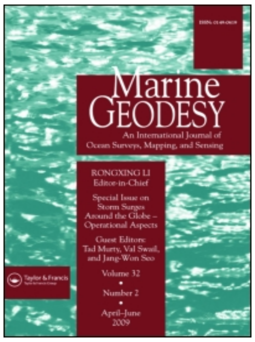

Marine Geodesy

ISSN: 0149-0419 (Print) 1521-060X (Online) Journal homepage: http://www.tandfonline.com/loi/umgd20

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To cite this article: F. D. Esteban, A. Tassone, M. Menichetti & E. Lodolo (2017) Application of Slope Maps as a Complement of Bathymetry: Example from the SW Atlantic, Marine Geodesy, 40:1, 57-71, DOI: 10.1080/01490419.2016.1269033

To link to this article: http://dx.doi.org/10.1080/01490419.2016.1269033

Accepted author version posted online: 12 Dec 2016.
Published online: 12 Dec 2016.

MARINE GEODESY
2017, VOL. 40, NO. 1, 57–71
http://dx.doi.org/10.1080/01490419.2016.1269033

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Application of Slope Maps as a Complement of Bathymetry: Example from the SW Atlantic

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ABSTRACT
Topographic and bathymetric maps are commonly used to represent the morphology of the Earth's surface at different scales. However, there are specific geological aspects or features that may be masked or not sufficiently highlighted by solely those data. This article shows how the slope maps (or clinometrics), elaborated from the same bathymetric data, are a useful tool to overcome these limitations. To this purpose, we analysed an example of the South-Western Atlantic area where a slope map was produced from the General Bathymetric Chart of the Oceans (GEBCO) bathymetric grid. We show how the slope maps can significantly improve the morpho-bathymetric (or topographical) descriptions and allow extrapolation of interpretations or observations from analysis of seismic sections, identification or highlighting of small morpho-structures, and inference and the distinguishing of areas of diverse morphologies in relation with the sedimentary processes. We propose and discuss the use of slope maps as a complement to bathymetric maps for specific geological studies at macro- and meso-scales.

ARTICLE HISTORY
Received 7 June 2016
Accepted 1 December 2016

KEYWORDS
Bathymetry; geomorphometry; slope; southwestern atlantic; terrain analysis

Introduction

Bathymetric maps represent relief or seafloor topography and their use allows identifying different morpho-bathymetric elements (or landform type), such as abyssal plains, continental shelves, ridges, trenches, and fracture zones (Figure 1). However, bathymetric maps have some limitations. Generally, it is difficult to determine the location of slope breaks (e.g., of the continental shelf) that may indicate the boundary of a morpho-bathymetric feature or a sedimentary body. The macro-scale morpho-bathymetric features can mask the meso-scale ones. In studies of regional or global scale, there may be minor morpho-structural elements of geological relevance that are not evidenced in bathymetric maps.

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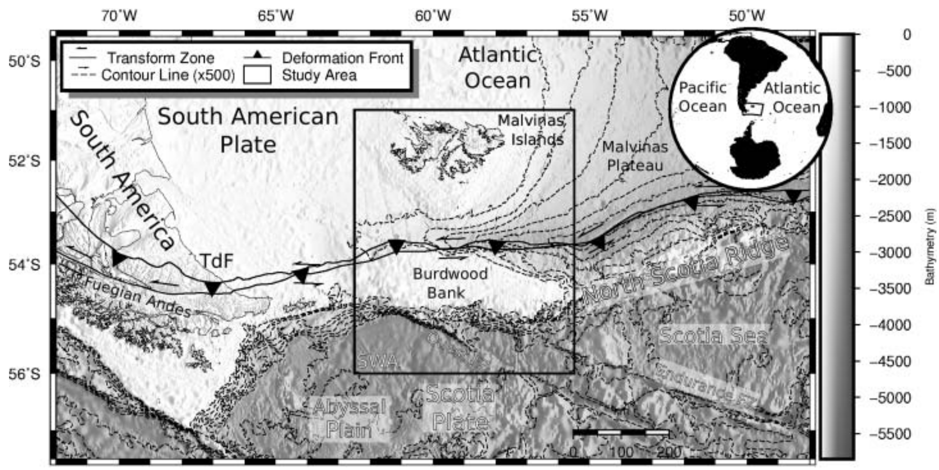

Figure 1. Bathymetric regional map (source: GEBCO) with the location of the study areas of the South-Western Atlantic Ocean (SWA). TdF: Tierra del Fuego Island. The structures are taken from Esteban (2014).

Identification of slope breaks allows a better description, characterization, and comparison of morpho-bathymetric elements and generally improves the regional study. The boundary of many of the undersea features such as slope feet, canyons, shelves, trenches, troughs, and fracture zones are defined by slope breaks (International Hydrographic Organization [IHO] 2013). Contour lines (every 10, 50, and 100 m) have been recently used to map those slope breaks by Harris and Whiteway (2011) and Harris et al. (2014). Moreover, recognition and mapping of meso-scale reliefs may allow identifying geological structures (as contourite deposits and folds axes) superimposed on to the macro-scale reliefs. The slope (or clinometric) maps, calculated from the relief gradient, constitute a useful tool to identify and emphasize these aspects.

