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Full Length Research Paper

Estimation of crustal thickness by combination of two geophysical methods: A case study

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In this study an extended geophysical survey using gravity and high angle refracted seismic methods with recorded earthquake has been carried out in Kerman province in southeast of Iran. The purpose of the applied geophysical surveys was to provide information on crustal structure and lithospheric thickness. The purpose of this research is focused on determination of Moho depth and for this reason several profiles for both methods were performed and by use of topography and gravity data with a reasonable combination with high angle refracted seismic data and earthquake record, the crustal and lithospheric thickness of Kerman province in the southeast of Iran was calculated. Oldenburg- Parker algorithm was the base of gravity survey of the present work but by use of Matlab programming environment and generated C Sharp computer codes was optimized, improve and then executed. For seismic data, a least-squares analysis of the travel-time data was made and the uncertainties were taking in to account. Finally, depth calculations for the velocity discontinuities and gravity anomaly contour maps were made. The comprehensive comparison between the obtained results and other studies on the selected area showed good agreement, which verified the ability of produced code.

Key words: Geophysical methods, crustal thickness, MOHO R.A.T 1.01.

INTRODUCTION

Kerman Province is one of the 30 provinces of Iran, which is located to the southeastern of Iran in 54 °21′ to 59° 34′ east longitude and 26°29′ to 31°58′ north latitude. It is in the southeast of the country. Its center is Kerman. The province of Kerman is the second largest in Iran, with area of 181,714 km² and 2652413 populations. As shown in Figure 1, Baft, Bardsir, Bam, Jiroft, Rafsanjan, Zarand, Sirjan, Shahr-e-Babak, Kerman, Mahan and Kohnoj are the main towns of this province.

In general, Kerman province can be a part of Central Iran zone in structural units and extent of sedimentary basins viewpoint. In addition, this province can be related to Tabas block and Tabas-Kerman ranges with respect to tectonically units. To explain the sedimentary basin of Central Iran and the thickness of out crop is over 10,000 meters, which has been caused from erosion of older rocks. This set has metamorphed severely because of Katangan Orogeny and has formed platform of Central Iran that is covered by continental or shallow marine sediments since late Precambrian to Triassic. The crystalline bedrock of central Iran and plat formic coverage has been broken, at least since Paleozoic era and regarding to stratigraphy gap in some of its regions has imposed vertical movement, with its effect in generation of tertiary volcano. In viewpoint of stratigraphy, Precambrian litho logic units of central Iran which is located directly below fossil bearing sediment of Precambrian has been known in Azerbaijan, Golpayegan, Yazd mountains, Kerman and Tabas. As shown in Figure 2. The active tectonics of Iran is dominated by the northward motion of Arabian plate with respect to Eurasia. At 56^{o} E longitude, ~25 mm/yr of north-south shortening is accommodated across Iran (Sella et al., 2002; Vernant et al., 2004). Several large earthquakes have occurred on the right-lateral strike-slip fault systems along the western margin of the Dasht-e-Lut (Berberian et al., 2001), which accommodate

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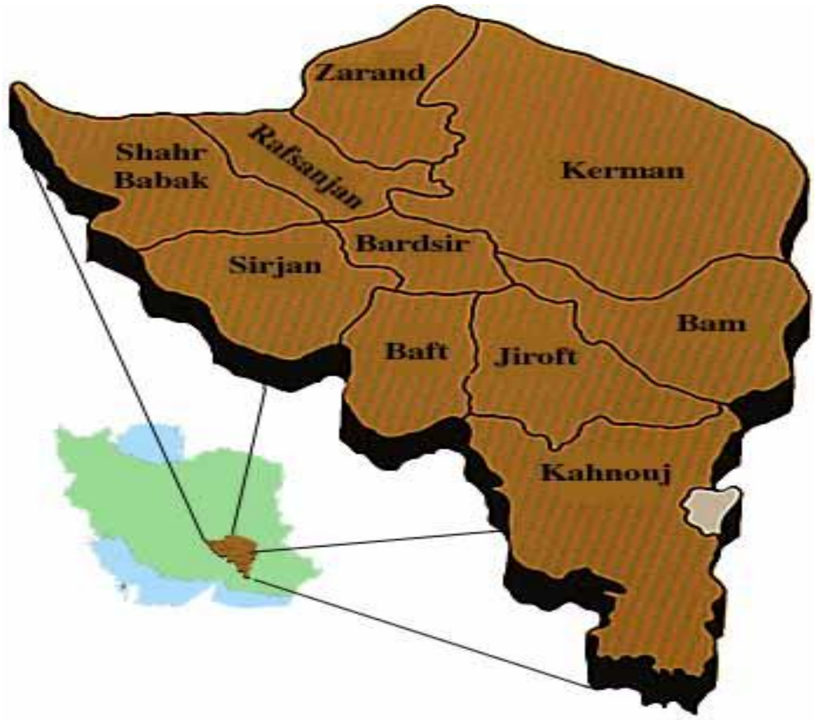

Figure 1. Location of Kerman province in Iran and its main townships.

