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Reply to comments by J. García Abdeslem on: "Gravity field of the southern Colima graben"

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We thank Juan García-Abdeslem (1995) for his interest in our gravity study in the area of the southern Colima graben (Bandy *et al.*, 1993). The structure and tectonics of this region are currently subject to much debate. We welcome this opportunity to clarify our original work and to extend our analysis to include 2.5-D models. Based on the comments by J. García-Abdeslem (JGA) we select three main topics which may require further explanation or investigation. These are: (1) whether our profile is correctly oriented; (2) why a 2-D modeling procedure was used for a case where the structure is clearly not 2-D and, more importantly, whether this simplified approach produces results significantly different than the theoretically more appealing 2.5-D method; and (3) what the non-uniqueness inherent in the gravity method implies in terms of the validity of our conclusions.

We take this opportunity to point out a correction to our 1993 paper. All the figure captions are correct, but the maps illustrated in figures 2 and 4 should be switched.

PROFILE ORIENTATION

Apprehension exists about the fact that our profile is oriented parallel to the overall strike of the contours of the Bouguer/Free-Air anomaly map. It is important to understand that we are not proposing to model the Bouguer/Free-air anomaly field but the residual gravity field; that is, the Bouguer/Free-air gravity field minus the regional field. In our study area there are two main components of the Bouger/Free-air anomaly field, namely one component produced by the regional structure of the trench-arc system (the regional field which is not of interest to the present study), and a component produced by the southern Colima graben (which is of interest to the present study). The first step in our analysis was the removal of the regional field from the Bouguer/Free-Air anomaly field. This removal is extremely time-consuming if explicitly done for the entire field; thus, we chose a simplified approach. On page 565 of Bandy *et al.* (1993) we described what we did (the profile was oriented parallel to the regional contours), but we neglected to explain why we did this. The reason was that by orienting the profile parallel to a regional contour, the regional field is effectively removed (to within a constant, the constant being the value of the regional field along the profile) from the Bouguer/Free Air anomaly. The constant does not affect our result, as we are interested in modeling the relative change in the residual field across the southern Colima rift and not the absolute magnitude of the field at any particular location. If we had taken the time to explicitly remove the regional field and countour the residual field, clearly our profile would have been oriented roughly perpendicular to the contours of the residual field. This might have prevented the present misunderstanding. We would also like to point out that, given the NE-SW orientation of the structural features comprising the southern Colima Graben, the NW-SE orientation of our profile is clearly the correct orientation.

2-D vs 2.5-D

Before going into the applicability of the 2-D model in the case of the southern Colima graben two points need clarification. First, we have tried unsuccessfully to duplicate the 0.5 aspect ratio for the southern Colima graben claimed by JGA. If both grabens are included we obtain an aspect ratio of between 0.8 and 1.0. If each graben is considered separately, we obtain an aspect ratio of around 2.0. Second, the parameters JGA chose to use in his modeling are nowhere close to those characteristic of the southern Colima graben. Specifically, (1) the thickness of our prisms (corresponding to the two grabens) are 6 and 8 km, whereas JGA uses 1 km, (2) the density contrast of the two prisms is -0.17 g/cm^3, whereas JGA uses 1.0 g/cm^3, and (3) our prisms generally lie within 100 meters of the reference surface, whereas JGA uses 1 km. Thus, we find it difficult to use his Figure 1 to judge the applicability of the 2-D method for the southern Colima graben.

A more appropriate theoretical model is as follows (Figure 1). Assume a rectangular prism, 100 km wide, 5 km deep, exhibiting a density contrast of -0.17 g/cm^3. The top of this prism lies at the reference level and the gravitational attraction of the prism is calculated at the center of the prism. For an aspect ratio of 1.0 (strike length 100 km) the difference between the 2-D (infinite strike length) and 2.5-D models is 0.47 mgals which is within the estimated accuracy (±0.6 mgals) of the survey reported by Bandy *et al.* (1993). Even granting an aspect ratio of 0.5 as calculated by JGA (strike length 50 km), the difference is only 1.5 mgals. This value exceeds the stated uncertainties but it represents only 3% of the anomaly to be modeled (-50 mgals) and is unlikely to significantly affect our conclusions. Hence, the 2-D approach is justified based on these results.

To further illustrate this point we recompute the gravity anomalies along profile A-A' by using a 2.5-D modeling algorithm. The model is the same as that used in Bandy *et al.* (1993) except that topographic relief was omitted for simplicity. This has no major effect since the profile runs along the coast. In Figure 2 we compare results for strike lengths of 200 km, 100 km and 50 km, and for the 2-D model (infinite strike length). As expected,

