ISOSTATIC CONDITIONS IN SOUTHERN AND EASTERN YEMEN AND THEIR IMPORTANT GEOLOGIC IMPLICATIONS

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Abstract

Fifty-nine gravity basic stations distributed in southern and eastern Yemen are considered to obtain the regional Bouguer anomaly and isostatic maps of the covered region. The obtained maps show many high amplitude negative anomalies which are related to high elevation area and mass deficiency beneath the continental crust.

Isostatically the study region seems to be overcompensated in high land, while it is nearly complete compensation in low land area. The region requires an upwelling of the mantle material to compensate the mass deficiency in the region. Such process also requires uplift in the earth's surface, which should have a relation with the tectonic and geomorphologic processes acting in the region such erosion. A complete gravity measurement stations to cover the whole territory of Yemen will provide insight picture about the regional geology of Yemen.

حالات توازن القشرة الارضية في جنوب وشرق اليمن وأبعادها الجيولوجية

الخلاصة

تسعة وخمسون محطة اساس جذبية موزعة في جنوب وشرق اليمن قد اخذت بنظر الاعتبار للحصول على خرائط اقليمية لبوجير والتوازن للقشرة الارضية للمنطقة المغطاة بها . ان الخرائط التي حصل عليها تبين العديد من الشواذ الجذبية السالبة عالية السعة التي ترتبط مع المناطق ذات الارتفاع العالي والى النقصان في الكتلة تحت القشرة الارضية.

ومن ناحية توازن القشرة الارضية فالمنطقة تظهر وكأنها في حالة فوق متوازن بينما تكون تقريبا في حالة توازن في الاراضي الواطئة . إن المنطقة تحتاج الى صعود مواد الجبة لتوازن نقصان الكتلة في المنطقة ومثل هذه العملية تحتاج أيضا الى رفع في سطح الارض التي لها علاقة مع العمليات التكتونية والجيومورفولوجية التي تنشط في المنطقة مثل التعرية. ولعل إجراء قياسات جذبية تغطي جميع اراضي اليمن سوف توفر صورة أفضل لجيولوجية اليمن.

Introduction

The isostatic anomaly maps are useful for geophysical and tectonic evaluation of different parts of the earth.

Calculations based on gravity measurements show that isostatic balance is approximately maintained over extensive areas of the earth's crust. The distribution of Bouguer anomalies over the world correlates with topography; free air anomalies are in general near zero. In certain regions, free air and Bouguer anomalies are sufficient to give evidence of sharp changes in mass distribution in the crust and upper mantle as well as distribution of isostatic balance [1]

Empirical formulae have been derived between Bouguer anomalies and the crustal thickness and between Bouguer anomalies and elevation [2, 3, and 4]. The results obtained from these formula and studies indicate that gravity field and

surface relief are closely connected with crustal thickness.
The only clue that can be used for recognizing the actual condition of isostasy, if there is no seismic data, are the sign of the free air and isostatic anomalies and geologic evidence for uplift or subsidence [5]. If the regional free air and isostatic gravity anomaly values are negative and there is evidence of uplift, the crust probably has a subnormal density and thickness for surface elevation; if the regional anomalies are positive and there is evidence of subsidence, it is probable that the crust has an abnormal density and thickness. Isostatic anomalies are usually used for defining areas of abnormal gravity relations.
Normally, the isostatic correction has been made on the basis of surface elevation data and the isostatic model. The residual values between the corrected observed gravity value (for free air, Bouguer and isostasy) and the theoretical gravity value at the latitude of the station is referred as the isostatic anomaly. When the isostatic anomaly is equal to zero, perfect isostatic compensation exists in the region. In case of positive isostatic values (i.e. overload) the area is considered as an under compensation area (deficiency of mass). The isostatic overcompensation area is this one showing negative isostatic anomaly [6].

