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Demarcation of continental-oceanic transition zone using angular differences between gradients of geophysical fields

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SUMMARY

The commonest technique for determination of the continental-oceanic crustal boundary or transition (COB) zone is based on locating and visually correlating bathymetric and potential field anomalies and constructing crustal models constrained by seismic data. In this paper, we present a simple method for spatial correlation of bathymetric and potential field geophysical anomalies. Angular differences between gradient directions are used to determine different types of correlation between gravity and bathymetric or magnetic data. It is found that the relationship between bathymetry and gravity anomalies can be correctly identified using this method. It is demonstrated, by comparison with previously published models for the southwest African margin, that this method enables the demarcation of the zone of transition from oceanic to continental crust assuming that this it is associated with geophysical anomalies, which can be correlated using gradient directions rather than magnitudes. We also applied this method, supported by 2-D gravity modelling, to the more complex Liberia and Cote d'Ivoire-Ghana sectors of the West African transform margin and obtained results that are in remarkable agreement with past predictions of the COB in that region. We suggest the use of this method for a first-pass interpretation as a prelude to rigorous modelling of the COB in frontier areas.

Key words: Continental margins: divergent; Continental margins: transform.

INTRODUCTION

The determination of continental-oceanic crustal boundary or transition (COB) zone is important in plate tectonic reconstructions and for estimating heat-flow through time, which have implications for hydrocarbon maturation and reservoir quality. Accurate mapping of COB is thus a priority task in hydrocarbon exploration in frontier areas of offshore continental margins. A typical passive continental margin reveals segmentation into three parts: (i) continental, (ii) transitional or thinned continental and (iii) oceanic crust. Transitional crust has a variable width ranging from tens to several hundred km and is characterized by sedimentary deposits that can be transported toward oceanic crust complicating its demarcation. Lateral density and magnetization variations are widely used for COB demarcation and tectonic studies (e.g. Watts 1988; Sleep & Fuyita 1997; Watts & Fairhead 1999; Torsvik *et al.* 2009). Free-air gravity anomaly remains the popular choice in such studies since it provides a broad assessment of the degree of isostatic compensation of an area (Dehlinger 1978; Bott 1982; Watts 2001; Torge 2003; Audet & Mareschal 2007) while it is strongly correlated with local, uncompensated bathymetry (McKenzie & Bowin 1976; Göttl & Rummel 2009). Gravity modelling studies suggest that over a passive margin, the transition from continental to oceanic crust is characterized by the presence of 'edge effect' associated with the hinge zone marking the change from normal continental to transitional crust and an 'outer high' gravity anomaly related to the change from transitional to normal oceanic crust (e.g. Pawlowski 2008; Hirsch *et al.* 2009). Thus in ideal conditions, appropriate edge-detection attributes can be used to delimit the zone of transitional crust.

Seafloor cooling age and associated magnetic anomaly isochrones are also widely used to determine COB and reveal spreading history. Magnetization of oceanic and continental crust differs significantly. Hemant & Maus (2005) discussed the absence of a prominent magnetic anomaly along the COB. Seafloor magnetic anomalies typically trend parallel to shore and are disrupted by transform faults. The landward border of the oceanic crust can be mapped by the termination of the magnetic isochrones pattern.

While gravity and magnetic data are used to determine the COB, their interpretation is usually performed visually (and hence subjective) or through rigorous time-consuming numerical modelling and integration of diverse data types (e.g. Pawlowski 2008; Hirsch *et al.* 2009). There is a need for a simple objective method to correlate lateral bathymetric, density and magnetization changes or for an effective edge-detection attribute to demarcate the COB zone.

In this paper, we propose an approach for correlating geophysical anomalies associated with the transition from oceanic to continental crust based on a simple qualitative criterion. This criterion, the angle between map gradients, determines the type of correlation between different geophysical properties. Our assumption is that the knowledge of the type of correlation between gravity and/or magnetic anomalies and bathymetry gives information about source location and permits the demarcation of the zone of transitional crust. For this spatial analysis problem, the joint use of gradient properties of two geophysical images results in a form of spatially referenced map that emphasizes regional trends with different levels and types of correlation. We note that the cross-gradient method (Gallardo & Meju 2004) can also be used to determine the morphological correlation between images (Jilinski *et al.* 2010). Here, we prefer the use of angular differences between map gradients owing to its computational simplicity. Since continental-oceanic crust boundary may be associated with significant lateral density, magnetization and/or water-depth changes, we expect that angles between their field gradients will be a diagnostic attribute for geological characterization of continental margins.