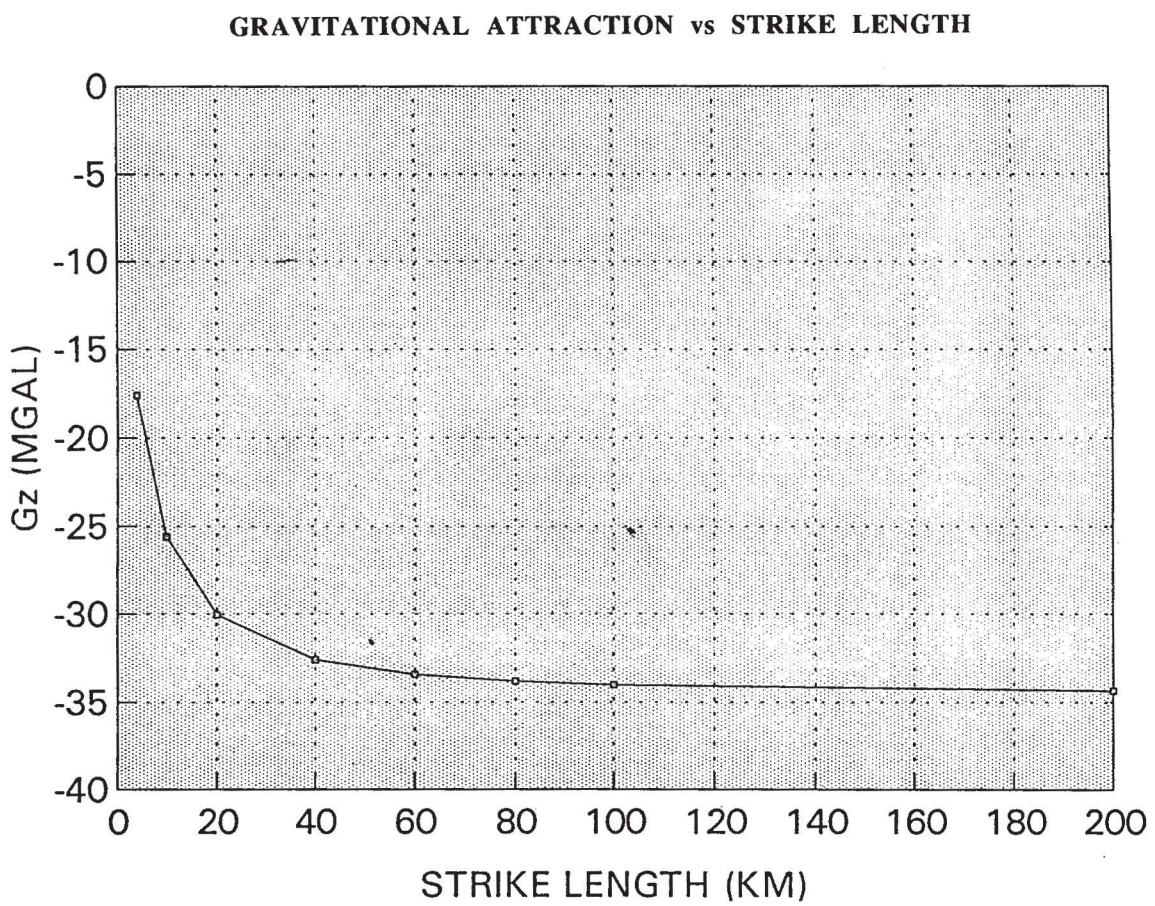

Fig. 1. Graph illustrating the gravitational attraction of a rectangular prism versus strike length (see text for details).

there is very little difference between the 2-D anomaly and the anomalies calculated from the various 2.5-D models. The density contrasts were the same for the various models. Hence, our interpretation is not affected by the use of 2-D modeling.

JGA makes the point that the Free-Air values are strongly affected by bathymetry. However, the effect on the residual field is not nearly as great. A rough calculation indicates that bathymetric fluctuations in the offshore area contribute less than -3 mgals to the residual field along our profile except at locations near the Río Armería submarine canyon. 2.5-D modeling of this submarine canyon indicates that, for a station located directly over the canyon, the contribution to the residual field is -12 mgals; however, the half-wavelength of the anomaly produced by the canyon is only on the order of 5 km. Thus, the broad, -50 mgal anomaly along our profile cannot be due solely to bathymetric fluctuations, and is certainly not due to the effects of the submarine canyon. The effect of the Armería submarine canyon on the Free-Air gravity field is readily visible on both the regional and local field maps as a narrow, roughly v-shaped perturbation in the contours located within the center of the broad -50 mgal anomaly at roughly 18°50'N, 104°2'W.

NON-UNIQUENESS

JGA states that "*the two-dimensional model depicted in [our] Figure 5, and particularly the proposed thickness and density of the seaward extension of the Colima graben should be viewed with some caution*". This is good advice. We stated a similar caution in the last paragraph of our paper: "*the sediment thickness within the grabens and the shoaling of the Moho are uncertain due to the non-uniqueness inherent in gravity*". We made this statement not because of the modeling algorithm used, but because of the non-uniqueness inherent in gravity modeling; especially in regions lacking other types of constraining data. The uncertainties due to the non-uniqueness of the method are far greater than those arising from the type of method employed. The depth to the Moho has a profound effect on the thickness of sediments within the graben derived from the gravity data; the shallower the Moho the thicker the sediments and vice versa. Since the depth to the Moho is ill-constrained, our resulting model is also ill constrained, regardless of the modeling program employed. However, this does not affect our main conclusion, namely that a southern Colima graben infilled by low density material is consistent with the existing gravity data.

