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Estimation of Earth Structure by Satellite Gravity Analysis of Peninsular Malaysia

(Anggaran Struktur Bumi melalui Analisis Graviti Satelit di Semenanjung Malaysia)

NURUL FAIRUZ DIYANA BAHRUDIN*, UMAR HAMZAH & WAN ZUHAIRI WAN YACCOB

ABSTRACT

Power spectral analysis was successfully carried out on satellite gravity data along 10 East-West profiles of about 140 to 320 km length across Peninsular Malaysia beginning from its border with the Straits of Malacca towards the South China Sea coastline. Power spectrum curves obtained clearly indicate the presence of three major slopes corresponding to four type of materials with different dominant densities. Depth curves computed from all these profiles produced three major dominant peaks beginning with the deepest one at about 33 to 42 km, followed by intermediate depth of 18 to 26 km and the shallow peaks at about 3 to 10 km. The shallowest depth is interpreted as representing geological formation such as the Mesozoic and Palaeozoic deposits including the granite intrusion classified as basement. Underlying the basement is the upper crustal material extending to Conrad discontinuity at depth of about 18 to 26 km. Earth materials below the Conrad discontinuity constitutes of the lower crustal material overlying the border of upper mantle at depth of 33 to 42 km representing the Mohorovicic discontinuity.

Keywords: Earth structures; satellite gravity data; spectral analysis

ABSTRAK

Analisis kuasa spektrum telah dijalankan ke atas data graviti satelit sepanjang 10 garis rentas timur-barat Semenanjung Malaysia. Panjang garis rentas berjulat antara 140 hingga 320 km. Lengkung kuasa spektrum menunjukkan kehadiran tiga kecerunan utama yang mewakili empat bahan yang mempunyai ketumpatan yang berbeza. Lengkung kedalaman yang diperoleh daripada kecerunan tersebut menghasilkan tiga puncak dominan bermula daripada kedalaman maksimum 33 hingga 42 km diikuti dengan kedalaman sederhana 18 hingga 26 km dan puncak paling cetek pada kedalaman 3 hingga 10 km. Kedalaman paling cetek ditafsirkan mewakili formasi geologi yang berusia Mesozoik dan Paleozoik termasuk granit yang dikelaskan sebagai besmen. Lapisan besmen ini menindih lapisan kerak atas yang didasari oleh satah ketakselarasan Conrad pada kedalaman 18 hingga 26 km. Bahan bumi di bawah ketakselarasan Conrad terdiri daripada kerak bawah yang menindih sempadan mantel atas pada kedalaman 33 hingga 42 km yang ditafsirkan sebagai satah ketakselarasan Mohorovicic.

Kata kunci: Analisis kuasa spektrum; data graviti satelit; struktur bumi

INTRODUCTION

Earth subsurface structures have long been established by analyzing the seismic waves emanating from earthquake shocks, which moved within the globe. The inhomogeneity of earth structures may have been a strong reason to a slight difference in depth determination of crustal and mantle boundaries at different places in the world. Many geophysical researches were carried in Asian regions especially in estimating the upper crustal surface below the basement, Conrad discontinuity separating the upper and lower crust as well as the Moho discontinuity, which is demarcating the top of upper mantle (Iwasaki et al. 2013). The earth subsurface layer thickness and depths of boundaries separating them were determined basically not only by seismic but also by potential theory techniques such as gravity and magnetic modelling as well as power spectrum analysis (Prutkin & Saleh 2009). Examples of results from land and airborne gravity and magnetic surveys were published by Asano et al. (1985), Kaila et al. (1987), Kumar et al. (2016) and Singh et al. (2015) in studying the Indian, China, and Japan continents. Almost similar results were reported by Kivior et al. (2013) and Zhu and Kanamori (2000) in the study of earth structures beneath American and European continents. In this paper, results of earth structure by power spectral analysis of satellite gravity data are presented and compared with other findings. The power spectral method on potential data has been widely used to determine the earth subsurface structures since it was introduced by Bhattacharyya (1966) followed by Spector and Grant (1970) as well as many other researchers such as recently by Kumar et al. (2016). In the power spectral technique the time function gravity data are converted to frequency function by Fast Fourier Transform (FFT) to be represented by Fourier series consisting of various frequencies which characterizing the source depth anomalies (Bansal & Dimri 2001; Dimitriadis et al. 1987; Gomez et al. 2005; Spector & Grant, 1970) and related to the geological structures including the position of crust and mantle (Treitel et al. 1971).

Maden et al. (2009) studied the orogenic belt in determining the tectonic structure and crust of east Pontide, Turkey by gravity and magnetic survey where they found the Mohorovicic thickness is about 29 to 47 km. The thicknesses were estimated by spectral analysis technique of aeromagnetic data. A similar technique was used by Rina (2008) to determine the Mohorovicic depth ranging from 15 to 37 km in East Java, Indonesia. These depths can be considered as main references for this study since it is very closed to the study area. Mapping of crustal thickness by marine gravity data in South China Sea was carried out by Bai et al. (2014) resulting to the finding of Mohorovicic depth within 26 to 27 km. Latiff and Khalil (2017) studied Moho boundary in Peninsular Malaysia by analyzing earthquake seismological data and found out that depth of Moho is about 28 to 32 km. Finally, Macpherson et al. (2012) studied Sumatera crustal thickness ranging from 16 to 30 km also by earthquake seismological data without mentioning the details on Conrad and Mohorovicic discontinuity depths.

