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The Relation of Topography and Gravity Anomalies with Magnitude of Earthquakes in Iran

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ABSTRACT

In this paper the relation of earthquakes magnitude with topography and gravity anomalies including isostatic, Booger, free air and gravity disturbance in Iran have been studied. In addition, correlation between topography and gravity anomalies is investigated separately and the results are presented. To do this, Iran is divided into four square regions with (2´× 2´) dimensions and in these quadrangles the above parameters are collected. Then, the vector and raster maps of the area were prepared for studied parameters using the ARC GIS software. Combining data layers results in comprehensive map of earthquakes equal or greater than 4 in magnitude, topography and gravity anomalies in Iran and the topography and gravity anomalies data of epicenters have been identified. Then using advanced statistical methods and using SPSS software, the correlation between magnitude of earthquakes, topography and gravity anomalies was examined and analyzed. Among the studied parameters, topography has the highest correlation with magnitude of earthquakes in Iran and gravity and Bouguer Anomalies have low correlation with earthquakes magnitudes. The isostatic and free-air anomalies show only show significant correlation with 4.5 to 5 magnitude earthquakes.

Keywords Earthquake, Topography, Gravity anomalies, Correlation, Iran.

INTRODUCTION

Earthquake is one of the unexpected events that has always threatened humans throughout the history. Every some while a big and destructive earthquake happens on earth and causes a lot of life and economic harm. Researchers have done many studies on seismicity in order to reduce the dangers of it. Many parameters are effective on seismic of a region such as tectonics, topography and geophysical features of the region. Although foreseeing earthquakes has not been possible until now due to the numerous factors affecting it, this phenomenon is under study as an important and potential danger. The Iran plateau is

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located in the geographical limits of 25 to 40 degrees Northern latitude and 40 to 64 degrees Eastern longitude. This plateau is one of the active tectonic regions and a part of orogeny of Alp- Himalaya and is located between the Arabian stable plate and Eurasia. It is a vastly and strongly deformed regional crust that is active in terms of seismicity. This high plateau has active deformation and high seismicity under the compressive flotation powers and affected by surface driven and strike slip faults. This plateau has different tectonic units with regular structures. It has been deformed and developed since Proterozoic era until present (Berberian 2014). Continental convergence of about 35 mm per year between the plates of Asia and Saudi Arabia has caused to form a land with a vast amount of deformations with latitude of over 1,000 km. The active deformations of this plateau include intercontinental shortening, thickening in parts of the plateau, Subduction of Saudi Arabia to underneath Makran in the southeast and Strike-slip faulting in the plateau. The Iran country with area of 16,48000 sq km is located in the center of Iran plateau. It has different tectonics and topography due to orogeny belt of young collision zone, structure zone and diverse seismic activity and semi-rigid blocks (Berberian 2014). This region is limited in southeast by the main Zagros fault and in the north by Alborz fault. The dispersion of earthquakes varies in different parts of Iran. The seismic area of Alborz has rather low seismicity with high magnitude and destructive and it is usually along with superficial faulting. However, Zagros has more earthquakes with low magnitudes and big and destructive earthquakes happen rarely in there (Zamani et al. 2009). Faulting together with earthquake is rare in Zagros.

Studies show that the stress caused by big topographies and gravity anomalies can cause seismicity (Jeffreys 1976). More precise research shows that altitude difference of 1500 m in topography of the region can cause shear stress difference up to 10 mega-pascal in the Earth's crust. The increased stress in lithosphere can cause strain accumulation and earthquake. The mountains are themselves evidence of high level of stress.

The stress difference induced by topography is noticeable and can be effective in deformation of Earth's crust. These changes might help create earthquakes (Vvedenskaya 1969). Given the topography of Earth's crust, the reaction and curvature of lithosphere is affected by wavelength of the above load imposed. The curvature range of lithosphere affected by sinusoid load is calculated by equation (1) (Turcotte and Schubert 2002) :

$$W_0 = \frac{h_0}{(\rho m / \rho c) - 1 + (\mathrm{d} / \rho c g)\,(2\mu/\lambda)^4} \qquad (1)$$

Where, W_0 stands for the curvature of lithosphere, λ is topography wavelength, ρm is the density of Earth's mantle, ρc is the density of crust and h_0 is the topography altitude.

$(D/\rho c g)^1/\,4$ has length dimension and is dependent on wavelength of lithosphere. D is flexural rigidity and is calculated based on equation (2) :

$$\mathrm{D} = \left[Eh^3 \Big/ 12\,(1 - v^2) \right] \qquad (2)$$

Where, h is elastic thickness of the lithosphere, E and v are elasticity coefficient and Poisson's ratio of the crust.

