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Identification of Gravity Lineaments for Water Resources in the Crystalline Massif of Hoggar (South of Algeria)

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Abstract

The Hoggar is a rock mountain located in the South of Algeria. It is a crystalline massif characterized by granitic substratum with a weak sedimentary cover. The pluviometry is low in this region and is characterized by possibilities of floods of big capacities of water. The infiltration of these important quantities of water remains low because of the insufficiency of systems of retains. The problem in this case is locating the water in weathered zones, beyond 50 m, above granites. The weathered areas could be sometimes aquifer at their base. So, this can be interesting if they rise above intensely fractured rocks and/or suitable geometry of the substratum. The fractured rocks and the suitable geometry of the substratum could be linked to natural reservoirs. The perfect case is that this structure is covered by a rather important thickness of silts to let the infiltration of the water. So, to identify the various juxtaposed structures with different densities and delineate gravity lineaments, faults, and cavities, the gravimetric method was preferred. The aim of this work is integrating all geometric and gravimetric observations, models, and approaches so as to provide consistent and reliable information for making decision regarding the location of drilling.

Keywords: gravity, anomalies, structures, faults, granitic substratum, silts, filtering, modeling, continuous wavelet transform, drilling, water

1. Introduction

The aim of the gravimetric prospecting is to measure the gravity field variations and to interpret the anomalies caused by lateral homogeneities of densities and crust thickness.

The interpretation target is to identify the anomalies' causative structures. It means shaping the structures by their geometrical form, depth, dimension, and so on and their physical properties such as density contrast, which could be answers to the posed problem.

The gravimetric anomalies shape reveals geological bodies' geometry. The structures may be represented by simple geometrical forms such as spheres for saliferous dome, heap mineralized, underground cavities, or as cylinders for folds, dykes, ore bodies, or half-plans for substratum fracturing, faults, flexures, thrusting, subduction zones, and so on.

The relative measures of gravity aim at determining the variations of the gravity g from a station or measure point to the other one. The variation of g for each station is measured in relation to the value in the base station. These measures are achieved with gravimeters. The basic gravimeter is a pendulum in which a mass m is suspended from a spring. The variation of g between two sites causes an extension of the spring. As the extension of the spring is proportional to the gravity, the variations of g between the base station and the successive stations can be measured by determining the value of g at each station.

The gravity upon the earth surface varies according to five factors: the latitude, the altitude, the surrounding relief, the astronomical effects, terrestrial tide, and the density of rocks in the crust and upper mantle.

The variations of g related to the first four factors are attributable to external causes. Only the variations of g reflecting density variations of the crust structures are considered, such as those due to the internal causes and represent an interest for gravimetric prospecting. Hence, the measured values of g in the field must be corrected from the external effects so that the gravity anomalies would be highlighted.

The Bouguer anomaly map is the basic document for interpreting gravimetric data. It is the difference between the measured and corrected gravity for each measured point (Faye, Bouguer, and terrain corrections) and the theoretical value computed for the same point on the ellipsoid. The Bouguer anomaly map enhances the deep and extended structures. The short wavelength anomalies on the Bouguer anomaly map correspond to density variations caused by structures in the crust such as substratum fracturing, saliferous dome, underground cavities, ore zone, and so on.

The Bouguer anomaly is the sum of contributions of each formation in the basement. As we are interested to individual contribution, filtering is then necessary to detect the bodies of geological interest. The advantage in water prospecting is that the interesting structures display very clear gravimetric characteristics that enable the choice of the anomalies to keep. After filtering the anomalies (gradient, continuation...), the localization of the causative structures of the anomalies is determined by the continuous wavelet transform method.

The gravity prospection concerns five terrains in the Tamanrasset region, positioned at coordinates: 05°31'–05°38' of longitude and 22°47'–22°52' of latitude. The studied area is located in the Hoggar (**Figure 1**) which is a crystalline massif. The prospected zone is characterized by a domain of metamorphic Precambrian rocks, intruded in Pharusion by granites and covered in some sites by volcanic sewage (**Figure 2**). The different tectonic phases inferred a complex structure characterized by many tectonic accidents which affect the substratum in most of the cases. The climate of this region is classified as arid with low rainfalls and high evaporation. Many oueds cross the area coming from the Mount of Atakor. The area has: a granitic substratum which is impermeable, an altered or weathered substratum in favor of an accumulation of water; silts acting as main reservoir and finally fractured zones and contacts allowing water flow. This work leads to investigate and to identify buried structures such as contacts and faults which could be traps, where water can circulate, determining the thickness of alluvial curvature, so that these information could help for making decision regarding the location of drilling. To achieve that, the gravity data are processed with different methods such as gradients, upward continuation, and continuous wavelet transform; this can lead to an updated structural map for the studied area based on Bouguer gravity anomaly data. The most important information, in terms of contrast density structures at nearsurface or depth, will be very useful for making decision regarding the location of drilling.

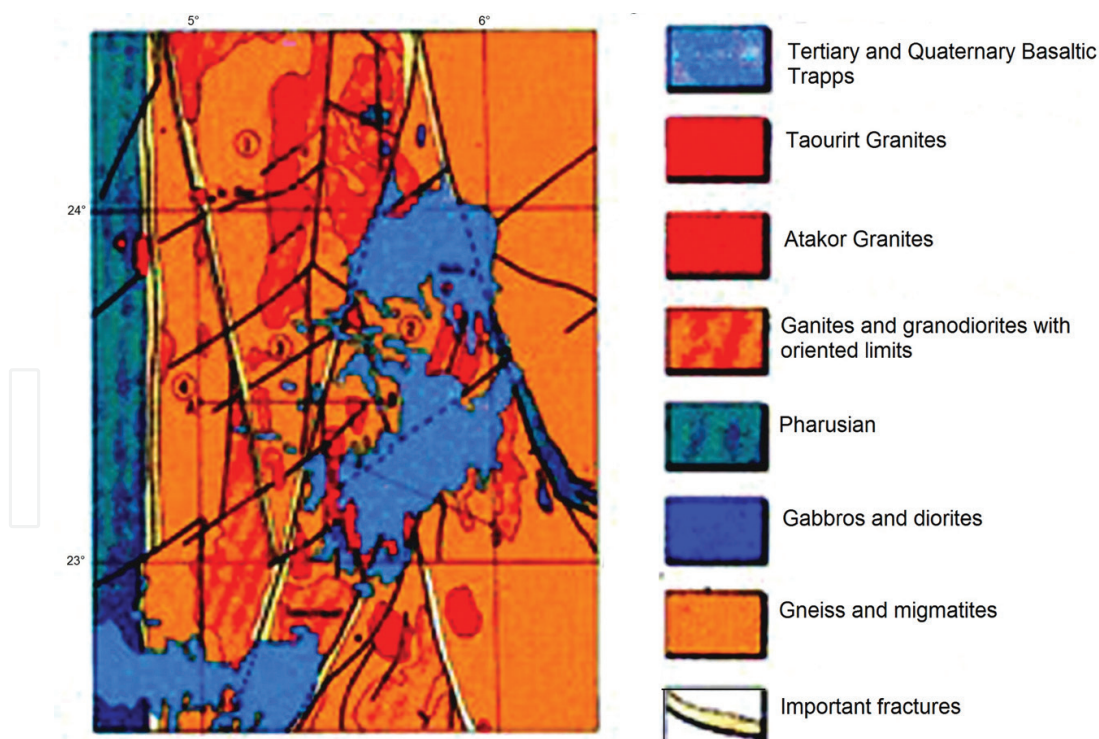


Figure 1. Geological map of the Hoggar.