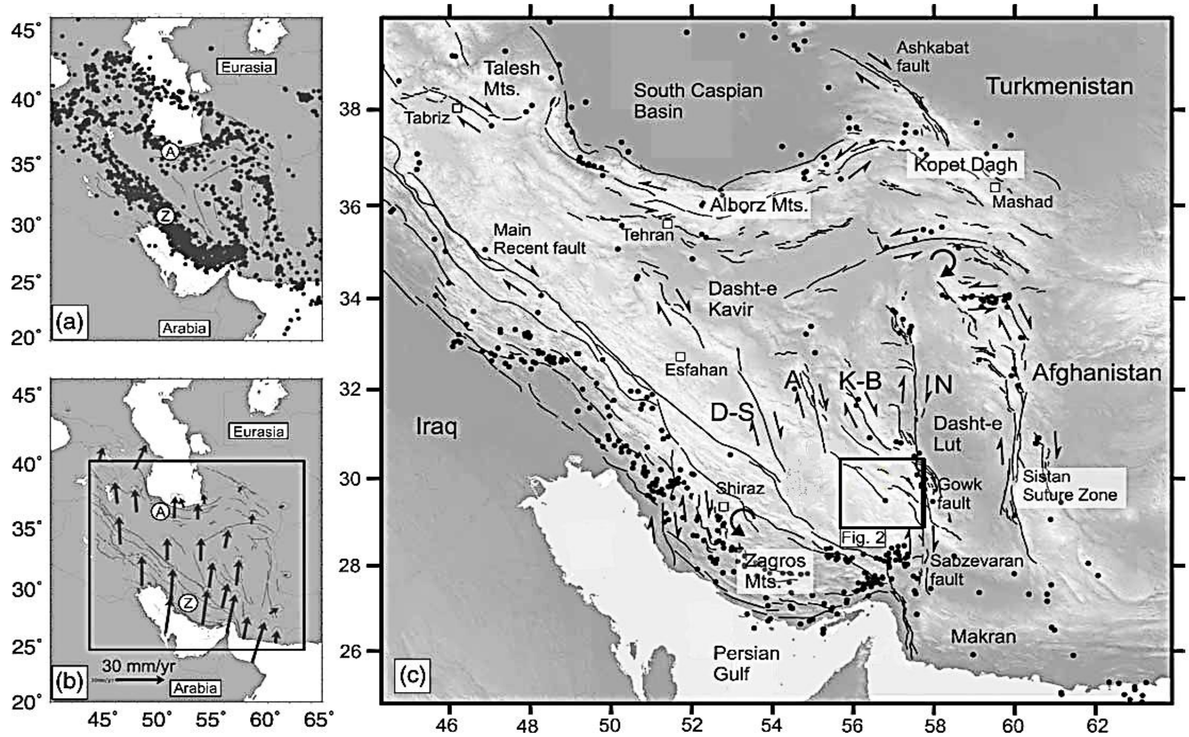

Figure 2. (a) Instrumentally recorded earthquake epicenters in Iran from the catalogue of Engdahl et al. (1998). (b) A velocity field for Iran determined from repeated GPS measurements (Vernant et al., 2004). Both the seismicity and the deformation measured by GPS are concentrated in central parts of Iran including the selected region (c) Shaded SRTM topography of the studied area showing the major active faults (DehShir (D-S), Anar (A), Kuh-Banan (K-B) and Nayband (N)).

right-lateral shear between central parts of Iran and Afghanistan. However, low rates of seismicity lead the parts of central Iran, west of Dasht-e Lut desert to be considered as relatively strong and non-deforming crustal blocks, in which relatively few active faults have been mapped and relatively few historical earthquakes are recorded (Ambraseys and Melville, 1982).

BASIC CONCEPTS OF THIS STUDY

Geophysical surveys have many applications in earth science, engineering and industry as well as for academic research. One of the important purposes of geophysical methods is the study of earth's crust incases of tectonic and seismicity. The gravity method is a nondestructive geophysical technique that measures differences in the earth's gravitational field at specific locations. It has found numerous applications in engineering and environmental studies including locating voids and karst features, buried stream valleys, water table levels and the determination of soil layer thickness. Applications of gravity to mineral deposit environmental considerations includes; identification of lithologies, structures and at times, ore bodies themselves (Wright, 1981). The strength of the gravitational field is directly proportional to the mass and therefore the density of subsurface materials. Anomalies in the earth's gravitational field result from lateral variations in the density of subsurface materials. Several researchers such as Cordell and Henderson (1968), Dyrelius and Vogel (1972), Ramesh Babu and Bhaskara Rao (1990, 1991) provided different algorithms to account common denominator of the relevant density with the known gravity anomaly. On base of equivalent layer, Tsuboi (1983) proposed a simple and efficient method to account 3D topography derived from a density intersection. On base of Parker (1973) scheme, Oldenburg (1974) realigned the straight algorithm. The base of Parker's platform is the Fourier transform of gravity anomaly. Oldenburg proved that it is possible to modify Parker scheme to determine the geometry of density intersection from gravity anomie. On base of the mentioned platform of Oldenburg and Parker, Nagendra (1996) generated a FORTRAN computer code to analyze 2D gravity data, Ortiz and Agarwal (2004) produced a Matlab code. Their code was on base of Oldenburg-Parker but developed for 3D to determine the density intersections according to gravity anomaly. They employed the 1D suggested Equation 1 by Parker (1973) as:

$$F(\Delta g) = -2\pi\rho G e^{(-kz0)} \sum_{n=1}^{\infty} \frac{k^{n-1}}{n!} F[h^n(x)] \quad \cdots \quad (1)$$

Where: F(Δg): Fourier transform of gravity anomaly, G: universal gravity constant, ρ: density difference between the crust and mantle, K: wave number, h(x): crust depth and Z: average depth of the source.

Oldenburg (1974) modified this equation to account the depth of undulation intersection from gravity anomie with continuous approximations, which is given in Equation 2.

$$F[h(x)] = -\frac{F[\Delta g(x)]e^{(+kz0)}}{2\pi\rho G} - \sum_{n=2}^{\infty} \frac{k^{n-1}}{n!} F[h^n(x)] \cdots\cdots \quad (2)$$

This equation allows determining the crust surface topography by an iterative and inversion method. Because of instability reverse effect in high frequencies, a low pass filter is embedded to provide series convergence. The defined filter in Equation (3) is used to limit the high frequencies in the Fourier spectrum of gravity anomie.

$$HCF(k) = \frac{1}{2}[1 + \cos(\frac{k - 2\pi WH}{2(SH - WH)})] \cdots\cdots (3)$$

$$WH \prec k \prec SH$$
$$HCF(k) = 0, k \succ SH$$
$$HCF(k) = 1, k \prec WH$$

Seismic methods, as typically applied in exploration seismology, are considered as active geophysical method. In seismic surveying, ground movement caused by some source is measured at a various distances from the source. The type of seismic experiment differs depending on what aspect of the recorded ground motion is used in subsequent analysis. In 1909, Andrija Mohorovicic used travel-times from earthquake sources to perform a seismic refraction experiment and discovered the existence of the crust-mantle boundary now called the *Moho*. In the gravity method, Moho depth is an important parameter in determination of the crust structure and therefore its lateral variations play an important role in seismic wave diffusion.