Materials and Methods

Reduced satellite Bouguer gravity data used in this study were obtained by Earth Gravitational Model website. A total of about 1000 data points covering Peninsular Malaysia were selected for power spectral analysis and with a slight editing used as input for processing by Oasis Montaj computer software. In the power spectral analysis, Bouguer gravity data along 10 E-W profiles were chosen and stored in the input data files (Figure 1).

Spacing between each profile is about 50 km and the distance between each sampling points is about 1.2 to 2.6 km. The gravity data were then transformed from the space domain into the frequency domain by means of FFT. Considering a constant density contrast (, the Fourier Transform of the field gravity data h(x), can be written as

$$\Delta g(k) = \left(\frac{2G\Delta\rho}{k}\right) \int_{-\infty}^{\infty} e^{-jkx}\, e^{-|k|h(x)}\, dx \qquad (1)$$

where k is the wavenumber (=1/wavelength); and G is the international gravity constant (Mishra & Pederson 1982). In this study, the value of density contrast ($\Delta\rho$) used for determining the Moho discontinuity is 0.2 gm/cc, while for estimating the Conrad discontinuity the density contrast ($\Delta\rho$) used is 0.4 gm/cc. This equation can be simplified by expanding the exponential and taking into account only the first order and written as

$$\Delta g(k) = 2G\Delta\rho\; e^{-j|k|h_0} \Delta h k \qquad (2)$$

This equation directly relating between the computed gravity spectra and the unknown mean depth, h_o, of the interface, perturbated by the term Δh (k). The non-linear effect of Δh (k) is negligible in case of long wavelengths and the relation between gravity spectra and depth becomes almost log-linear (Mishra & Pederson 1982). Therefore, depth to the source of anomaly can be estimated from the slope of the spectra. In the processing stage, the MAGMAP operator is chosen for the data to be gridded. The gridded data are then transformed by applying FFT filter into the wave number domain by assuming density contrast ($\Delta\rho$) as constant. This transformed data will be used to calculate and display the radially averaged energy power spectrum. The depth to the source of anomaly is determined by the equation given as

$$h = -\frac{s}{4\pi}. \qquad (3)$$

where h is the depth; and s is the slope of the log (energy) spectrum.

Results and Discussion

In general, the anomaly source depth range computed for each line is from 0.03 to a maximum of about 42 km. The deepest depth observed in Profile7 (100.62°E, 4.52°N) situated in the northern part of Peninsular Malaysia can be associated with the deepest upper mantle surface and hence the thickest crustal layer in the study area. Basically similar pattern are observed in all profiles of radially averaged energy spectrum curves which are displaying three major slopes interpreted as representing deep, intermediate and shallow anomaly depth source. Profile A with length (145 km) of located at longitude 102.8°E and latitude of 1.8°N, which is in the most southern part of Peninsular Malaysia, indicates the presence of three major slopes with different depth. The depths calculated from the spectral curve are shown in Figure 2(a), which are estimated at 20.63 and 8.0 km. These depths represent boundaries of different geological properties estimated as Conrad discontinuity and top of basement. Figure 2(b) shows similar spectral analysis curve and depth estimate from it representing Profile B located at longitude 102.11°E and latitude of 2.26°N with length of 207 km. As for this profile, the maximum peak calculated from the slopes is 24.58 km which also equivalent to Conrad discontinuity separating the upper and lower crustal materials. The second highest peak is detected at 11.48 km depth, which can be correlated with top of basement layer. Average of basement top layer is about 9 km.

Profile C with length of 240 km located further north of Profile B along longitude of 101.45°E and latitude of 2.71°N is shown in Figure 2(c). The power spectrum curve and the depth slope give much deeper depth of 33.39 km interpreted as separating upper mantle and lower crustal materials equivalent to Moho discontinuity surface. The second highest peak was observed at 17.21 to 18 km representing Conrad discontinuity while the numerous lower peaks were observed between 3.89 and 10 km representing basement layer. Moho depth was not obtained in Profile A and B due to shorter profile length compared to Profile C. Profile D located further north of Profile C along longitude of 101.31°E and latitude of 3.15°N is shown in Figure 2(d) displaying three slopes of power spectrum curve with three major peaks representing depths of boundaries separating the earth structures. The highest and maximum depth peak is at about 36.54 km interpreted to be representing Moho discontinuity separating the upper mantle and the lower crustal materials. The Conrad discontinuity is estimated from the lower peak at depth of 21.49 km and the basement top is estimated from many shallow peaks below 10 km depth. Profile E with length of 265 km located at longitude 100.98°E and latitude of 3.61°N (Figure 2(e)). The highest and maximum depth peak is at about 33.73 km interpreted to be representing Moho discontinuity separating the upper mantle and the lower crustal materials. The Conrad discontinuity is estimated from the lower peak at depth of 21.80 km and the basement top is estimated from many shallow peaks below 10 km depth. Profile F located at longitude 100.76°E and latitude of 4.06°E with length of 294 km is shown in Figure 2(f). The highest and maximum depth peak is at about 33.31 km interpreted to be representing Moho discontinuity separating the upper mantle and the lower crustal materials. Meanwhile for the second peak is observed at depth of 20 km representing the Conrad discontinuity and the basement is estimated at depth below 10 km.

