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ANALYSIS OF GRAVITY MEASUREMENTS ALONG SOME PROFILES ON-SHORE, OF QATAR PENINSULA

By

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تحليل القياسات التثاقلية على طول بعض القطاعات في المنطقة البرية، لشبه جزيرة قطر

كيزرس كريستوفر١، كمبل يواخيم٢، (ثروت عبد الفتاح ، إبراهيم القصاص ، النعيم علي العبيد)٣

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أُسْتخدمت طريقة التثاقلية للتعرف على توزيع الكثافة تحت السطح وكذلك لجمع معلومات عن التراكيب الجيولوجية تحت السطحية والتي تعتبر مكامن مناسبة لخزن النفط، وقد تم إجراء القياسات على طول ثلاث قطاعات تمتد من الشرق - للغرب ومن الشمال الشرقي إلى الجنوب الغربي وبأطوال تتراوح من ٤٠ كم إلى ٧٥ كم.

وبعد إجراء المعالجات اللازمة تم فصل المركبة المحلية والتي وجد أنها تقريباً $200\ \mu$ Gal/km ثم أستخدمت عملية النمذجة المتقدمة باستخدام برنامج IGMAS حيث أوضحت النماذج أن العمق حتى صخور القاعدة ٩كم له إختلاف في حدود + ٥٠٠متر. وقد تم تحديد شكلين أساسين يضربان في إتجاه الشمال - الجنوب مرتبطين مع قوس قطر التركيبي، كما أوضحت الدراسة أن عمق صخور القاعدة يرتفع بحوالي ٢كم من الشاطىء الشرقي إلى الغربي، وذلك يعني إنحدار مقداره ٤٪، وهذه الدراسة تؤكد أن الجاذبية العالية تعتبر قيمة حيث تعطي معلومات جديدة في الكثافة السطحية المقارنة على الشواطىء القطرية.

Keywords : Gravity — Modelling — Inversion

ABSTRACT

A gravity study on the Qatar Peninsula was conducted to learn about density contrasts in this region and to gain information about subsurface geological structures favourable for oil and gas reserves. We recorded high quality gravity data along three West-East, Southwest-Northeast tending profiles of lengths 40, 65 and 75 km through the country. After reducing the data in the conventional way and, in a first approach, subtracting a linear trend of roughly 200 μ Gal/km, the residual Bouguer anomaly is found to be of the order ± 2 mGal. Forward modeling using the software IGMAS as well as application of a simple inversion technique for calculating the density distribution of the subsurface revealed that the basement topography varies about ±500 m at depths around 9 km. Mainly two North-South striking features can be identified which may be associated with anticlinal structures like the Qatar Arch. Reconsidering the West-East tending linear trend in the Bouguer anomaly, the gravity data suggest an overall rise of the basement depth by up to 2 km from the West coast of Qatar Peninsula to its east coast, meaning a slope of 4%. The study confirms that high quality gravity data contains valuable, new information on subsurface density contrasts for on-shore Qatar.

INTRODUCTION

The State of Qatar is the owner of the largest single non associated natural gas field, so far known, on the Earth. This makes Qatar to be one of the world's five countries with the biggest gas reserves [1]. On-shore oil operations mainly comprise production in one large oil field, i.e. the Dukhan Oil Field in the western coastal part of the peninsula. It is confined to depths between 2 and 3 km. Apart from drillings showing the stratigraphy of the near surface area there is a lack of information about the deep crustal structure of the peninsula. Previous geophysical investigations include airborne magnetics as well as airbone and sea gravimetry. Several oil companies have worked on seismic investigations mainly off-shore [2,3].

In gravimetry, gravity acceleration is usually observed on the surface by mass-spring type gravimeters. Anomalies are due to rock density variations within the subsurface. The unit of gravity is Gal, 1 Gal = $10^{-2}\,m/s^2$. The method is widely applied as a useful tool in exploring the subsurface, e.g. in oil and gas exploration, where sediment basins possibly containing hydrocarbons are investigated to locate structural traps as anticlines, fractures and salt domes [4].

There is a similar interest for the Qatar Peninsula to learn about its subsurface geological structures. Particular open questions are whether filed gravity measurements are appropriate to image the topography of the basement below the sedimentary cover here, and whether changes in the basement depth can be associated with anticlinal structures or major fault zones. Thus, a pilot gravity survey was carried out to provide data that is helpful for planning further geophysical studies and interpreting other, related observations.

Geology and regional gravity field

The Qatar Peninsula lies within the Eastern Arabian sedimentary basin and consists of 8-10 km thick sediments. Its appearance above sea level is realted to the presence of a broad anticline (Qatar Arch) extending north into the Gulf [5]. Its surface topography is rather flat, reaching a miximum height of about 100m a.s.l. in the southern part. The general stratigraphic sequence is supposed to consist of a number of sedimentary layers (clays, sandstone, limestone, dolomite, clastics, beside some evaporites) from Quanternary back to Devonian [5]. As the deepest well on-shore Qatar ends in a sequence of lower Devonian sandstones, little is known about the formations below. The basement which forms most of the continental crust is believed to consist of granite and andesite. Fracture zones and faults are only known to occur in the western part of the peninsula (Dukhan region), but presumably also exist in other areas.

