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Three-Dimensional Gravity Model of the Southern Jordan Dead Sea Transform

نموذج جيوفيزيائي ثُلاثي الأبعادِ لمعطيات تسارعات الجاذبية في منطقة إنهدام البحر الميت

Radwan El-Kelani

Earth Sciences and Seismic Engineering Center, An-Najah National University, Nablus, Palestine

E-mail: radwan@najah.edu

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Abstract

A three-dimensional interpretation of the newly compiled Bouguer anomaly map of the Dead Sea Transform (DST) is presented. A high-resolution 3-D model constrained with the seismic results reveals a possible crustal thickness and density distribution beneath the Rift. The negative Bouguer anomalies (-130 mGal) along the axial portion of the Rift floor, as deduced from the modelling results, are mainly caused by deep seated basins of light sediments (≥10 km). The inferred zone of intrusion coincides with the maximum gravity anomaly over the eastern flank of the Rift. The intrusion is displaced at different sectors along the NW-SE direction. The zone of the maximum crustal thinning (≤30 km) is attained in the western sector at the Mediterranean. The southeastern plateau, on the other hand, shows by far the largest crustal thickness in the region (38-42 km). Linked to the left lateral movement of ~ 107 km at the boundary between the African and Arabian plates, and constrained with recent seismic data, a small asymmetric topography of the Moho beneath the DST was modelled. The thickness and densities of the crust ranging from 2650-2900 kg/m^3 suggest that the DST underlain by a continental crust. The deep basins, the relatively large nature of the intrusion and the asymmetric topography of the Moho, lead to the conclusion that a small-scale asthenospheric upwelling(?) might be responsible for the thinning of the crust and subsequent rifting of the DST during the left lateral movement.

Key words: Bouguer anomalies, three-dimensional modelling, Dead Sea Transform, crustal densities.

مُلخَّص:

فَسَّرت هذه الدراسة أحدث خريطة لشواذات بوجير الواقعة فوق مناطق إنهدام البحر الميت، وذلك بوساطة بناء نموذج ثلاثي الأبعاد لتسارعات الجاذبية الأرضية. حيث تم استخدام أحدث معطيات نتائج السيزمية المتوافرة لتحديد سماكات القشرة الأرضية وتوزيع الكثافات تحت َنطقة الانهدام في بناء النموذج الأولي. وقد أشارت حسابات النموذج المعدل أن حوضاً َن الرسوبيات الخفيفة تصل سماكتها إلى أكثر َن ١٠ كم تحت إ َتداد حفرة الإنهدام هو المسبب لشواذات بوجير السالبة (-130 mGal) في حين يتسبب تواجد جسم ناري جوفي كبير تحت َناطق الكتف الشرقي للانهدام في ظهور شواذات بوجير َوجبة. وتشير حسابات النموذج أيضا إلى أن سماكة القشرة الأرضية تقل باتجاه الغرب لتصل إلى أقل َن ٣٠ كم بالقرب َن شواطئ البحر المتوسط في حين تصل سماكة القشرة الأرضية الى عمق ٤٢ كم تحت الهضبة الجنوبية الشرقية. كما يظهر النموذج عدم تماثل في طبوغرافية الموهو تحت حوض البحر الميت و تشير سماكة وكثافة القشرة الأرضية المحسوبة َن النموذج ($2650\text{-}2900\ kg/m^3$) إلى أن إنهدام البحر الميت يقع فوق قشرة قارية. إن تواجد الحجم الكبير للجسم الـ ّاري، وتكوُّن أحواض رسوبية عميقة كذلك، وعدم التماثل في طبوغرافية الموهو يُفَسَّر بصعود جزئي لمواد الغلاف اللَّدن (الاسثي ّوسفير) تحت الجزء السفلي للقشرة الأرضية أثـ ّاء الحركة الأفقية بين الصفيحتين العربية والافريقية، والذي يمكن أن يكون سبباً أيضا في ترقّق القشرة الأرضية تَلاه إنهدام البحر الميت.

1. Introduction

The unique geological setting of the Dead Sea Transform, where the inception of plate boundaries within the continental rift is clearly observed, makes the region the main focus of interest for geoscientific researchers. The nature of the crust underlying the eastern and western shoulders of the Rift as well as the Dead Sea depression (Jordan Rift Valley) have been controversial among researchers for the past five decades. Consequently, the crustal structure of the Dead Sea Transform and its both eastern and western plateaus have been well studied and documented (1-12). Based on both reflection/refraction seismic experiments and gravity data, there is a gradual transition from the continental crust of the eastern part of the rift (Arabian Plate) with thicknesses of 35-40 km (4, 6, 34) to the crust of the eastern Mediterranean (Palestine Sinia Plate), that is assumed to be partly underlain by typical oceanic crust with thicknesses smaller than 10 Km (1, 4, 12).

In the present work, an attempt is made to prepare a high-resolution 3-dimentional gravity model of the southern part of the Jordan Dead Sea Transform (Fig. 1). The results of the recent seismic reflection/refraction experiments in Wadi

Araba, which cross the eastern and western Jordan Rift Plateaus (13-19) have been used to constrain the initial 3-dimentional gravity model of the graben. The gravity data were mainly collected by the Natural Resources Authority (NRA) of Jordan and the Geophysical Institute of Israel (GII) during the period 1980-2002.

