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Full Length Research Paper

Crustal structure of the Northwestern part of the Arabian Shield in Saudi Arabia deduced from gravity data

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The present-day tectonics of the Northwestern Region of Saudi Arabia is affected by the tectonics related to the Red Sea floor spreading. The tectonic movemets related to the Red Sea floor spreading creat great variations in the crustal structure and depth of Moho discontinuity through this region. Gravity data have been acquired from Earth Gravitional Model (EGM-2008) and analyzed to estimate the crustal thickness under this region. 2-D gravity modeling have been conducted along eleven profiles oriented ENE-WSW and NW-SE to verify the lateral variations of the crust and mantle beneath these profiles. Accordingly, the upper layer of the crust is represented by sedimentary rocks underlying by basement layer that extends until the Moho discontinuity. The crustal thickness increases eastward,and the depth to the Moho is 25 km in the western part, along the Red Sea and increased upto 38 km through the Arabian Shield. These results are in agreement with the previous deep seismic and seismological investigations. The relation between recent earthquake swarms at Harrat Al-Shaqah area and the variations of Moho depth through the Northwestern Region has been clarified. It can be concluded that, these earthquake activities are of crustal origin and occurred due to the stresses exerted upon the pre-existed faults by mantle upwelling in this region. These results can be confirmed by the presence of the recent volcanic activities that experienced the Western Region of Saudi Arabia.

Key words: Western Region of Saudi Arabia, Red Sea, tectonics, Arabian Shield.

INTRODUCTION

The studied Northwestern part of Saudi Arabia extends between the latitudes 21 to 27° North and longitudes 36 to 43° East (Figure 1). This area was recently affected by two of the earthquake swarms in October 2007 and on 19 May, 2009. The most recent swarm was initiated on 18 April, 2009 at Harrat Al-Shaqah Northwest of Al- Medinah and reached its maximum on 19 May, 2009 where an earthquake with moment magnitude, M_w of 5.7 had occurred (Al-Amri and Fnais, 2009). This earthquake swarm lasted more than six months. Since that time, the area received a lot of attention through seismological, aeromagnetic and geological investigations. However, there is lack of data about the crustal structure of this region, the present study suggested fulfilling of this gap

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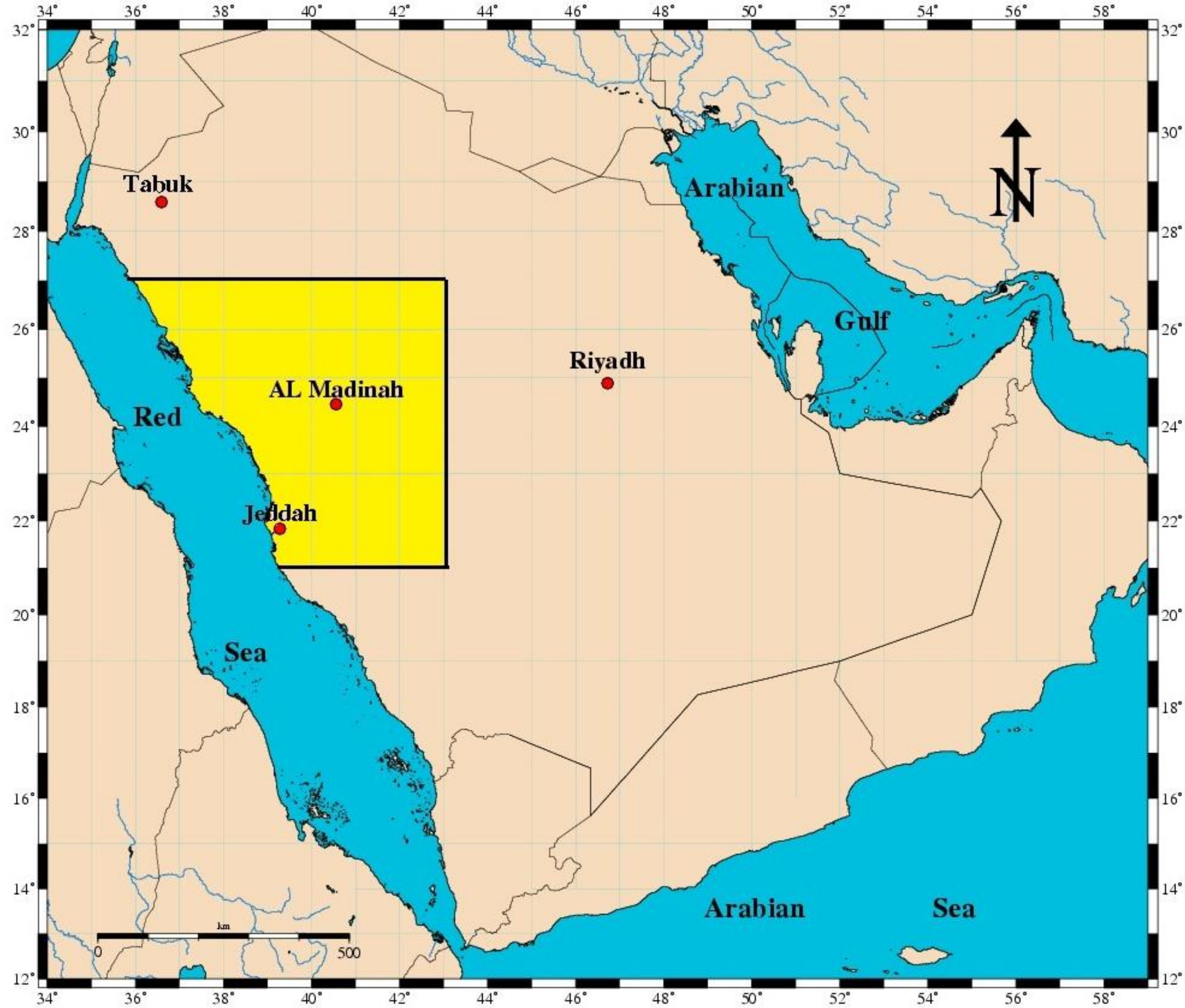

Figure 1. Location map of the study area.

through mapping of the crustal thickness through the Northwestern Region. Clarification of the relation between the depth of Moho discontinuity and earthquake occurrences in the Northwestern Region is planned as well.

The gravity method has been successfully applied for determining the crustal thickness for selected areas all over the world on spatial basis through contour maps (for example, Mahatsente et al., 1999; Ce´line Tirel et al., 2004). Gravity modeling approach is conducted to illustrate the lateral changes in the crustal structure and Moho depth under the study area that could explain the cause of the earthquake activities in the region.

TECTONIC FRAMEWORK

The Arabian Shield is constituted mainly by the Precambrian basement rocks intruded by granites and covered with (Figure 2) the Cenozoic basaltic lava fields (Coleman et al., 1983; Camp and Roobol, 1992; Sharland et al., 2001).

Three major tectonic trends prevailing through the Arabian Shield, 1) the N-S directed oldest trend was formed during the Precambrian, 2) the NW-SE directed faults (Najd faulting system) is responsible for rifting and opening of the Red Sea. 3) The NE-SW oriented faults that are well developed in the west central part of the

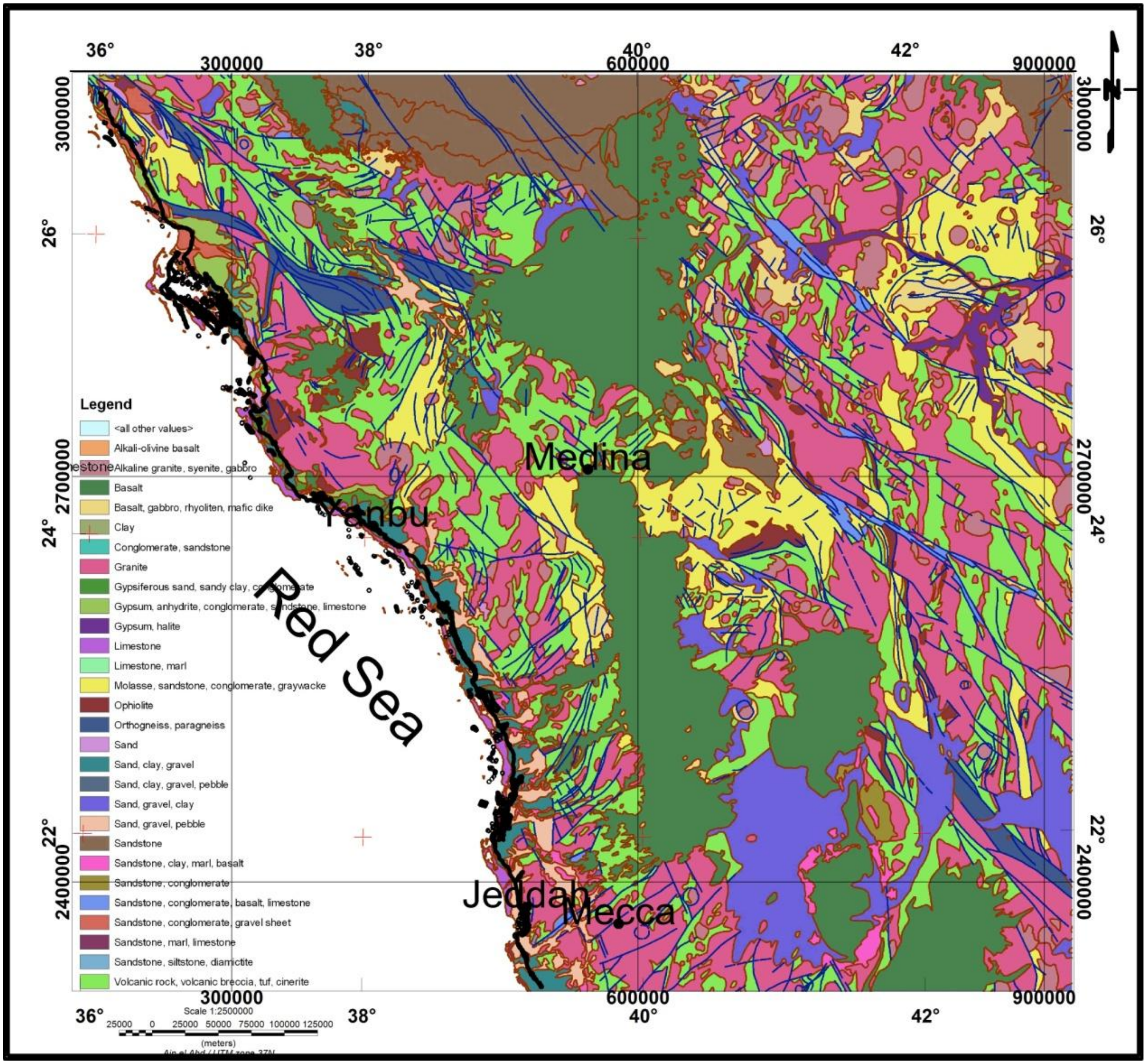

Figure 2. Geological map of the study area (modified after Saudi Geological Survey, SGS).

Shield. These faults were reactivated during the Tertiary as a result of Red Sea opening.

According to Nehlig et al. (2002) and Camp and Roobol (1992), the Red Sea began to open at about 25 to 30 Ma. The Arabian Shield is divided into five terranes (Asir, Hijaz, Midyan, Afif and Ar Rayn), separated by four suture zones, namely, Bir Umg, Yanbu, Nabitah and Al-Amar (Stoeser and Camp, 1985). The western part of the shield is composed of at least three intraoceanic island arc terrane (Asir, Hijaz and Midyan) where as the eastern arc contains one terrane of continental affinity (Afif) and another terrane of possible continental affinity (Ar Rayn) (Figure 3). The origin of recent volcanic activity is related to the opening of the Red Sea and the mantle upwelling beneath western Arabia. The older volcanic in the area have been determined as olivine transitional basalts and the alkali olivine basalts (Coleman et al., 1983).