Profile G is the longest profile with length of 315 km (Figure 2(g)) located at longitude 100.26°E and latitude 4.52°N which associated with the upper mantle layer at depth of 41.48 km. This depth interpreted as Moho discontinuity, while for Conrad discontinuity is interpreted at depth of 26.01 km which separating the upper and lower crust layer and the basement is estimated at depth below 10 km. Profile H located further north of Profile G along longitude of 100.4°E and latitude of 4.96°N with length of 326 km is shown in Figure 2(h). Figure 2(h) displaying three slopes of power spectrum curve with three major peaks representing depths of boundaries separating the earth structures. The highest and maximum depth peak is at about 38.81 km interpreted to be representing Moho discontinuity separating the upper mantle and the lower crustal materials. The Conrad discontinuity is estimated from the lower peak at depth of 22.9 km and the basement top is estimated from many shallow peaks from 5.09 to 10 km depth. Profile I located at longitude 100.16°E and latitude 5.42°N is shown in Figure 2(i). The highest and maximum depth peak is at about 34.89 km interpreted to be representing Moho discontinuity separating the upper mantle and the lower crustal materials. The Conrad discontinuity is estimated from the lower peak at depth of 21.49 km and the basement top is estimated from many shallow peaks below 10.39 km depth. Profile J located at longitude 100.34°E and latitude 5.87°N only has 2 peaks at depth 28.89 and 8.64 km represent the Conrad discontinuity and basement (Figure 2(j)).

Depth curves can be classified into three dominant depth group based on its peak position. The highest peak with maximum depth of about 33 to 42 km appeared in 7 profiles with the exception of profile 1, 2, and 10 which are located in the most southern and northern part of the study area. The highest peak observed correspond to the deepest part of earth materials which is most likely related to the Moho discontinuity. The second peak observed in the depth curve almost by all profiles ranging from 18 to 26 km is interpreted as the Conrad discontinuity. The numerous remaining shallow peaks in the depth-wave number panels ranging from 0.03 to 18 km can be interpreted as maximum depth of basement rocks consisting of Mesozoic, Paleozoic and igneous intrusion (Table 1).

Similar range of depths were also observed by Loke et al. (1983) and Ryall (1982) based on gravity modelling along east-west between Kuala Selangor to Kuantan (Table 2). Depth of basement and Conrad discontinuity by Loke et al. (1983) and Ryall (1982) were 10 to 12 km and 18 to 20 km, respectively, meanwhile depth of Moho discontinuity was not detected. Asano et al. (1985) used seismic technique to discover depth of basement, Conrad and Moho discontinuities in Honshu, Japan to be approximately about 3 to 8 km, 15 to 20 km, and 35 to 40 km, respectively. Similar seismic study by Kaila et al. (1987) in India found equivalent depth of basement, Conrad and Moho discontinuities. Mooney et al. (1998) in the study of global subsurface structure found the maximum of crustal thickness around South East Asia to be about 30 km depth. Rina (2008) studied crustal layers in Jawa Timur, Indonesia which is very close to our study area by power spectrum technique of gravity data found that Moho discontinuity depth is about 25.6 km. This depth is about 7 km less than our finding which is at 33 km depth. Kieling and Roessler (2011) and Kumar et al. (2016) also observed similar depth of Moho discontinuity at 25 to 38 km in Peninsular Malaysia and 30 to 32 km in India by using seismic technique and power spectral analysis on gravity data. All these case studies further confirm the validity of our result regarding the crustal-mantel depth. Table 2 shows the comparison of the average results of this study with the other findings.

Figure 3 shows the variations of basement, Conrad and Mohorovicic depths obtained from spectral analysis of 10 profiles from south to north of Peninsular Malaysia. Mohorovicic depth varies from 33 to 42 km below the surface along 7 profiles with the exception of last three profiles where the maximum depth observed were very shallow from 20 to 25 km which are most likely not considered as Moho depth. Conrad discontinuity were shown in Figure 3 as depth variations from 19 to 25 km. Basement depth variations are almost consistent between 5 and 8 km depth. The difference of lower crustal layer depths of about 8.73 km around the Moho discontinuity located at 4.-4.5°N can be used as an indicator of possible rifting event in that layer which probably caused the seismic activities such as minor tremors and active faults at Bukit Tinggi, Pahang.

