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Application of GOCE Satellite Gravimetric Data For Mineral Exploration

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Abstract* - Gravity is directly proportional to density thereby making possible the use of measurable gravity in mapping the density variations in the earth's interior. The use of density as a means of mineral exploration is cost-effective for wider area coverage. GOCE gravity data, collected by ESA's GOCE satellite at 255km altitude and 10km intervals leading to the acquisition of multiple gravity points over the globe made possible the application of gravimetry in mineral exploration. Gravity disturbance data sourced from BGI- was corrected with WGM2012 corrections computed using EGM2008 geoid and ETOPO1 models, with reference gravity computed using the Somigliana formula. The gravity disturbances were mapped over Zambia using Surfer and Q-GIS, with over 600 control points of known mineral occurrences plotted together with other surface features like roads, rivers, railways, etc. By relating the control points to the varying gravity disturbances using the triple integral principle, a cautious analysis led to the geological classification of the gravity disturbances which essentially involved mapping predominant mineral occurrences across different parts of Zambia. During ground truthing, it was observed that the results within a particular area of interest on the classified map, and those obtained using four (4) different metal detectors as well as another remote sensing method tallied. The metal detectors used were the GR-100MINI, AKS, AKS plus 3D, and Garrett Ace 400, each with its own characteristics. From the map outputs, the results showed that GOCE data can be used for geological classification and delineation of terrain types. The delineation of terrain types on the classified map output matched that on existing geological maps and also offered the delineation of sub-terrain types.

Keywords - Gravity, GOCE, mineral exploration, geological, GIS.

I. INTRODUCTION

Most countries in different parts of the world strive to make the most out of their naturally occurring mineral wealth. To achieve this, the normal channel that is undertaken involves exploration, discovery, and then mining activities follow thereafter. Mineral exploration is feasible through a number of methods that includes geochemistry, geophysics, density, etc. [1]. Each of these methods works by taking into consideration one particular property of rocks e.g. resistivity, sensitivity, density, chemical properties, etc. [2]. This research was undertaken with the aim of showing the feasibility of applying densities of rocks as a means of exploring minerals whilst addressing the cost-effectiveness of this method in exploring a huge area.

In Zambia, mineral exploration has largely been dependent on terrestrial methods of exploration. One of the reasons this has been the case is due to the scantiness of gravity data. A Bouguer gravity survey carried out in Zambia between 1971 and 1973 [3] was only focused on the main roads which were motorable.

Traditional methods of mineral exploration i.e. terrestrial methods- involve high costs and longer periods of time in the field. But the advancement in technology e.g. the launch of the GOCE (Gravity field and steady-state Ocean Circulation Explorer) has made available pieces of data that can be fruitful in exploring minerals, especially over very large areas.

The GOCE satellite was the first core-earth exploration mission under ESA (European Space Agency) Living Planets Program. Launched in 2007, GOCE measured the gravitational gradient with high spatial resolution and precision in three dimensions along a well-characterized trajectory. The purpose of the GOCE mission was to acquire gravity gradient data to derive new Earth models of the static gravity field and also a geoid with high accuracy and resolution. The goal of the GOCE mission was to achieve 1 mGal accuracy for the gravity anomaly and 2 cm accuracy for length scales up to 100 km for the geoid. Such advances in existing knowledge of the Earth's gravitational field have helped develop a more comprehensive understanding of the physics of the Earth's interior, interactions between tectonic plates, and ocean circulation [4].

To achieve the goals of this research, gravity disturbance data from BGI (International Gravimetric Bureau) was downloaded and uploaded into Surfer for visualization and analysis. Further analysis was carried out in QGIS where a set of control points of known mineral occurrences across Zambia were plotted with the aim of learning the relationship between the control points and the gravity disturbances.

This study mainly focused on bringing to light the correlation between the geological formations in the deeper interior of the earth and the shallower subsurface as well as determining the extent to which the gravity disturbance data could be applied in the exploration of minerals, yet anchored on providing cheaper means of carrying out mineral exploration. This was achieved by reducing the mineral search grid by doing a geological classification of the whole of Zambia.

II. Study Area

The study area was Zambia, located within the grid from 21°E to 34°E and 18°S to 8°S.