The degree of compensation c is defined as the ratio of the created curvature in lithosphere under topography load to the maximum possible curvature to reach isostatic balance in equation (3) :

$$\mathrm{C} = \frac{(\rho m - \rho c)}{\rho m - \rho c + \left(D / g \left(2\mu / \lambda \right)^4 \right)} \qquad (3)$$

If we draw C based on $\frac{\lambda}{2\mu} \left[g \left(\frac{\rho m - \rho c}{D} \right) \right]^{1/4}$,

the following graph is created :

Therefore, degree of compensation of isostatic balance depends on topography wavelength (λ), elasticity coefficient E and Poisson's ratio v and lithosphere elasticity thickness (h), density differ-

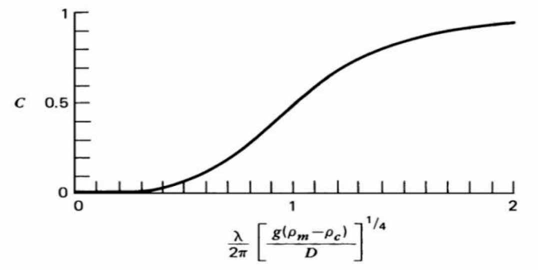

Fig. 1. Graph of degree of compensation of lithosphere curvature and $\frac{\lambda}{2\mu}\left[g\left(\frac{\rho m-\rho c}{D}\right)\right]^{1/4}$ (Turcotte and Schubert 2002).

ence of mantle and crust ($\rho_m - \rho_c$). By inserting the amounts of parameters in the quation related to C and considering compensation capability of 50% we can find the wavelength effective on isostacy by help of the graph in Figure 1. Topography with shorter wavelength is maintained enough by the rigid lithosphere and creates no curvature, but topography with long wavelength creates curvature in lithosphere and creates earthquakes and reaches balance throughout geological era.

Previous research

The relation between isostatic anomalies and earthquake focal distribution has been studied by a number of researchers. In Italy, Bouguer Anomalies were used to find the large earthquakes center (magnitude of more than 6) and it was concluded that the center of large earthquakes is located on a part of active faults. To check this issue and determine the exact center of earthquakes, a combination of Bouguer Anomalies and altitude were used. It was stated that recognition of such regions will be helpful for forecasting studies

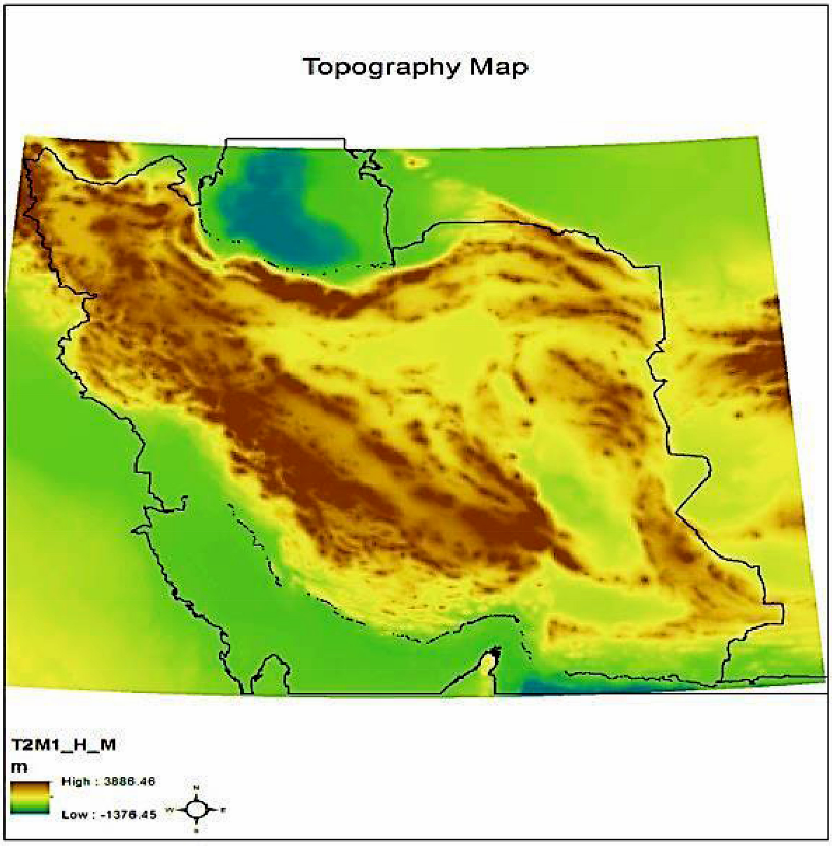

Fig. 2. Topography map of Iran based on 2 minute data.