ANALYSIS FRAME WORK

The models of crust structure study, has a great dependence on quality and quantity of gravity and seismic data. The benefits of each theoretical methods decrease because of the low covering and quality of data and even sometimes become meaningless. The current study has been done in the southern zone of Kerman province in areas that lack gravity data, is the main weakness of the work. However, the measured points in this area and referring these points to the international gravity network of 1971 and also applying the international gravity formula of 1980 for gravity anomie, as well as using generated software by authors for calculation of Moho depth could take over to this problem. By consideration of the mentioned point, obtained, acquainted and collected data after processing

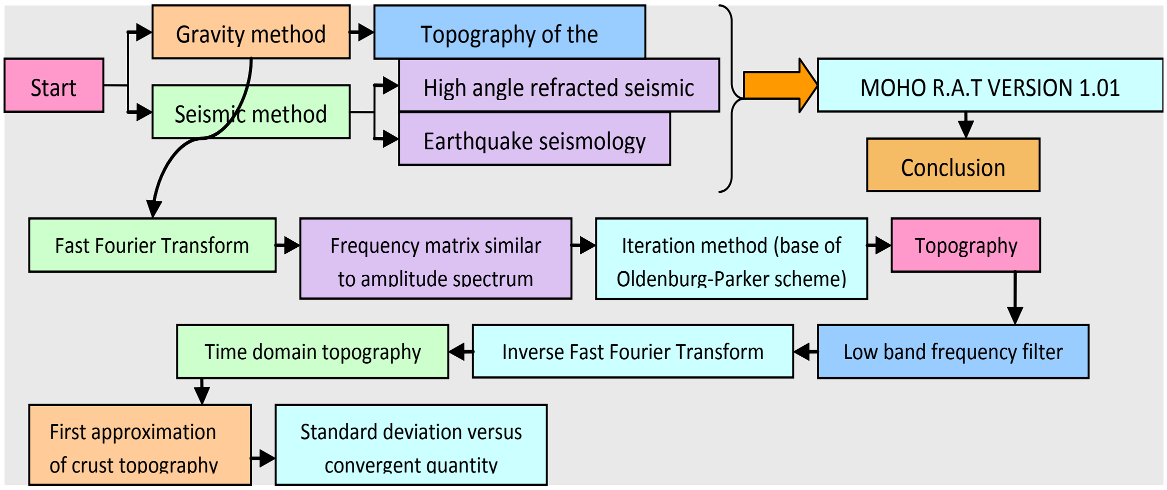

Figure 3. Modular concept of the research method.

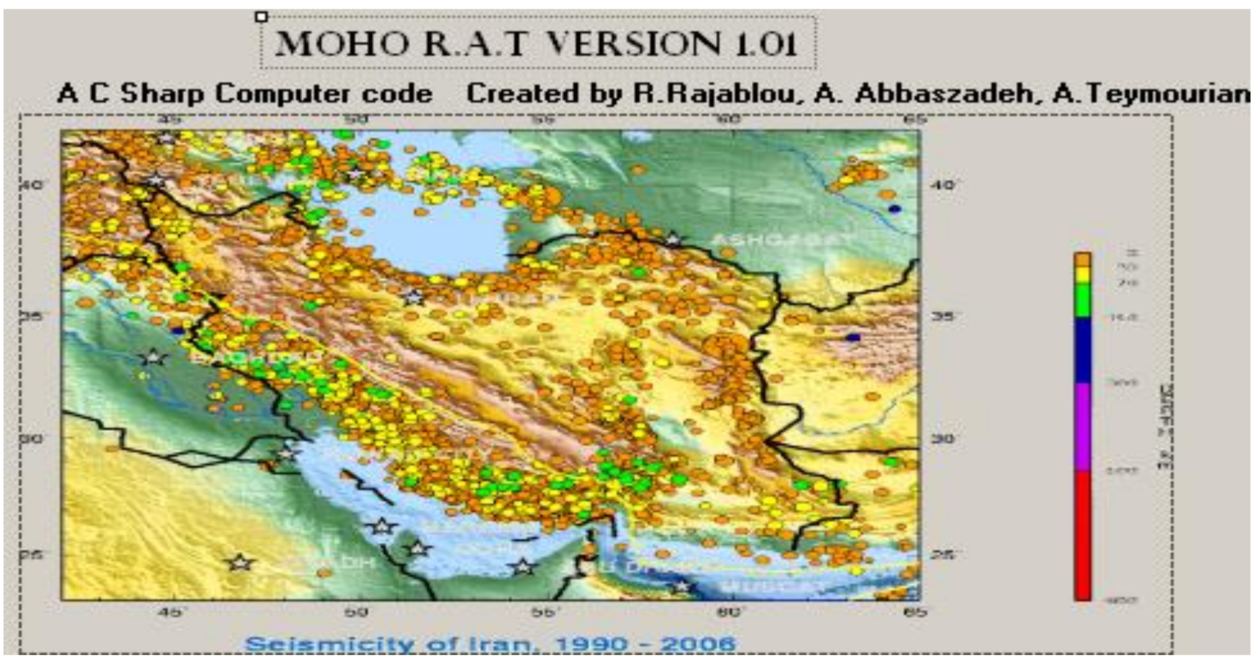

Figure 4. The start screen of the generated code by authors.

can be employed in a modular frame as indicated in Figure 3. In order to increase the accuracy of the study and take over the encountered problems, the authors generated a visual user interface computer code by C Sharp computer language to perform this study, which is shown in Figure 4. This code with a geophysical platform and moderate range of mathematical calculation applications is capable to execute and process the gravity and seismic data and its output is both in the forms of numerical and graphical. The topography of the crust will determine by gravity section of this code and modeling of the studied area is the duty of seismic section. After calibrating the input parameters, the constructed model was used to obtain the crust topography and Moho depth of investigated area. The main goal of this phase of the study was to evaluate the "MOHO R.A.T 1.01" capabilities in response to aim of this study. The results of these trials were compared to existing field and laboratory relationships and appropriate adjustments were made to the model parameters.