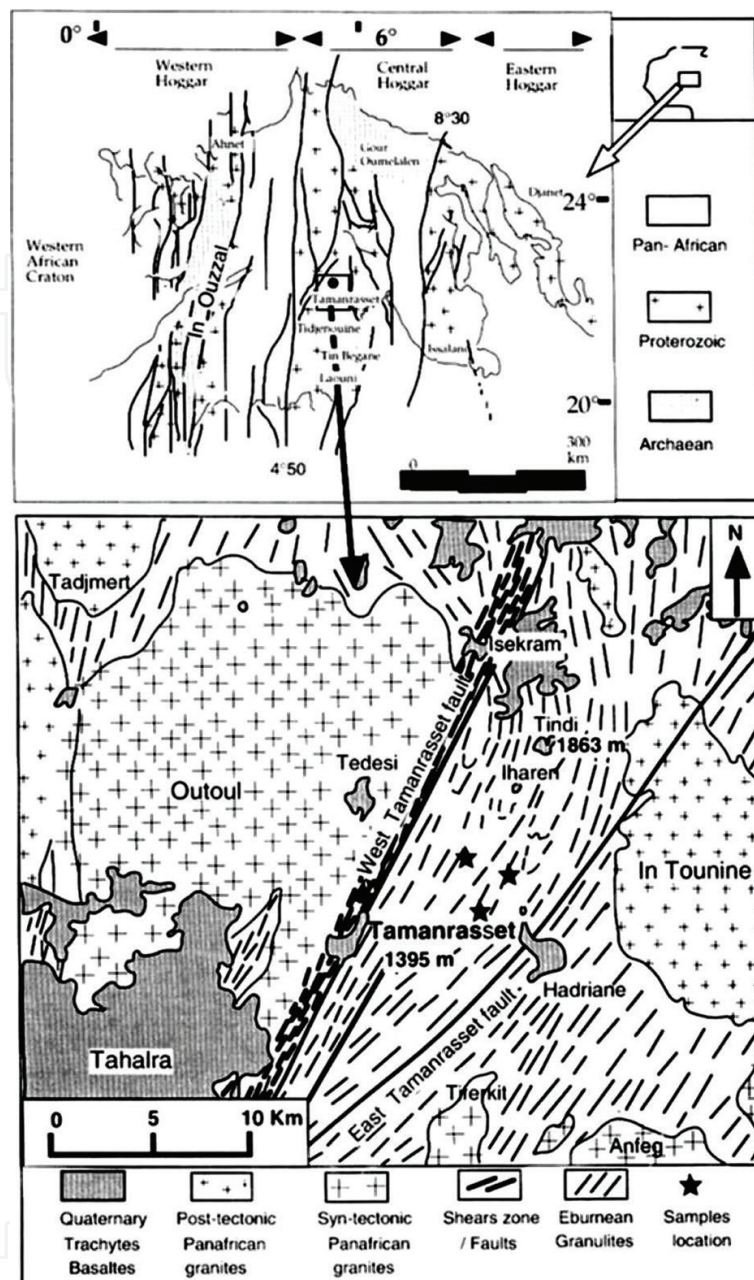


Figure 2. Geological map of the surveyed area.

2. Gravity prospecting

The gravity survey is achieved by the use of two different micro gravimeters “Lacoste Romberg” and “Scintrex CG3” (Figure 3). These kinds of gravimeters are suitable for such local studies because of their good instrumental precision of 1 μgal and meet the most stringent accuracy requirements. The devices are endowed with an electronic system of reset, with an automatic controller of bubbles level and, a system of storage and data pre-processing. All this confers them a precision of effective measure lower than 5 μgal . To tie the gravimetric network, the



Figure 3. The gravimeter Lacoste and Romberg.

international gravimetric reference station of Tamanrasset is used. From this reference station, secondary gravimetric basis located in the center of each surveyed area are realized. Otherwise, the sampling measurement points is 20 m, so that the density contrast of structures located nearsurface or at low depth could be clearly highlighted. For every surveyed zone, an extension of the measures along profiles beyond the limits of the zone was completed in order to avoid edge effects and artifacts in processing. There are more than 2500 measurement points for the five surveyed areas (**Figure 4**). The altitude at every measure point performed with an automatic level type WILD "SOKKIA" B20 with compensator is used. The precision of the device is about 0.5 mm or 2 mm/km. The altitudes of prospected areas are determined with a precision of 2 cm (**Figure 5**). The coordinates limiting the surveyed areas are determined by single-frequency GPS (Garmin GPS 12) and the meshing of measurement points is made with the use of theodolite (Zeiss 020 B).

The Bouguer anomaly is performed as follow:

$$A_b = G_m - G_{th} + A_f - P + T$$

where A_b is the Bouguer anomaly, G_m is the measured gravity, G_{th} is the gravity computed on the reference ellipsoid or latitude correction, A_f is the "free air" or Faye correction, P is Bouguer correction, and T is terrain correction.

As the investigated areas have limited dimensions, the latitude correction is supposed constant, hence only the Bouguer correction is applied to the observed gravity. This correction depends on density and altitude and is defined as follow:

$$A_f - P = (0.3086 - 0.0419) \cdot h$$

in mGal/m. The density $d = 2.7$ is determined by the method of Nettleton. As the altitudes precision is 2 cm, the corrections are determined with precision of 4 μ gal and the Bouguer anomaly values are determined with precision of 7 μ gal.

