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3D modeling and reserves estimation using gravity data of Hajjar central orebody (Marrakech region, Morocco)

Modélisation 3D et estimation des réserves par les données gravimétriques du corps minier central de Hajjar (Région de Marrakech, Maroc),

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Abstract. The Hajjar orebody is one of the most important polymetallic (Zn+Pb+Cu) deposits in Morocco. It is considered as a typical example to estimate mineral resource and to develop orebody modelling. Due to its remarkable physics properties (density and susceptibility), the deposit permits to validate geophysical models for mining prospection. The aim of this work is to better estimate the Hajjar orebody resource in a 3D model using gravimetric data. We use Geosoft oasis montaj and GM-SYS to process the gravity data, provided by Geophysical survey of Ministry of Energy, Mines and Sustainable Development. A near-real morphology of the ore clusters is issued from interpolation between 9 2¾-D profiles in order to calculate the 3D model. The obtained 3D models allowed us to estimate the resource of Hajjar central orebody (20 MT). The comparison with the deposit geostatistical model led to validate our 3D model. The error has not exceeded the threshold of 20%. Given that, this modelling approach allows the orientation of reconnaissance works and thus reducing exploration costs.

Keywords: Hajjar mine, Morocco, gravimetry, numerical modelling, 2¾-Dmodel, 3D model, reserve estimation.

Résumé. Le corps minéralisé de Hajjar est l'un des plus importants gisements polymétalliques (Zn + Pb + Cu) au Maroc. Il est considéré comme un exemple typique pour l'estimation des ressources minérales et pour développer la modélisation des corps minéralisés. En raison de ses propriétés physiques remarquables (densité et susceptibilité), le dépôt permet de valider les modèles géophysiques pour la prospection minière. Le but de ce travail est de mieux estimer la ressource à partir d'un modèle 3D en utilisant des données gravimétriques. Nous utiliserons Geosoft oasis montaj et GM-SYS pour le traitement des données gravimétriques, fournies par le ministère de l'Énergie, des Mines et du Développement durable. Une morphologie quasi-réelle de la ressource provient de l'interpolation entre 9 profils 2¾-D afin de calculer le modèle 3D. Ce dernier nous a permis d'estimer les réserves du gisement central de Hajjar (20 MT). La comparaison avec le modèle géostatistique du dépôt a permis de valider notre modèle 3D. L'erreur n'a pas dépassé le seuil de 20%. Étant donné cela cette approche de modélisation permettra l'orientation des travaux de reconnaissance et ainsi la réduction des coûts d'exploration.

Mots-clés: Mine de Hajjar, Maroc, gravimétrie, modélisation numérique, modèle 2¾-D, modèle 3D, estimation des réserves.

INTRODUCTION

Kuroko-type volcanogenic Massive Sulphide (VMS) deposits are a well-known type of ore deposits, very widespread in different geodynamic contexts and at different epochs (Lambert & Sato 1974, Routhier *et al*. 1978, Hutchinson, 1982). They are of great economic importance (over 800 Zn-Cu-Pb mines), with an average size in the order of one million tons and with favourable physical characteristics for indirect exploration. Among these indices, two are mostly used: density (gravimetric prospection) and magnetic susceptibility (magnetic prospection). Polymetallic sulphide clusters generally consist of massive or banded sulphides (more than 90% of sulphides). The ore density varies according to the nature of mineralization: massive (4-5 g/cm^3) or dispersed stockwerks as in the hydrothermal feeding area (3-4 g/cm^3), but it's always higher than the average enclosing rocks density (2.6-2.7 g/cm^3). 90% of the VMS sulphide clusters are iron, pyrite and/or pyrrhotite sulphides. In the case of pyrrhotite sulphide clusters, magnetization and density are good physical parameters for detection because this polymetallic mineral is strongly magnetic and dense. The most well-known polymetallic pyrrhotite sulphide clusters are located in South-Iberian province (Routhier *et al*. 1978). Neves Corvo (over 120 Mt) in Portugal is one of the huge deposits in this region.

Our study area is part of the extension of this metallic variscan province in Morocco. From geological and metallogenic point of view, the Hajjar orebody (Marrakech region, Fig. 1) is a deposit of great economic importance (over 15 Mt). The use of an airborne geophysical survey in mining exploration of the central Jebilets and Guemassa massifs (Fig. 1) began in the 1960s by the "Société Anonyme de Prospection Aéroportée (SAPA)" and "Compagnie Générale de Géophysique (CGG)". However, the most important discovery of this survey was the Hajjar mine in the 80s, following a drilling control campaign of an aeromagnetic anomaly of the polymetallic deposit in Guemassa massif (Marrakech region). This discovery constitutes an excellent case of success in mining prospection using airborne geophysical survey.