SUMMARY

First, we strongly disagree with the suggestion that our profile is not oriented properly. The profile is oriented perpendicular to the strike of the graben, which allows us to investigate its structure. Second, the errors associated with employing the 2-D method instead of the 2.5-D method are small and thus use of the 2-D method is justifiable. Third,

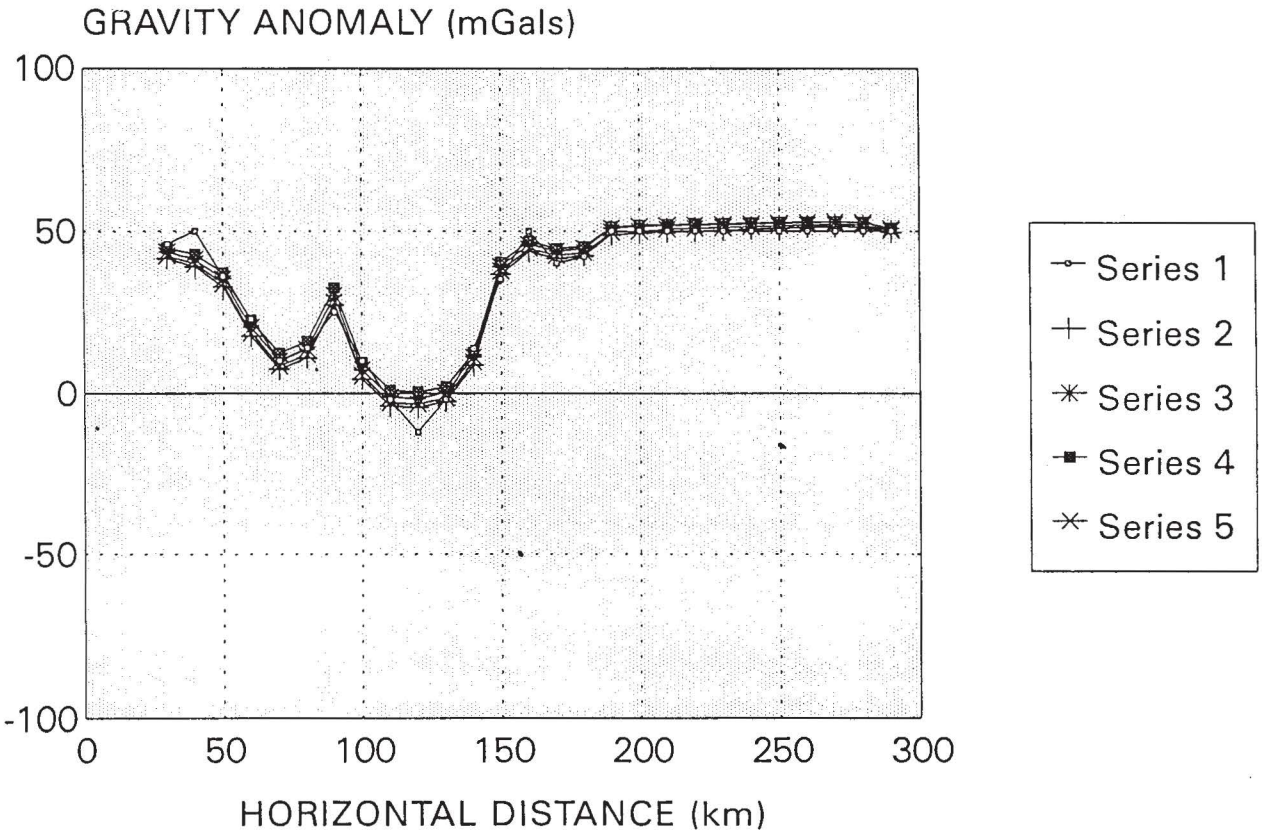

Fig. 2. Comparison of the observed gravity (series 1) over the southern Colima Graben with the gravity anomalies calculated from models where the strike length of the polygonal bodies are infinite (series 2), 200 km (series 3), 100 km (series 4), and 50 km (series 5). See text for details of the modeling procedure.

the uncertainties in the resulting geological model produced by the unconstrained nature of the problem override the uncertainties introduced by the choice of modeling algorithm.

We appreciate the opportunity provided by the comments of JGA to highlight the controversy surrounding the presence of a graben structure in the offshore region of the southern Colima graben/rift.

We stress that the gravity data are consistent with the existence of such a graben, which may also be seen in seismic reflection data (Figure 6 of Michaud *et al.*, 1990) across the offshore prolongation of the Colima Graben. Their profiles show that the near surface reflectors on both the NW and SE margins of the offshore portion of the southern Colima rift dip towards the rift zone. Since our study was published, direct observations of normal faulting have been made on the NW margin of the rift zone during the NAUTIMAT cruise of which one of us (WLB) was a participant. One might still argue that the offshore extension of the Colima rift is not a full graben structure; but it is clear to us that subsidence is occurring within the rift.

Perhaps we should have gone to greater lengths to make our original methods, assumptions and results more explicit.

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