The results of the illustrated procedure are shown in Figures 5, 6 and 7 respectively. At last, by software

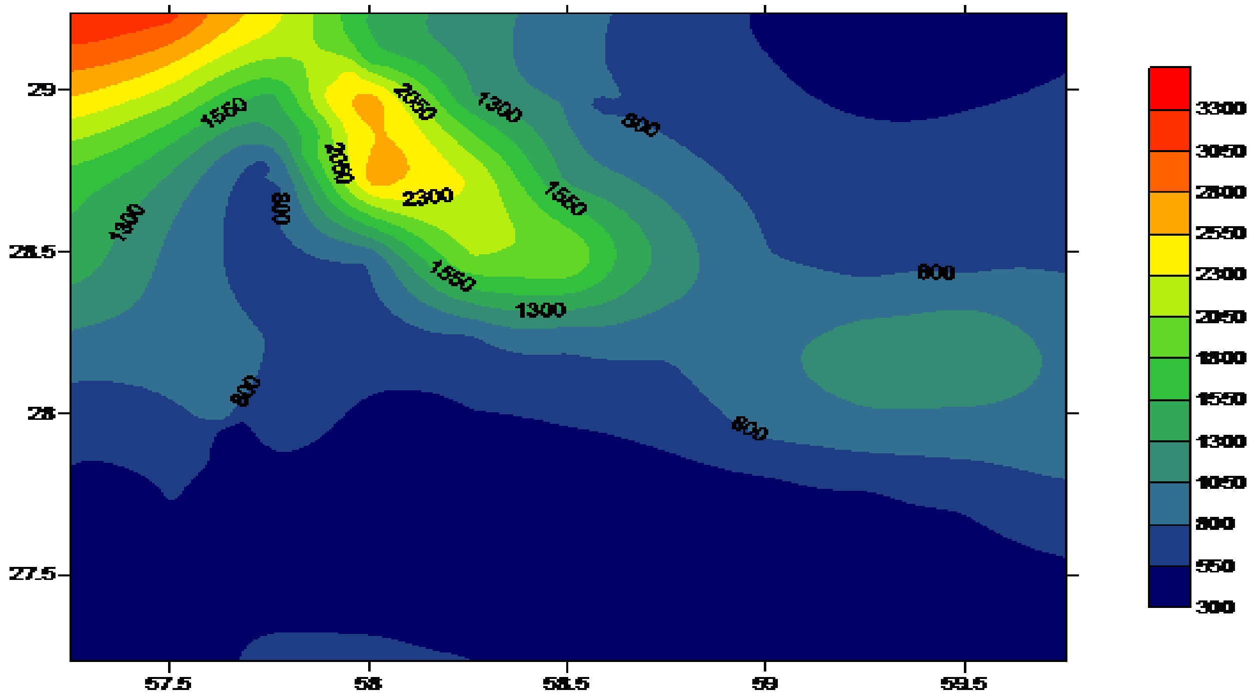

Figure 5. Topography contour map of selected zone (250 meter distance of contour lines).

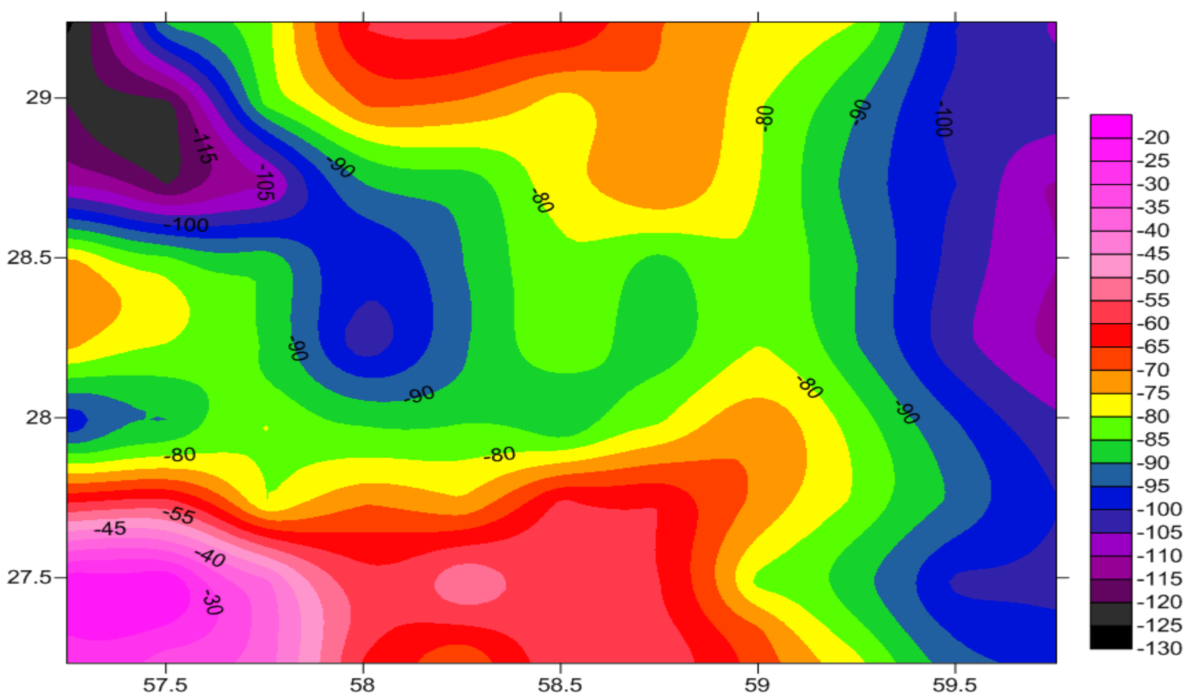

Figure 6. Contour map of computed Bouguer anomaly in investigated region (5 mgal distance of contour lines).

combination and generated code, the 3D view of the area after calculations was plotted and shown in Figure 8.