The regional Bouguer gravity derived from the database of the Bureau Gravimétrique International (B.G.I., Toulouse, France) is shown in Fugure 1. There are mainly two trends meeting around Qatar Peninsula: increasing gravity from the southwest of Saudi Arabia towards the Gulf and decreasing gravity from the Gulf towards the northeast, i.e. to Iran. The latter is connected to the Zagros mountain root [6,7]. Since data are scarce in Eastern Saudi Arabia (only three data points are included in the B.G.I. database), the presence of small scale features in the gravity field of this region is not resolved.

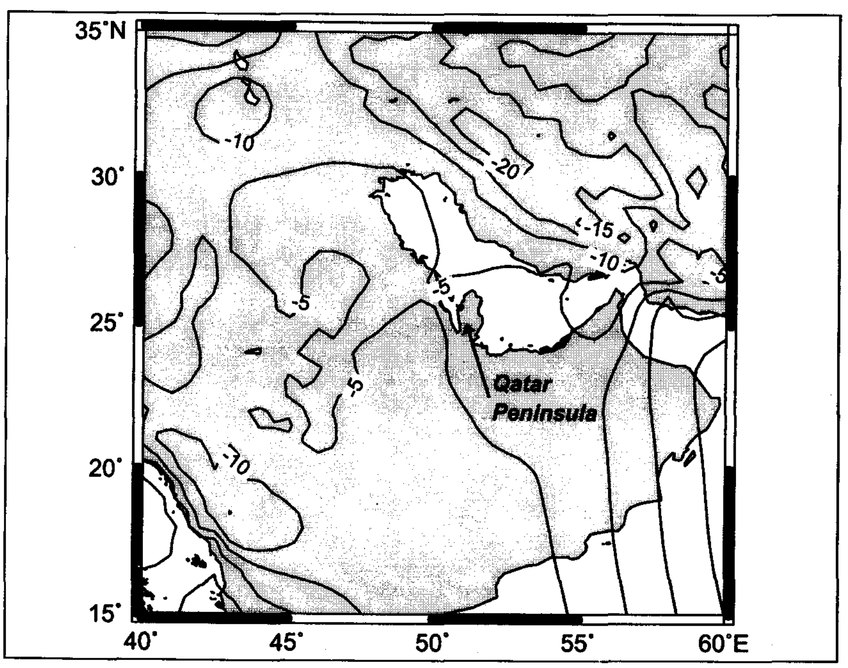

Fig. 1 : Regional gravity field (Bouguer anomaly) derived from the B.G.I. database.

Field work and data processing

In a joint scientific research project between the University of Qatar and Bonn University, Germany [8], gravity readings have been taken along three profiles (Figure 2). Two of them run from the capital city of Doha along the main roads to the western coast; Profile P1 ends in Dukhan, P2 in Abu Samra. Profile P3 runs from Mukainis (halfway between Doha and Abu Samra) to Umm Bab.

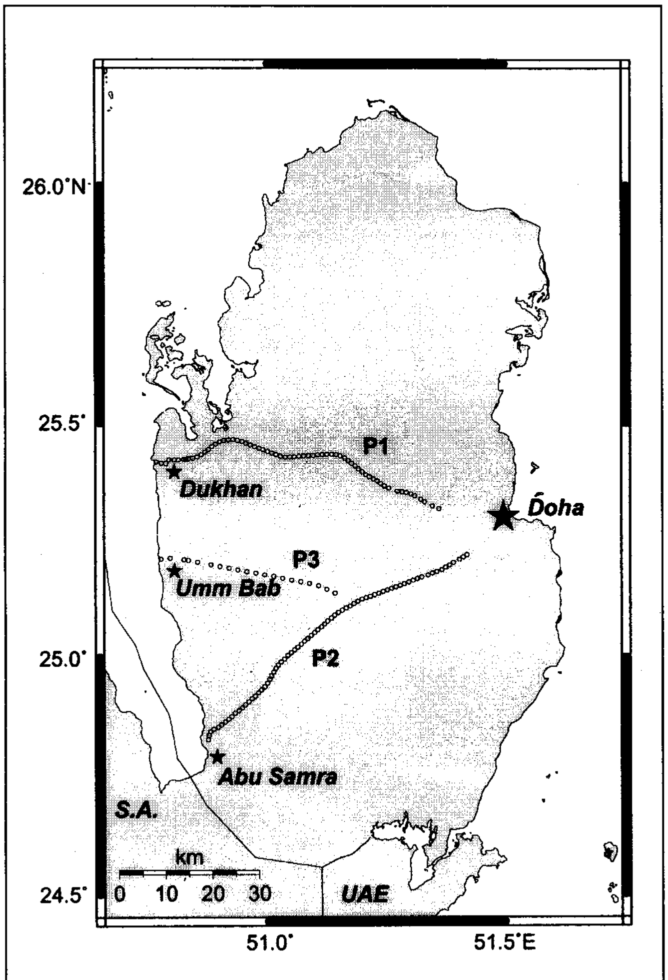

Fig. 2: Locations of the gravity profiles P1, P2 and P3 on Qatar Peninsula with places where readings have been taken (S.A. = Saudi Arabia, UAE = United Arab Emirates).