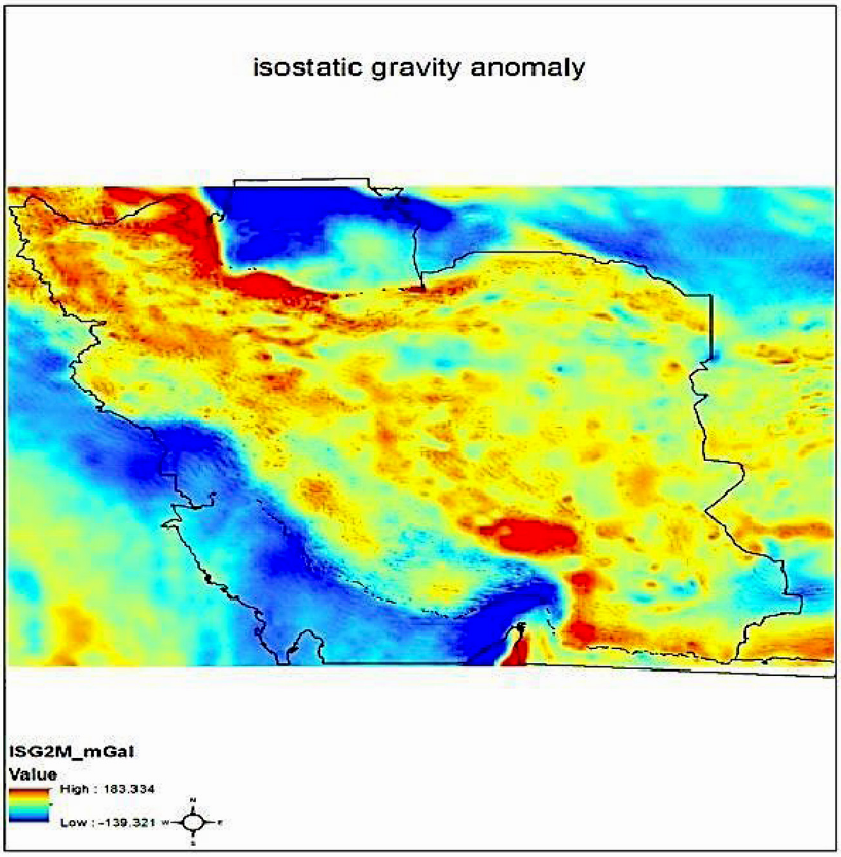

Fig. 3. Isostatic anomalies map of Iran based on 2 minute data.

and earthquake risk and active faults development mechanism simultaneous with earthquake.

Research has been done also on Iran plateau with regard to seismicity, topography and gravity anomalies. Zamani et al. (2014), Zamani and Farahi Ghasre – Aboonasr (2011) used the parameters seismicity, topography and gravity anomalies to zone Iran and concluded that seismicity and gravity anomalies, isostasy and Booger are og high importance in this zoning. Zamani et al. (2014) studied the effective elastic thickness (T*e*) in the collision zone between the Arabian plate and Eurasia in Iran using Wavelet coherence. In this method, they used topography and Bouguer Anomalies data and concluded that the average effective elastic thickness of Iran is 35.9 and ranges from 14.2 to 62.2 km. The least thickness is related to the central block and the East Belt of Iran and the most amount of it is located in the East of the Caspian Sea basin. Finally, they stated that effective elastic thickness is more than seismic thickness ($Te > Ts$).

Collection and analysis of data

The data under study in this research includes the data of earthquake, topography, isostatic and gravity anomalies, Booger and free-air. The data related to earthquakes with 4 or more magnitude ($m \geq 4$) were taken from 1909 to 2016-2017 Catalog of International Center for Seismology Site (ISC 2017). Then,