Slope maps are used to represent the land relief, but in contrast to topographic maps where the altimetry is represented numerically with contour lines or with colour bands, the slope values correspond to the angle (in degrees) of the Earth's surface. They show quantitatively the maximum slope of the relief. This allows to clearly identify and correlate the homoclinal (horizontal and inclined) areas as well as smooth and abrupt changes in slopes (breaks). These aspects cannot be easily seen on bathymetric maps since in them the slopes are perceived only qualitatively. That is why the slope maps have certain advantages over bathymetric (topographic) maps.

The slope maps have been known for decades (see Pike et al. 2009 and references therein). Originally, the elaboration of these maps was limited because its elaboration was tedious and time-consuming, and the results were poor (due to the accuracy of the data). But, with the development of computers, Geographic Information System and Digital Terrain Models (DTM), this is no longer the case. However, nowadays the use of slope maps and geomorphometry, in general, for structural studies is limited (Diaz-Torres et al. 2012; Ganas et al. 2005; Jacques et al. 2014; Lecours et al. 2016). Studies in off-shore areas are mainly related to the regions with swath bathymetric data (Eichhubl et al. 2002; Hernández-Molina et al. 2010; Ismail et al. 2015; McAdoo et al. 2000; Rovere et al. 2014; Strozyk et al. 2009; Wilson et al. 2007), although single beam echosounder is also used (e.g. Moskalik et al. 2013). The marine applications of geomorphometry are mainly oriented to geohazards, hydrodynamics, geomorphological mapping, biogeography, ecology, habitat mapping, and anthropogenic activities (see Lecours et al. 2015, 2016 and examples cited therein). The most developed applications of geomorphometry on land generally include hydrology, geomorphology, neotectonics, soil science, and agriculture (see Pike 2002; Grohmann 2004; Grohmann et al. 2007; Hengl and Reuter 2009 and examples cited therein). However, these applications generally deal with micro-scale features and analysis of slope maps related to meso- and macro-scales is lacking.

The slope maps have the advantage that they are easy to create and their results are intuitive and easy to understand. Instead, other geomorphometric parameters (e.g. curvature, fractal dimension, and terrain roughness) are more difficult to elaborate and some experience and training are required for their understanding and use. For these reasons, this contribution is centred on the advantages and limitations of slope maps.

We believe that the use of slope maps has advantages and applications that exceed its common uses and that they should be used in a generalized way for different types of geological studies (such as geomorphology, sedimentology, and structural geology) and at different scales. In this contribution, we evaluate the application of slope maps for the analysis of meso- and macro-scale marine features. We have selected an area located in the South-Western Atlantic Ocean (SWA; Figure 1) as an example. In this area, a geological complexity shows the diversity of morpho-bathymetric units that allow a better analysis of the advantages of the methodology.

Database and methods

Database

The bathymetric data used are the General Bathymetric Chart of the Oceans (GEBCO 2014 grid, v. 20141103). It has a horizontal resolution of 30 arcsec *(ca.* 926 m), which was largely generated by combining quality-controlled ship depth soundings and multibeam data, with the predicted depths between the sounding points guided by satellite-derived gravity data (Figure 2; Weatherall et al. 2015). The predicted depths are based on Sandwell and Smith gravity anomaly (v. 16.1; Sandwell and Smith 1997). Moreover, seismic section RC2106-145 was used to show the morpho-bathymetric features in a profile (see http://www-udc.ig.utexas.edu/sdc/cruise.php?cruiseIn=rc2106 for details).

The Generic Mapping Tools software (v. 5.1; Wessel et al. 2013) was used to generate the slope grids (as well as the maps and 3-D blocks) from the GEBCO bathymetric data. The resulting slope grid has the same spatial resolution as the original grid (30 arcsec; *ca.* 926 m).

In the study area, the data have a good accuracy (less than 50 m) due to the high data density of the surveyed area (Figure 2). In addition, the area has been widely studied by the authors with seismic data (multi- and monochannel; Figure 2), which allow to confirm the morpho-structures identified in the bathymetric data (Esteban 2014; Esteban et al. 2010, 2011, 2012, 2013; Perez et al. 2015).

In this work, we will refer to macro- and meso-scales. The first term refers to the regional features (more than 100 km in length and differences in depths higher than 2000 m), which are clearly identified in bathymetric maps (e.g., abyssal plain and Burdwood Bank; Figure 1). The meso-scale corresponds to moderate features (*ca.* 10–100 km in length and differences in depths of *ca.* 100 m). The micro-scale is referred to local features (less than 10 km in