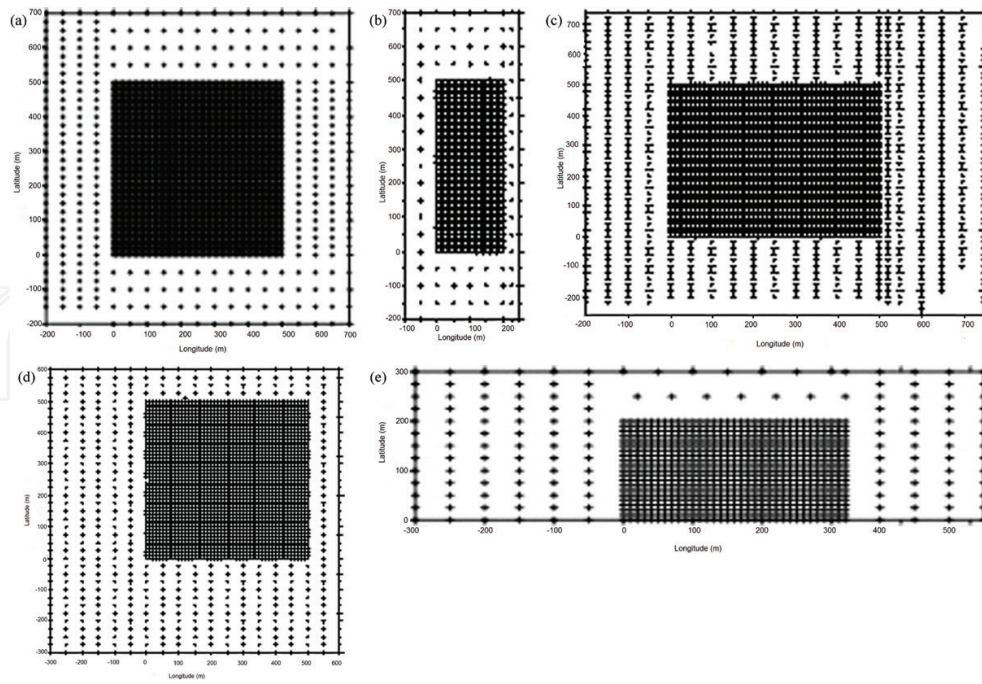


Figure 4. (a) Location of gravity measurements points of terrain 1 with the extensions. (b) Location of gravity measurements points of terrain 2 with the extensions. (c) Location of gravity measurements points of terrain 3 with the extensions. (d) Location of gravity measurements points of terrain 4 with the extensions. (e) Location of gravity measurements points of terrain 5 with the extensions.

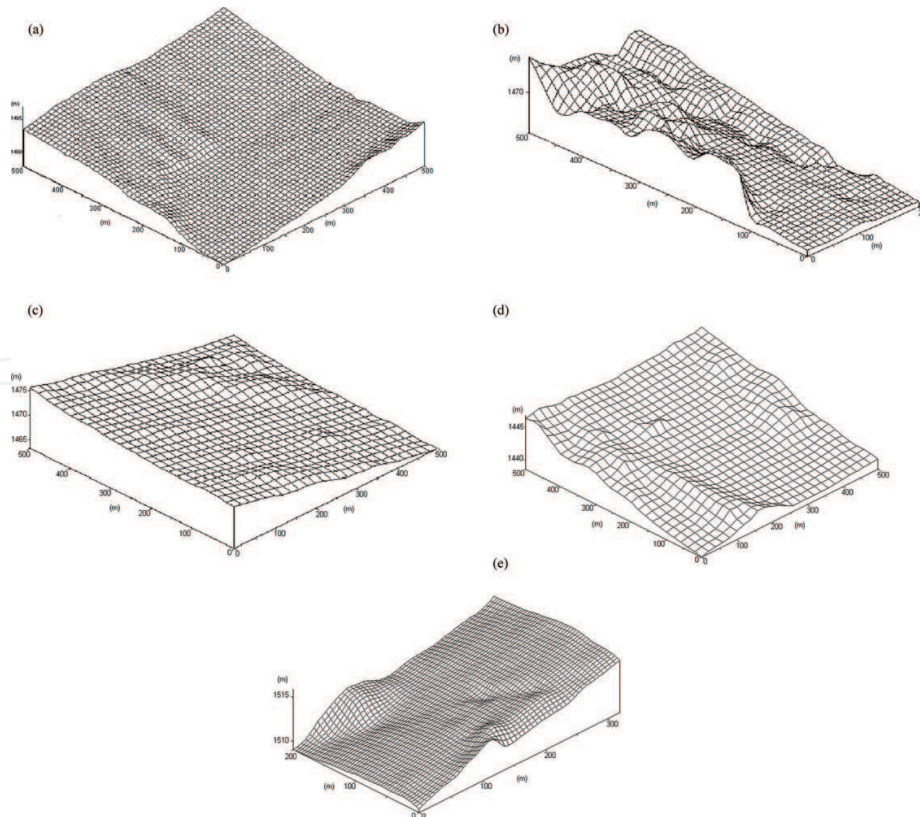


Figure 5. (a) Altitudes map of terrain 1. (b) Altitudes map of terrain 2. (c) Altitudes map of terrain 3. (d) Altitudes map of terrain 4. (e) Altitudes map of terrain 5.

The Bouguer anomaly maps are drawn on a regular grid with the use of “inverse distance” interpolation method and an equidistance of levels of 100 μgal .

3. Data processing

Once the Bouguer anomaly maps are established for the five zones, all processing methods are applied on the Bouguer anomaly data to extract the useful information. In what is going to follow, we choose to show the results obtained for one surveyed area (Terrain 4), knowing that all processing methods were applied for the four other areas.

The studied area which corresponds to terrain 4 or site n°4 in **Figure 6**, is located at 2 km in the North of Tamanrasset. The gravity survey covers a surface of 500×500 m, with equidistance of 20 m (**Figure 4d**). The map of the Bouguer anomaly is the basic document for gravimetric interpretation and this map is the sum of different measured effects: superficial, intermediate, and deep, in vertical direction. Thus, to separate all these effects, it is necessary to apply different filters. As we are interested in local anomalies, the first processing method used consists in eliminating the regional effect from the Bouguer anomaly map by the use of the polynomial method at different orders [1]. For a better identification of gravity lineaments, different methods are used, such as the vertical and directional gradients [2] which are used to highlight the short wavelength anomalies. On the other hand, the upward continuation at different altitudes [3] method enhances the long wavelength anomalies by attenuating superficial anomalies and strengthening deep ones [4–6]. To localize the anomalies causative structures at surface and depth, the continuous wavelet transform method is used [7–10].