GRAVITY DATA ACQUISITION AND PROCESSING

Gravity data for the study area (Figure 4) has been acquired from the Earth Gravitational Model EGM-2008 that provides information on areas previously lacking data

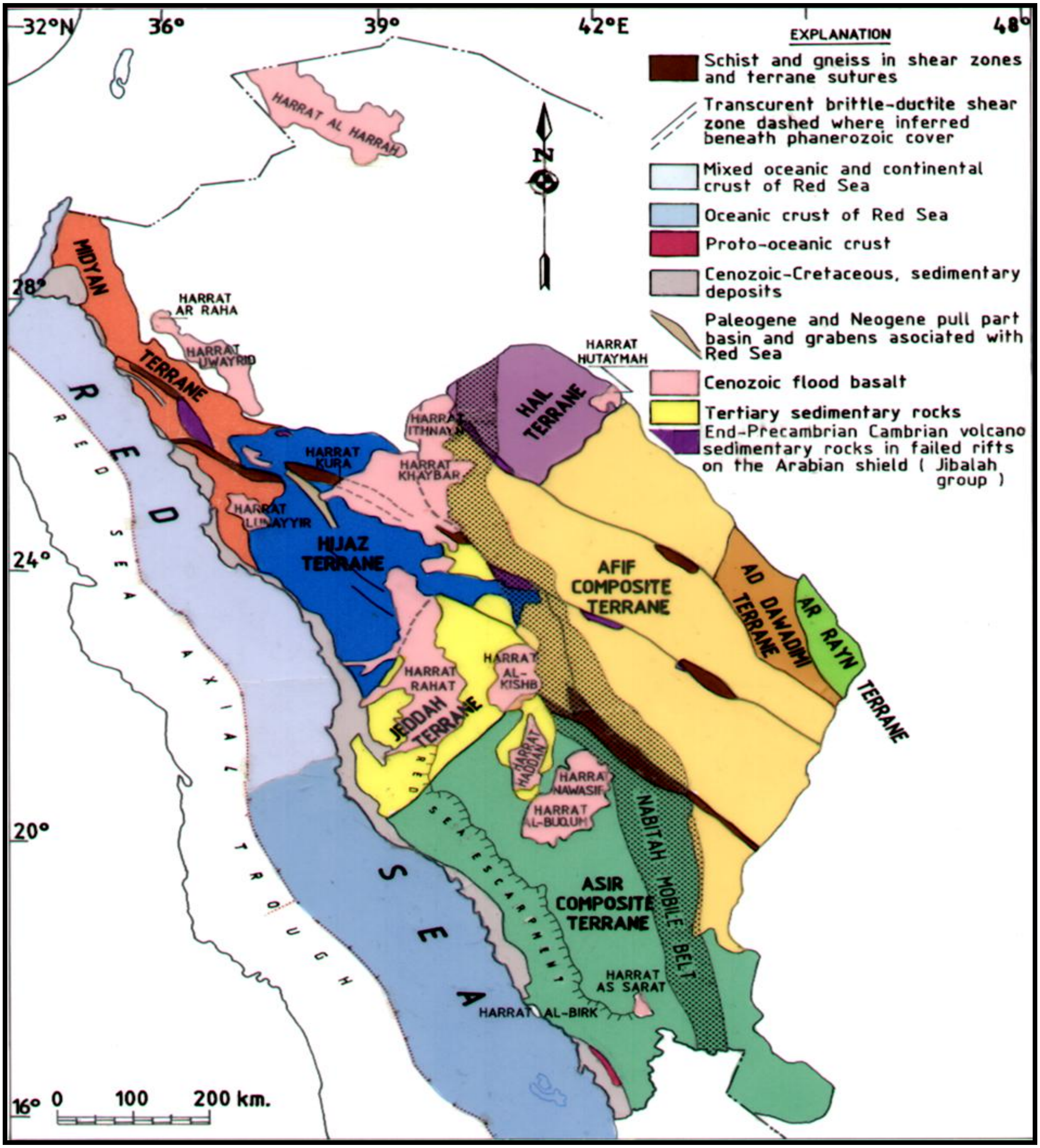

Figure 3. Tectonic map of the Arabian Shield showing the Cenozoic lava fields (Harrats) of Saudi Arabia (Johnson, 1998).

and extends across natural and artificial boundaries. CHAMP (Gerlach et al., 2003), GRACE (Tapley and Reigber, 2001) and GOCE (Drinkwater et al., 2003) satellite missions have been launched on 2000, 2002, and 2007, respectively for measuring the global gravitational field with different techniques and resolutions. The observed data has been used to derive a variety of global geopotential models, which express the

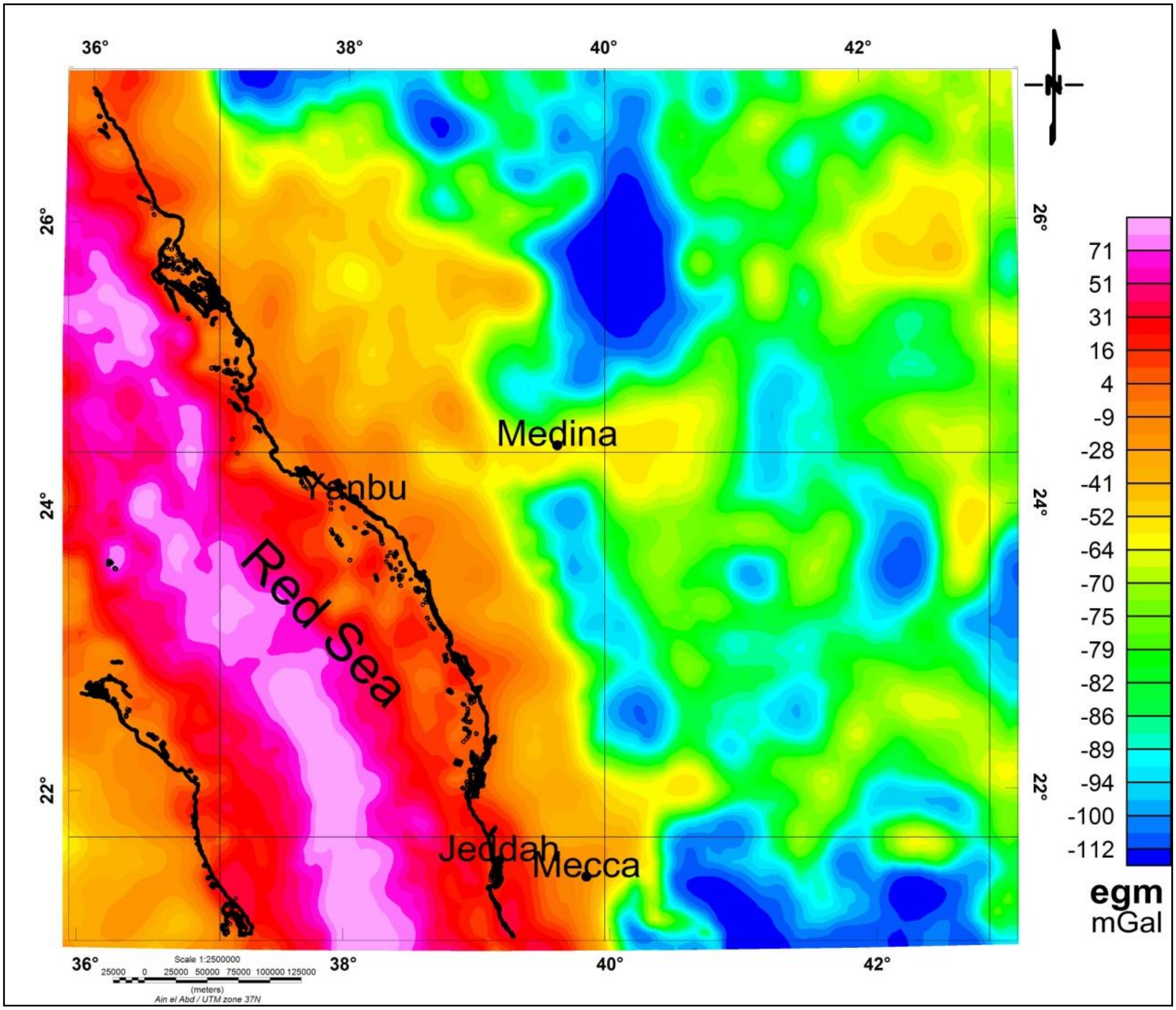

Figure 4. EGM-2008 Bouguer anomaly map.

Earth's gravity field in terms of spherical harmonic basis functions. These models improve the global gravitational field to wavelengths greater than 200 km. However, in an optimal approach the CHAMP/GRACE based and latest surface gravity data sets are combined to derive EGM2008 model (Pavlis et al., 2008). This model contains the high precision and homogeneity in the long- to medium-wavelength part and extends the resolution to better than 100 km.

Therefore, it provides suitable data for geological and geophysical applications. However, these data are currently provided as free-air gravity disturbances while the geological and geophysical applications require Bouguer anomaly data at the Earth's surface, so the EGM-2008 data are transformed into Bouguer data (Figure 4). Figure (4) presents an increase in the gravity value towards the Red Sea which may be due to the decreasing of Moho depth. The presence of negative anomalies extended are often parallel to the Red Sea coast but at a relatively distance, which could be attributed to basinal shapes that are probably formed by tectonic processes during rifting and opening of the Red Sea operations. In addition, transverse anomalies are observed near the coast of the Red Sea, which are most likely produced from transform faults. These anomalies changed the shape of the coast by forming huge structure in the area with several kilometers extension inside the Arabian shield.

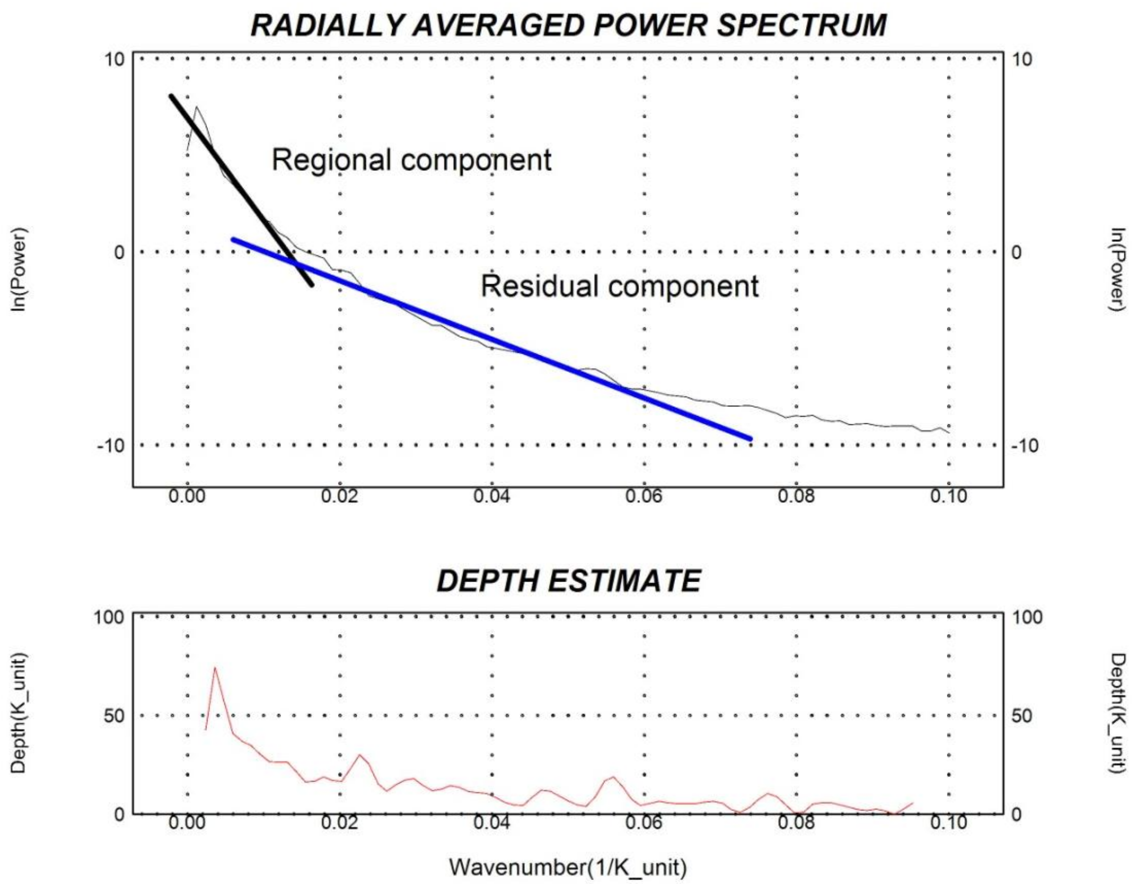

Figure 5. Power spectrum of EGM-2008 Bouguer anomaly map.