FIGURE 1. Bouguer gravity anomaly map of Peninsular Malaysia with position of traverse profiles used in the power spectral analysis

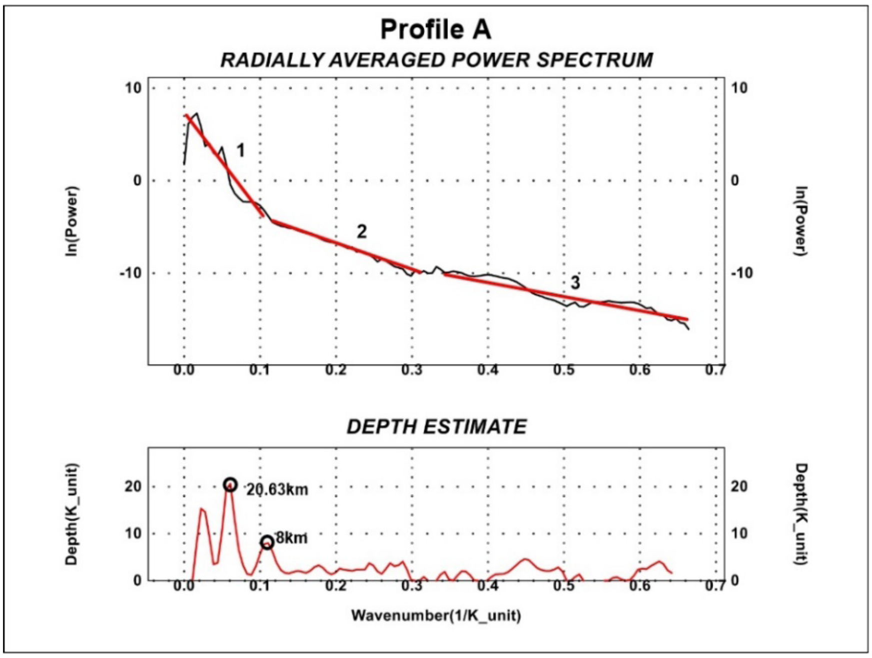

FIGURE 2. (a) shows the radially averaged power spectrum of profile A indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

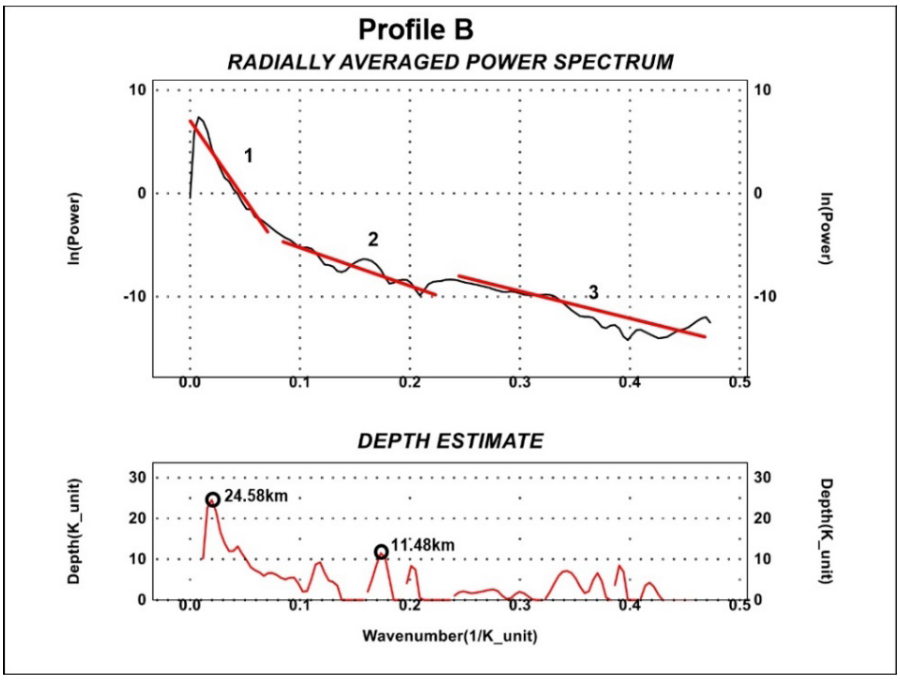

FIGURE 2. (b) shows the radially averaged power spectrum of profile B indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