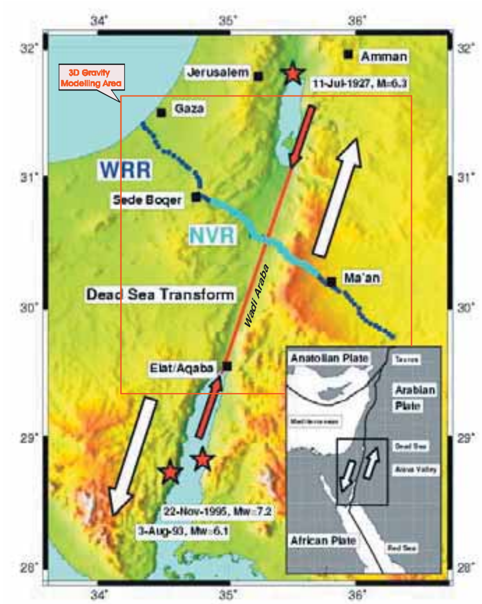

Figure 1. *Location map of the study area and the seismic experiments in the Middle East. The 260 km long wide-angle reflection/ refraction profile (WRR, blue dots) crosses Palestine and Jordan. The near-vertical seismic reflection profile (NVR, cyan) coincides with the inner 100 km of the WRR. A red line and two red arrows indicate the Dead Sea Transform (DST) between the Dead Sea and the Red Sea (i.e. Wadi Araba Fault). The white arrows indicate the left-lateral motion of 107 km between the African and Arabian plates. Red stars mark large earthquakes (modified after 13).*

The present study incorporates additional gravity survey carried out during March-May 2002 by joint collaboration between several geophysical institutes: Germany (FU Berlin); Jordan (NRA) and Palestine (Earth Sciences and Seismic Engineering Centre (ESSEC) at An-Najah National University).

The spacing of the gravity stations along lines and grids, for both gravity data sets collected by the NRA and the GII, and gravity survey performed by the joint collaboration between FU-Berlin, the NRA and the ESSEC, ranges from 0.05-5 Km, and the average accuracy of gravity data is about 0.01 mGal. The two data sets were reduced using a density value of 2670 kg/m^3. Moreover, the gravity data are terrain corrected up to zone I (160 km) using topographic charts and Hammer Table (20).

2. Geological Setting

The general geological information of the study area has been incorporated both in the qualitative and quantitative interpretation stages of the observed Bouguer gravity anomalies. The available compiled geological map of Jordan and Palestine (Fig. 2), which covers only part of the modeling area, was used in determining the lateral dimension of the major rock units outcropping on the surface of the Rift floor and the adjoining plateaus (A compiled geological map of the whole study area is, unfortunately, not available because of the current political situation). Thus, the geological information needed for the northern part has been obtained from the NRA and the GII). A clear understanding of the regional geology of the Dead Sea Transform and the adjoining region is, therefore, necessary for the modelling and interpretation of the gravity data. A short account of the regional geology of the Dead Sea Transform is given below.

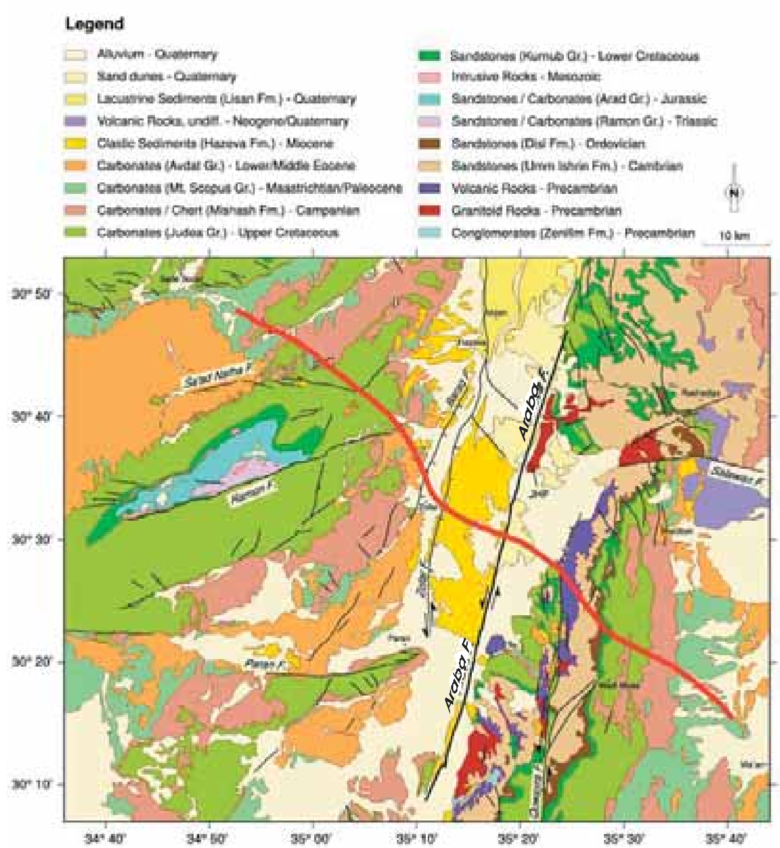

Figure 2. *Geological Map of the modelling planes; the red line represents the near-vertical seismic reflection profile (35).*