Table 1. Parameters of selected gravity profiles.

Profile No.	Profile name	Direction	Total length (km)
1	A-A'	ENE-WSW	440
2	B-B'	ENE-WSW	540
3	C-C'	ENE-WSW	900
4	D-D'	ENE-WSW	880
5	E-E'	ENE-WSW	600
6	F-F'	ENE-WSW	580
7	G-G'	ENE-WSW	500
8	H-H'	NW-SE	790
9	I-I'	NW-SE	740
10	J-J'	NW-SE	700
11	K-K'	NW-SE	660

EGM-2008 Bouguer anomaly map subjected to filtering and analytical procedures at superficial and deep alterations are as follows; 1) Frequency analysis technique which has been applied to separate the gravity component that is related to the surface sources from that related to deep and wide geologic sources. The two dimensional power spectrum curve (Figure 5) shows two linear segments related to regional and residual components. Band pass filtering technique has been applied to produce regional and residual gravity maps (Figures 6 and 7). The frequency range used for regional map is low wave number cutoff = 0 and high wave number cutoff = 0.008 cycle/km while, for residual map low wave number cutoff=0.008 and high wave number cutoff=0.068 cycle/km have been conducted.

Upward-continuation technique has been applied for Bouguer map at different levels 5 and 40 km (Figures 8 and 9). These figures clarified the identical structure of regional EGM-2008 Bouguer anomalies, where the higher anomalies stretching out along the Red Sea have been observed. Accordingly, the increasing of the upward levels, the more regional anomalies become clearer and the residual anomalies disappear (Figure 9).

GRAVITY MODELING

The 30-km upward continued gravity field map has been dissected into eleven profiles (Figure 10) with different lengths and directions (Table 1) to estimate the crustal thicknesses where, the upward continuation procedure

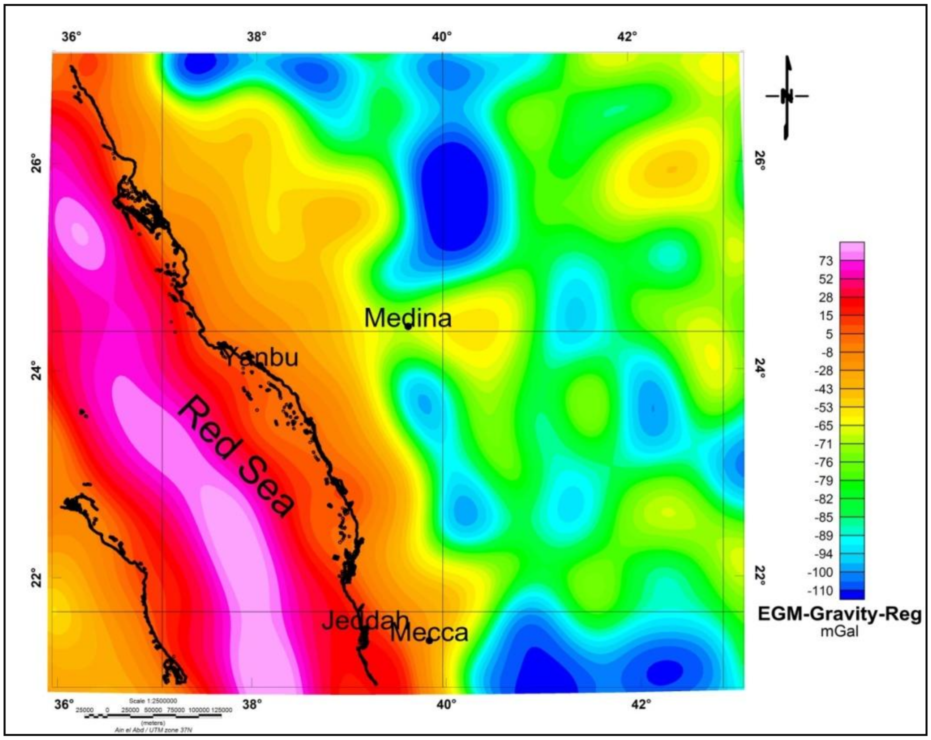

Figure 6. Regional map for EGM-2008 Bouguer anomaly.

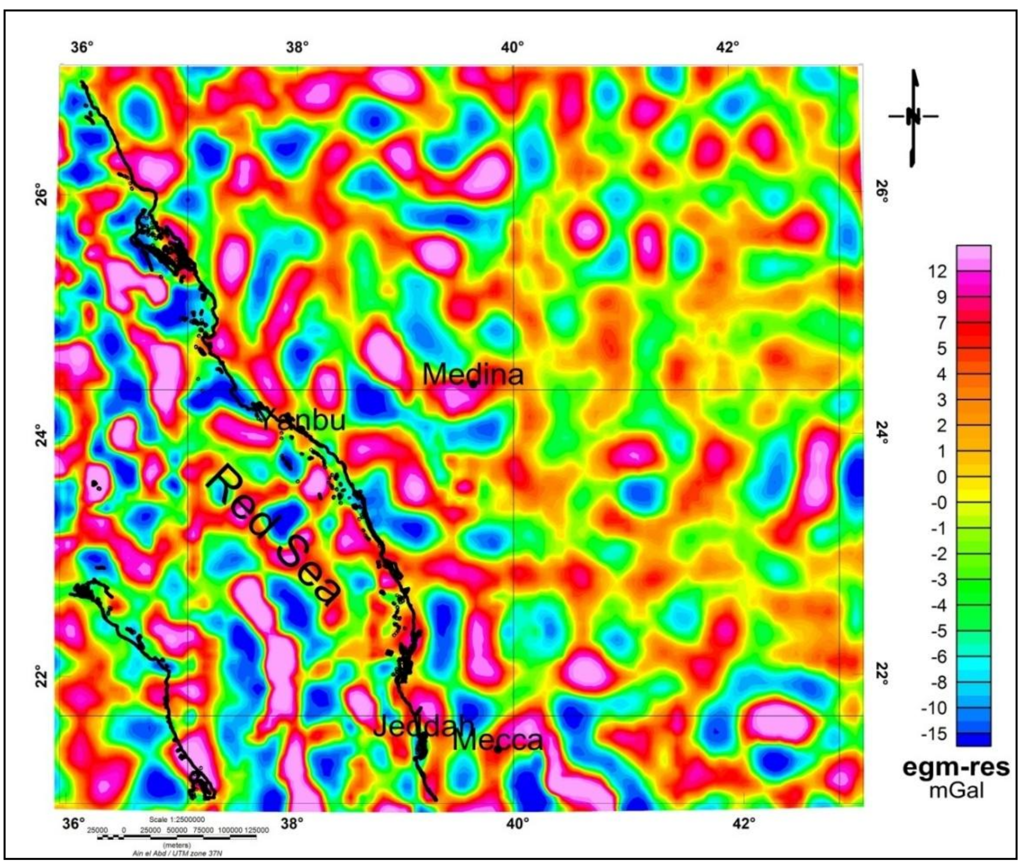

Figure 7. Residual map for EGM-2008 Bouguer anomaly.

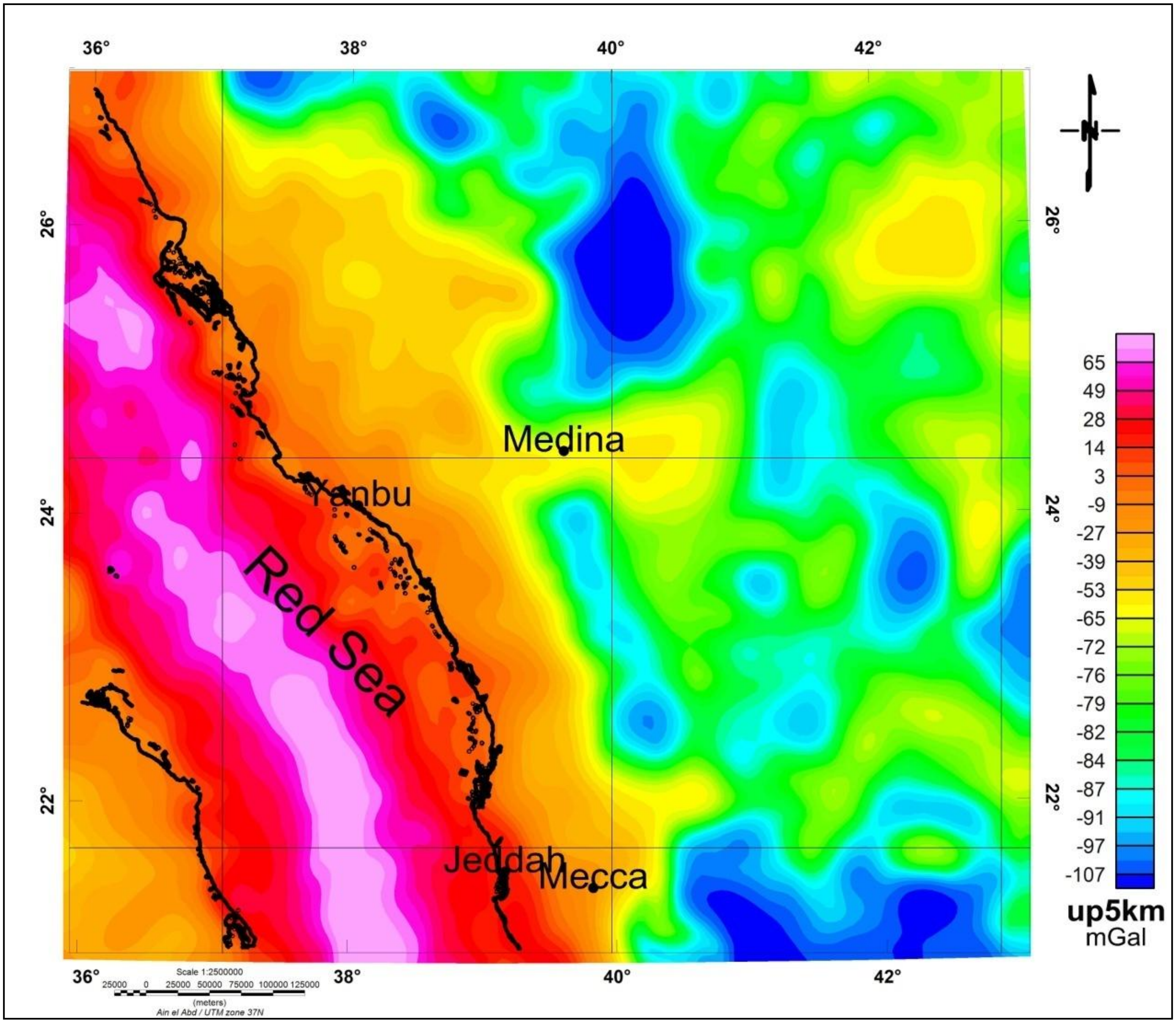

Figure 8. Upward continuation of the gravity field up to 5- km altitude.

for broader and deeper anomalies is used to study the crustal thickness on regional scale. This process has been applied to suppress the shallow anomalies and therefore accentuating the deep sources including Moho discontinuity (Zeng, 1989).

However, there is no standard height for the upward continuation to suppress the gravity effect of the shallow features, the map of 30 km altitude represents the most appropriate one, at which all the short wave taught shallow anomalies disappeared at the expense of long wavelength deeper anomalies. The regional deeper anomalies are due to the crustal thickness variation in the region.

Figure (10) presents seven profiles extend ENE-WSW (from A-A' to G-G') and four profiles oriented NW-SE (H-H' to K-K'). The input density values for modeling are 2.8 gm/cm^3 for crustal rocks, and 3.3 g/cm^3 for the mantle rocks. These values have been selected based on previous studies (Sandwell, 2001; Manea et al., 2003; Seber et al., 2001).