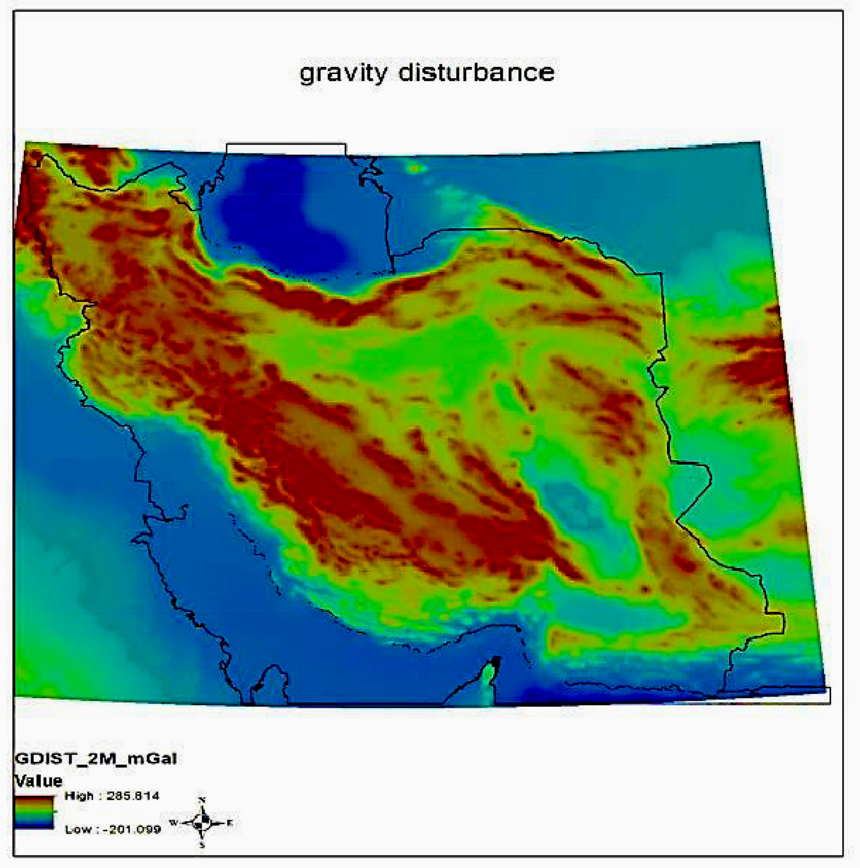

Fig. 4. Gravity anomalies map of Iran based on 2 minute data.

to ensure the accuracy of the data, given that from 1964 onwards the number and accuracy of earthquake recording devices have increased, seismic data from the beginning of 1964 to the end of 2016 were used. Topography, isostatic and gravity anomalies, Booger and free-air data were taken from International Institute of Gravity Website (BGI 2012) with a precision of 2 minutes. All the data including earthquakes, topography and gravity anomalies have been prepared in the limited area of 25 to 40 degrees in North latitude and 40 to 64 degrees in East longitude. The mentioned data were turned into raster and vector maps with the help of the ARCGIS10 software, which is very powerful software for converting numerical data to digital maps with coordinates. For each of the topographic data, gravity anomalies and earthquake data a raster map and GIS map were prepared as, the topography map (Fig. 2), isostasy map (Fig. 3), gravity anomalies map (Fig. 4), free-air anomalies map (Fig. 5) Bouguer Anomalies map (Fig. 6) and earthquake maps (Figs.7—9).

Zamani et al. (2014) have divided Iran to 13 environmental regions with regard to different geological,topographic, geophysical and other parameters in which the parameters under study in this research have played a fundamental role. Therefore, based on this, the zoned area map of these researchers has been used in this study as a fundamental map.

This map is used as a GIS layer and earthquake data is placed on this layer with the help of ARCGIS

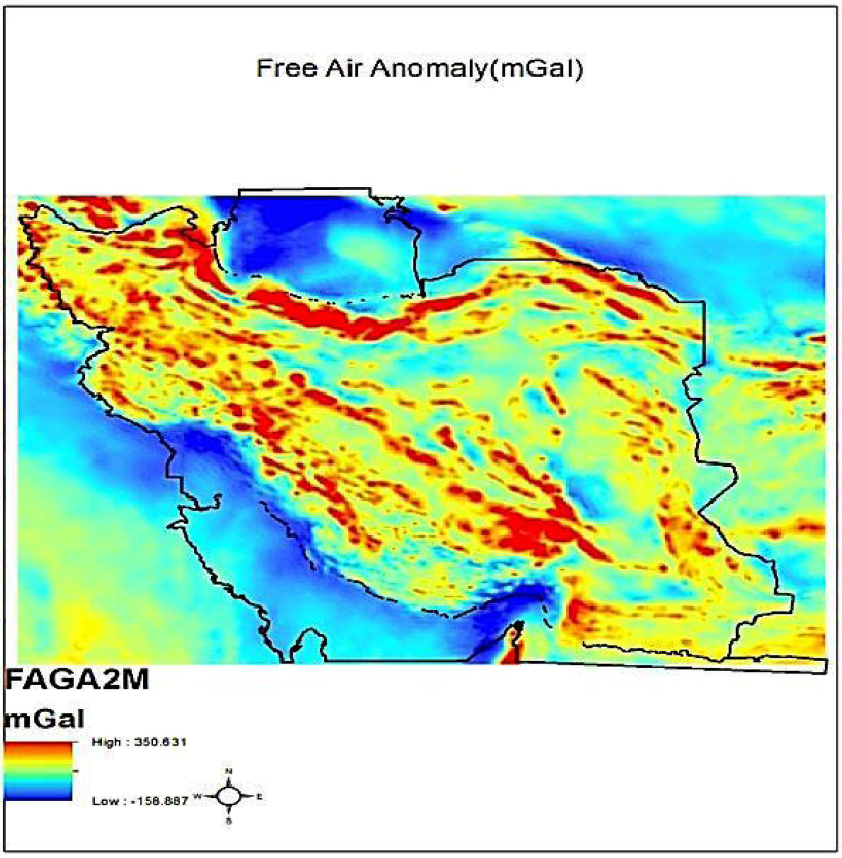

Fig. 5. Free-air anomalies map of Iran based on 2 minute data.