The Dead Sea Transform forms a part of the largest Tertiary-Quaternary rift system which extends from Gulf of Aqaba in the south to Syria and Turkey in the north (Fig. 1). The Rift, like the rest of the East African Rift System, has undergone a very complicated geological evolution and tectonic history. The regional geology and structural evolution of the Dead Sea Transform system have been extensively described and well documented (8, 21-25). A simplified geological sketch map of the Dead Sea Transform, illustrating the main geological units and locations of the main structural trends, is shown in Figs. 1, 2. Volcanic rocks of Tertiary to Early Cambrian such as volcaniclastic, calc-alkaline granitoids and rhyolites are abundant within the Rift floor and the adjoining plateaus (26). The pre-Cambrian basement rocks in the Dead Sea Transform system, except in the northern Aqaba at the extreme south of the Transform, are mostly covered by more recent Tertiary volcanic rocks to Early Cambrian volcanosedimentary succession and Mesozoic sediments. The oldest sedimentary sequence, on the other hand, is masked by sediments of Middle to Upper Pleistocene age where light deposits of Pleistocene to Holocene age are common within the rift valley. The main trend of the tectonic structure in the graben is the same as of the Dead Sea Transform, which is dominantly of NNE-SSW direction (8, 27). Within the Rift floor, three major geotectonical provinces are recognizable: The Gulf of Aqaba; Wadi Araba and Dead Sea-northern region, (see Fig. 1).

3. Gravity data analysis

In order to interpret the gross crustal structure of the Dead Sea Transform, a Bouguer anomaly map at a constant contour interval of 5 mGal has been prepared (Fig. 3). The newly compiled Bouguer gravity map is based mainly on the regional gravity data collected by the Natural Resources Authority (NRA) of Jordan and the geophysical Institute of Israel (GII). The general trend of the Bouguer gravity anomalies in the Rift is NNE-SSW. The map reveals a relatively large-scale local positive Bouguer anomaly over the eastern Dead Sea high lands. The anomaly increases in magnitude with a disappear in the relief of the topography and attends its maximum of -10 mGal along an axial of NW-SE trend. Closer geological and structural observation (Figs. 1 & 2) of the axes of the maximum anomaly suggests that its general trends follow an inferred zone of intrusion along the Karak-Wadi El-Fayha (KWF) fault system (33).

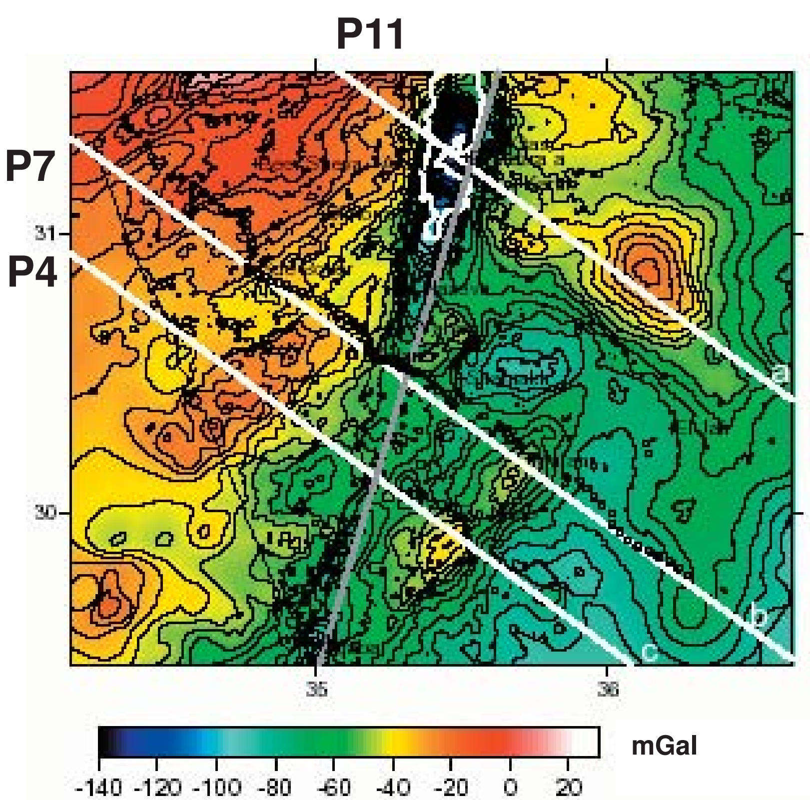

Figure 3. *Compiled Bouguer anomaly map of the southern part of the Jordan Dead Sea Transform (contour interval 5 mGal). The solid lines a, b,c (white) show the locations of the 3-dimensional modelling vertical planes p4, p7, p11 among 14 modelled cross-section.*

The quite different nature of the Bouguer gravity map (Fig. 3), on the two opposite facing plateaus, is marked by a steep gravity gradient along the eastern escarpment of the Rift floor and a relatively moderate gravity gradient along the western escarpment. The Bouguer gravity on the south eastern plateau (Fig. 3) reaches a minimum value of -90 mGal east of Ma'an (El-Jafr depression) whereas the gravity over the western plateau first decreases to a value of -40 mGal in the south western part, then gradually attends its maximum value of 20 mGal in the north. The minimum anomaly in the Rift floor is terminated at two places by NW-SE-trending gravity gradients. The first gravity gradient coincides with the boundary of the Dead Sea basin as full-graben. The second gradient marks the Miocene sediment deposits in Timna and Gharandal basins in Wadi Araba.