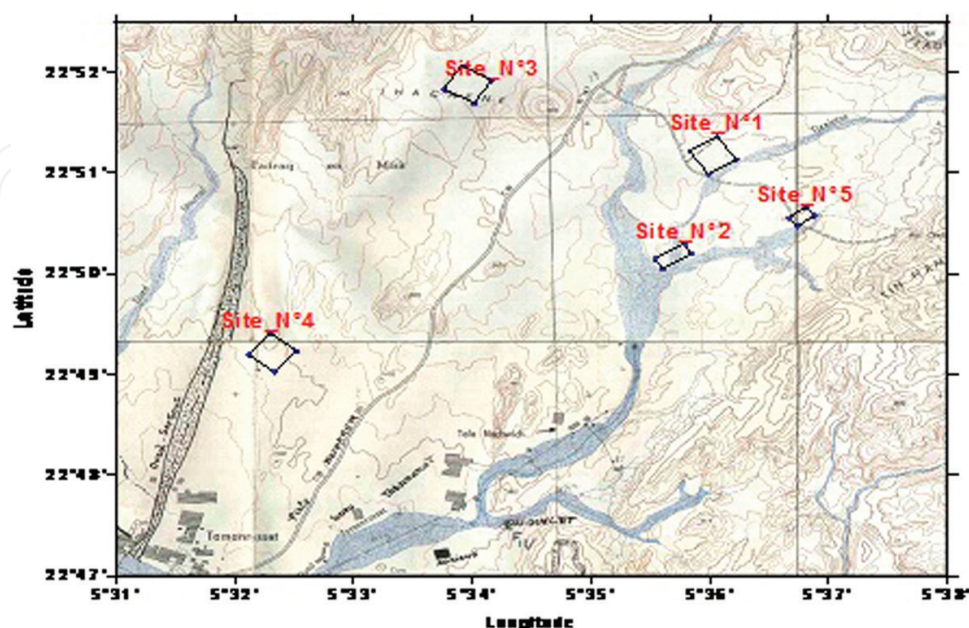


Figure 6. Location of the five surveyed areas in Tamanrasset region.

4. Interpretation and results

4.1. Description of processed maps

The Bouguer anomaly map (**Figure 7**) shows a series of positive and negative anomalies elongated in the NE-SW direction. The values of the Bouguer anomalies are ranged between -110.650 and -111.500 mGal. The examination of this map suggests that the regional effect could be plane or paraboloid. The upward continued map of the Bouguer anomaly at an altitude of 150 m (**Figure 8**) shows that the regional effect is a paraboloid. **Figures 9a** and **b** correspond to the regional anomalies and, **Figures 10a** and **b** show the residual anomalies maps of order 1 and order 2, obtained by retrieving polynomials of order 1 and 2. The residual anomaly maps show the same trends as the Bouguer anomaly map, principally a series of negative anomalies in the center of the area bordered by positive anomalies.

The maps of horizontal gradient in x direction (**Figure 11a**), shows succession of anomalies in NNW-SSE direction, while the derivative in y direction (**Figure 11b**) illustrates an important gradient in the E-W direction. The vertical gradient map (**Figure 11c**) points out gravity lineaments in NNW-SSE and E-W directions.

The long wavelength anomalies are highlighted by the use of upward continuation at different altitudes (**Figure 12**). At greater altitudes than 150 m, the surveyed area is characterized by a positive anomaly and suggests that the structure responsible of this anomaly is relatively

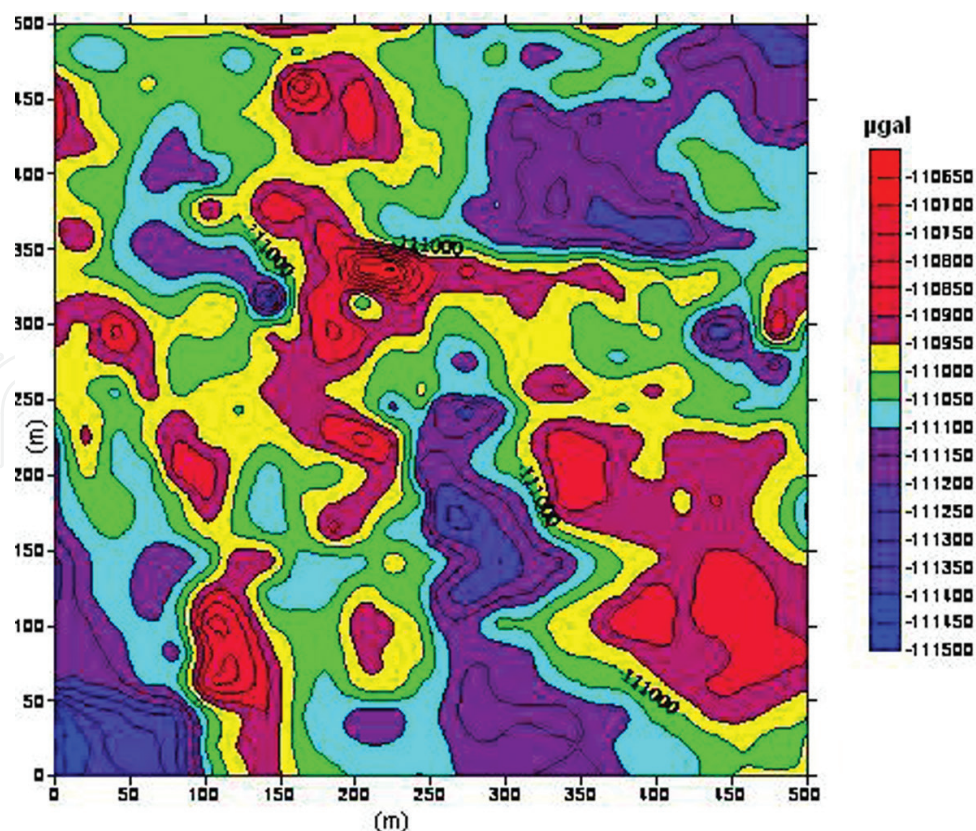


Figure 7. The Bouguer anomaly map of terrain 4.