software. Then, this layer is placed on top of 5 layers of topography and gravity anomalies and the final and comprehensive map on which all the parameters studied are located in one place was prepared (Fig. 7). After that, features complying with each earthquake was concluded by putting these multiple layers on each other. From these data, which includes earthquake data (4 Richter and more), topographic data and gravity anomalies relevant to the load and centers of earthquakes, an Excel file has been prepared for the whole of Iran.

The data were analyzed using SPSS software. In this analysis, the correlation between the magnitude of earthquakes and other parameters such as topography (elevation to sea level), gravity imbalance, isostasy, Booger and free cluster as well as the relation between topography and gravity anomalies have been investigated.

The data were analyzed using SPSS software with bivariate correlation with 90% reliability coefficient (probability of 10% error) and their statistical correlation was determined. Pearson correlation has been shown by Pc and error probability or significance coefficient has been shown by Sig. Tables 1—6 show the results of statistical calculations. m is the magnitude of earthquake in terms of body waves, T is topography, IS id isostatic anomalies, BA is Bouguer Anomalies, GD is gravity anomalies, FA is free-air anomalies based on 2 minute BGI data, N is the number of data, Pc is Pearson’s correlation coefficient and Sig is significance index with 10% reliability.

According to Table 1, the magnitude of earth-

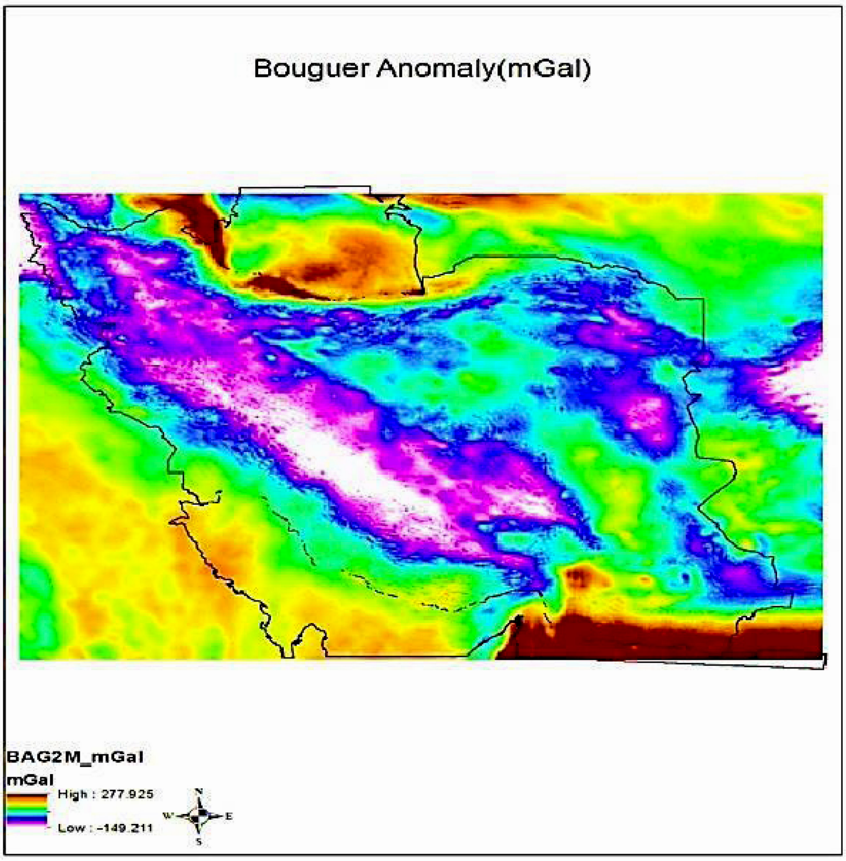

Fig. 6. Bouguer anomaly map of Iran based on 2 minute data.

quakes smaller than 4.5 Richter reverse correlation with topography and gravity anomalies and direct relation with Bouguer Anomalies. These earthquakes do not have significant relation with isostasy and free air anomalies gravity anomalies are dependent on each other.