The Gravity Data

The constructed gravity maps of People Democratic Republic of Yemen (PDRY) (previously) territory with a scale of 1:500,000 and 1:1000000 were based on gravity surveys carried out by the Soviet Petroleum Prospecting Expedition in 1976-1979 in Hadramawt area, in 1980-1981 in Qamar-Jeza depression, in 1982-1984 in the Shabwah area, in 1986-1987 in SW, SE and central parts of the PDRY, and by Iraq Petroleum Company (IPC) survey data in 1976-1978[7]. These surveys have been aimed primarily to study the structures and lithology of the sedimentary and basement rocks for petroleum exploration purposes.
The gravity surveys have used a network of basic stations. Pendulum stations situated in Aden, Er-Rayan and Al-Geida were the initial stations for constructing a basic grid which were later on used as the central system to develop the framing and filling grids of observation points. By 1988 a basic grid for the whole territory of PDRY has been accomplished. It consists of 3 pendulum stations, 17 astronomical and 40 base stations. The location of these stations is shown in Figure (1), and a description of each base station is given in an appendix in their report. [7].
The available information presented in the appendix is used in the present calculation. They are providing the coordinates X-Y and latitude value, elevation and gravity value for each station. The aim of the present paper is to construct an isostatic map for the covered area from these gravity basic stations since there is no previous study concerning this subject in the region. However, Zarubezhgeologia had mentioned that the gravity map of the PDRY for the continental part displayed vast gravity anomalies with amplitude of 50-100 mgal in the east and 150-160 mgal in the west. Along the coast the minimum passes into a zone of strong gravity gradient. They explained the regional anomalies as may be due to heterogeneously dense earth's crust and upper mantle in the young passive margin of the Arabian Peninsula south, i.e. the ascending asthenosphere of the upper mantle in the land part of the country was responsible for isostatic rise of the surface and eventually for a vast zone of gravity minimum and the two types of the crust, continental (less dense) and oceanic (dense) joining in the transitional zone of the Gulf of Aden producing a strong gradient.

Geologic Setting of Yemen

Yemen territory is divided into four principle physiographic provinces with subdivisions. The first province is a low lying coastal plain, extended mainly along the Red Sea and more restricted along the Gulf of Aden (Figure 2). The second province constitutes the mountainous areas in the Yemen High Plateau [8].
The Hadramawt – Mahra uplands form the third province, which is characterized by high level plateau, which are relatively well dissected. It covers a very large area with central flat lying mesas, which are separated by a gentle E-W down warp along the west Hadramawt and west Jezza. To the north, the province shelves gently down to the Rub Al-Khali desert. In the south it is broken up along the Gulf of Aden coast by numerous rift faults.
The fourth province is composed of comparatively flat lying sand seas and desert terrain. The main part of the province, the Rub Al-Khali, forms most of the northern boundary. A southerly extension of this province forms the central desert area of Ramlat Sabatayn.

On the basis of available detailed data, V/O Zaurbezhgeologiya had distinguished the main structural features. These either represented by exposed basement (Mahfid, Rayan, Mukalla areas) or it's up thrown blocks overlain by thin sedimentary sequences (Hoowarin). Based on these and other studies, the tectonic architecture of the Republic of Yemen in general is characterized by large Archean- Proterozoic basement blocks transected by the NW-SE trending Jurassic-Cretaceous intracratonic rift system of Ramlat Sabatayn Graben bordered to the south and west by Tertiary to present day Gulf of Aden and Red Sea rift systems.

Evidences for uplift or change in relief on the Red Sea margin during Pre-Jurassic to early Tertiary times are limited. The presence of paleosoils at the top of Tawilah Group, prior to eruption of volcanic rocks, and the absence of erosional periods within the sequence suggest that uplift is rather unlikely because of the lack of widespread extensional structures in the Phanerozoic sedimentary units of Yemen and Saudia Arabia. [9,10].