Moho depth vary along ENE-WSW profiles, where it ranges from 32 to 36 km along profile A-A' (Figure 11); from 26 to 32 km for profile B-B' (Figure 12); from 29 to34 km along profile C-C' (Figure 13); from 28 to 34 km underneath profile D-D' (Figure 14); from 28 to 34 km along profile E-E' (Figure 15); from 26 to 32 km through

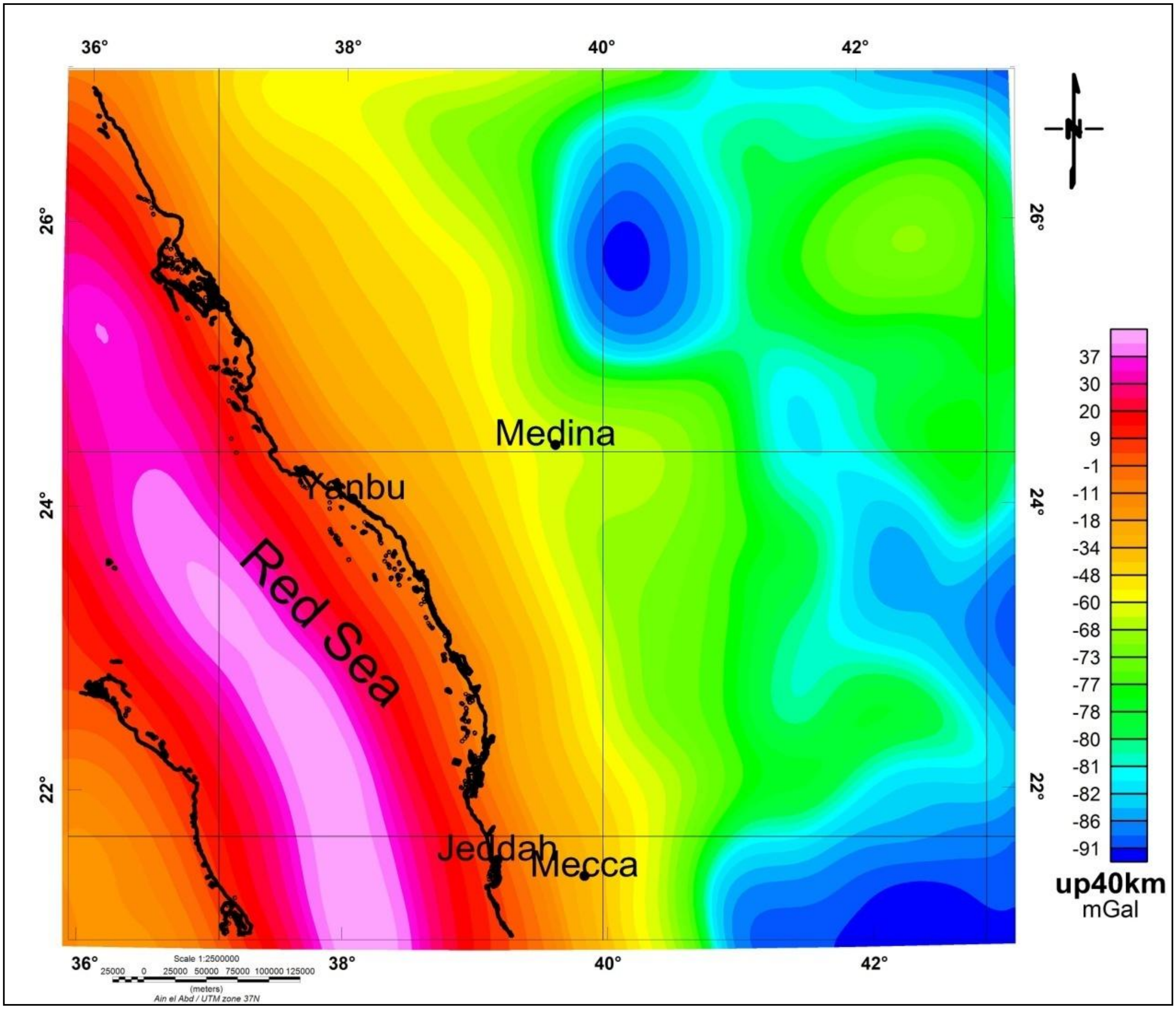

Figure 9. Upward continuation of the gravity field up to 40- km altitude.

profile F-F' (Figure 16) and from 27 to 32 km along profile G-G' (Figure 17). Furthermore, the NW-SE profiles illustrate the depth of Moho varies eastward as well where it is recorded at depth ranges from 28 to 32 km along profile H-H'(Figure 18); from 33 to 35 km through profile I-I' (Figure 19); from 34 to 36 km beneath profile J-J' (Figure 20) and from 37-38 km for profile K-K' (Figure 21).

According to the above-mentioned results, the depth of Moho has been estimated through the Northwestern Region of Saudi Arabia. Moho depth values are then contoured (Figure 22). This figure illustrates general increase of Moho depth, eastward from 25 km near the Red Sea coast up to 38 km through the Arabian Shield. This is correlated well with the hypothesis, which suggests a shallower depth of Moho under the Red Sea floor as a result of its opening.

SEISMICITY OF THE NORTHWESTERN REGION

The earthquake data that is related to the Northwestern Region of Saudi Arabia has been collected from different earthquake sources:

(i) Bulletins of the Saudi Geological Survey (SGS).
(ii) Preliminary Determination of Epicenters (PDE)

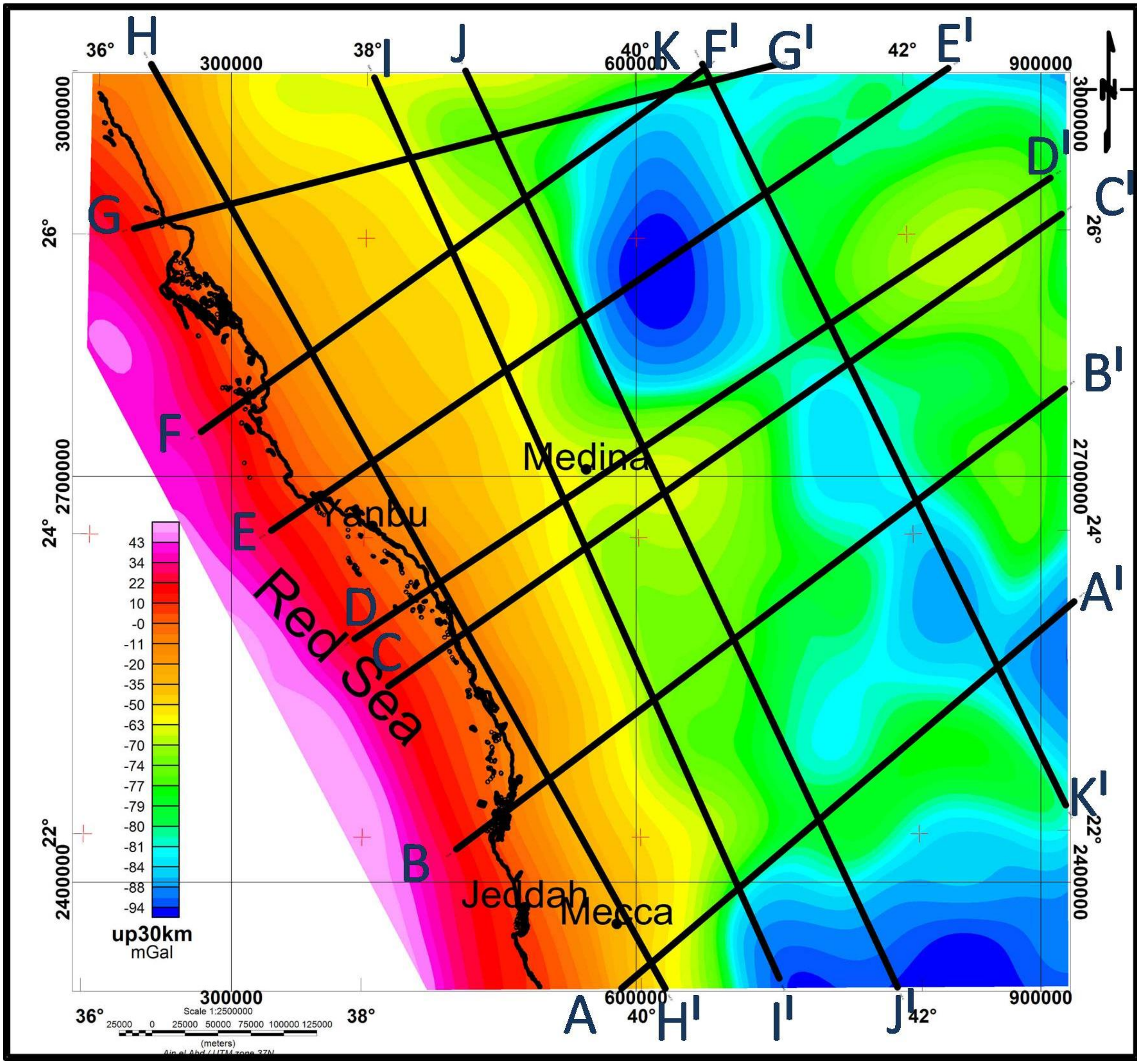

Figure 10. 2D gravity modeling profiles.

provided by the National Earthquake Information Centre (NEIC);
(iii) The International Seismological Center (ISC) online bulletin;
(iv) Regional catalogues of Poirier and Taher (1980) and Ambraseys et al. (1994).

These earthquake data have different magnitude scales, so all magnitudes scales were converted into Moment magnitude scale (M_w) using empirical relationships developed by Fnais et al. (2012) based on Harvard CMT catalogue. Then, the spatial distribution of the homogenous earthquake catalogue has been plotted into map (Figure 23). The aftershocks and foreshocks have been eliminated from the compiled catalogue using Gardner and Knopoff (1974) approach.

Figure (23) illustrates that, most of earthquakes are clustered at some certain localities as Harrat Al-Shaqah, Al-Madina and Jeddah-Mecca areas. Some of these earthquakes was destructive earthquakes and caused

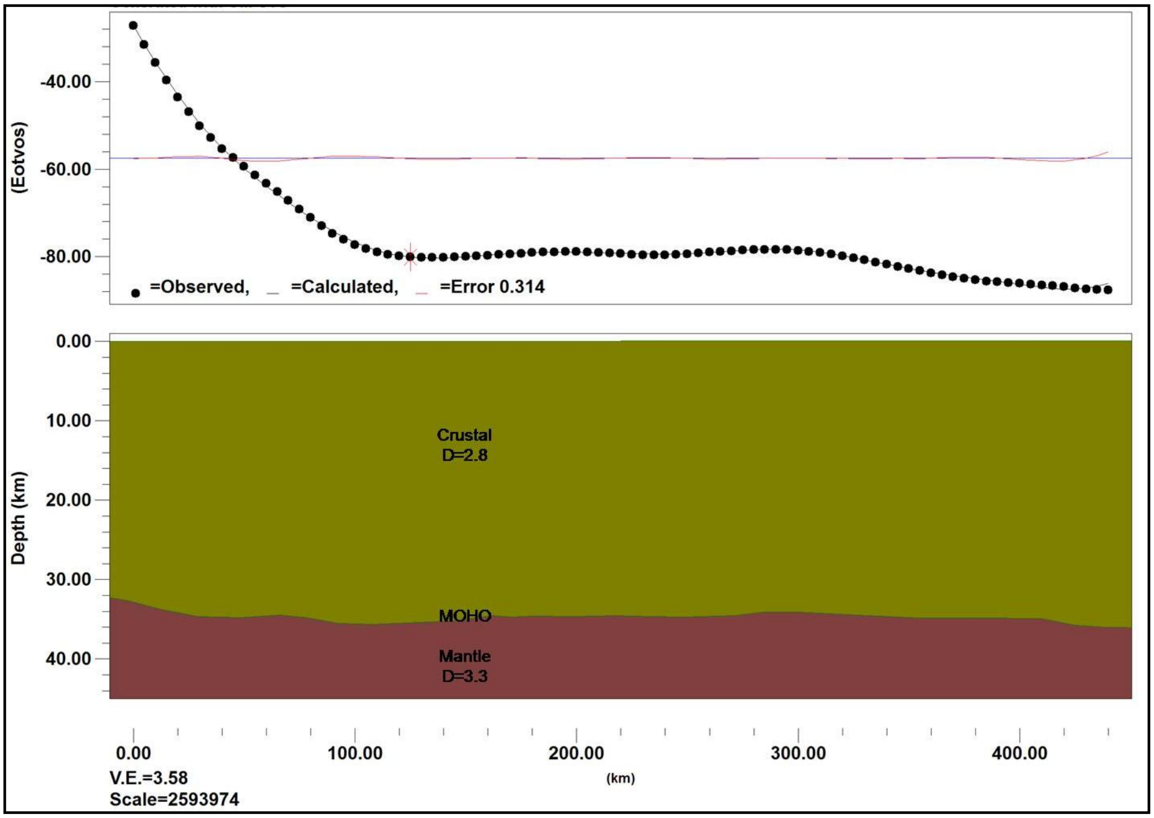

Figure 11. 2D gravity model A-A`.