The depth range of interest for this survey is approximately from 3 to 12 km. Assuming that the horizontal extent of a structure of anomalous density is at least the same as its depth and requesting that a gravity anomaly is hit at least at three adjacent positions to be identified as such, we need readings roughly every 1km. Accordingly, on Dukhan and Abu Samra profiles (P1, P2) a station distance of about 1 km was taken. Since some field time was left after completion of these, we added the Umm Bab profile P3 to our project, yet only by taking readings at 2km separations (roughly every hour during survey times). The instrument used was LaCoste & Romberg gravity meter LCR-G-1029 that is equipped with an electronic feedback system [9]. For controlling the instrumental drift, gravity was repeatedly observed at several base stations. The sation coordinates and height data were collected by the Centre for Geographical Information Systems (GIS) of Qatar using GPS (Global Positioning System) with an accuracy of ±5 cm in height. Air pressure has been controlled by taking data from Doha International Airport made available by the Dept. of Civil Aviation & Meteorology, Ministry of Communication & Transport.

The nominal resolution of oen reading is 1 μGal. The uncertainty resulting from the instrumental drift is estimated to be about ±10 μ Gal, air pressure changes were within a range of 10 mbar, resulting in gravity effects of order ±3 μ Gal [4]. The gravity data have been processed by applying the software 'feldgrav' and 'grav' [10]. The former reads the field data, computers the tidal effect, and prepares the data for the program 'grav', which computes a least squares adjustment of the data. The uncertainty resulting from adoption of a constant gravimetric factor, namely 1.17, in the tidal computation in a region with large marine tides (the Gulf is such a region) is about ±10 μ Gal. The weight unit error resulting from the final adjustment is 7 μ Gal, thus indicating high quality data. Further processing steps include removal of the latitude dependence (according to the Geodetic Reference System 1980; [11]), computation of the Free Air gravity contribution and of the Bouguer effect of masses above sea level. The use of a reduction density of 2.3 ± 0.2 g/cm^3 for the uppermost sedimentary layers leads to an uncertainty of ± 200 μ Gal, exceeding the previous error sources by a factor of 10. Figure 3 displays the remaining Bouguer anomaly (relative, as no absolute gravity data were available) for all the profiles. it shows trends of rising values from west to east for P1, P3 and from southwest to northeast for P2, respectively. These trends are much stronger than the regional field resolved in Figure 1. In a first approach to interpret the observations, we subtracted the linear trends from the Bouguer anomaly data. The causative depths for these trends can not be concluded from the data, but can be constrained by plausible reasonings presented later in this paper.