4. Three-dimensional gravity modelling

4.1 Methodology

As the general geological strike along the Rift floor is variable, a 3-dimensional modelling, covering an area of 66.2×10^3 km^2 with 14 vertical cross-section (planes), was applied to investigate the density distribution beneath the southern part of the Jordan Dead Sea Transform. The 3-dimensional forward gravity modelling package IGMAS, Interactive Gravimetry and Magnetic Analysis System (28), was used to establish the geometry and density distribution of the graben. IGMAS is an extended new version of the Interactive Gravity Application System IGAS developed by Götze and Lahmeyer (29). The method is based mainly on transforming the volume integral involved in the vertical attraction of a homogeneous polyhedron into a sum of line integrals suitable for computer programming. The program requires an input data structure along a definite number of vertical modelling planes perpendicular to the general geological strike. In each plane, the vertices of the assumed subsurface structures are interconnected to form a line separating two media with different densities (see Fig. 4). Lines of the neighbouring planes separating identical medium densities are joined to form triangles and, hence, layer boundary surfaces. The model so developed gives a more realistic approximation of the geologic structures (29, 30). One of the advantages of this method is its ability to approximate a body with a small number of polyhedrons. Consequently, any change in the shape of the body can be achieved with only few data manipulations. Besides, the simplicity of approximation in data handling and manipulation pertaining to the changes of the shape of the body, the method considers the earth curvature during the computation of the effects of very large structures.

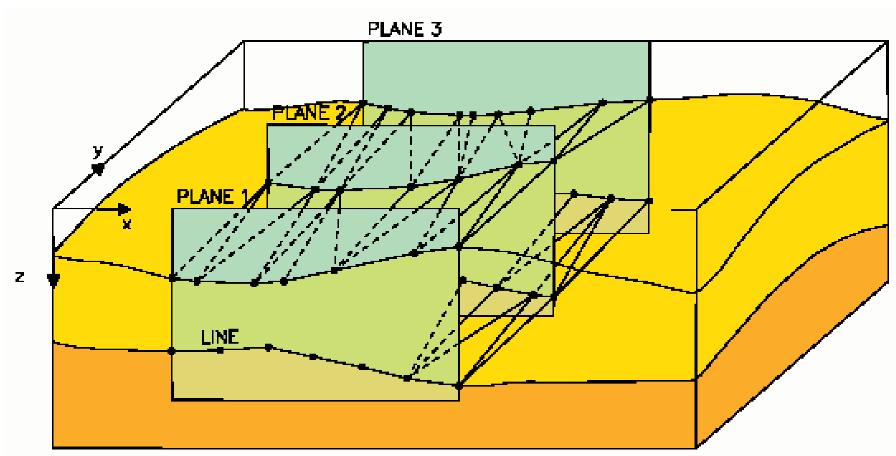

Figure 4. *Presentation of a simple two-layer substructure (29).*

The location and orientation of three selected vertical modelling planes are shown in Fig. 3. The orientation of the vertical planes is perpendicular to the general geological strike of the Rift. The vertical planes are parallel to each other, and the distances between the planes are variable along the Rift floor depending on the location of the anomalies, on the Bouguer map, and their corresponding causative bodies on the geological map.

4.2 Results and discussion

The sources of constraining data pertaining to the geometry and density of the initial gravity model are various published and unpublished studies (13-19, 31, 33-39). In particular, the determination of the initial crustal thickness and density values for the deep structure of the Rift are based on the results of DESERT Project: The seismic reflection/refraction lines (near-vertical incidence reflection and wide angel reflection refraction seismic) crossing the western and eastern Dead Sea flanks in the NW-SE direction (13); and the receiver function analysis (19). Table 1 shows (see also Fig. 5) the P-wave velocities of the structural units from the DESERT seismic experiment (13). Also shown are the estimated density values used for the regional 3-dimentional gravity modelling of the southern part of the Dead Sea Transform. The density values were estimated from the seismic velocities using Sobolev & Babeyko method (32): velocity-density conversion under certain pressure and temperature conditions.