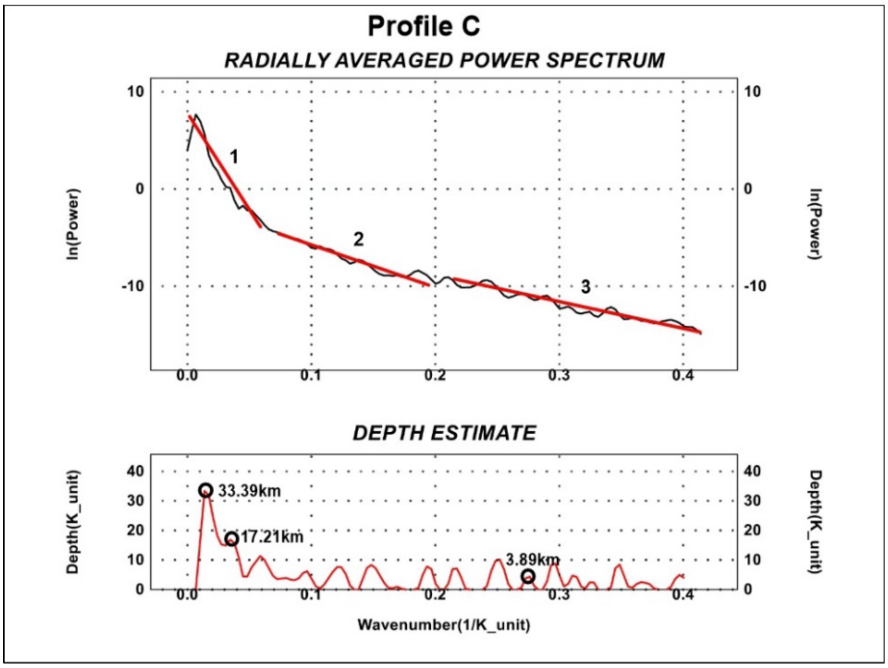

FIGURE 2. (c) shows the radially averaged power spectrum of profile C indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

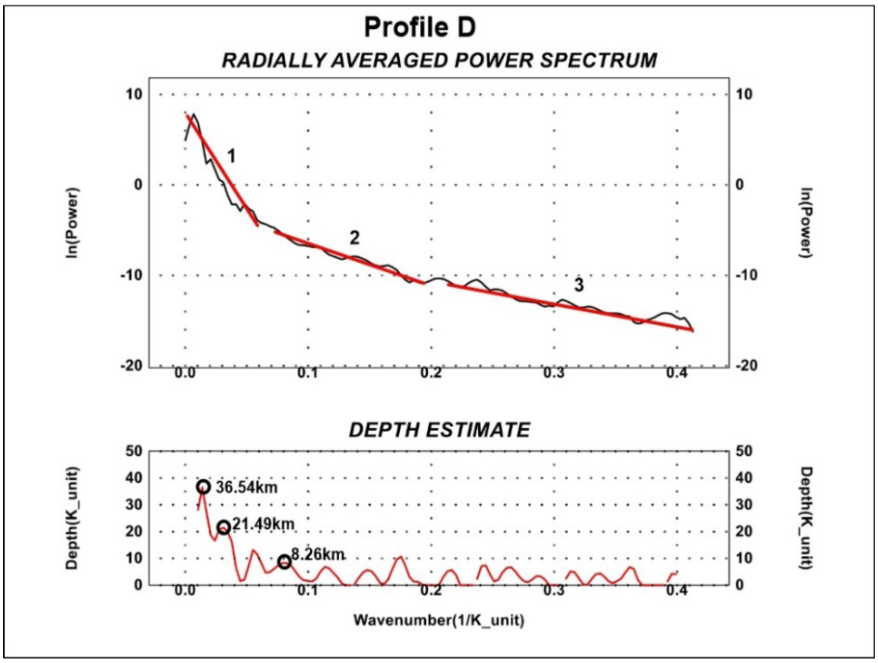

FIGURE 2. (d) shows the radially averaged power spectrum of profile D indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

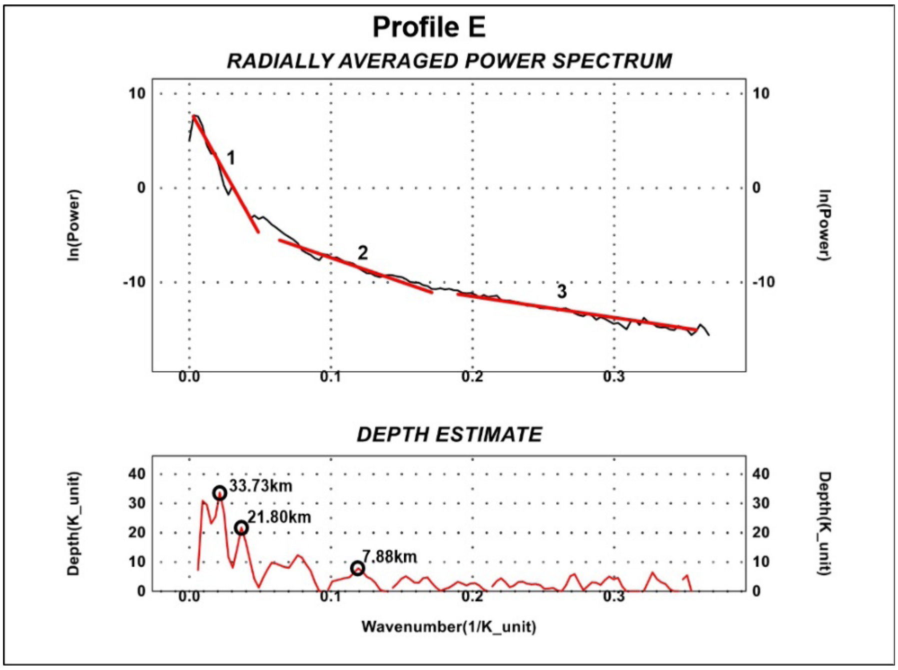

FIGURE 2. (e) shows the radially averaged power spectrum of profile E indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