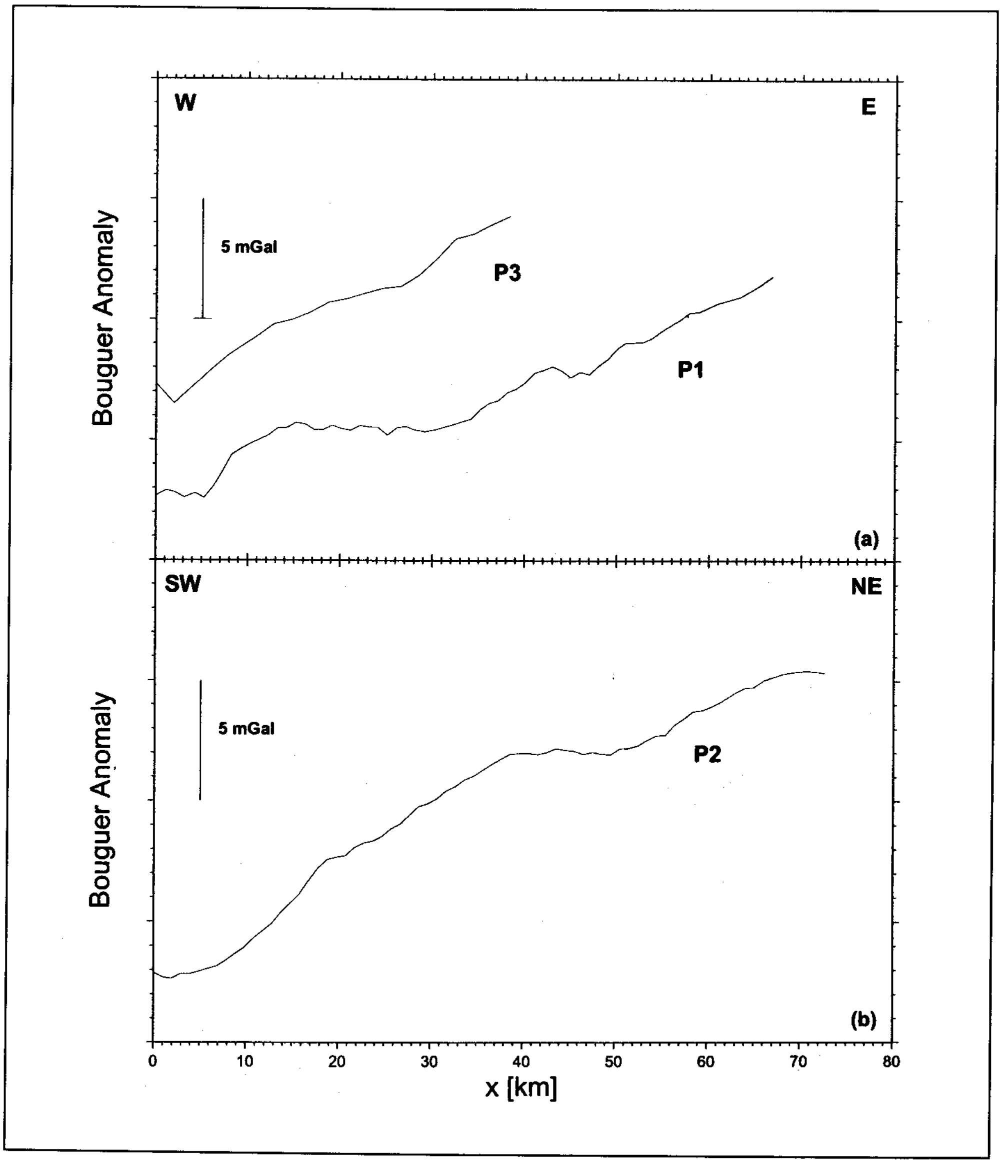

Figure 3 : Bouguer anomalies (a) Dukhan, Umm Bab profiles (P1, P3) and (b) of Abu Samra profile (P2).

Following the main topographic and geological lineaments, the main tectonic structures of Qatar Peninsula are supposed to be N-S striking. In Figure 4, the residual Bouguer anomalies for the three profiles are plotted versus longitude. In none of the profiles, the amplitude exceeds the range ±2 mGal. Recalling the tendency for N-S trends in Qatar, a broad positive anomaly stands out in P2 between longitudes 51.0° and 51.2° E and reduces northwardly. This feature could be related to the well-known Qatar Arch. Another poitive anomaly around longitude 50.9°E in P1 and P3 decreases from north to south and seems to have disappeared in the Abu Samra profile P2.

2D-modeling and interpretation

Concentrating on the residual Bouguer anomaly data, we have developed a model of the density distribution of the subsurface. Two procedures are known to solve this problem: inversion and forward modelling.

Inversion of local anomalies

Inversion means to run a mathematical algorithm that automatically calculates some density distribution of the subsurface from the field data based on certain criteria. In our case, geological constraints will be introduced.

Using the algorithm of Bott [12, 13]. the subsurface is first subdivided according to Figure 5 into a 2D two-layer model. In our study, the upper layer represents the sedimentary cover which is given a unform density of ∂ =2.5 g/cm^3, and the lower layer is bedrock with ∂=2.7 g/cm^3. The boundary is assumed to have an average depth of z_0=9 km. These

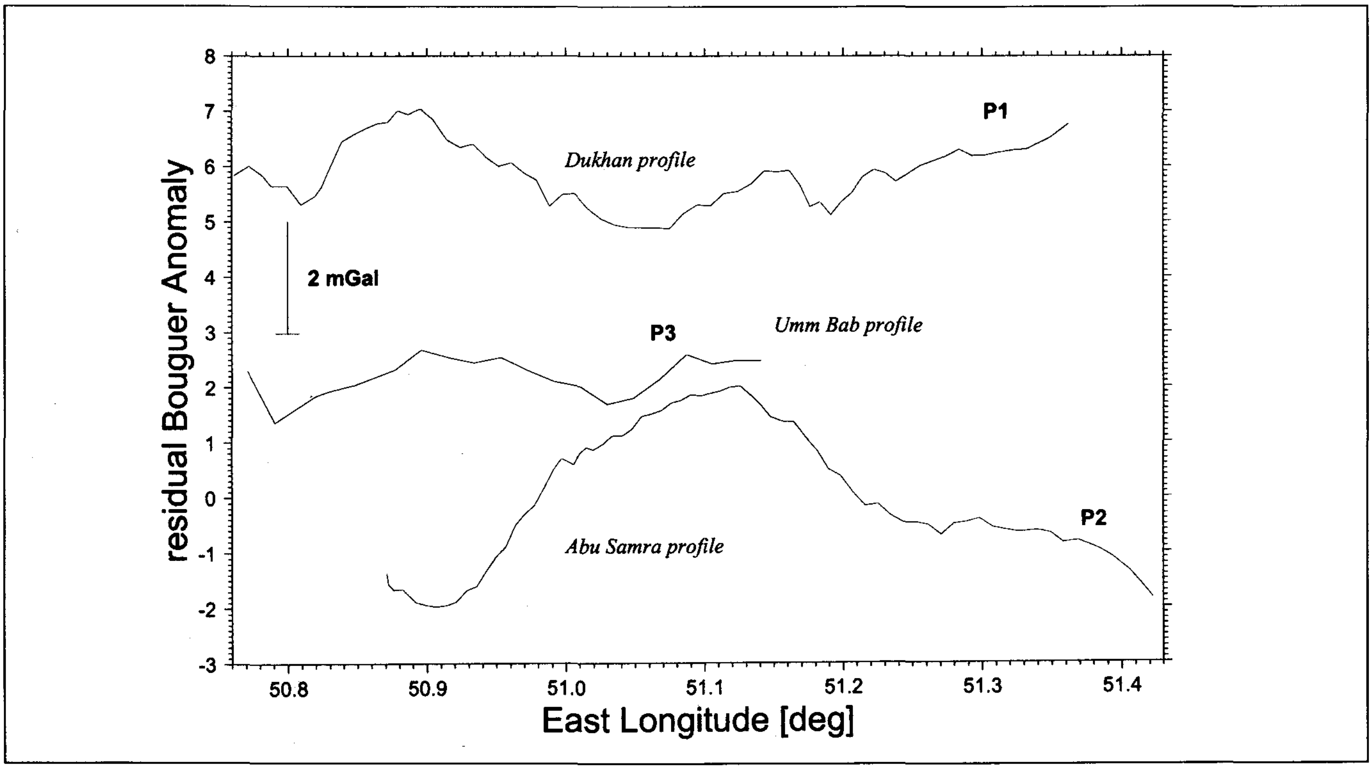

Figure 4 : Residual Bouguer anomalies with linear trends subtracted for the three profiles P1, P2 and P3.