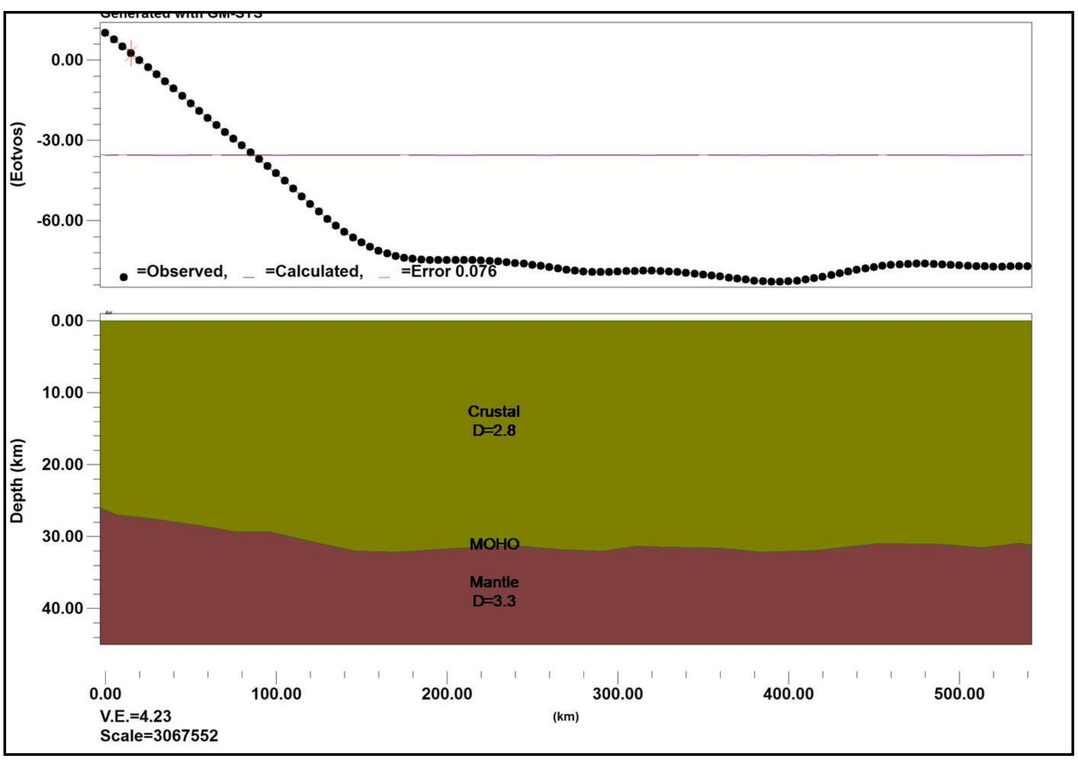

Figure 12. 2D gravity model B-B`.

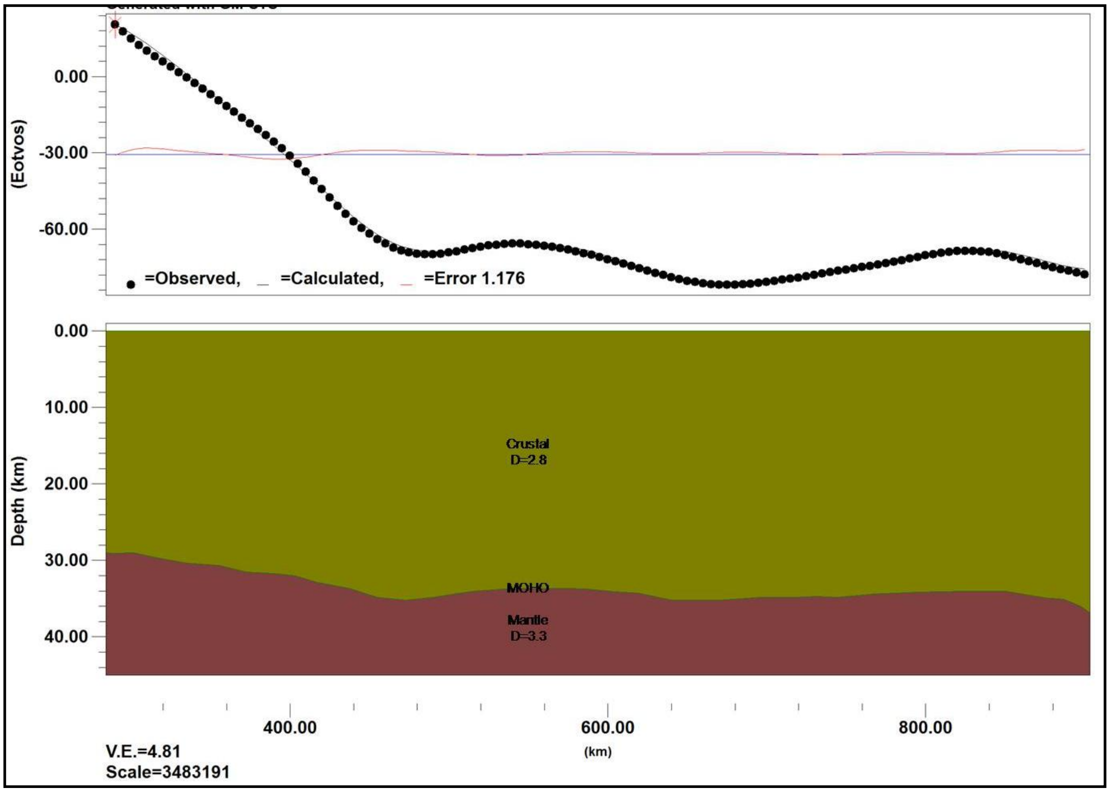

Figure 13. 2D gravity model C-C`.

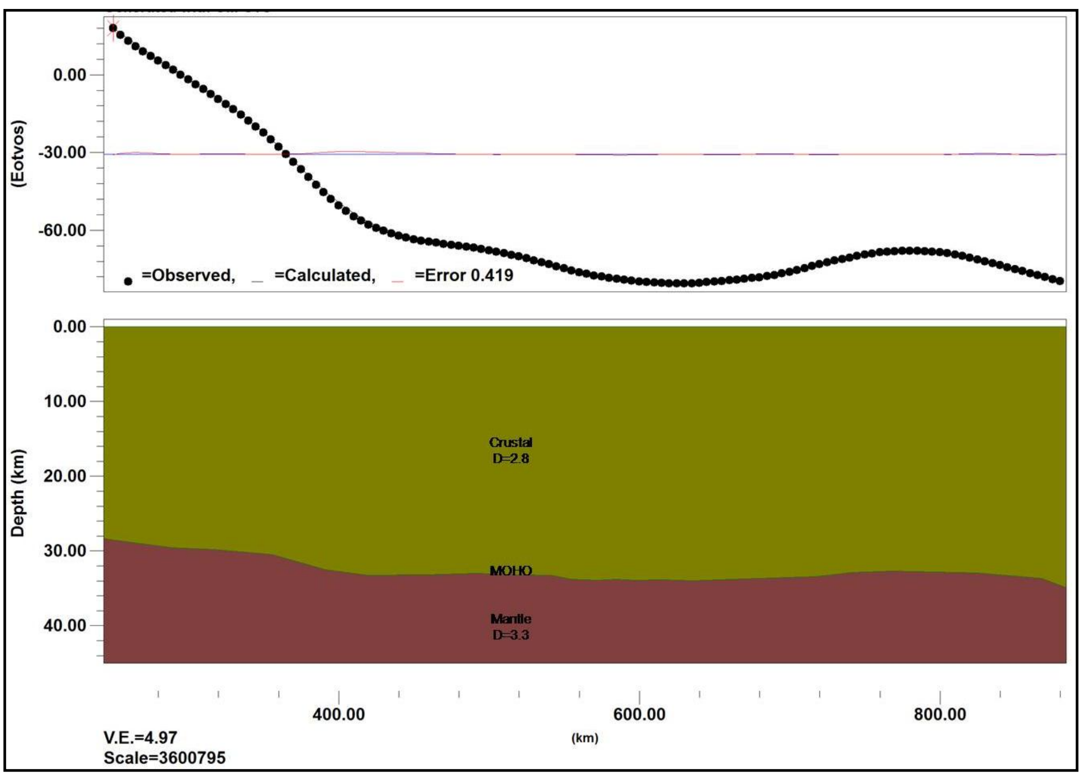

Figure 14. 2D gravity model D-D`.

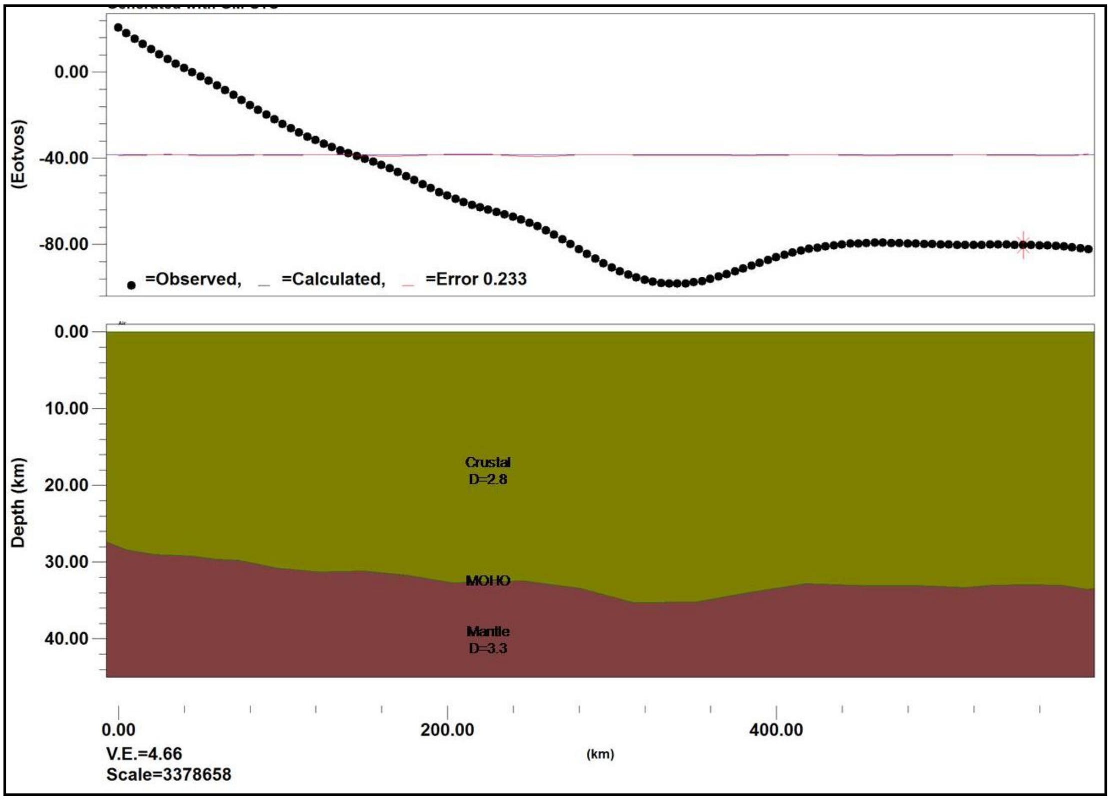

Figure 15. 2D gravity model E-E`.