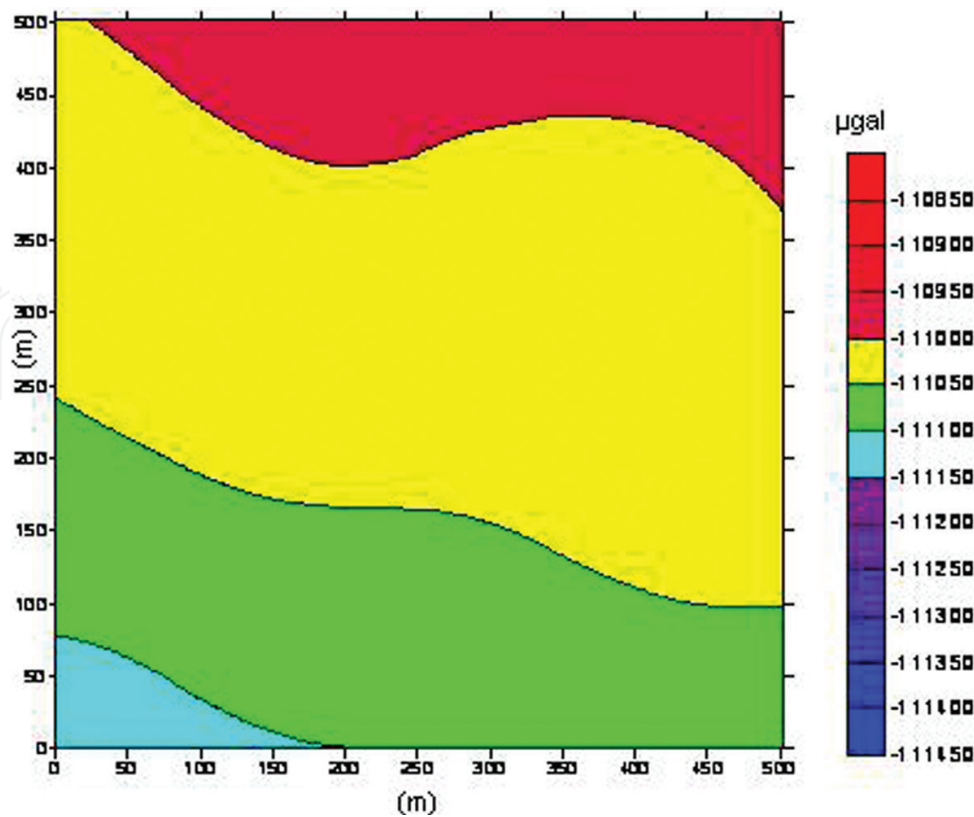


Figure 8. Upward continuation at 150 m of the Bouguer anomaly map of terrain 4.

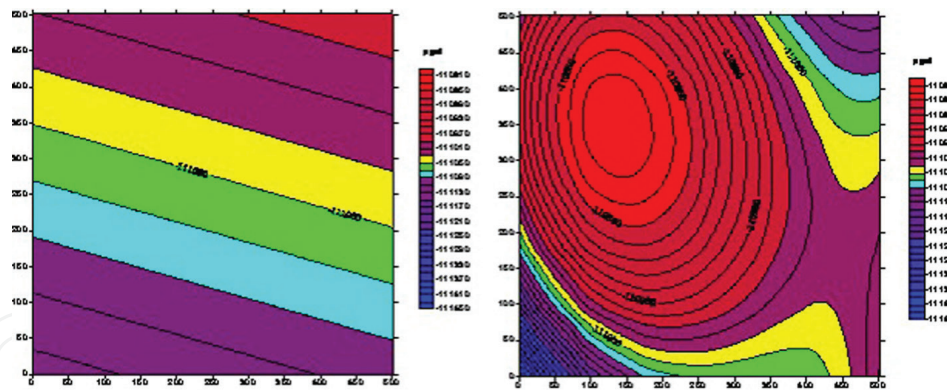


Figure 9. Regional anomalies maps of order 1 (left) and order 2 (right) of terrain 4.

deeply rooted, more than 150 m of depth. Between the altitudes of 10 and 50 m, the positive anomaly is formed by two different parts, crossed with a negative anomaly in the central part of the area along an N-S axis.

4.2. Identification and localization of anomalies causative bodies

The continuous wavelet transform method is used to identify and localize structures responsible of the anomalies both at surface and in depth. The method is applied on five profiles perpendicular to residual anomalies directions (Figure 10). The results obtained are displayed

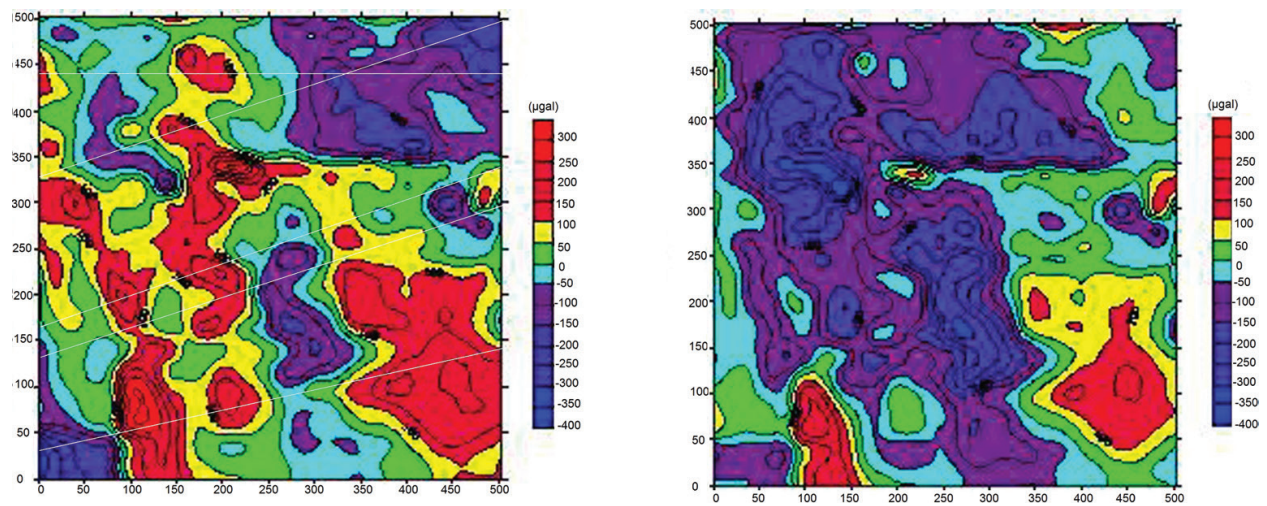


Figure 10. Residual anomalies maps of order 1 (left) and order 2 (right) of terrain 4. In white lines the processed profiles with the continuous wavelet transform in the Section 4.2.