model parameters are kept fixed. We now divide the bedrock into blocks having a vertical extent from that boundary down to infinity. Each block corresponds to one gravity station at the surface. The unknowns are the depths z_i of each block, i.e the distances from the surface to the boundary. In the inversion algorithm, these parameters are determined iteratively. In the first iteration, a depth increment proportional to the gravity datum on this station is substracted from the depth z_0. This value corresponds to the thickness of a Bouguer slab which would result in

$$z_i^{(1)} = z - \frac{g_{obs}}{2\pi\gamma\Delta\,\varrho} \qquad (1)$$

The Index (1) specifies the iteration number and Υ=6.67. 10^{-11} N. (m/kg)^2 is the gravitational constant. From this model, synthetic gravity values for each station j can be calculated using the analytical formula [14].

$$g_j^{syn} = 2\pi\gamma\Delta\varrho\sum_i In\left(\frac{z_{max}^2 + \Delta\, x_{i,j}^2}{z_0^2 + \Delta\, x_{i,j}^2}\right) \qquad (2)$$

Herein, $\Delta\, x_{i,j}$ denotes the horizontal distance between the two observation sites indexed i and j. In the kth iteration, a modification of the model depths $z_i^{(k-1)}$ can be estimated from these synthetic data, in analogy to equation (1):

$$z_i^{(k)} = z_i^{(k-1)} - \frac{g_{obs} - g_{syn}}{2\pi\gamma\Delta\partial} \qquad (3)$$

This procedure is continued until the root mean square (rms) error falls under a given value or does not change significantly.

As the algorithm is not stable, meaning that the model parameters do not coverage towards a definite value with increasing number of iterations, some constraint has to be introduced. Accordingly, after each full iteration (i.e. after solving eq. (3)) we lowpass filtered the model depths $z_i(k)$ by computing the weighted running mean of three adjacent data values. By this we achieve a stability of the model parameters as displayed in Figure 6. In the non-filtered case, the parameters diverge, whereas by filtering the model depths coverage towards stable values.

The results of the inversion (rms ≈ 0.2mGal for each profile, eafter 15 iterations) are shown in Figure 7. The block models mainly reveal structures which can already be seen in the observational data. Clearly, undulations of short wavelengths in the bedrock depth are, of course, less pronounced in the observations (as e.g. around x =20km and x =65 km in P2). The overall depth

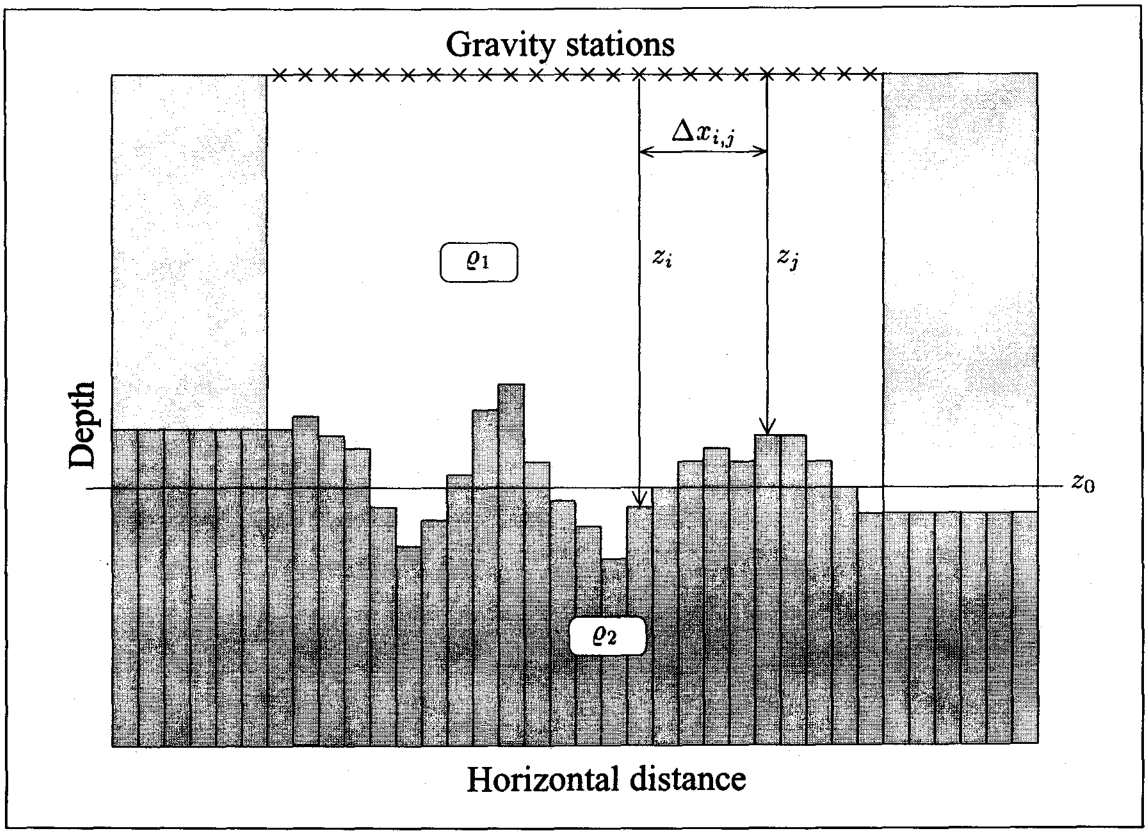

Fig. 5 : Model parameters for the inversion, z_0 is taken as 9km, ϱ_1, ϱ_2 as 2.5 and 2.7 g/cm^3, representing sedimentary cover and bedrock densities, respectively.