In southern and eastern Yemen, differential surface uplift may have elevated crust to a position such that certain sedimentary units are absent or lack of lateral continuity [11,12]. These authors have suggested that these areas were uplifted and that Pre-Cretaceous sediments were removed by erosion or that they were uplifted in Pre-Jurassic times and remained elevated for sometime. A period of late Eocene uplift and erosion can also be identified in southern and eastern Yemen [13,14], prior to development of the proto Gulf of Aden rift.

Concept of Isostasy Determination

Many systems have been used to determine the compensation effect of the earth; these are Airy, Pratt and Hayford systems. Depending on the elevation from sea level and Bouguer anomaly values, supported by seismic results., [1,15] obtained a proportional factor (-0.109) mgal/m between the elevation and Bouguer anomaly values.[16] found that the proportional factor equal to 0.11mgal/m for the case of complete compensation of a plate layer. The proportionality factor can be considered constant for zones of limited extent.

The normal correction for gravity data is achieved for the absolute values of the 59 gravity base stations, which is considered in present study, in order to obtain the Bouguer anomaly map (Figure3).

Elevations of 59 gravity base stations distributed over the studied area in the present paper are multiplied by the proportional factor – 0.11mgal/m in order to obtain the Bouguer gravity values in case of complete compensation (Figure3). These values equal to isostatic isocorrection values but they are differing only in their sign (Figure 4). The isostatic anomaly map is obtained by adding the isostatic isocorrection values to the Bouguer anomaly values. The mentioned construction procedure of isostatic anomaly map was applied for central and southern Iraq by [17] and [18].

The Isostatic Anomaly Map of the Studied Area

The constructed isostatic anomaly map obtained from the above procedure of calculation (Figure 5)) shows a very low gravity values. Although the number of gravity stations is limited and distributed over a vast area, it provides an indication of the behavior of gravity condition at this part of the Arabian Peninsula. The isostatic anomalies appear in a shape of clusters of negative anomalies around certain parts of the south and southeast Yemen Territory. The negative gravity values reflect the mass deficiency situation in the covered region beneath the continental crust.

However, in order the region to achieve isostatic compensation an upwelling material of the mantle is required to make the balance of the mass deficiency. Such upwelling process should be preceded by crustal uplift, i.e. an elevation of the surface of the ground surface. Tectonic activity and erosion processes should also accompany this process of uplifting. The geomorphologic features that are existed in the region such as deep valley cuts may indicate such activity. The isostatic anomaly map may give an answer that help to understand these features.

Bouguer Anomaly Values and Elevations Correlation of the Study Area

Bouguer anomalies for each individual station are plotted as a function of the elevation (Figure 6). This figure shows negative relation between Bouguer anomaly and elevation. The slope of the straight line of correlation is equal to 0.44 mgal/m. From the plot, it seems that the low elevation area represents a nearly complete compensated area (stable), while the high land is an overcompensation area.

It seems that the high elevation area in the past is in a position higher than its present elevation. The very high altitude caused a deep root in the mantle. The erosion factor may play a great role and affect the high terrain areas and at the same time the elasticity of the mantle did not response to the variation in elevation by the same velocity. This will cause the presence of large negative isostatic anomaly that related to root larger than expected from the elevation.

Conclusions and Discussion

The east and south of Yemen territory (PDRY) exhibited an overcompensated region from isostatic point of view. This means that the studied area is affected by a vertical pressure which is working continuously to upwelling mantle materials to compensate for the mass deficiency of the continental crust. Such process requires uplift in the earth's surface. The outcome from the isostatic anomaly calculations based on gravity data support the pervious studies concerning the various evidences of earth's surface uplift in Yemen territory mentioned in the geology part above.

The isostatic anomaly map for the present area gives an insight picture of the regional geology of Yemen and the processes of uplift and mantle upwelling that may have a relation to regional tectonic of the region. The great negative gravity values making closed anomalies may highlight the possibility of areas of mass deficiency which may be correlated with possible positions of hot spots beneath Yemen territory.