In this study, we seek to better estimate the Hajjar orebody resource in three-dimensional models established from gravimetric data. To achieve this objective, theoretical and practical understanding of analysis methods is required. Our approach consists of 3 levels:

(1) The first concerns the data processing and maps interpretation, in order to define parameters which, characterize ore body, for example: depth, overburden thickness, extension of the ore body, the densities distribution in the region, etc.

(2) The second level concerns the resource modelling from the gravimetric data. To do this,2¾-D modelling will be necessary as transition to 3D model.

(3) The third level concerns the development of 3D model with the minimum error, which will be defined as a reference model closest to the real model, in order to estimate the resource.

Given that, the major problem can be expressed in another term, in anticipation of the reconnaissance model work that succeeds geophysics (drilling), either in terms of morphology or in terms of estimated reserves.

In order to develop a 2¾-D and 3D modelling approach that will be a reference for the gravimetric ore bodies modelling, we use recent and well-known computer tools: Geosoft Oasis montaj and Geovia Surpac.

GEOLOGICAL SETTING

The Hajjar area (Fig. 1) is located at 35 km south-west of Marrakech characterized by moderate morphology with various elevations from 400 to 800 m. It is part of the Guemassa massif (SW western Meseta, Morocco). The Guemassa massif constitutes the southern extension of the variscan Jebilet massif (Fig. 1), which is separated by the Haouz basin which consists of a large depression filled with recent sediments resulting from the dismantling of the Atlas belt. Most of the sediments are made up of Neogene and Quaternary alluvia which may have filled up a Palaeozoic or a Mesozoic paleo-topography. The stratigraphic sequence is relatively complete. The hercynian basement which constitutes the substratum of these series outcrops in the Jebilet and the Guemassa massifs, located respectively towards the north and the centre of the basin. In the Jebilet, the basement (of this Jebilet part) is mainly built of metapelites corresponding to an argillaceous series intercalated with sandstone and limestone layers and assigned to Middle and Upper Visean (Essaïfi *et al*. 2003). At the end of the Carboniferous, several magmatic intrusions (gabbros and granites) were emplaced through this metamorphic series affected by a sub-vertical cleavage (Essaïfi 1995, Essaïfi *et al*. 2003, Lagarde *et al*. 1990). Southward, this basement disappears under the Haouz plain and reappears in the Guemassa massif where it is mainly composed of flyshoid carboniferous sequences (sandstone and pelite alternation) intercalated with limestone.

From a structural point of view, the area is characterized by a succession of several tectonic episodes (Soulaïmani 1991). The hercynian deformation which constitutes the major structural phase is marked in Namurian and Westphalian time by a significant compression responsible for the ENE–WSW to NE–SW orientation of regional cleavage. During this episode, two distinct domains were separated in the Haouz of Marrakech: The Guemassa massif in the West where the structures are oriented NE–SW to NS and the N'fis domain in the East, with a NNW–SSE single structural direction. After the hercynian orogeny, the area was subjected to the Oligocene Atlasic tightening which generated in particular the uplift of the Palaeozoic massifs of the Haouz of Marrakech. This tightening is mainly expressed by faulting tectonics of roughly ENE–WSW direction (Jaffal *et al.* 2010).

As far as mining is concerned, the hercynian basement of the Marrakech region hosts a large number of sulphide massifs. They are found as strata bound polymetallic mineralized bodies and often associated with volcanic rocks which crop up as submarine effusions of rhyolite and rhyo-dacite. These are volcano-clastic type mineralizations presenting a relatively distal character regarding the emplacement of the contemporaneous volcanic expressions (Bernard *et al*. 1988).

Such mineralizations are often associated with underlying stockworks zones. Their mineralogical and chemical characteristics indicate a strongly reducing environment leading to the paragenesis formation of syngenetic pyrrhotite of highly dominant primary origin of variscan age.

In the Guemassa–Jebilets metallogenic province, pyrrhotite ore deposits outcrop as limonitic products forming gossans. They are roughly organized along sub-meridian lineaments (Fig. 1). They are formed of mineral occurrences or ore bodies within the Visean volcano-clastic deposit of Sarhlef (Bernard *et al*. 1988). Felenc *et al*. (1986) proposed a genetic model in which such massive sulphide deposits are supposed to be emplaced during an extensional phase, during which sandy clay deposits infill in a sedimentary basin (Jaffal *et al*. 2010).

The Guemassa massif is followed by important magmatic activity characterized mainly by a bimodal plutonism emplacement. This led to high thermal perturbations generating a hydrothermalism which could appear as convection cells affecting magmatic bodies as well as their host rocks (Essaïfi & Hibti 2008). However, the proximity of sulphide ore enriched in base metals and the acid plutonism (depleted in base metals) may indicate that this kind of plutonism is the main source zone for this hydrothermal system (Essaïfi & Hibti 2008). The sulphide ore deposits of the Visean metallogenic province of Guemassa–Jebilets may have been emplaced in an epicontinental rift environment of the external zone of the hercynian chain (Lescuyer *et al*. 1998).