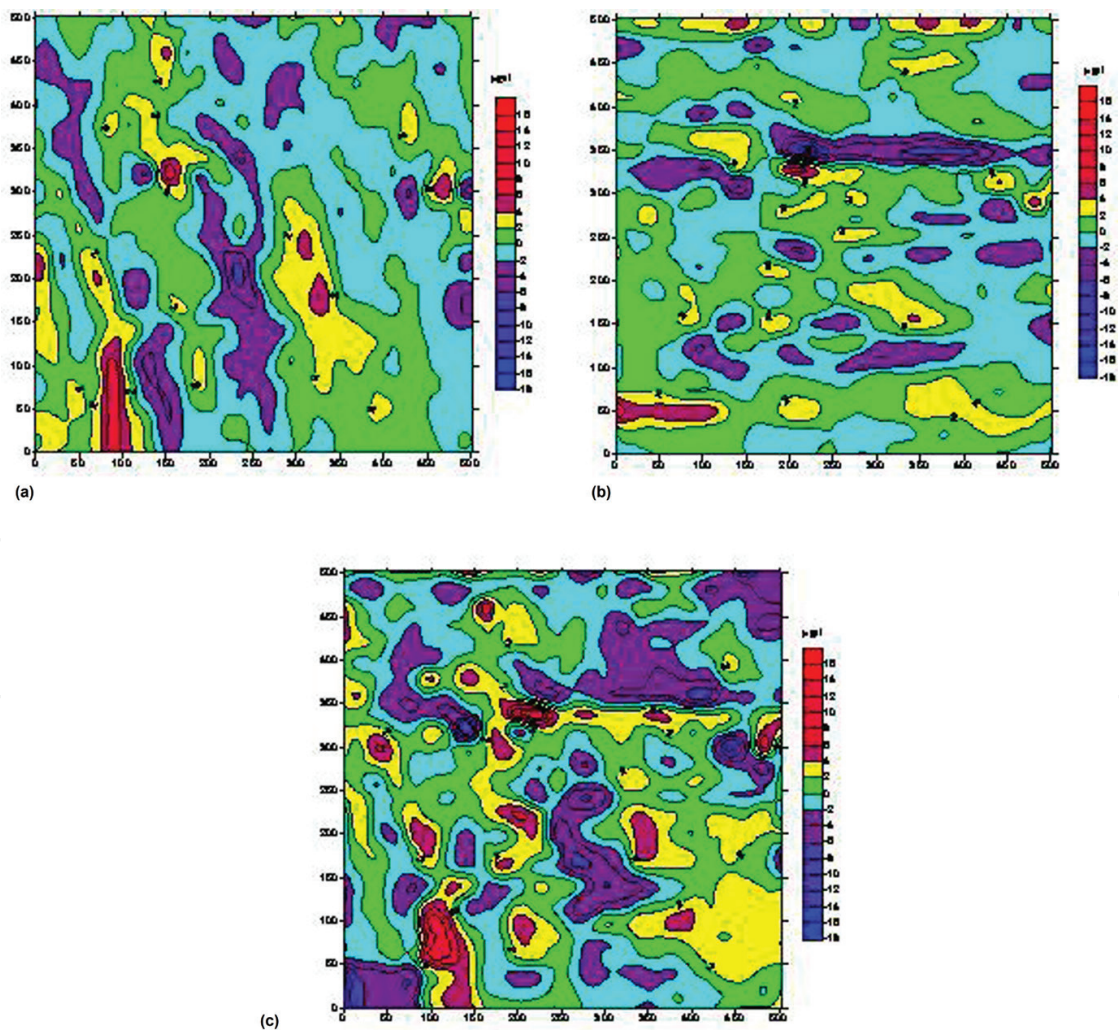


Figure 11. Gradients maps of terrain 4. (a) Horizontal gradient in x direction, (b) in y direction, and (c) vertical gradient.

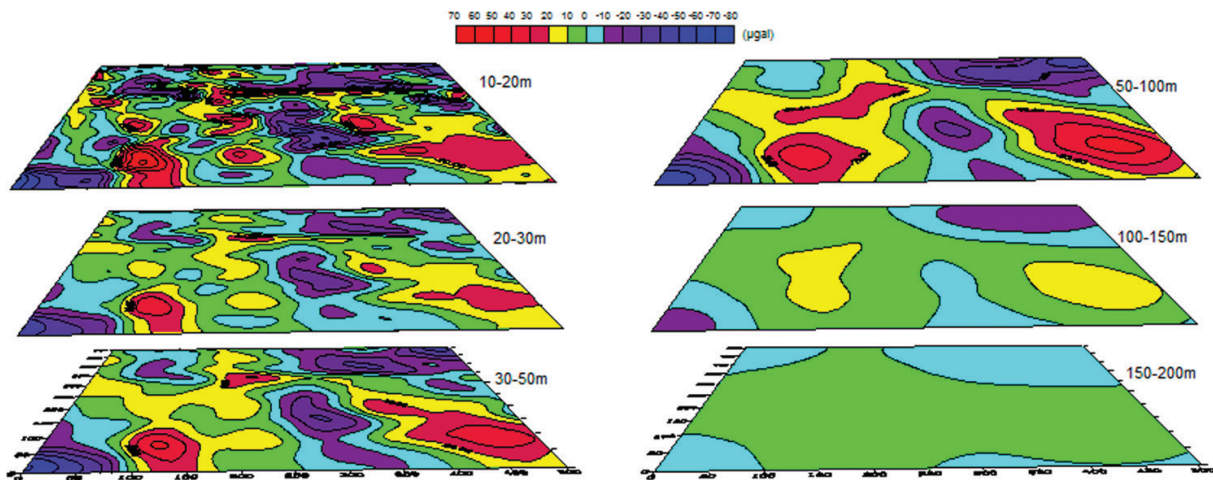


Figure 12. Upward continued maps differences of the Bouguer anomaly of terrain 4 at different altitudes (10–20 m, 20–30 m, 30–50 m, 50–100 m, 100–150 m, and 150–200 m).

in **Figure 13**. The figure in the top represents the signal corresponding to the gravity anomaly in mGal according to horizontal distance in m. The figure in the middle corresponds to the map of the modulus of the coefficients of the wavelet transform according to dilations in m and horizontal distances in m and, the figure in the bottom corresponds to the map of the maximum entropy according to horizontal distance in m and the depth of identified structures in m.

The **Figure 13a** shows the results obtained for the gravity profile 1 of the studied area. The intensity of the anomaly varies from -150 to 300 mGal. The map of the wavelet transform (middle) displays the signature of many contacts or faults. The first contact is identified in the entropy map, at horizontal distance of 100 m and at depth of 100 m. Between the distances of 120 and 140 m, a structure is identified at 40 m of depth. A second contact is identified at horizontal distance of 200 m and at depth of 100 m. At a distance of 220 m, the depth of the identified structure is 70 m. Between the distances of 221 and 230 m, the depth of identified structure is 40 m. A third contact is identified at horizontal distance of 260 m and at depth greater than 100 m. Between the distances 280 and 300 m, the identified structure is located at a depth of 65 m. The last identified contact along this profile is localized at a distance of 400 m and at depth greater than 100 m. The last identified structure is located at distances 480 and 520 m and at depth of 80 m.