First, we describe the adopted methodology for map correlation. Next, we demonstrate its usefulness in COB determination using available data from southwest African margin—which have been previously modelled in detail by Pawlowski (2008) and Hirsch *et al.* (2009). Finally, we apply the method and supporting 2-D gravity-magnetic modelling of the deep crustal structure to the more complex West African transform margin (WATM) considered to be a frontier area for hydrocarbon exploration (Flinch *et al.* 2009).

METHODOLOGY FOR CORRELATING MULTIPLE DIGITAL MAPS

Gradient directions are magnitude independent and are less affected by local peak anomalies within large-scale regional anomalies. To qualitatively characterize morphological correlation between two images we propose a simple and objective criterion—the angular difference between gradient directions. Angular differences between geophysical gradients are determined by the subtraction of individual gradient directions. For two different maps A and B, the angular difference between their respective gradients is determined as

$$\alpha = \theta_{\mathrm{A}} - \theta_{\mathrm{B}}, \tag{1}$$

where θ_{A} and θ_{B} are the respective individual gradient directions determined following Moore *et al.* (1993) and Wilson & Gallant (2000). The reader is referred to Jilinski *et al.* (2013) for a detailed description of the relevant gradient computation method.

The resulting angles range from 0° (codirectional) to 180° (opposite directions). Codirectional angles indicate direct correlation between both gradients, i.e. sources are directly correlated. Opposite directions indicate inverse correlation, i.e. sources are inversely correlated. The statistical dominance of a value over a region characterizes its type of correlation. Areas dominated by values other than direct or inverse correlation are deemed to be characterized by superimposition of different sources. For the case where non-correlation is due to additive noise, it is expected that the resulting angular differences will tend to be randomly distributed and appear as grid-sized spots in the resulting maps. The type of correlation is used to characterize different geological structures or geophysical properties.

APPLICATION IN OFFSHORE CONTINENTAL MARGIN DEMARCATION

It will be instructive to test this methodology by applying it to COB determination using available data sets variously interpreted at local to large-scale for comparison. The gravity anomaly data used in this study are from the Scripps Institution of Oceanography version 16 satellite-derived marine gravity anomaly data set (Smith & Sandwell 1997; Sandwell & Smith 2009). Magnetic data were extracted from World Magnetic Anomaly Map (WMAM) compilation (Maus *et al.* 2007). We expect the correlation between gravity 'outer effect' and 'edge effect' highs and bathymetry and/or (reduced to pole) magnetic anomaly to be enhanced using angular differences of their gradients. The resulting angles maps are plotted and the main patterns identified to help demarcate the COB in relation to bathymetry.

SOUTHWEST AFRICAN MARGIN

The COB was previously determined in a segment of the southwest African margin by Pawlowski (2008) and Hirsch *et al.* (2009) using combined gravity, seismic and isostatic studies. Pawlowski (2008) applied high-pass filters to highlight 'edge effect/outer high' anomalies from the depth related trend on Bouguer anomaly maps. However, in deepwater regions Bouguer correction generates overcorrection with large positive anomalies observed over deeper abyssal region and hence generates dominant long-wavelength inverse correlation with bathymetry (Jilinski *et al.* 2013). We therefore prefer to use angular differences between free-air gravity and bathymetry gradients.

The available bathymetric, free-air gravity and magnetic anomaly maps for the Orange basin in offshore southwest African margin are presented at Fig. 1. These constitute our test data. We refer the reader to the articles by past workers (Bird 2001; Pawlowski 2008; Hirsch *et al.* 2009) for lucid descriptions of the geology of this adopted test region. Note the linear (coast-parallel) anomalies in all the maps. In Fig. 1(b), there is a well-defined 'edge effect' gravity anomaly immediately seaward of the 200 m isobath and an 'outer high' coincident with the 3000 m isobath. Such linear anomalies should be straightforward to correlate.