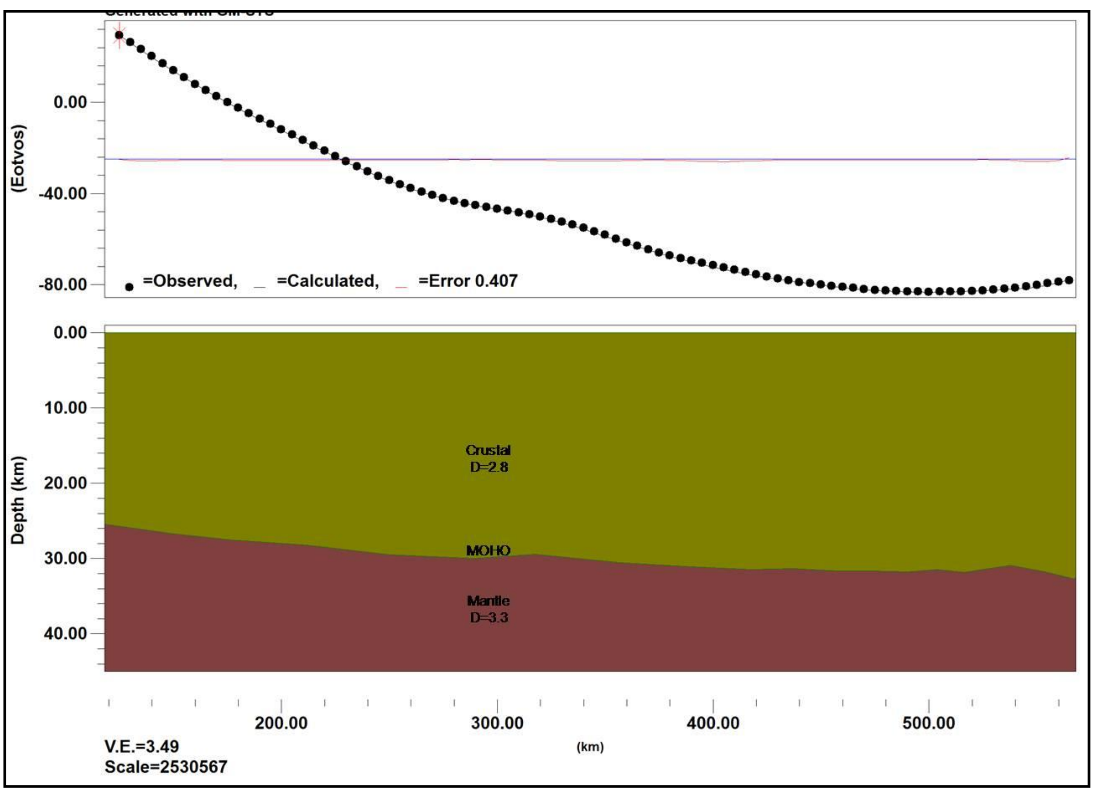

Figure 16. 2D gravity model F-F`.

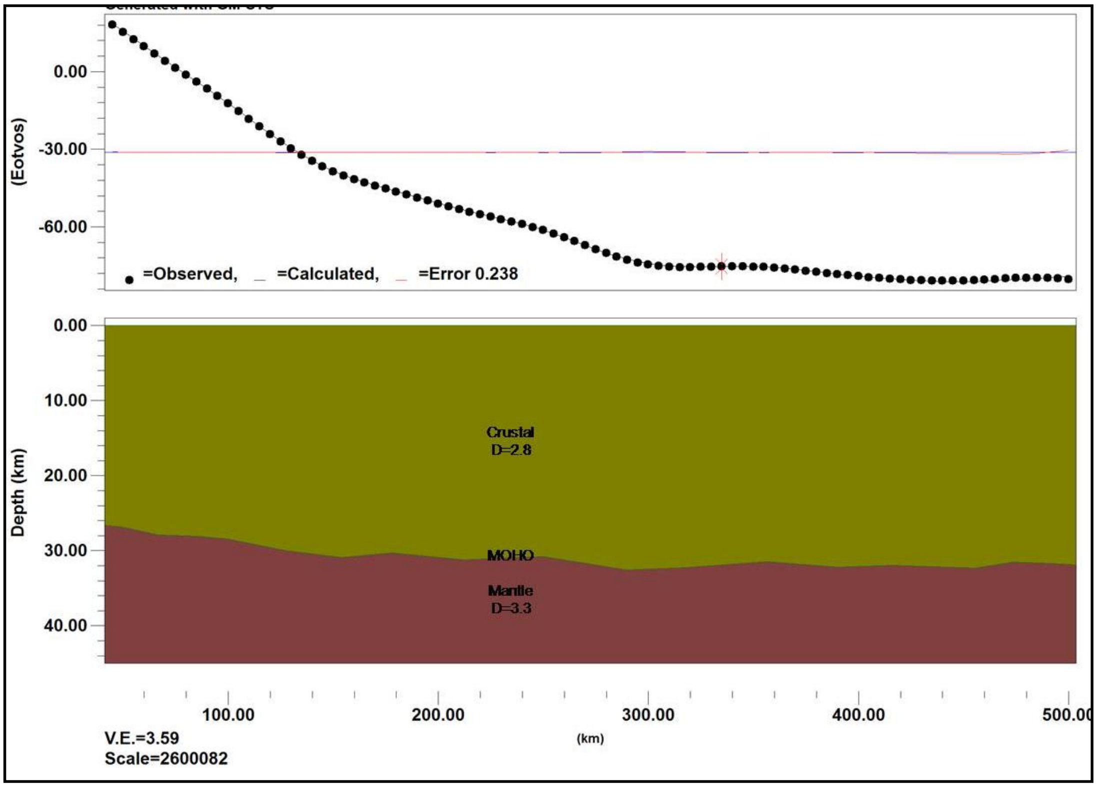

Figure 17. 2D gravity model G-G`.

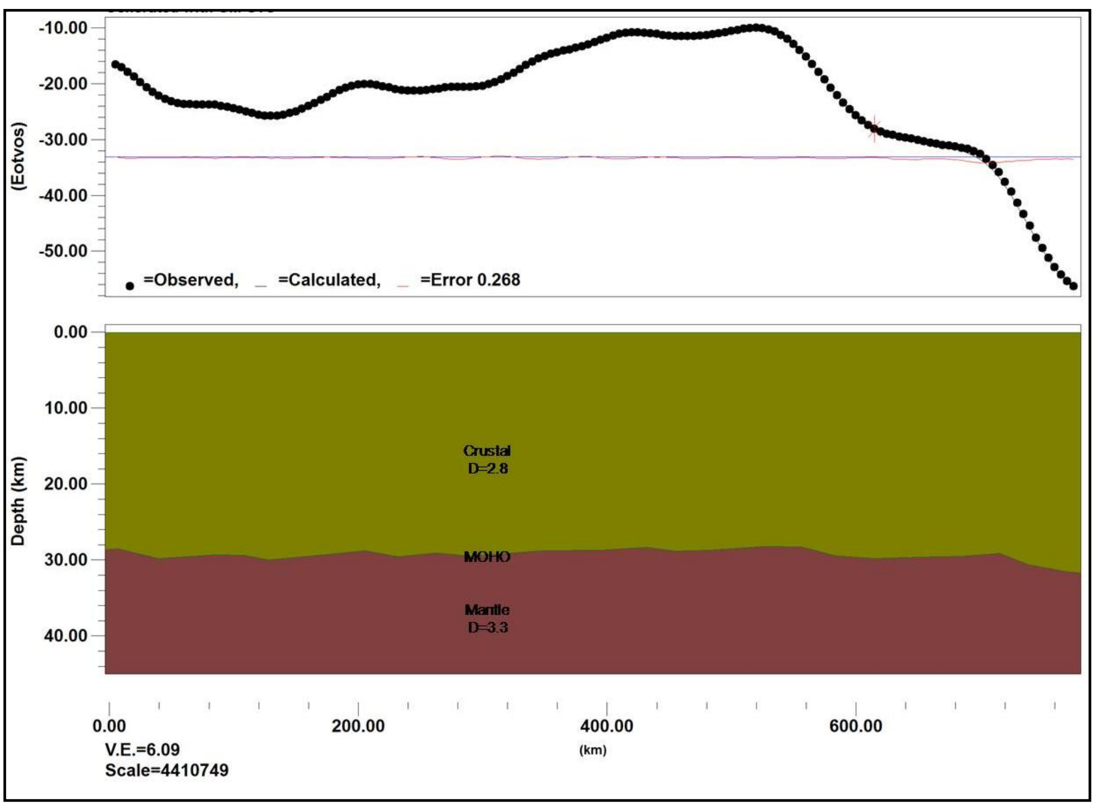

Figure 18. 2D gravity model H-H`.

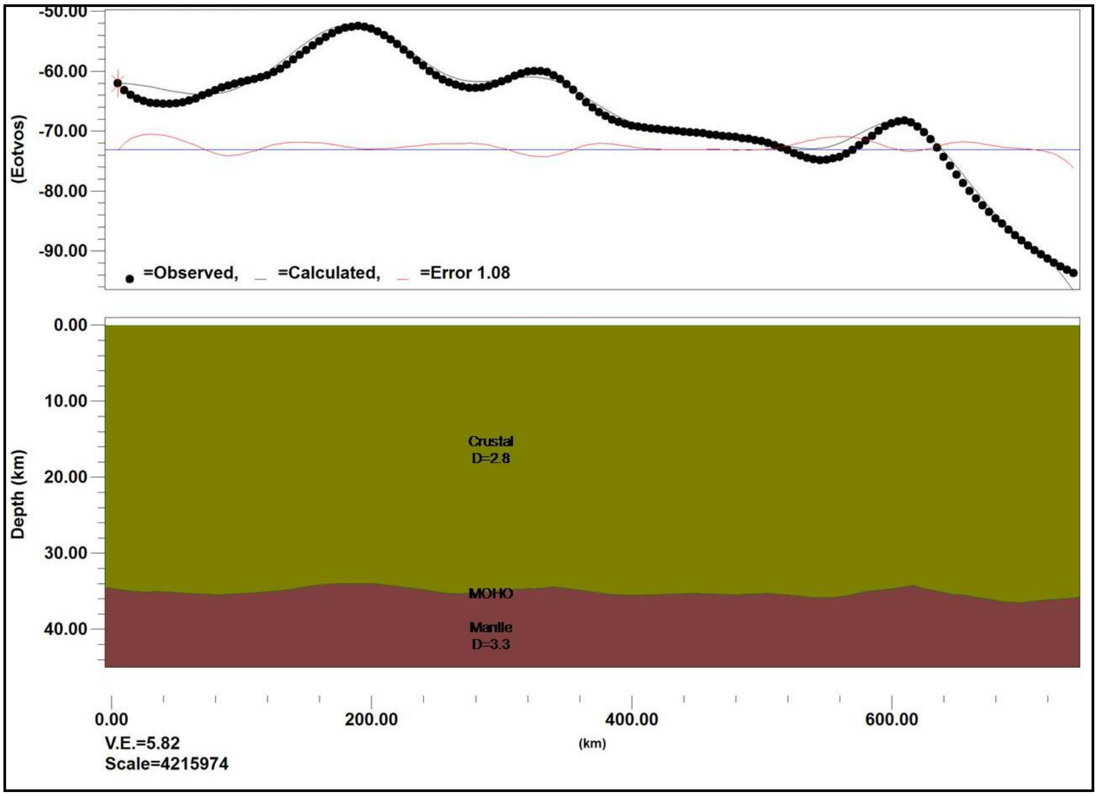

Figure 19. 2D gravity model I-I`.