III. Objectives

A. *Main Objective*

The main objective of this research was to apply the GOCE gravity field of the earth in the exploration of minerals

B. *Specific Objectives*

1) To generate a gravity disturbance map over Zambia and further delineate terrain types.
2) To geologically classify the gravity disturbances.

C. *Research Questions*

1) What is the correlation between the deeper crust and surface geology?
2) To what extent can GOCE gravimetric data be applied to supplement geological maps?

IV. LITERATURE REVIEW

A relationship exists between the density of a material and gravity such that the two values are directly proportional to each other as shown by the triple integral formula

$$g = k \iiint_v \frac{\rho dv}{l} \qquad (1)$$

Where g is gravity, k is the gravitational constant given by 6.6743×10^{-11} $m^3kg^{-1}s^{-2}$, *p* is the density, *v* is the volume and *l* is the separating distance [5].

Now, the density of rocks cannot be measured directly in the field. Therefore, this relationship that exists between gravity and density can be taken advantage of by using gravity data collected using airborne means to map the density variations in the interior of the earth. All objects composed of molecules and have mass also have their own densities measured in kg/m^3 [6]. Using gravimetry, rock types can be distinguished based on their varying densities [2] when (1) is applied.

Gravity disturbance is obtained by comparing the observed and normal gravity on two coinciding surfaces on the same level surface, i.e. the geoidal surface corrected gravity and the ellipsoidal surface theoretical gravity [7]. The result is attributed to density variations in the interior of the earth. The formula for gravity disturbance is given by:

$$\Delta \mathbf{g} = \mathbf{g_{obs}}(\mathbf{p}) - \mathbf{g_{theor}}(\mathbf{p}) = \mathbf{g_{obs}}(\mathbf{p}) - \boldsymbol{\gamma}_\mathbf{o}(\mathbf{Q_o}) + \boldsymbol{\delta}\mathbf{g_{FC}} - \boldsymbol{\delta}\mathbf{g_{TOP}} + \boldsymbol{\delta}\mathbf{g_{Atm}} \qquad (2)$$

Where $g_{obs}(p)$ is the observed gravity at point p on the topo surface, $g_{theor}(p)$ is the theoretical gravity, with corrections applied i.e. $\gamma_o(Q_o)$ is the normal gravity (correction for latitude and earth's shape) on the ellipsoidal surface, δg_{FC} is the free air correction, δg_{TOP} is the topographic correction and δg_{Atm} is the atmospheric correction [1].

The International Gravimetric Bureau (BGI) database has gravity data with corrections applied, incorporated in the World Gravity Map of 2012 – also called WGM2012 corrections – whose computations are based on the Earth Gravity Model of 2008 – also called the EGM2008.

The EGM2008 was developed through spherical harmonics expansion to a degree and order of 2160 through the model given by (3) below.

$$V = \frac{GM}{r}\left[1 + \sum_{n=2}^{\infty}\left(\frac{a}{r}\right)^n \sum_{m=-n}^{n} \bar{C}s\, \bar{Y}(\emptyset, \lambda)\right] \qquad (3)$$

Where GM is the geocentric gravitational constant and *(a/r)* is a scaling factor associated with the fully normalized, unit-less, spherical harmonic coefficients $\bar{C}s$ and $\bar{Y}$[8]

Through Somigliana's formula shown below as (4), theoretical or reference gravity shown in (2) was determined on the reference ellipsoid by BGI and hence we obtain the normal gravity.

$$\Upsilon = \frac{a\Upsilon_a cos^2\varphi + b\Upsilon_b sin^2\varphi}{\sqrt{a^2cos^2\varphi + b^2sin^2\varphi}} \qquad (4)$$

Where γ_a is the normal gravity at the equator, γ_b is the normal gravity at the poles, *a* and *b* are the major and minor axes of the reference ellipsoid respectively and $_\varphi$ is the latitude [9]

The normal gravity determination of the earth was developed based on the parameters of the Geodetic Reference System of 1980 [10] also known as the GRS-80 parameters. These are:

γ_a = 9.7803267715 ms^{-2}
γ_b = 9.8321863685 ms^{-2}
a = 6378137 m
b = 6356752.3141 m
e^2 = 0.00669438002290
k = 0.001931851353