The number of gravity stations used in the calculation is limited but they are distributed over most of the considered area. So to complete the above picture and to get solid results we recommend covering the whole territory of Yemen by gravity measurements. These measurements should be made at larger distance to be used for isostatic calculation. Then a comprehensive study can be carried out with the relation of tectonic activity and possible hot spots to answer the question why there are great gravity lows exceeding hundreds of milligals over many areas of Yemen territory.

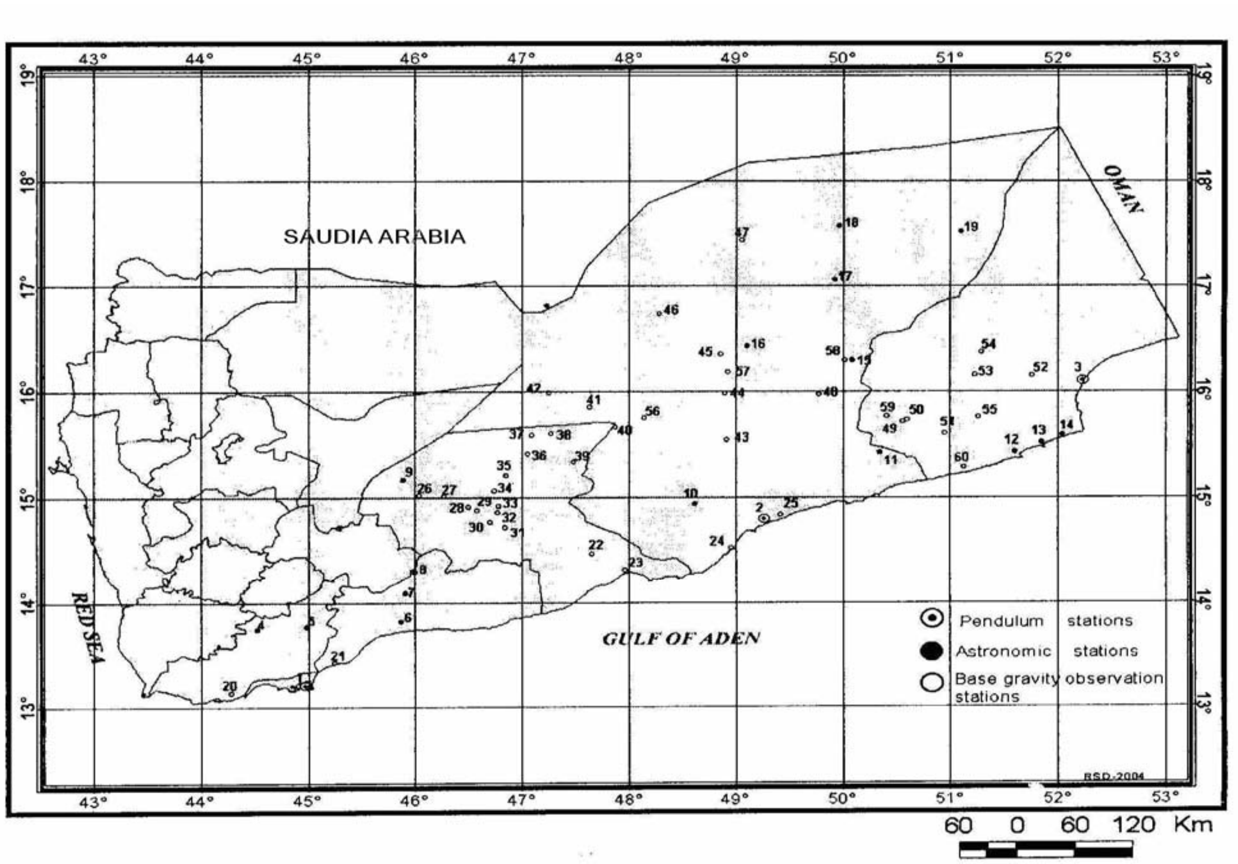

Figure (1): The grid base gravimetric stations that have been used in the present calculations (after V/O Zarubezhgeologiya – 1988)