Fig. 2(a) shows the resulting angular differences between the gradients of Free-air gravity and bathymetry maps. As expected, linear belts of alternate negative and positive correlations are obvious in this figure. The image shows that the 'edge effect' is characterized by an inverse correlation between gravity and bathymetry in the landward slope and a direct correlation at its seaward slope; a significant boundary is suggested between these two zones of opposite correlations. Further seaward at the 'outer-high' the relationship is similarly characterized by inverse correlation at its landward side and a direct correlation at its seaward slope. The two parallel dotted lines in Fig. 2(a) are the boundaries of the transition zone determined with the aid of rigorous modelling of potential field and seismic data by Hirsch *et al.* (2009, fig. 12). Note that these carefully determined COB boundaries by Hirsch *et al.* (2009) are in remarkable agreement with the boundaries interpreted from our angular difference map. Thus, this simple attribute may be useful for a quick first-pass interpretation of the possible COB zone in an area with defined gravity 'edge effect/inner high' and 'outer high' anomalies. Fig. 2(b) shows the computed angular differences between the gradients of the free-air gravity and total field magnetic intensity maps. It is obvious that there is no consistent pattern in this particular image

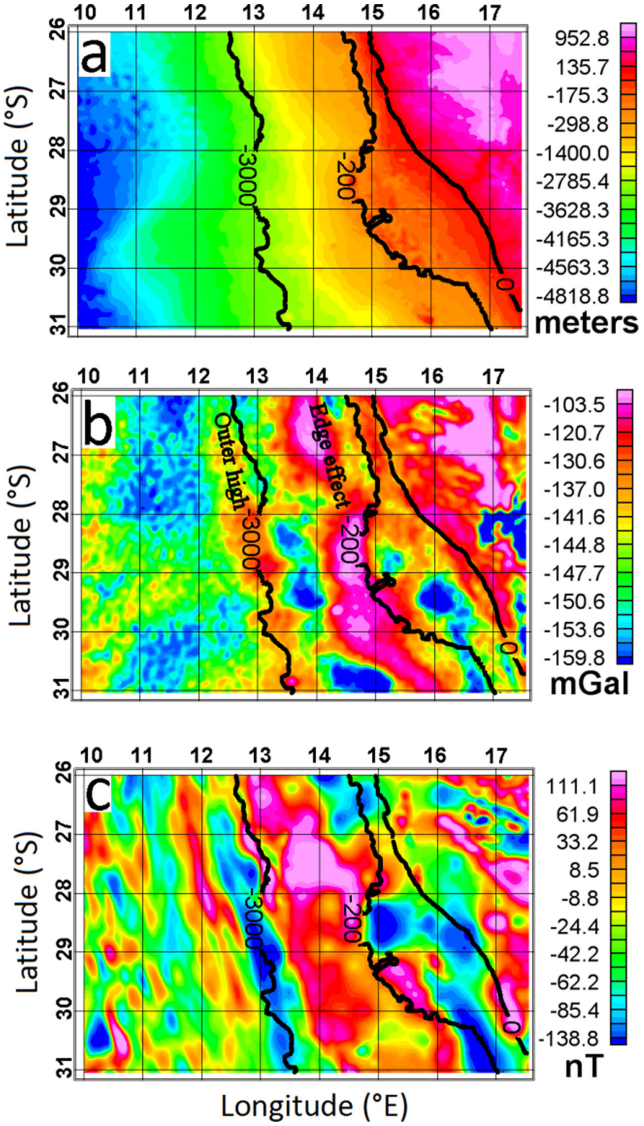

Figure 1. Orange basin (a) bathymetric map; (b) Free-air gravity anomaly map; (c) magnetic anomaly map. Isobaths show water depths of 0, 200 and 3000 m. In (b), note the gravity 'edge effect' anomaly just seaward of 200 m isobath and 'outer high' coincident with the 3000 m isobath.

that can be correlated to both the edge effect and outer high anomalies and hence the COB of Hirsch *et al.* (2009). We suggest that the gradient map of bathymetry and gravity is better for COB mapping in this setting. However, it is possible that a diagnostic pattern will emerge if we use instead, the magnetic data reduced to the pole but this was not done in the present proof of concept study.