range of the bedrock topography resulting from this modeling extends from roughly 8.5 km to 9.5 km. Application of an inversion alogorithm to a more refined model of the subsurface, allowing more geological details to be represented through a higher degree of freedom, is necessarily less controlled. Forward modelling is more appropriate to resolve finer structures.

Forward modeling of local anomalies

In this approach, some density distribution of the subsurface is provided and the model response is calculated. The density distribution is then modified step by step through the interpreter who follows a plausible geological concept until the model response sufficiently fits the field data. In this

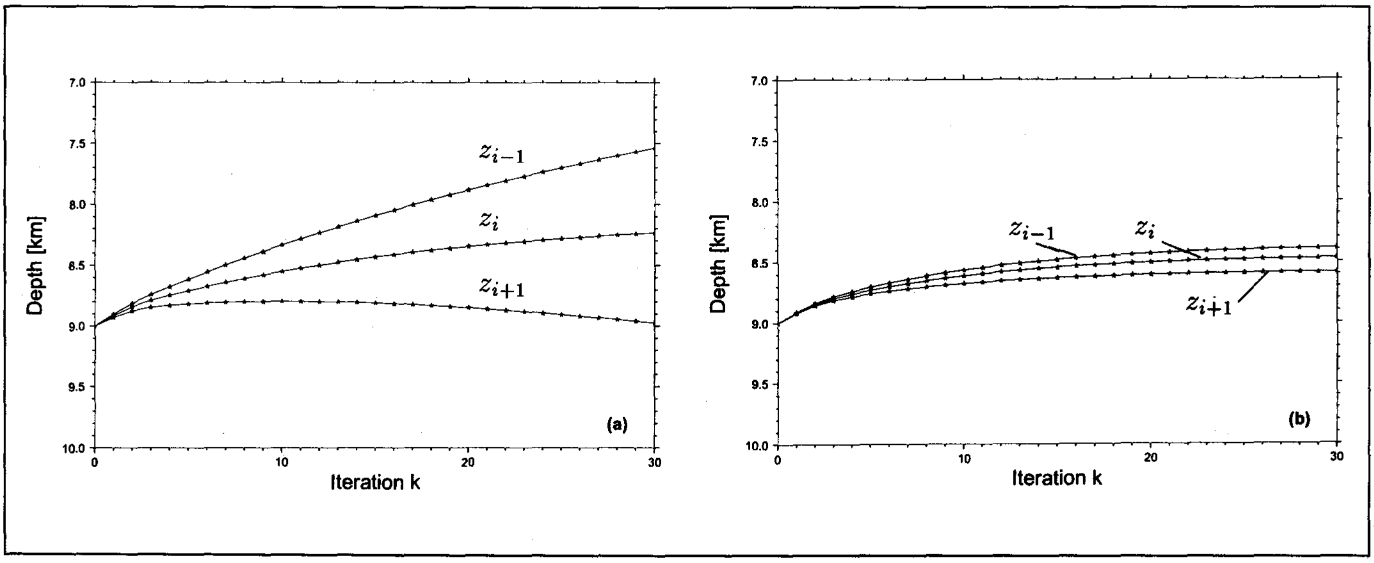

Fig. 6 : Change of depths z_{i-1}, z_i, z_{i+1} of adjacent blocks for evolving iteration number k, (a) without filtering, (b) when applying a running mean to these depths.

study, the software IGMAS [15] has been used for a 2D modeling. First we worked out simple block models with just a distinction between the bedrock and the sedimentary cover using the same densities as before (Figure 8). The vertical lines represent steep, hypothetical faults. The models give a rough idea about gross features in the subsurface (rms ≈ 0.3mGal for each profile), especially on the boundary of interest.

More detailed layerings are shown in Figure 9 (rms ≈ 0.15 mGal), where we have assumed a combination of subvertical faults and anticlines as the dominant structures. The sedimentary cover is divided into a several layers accord-