Gravimetry has a wide range of applications that include tectonic plate and fault detection. Using GRACE Satellite gravimetric data from BGI, ICGEM and NASA, the subsurface of the Sunda Strait of Indonesia was mapped. Gravity disturbances and Bouguer gravity anomalies were used for tectonic plate and fault detection. By contouring the gravity disturbance and Bouguer gravity data, plate patterns and faults were extracted, which were then superimposed with secondary geological data from USGS as part of validation [11]. For subsurface mapping covering a large area as this, space geodesy is a low-cost method. Underlying geology that has not been detected/mapped visually from surface mapping can be detected using gravity data.

Using gravimetric data, Shirazy, Nazerian, Khayer, and Hezarkhani [12] estimated the depth of mineral deposits at the Jalalabad mine in the Kerman province of Iran. Non-uniform anomaly maps were produced that depicted various objects underneath the earth at various depths with varying densities. The density of rocks underground are said to affect the acceleration due to gravity at different points on the earth's surface, hence the value is never constant everywhere on the surface. Because of this, the variations in densities of rocks underground are observed, sorely based on gravity measurements. Therefore, geological deposits are distributed in that manner

Zambia's geological terrain is grouped into main distinct terrain formations such as the Irumide belt, Choma-Kalomo block, Lufilian arc, Mozambique belt, Hook Granite complex, Kasai craton, and the Zambezi belt, that offer mineral exploration potential within the country [3]. These terrain types are hosts to different mineral types.

V. Methodology

A. Downloading Gravity Data

The gravity disturbance data used was downloaded from ESA through BGI. The area of interest or grid was specified using geographical coordinates, so that only gravity data for the area of interest was returned by the system. The gravity data was in text format, bearing location data and the gravity value per location.

B. Processing and Visualization in Surfer

The downloaded gravity data text file was saved as a CSV Microsoft Excel file to facilitate its use in Surfer software. The gravity data were gridded and interpolated using Kriging interpolation to generate contours depicting gravity variations. 10 mGal was specified as the contour interval. This output was saved as a TIFF file and exported to QGIS for further analysis.

C. Pre-analysis

To truly investigate and test (1), a dataset consisting of 63 control points was plotted on the TIFF gravity thematic layer in QGIS. These control points were mine locations and other known mineral occurrences site. The same control points were also imported into Surfer in order to extract the gravity disturbance value at those locations. This was done to check the consistency of these values with the relationship that the triple integral formula gives between gravity and density of materials in the interior of the earth.

D. Analysis in QGIS

Further analysis was performed with an increase in the number of control points gradually to over 600, and studying their distribution with respect to the mineral type per point and its property, essentially the weight. The analysis of the gravity disturbances and the control point distribution led to the production of the gravity disturbance map and thereafter a satellite based geological classification map.

E. Geological Classification

During analysis, particular attention was paid to the contour bands that hosted particular control points. These control points guided the prominent existing mineral type per contour interval. The contour bands or intervals were then classified as having a particular prominent mineral type. The classes were represented by digitizing in QGIS, and the output was a classification map.

F. Ground Truthing

To verify the classification results, a series of activities that included field visitations were undertaken.

1) Remote Sensing technique

A remote sensing method was outsourced from a named company that performs mineral exploration by detecting hydrogen gas emissions from buried rocks. Through ratios or differencing of the hydrogen emissions in SWIR and NIR of the electromagnetic spectrum, a particular amount of emission of the gas is attributed to a specific rock type. This method, when applied in the ground-truthing area (mining license number 23082-HQ-SML in Kasempa district, North Western province of Zambia), confirmed the presence of emeralds and copper in that area as detected using gravity disturbances.

2) Terrestrial Detection

A number of handheld metal detectors such as the GR-100MINI Metal Detector, AKS Metal Detector, AKS Plus 3D, and Garrett Euro Ace Gold Detector were used for this exercise in the ground-truthing area. Each of these detectors has its own characteristics or specifications.

3) Geochemical Sampling

Within the ground truthing area, 38 samples were collected which were taken for geochemical tests. The geochemical results also confirmed the gravimetry results.

VI. Results

A. Gravity Disturbance Map

The processing and analysis in Surfer led to the visualization of the gravity disturbances with contours at 10mGal interval.