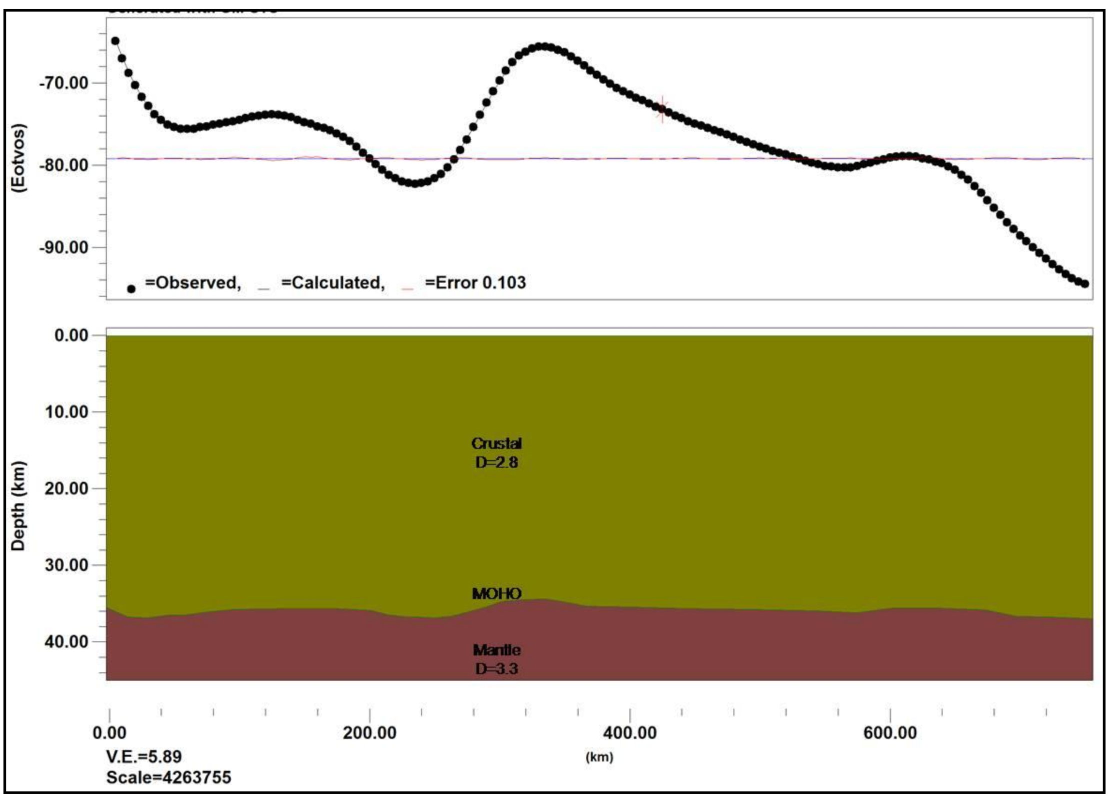

Figure 20. 2D gravity model J-J`.

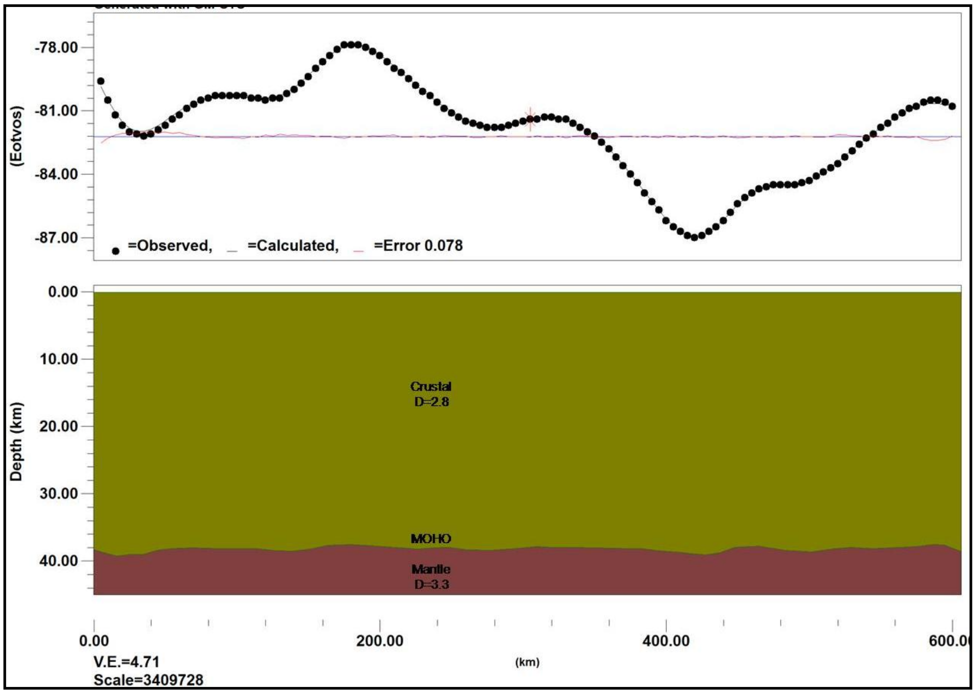

Figure 21. 2D gravity model K-K`.

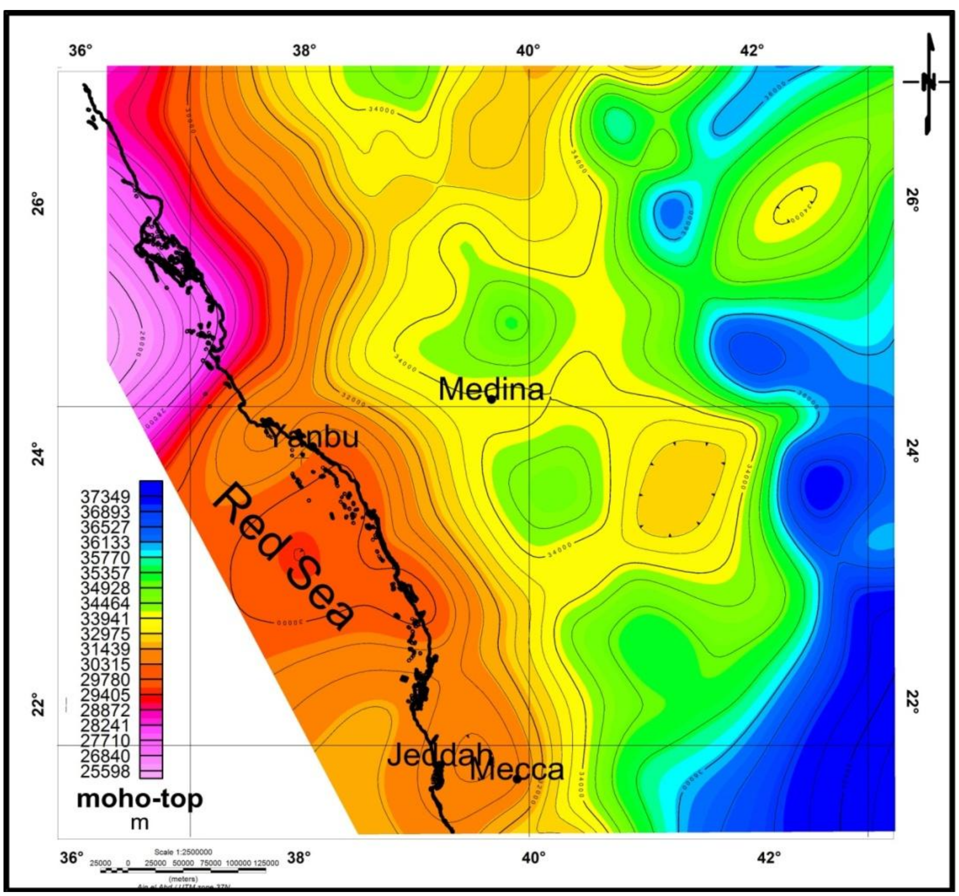

Figure 22. Depth of Moho as derived from eleven regional model.

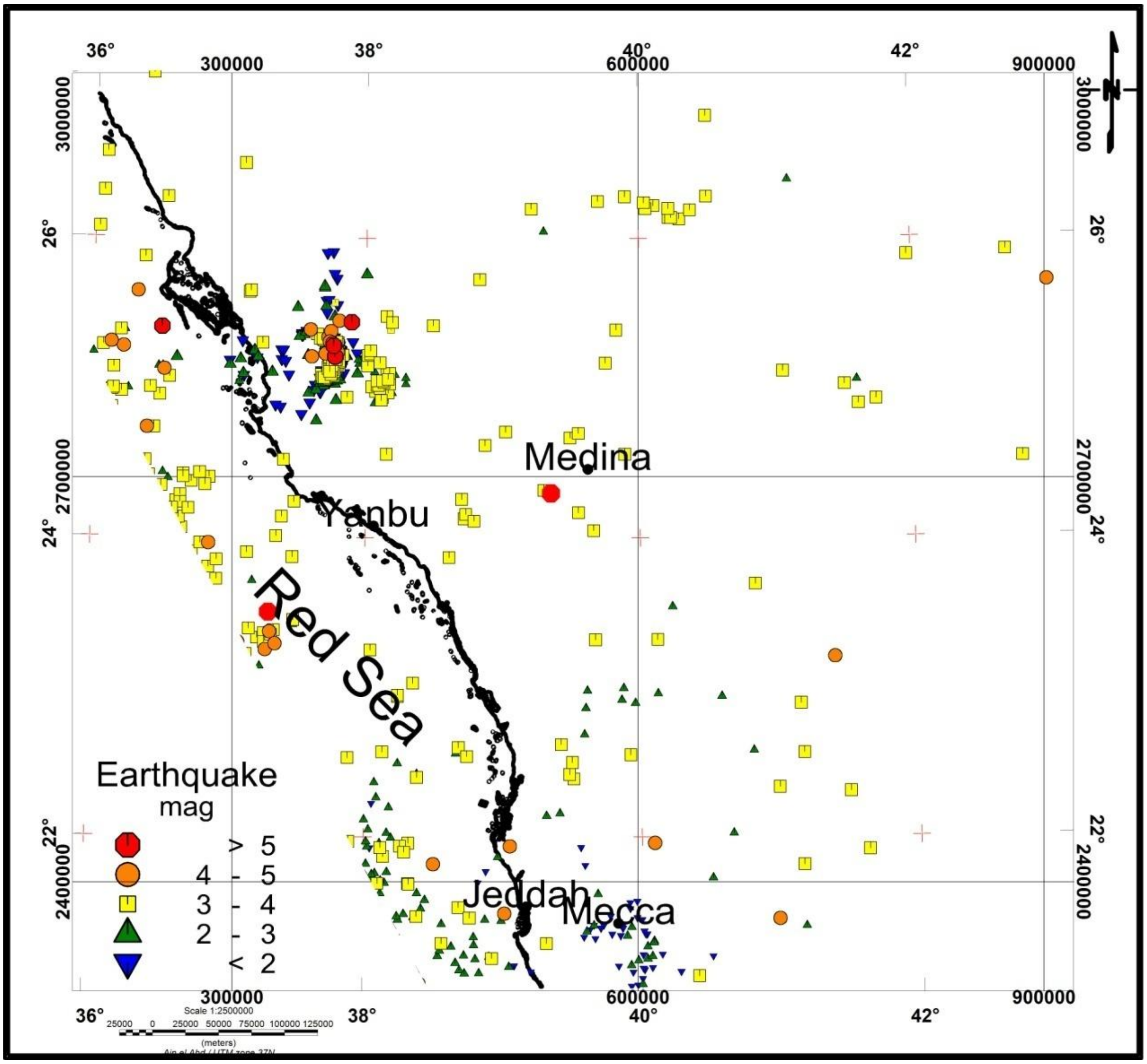

Figure 23. Seismicity of northwestern region of Saudi Arabia.

panic (for example, 1260 Al-Madina and 2009 Al-Shaqah earthquakes).

DISCUSSION AND CONCLUSIONS

The present study clarified that the depth to Moho is generally increased eastward where it ranges from 25 km along the Red Sea and reached up to 38 km through the Arabian Shield. These results compared well with the previous studies as follows; Sandovl et al. (1998) stated that the crustal thickness in the Arabian Shield area varies from 35 to 40 km in the West to 45 km in Central Arabia; Al-Amri (1999) proposed that the crust is thick (43 km); Rodgers et al. (1999) illustrated that the Moho has 36 km depth underneath the Arabian Shield while it increases up to 40 km through the Arabian Platform; Kumar et al. (2002) indicated that the Moho depths vary between 35 and 38 km; Al-Damegh et al. (2005) showed that, the average crustal thickness is 39 km for the Arabian Shield while thins to about 23 km along the Red Sea coast; and Al-Amri et al. (2008) estimated the crustal thickness between 24 and 30 km.