As known, the Moho boundary express the main change in seismic velocity, petrology, chemical mixtures; and its depth is used to identify the overall structure of the crust, geology and the tectonic. Refractive seismic

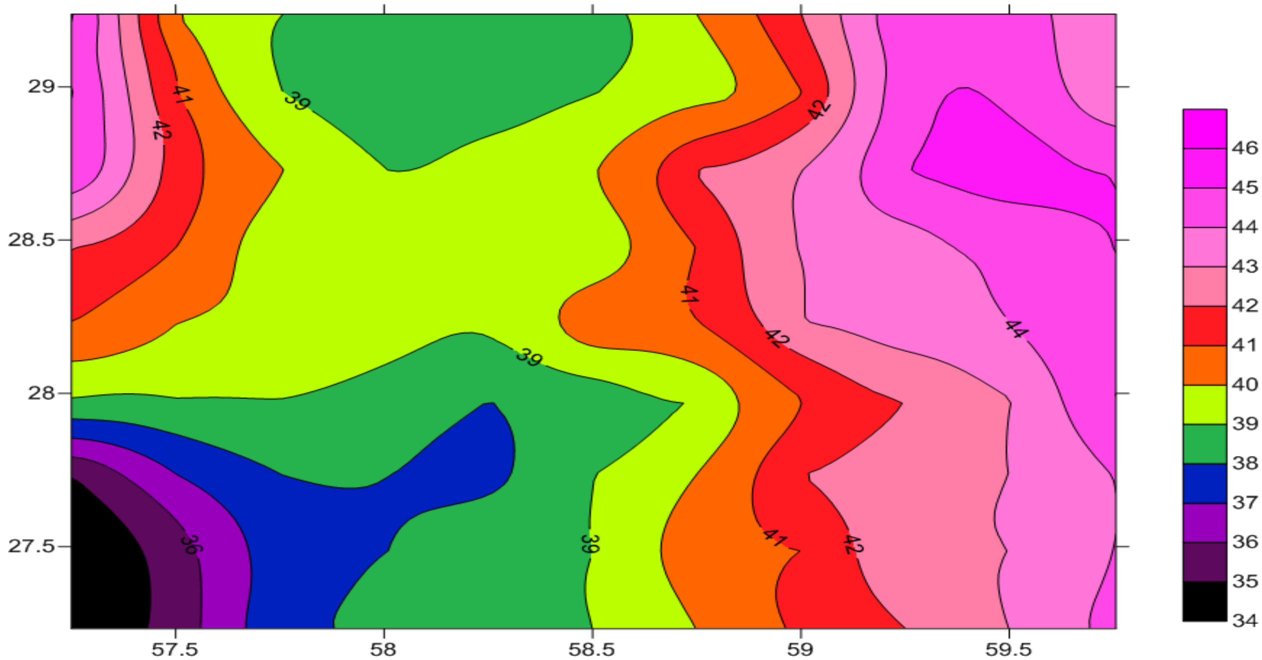

Figure 7. Computed contour map of Moho depth by gravity method in studied area (1 km distance of contour lines).

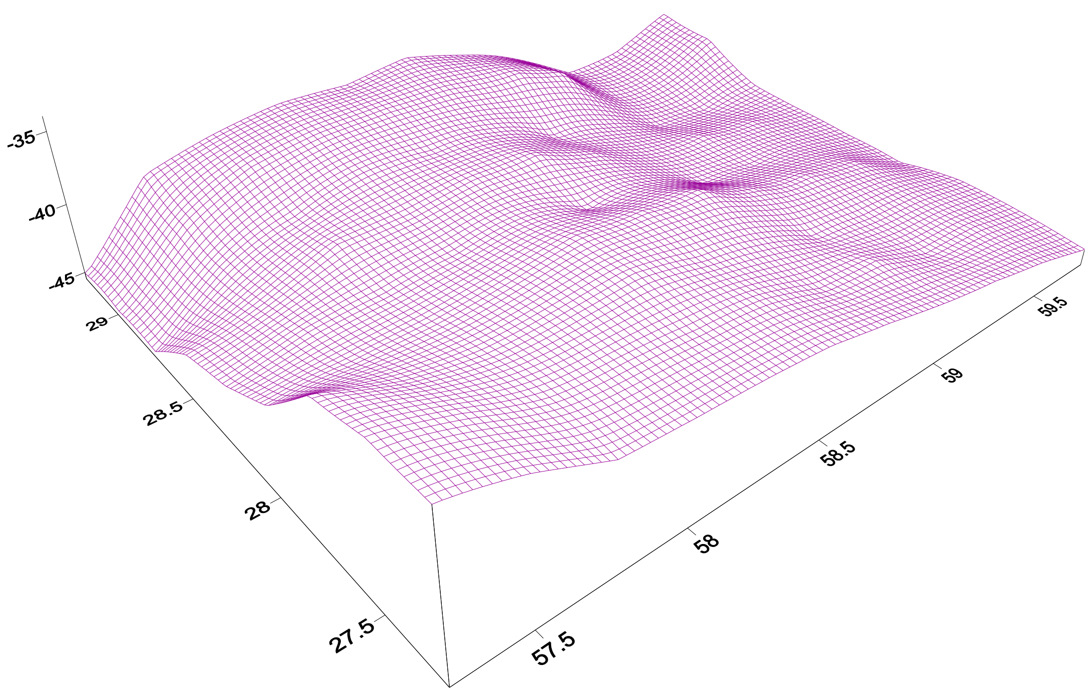

Figure 8. 3D view of the Moho depth in southern part of Kerman province.