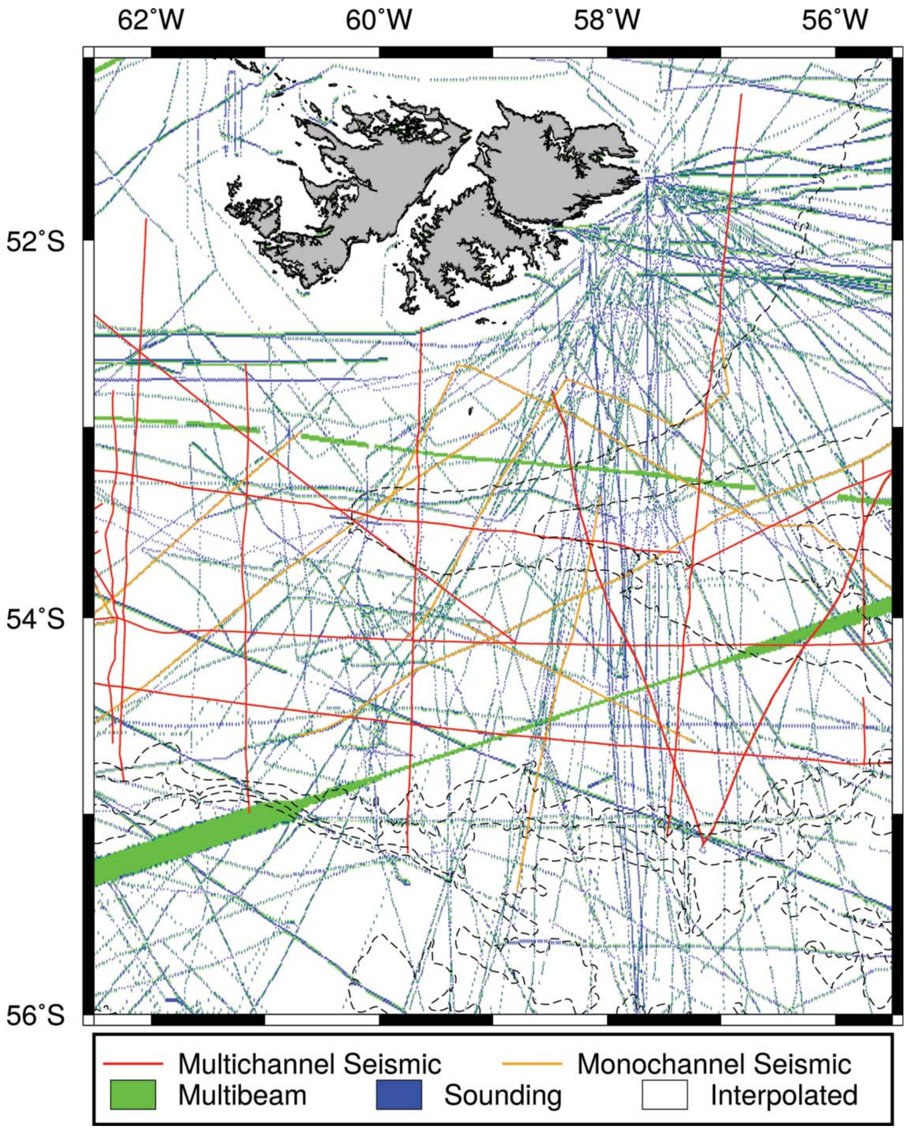

Figure 2. Identification of the source data of the GEBCO grid and seismic lines. The contour lines (dashed black line)—every 500 m. See location in Figure 1.

length and differences in depths less than *ca*. 100 m), which are not analysed due to the accuracy of the data set.

Fundamentals of slope maps

The slope maps, as shown in figures 3 and 4, clearly distinguish horizontal areas such as abyssal plains (Scotia Sea), continental shelves (Argentina and Burdwood Bank); areas slightly sloping as folds in a fold-and-thrust belt; or strongly sloping areas (continental slope).

The elaboration of the slope maps is done by calculating the gradient of the relief. From a mathematical point of view, the calculation of the slope gradient corresponds to the modulus

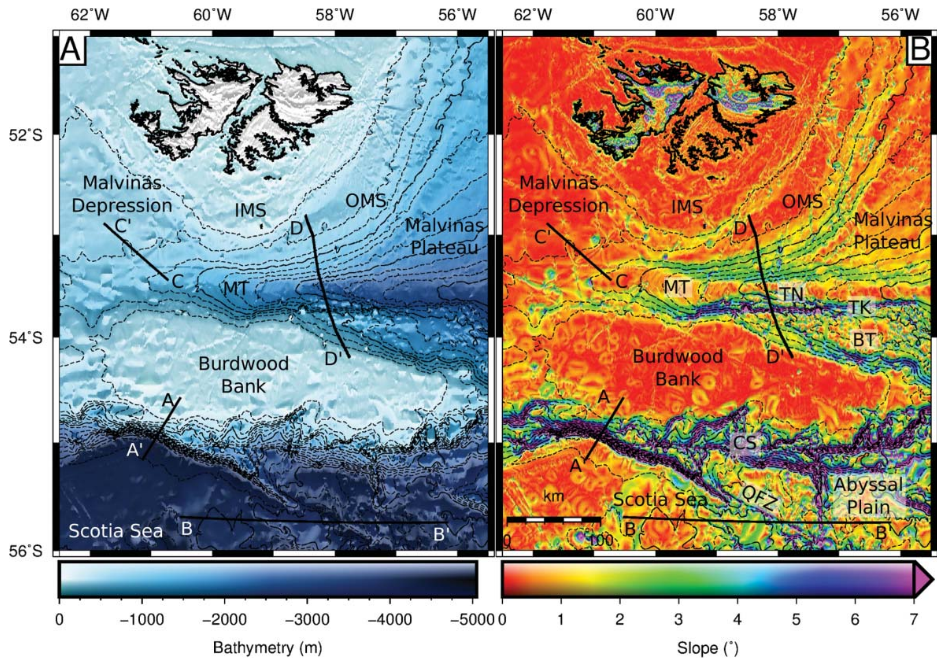

Figure 3. (a) Bathymetric and (b) slope map of the SW Atlantic. Letters (A–D) indicates location of profiles of Figure 7. Profile D coincides with seismic section RC2105-145. See location in Figure 1. The contour lines (dashed black line)—every 250 m. BT, Burdwood Terrace; CS, continental slope; IMS, inner Malvinas shelf; MT, Malvinas Trough; OMS: outer Malvinas shelf; QFZ, quest fracture zone; TN, thin-skinned fold-and-thrust belt; and TK: thick-skinned fold-and-thrust belt.

of the first derivative of the ground surface and reflects the maximum elevation change (see Olaya 2009 for more information). The processing using the first derivative is similar to the gradient analysis (Introcaso et al. 2008), and the analytical signal methodology (Nabighian 1972, 1984; Roest et al. 1992) is similar to the potential data processing.

