The widest measured portion of a shelf in the present study (~1,850 km) was for a transect across the as well as being the most variable outside the polar region, was the European shelf (mean = 278 km, median = 124 km, standard deviation = 333 km, longest single transect >1200 km). Explanation for the large values observed across Europe's margin comes in large part from the North Sea.

Shelves along the coastline of Southeastern Asia and Northeastern Australia are also wide, with some individual transects spanning across the South China and Arafura Seas in excess of 1000 km (>1400 km and >1300 km, respectively). Although wide shelves may be areas with large deltas, carbon incineration can be maximized in these areas (e.g., the Gulf of Papua) [ *Blair and Aller* , **2012**]. These wider sections are, however, counterbalanced by shelves in other parts of the same region with widths less than 1 km (the shortest transect for the SE Asian region was measured at 0.3 km). But, these narrow shelves (i.e., <1 km) represent distances less than the resolution of the interpolated ETOPO1 source bathymetry and so should be interpreted with caution. Nevertheless, narrow shelves with fluvial input are known to be areas of high carbon burial efficiencies (e.g., Waiapu River shelf, New Zealand) [ *Blair and Aller* , **2012**]. The clear left-tending skew in the shelf widths for Asia (mean = 179 km, median 68 km, standard deviation = 251 km) demonstrates this large width dichotomy—attributable to the tectonic complexity of the region [ *Shepard* , **1973**]. Not surprisingly, those shelves resident along convergent margins (e.g., the west coasts of North and South America, the Indian Ocean, parts of East Asia, and the Mediterranean) are the narrowest (Figures 3c and 4). This latter group also are the shallowest on average (mean = 117 m along Western South America; mean = 130 m along the Indian Ocean).

Variation in shelf character (i.e., the shelf-like nature of a region) can be assessed by considering the area that is identified as nonshelf within the boundary of a shelf region. Nonshelf pixels in the present analysis data include portions of canyons, troughs, ridges, escarpments, and other bathymetric features that do not satisfy one or more of the shelf selection criteria. Globally, about 25% of the defined shelf regions are classified as nonshelf; this is in general accord with the findings of *Harris et al* . [**2014**] who estimate high-relief shelf (>50 m vertical change over 5 km) is ~24.8% of the total shelf area. Regions with high nonshelf percentages include Asia, the Indian Ocean, and Antarctica—the latter of which has >50% classified as nonshelf. The significance of this finding is that while the ocean coastal plains should be recognized as potentially broad, flat, and fairly continuous regions, they are in fact complex, commonly interrupted by areas of different geomorphic character, and this can have important implications physically (e.g., for upwelling), geologically (e.g., for material transport downslope), ecologically, or otherwise. While this global perspective on the shelf is important, to learn more about shelf morphology and function, analysis of high-resolution bathymetric data is essential. The reality remains, however, that much (likely >90%) of the Earth's ocean coastal plains have yet to be mapped using multibeam echo sounding. To do so is a critical next step for ocean science.

## 4 Conclusion

Here we present a new, modern analysis and description of the subaqueous edge of the landmasses (i.e., the global coastal ocean plains or continental shelves). The approach taken was unique for its objectivity, broad applicability, and new insights. Using a quantitative, reproducible terrain classification method, and contemporary data and research [ *Wright et al* ., **2001**], a much improved understanding of the land-sea boundary is realized. Based on global data, it is determined that the continent-ocean basin transition occurs as deep as ~1200 m, and slopes are <0.7°. After mapping the shelf globally based on depth, morphology, and continuity, results show that shelves are deeper (mean depth is ~258 m), wider (mean width is ~143 km), and more steeply sloped (mean slope is 0.5°) than previously reported. The width and depth of the shelf varies dramatically by region and within most regions due to tectonic processes and geologic history, and this morphological variability has important

Also, sediment, solute, and carbon cycling are strongly affected by the nature of the margin, and shallow and narrow margins of active margin areas around much of the Pacific are locations where carbon is more efficiently exported and buried. Finally, the amount of nonshelf area within different shelf regions of the Earth was determined to be ~25%, and this is critical because it highlights how shelves are not simply wide, flat, homogeneous terrains. Rather, they are commonly dissected and rugged, and for this reason, and for their incredible importance, more effort is needed to map these coastal zones using state-of-the-art multibeam technology.

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