method is used for estimating Moho depth in this survey. About 9 seismic stations are considered in the south of Kerman province and the situation of them are determined and located as shown in Figure 9. In these seismic stations, 3 main groups of data including that of Bam earthquake (2003, Iran) as shown in Figure10 and two groups of refractive recorded seismic data which is indicated in Figure 11 are taking into account which are

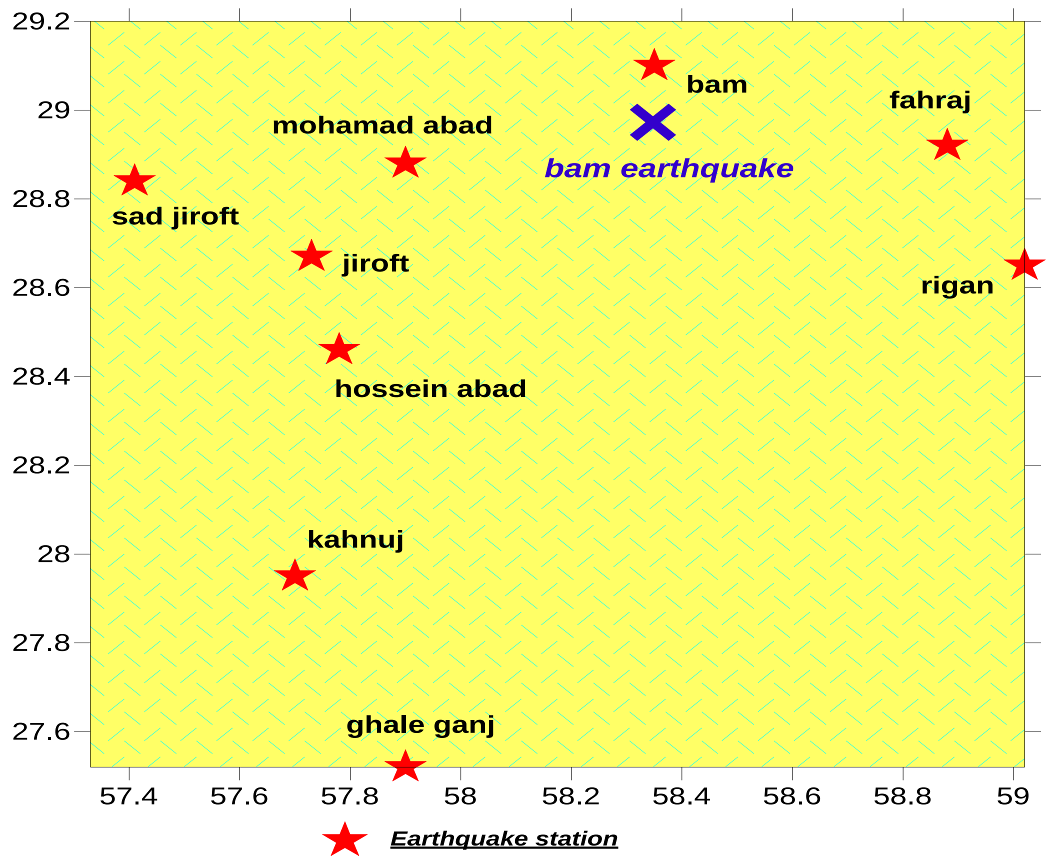

Figure 9. Seismic stations' location in the south zone of Kerman.

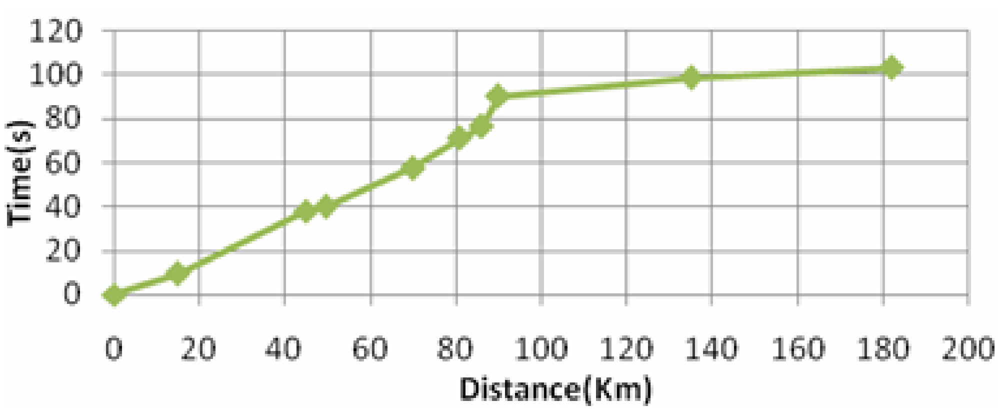

Figure 10. Computed arrival time of P wave in Bam earthquake.

high angle seismic refraction. By assumption of uniform density of the crust for the selected region and by use of dual flat method, arrival time in each station computed and the arrival time curves on base of station distances were plotted. These graphs were analyzed to determine the graph slopes and computation of velocity in each layer. At the final step and by use of the achieved velocity in layers, Moho depth was computed. The results of this part were summarized in Tables 1 and 2. To combine the obtained results and by use of the generated code the map of Moho depth on base of seismic and gravity methods are produced for the southern part of Kerman Province as indicated in Figure 12.