Furthermore, in Marrakech region, the massive sulphides are found as ore deposits or gossans especially in the hercynian basement outcrops of Jebilet and Guemassa. These sulphides are generally organized along sub-meridian lineaments often associated with shear zones, lithological contacts and major accidents of this hercynian basement (Marcoux *et al*. 2008; Moreno *et al*. 2008). The structural control of these sulphides is currently accepted by the scientific community (Essaïfi 1995, Essaïfi & Hibti 2008).

We will find in the recent study undertaken by Essaïfi & Hibti (2008) several illustrations of this tectonic control of mineralization in the Jebilet hercynian massif (Jaffal *et al*. 2010). The Hajjar deposit is characteristic of a volcano-sedimentary environment dominated by pyrrhotite as iron sulphide and having an intimate connection with rhyolite to rhyo-dacitic volcanism (Haimeur 1988, Hibti 1993, Zouhry 1998, Hibti 2001).

The sulphide mineralization of Hajjar is encased between a basal series of volcanic and volcano-sedimentary type, and a clayey and carbonated summit series (Hibti 1993 and 1999, Leblanc 1993, Eddebbi *et al*. 1998, Ferrari 1998, Zouhry, 1998). These two series are correlated to the Jebilet series: Sarhlef and Teksim, described by Huvelin (1977) and Bordonaro (1983).

The orebody deposit is located with an important Plio-Quaternary overburden from which emerge visean base outcrops consisting essentially of stoneware-disseminated pyrrhotite (Hathouti 1990).

DATA AND METHODOLOGY

The methodological approach adopted to achieve the objectives of this work is four fold: (1) implementation of a multidisciplinary geophysical study based on the data processing, analysis and interpretation; (2) 2¾-D resource modelling according to the gravimetric data, following many profiles, through which we will deduce the morphology (Mega lens), the dip and the extension of the orebody; (3) 3D gravimetric resource modelling and its reserve estimation; and (4) comparison between the gravimetric obtained model and geostatistical model in terms of estimated reserves.

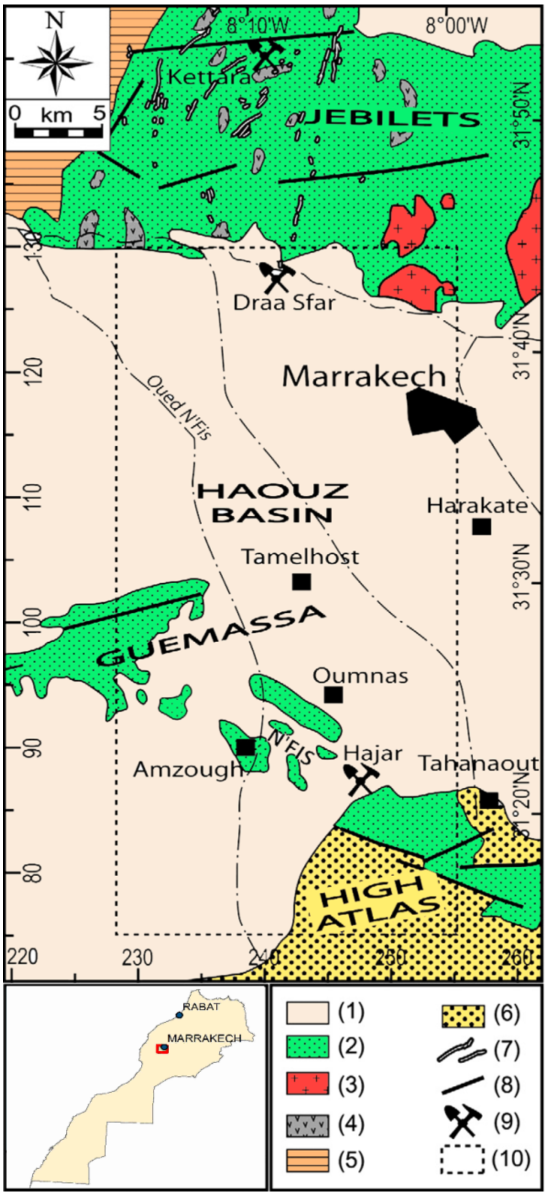

Figure 1. Simplified geological map of Guemassa area. (1) Mio–Plio–Quaternary cover, (2) Metapelites hercynian basement, (3) Hercynian granite, (4) Visean gabbro, (5) Cambro-Ordovician formations of the Western Jebilets, (6) Mesozoic series of the High Atlas, (7) Gossan, (8) Fault, (9) Mining site, (10) Study area boundary (from Jaffal *et al*. 2010 simplified).