Geologic background

The study area includes both the oceanic crust (Scotia Sea; Figures 3 and 4) and the continental crust (from Burdwood Bank to the north). The Burdwood Bank is a part of the North Scotia Ridge and corresponds to the eastwards extension of the Fuegian Andes (Figure 1). A thick-skinned fold-and-thrust belt (TK) characterizes the northern areas of the Burdwood Bank (Figures 3 and 4). It extends *ca.* 200 km in east–west (E-W) direction with Paleogene piggyback basins (Figure 4; Bry et al. 2004; Esteban 2014; Platt and Philip 1995). The Burdwood Terrace corresponds to an accretionary prism or relict collision complex generated by the oblique convergence of the Burdwood Bank against the Malvinas Plateau (Ludwig and Rabinowitz 1982).

The Malvinas shelf is a Paleozoic formation that outcrops in the inner shelf that deepens to the edges (Platt and Philip 1995). In the outer Malvinas shelf, the structural high is covered by Meso-Cenozoic sediments that constituted the South Malvinas Basin (Figure 4, Bry et al. 2004). To the southeast (SE), a large contourite deposit lies unconformably on the Cretaceous sequence (Koenitz et al. 2008) and corresponds to the outer Malvinas shelf

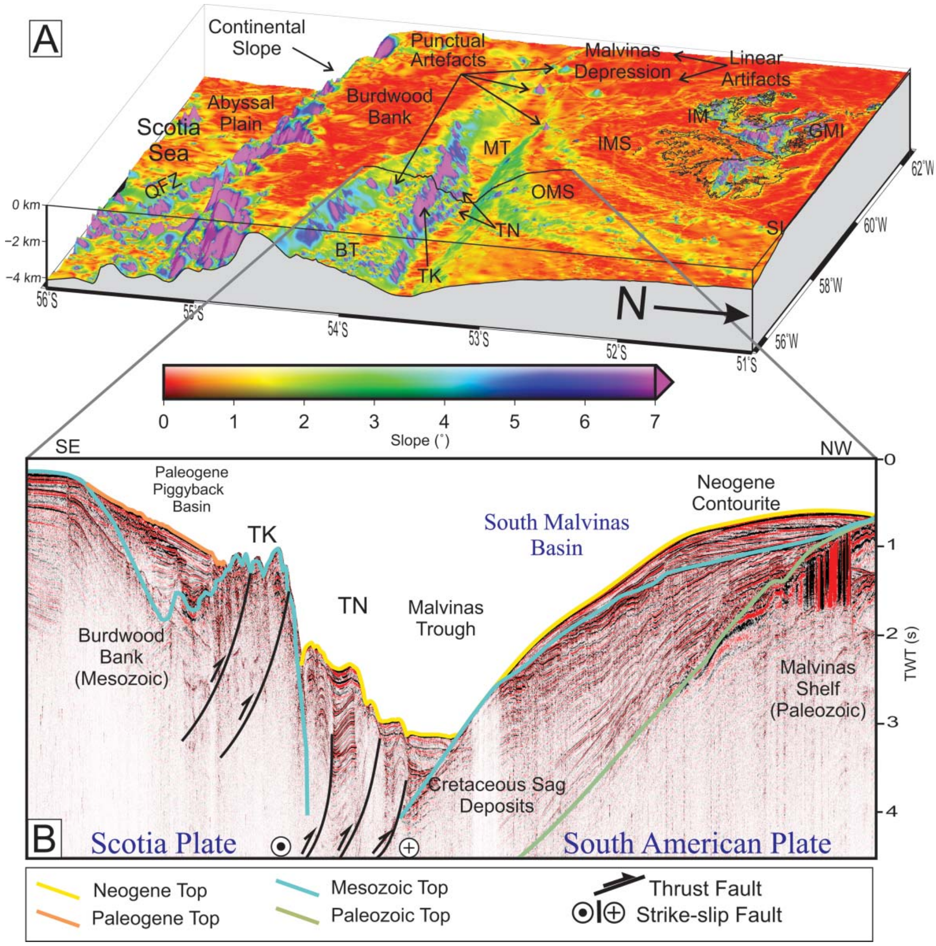

Figure 4. (a) 3-D view from the east of the SW Atlantic area. The figure is constructed by bathymetric grid (source: GEBCO) with the slope map superimposed (Figure 3b). (b) The multichannel seismic section (RC2106-145) between the Burdwood Bank and the Malvinas shelf provided by the Lamont–Doherty Earth Observatory (LDEO). Interpretation are taken from Esteban (2014). BT, Burdwood Terrace; GMI, Gran Malvina Island; IMS, inner Malvinas shelf; MT, Malvinas Trough; OMS, outer Malvinas shelf; QFZ, quest fracture zone; SI, Soledad Island; TN, thin-skinned fold-and-thrust belt; and TK, thick-skinned fold-and-thrust belt.