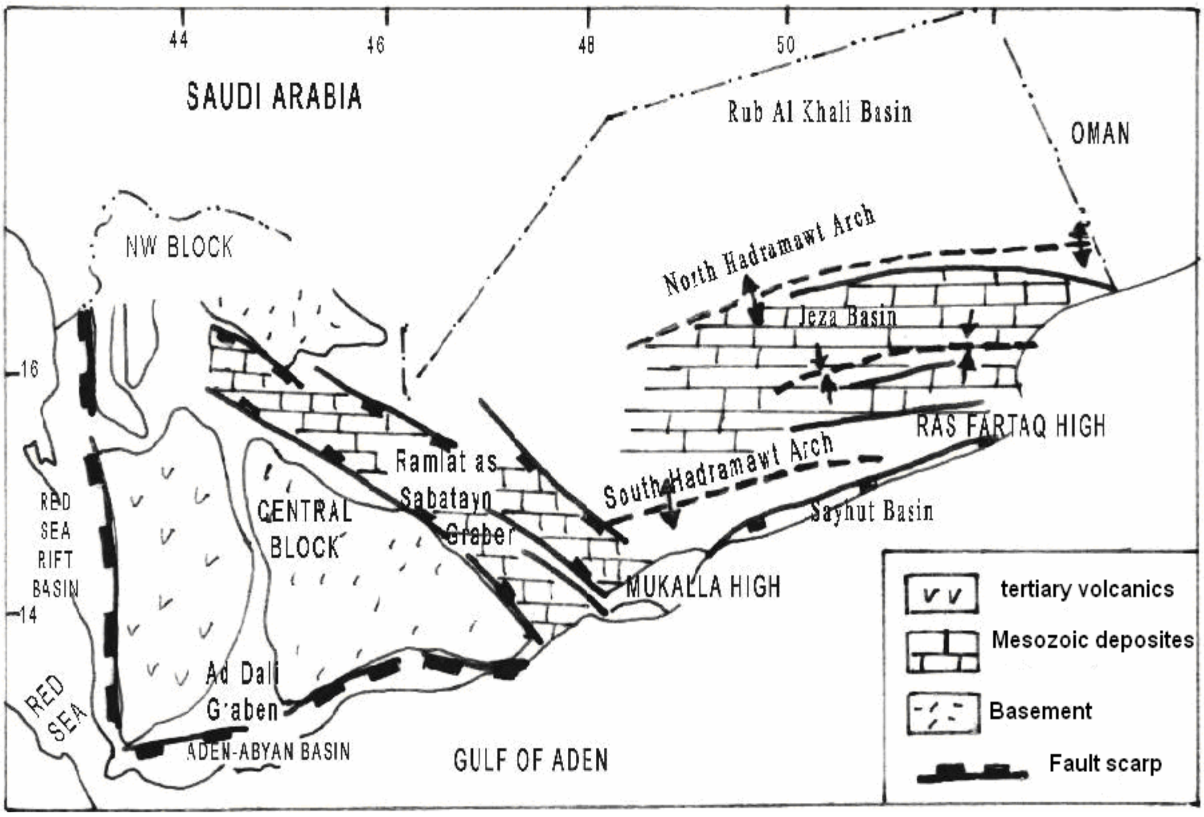

Figure (2): Tectonic features of Yemen

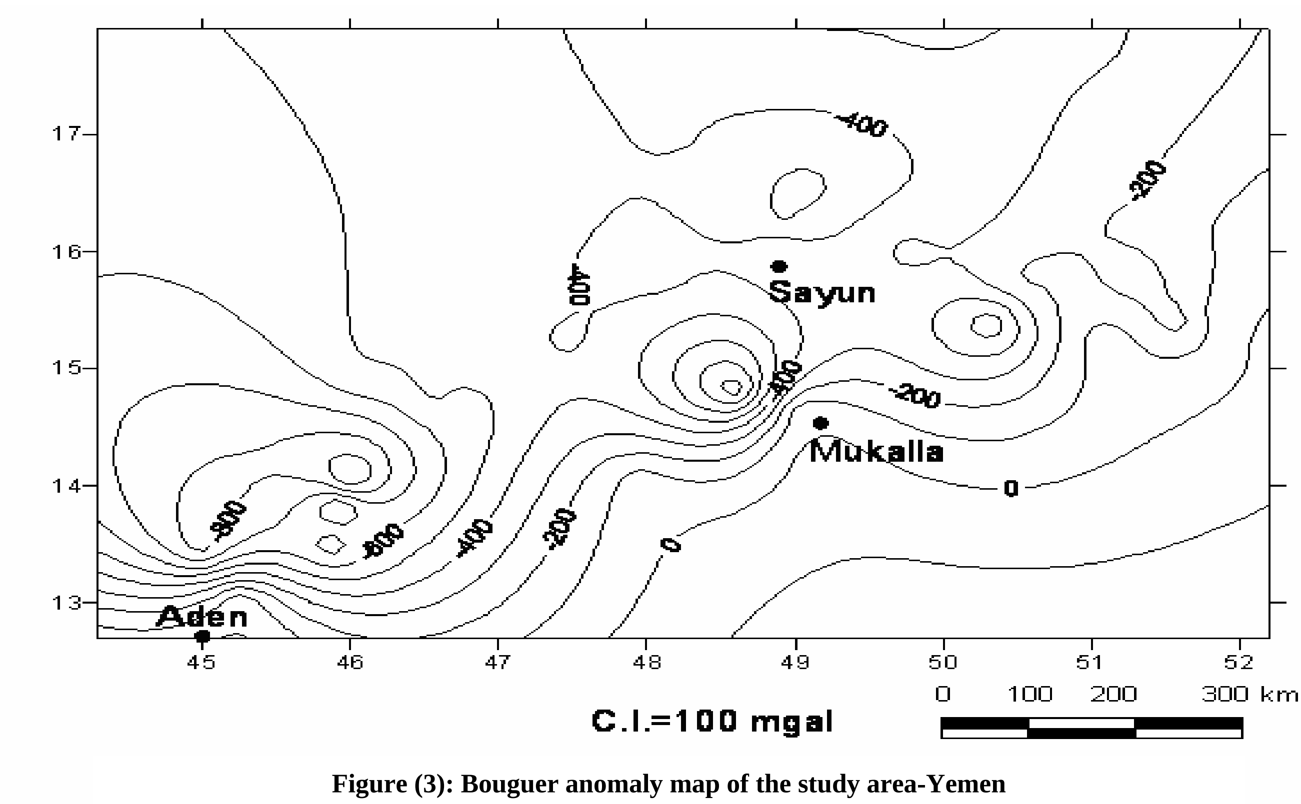

Figure (3): Bouguer anomaly