For completeness, we also applied the approach to a wider area covered in Pawlowski (2008) and obtained remarkably consistent results, but our inferred boundaries showed a better match to those of Hirsch *et al.* (2009) in the overlapping region. Will this correlation method be sufficient on its own for COB mapping in regions of more complex structural trends such as the WATM? We address this question next.

WEST AFRICAN TRANSFORM MARGIN

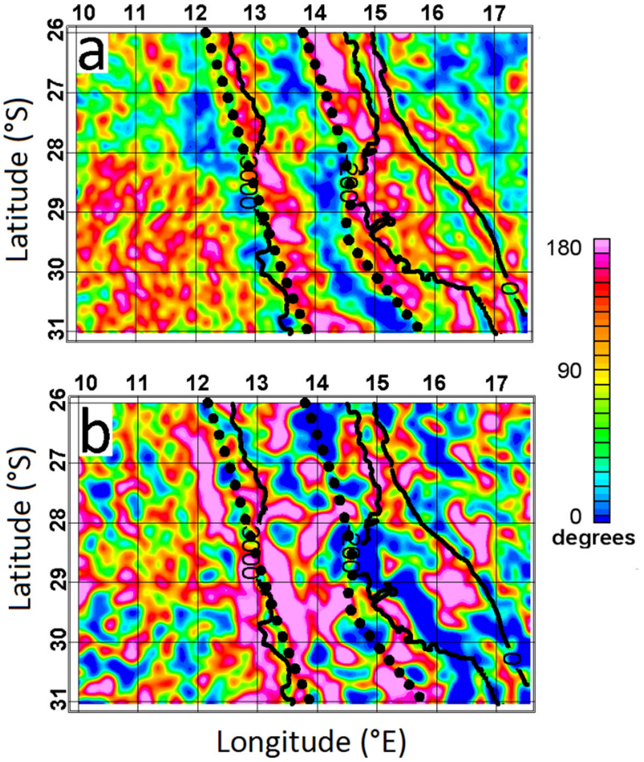

Figure 2. Angular differences between bathymetric and free-air gravity gradients (a) and between gradients of free-air gravity and low-pass filtered magnetic anomalies (b) of the Orange basin. The thick dotted lines show the COB determined by Hirsch *et al.* (2009).

Transform margins are characterized by a ridge, steep uniform slope, large sedimentary deposits and abrupt transition between continental and oceanic crust (Scrutton 1979; Bird 2001). Transform fracture zones control the borders of Cretaceous sedimentary basins on both Brazilian and African sides of the Atlantic, and the WATM (Fig. 3) is a frontier area for hydrocarbon exploration (e.g. Burke *et al.* 2003; Purdy & MacGregor 2003; Flinch *et al.* 2009). Here, there are limited zones of coast-parallel structural trend near the coast but Equatorial fracture-zones dominate the structure as can be seen in the bathymetric, Free-air gravity and magnetic anomaly maps (Fig. 3). In many parts of the WATM, there are no clearly defined coast-parallel 'edge effect' and 'outer high' gravity anomalies as apparent in Fig. 3(b). Consequently, direct determination of the COB from regional maps of our gradients attribute will be a difficult proposition, and any analysis of our simple gradients attribute must be supported by numerical modelling of the deep structure across a given sector of the WATM. For simplicity, we refer to the region between longitude 2°W and 5°W in Fig. 3 as the Cote d'Ivoire-Ghana sector and the region between longitude 9°W and 12°W as the Liberia sector of the WATM.