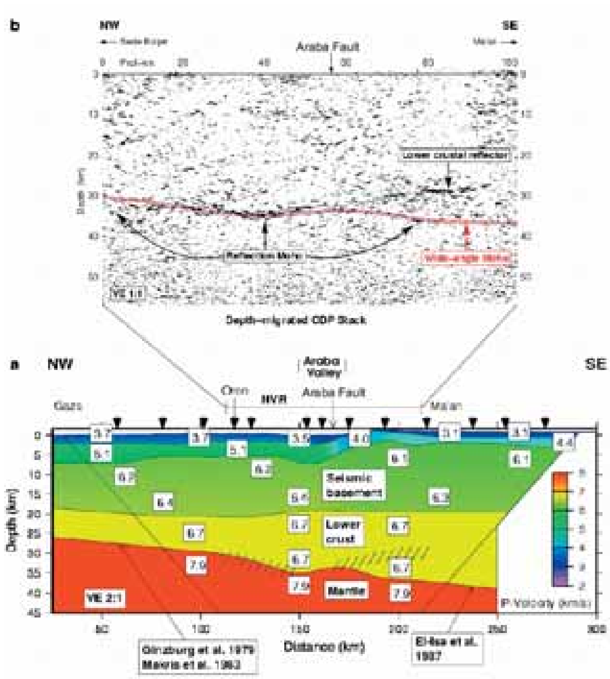

Figure 5. *a) 2-D P-velocity model (velocities in km/s) for the WRR experiment. The shots (triangles at top) were recorded by 99 three-component instruments along the whole profile and 125 vertical component geophone groups in the Araba Valley. The hatched symbols near the Moho, the border between yellow and red colours, indicate the location of bands of strong reflections. b) Automatic line drawing of the depth-migrated seismic CDP section of the NVR experiment. The red band indicates the location of the Moho (crust/mantle boundary) as derived from the WRR experiment in (a). The black arrows mark the break-off of reflectivity, generally interpreted as the Moho in seismic reflection data (13).*

The density measurements from several boreholes, drilled for geothermal investigations or oil exploration, have also been taken into consideration (33). Although the boreholes are not too deep to furnish density information on the large and deep crustal structure of the Rift, the measured density values have been used to control the densities of the shallow rock units incorporated in the model.

Table 1. *The P-wave velocities of the geological units from the wide angle reflection/ refraction seismic experiment (13).*

Geological Units	Velocity Vp (km/s)	Density (kg/m^3)
Sediments	3.3 – 5.2	2500 –2650
Upper crust	6.2 – 6.1	2750– 2700
Lower crust	6.7	2900
Upper mantle	7.9	3300

Sections through the final model along planes 4, 7 and 11 are shown in Figs. 6-8. A section from the central sector of Wadi Araba (Fig. 6) was selected over the DESERT seismic line (refer to Fig. 3 for the locations of the modelling planes). The model portrays a possible crustal thickness and density distribution beneath the graben and eastern and western Rift flank. The model allows for a slight thinning of the crust beneath the western plateau, whereas a gentle dip in the NE direction is indicated. It shows a steady increase in the depth of the crust mantle transition (Moho) from ~ 29 km at the Mediterranean to ~ 42 km beneath the eastern plateau (19, 34). Also the model confirms the asymmetric topography of the Moho beneath the Dead Sea Transform (13).

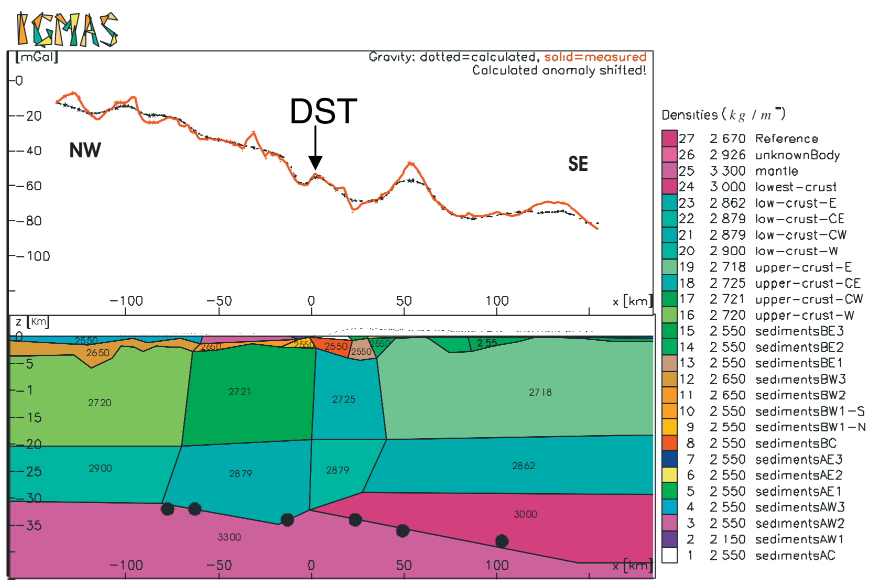

Figure 6. *A vertical cross-section of the 3-dimensional model beneath the DESERT transect (p7). The density values of the geologic units are given in kg/m³. The solid black circles indicate the Moho depth from the receiver function data (19).*

The model consists of a density of 2150 kg/m^3 (the graben deposits); 2550 kg/m^3 (the Mesozoic carbonate platform); 2650 kg/m^3 (Upper Cambrian/Lower Ordovician sandstone). A density of 2710-2720 kg/m^3 for the crystalline basement (Upper Crust); 2900-3000 kg/m^3 (Lower Crust) and 3300 kg/m^3 for the upper mantle material. The model maps the seismic constrained sub-horizontal lower crust reflector (13) at a depth between 28 km and 32 km beneath the eastern flank.