map of the study area-Yemen

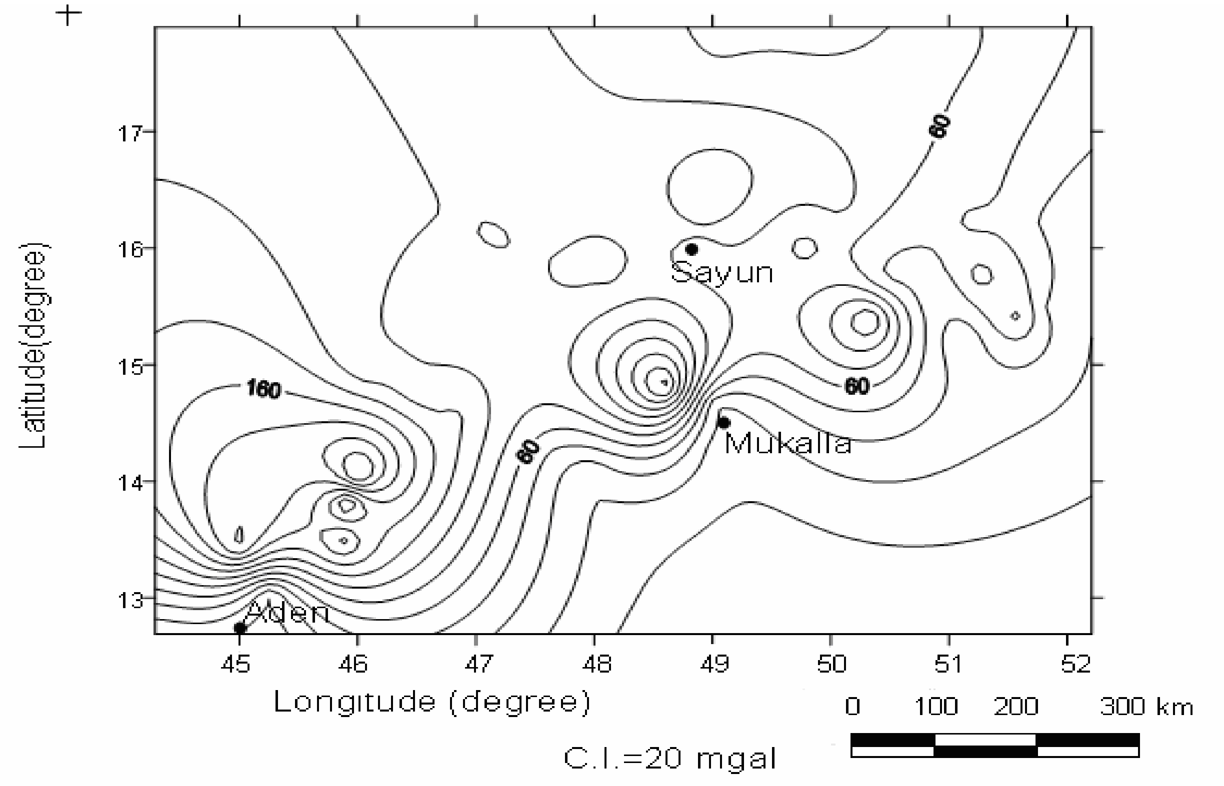

Figure (4): Isostatic isocorrection map of the studied area-Yemen