The **Figure 13b** shows the results obtained for the gravity profile 2 of the studied area. The intensity of the anomaly varies from -180 to 150 mGal. The map of the wavelet transform (middle) displays the signature of many contacts. The first one is identified in the entropy map, at horizontal distance of 100 m and at depth of 80 m. A structure is identified at 30 m of depth and horizontal distance of 120 m. A second contact is identified at horizontal distance of 140 m and at depth of 100 m. At a distance of 240 m, the depth of the identified structure is 30 m. A third contact is identified at horizontal distance of 260 m and at depth of 35 m. Between the horizontal distances of 280 and 300 m, the identified structure is located at a depth of 70 m while between the distances of 320 and 340 m, its depth reaches 65 m. Another

identified contact along this profile is localized at a distance of 460 m and at depth of 70 m. The last identified structure is located between distances 480 and 490 m and at depth of 40 m.

The **Figure 13c** displays the results obtained for the gravity profile 3 of the surveyed area. The intensity of the anomaly varies from -100 to 150 mGal. Many contacts and structures are identified along this profile. The first contact is identified at horizontal distance of 20 m and at depth of 30 m. At the distance of 30 m, the structure is identified at 12 m of depth. The second contact is localized at horizontal distance of 60 m and at depth of 90 m. Between distances of 180 and 210 m, the depth of the identified structure is 80 m. Another contact is identified at horizontal distance of 220 m and at depth greater than 100 m. Between the distances 260 and 285 m, the identified structure is located at a depth of 85 m, while at the horizontal distance of 300 m, its depth reaches 20 m. Another contact is localized at a distance of 320 m and at depth of 70 m. The identified structure is located at horizontal distance 340 m and at depth of 20 m and another contact is identified at 360 m with a depth of 55 m. At the distance of 400 m, the depth of the structure reaches the 10 m and the last contact is identified at a depth of 70 m and horizontal distance of 480 m.

The **Figure 13d** displays the results obtained for the gravity profile 4 of the surveyed area. The intensity of the anomaly varies from -220 to 150 mGal. The first structure is identified between horizontal distances of 10 and 30 m, at depth of 10 m and reaches the 40 m of depth at distance of 40 m. An identified contact is located at distance of 60 m and the depth of 80 m. Between the distances of 80 and 100 m, the depth of the structure reaches 25 m. The second contact is localized at horizontal distance of 140 m and at depth exceeding 100 m. Another contact is identified at a distance of 320 m and the depth of 90 m. Between distances of 330 and 350 m, the depth of the identified structure is about 50 m.

The **Figure 13e** shows the results obtained for the gravity profile 5. The intensity of the anomaly varies from -200 to 150 mGal. The first identified structure is localized between the distances 10 and 30 m at 10 m of depth, further at the distance of 100 m its depth reaches 20 m. Two contacts are identified at horizontal distances of 140 and 260 m respectively deeper than 100 m.

By stacking the results of the continuous wavelet transform applied on more profiles extracted from gravity anomalies map of this area, we establish the depth map for this zone. The gravity anomalies and depth maps are overlaid (**Figure 14**), two weathered zones elongated in the NW-SE appear on this map, and these weathered zones are staggered relative to each other by a fault with NE-SW direction. Another weathered zone is identified in the NE part of the area and is fairly deeply rooted. The depth of these weathered zones is about 120 m.

4.3. Discussion

A compilation of identified structures for the five surveyed areas is shown in **Figure 14**.

For the first terrain (**Figure 14a**), the granitic substratum rises in the NW and SW parts of the terrain 1 and it is crossed in its central part by a fault. It is covered by two weathered zones elongated in the N-S direction and located at longitudes of 150 and 200 m, respectively. The

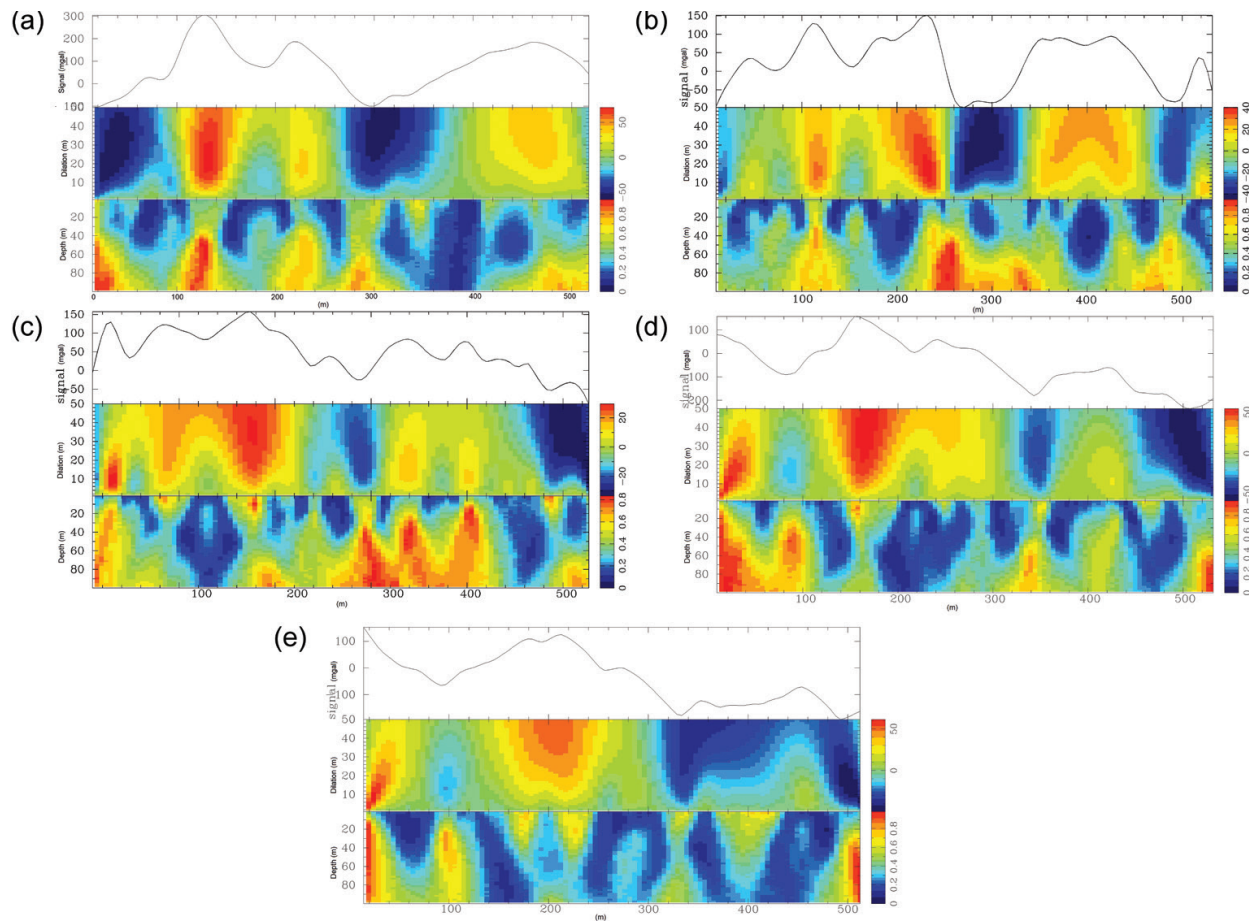


Figure 13. (a) Localization of gravity anomalies causative bodies along the profile 1 of terrain 4. (b) Localization of gravity anomalies causative bodies along the profile 2 of terrain 4. (c) Localization of gravity anomalies causative bodies along the profile 3 of terrain 4. (d) Localization of gravity anomalies causative bodies along the profile 4 of terrain 4. (e) Localization of gravity anomalies causative bodies along the profile 5 of terrain 4.