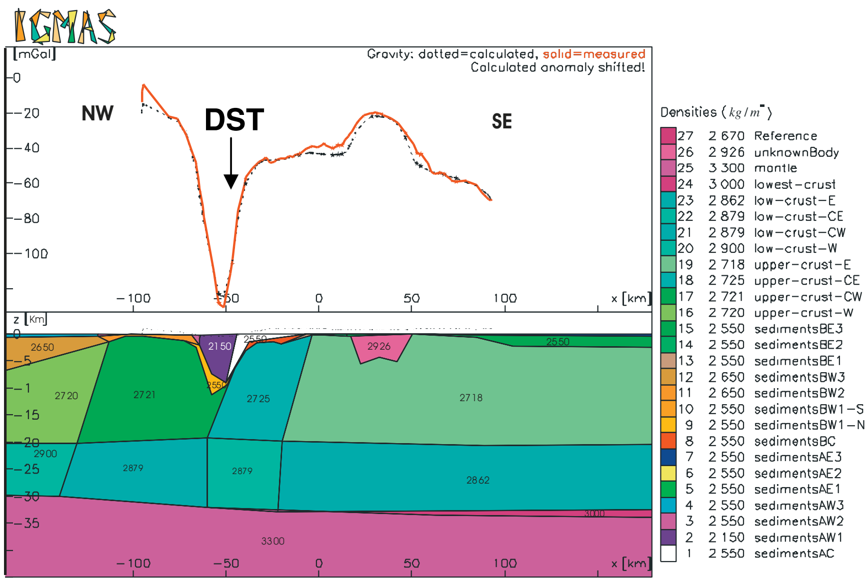

Figure 7. *A vertical cross-section of the 3-dimensional model beneath the Dead Sea basin (p11). The density values of the geologic units are given in kg/m³. An intrusion with assigned density 2926 kg/m³ is modelled beneath the eastern highlands.*

The modelling showed that the regional gravity trend towards NW-SE direction reflects the potential field effect caused by the density materials of the lower crust and upper mantle (Moho). The relatively long-wavelength negative anomalies explain sediment materials in the Rift floor (Dead Sea depression, Gharandal and Timna basins), and beneath Ma'an plateau (El-Jafr depression) to a depth range between 3 km and 11 km with density values of 2150 kg/m³ and 2550 kg/m³. The relatively long-wavelength positive anomalies were modelled using the density of 2710-2720 kg/m³ of different magmatic complexes basement rocks underlain the area at a very shallow depth (0-0.2 km). The local short-wave length positive anomalies are best explained in terms of non-modelled near-surface igneous intrusions of the basic type that are located at different depths within the basement or sedimentary cover.

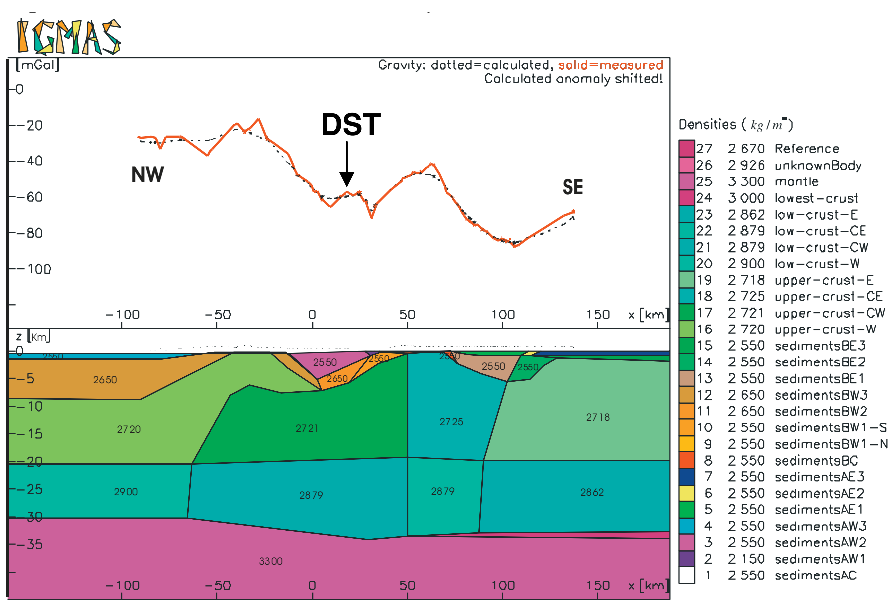

Figure 8. *A vertical cross-section of the 3-dimensional model from the southern sector of the Dead Sea Transform (p4). The density values of the geologic units are given in kg/m^3.*

The model indicates a lateral variability of the density within the upper and lower crust (Figs. 6, 7 and 8) that might be attributed to the different stages of differentiation (different rock forming minerals) of the hot upper mantle material on its way to the lower crust as well as the crystalline basement. On the other hand, the local relatively long-wavelength positive anomaly over the eastern part of the modelling area (Fig. 7, see also Fig. 3) was explained as near-surface igneous intrusion. The gravity effect, caused by the intrusion, was determined by varying the geometry as well as its depth with fixed density of 2926 kg/m^3 (see Fig. 7). The fit was, however, achieved also by using the assigned densities 3000 and 3100 kg/m^3, but of course with less depth. The density of the intrusive body, as deduced from the values 2930, 3000 and 3100 kg/m^3 which are not much larger than the lower crust (2900 kg/m^3) is most probably of mantle or crust-mantle origin. Such a situation, however, could arise as a result of the petrologic differentiation of the mantle-derived material. The shallowest depth to the top of the intrusion is in the range 0.03 km (below zero level) and 0.32 km varies along 35 km axial plane in the NW-SE direction. The bottom of the intrusion, with assigned density 2926 kg/m^3, is located within the crystalline basement at depths between 4.7 km and 5.5 km.