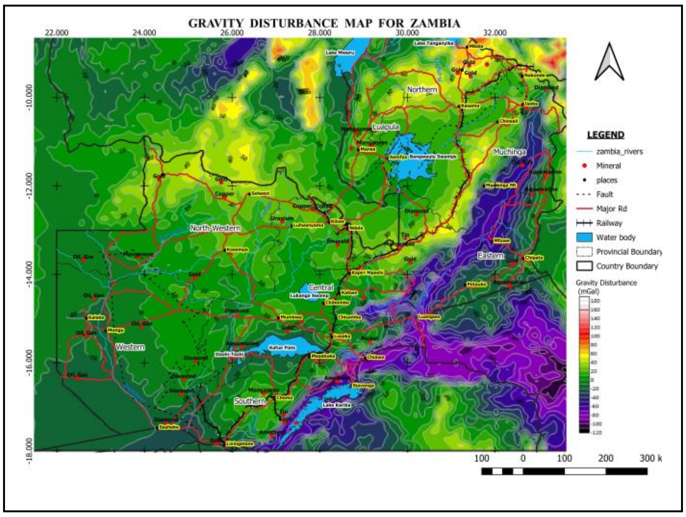

Fig. 1. Gravity disturbance map for Zambia.

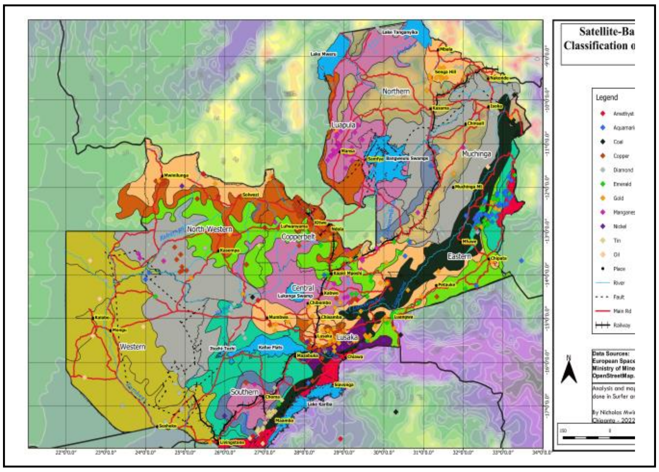

Fig. 2. Satellite-based gravimetric classification map.

As seen on the gravity disturbance map in Fig.1 above, the observed gravity values are depicted to vary across different areas. Places having equal gravity disturbance values are connected by contours. Regions of significantly high gravity disturbance values are occurring within the light green-red-white spectrum according to the legend, as shown, whilst regions with lower gravity disturbance values are depicted with a darker shade of green and all shades of purple. At this point, the gravity disturbance map did not contain any geological meaning, as it translates only to density variations until the classification of these anomalies was been done.

B. Satellite-Based Gravimetric Classification of Zambian Geology Map

By plotting various points of known mineral occurrences and other additional shapefiles, spatial patterns relating to the plotted features and the contours generated on the gravity disturbance map were studied carefully in order to embark on the supervised geological classification process. Geological knowledge was an ultimate input into the classification. To classify an area as to which mineral type is more prominent in that area, control points with specific mineral types were related to the contour bands within which they were most occurring. For example, it is noted that Aquamarine was falling within gravity disturbance values of between -20mGal to -2mGal. Therefore, after plotting known points with Aquamarine occurrence, the contour within which the points lie would then be digitized to depict a region with higher probabilities of having the same mineral type. The Satellite-Based Gravimetric Classification map is given in Fig. 2.

The delineation on the map on Fig. 2 gives a profound understanding of the sub-terrain types or structural provinces that exist in Zambia. The gravimetry method, therefore, acted as a supplementary tool in establishing sub-terrain types of the main terrain types that exist in Zambia. When the outline of classes in Fig. 2 is compared to the outline of the main terrain types in Zambia, an indication of how tectonic belts are delineated shows how space methods can be adopted as tools to improve upon the conventional methods of exploration by delineating sub-terrain types within the main terrain types.