Hansen et al. (2007) stated that the lithospheric thickness varies considerably, a thin part centered on the Red Sea rift axis but thickening toward the Arabian interior (Figure 24). Gravity data fit well with structural model while the derived structure is consistent with active rifting processes.

The relation between earthquake occurrences through the Northwestern Saudi Arabia Region and the variation of Moho depth can be illustrated from Figure 25. This

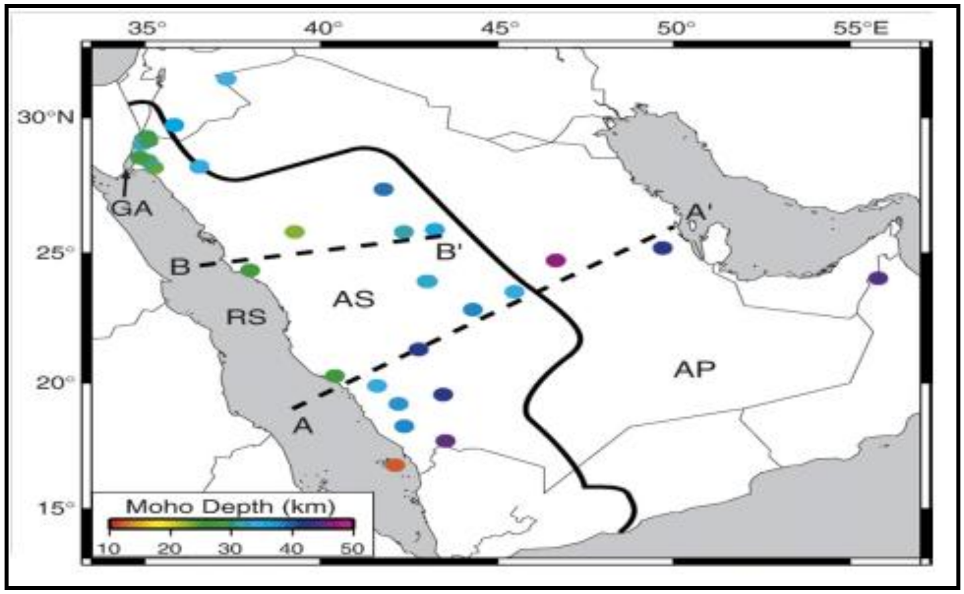

Figure 24. Map showing the boundary depths beneath Arabia. (RS: Red Sea, GA: Gulf of Aqaba; AS: Arabian Shield; AP: Arabian Platform) (Hansen et al., 2007).

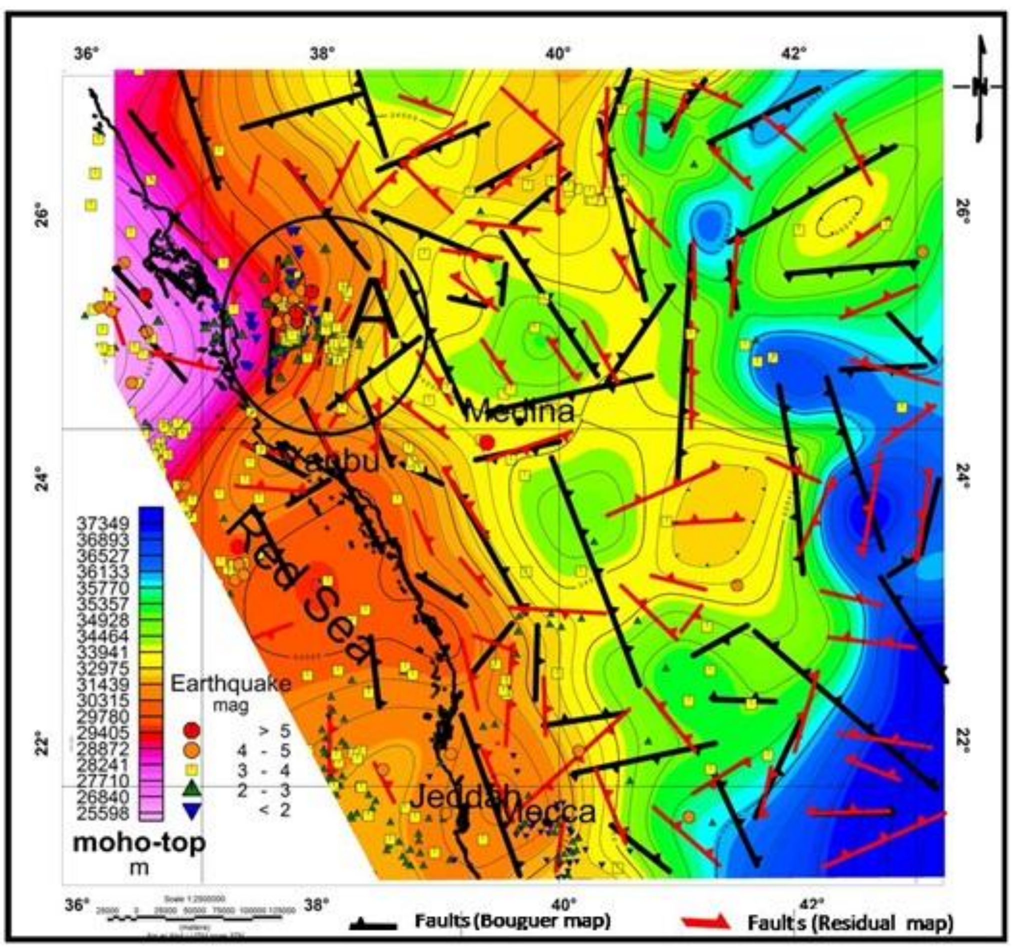

Figure 25. Map showing the depth of Moho as Interpreted form the EGM-2008 Bouguer gravity map and earthquakes along with subsurface faults in the area (Fnais et al., 2012).

figure shows that, the earthquakes clustered in Harrat Al-Shaqah area (region A) is associated with two major subsurface faults, along which the Moho surface is relatively shallower, which well explains the reason for these earthquakes inside the stable Arabian Shield. The earthquake activities in this area are caused by stresses exerted upon these faults by the mantle upwelling. This region also experienced some recent volcanic activities, which is in good agreement with the above given conclusion.

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REFERENCES

Al-Amri AM (1999). The crustal and upper-mantle structure of the interior Arabian Platform. Geophys. J. Int. 136:421-430.

Al-Amri AM, Fnais MS (2009). Seismo-volcanic investigation of 2009 earthquake swarms at Harrat Lunayyir (Ash Shaqah), Western Saudi Arabia. Int. J. Earth Sci. Eng. (In press).

Al-Amri AM, Rodgers A, Tariq AA (2008). Improving the level of seismic hazard parameters in Saudi Arabia using earthquake location. Arab. J. Geosci. 1:1-15 DOI 10.1007/s12517-008-0001-5.

Al-Damegh K, Sandvol E, Barazangi M (2005). Crustal structure of the Arabian plate: New constraints from the analysis of teleseismic receiver functions. Earth Planet. Sci. Lett. 231:177-196.

Ambraseys NN, Melville CP, Adams RD (1994). The seismicity of Egypt, Arabia and Red Sea, Cambridge University Press.

Camp VE, Roobol MJ (1992). Upwelling asthenosphere beneath western Arabia and its regional implications. J. Geophys. Res. 97:15255–15271.

Ce´line T, Fre´de´ric G, Christel T, Jean-Pierre B (2004). Aegean crustal thickness inferred from gravity inversion. Geodynamical implications. Earth Planet. Sci. Lett. 228:267–280.

Coleman RG, Gregory RT, Brown GF (1983). Cenozoic volcanic rocks of Saudi Arabia, Saudi Arabian Deputy Ministry for Mineral Resources Open-File Report USGS-OF-03-93.

Drinkwater MR, Floberghagen R, Haagmans R (2003). GOCE: ESA's first Earth explorer core mission. Earth gravity field from space – from sensors to Earth sciences. in: Beutler, G., Drinkwater, M.R., Rummel, R. et al. (Eds.), Space Sciences Series of ISSI. Kluwer Academic Publishers, Dordrecht, Netherlands, 18:419–432. ISBN 1-4020-1408-2.

Fnais MS, El-Araby HM, Kamal A-R, Elawadi E Al Soma A (2012). Identification of Active Tectonics affecting West-central Saudi Arabia from Gravity and Earthquake data. Arab Gulf J. Sci. Res. (Submitted).

Gerlach C, Földvary L, Svehla D, Gruber T, Wermuth M, Sneeuw N, Frommknecht B, Oberndorfer H, Peters T, Rothacher M, Rummel R, Steigenberger P (2003). A CHAMPonly gravity field model from kinematic orbits using the energy integral. Geophys. Res. Lett. 30: Art.No.2037.

Gardner JK, Knopoff L (1974). Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian? Bull. Seismol. Soc. Am. 64:1363-1367.

Hansen S, Rodgers A, Schwartz S, Al-Amri A (2007). Imaging Ruptured Lithosphere Beneath the Red Sea and Arabian Peninsula. Earth Planet. Sci. Lett. 259:256-265.

Johnson PR (1998). Tectonic Map of Saudi Arabia and Adjacent Areas, Ministry of Petroleum and Mineral Resources, Deputy Ministry Mineral, Resources Technical Report USGS-TR-98-3, Jeddah, Saudi Arabia.

Kumar MR, Ramesh DS, Saul J, Sarkar D, Kind R (2002). Crustal structure and upper mantle stratigraphy of the Arabian shield. Geophys. Res. Lett. 29(8):1242, DOI: 10.1029/2001GL014530.

Mahatsente R, Jentzsch G, Jahr T (1999). Crustal structure of the Main Ethiopian Rift from gravity data: 3-dimensional modeling. Tectonophysics 313:363-382.

Manea M, Manea VC, Kostoglodov V (2003). Sediment fill in the Middle America Trench inferred from gravity anomalies. Geofísica Int. 42(4):603-612.

Nehlig P, Dubreuil N, Guerrot C, Eberle JM, Kluyver HM, Lasserre JL, LeGoff E, Nicol N, Salpeteur N, Shanti M, Thieblemont D, Truffert C (2002). A Review of the Pan-African Evolution of the Arabian Shield. GeoArabia 7(1):103-124.

Pavlis NK, Holmes SA, Kenyon SC, Factor JK (2008). An Earth Gravitational Model to Degree 2160: EGM2008; General Assembly of the European Geosciences Union, Vienna, Austria.

Poirier JP, Taher M (1980). Historical Seismicity in the near and middle east, North Africa, and Spain from Arabic documents (VIIth-XVIIIth century). Bull. Seismol. Soc. Am. 70:2185-2201.

Rodgers AJ, William RW, Mellors RJ, Al-Amri A, Zhang Y (1999). Lithospheric structure of the Arabian Shield and Platform from complete regional waveform modelling and surface wave group velocities. Geophys. J. Int. 138:871-878.

Sandvol E, Seber D, Barazangi M, Vernon F, Mellors R, Al-Amri A (1998). Lithospheric seismic velocity discontinuities beneath the Arabian Shield. Geophys. Res. Lett. 25(15):2873–2876.

Sandwell DT(2001). Crustal Structure, Isostasy and Rheology. web: http://topex.ucsd.edu/geodynamics/08crust_rheology.pdf.

Seber D, Sandvol E, Sandvol C, Brindisi C, Barazangi M (2001). Crustal model for the Middle East and North Africa region: Implications for the isostatic compensation mechanism. Geophys. J. Int. 147:630-638.

Sharland PR, Archer R, Casey DM, Davies RB, Hall SH, Heward AP, Horbury AD, Simmons MD (2001). Arabian plate sequence stratigraphy. GeoArabia Special Publication 2.

Stoeser DB, Camp VE (1985). Pan-African Microplate Accretion of the Arabian Shield. Bull. Geol. Soc. Am. 96:817-826.

Tapley BD, Reigber C (2001). The GRACE mission: Status and future plans. EOS Trans. Suppl. 82(47):G41C-02.

Zeng H (1989). Estimation of the degree of polynomial fitted to gravity anomalies and its application. Geophys. Prospect. 37:959-973.