Gravity Data

Genrally, gravimetry may be used when either the magnitude of gravitational field or the properties of matter are of interest. It allows differentiating underground bodies and structures. Hence the importance of using gravity data to locate hidden sulphur clusters in depth. After part the discovery by the HS1 drilling of the Hajjar sulphide mineralization, a detail gravity survey was carried out by the Geophysical Survey of the Directorate of Geology in May 1984. The area extension is 3.2 km long and 1.6 km wide. In total, 1089 gravity stations were measured(over 9 profiles, Fig. 2.a). The station spacing is 25 m. However, the spacing between the profiles is 200 meters except, the 5 central profiles the spacing is reduced to 100meters.The data acquisition was carried outby Lacoste & Romberg gravimeter, with a resolution of 0.01 mgal.

Data reduction

We use Geosoft Oasis montaj (Geosoft 2017) (software licence acquired by the Ministry of Energy and Mines, Morocco) in different steps of data processing and interpretation. The Bouguer anomaly was calculated for density of 2.67 g/cm3, and included all the details of corrections. We describe here major steps of data reduction.

Surface-Fitting Residualizing

The Bouguer anomaly map represents gravity anomalies. It shows the preliminary response of the ground. Therefore, the interpretation of the obtained map should take into account the effect of the regional gravity field due to the regional geological structures. In our case (Fig. 2.a), the observed anomalies in the northwest and southern parts can be interpreted as being sedimentary depletion and thinning, respectively.

The regional effect is sometimes represented by a low-order analytic surface. The parameters of the analytic surface are usually determined by a least-squares fit (Agocs 1951) or some similar operation. How closely the surface fits the data depends on the order of the surface and the magnitude of the area being fitted. The orders of fit for a one-dimensional case are illustrated in Nettleton (1976). The regional surface is often given by a polynomial or the low-order components of a 2D-Fourier surface. The selection of order is usually made by examination of trial fits of several different orders. Surface fitting is sometimes done to isolate and emphasize trends. Results from Coons *et al*. (1967) are shown in revealed that the trend becomes more evident as the order increases up to some point, about tenth order for the data. The residual for low order still contains appreciable regional trend and thus low orders are not very effective in separating the regional from the residual. Likewise, high-order surfaces are not effective because much of the sought-after anomaly is mixed with the regional in the surface fit (Telford *et al*. 1990). Polynomial filter calculates n^{th} (maximum nine) order trend of a data channel by least square best-fit polynomial. The trend is then evaluated and placed in a new channel. An optional residual channel (input trend) may also be created. In our case, we applied a polynomial trend filter by choosing the 5^{th} order to separate the anomalies (Fig. 2.a). We believe it is a suitable order for separation taking into account the geological context of the studied area.

Gravity Interpretation

The depth determination from gridded gravity data is based on Euler deconvolution. We use the Gravity Interpretation extension of Geosoft program to perform the Euler 3D Deconvolution processing (Geosoft 2017). Euler deconvolution was first developed by Thompson (1982) and later extended by Reid *et al*. (1990). Since then, it has been adapted and improved upon by Keating (1998), Mushayandebvu *et al*. (2004) and many others. This popularity is largely due to its great simplicity of implementation and use, making it the tool of choice for a quick initial interpretation.

In many cases, maps of gravity data (and transformations thereof) provide good constraints on the horizontal location of an anomaly source. Euler deconvolution adds an extra dimension to the interpretation. It estimates a set of (x, y, z) points that, ideally, fall inside the source of the anomaly. Euler deconvolution requires the x, y, and z derivatives of the data and a parameter called the Structural Index (SI). The SI is an integer number that is related to the homogeneity of the potential field and varies for different fields and source types (Stavrev & Reid 2007). For example, in the case of total field gravity anomaly data, a sphere is represented by SI=2, whereas a dyke is represented by SI=0. There are many methods that can estimate the SI and we refer the reader to Barbosa *et al*. (1999) and Melo *et al*. (2013). In order to determine the depth contact between the ore body and the other formations (sedimentary overburden and visean basement), we opted for a SI= 0, max depth tolerance = 15 m, windows size = 140 m, survey elevation = 800 m.

Apparent density filter

To map an apparent density, we use the bulk density filter which assumes a simple model layer of fixed thickness and varying density to explain an observed gravity field. The response is assumed to be caused by a collection of vertical, square-ended prisms of infinite depth extent, the horizontal dimensions of which are equal to the input grid cell size. This is an idealized approximation hence the descriptor *Apparent* (MAGMAP 2015). The horizontal dimensions are equal to the cell size of the input (14 m x 14 m) with a model thickness of 8 m.

$$\mathrm{L}\left(\mathrm{r}\right) = \frac{r}{2 \times \pi \times G \times \left(1 - e^{-tr}\right)} \qquad (1)$$

G: gravitational constant. t: Thickness of the model.
r: The residual anomaly value in a block.