C. Ground truthing

As part of ground truthing, data verification of the Space-based Gravimetric Classification of Zambian Geology Map shown in Fig. 2 above was done on the ground in Solwezi, North-Western province of Zambia. The ground truthing area was bordered by a mining license of number 23082-HQ-SML on plot number 1120, Kazomba, Solwezi. According to the space-based gravimetric classification, the study area indicated the presence of Copper, Gold, and Emerald. The physical ground verification exercise was imperative for this study as it sought to determine the correlation between the deeper crust and the subsurface geology. One of the corrections applied to the observed gravity values (i.e. the free air correction) removes a certain thickness of the earth's crust hence the Space-based Gravimetric Classification of Zambian Geology Map only speaks to the underlying masses that are deep below the earth's surface, say >1000m. The ground verification exercise using handheld metal detectors confirmed the gravimetry results.

D. Remote Sensing Method of Hydrogen Emission detection

This method uses ratios or differencing between the Visible/Near Infrared (VNIR) and Short Wave Infrared (SWIR). By the use of sensors on-board a satellite sensing hydrogen gas emissions from buried deposits underneath the earth's surface as the gas escapes through cracks, emissions recorded are differenced and visualized in form of imagery that indicates the possible locations (shown by the emissions of hydrogen) bearing higher and/or lower hydrogen emission concentrations of specific rock types. This piece of data serves as very good ancillary data that can be incorporated with other methods to consider a more meaningful geological interpretation of mineral exploration results. Fig. 3 shows the result from the remote sensing technique that was outsourced.

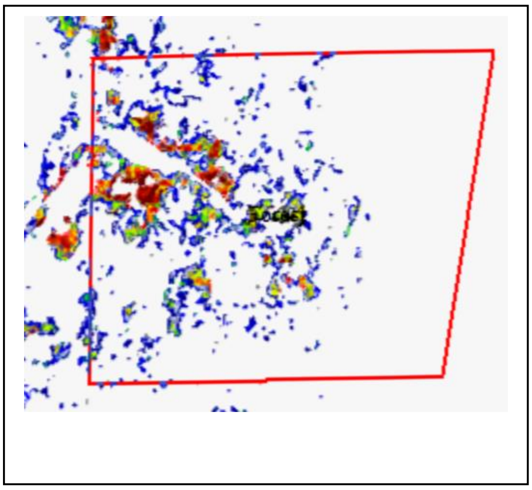

Fig. 3. Hydrogen emissions showing locations of emeralds

The deep red regions show places where the hydrogen emissions pertaining to emerald were detected.

VII. Discussion

An extensive study of the spatial patterns depicting fluctuations in gravity disturbances as shown by contours on the map in Fig. 1 was an integral part of the research that led to construing the anomalies with respect to geology. On the gravity disturbance map, spatial patterns and relationships can be observed between the gravity disturbance and the features on the earth's surface i.e. control points of known mineral occurrences and locations of existing mines that were plotted onto the gravity disturbance map to aid the interpretation of how gravity disturbances were distributed.

Looking at the distribution of the mines and control points on the map, one can see the association between mineral types per location and gravity disturbance values. For example, most mines on the Copperbelt province of Zambia are located in a region or belt of gravity disturbance values ranging between 20-40mGal, which is a significant amount translating to the richness in densities of the interior masses in that expanse.

By undertaking a mindful study of the trends shown on the gravity disturbance map given in Fig. 1, one can identify regions over Zambia showing very low or very high gravity disturbance values (e.g. low gravity disturbances of < 0 mGal in the Western province and high gravity disturbances of around 80 mGal in Muchinga and Northern provinces), which translate to very low or very high concentrations in the interior of the earth, hence signifying a rich interior, but only in terms of densities of various material types. It is cardinal to note that at this point, the trends on the map in Fig. 1 have no geological meaning. Hence the need for multiple control points with known geological attributes (i.e. the type of mineral occurrence at that point) that aided the satellite-based classification process. Also, we can further extend our observations on Fig.1 by remarking on the very higher gravity disturbance values in the neighboring Congo DR's Katanga region which is very famous for mineral wealth world over. The earth's gravity field is a game changer in mineral exploration.