The gravity model also incorporates the sediments of the Rift floor and Dead Sea depression (Fig. 7, see also Fig. 3), surrounded by crystalline basement rocks. As discussed above, the negative anomalies are attributed to local sediment basins. The lowest negative anomaly ~ -130 mGal over the Dead Sea is well explained (33, 36, 38 and 39) with a density value of 2150 kg/m^3 attached to the Pleistocene light sediment fills of the Dead Sea depressions (Figs. 7 and 3). The total thickness of the Pleistocene sediments beneath the southern part of the Dead Sea depression, as obtained from the gravity modelling, is over 10 km (Fig. 7). However, recent results of 3-dimensional gravity modelling beneath the central part of the Dead Sea basin indicate great thickness of 12-16 km for the Pleistocene sediments of the basin (33).

The crystalline basement (Figs. 6, 7 and 8), which is considered here between ca. 20 km and the bottom of the sedimentary layer, has been modelled with density values in the range 2710 kg/m^3 beneath the western flank and 2720 kg/m^3 beneath the eastern plateau. The top interface of the crystalline basement beneath the Rift floor (Figs. 6, 7 and 8) is generally marked by the maximum thickness of the sedimentary layer (over 10 km; Fig. 7). The minimum depth has been observed beneath the eastern Rift flank, where the mantle or crust-mantle material exists in the form of an intrusion (Fig. 7). The unit generally thickens towards the adjoining plateaus (eastward and westward from the Rift floor). However, the crystalline basement has a thickness of ~9 km in central sector of the Rift (Fig. 7). This unit, even, attends further its minimum thickness under the northern part of the study area (33).

The Moho-depth map of the Dead Sea Transform is shown in Fig. 9 (IGMAS options allow to highlight the boundary between the crust and the upper mantle beneath the vertical cross-sections of the 3-dimensional model, where the computed depths given automatically in a data file and sent interactively by IGMAS to be drawn as a Moho depth map). The contour lines represent the crustal thickness distribution beneath the Rift as well as its eastern and western flanks. As expected, the computed depths to the crust-upper mantle interface (Fig. 9) resemble the general shape of the

Bouguer gravity anomaly shown in Fig. 3 The asymmetric topography of the Moho beneath the Dead Sea Transform (Fig. 6) separates the thinnest part of the crust, which is shown as a morphological low (≤30 km) in Fig. 9 (the Moho depth map) beneath the western flank of the Rift, and the thickest crust beneath the south eastern plateau.

The morphological low trend of the Moho-depth map coincides with the maximum gravity anomaly over the western flank of the Rift (Fig. 3), whereas the morphological high (≤42 km) of the Moho-depth map correlates with the minimum gravity anomaly over the south eastern plateau. The general trend of the Moho deepening from west to east is confirmed by the DESERT Group (13), and by the interpretation of potential field data (34). Also, it is in a good agreement with the results obtained from receiver function study across the Dead Sea Transform (19).

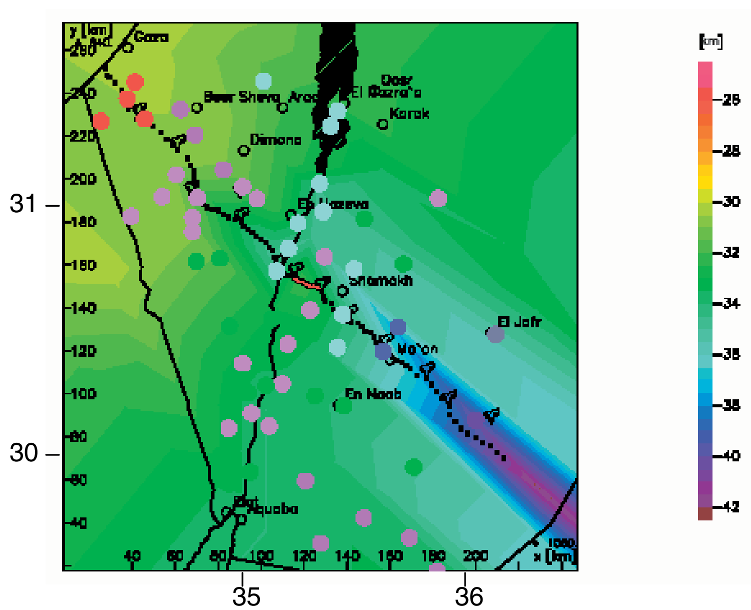

Figure 9. *Moho depth map beneath the 3-dimensional gravity modelling area of the Dead Sea Transform (contour interval 0.5 km, scale 1:30000). Also shown is the moho depth (circles) from the receiver function data (19).*

The contour map, shown in Fig. 10, of misfit (gravity differences) between the measured Bouguer anomalies in Fig. 3 and the computed Bouguer anomalies obtained from the 3-dimensional modelling (Figs. 6-8) reveals a prominent modelling discrepancy of ±5 mGal (the histogram beneath the contour map in Fig. 10 shows a statistical display of the percentages of the gravity differences). However, for a regional gravity modelling, the computed Bouguer gravity map is acceptable.