GM-SYS Profile Modelling

GM-SYS Profile Modelling is an intuitive and feature-rich workflow for gravity modelling which provides many opportunities to constrain modelling variables. It enables to test geologic model accuracy by comparing the model's gravity response to observed measurements. The methods used by GM-SYS to calculate the gravity model response are based on the methods of Talwani *et al*. (1959) and Talwani & Heirtzler (1964) and make use of the algorithms described in Won & Bevis (1987). Two-and-a-half dimensional calculations are based on Rasmussen & Pedersen (1979). Methods proprietary to NGA have been used to improve the efficiency and speed of the calculations and to make them better suited to an interactive environment. For validation, the results from GM-SYS have been found to be comparable to other published results; see Campbell (1983).

RESULTS

Residual anomaly map

The obtained solution is a solution among several, which means that it's not unique. For example, if the trend is established by a different degree, we will have different solutions, but they are both valid. We extract the residual gravity anomalies in order to extract the maximum informations and interpret them to highlight the mining resource (main body of Hajjar). The residual anomaly amplitudes don't exceed 1 mgal (Fig. 2.b), and highlights four positive anomalies. Indeed, these four defects are located approximately equidistant from each other.

The first (Al) discloses an abnormality E-W and whose apex is located on the left of anomaly center. In this space, we distinguish, within the same anomaly (0.39 mgal) another amplitude abnormality (0.48 mgal) whose oriented N-S.

The second anomaly (A2) on the East side of the first, marks a circular anomaly whose axis is ESE-WNW, and the amplitude reaches 0.35 mgal.

The third anomaly (A3) is located south of the first, it shows two separate anomalies (0.32 and 0.3mgal), and have two axes of different directions.

The fourth anomaly (A4) is located north of the map, it presents an anomaly surrounded by others of small amplitude but significant (0.21, 0.24 and 0.27 mgal).

Therefore, this map helped to highlight four main anomalies, the central one shows the response of the Hajjar orebodies included central orebody deposit, an abnormality characterized by high amplitude and a very large extent which expresses the resource importance. The calculation of the density shows a density variation between 2.47 to 4.22 g/cm^3 localized essentially in the main body, with a significant extent. This density confirms the existence of the polymetallic ore and which consists of 10% Zinc, 3% Lead, 1% Cooper, 30% of sulphur, 75 g/t silver (Farhan & Souni 1999).

Euler deconvolution map

Figure 2.c shows the orebody contacts with other formations and their depths, according to our goal of determining the mineralization overburden average depth, the residual anomaly overlay map and that of Euler solutions shows the ore body alignment with the centred past line, filtering has eliminated invalid solutions (Tab. 1):

Table 1. Table of Euler solution statistics.

	Elevation (m)
Minimum	570
Mean	730.2
Maximum	851.72
Standard deviation	30.8

The overburden thickness was determinate by calculating the difference between the maximum and the average depth of the disturbing sources (Maximum-Mean = 851.72 – 730.20). The orebody depth is determined from the preceding result, by integrating the standard deviation (-121.52 – 30.80), as result we conclude that: Overburden thickness = 121.52 m and Orebody depth = -152.30 m from the surface.

2¾-D mining resource modelling

To develop 2¾-D model, we have chosen the L2600 profile, being the central profile (Fig. 2.a) and where we have the maximum amplitude of the gravimetric anomaly. Based on the parameters detected from the geophysical study (depth, thickness of the sedimentary overburden), the modelling principle consists in the creation of blocks set which defines the terrain structures, each one with its specific density. In the beginning, the creation of geological background that will generate our model is necessary, its block which presents the terrestrial crust, the governing blocks (Fig. 3.b) by order are:

- Earth Crust (density = 2.8 g/cm^3: Light green);
- Adjacent Rocks (density = 2.67 g/cm^3: Green);
- Visean base (density = 2.7 g/cm^3: Blue);
- Sedimentary overburden (density = 2.67 g/cm^3: Yellow);
- Mineralized body (density = 4 g/cm^3: Red).