As mentioned in the preceding paragraphs, the gravity disturbance map does not possess geological meaning as it is. Due to this fact, it was therefore seen as a necessary step to gather a dataset of control points that aided the geological classification process. We see the result of this step in Fig. 2. The Satellite-based Classification of Zambian Geology Map spans classes of different areas whose basic classification criterion is the gravity disturbance value associated with that particular class and the predominant control points in that gravity disturbance band. A particular class, for example, the Gold class, will not be limited to having gold control points, meaning it may have copper control points within it. For this fact, the classes must not be misunderstood as having one mineral type only. The mineral classes must be thought of as not having distinct boundaries but actually having a cascading tendency thereby causing overlaps with neighboring mineral classes at different levels or heights. With this mentioned, it is therefore worth noting that gravity disturbances are obtained by subtracting gravity values on one surface from another surface through the orthometric height. Hence a picture must be drawn in the reader's mind depicting the mineral classes on the geoidal surface.

The Zambian main terrain types or blocks in the existing geological maps give geological provinces that host different types of minerals. Using gravity data, the classification arrived at gives an accurate and more detailed delineation of the main terrain types thereby having sub-terrain types within the existing main ones. For example, a study of the near-circular Choma-Kalomo block area in the southern part of Zambia as the main terrain type on the classified map will reveal four (4) sub-terrain types as classified using gravity data. And this comes with a lot more detail as it gives the main mineral type hosted in each sub-terrain type. For the Choma-Kalomo block, it was discovered that it is actually subdivided into three (3) sub-terrain types that host mainly Tin, Manganese, and Aquamarine as shown in Fig. 2 with further possibilities of Amethyst, Emerald, Coal, Nickel, and Diamond. A similar approach can be taken to make reference to other structural provinces of Zambia such as the Kalahari block, the Karoo sequence of the rift valley, the Bangweulu block, etc.

The classification map must be used hand in hand with the trend map. That way, within the main and sub-terrain types, one is able to read trends of increasing or decreasing concentration that the GOCE gravity data brings about. It is now possible to check places of higher-lower concentration within a particular geological block formation. The increasing and decreasing gravity disturbances signify the increasing and decreasing densities of materials in the interior. Therefore, given a particular area, one is able to determine the types of minerals in that area as well as point out regions with the highest concentrations based on the densities as shown on the trend map.

A cross-examination of existing geological maps and the satellite-based classification map revealed how the former conveys surface (sub-surface) mineral information whilst the latter conveys geological information of the deeper interior of the earth. Both pieces of information are vital for the development of a mining area.

It is also worth noting that in most scenarios on the map outputs, the value of the gravity disturbance per control point plotted is actually different for the same mineral type in different areas. The reason for this is due to the fact that most minerals do not exist in their pure form in the earth's crust, but rather exist in compounded forms as mixtures with other mineral types and also mere rocks. Hence the gravity disturbance values for the same mineral type may differ in different locations due to the coexistence of different earth materials together.

In essence, the gravimetry method used in this research reduces the mineral search grid from the entire country into specific smaller classes or portions or areas of land. As the search grid reduces, exploration costs become lower and the time spent on exploration activities becomes less too.

In as much as the gravity disturbances are useful in locating places of higher densities in the interior, one downside is that the gravity disturbances, due to the corrections made to the observed gravity, only translate to masses in very deep depths of the earth, say around 1000 meters, due to the free air correction that reduces gravity values to the geoid. Hence it may be challenging to actually reach the buried material unless one does drilling. This was the reason it was imperative to establish the correlation between the deeper crust and the sub-surface of the earth. And hence it was discovered, as it is apparent from verified points plotted on the classification map that there is a correlation in most areas as most verified points fall in or near classes bearing the same mineral as the control point. The control points were sampled at shallow depths of not more than 2 meters, and were subjected to geochemical tests, so we do have confidence in the points.

VIII. Conclusion

With the gravity disturbance map and the geologically classified gravity disturbances generated over Zambia, these research outputs provide detailed mineralization information of the Earth's interior from the GOCE satellite gravity data. It can be inferred that mineralization and sub-terrain type's information in an area of interest can be determined by the use of GOCE gravity field thereby supplementing the existing geological maps. The method is cost-effective, in that it reduces the mineral search grid and also the time spent on mineral exploration.

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