(Figure 4). The Malvinas Trough consists of Neogene turbidite deposits that overlie the Cretaceous units (Koenitz et al. 2008). An incipient folding of these deposits form the thin-skinned fold-and-thrust belt (TN) that spans *ca*. 60 km with anticlinal axis oriented WNW-ESE (Esteban et al. 2014; Figures 3 and 4).

Results

Theoretical explanation of the application of slope maps

For a better explanation of the utility of the slope maps, some theoretical topographic profiles and their corresponding slope profiles are analysed (Figure 5). The profile A1 is similar

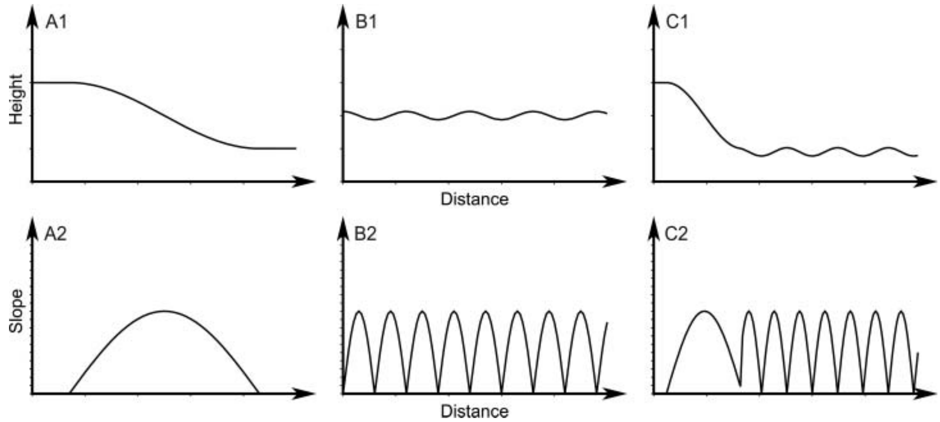

Figure 5. Theoretical topographic profiles (top) with their respective slope profiles (bottom).

to a topography dominated by a high-amplitude surface anomaly (or variation) characterized by two flat areas with an intermediate (slope) transition. In real cases it would correspond to the transition of a plateau to a plain or between a continental shelf and an ocean basin. The height differences would be clearly highlighted in a topographic map. However, the maximum values of the slope profile (A2) highlight the transition area where the slope is greatest.

The profile B1 is similar to a topography dominated by low-amplitude anomalies. For example, in nature this could be seen in a field of dunes in a succession of hills or in the typical roughness of the seafloor. On a topographic map, the reduced height variations would be difficult to appreciate. In contrast, the slope profile (B2) shows an alternation between the null and maximum values in relation to the flat and inclined areas, respectively. In a slope map these variations are clearly identified.

The profile C1 combines the previous two. It exhibits a high-amplitude anomaly followed by others with a low amplitude. On a topographic map, only the high-amplitude anomaly is clearly identified while the low-amplitude anomalies are masked. In contrast, in the slope profile (C2) both anomalies are clearly reflected.

From the analysis of the above examples, it is clear that the bathymetric maps only allow to clearly discriminate the anomalies or variations of high amplitude. Instead, the slope maps highlight the slopes of both types of the anomalies.

Morpho-bathymetry of the southwestern Atlantic Ocean

In the region of SWA, seven principal morpho-bathymetric units are identified: abyssal plain, fracture zones, continental slope, Burdwood Bank, Burdwood Terrace, Malvinas Trough, and Malvinas shelf (Figures 3 and 4). These units can be clearly identified by their bathymetry (Figure 3) that varies from less than 200 m in the Burdwood Bank and the Malvinas shelf to more than 4000 m in the Malvinas Trough and in the abyssal plain. The macro- and meso-scale morpho-bathymetric units are described below.

In the study area, the abyssal plain is characterized by depths greater than 4000 m and slopes ranging from 0° to 4°, the Quest and Endurance Fracture Zones are characterized by a northwest–southeast (NW-SE) orientation, depths between 2500 and 4000 m, and steep slopes (>5°; Figures 3 and 4).

The continental slope has an E-W trend with moderate to high slope angle values (>2°; Figure 3). It presents depths ranging from *ca.* 200 to 3500 m, and its limits with the Burdwood Bank and the abyssal plain are marked by slope breaks (Figures 3 and 4).

The Burdwood Bank is located south of the study area (Figure 3). It is a platform characterized by shallow depths (<200 m) and very low to null inclinations (<0.5°; Figures 3 and 6). Its total length is about 360 km and narrows to 115 km in the west (W) and to 80 km to the east (E). Its northern border with the Malvinas Trough is determined by an E-W slope break that steeps towards the east from *ca.* 1° to more than 5° (Figure 6). Towards northeast (NE), the border with the Burdwood Terrace is defined by a NW-SE slope break with moderate inclinations (*ca.* 3°).

The Burdwood Terrace is located between the Malvinas Trough and Burdwood Bank (Figures 3 and 6). It is characterized by the intermediate depths (1000 m), which increase towards the northwest (NW) (2500 m). It has an undulating surface with slopes ranging from 0° and 4° (Figure 6). In map view, it has a triangular shape with a length of *ca.* 160 km in the E-W direction. Its boundary with the Malvinas Trough is marked by an E-W steep slope (>7°).