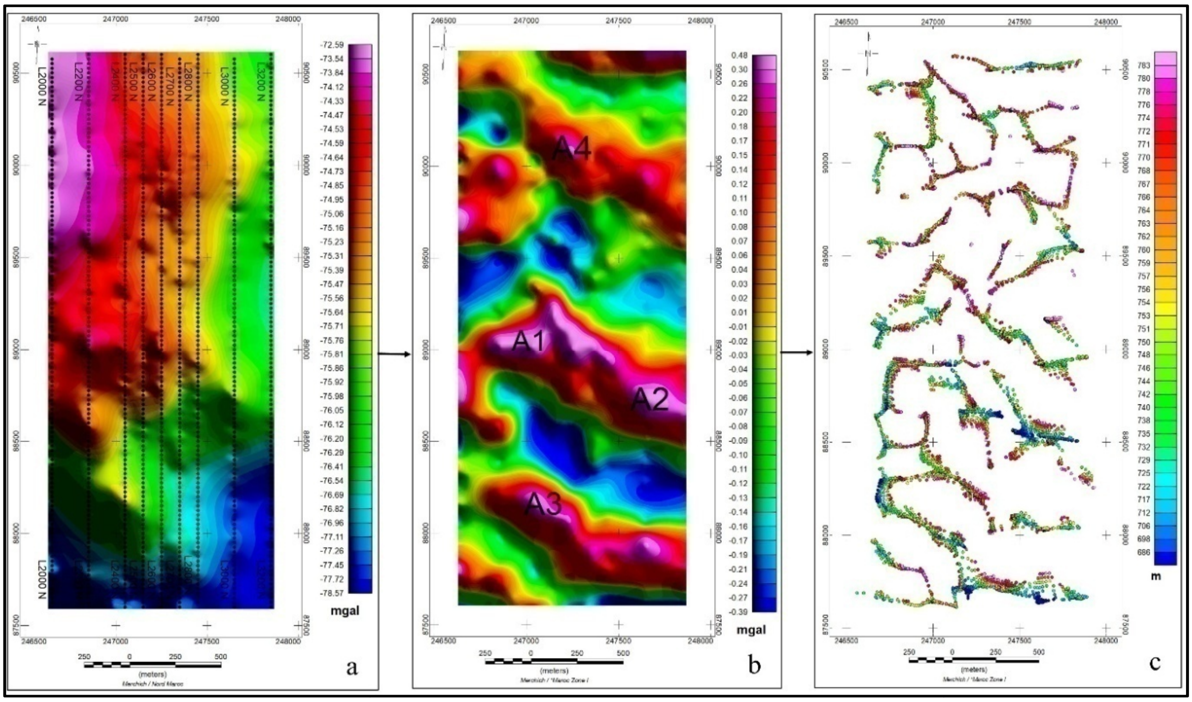

Figure 2. a. Bouguer anomaly map (2.67 g/cm^3) with Lines and stations (points) of gravity surveys. b. The residual gravity map. c. Euler deconvolution map to SI = 0.

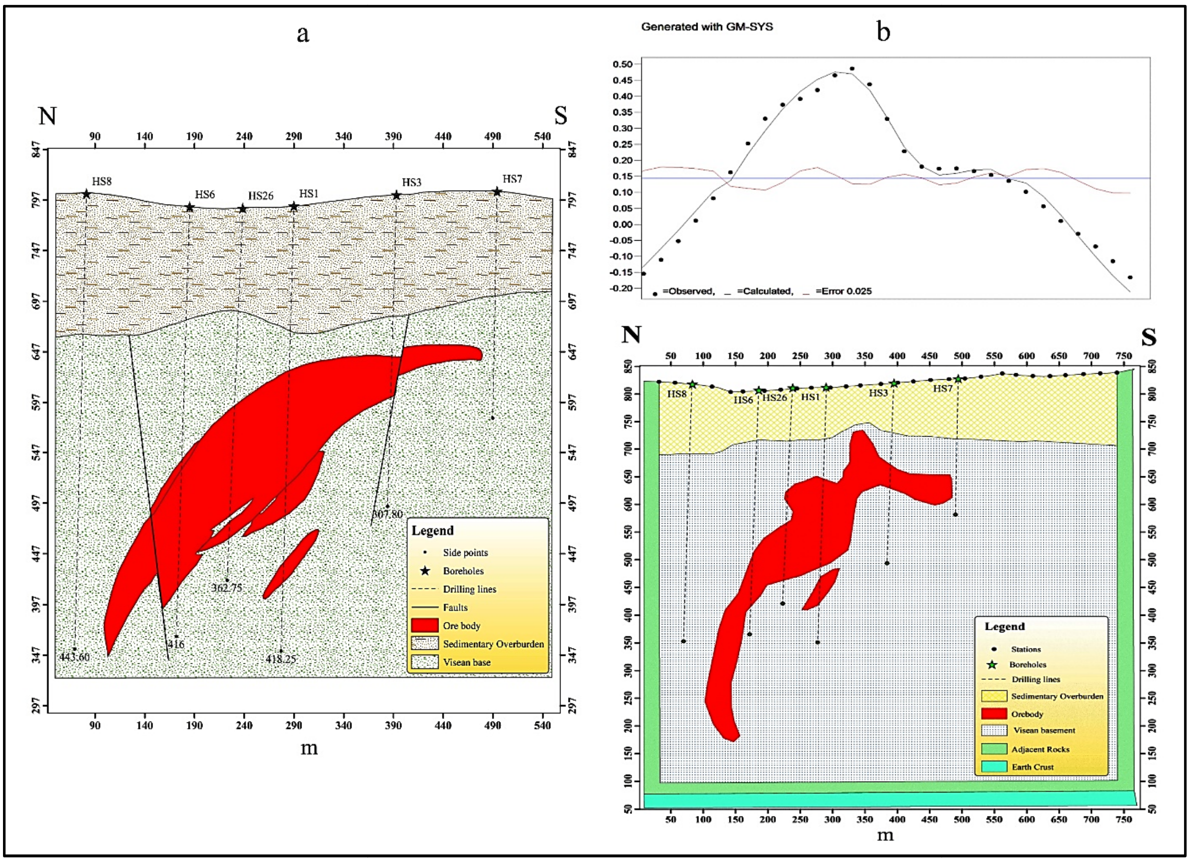

Figure 3. a. Established section from the drilling data and supplemented by the results of mining works (Hathouti 1990) modified. b. 2¾-D model generated with GM-SYS over L2600.