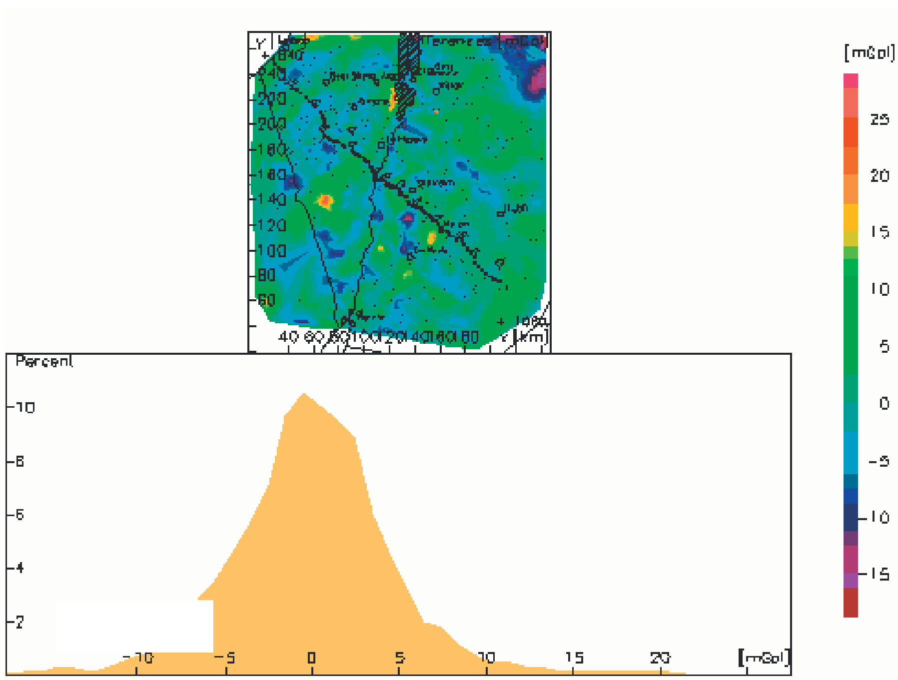

Figure 10. *Histogram of gravity differences between measured and computed Bouguer anomalies (correlation coefficient 0.98). Also shown is the misfit between the measured and computed Bouguer anomaly map of the study area (contour interval 1 mGal).*

5. Conclusions

The newly compiled Bouguer anomaly map of the Dead Sea Transform enabled us to establish a possible density model along the Dead Sea Transect (DESERT). The seismic information and the uniform ground coverage of the gravity points helped in modelling and interpreting the gravity data which reveals some aspects about the crustal structure of the Dead Sea Transform that are useful for supplementing other constrains in the geological synthesis. The gravity data have proved to be useful for delineating shallow and deep structures and helping the definition of models which agree with the basic information supplied by the previous geophysical investigations as well as from geological knowledge.

The Bouguer anomaly map of the study area is characterized by the presence of different anomalies that differ in their amplitudes, sizes and trends. These anomalies are caused by combination of various sources that are located at different depths. The most prominent feature of the Bouguer map is the presence of minimum anomaly in the Rift floor which coincides with the boundary of the Dead Sea basin as full-graben and reaches a minimum value of -130 mGal over the northern part of the Dead Sea; negative Bouguer gravity on the south eastern plateau reaches a minimum value of -80 mGal east of Ma'an (El-Jafr depression); positive gravity anomaly over the western plateau attends a maximum value of 20 mGal in the north and correlates with a high density value of the upper crust material beneath the north western part of the modelling area; a relatively large-scale local positive Bouguer anomaly over the eastern Dead Sea highlands, with a maximum value of -20 mGal along an axial of NW-SE trend, where its general trends follows an inferred zone of intrusion along the Karak-Wadi El-Fayha (KWF) fault system.

The high-resolution 3-dimensional gravity model is constrained by seismic information from the DESERT seismic experiments in the southern part of the Dead Sea Transform. The final 3D gravity model indicates that the Rift floor and its eastern and western plateaus are underlain by a continental crust within assigned densities ranging from 2650-2900 kg/m^3. The negative Bouguer anomaly over the Dead Sea basin is modelled as internal sedimentary basins filled by light density young sediments with assigned density 2150 kg/m^3 and depths in the range 8-12 km.

The local positive anomaly, on the other hand, is modelled as differentiated basic igneous materials (intrusion) within the upper most part of the crust (<1 km) using the assigned densities 2930, 3000 and 3100 kg/m^3 which is most probably of mantel or crust-mantel origin. The gravity gradients, marking the two opposite facing escarpments of the Rift, are also well modelled.

The Moho-depth map indicates the thinning of the crust beneath the western flank of the Rift (≤30 km), and the thickest crust beneath the south eastern plateau (38-42 km). On the other hand, a symmetric topography of the Moho is modelled beneath the Dead Sea transform.

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