In the study area the Malvinas Trough is a deep depression with a length of *ca.* 430 km in the E-W direction and 20 km in the north–south (N-S) direction. It is characterized by a low and regular inclination to the east (*ca.* 1°). Its depth decreases westwards from 3200 to 600 m (with a relatively gentle transition to the Malvinas depression). In its central part, at *ca.* 58° W, a series of 60-km-long hills with a WNW-ESE orientation and maximum slopes of *ca.* 3–4° (Figures 4 and 6). Its northern and southern boundaries are clearly marked by steep slopes. The northern boundary of the Malvinas Trough with the Malvinas shelf displays slopes of *ca.* 4° in the central part. To the south, it borders with the Burdwood Bank and the Burdwood Terrace, with slopes that range from 2° in the western sector to more than 8° in the eastern sector.

The Malvinas shelf has a slightly triangular shape with a length of 350 km in the E-W direction and 200 km in the N-S direction. This unit displays boundaries with the Malvinas Trough to the south (S), the Malvinas Plateau to the E, and the Malvinas depression to the SW. It is characterized by shallow depths (<750 m) and a gentle slope (<0.5°). A slope break (*ca.* 1.5°) identified at a depth of *ca.* 250 m divides the shelf into two concentric areas (Figure 3). The inner shelf develops around the Malvinas Islands and has a width of *ca.* 60 km. The outer shelf reaches a maximum width of *ca.* 40 km to the SE. It shows a progressive increase in the slope values from *ca.* 0° to 3° to the S-SW. The southern boundary of the platform is marked by a moderate slope break.

In the study area, the Malvinas Plateau presents a triangular shape area located NE. It is characterized by gentle regular slopes that progressively increase towards SSE (from *ca.* 0 to 1.5°). Its depth ranges from *ca.* 1500 m to the N to 2500 m in the SW. Its north-western and southern boundaries are clearly marked by steep slopes (*ca.* 3°) with the outer Malvinas shelf and with the Malvinas Trough, respectively.

The Malvinas depression is located NW and has a triangular shape in plain view. It has very smooth slopes (<0.5°) and depths of *ca.* 400 m, and its limits with the Malvinas shelf (NW) and Malvinas Trough (S) are defined by smooth transitions (Figure 3).

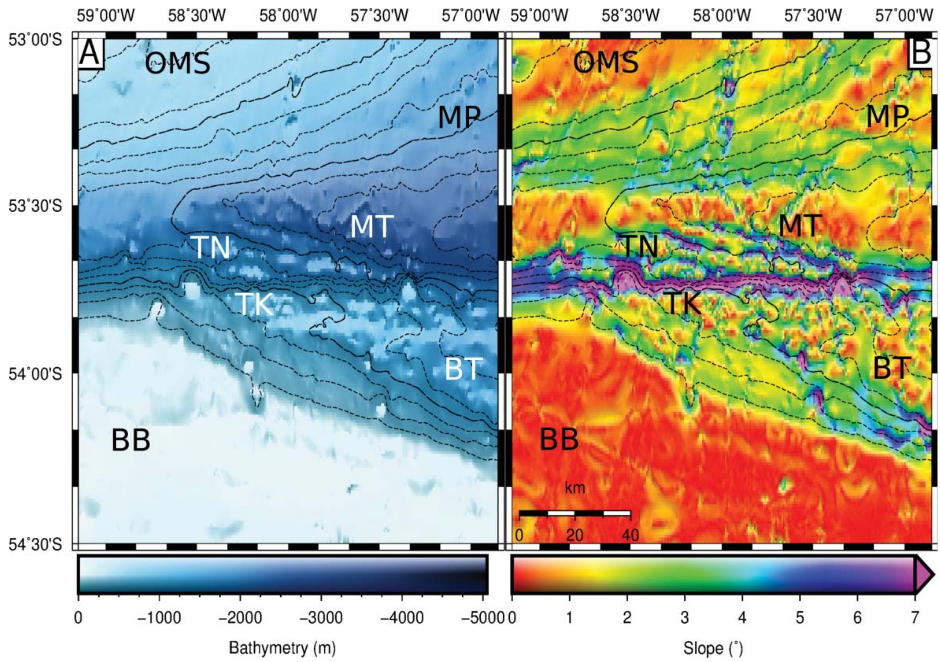

Figure 6. (a) Bathymetric and (b) slope map of the Malvinas Trough (MT). BB, Burdwood Bank; BT, Burdwood Terrace; MP, Malvinas Plateau; OMS, outer Malvinas shelf; TN, thin-skinned fold-and-thrust belt; and TK, thick-skinned fold-and-thrust belt.

Discussion: Usefulness and limitations of the slope maps

Advantages of the slope maps for geological studies

The slope maps have certain advantages for geological studies as described below:

(1) Slope maps improve the description of morpho-bathymetric units. The use of slope maps allows identifying and defining the boundaries of the morpho-bathymetric units. They can discriminate between transitional boundaries (e.g. between the Malvinas Trough and the Malvinas depression; Figure 7) and sharp limits marked by slope breaks (e.g. the Malvinas Trough and the Malvinas Plateau; Figures 3 and 4). In the last case the boundaries of the morpho-bathymetric units are more precisely located. This in turn, results in a better determination of the dimensions and shapes of the units. For example, determination of the Burdwood Bank dimension is necessary to locate the slope breaks that determine its boundaries, which are clearly highlighted by slope maps (Figure 3). In the profile A (Figure 7) an abrupt change of colour is observed in the slope profile associated with the boundary of the Burdwood Bank, while in the bathymetric profile the change is smooth. Furthermore, the quantification of the slope allows a more detailed description of morpho-bathymetric units itself. For example, the slope maps allow to describe more precisely the Burdwood Bank flat nature ($<0.5°$) or the Burdwood Terrace undulating surface (Figures 4 and 6). An improved description of the morpho-bathymetric units would allow a more precise comparison between different units (from the same region or from other areas around the world), which could indicate similar (or different) processes acting in the different units.