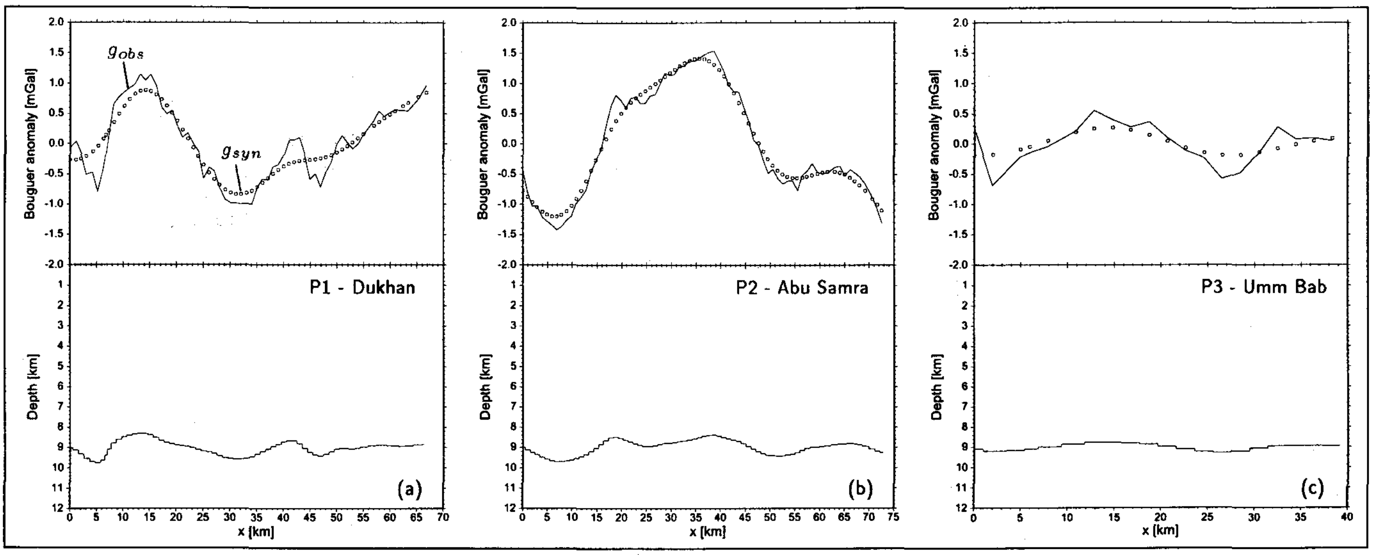

Fig. 7 : Inversion results for profiles (a) P1, (b) P2 and (c) P3. Solid lines g_{obs} in the upper diagrams are the observed gravity data, circles show the synthetic gravity values g_{syn} according to the block model depths z_i which are represented by the step functions in the lower diagrams.

ing to data from drillings and seismics [16]. Rather steep gradients as in P1 around x=7 or 45 km are best modeled by faults whereas smooth variations in gravity, as e.g. between x=15 and 30 km, can be attributed to a bending of layers. Acordingly, in profile P2, faults occur around x=12 and 48 km, and an anticline between x=26 and 48 km. Note that for this modeling we have adopted two further assumptions: (1) the successions of density values with depth are kept constant for all the sedimentary formations; (2) the general stratigraphy as it is known from some drillings in the Dukhan region is applied to all the profiles.

The total anomaly

Recalling the linear trends in the gravity data displayed in Figure 3, we have finally input the total anomaly into the inversion algorithm using the same density values (2.5 and 2.7 g/cm³) and initial depths as before. After rougly 15 itera-

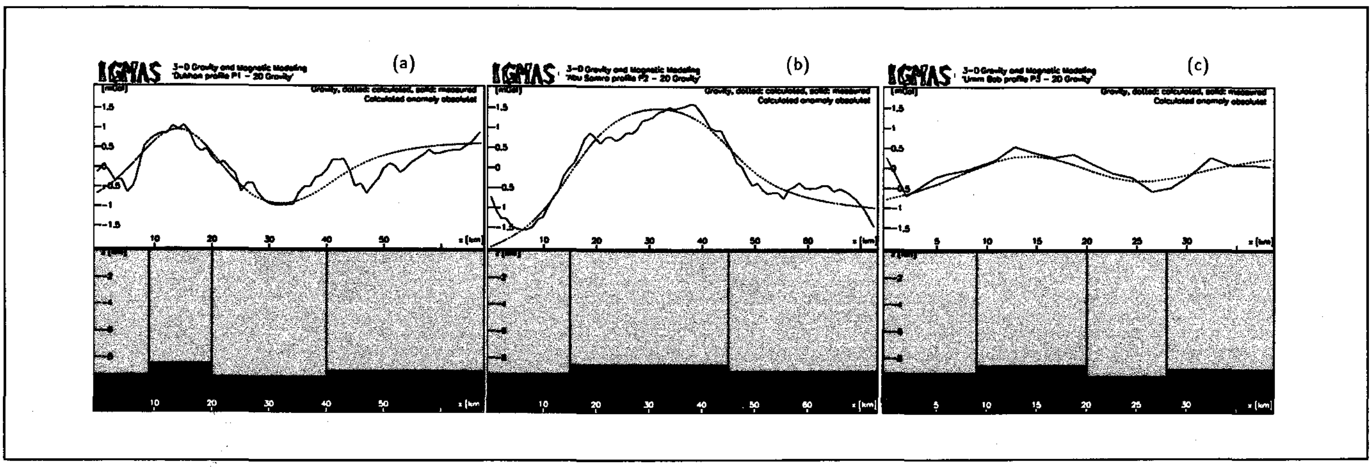

Fig. 8 : Simple block models for profiles (a) P1, (b) P2 and (c) P3 from 2D forward modeling with IGMAS ([15]).