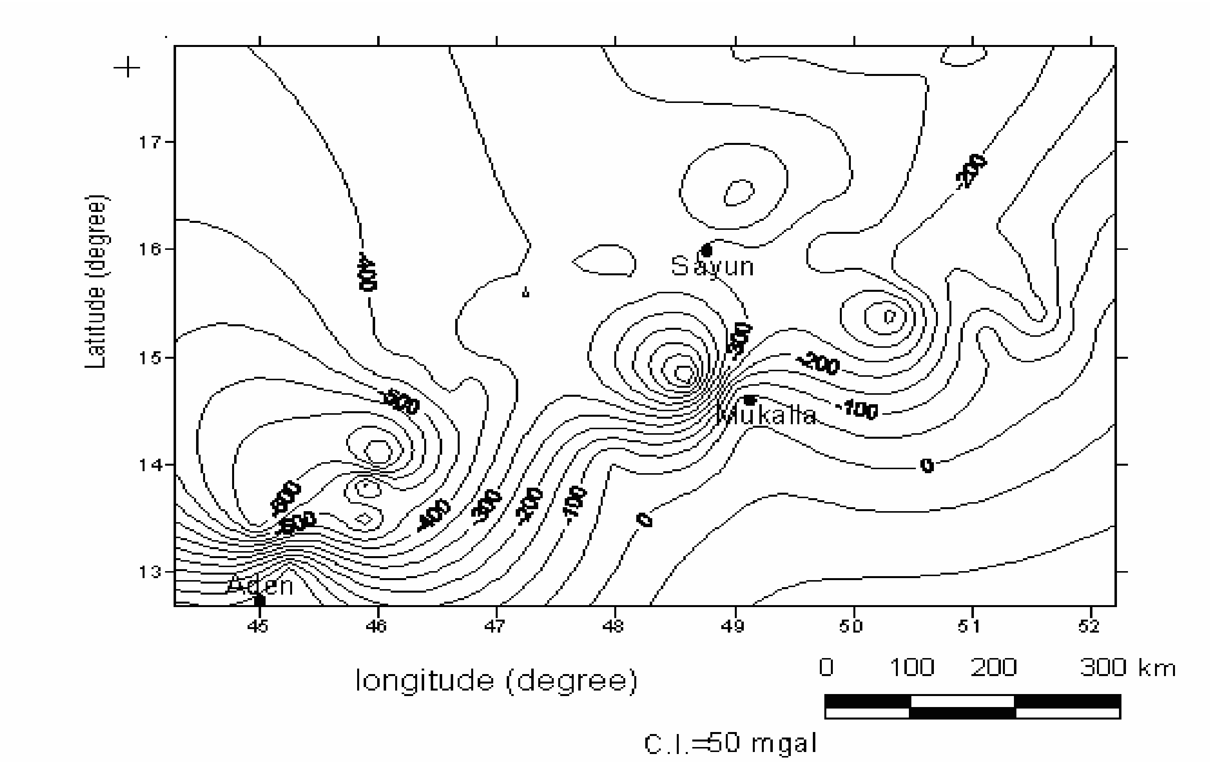

Figure (5): isostatic anomaly map of the studied area- Yemen

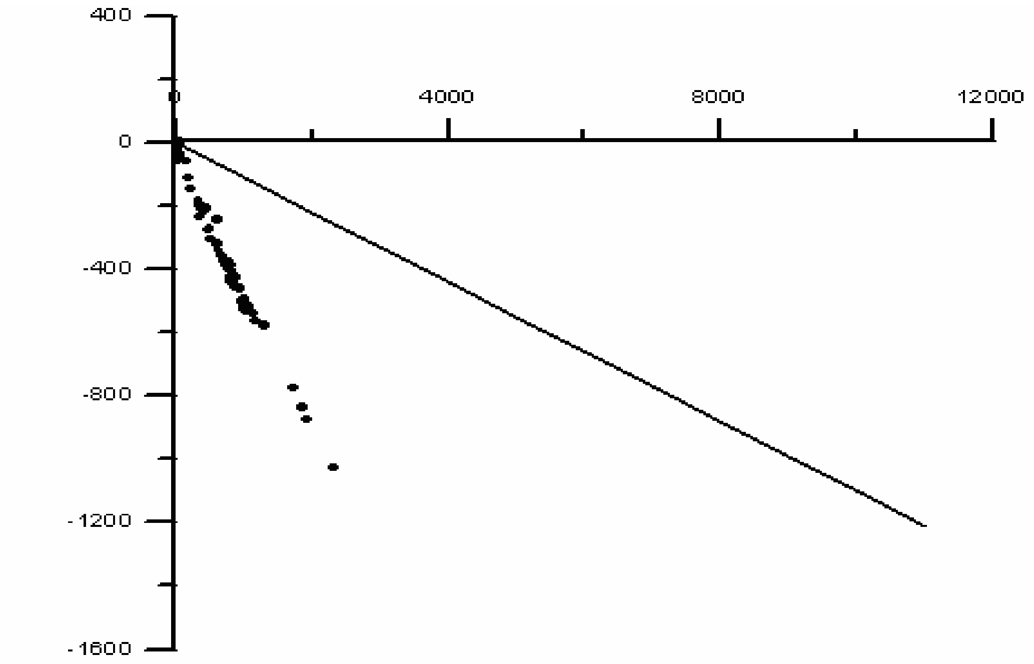

Figure (6): Bouguer gravity anomaly versus elevation for the studied area and the ideal relation for complete compensation

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