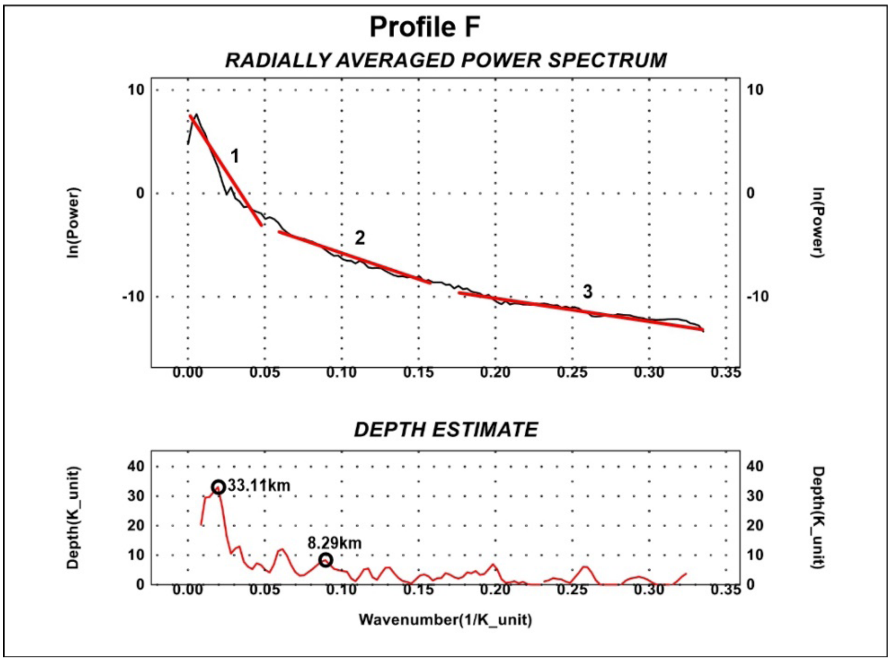

FIGURE 2. (f) shows the radially averaged power spectrum of profile A indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

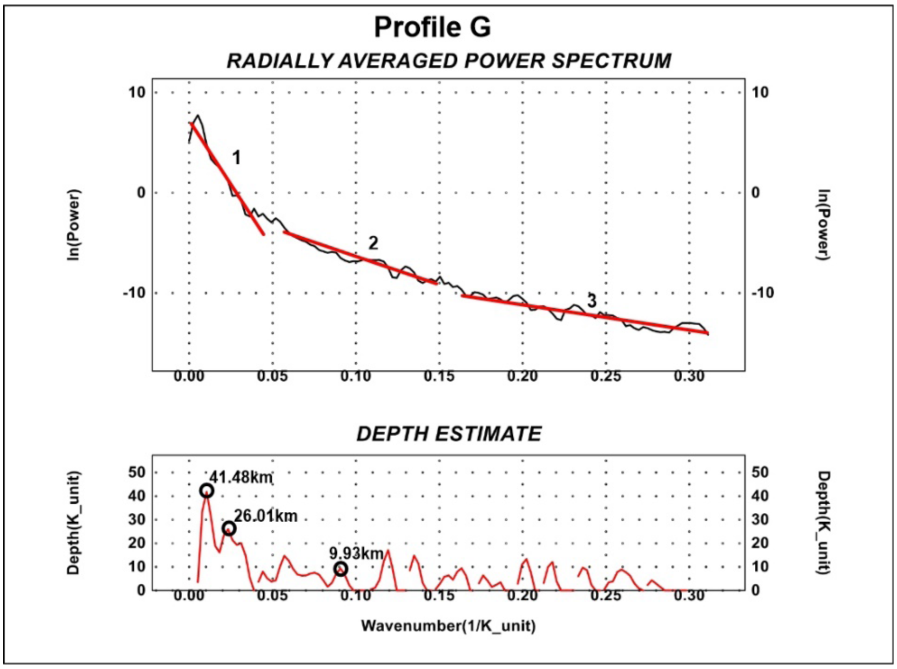

FIGURE 2. (g) shows the radially averaged power spectrum of profile G indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