In Fig. 3(b), note the suggested presence of a subdued 'outer high' gravity anomaly at the southwestern part of the Liberia sector and the anomalous gravity signature of the marginal ridge in the Cote d'Ivoire-Ghana sector (Scrutton 1979). These could permit the determination of the location of the COB. We have computed the angular differences between the usual gradients maps for WATM (Fig. 4) and also constructed 2-D crustal models along profiles crossing major tectonic structures in the Cote d'Ivoire-Ghana sector (Fig. 5) and the Liberia sector (Fig. 6). The locations of the 2-D profiles presented in Figs 5 and 6—a NE–SW line in the Liberia sector and a NW–SE line in the Cote d'Ivoire-Ghana sector—are shown

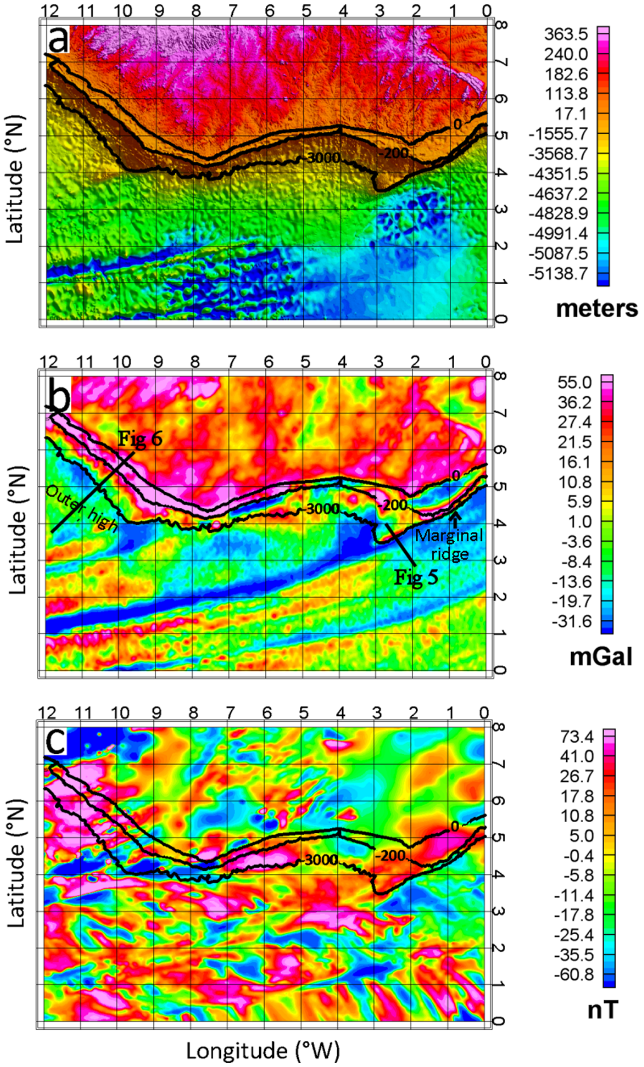

Figure 3. West African transform margin (a) bathymetric map; (b) Free-air gravity anomaly map; (c) magnetic anomaly map. Isobaths show water depths of 0, 200 and 3000 m. In (b) are shown gravity 'edge effect' and marginal ridge anomalies as well as the locations of 2-D gravity profiles of Figs 5 and 6.

in Fig. 3(b). The gravity modelling was based on the algorithm of Won & Bevis (1987).

In Fig 4(a) are shown the computed angular differences between the gradients of Free-air gravity and bathymetry maps for the WATM. The black dotted lines denote our interpreted zone of transitional crust based on: (i) the characteristic pair of inverse and direct relationship between gravity and bathymetry at 'outer high' and the marginal ridge and (ii) inferences from 2-D gravity modelling (see Figs 5 and 6). The independently determined COB by the Ocean Drilling Program (ODP) workers (Mascle *et al.* 1998) is also shown as a yellow dashed line in this figure for comparison. Note the remarkable agreement between both interpretations of the COB in this otherwise complex region. In Fig. 4(b) it is apparent that any interpretation of the angular differences between gravity and total field magnetic gradients can at best be conjectural. It is possible that a transformed magnetic (pseudo-gravity or reduced to pole) anomaly may be better correlated with bathymetry for COB mapping but we did not investigate this.