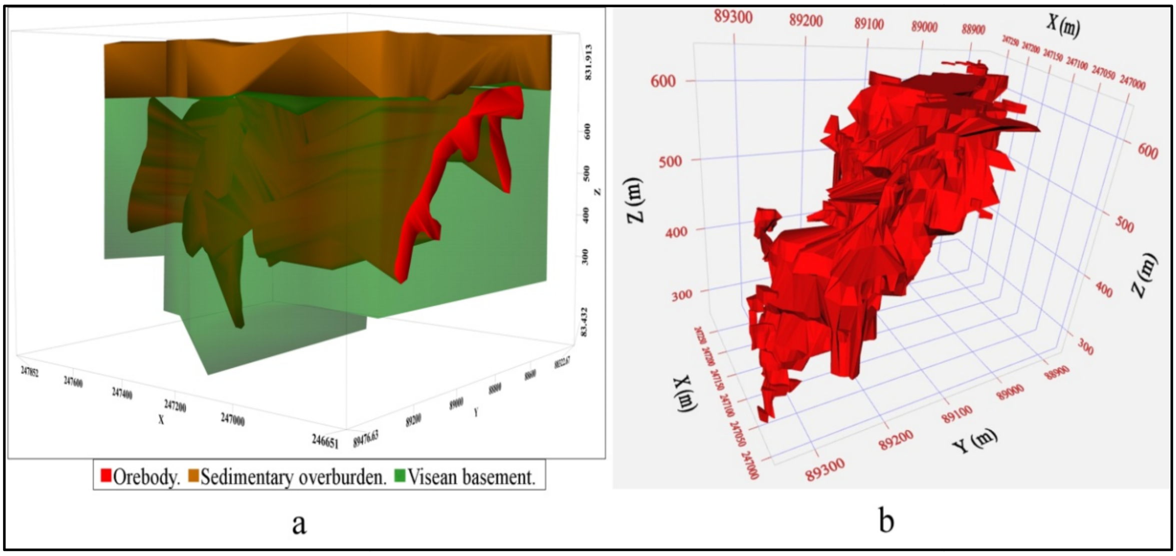

Figure 4. a. 3D geological model (sedimentary overburden, orebody and banking). b. Perspective view of the geostatistical model (provided by Jaffal from Managem).

The main model component is a body with density of 4 g/cm^3, the corresponding gravity anomaly calculated with that observed, is obtained by ore body morphology adjustment, using the inversion module. The various bodies obtained are defined by their densities and colours (Fig. 3.b).

To check the validity of our model we compare the model obtained with GM-SYS (L2600) with the section made by the reconnaissance drill holes (Fig. 3.a). For the model's comparison (Tab. 2), we need to be based on a characteristic and common parameter. To do this, we opted to compare the two model surface's, being a parameter that belongs to the final results and not to the model entries. However, the comparison revealed that the average is acceptable (≤ 20%), it is between 4% and 8% (valid model).

Table 2. Comparison table between drilling (Hathouti 1990) and gravimetric models.

Model	Drilling model	GM-SYS model
Surfaces (m²)	31072	29176
Model error	-	± 2.4%
Surface included model error (m²)	31072	28476≤S ≤29876
Average between model surfaces (m²)	1896	
Average between model surfaces included model error (m²)	1196 ≤ Average ≤ 2596	
Average between models in %	6%	
Average between models included model error in %	4%≤ Average ≤ 8%	

3D Modeling

After Foudil-bey (2012), geological model can be represented numerically by geometric structure, using the computer tools. By definition, geological modelling is a geometrical illustration of an object in the subsoil, but it is tough to find a determination of the geological model word, because its definition differs from one specialty to another (Massot 2002, Abdelfettah 2009). In fact, the tendency in geophysics is the representation of the basement by allocating physical properties (density, velocity, magnetization, etc.) in 2D or 3D. We will represent the basement by geometries structure. Nonetheless, the aim of the model is a simplified subsoil illustration, which helps us to have geological and geophysical interpretation.

From the various models built by GM-SYS (same approaches as the L2600 model) using a computer tool for geological and mining modelling (GEOVIA Surpac), we correlated between them for a volumetric geological representation. This approach led to create the three-dimensional geological model (Fig. 4.a). Model that will help us to calculate the ore resource (Tonnage).