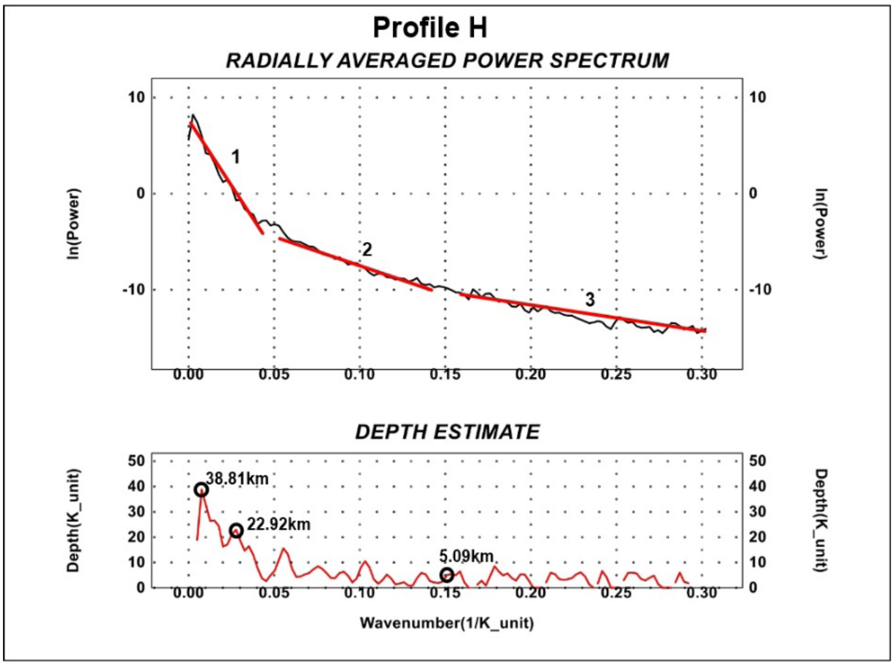

FIGURE 2. (h) shows the radially averaged power spectrum of profile H indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

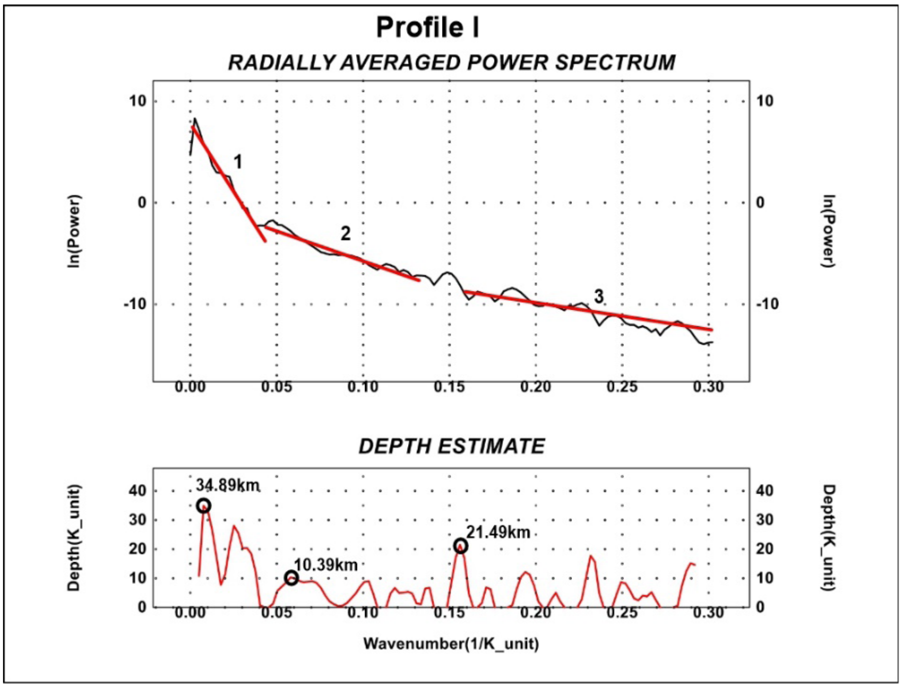

FIGURE 2. (i) shows the radially averaged power spectrum of profile I indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

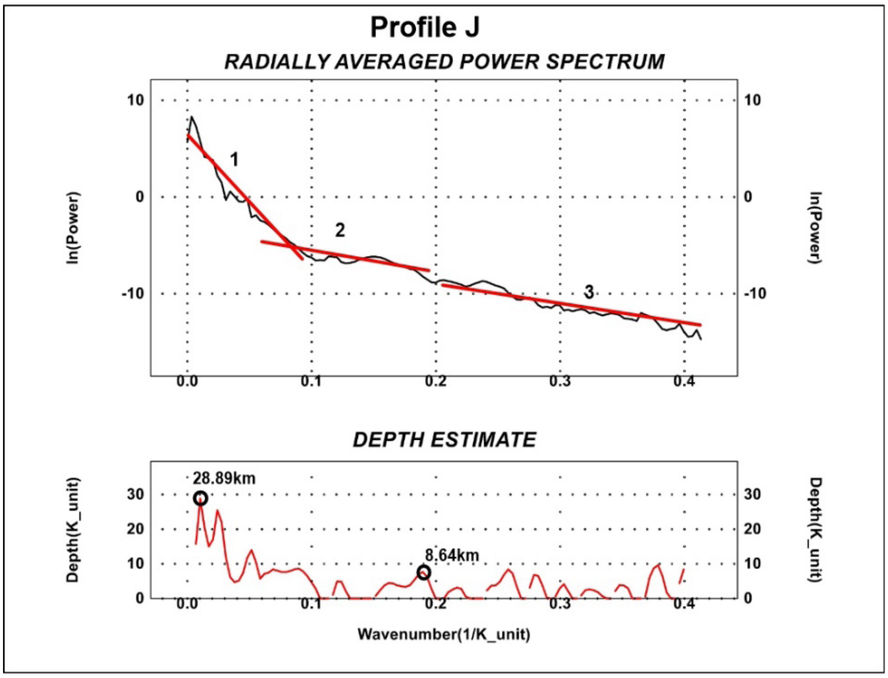

FIGURE 2. (j) shows the radially averaged power spectrum of profile J indicating the dominant slope of 1 to 3 and the depth curve indicating the depth of the slope