According to Table 2, the magnitude of earthquakes with 4.5 to 5 Richter has reverse correlation with gravity anomalies (isostasy, gravity anomalies and free-air) and direct correlation with Bouguer Anomalies. It has reverse correlation with topography. Gravity anomalies are correlated.

According to Table 3, the magnitude of earthquakes with 5 to 5.5 Richter do not have any correlation with topography and gravity anomalies. Gravity anomalies have strong correlation with each other.

According to Table 4, magnitude of earthquakes with 5.5 to 6 Richter do not have significant correlation with topography and gravity anomalies. Gravity anomalies are correlated to each other, except for free- air anomalies and Booger which are not correlated.

According to Table 5, magnitude of earthquakes with 6 Richter and more have positive and direct correlation with topography and the magnitude increases with increase in altitude. These earthquakes do not have correlation with isostasy anomalies and Booger, but are correlated with free-air and gravity anomalies. According to Table 6, if we examine the correlation of all the earthquakes focal with gravity anomalies

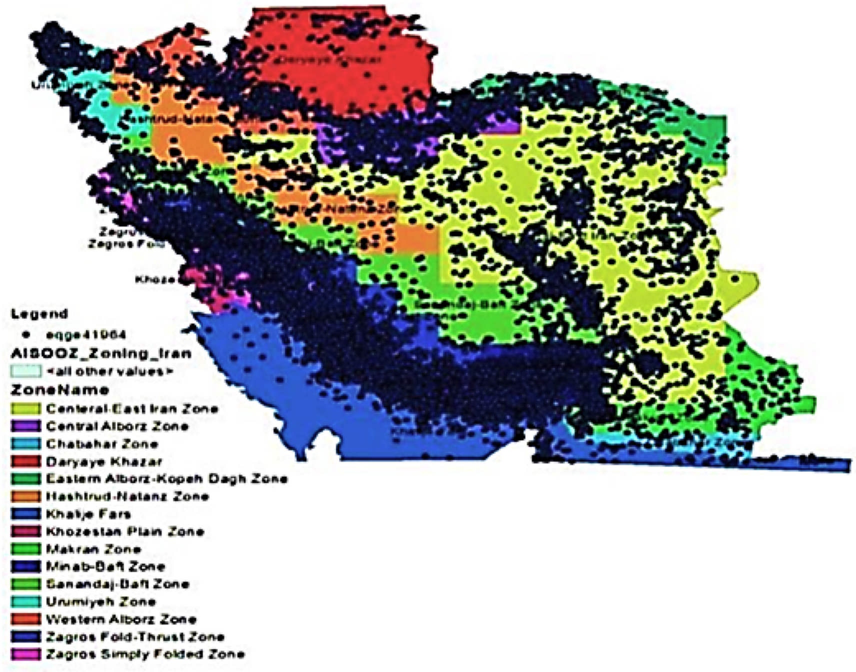

Fig. 7. Map of earthquakes in Iran with over 4 Richter from 1964 to 2016 (GIS map derived from Zamani et al. (2000).

and topography, we realize that the magnitude of earthquakes has reverse correlation with topography and gravity anomalies and direct correlation with Bouguer Anomalies.The magnitude of earthquakes

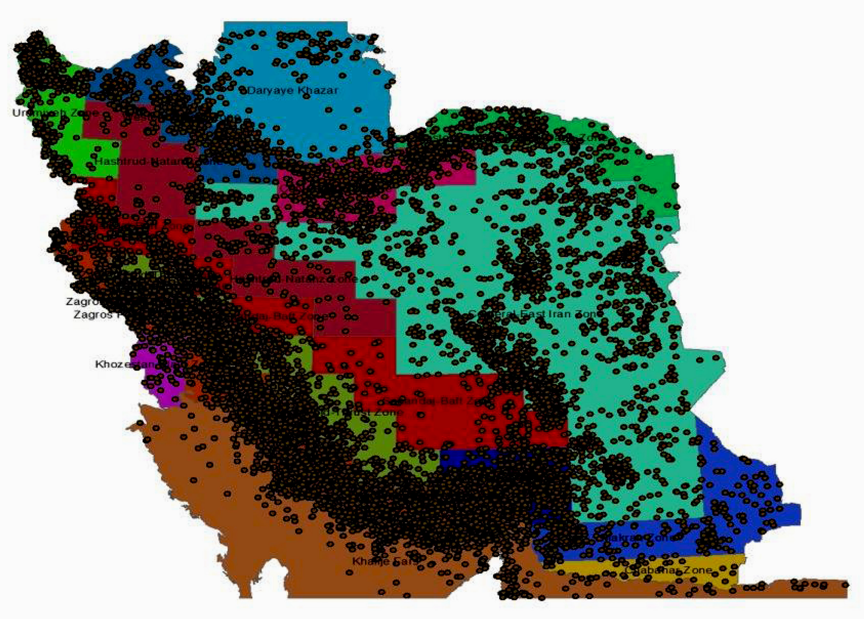

Fig. 8. Map of earthquakes in Iran with magnitude of 4 to 5 Richter from 1964 to 2016.