depth of these weathered zones reaches 75 m and at this depth the substratum appears highly fractured. This map shows the deepest sources are located at longitudes of 70 and 150 m with a maximum at latitude of 270 m.

The **Figure 14b** shows that the granitic substratum is very deep in the terrain 2 and rises in the NW and SE parts of the area. In the central part of the terrain, the substratum remains very deep. In the NE and southernmost parts of the surveyed terrain, the substratum is covered by weathered zones. The structures depth is very important in the northern part of the area which is intensely fractured. In the terrain 3 (**Figure 14c**), the granitic substratum rises in the eastern part of the area where it is crossed by a fault of NW-SE direction and, in the western part of the area where it is less deep. In the central part of the area, some weathered zones of low thickness cover the granitic substratum; here, the depths do not exceed the 10 m. In the southern part of the area, the depths become very important but it is the limit of the terrain 3. In the terrain 4 (**Figure 14d**), the granitic substratum is deep. Two weathered zones in NW-SE direction appear and are shifted with respect to each other by a fault in NE-SW direction. Another weathered deep zone is located in the NE part of the area. The weathered zones

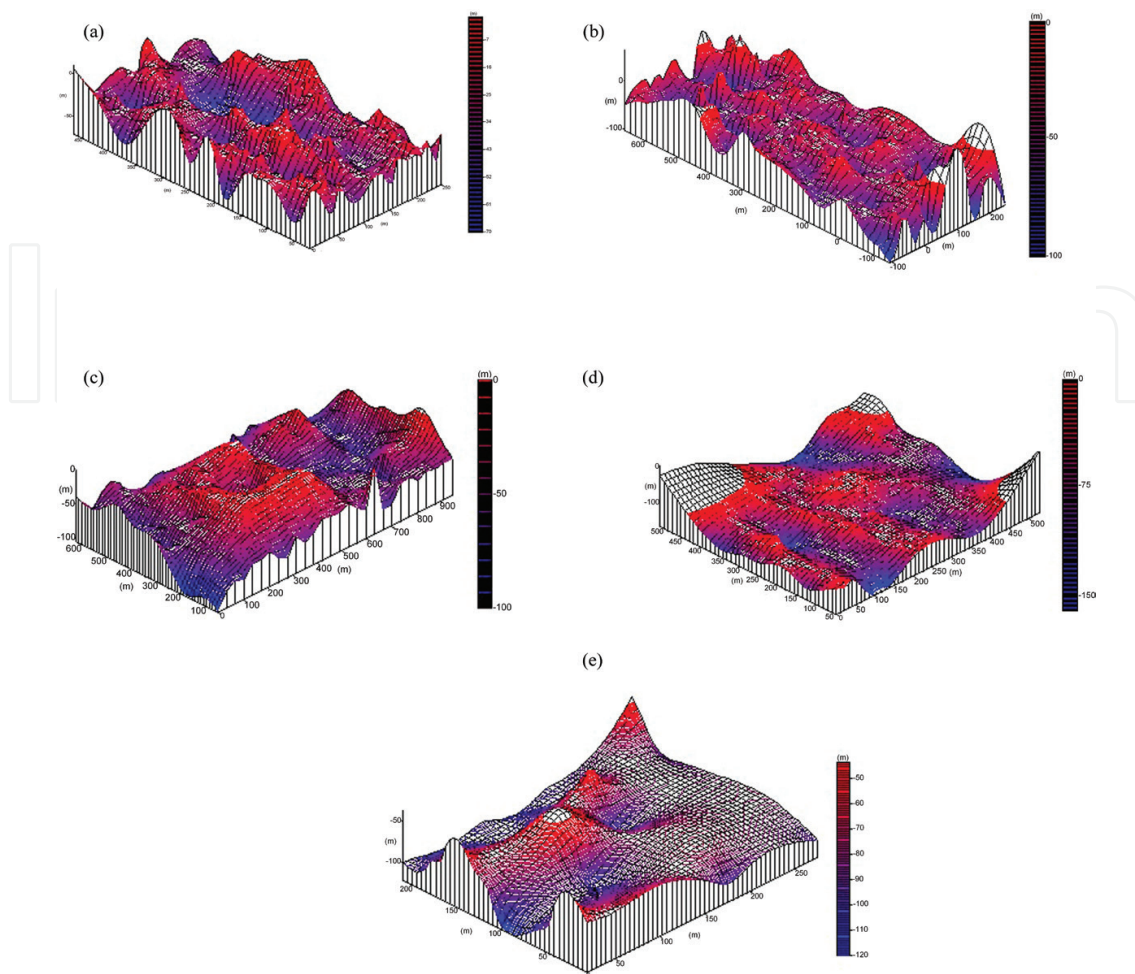


Figure 14. (a) Structures depths map of terrain 1. (b) Structures depths map of terrain 2. (c) Structures depths map of terrain 3. (d) Structures depths map of terrain 4. (e) Structures depths map of terrain 5.

depth is about 120 m. The **Figure 14e** shows a weathered zone in the central part of the terrain 5 which is crossed by a series of faults with NNE-SSW direction. The weathered zones depth reaches 80 m.

5. Conclusion

The gravity survey conducted in the Tamanrasset region and covering five areas lead to map gravity lineaments. By the use of the different processing methods (gradients, upward continuation, wavelet transform) applied on gravity anomalies data, the faults, contacts, granitic substratum, and weathered zones are identified and localized at near surface and at depth. On the basis of this work and achievements, drillings were set up in every surveyed area. There were three areas where the water was found and allowed to feed the city of Tamanrasset. Ten years later, a definitive solution to the problem of the water supply for the Tamanrasset city was found; the water is returned by the city of In Salah toward the city of Tamanrasset via a 700 km water main.

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