According to Figure 7, obtained Moho depth by gravity

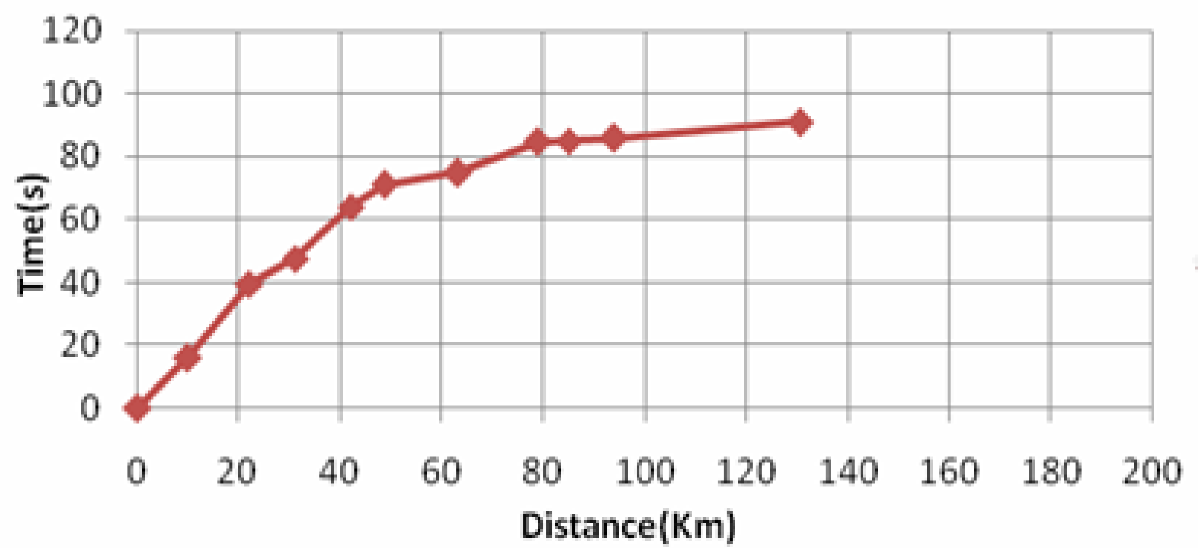

Figure 11. Arrival time of refractive seismic data in the studied region.

Table 1. Computed Moho depth by P and S wave velocity by earthquake seismology.

V_p(first layer)	1.1 km/s
V_p(second layer)	7.1 km/s
V_s (first layer)	0.635 km/s
V_s (second layer)	4.1 km/s
Moho Depth	38.49 km
X_{cros}	90 km

Table 2. Computed Moho depth by P and S wave velocity by high angle refraction seismic method.

V_p(first layer)	1 km/s
V_p(second layer)	6.7 km/s
V_s (first layer)	0.578 km/s
V_s (second layer)	3.82 km/s
Moho Depth	38.2 km
X_{cros}	92 km

method in this area with 500 m accuracy was 34 to 46 km. By selection N-S gravity profile including the Bam, Mohammad abad Maskoon, Jiroft, Hossein abad, Kahnuj and Ghale ganj seismic stations, Moho depth varied 37.6 to 39.8 km as shown in Figures 12 and 13, but by seismic analysis in the mentioned profile (N-S), average Moho depth obtained 38.2 km which is shown in Figure 14 respectively. To better realizing of the obtained results of this study, a comparison between the gravity and seismic methods were made and was indicated in Figure 15 and its numerical analysis was pointed in Table 3.

Conclusion

Geophysical Software and Algorithm papers must describe a useful algorithm for solving a problem of geophysical significance. Papers should describe a problem, how the algorithm is meant to solve the problem and the workings of the algorithm itself. A GUI C Sharp computer code was developed on base of Oldenburg-Parker scheme with addition of seismic capabilities and to prove the modification and verification of the proposed algorithm, a case study in southern part of Kerman province of Iran were conducted. At first, we evaluate reference crustal thickness, which means the thickness under 0 m elevation, assuming that topography of studied region is fully supported isostatically. Because the supporting mechanism of topography depends on its wavelength, we can estimate the elastic thickness by investigating relationship between topography and gravity on wavelength domain. The resulting values presented in the tables of context. The data of Bouguer gravity and topography were inverted to obtain the crust thickness of this region. In order to reduce the effect of regional non-isostasy we corrected the reference Moho depth in the inversion with regional topography relief, and performed multiple iterations to make the result more reliable. The obtained crust thickness of this area the contour maps within variable contour lines were made. Then we analyzed the correlation between the Bouguer gravity anomaly and fluctuation of the Moho depth. According to presented figures, obtained Moho depth by gravity method in this area with 500 m accuracy was 34 to 46 km. By selection N-S gravity profile including the Bam, Mohammad abad Maskoon, Jiroft, Hossein abad, Kahnuj and Ghale ganj seismic stations, Moho depth varied 37.6 to 39.8 km. But by seismic analysis in the mentioned