Resource evaluation

For the tonnage calculation, mining modelling software was used (GEOVIA Surpac) to have the modelled solid volume, though the reserve estimate may be drawn that despite the contents. The presence of ore grade is essential to estimate reserve. Whereas, the modelled solid shows the set of all dense included body, as stockwerks (10% of the ore body), while the distribution of contents is: "10% of Zinc, 3% Lead, 1% Copper: 30% sulphur, 75 g / t silver, "the reserve is estimated from the model is reported in table 3.

Table 3. Reserve estimation.

Total gravimetric model volume (m^3)	50674682
Distribution of contents (%)	10% Zinc + 3% Lead + 1% Cooper = 14%
Ore volume (m^3)	(50674682 x 14%) = 7094455
Ore volume without stockwerks (10%) (m^3)	6385009.5
Ore body average density (g/cm^3)	3 .56
Estimated Reserve (MT)	22.7

Table 4. Comparison table between gravimetric and drilling (provided by Jaffal from Managem) models.

	Drilling model	Gravimetric model (without stockwerks)
Ore volume (m^3)	5635762	6385009.5
Gravimetric model error (%)	-	-2.4
Gravimetric model error (MT)	-	-0.6
Estimated Reserve (MT)	20	22.7 - 0.6
Average error between models		10.5%

DISCUSSION

After having elaborated 3D model from correlation between the 92¾-D profiles modelled using GM-SYS and performed comparison between the 2D sections of the L2600 profile and drilling, we discuss here the resource estimation in terms of model error decreasing, then we compare between our 3D model and geostatistical model (drilling) of the resource (Fig. 4.b) trying to validate our approach in this study. The percentage of ore stockwerks and other outside elements present 10% of the ore volume, as result we have a model error due to these formations. In order to reduce the average between the gravimetric model and that of the boreholes, we will retain an error on the estimation of RMS=-2.4 as average error generated by GM-SYS.

Based on the results of the showed in table 4, we have an estimated reserve of 22.7 MT with model error generated by GM-SYS of ±2.4%. In terms of the error reduction, we opted for a negative error, equal-2.4% as previously mentioned. Comparison between geostatistical and gravimetric model needs unified unit, this led us to establish a comparison in terms of resource in MT and not in terms of volume, this being the error generated by GM-SYS in MT equal (-2.4% x 22.7 MT = -0.6 MT). This error will be added from the previous reserve (22.7-0.6 = 22.1 MT), which will give a reserve that be the basis for comparison with the real resource (Ore volume of drilling model m^3 x density g/cm^3 = 20 MT). However, the error between the two models, gravimetric and geostatistical model is calculated from the formula below.

Since the error has not exceeded the threshold of 20%, we consider our result as very encouraging, which implies validity of the developed modelling concept. Table 4 summaries the comparison between drilling model and our 3D model inferred from gravimetric data with calculated errors. Finally, to corroborate our model validity, we tested another model developed by Bellott *et al.* (1990) using the magnetic data. After comparing those models, we have found the same ore body’s geometry, but in the case of gravimetry data we have an increase in the accuracy either for the parameters: Depth, overburden thickness, lateral extension, tilt, etc. Or for the 2¾-D and 3D models.

$$Error(\%) = \frac{|real\ resource - estimated\ resource|}{real\ resource} \times 100 = \frac{|20\ MT - 22.1\ MT|}{20\ MT} \times 100 = 10.5\%$$

Formula of the calculated error between gravimetric and geostatistical model.

CONCLUSION

This investigation highlighted the contribution of the gravity data in the geophysical modelling of Hajjar central orebody. It was primarily based on the application of fundamental and numeric geophysics tools (theory, data processing, 2¾-D and 3D modelling), knowing that gravimetry is a powerful tool in geophysical exploration especially in mining exploration. The section from drilling and mining works of Guemassa Mining Company is established along the line where the maximum gravity anomaly coincident. It is noted that both models (drilling and gravity) are adjusted to one another in a firmly seated manner, which confirms the validity of our modelling approach and principle, however, according to the established 2¾-D and 3D models, the contribution of gravimetry in resource modelling is obvious.

We can conclude that our assumption is valid, as long as the variation rate between the two models, estimated reserve and drilling model reserve does not exceed 20%. Moreover, this study led determination of different parameters which define the orebodies, and allowed to represent 3D density distribution in the region subsoil, "essentially the principal body": dip, depth, density morphology, overburden depth, volume, resource, etc.

At the end, the gravity data is a very powerful tool for mineral resources estimation and its 2¾-D, 3D modelling. This model developed in our case can be considered as an approach that can be applied generally to different deposits. In fact, this type of modelling, allows the orientation of reconnaissance works that succeeds geophysics, mainly, drilling recognition, which will lead to a rational recognition, then a reduction in exploration costs.

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