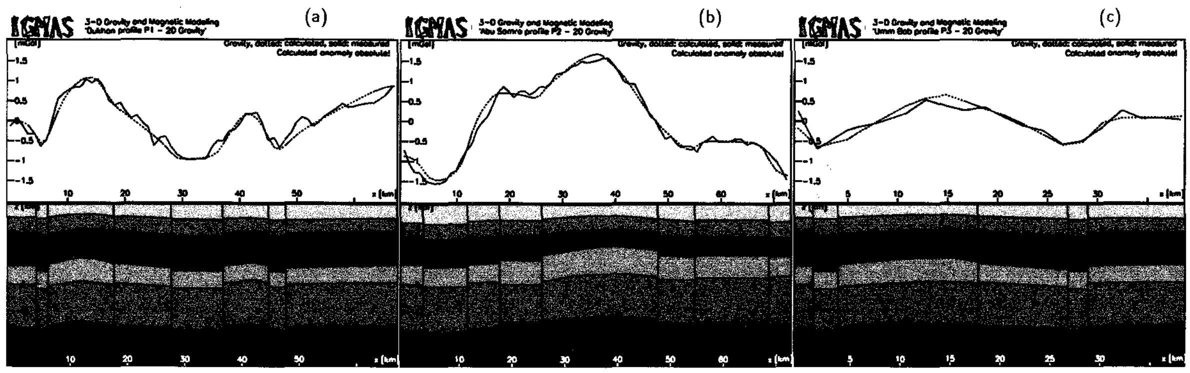

Fig. 9 : Refined models for profiles (a) P1, (b) P2 and (c) P3 through forward modeling using IGMAS ([15]). Densities of layers from top to bottom are 2.4, 2.6, 2.7, 2.5, 2.6 g/cm³ (sedimentary cover) and 2.7 g/cm³ (bedrock).

tions, the rums-errors fall under 0.2 mGal and show no further significant change. The local anomalies from the previous sections are now superimposed by a rise of the bedrock topography from west to east for P1 and P3 and from south-west to northeast for P2 (Figure 10). The magnitude of this rise is roughly 40m/1 km, thus giving a slope of 4%. This is a plausible value indicating no contradiction with geological constraints. In case of greater causative depth for the linear trend, a larger contrast in density or a steeper gradient has to be assumed. So far, there are no arguments for these assumptions, but further geophysical investigations or the combination of our data with detailed off-shore gravity information (not available to us) may validate this point.

Conclusions

The high quality gravity data obtained along three profiles on-shore Qatar has been modeled by inversion and by forward modeling. The resulting models are based on the given constraints, e.g. the division into basement and sediments at a depth of about 9 km, or the insertion of faults. Provided that these assumptions are valid we arrive at a sub-

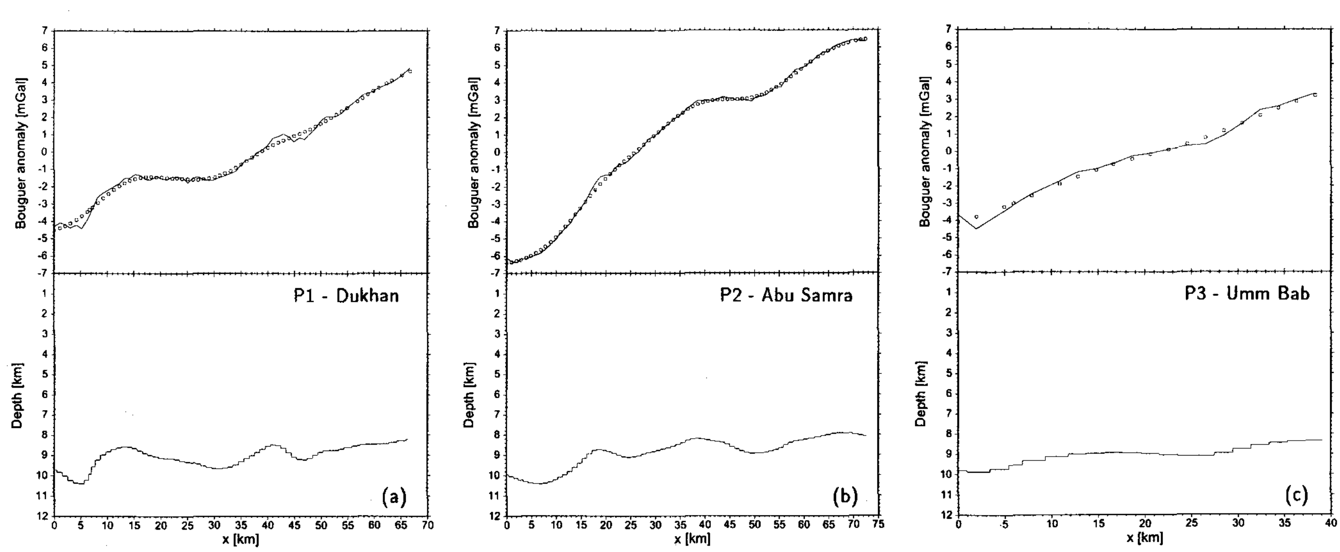

Fig. 10 : Inversion result of total anomalies for profiles (a) P1, (b) P2 and (c) P3 assuming the linear trend to be caused by a slope in the bedrock topography.

surface structure of the Qatar Peninsula as presented in Figures 9 and 10. If the linear trend is caused by a slope of the bedrock topography at around 9km depth, an eastward rise of 2 km across the Qatar Peninsula is found. Other causative depths, however, do not lead to a better fit between the observations and the model. The study shows that field gravity measurements are useful to constrain the topography of the boundary between basement rock and sedimentary cover. Local anomalies in the Qatar data can be interpreted as steep faults and anticlines.

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