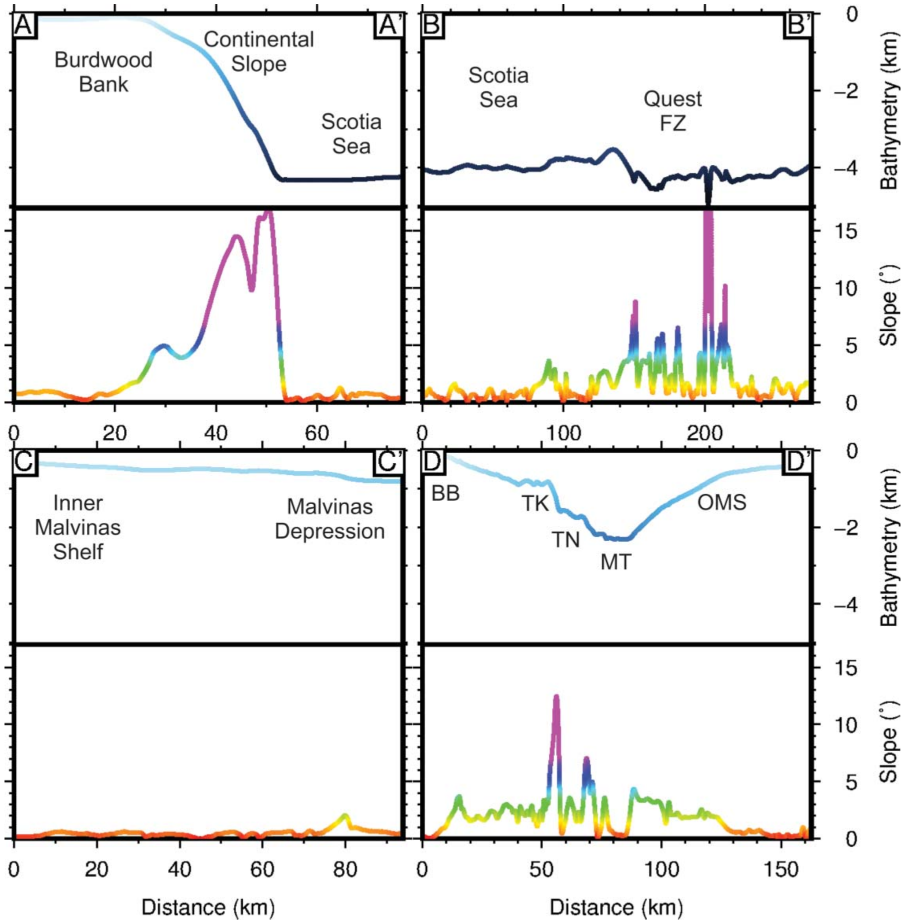

Figure 7. Real examples of topographic profiles (top) with their respective slope profiles (bottom). See Figure 3 for colour code and location. BB, Burdwood Bank; MT, Malvinas Trough; OMS, outer Malvinas shelf; QFZ, quest fracture zone; TN, thin-skinned fold-and-thrust belt; and TK, thick-skinned fold-and-thrust belt.

(2) Slope maps emphasize the location of slope breaks of geological relevance. For example, the boundaries of the Malvinas Trough and of the sedimentary deposits (contourite) of the outer Malvinas shelf are clearly highlighted (Figures 4 and 7d). The other examples are the boundaries between the continental shelf – continental slope and the continental slope – abyssal plain (Figures 3 and 7a).

(3) Slope maps are able to identify or highlight meso-scale geological landforms. The use of slope maps can highlight structural and sedimentological features that are difficult to recognize in bathymetric maps. Examples of this are the folds of the TN in the Malvinas Trough and the contourite deposit of the outer Malvinas shelf (Figures 4 and 6). In the profile D (Figure 7) the relief associated with the TK and the TN are highlighted in the slope profile by a strong colour change while in the bathymetric profile the colour change is smooth.

(4) Slope maps are used to infer and distinguish diverse morphologies in relation with sedimentary processes. On areas characterized by the oceanic crust, the development of a

sedimentation dominated by gravitational processes (turbidity and contour currents) will tend to fill the bathymetric lows, resulting in a smoothed seafloor. In a slope map, these areas will present a homoclinal slope. Instead, the areas of low or null sedimentation will tend to have a typical ocean crust roughness, which, in a slope map, will be observed as alternating inclined and horizontal areas. The profile B shows a transition of roughness in the Scotia Sea from a smooth seafloor to the W to a rough one to the E (Figure 7). The smooth area corresponds to a mounded drift that infill the bathymetric lows of the seafloor (Perez et al. 2015).