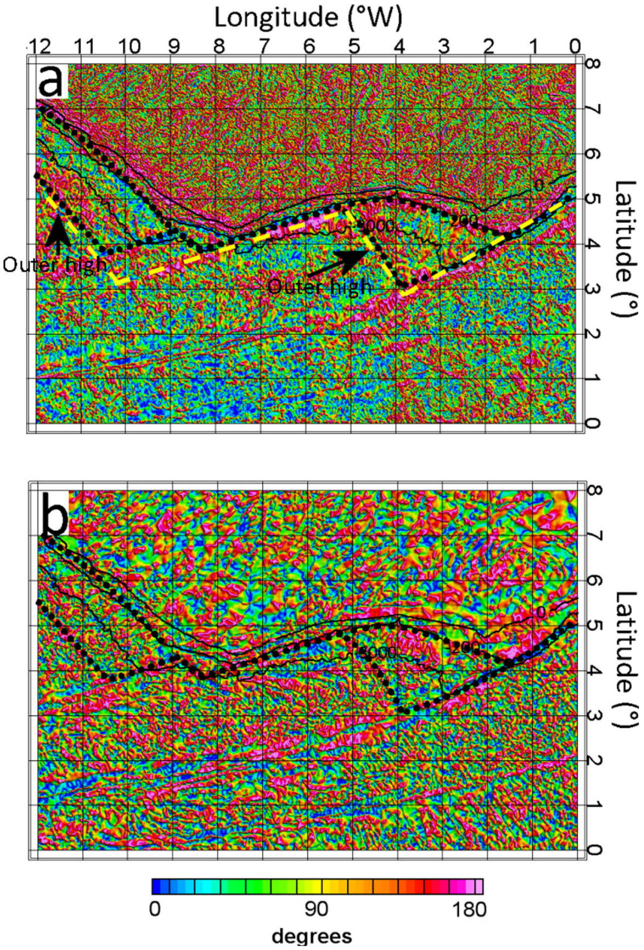

Figure 4. Angular differences between bathymetric and free-air gravity gradients (a) and between free-air gravity and low-pass filtered magnetic anomaly gradients (b) at the West African transform margin. Dotted lines indicate our interpreted zone of transitional crust. The yellow dashed line shows the COB determined by Mascle *et al.* (1998).

There is good support for our interpreted COB from gravity modelling as shown in Figs 5 and 6. Coincidentally located 2-D profiles of the angular differences between gravity and bathymetry and between gravity and magnetic anomalies are also shown for comparison in these figures. For the Cote d'Ivoire-Ghana sector, we used the available published information (see Bird 2001) to constrain the gravity modelling (Fig. 5). Note the distinctive gravity high over the marginal ridge. In the gravity-bathymetry angular difference profile, there is a sharp transition from direct correlation to inverse correlation over the marginal ridge such that its position could be reliably determined using our simple attribute. There is a similar sharp transition over the Romanche fracture-zone (FZ) in both the bathymetry-gravity and gravity-magnetic gradient angles coinciding with our interpreted boundary between pure oceanic and continental crust.

We used information from proprietary seismic data to constrain the depth of sediments in the model for the Liberia sector and it led to a better fit of the broad gravity low at profile distance 70–200 km, that is, between the 'edge effect' and 'outer high' gravity anomalies (Fig. 6). It would appear that the transitional crust is more than 100 km wide and can be demarcated by virtue of the 'edge effect' and 'outer high' (Fig. 3b) present here.