Fig. 9. Map of earthquakes in Iran with magnitude of 5 Richter and more from 1964 to 2016.

is not related to isostasy and free air anomalies. In all the cases, topographic bumps are strongly correlated with gravity anomalies.

About 60% of earthquakes ($m \geq 4$) are 4 to 4.5 Richter and the other 30% of earthquakes have magnitude of 4.5 to 5 Richter. Therefore, with regard to the high number of earthquakes with magnitude of 4 to 5, the correlation of these earthquakes with topography and gravity anomalies will be of more reliability and more ensuring.

CONCLUSION

Considering the results obtained from bivariate correlation tables and the significant relation between the earthquake magnitude, topography and gravity

Table 1. The correlation of earthquakes ($4 \leq m < 4.5$) with topography and gravity anomalies (N = 5426).

$4 \leq m<4.5$		m	T	IS	GD	BA	FAA
m	Pc	1	-0.027	0.015	- 0.026	0.057**	0.002
	Sig		0.052	0.280	0.057	0.000	0.863
T	Pc	-0.027	1	0.612**	0.998**	-0.675**	0.884**
	Sig	0.052		0.000	0.000	0.000	0.000
IS	Pc	0.015	0.612**	1	0.620**	0.000	0.785**
	Sig	0.280	0.000		0.000	0.980	0.000
GD	Pc	-0.026	0.998**	0.620**	1	-0.681**	0.880**
	Sig	0.057	0.000	0.000		0.000	0.000
BA	Pc	0.057**	-0.675**	0.000	-0.681**	1	-0.262**
	Sig	0.000	0.000	0.980	0.000		0.000
FAA	Pc	0.002	0.884**	0.785**	0.880**	-0.262**	1
	Sig	0.863	0.000	0.000	0.000	0.000	

Table 2. The correlation of earthquakes (4.5 ≤ m < 5) with topography and gravity anomalies (N =2385).

4.5 ≤ m<5		m	T	IS	GD	BA	FAA
m	Pc	1	-0.051*	-0.050*	-0.053**	0.040*	-0.038
	Sig		0.013	0.015	0.010	0.048	0.065
T	Pc	-0.051*	1	0.559**	0.998**	-0.613**	0.863**
	Sig	0.013		0.000	0.000	0.000	0.000
IS	Pc	-0.050*	0.559**	1	0.566**	0.141**	0.775**
	Sig	0.015	0.000		0.000	0.000	0.000
GD	Pc	-0.053**	0.998**	0.566**	1	-0.621**	0.857**
	Sig	0.010	0.000	0.000		0.000	0.000
BA	Pc	0.040*	-0.613**	0.141**	-0.621**	1	-0.138**
	Sig	0.048	0.000	0.000	0.000		0.000
FAA	Pc	-0.038	0.863	0.775**	0.857**	-0.138**	1
	Sig	0.065	0.000	0.000	0.000	0.000	

anomalies, the following results can be concluded :

The magnitude of earthquakes less than 5.5 Richter is dependent on topography and decreases with increase in altitude, while the magnitude of earthquakes with 6 Richter and more has increased with altitude.

Isostatic anomalies are only correlated with earthquakes with 4.5 to 5 Richter.

The magnitude of earthquakes with less than 5 Richter decreases with the increase of gravity anomalies, but the magnitude of earthquakes with 6 Richter and more increases with the in crease ingravity anomalies. Thus, the correlation between the magnitude of earthquakes and topography and gravity anomalies have a similar process.

Increased Bouguer Anomalies is accompanied by the increase in magnitude of earthquakes smaller than 5 Richter. Free-air anomaly has reverse correlation with the magnitude of earthquakes with 4.5 to 5 Richter and direct correlation with the magnitude of earthquakes with 6 Richter and more.

Gravity anomalies have correlation with topography. By increasing altitude, gravity anomalies except for Bouguer Anomalies increase.

Isostatic anomaly and Booger Abnormality have direct correlation with other gravity anomalies.

Gravity anomalies have reverse correlation with Bouguer Anomalies and direct correlation with free-air anomalies.

Therefore, with regard to the frequency of

Table 3. The correlation of earthquakes (5 ≤ m < 5.5) with topography and gravity anomalies (N = 465).