(5) Slope maps can integrate and complete interpretational observations from seismic sections. The combination of slope maps and seismic data allow obtaining information otherwise difficult to detect with just the use of seismic and bathymetric data alone. For example, in the seismic section RC2106-145 (Figures 4 and 6), TK and TN were identified between the Burdwood Terrace and the Malvinas Trough. By using the slope map it was possible to extrapolate each one in the plane, and thus the orientation and extent of the identified structures were determined: the front of the TK corresponds to the steep slope extending in an E-W direction, and the TN anticlines are correlated with the hills with WNW-ESE orientation of the Malvinas Trough (Figures 4 and 6). This application may be particularly important for submerged areas where data are expensive to acquire or of poor quality.

(6) Slope maps can highlight anomalous data (or artefacts) present in the DTM. For example, in the case of GEBCO grid, two types of artefacts are identified: (a) points with outlier values and (b) lines that match the tracks of the ships that surveyed the bathymetric data (Figures 2 and 4). In general, the anomalous point data are clearly recognized as small circular areas of high slope (Figure 8). The identification of these anomalous data is a helpful tool not only for the analysis and interpretation of the DTM but also for its preparation (see Reuter et al. 2009).

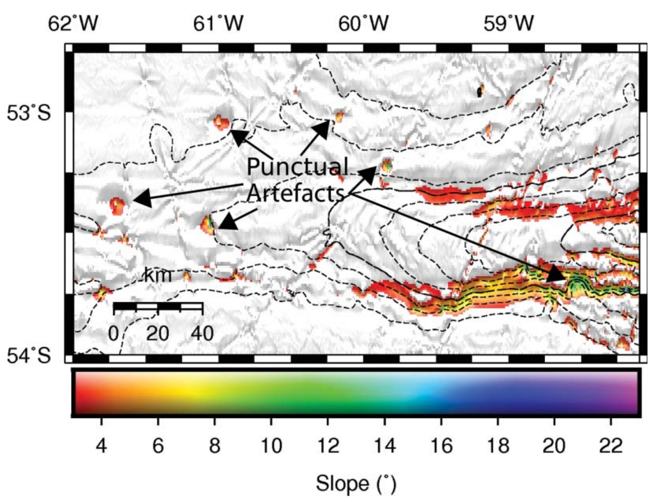

Figure 8. Slope map of the SW Atlantic centred on the Malvinas Trough (MT) with slope higher than 3°. This analysis helps identifying small circular areas of high values, which are often related to punctual artefacts. See Figure 4 for a 3-D view.

Limitations of slope maps for geological studies

The slope maps, when analysed singularly have certain limitations compared to the bathymetric maps: Since they highlight the meso-scale bathymetric variations, the large-scale variations may not be recognized. For example, the general deepening to the NE of the Burdwood Terrace is difficult to appreciate in the slope map given the meso-scale superimposed undulating topography (Figure 6). In contrast, in the Malvinas Trough, where there is no meso-scale relief (except for the TN), the regional slope can be clearly seen. This limitation can be avoided by using bathymetric maps or contour lines.

Another limitation is the lack of geographic direction of the slopes. Again, this can be identified by bathymetric maps or contour lines.

Contour lines versus slope maps

The great usefulness of the contour lines is to infer the slope magnitude from the high or low density of the contour lines (or isobaths). However, this technique has some limitations. First, this appreciation is only qualitative (or quali-quantitative), i.e. it is not possible to directly view the slope values from isobaths on a map, and this limits the application of the previously described advantages.

The second limitation in using the contour lines is its resolution. In the bathymetric maps, the isobaths are drawn at a given equidistance (for example, every 50, 100, 200 m, etc.) that define an additional resolution limit (besides the original grid resolution given by the bathymetric acquisition technique and the interpolation method). Topographic features of the size of the equidistance (or smaller) will be poorly identified. An example of this are the folds of the TN in the Malvinas Trough (Figure 6). It is formed by a series of *ca.* 50–60 km anticlines of long with a WNW-ESE orientation developed in the Malvinas Trough (Esteban et al. 2014). In Figure 6, the contour lines are drawn every 250 m, which does not allow to clearly identifying the morphology of the folds. Although a decrease of equidistance between isobaths would improve its resolution, it would also cause a loss in the quality of the figure given the large number of lines that saturate it.

Conclusion

The use of slope maps, as shown in this study, has some advantages for geological studies at meso- and macro-scale such as improving the morpho-bathymetric or topographic descriptions, integrating and completing observations or interpretations from seismic sections, identifying or highlighting minor geological landforms, inferring and distinguishing areas of low and high sedimentation on the seabed, and inferring changes in the outcropping lithologies. However, these maps have certain limitations (mask regional slopes, do not indicate the orientation of the slopes), which can be avoided by combining them with bathymetric maps or contour lines.

The slope maps allow overcoming the limitations of the use of contour lines. First, these maps quantitatively show the value of the slope. Second, they do not present a limitation in resolution since all bathymetric data are used for its generation.

Therefore, we conclude that the slope map gives important information to study the geology of an area. For better results, they should be used as a complement of bathymetric (or topographic) maps.

Acknowledgements

The authors thank the two anonymous reviewers for constructive comments and suggestions that improved the paper.

Funding

This work was partially funded by the *Agencia Nacional para la Promoción de la Ciencia y Tecnología* (ANPCyT-FONCyT) with grant PICT 2013 No. 2236 Tipo I (A) and by CONICET through PIP-CONICET No. 112201101 00618.

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