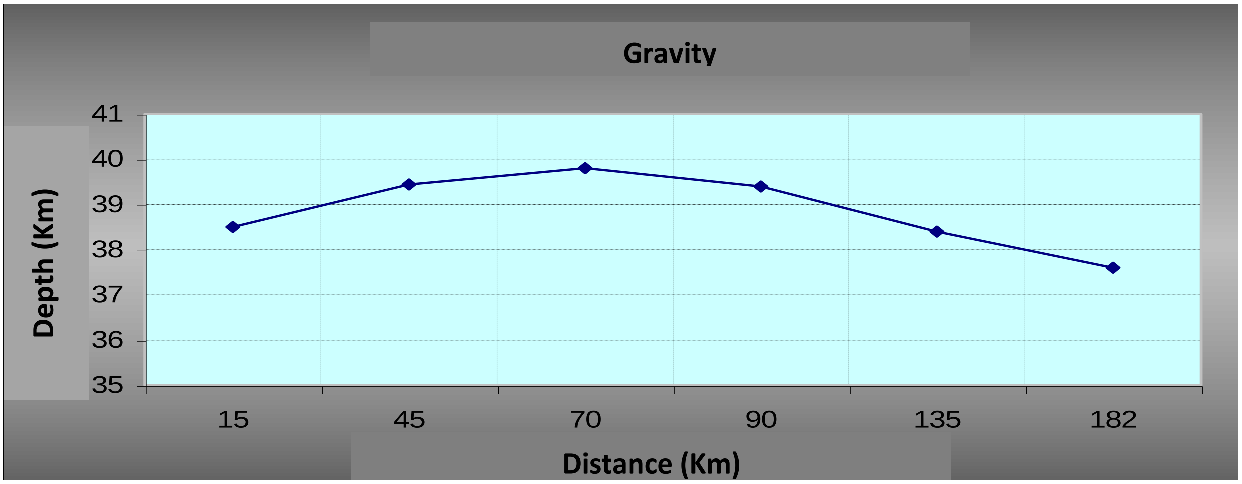

Figure 13. Variation of Moho depth with changing the profile with N-S trend.

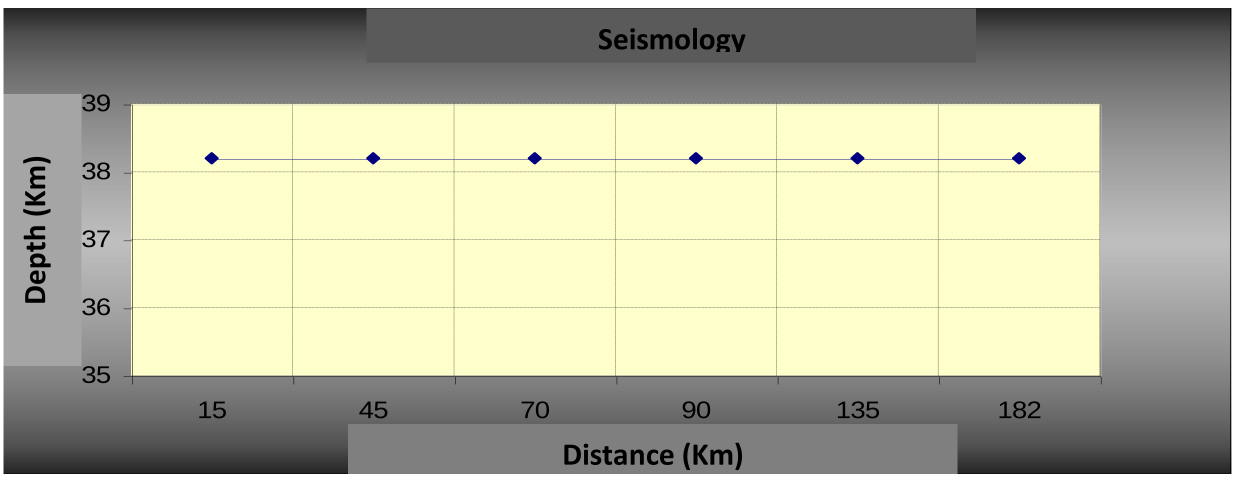

Figure 14. The average of Moho depth in the studied area by refractive seismic method in N-S profile.

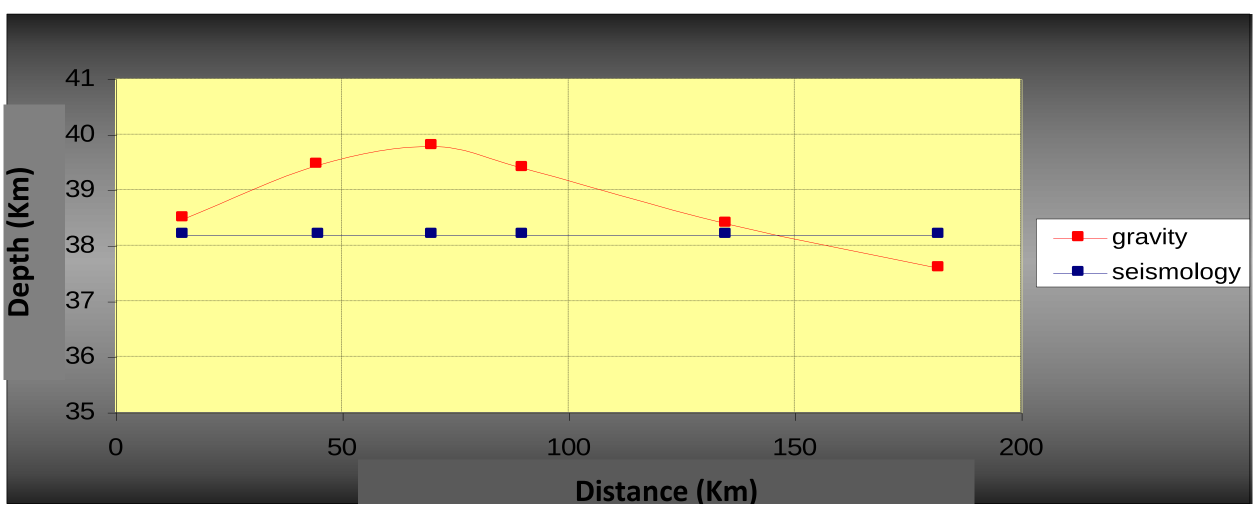

Figure 15. Comparison between Moho depth in the region by gravity and seismic.

Table 3. Difference between Moho depth with gravity and refractive seismic method.

Station	Different Moho depth from gravity and seismology method (km)
Bam	0.3
Mohamad abad	1.2
Jiroft	1.6
Hosein abad	1.2
Kahnuj	0.2
Ghale ganj	0.6

profile (N-S), average Moho depth obtained 38.2 km. The numerical analysis shows that the difference in the crust thickness deduced from the two various methods are less than 2 km. After comparing our result with other studies, it is verified that our method obtained a clear and better results from the previous done in this region.

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