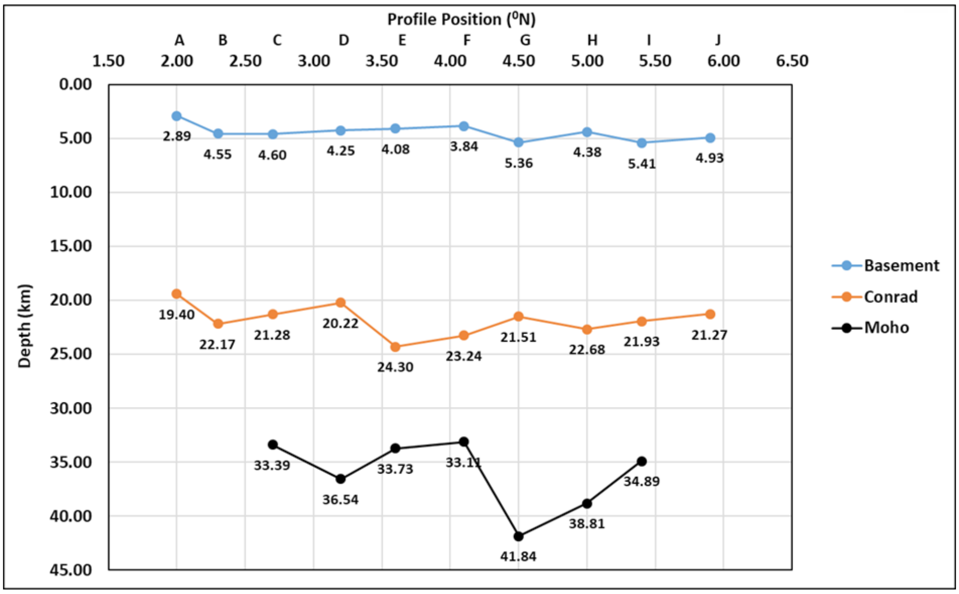

FIGURE 3. Depth variations of basement, Conrad, and Mohorovicic discontinuities based on spectral analysis of each profile from N-S of Peninsular Malaysia

TABLE 1. Shows the depth range of Conrad, and Moho discontinuity obtained by profile 1 to 10 in the study area

Peak/Depth (km)			
Profile	Basement	Conrad discontinuity	Mohorovicic discontinuity
A	9.32	20	-
B	9.84	25	-
C	10.04	18	33.39
D	9.66	20	36.54
E	9.77	22	33.73
F	9.93	20	33.11
G	9.93	26	41.84
H	8.55	22	38.81
I	9.77	20	34.89
J	9.61	25	-

TABLE 2. Results of average basement depths, Conrad, and Moho discontinuities obtained by several researchers as compared to this study

Researcher/Area	Method	Discontinuity		
		Basement depth (km)	Conrad depth (km)	Moho depth (km)
Ryall 1982 & Loke et al. 1983 (Peninsular Malaysia)	Modelling using potential data	10 - 12	18 - 20	-

Asano et al. 1985 (Honshu, Japan)	Seismic	3 - 8	15 - 20	35 - 40
Kaila et al. 1987 (Mahanadi Delta, India)	Seismic	6	17.5-20.5	30 - 34
Mooney et al. 1998 (Global)	Seismic	-	-	30
Rina 2008 (Jawa Timur, Indonesia)	Power Spectrum on gravity data	2.7	-	25.6
Kieling & Roessler 2011 (Peninsular Malaysia)	Seismic	2 - 6	12 - 19	25 - 38
Kumar et al. 2016 (Odisha, India)	Spectral Analysis on the gravity data	8	14 - 15	30 - 32
Our Study (Peninsular Malaysia)	Power Spectrum on gravity data	3 -10	18 - 26	33 - 42

Conclusion

Spectral analysis technique of Bouguer gravity data in Peninsular Malaysia showed three spectacular dominant slopes associated to depths of basement, Conrad, and Mohorovicic discontinuities at about 3 to 10 km, 18 to 26 km, and 33 to 42 km, respectively. These depths are in good agreement as obtained by seismological, gravity and magnetic modelling techniques.

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Nurul Fairuz Diyana Bahrudin*, Umar Hamzah & Wan Zuhairi Wan Yaccob
Geology Programme
School of Environmental Sciences and Natural Resources
Faculty of Science and Technology
Universiti Kebangsaan Malaysia
43600 UKM Bangi Selangor Darul Ehsan
Malaysia

Nurul Fairuz Diyana Bahrudin
Environmental Tracer Application Group Waste
Technology and Environmental Division
Malaysian Nuclear Agency, Bangi
43000 Kajang, Selangor Darul Ehsan
Malaysia

*Corresponding author; email: nurulfairuz@nuclearmalaysia.gov.my

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