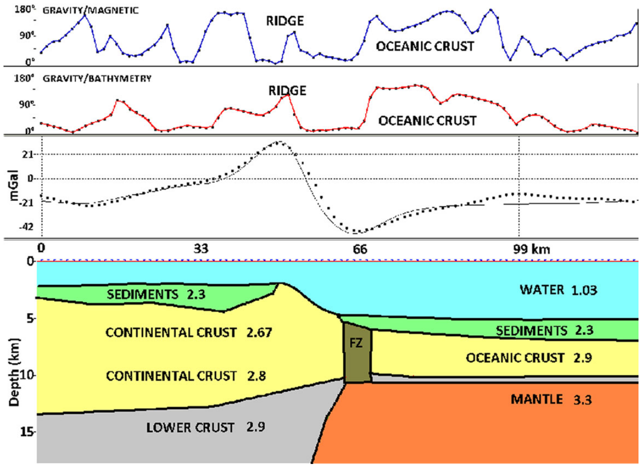

Figure 5. A 2-D gravity model for Cote d'Ivoire-Ghana sector of the WATM. The line of section is shown in Fig. 3(b) and starts near the Cote d'Ivoire-Ghana border, crosses the Deep Ivorian Basin, the Cote d'Ivoire–Ghana marginal ridge, and the Romanche Fracture Zone (FZ). Shown are the crustal density model (lower panel), fit between the observed and modelled data (middle panel), and plots of coincidentally located profiles of angular differences between gradients of gravity and bathymetry and between gradients of gravity and magnetic anomalies (top panels).

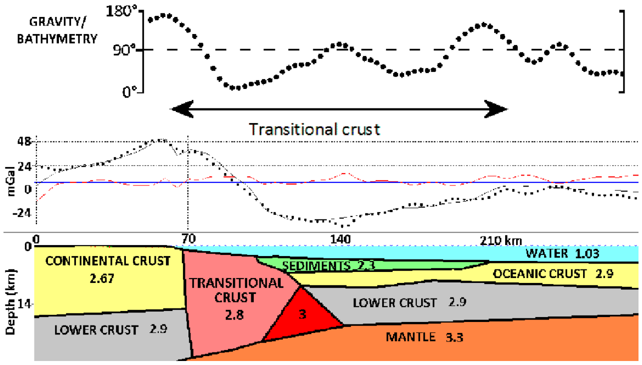

Figure 6. A 2-D gravity model for Liberia sector of the WATM. Shown are the density model (lower panel), the fit between the observed and modelled data (middle panel), and coincidentally located profile of angular differences between gradients of gravity and bathymetry anomalies (top panel). The line of section is shown in Fig. 3(b).

DISCUSSION AND CONCLUSION

We have presented a simple method that can aid the determination of the level of correlation between geophysical maps based on their morphological properties. We use a new attribute, the angular difference between gradient directions, which has the following features: (i) computational ease, (ii) straightforward visualization and (iii) the possibility to correlate any two geophysical images irrespective of their physical nature and relationship. However, our results showed that while this method does not require rigorous modelling of bathymetry, gravity and magnetic anomalies, additional information is needed for the geological interpretation of the attributes. An adverse characteristic of this method is that it is sensitive to noise induced morphological distortions, limiting the application of high-pass filters. Despite these limitations, the method proved effective in determining correlations between gravity and bathymetric or magnetic anomalies and mapping the boundaries of major geological features with enhanced horizontal gradients.

To assess the practical usefulness of this method in determining the COB zone, we applied it to data from the southwest African margin and compared our results with the COB interpretations of Pawlowski (2008) and Hirsch *et al.* (2009). The main assumption here is that the COB margins are associated with gravity and magnetic anomalies due to the presence of the transitional crust. Our results from bathymetry and gravity correlations showed excellent agreement particularly with Hirsch *et al.* (2009) interpretation of the boundaries of the transitional zone separating pure continental and oceanic crust in the Orange basin sector of the southwest African margin. We also applied the new attribute, supported by rigorous 2-D gravity modelling and some seismic constraints, to COB determination in the WATM. We found that there is a diagnostic gravity signature of the marginal ridge in the Cote d'Ivoire-Ghana sector, and 'edge effect' as well as 'outer high' gravity anomalies in the southwestern part of the Liberia sector that enable us to determine the possible location of the COB in good agreement with the earlier ODP result of Mascle *et al.* (1998).

We conclude that angular differences between the gradients of gravity and bathymetric maps can be used as an attribute to quickly demarcate the transition zone between continental and oceanic crust in offshore regions where there are significant linear belts of 'inner high' and 'outer high' gravity anomalies. In regions where the coast-parallel gravity anomalies are disrupted by transform fracture-zones, special attention to local structure is needed and requires additional multi-dimensional modelling of the geophysical anomalies.

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