5 ≤m <5.5		m	T	IS	GD	BA	FAA
m	Pc	1	0.007	-0.051	0.006	0.015	0.020
	Sig		0.876	0.272	0.901	0.741	0.661
T	Pc	0.007	1	0.513**	0.998**	-0.637**	0.835**
	Sig	0.876		0.000	0.000	0.000	0.000
IS	Pc	-0.051	0.513**	1	0.522**	0.179**	0.771**
	Sig	0.272	0.000		0.000	0.000	0.000
GD	Pc	0.006	0.998**	0.522**	1	-0.641**	0.833**
	Sig	0.901	0.000	0.000		0.000	0.000
BA	Pc	0.015	-0.637**	0.179**	-0.641**	1	-0.118*
	Sig	0.741	0.000	0.000	0.000		0.011
FAA	Pc	0.020	0.835**	0.771**	0.833**	-0.118*	1
	Sig	0.661	0.000	0.000	0.000	0.011	

Table 4. The correlation of earthquakes ($5.5 \le m < 6$) with topography and gravity anomalies (N = 91)..

$5.5 \le m < 6$		m	T	IS	GD	BA	FAA
m	Pc	1	0.132	0.009	0.129	-0.160	0.060
	Sig		0.213	0.934	0.221	0.129	0.574
T	Pc	0.132	1	0.456**	0.998**	-0.624**	0.833**
	Sig	0.213		0.000	0.000	0.000	0.000
IS	Pc	0.009	0.456**	1	0.481**	0.278**	0.781**
	Sig	0.934	0.000		0.000	0.008	0.000
GD	Pc	0.129	0.998**	0.481**	1	-0.623**	0.835**
	Sig	0.221	0.000	0.000		0.000	0.000
BA	Pc	-0.160	-0.624**	0.278**	-0.623**	1	-0.097
	Sig	0.129	0.000	0.008	0.000		0.360
FAA	Pc	0.060	0.833	0.781**	0.835**	-0.097	1
	Sig	0.574	0.000	0.000	0.000	0.360	

Table 5. The correlation of earthquakes ($6 \le m$) with topography and gravity anomalies (N=23).

$6 \le m$		m	T	IS	GD	BA	FAA
m	Pc	1	0.437*	0.144	0.452*	-0.270	0.357
	Sig		0.037	0.513	0.030	0.213	0.095
T	Pc	0.437*	1	0.337	0.997**	- 0.517*	0.842**
	Sig	0.037		0.115	0.000	0.012	0.000
IS	Pc	0.144	0.337	1	0.371	0.556**	0.750**
	Sig	0.513	0.115		0.081	0.006	0.000
GD	Pc	0.452*	0.997**	0.371	1	-0.498*	0.854**
	Sig	0.030	0.000	0.081		0.016	0.000
BA	Pc	-0.270	-0.517*	0.556**	-0.498*	1	0.021
	Sig	0.213	0.012	0.006	0.016		0.924
FAA	Pc	0.357	0.842**	0.750**	0.854**	0.021	1
	Sig	0.095	0.000	0.000	0.000	0.924	

earthquakes that indicates the high probability of earthquakes with less than 5 Richter and the results obtained from the correlation tables, it can be concluded that the most influence on Iran's earthquakes is related to topography, gravity anomalies and Bouguer Anomalies. Isostatic and free-air anomalies have less correlation with seismicity. Given that topography with high wavelength can influence isostatic anomalies, it is necessary to include vaster areas in studies on isostasy. According to Zamani et al. (2014) who

Table 6. The correlation of all the earthquakes with topography and gravity anomalies (N =8209)..* Correlation is significant at the 0.05 level (2- tailed).

Total		m	T	IS	GD	BA	FAA
m	Pc	1	-0.031**	-0.004	-0.033**	0.056**	-0.006
	Sig		0.005	0.729	0.003	0.000	0.568
T	Pc	-0.031**	1	0.589**	0.998**	-0.654**	0.875**
	Sig	0.005		0.000	0.000	0.000	0.000
IS	Pc	-0.004	0.589**	1	0.597**	0.056**	0.781**
	Sig	0.729	0.000		0.000	0.000	0.000
GD	Pc	-0.033**	0.998**	0.597**	1	-0.661**	0.871**
	Sig	0.003	0.000	0.000		0.000	0.000
BA	Pc	0.056**	-0.654**	0.056**	-0.661**	1	-0.217**
	Sig	0.000	0.000	0.000	0.000		0.000
FAA	Pc	-0.006	0.875**	0.781**	0.871**	-0.217**	1
	Sig	0.568	0.000	0.000	0.000	0.000	

reported the elastic thickness of lithosphere in Iran to be 35.2 km and by the help of the graph in Figure 1, we can consider the average topography wavelength effective on isostasy in Iran as 540 km.

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