An Introductory Geophysical Exercise Demonstrating the Use of the Gravity Method in Mineral Exploration

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ABSTRACT
Teaching geophysics to earth-science classes can present particular difficulties. This is because the majority of students are often numerically weak, but the presence of a few highly numerate individuals is not uncommon. Due to its conceptual simplicity, the gravity method is recommended as the starting point for an introductory course in geophysics. This is because the physics behind the method is conceptually straightforward and the rationale for the reduction and interpretation of the data can be easily understood based on simple equations. Also, widely applicable concepts can be introduced within a relatively simple context.

An exercise based on the use gravity measurements for exploration for a manganese deposit in the north of Western Australia is described. During this exercise, following reduction of the data, regional and residual anomalies must be separated and the latter interpreted in terms of the depth to its source and the excess mass causing the anomaly. To illustrate the different corrections in the reduction process and their relative magnitudes, a Macintosh-based program GRAVANOM has been developed. This program calculates drift, elevation, and latitude corrections for a profile of gravity observations and plots the profile after each correction has been applied. Survey parameters such as trend, elevations along the profile, and reduction density can be interactively adjusted and the effect on the Bouguer anomaly observed.

Keywords: Education – computer assisted, geophysics – applied, miscellaneous and mathematical geology.

Introduction
The ability to understand and especially to interpret geophysical data is an essential skill for any earth-science graduate. This is especially true in a country such as Australia where most geology majors find employment as earth scientists with local oil or mining companies. Thus, the students are primarily interested in the use of geophysics in resource exploration and need to be able to both interpret geophysical data and integrate it with geological information and observations. Nevertheless, it is important they have a reasonable understanding of the procedures that led to the dataset to be interpreted. This will enable them to recognise artifacts and also appreciate the limitations that are an inherent part of many types of geophysical data.

Teaching geophysics to geology majors creates particular problems (Dentith and Trench, 1992). Traditionally, geology students have comparatively low levels of numeracy and, more importantly, are uncomfortable with the equation-based analytical teaching approaches used in, for example, physics. The problem is exacerbated by the fact that there are frequently a limited number of more numerate individuals within geoscience classes who may be planning to major in, for example, geophysics or engineering. It is the experience of the writers that it is not necessary to completely remove the numerate aspects of geophysics in order to educate geoscience students in the fundamentals of geophysics. However, it is essential to provide time for adjustment to a more numerically based approach and to build confidence within the class in the use of equations as the basis for their understanding.

This paper describes an exercise and a related computer program that are specifically designed for geology majors encountering geophysics for the first time. However, suggestions are made for modifications to retain the interest of more numerate students. The gravity method is chosen as a vehicle for the introduction since, in the opinion of the writers, this is the conceptually most easily grasped of the various geophysical methods, basically requiring a familiarity with simple equations and a passing acquaintance with the forces associated with rotating bodies. Broadly applicable geophysical concepts such as data reduction, anomaly separation, and simple interpretation methods can also be introduced within the context of the gravity method and are an important aspect of the exercise. In addition to an understanding of the gravity method itself, it is intended that, when more complex geophysical methods are introduced, the necessary confidence and familiarity to tackle the subject will already have been created.

Finally, there is clear evidence that students increasingly want to see an obvious link between what they are being taught and their future employment. Academic exercises that may be just as relevant in terms of principles are noticeably less well received than those whose "real-life applications" are more obvious. For this reason the exercise that has been devised uses the context of geophysical exploration for manganese in Western Australia. The exercise is described at the end of this paper, which first concentrates on the methodologies that comprise the exercise.
Gravity Method

A good reason for beginning a geophysical course with the gravity method is that most students will be familiar with the basic concepts of gravity, although experience shows that only a minority are aware or recall that gravity is not constant at 9.81 m/s² across the entire Earth's surface. Low-level succinct reviews of the concepts of gravity can be found in Hewitt (1989) and Chapman (1995). The latter text is particularly useful since it uses earth-science examples and its relevance extends beyond geophysical courses. There is also the opportunity to refer to familiar ideas, such as Hooke's Law when describing how gravity is measured, and also to entertain the class with asides regarding such colourful and interesting historical characters as Robert Hooke and Isaac Newton (see for example White, 1997).

As a starting point, students need to be familiar with the form of the gravitational equation, specifically the fact that the attraction between masses is proportional to the product of the masses involved and inversely proportional to the square of their separation. Fortunately this equation is very simple, and it provides an easy framework for understanding the use of gravity in the context of geophysical exploration. More importantly, it allows the students to gain or regain confidence in basing their understanding on a mathematical expression.

The reader is referred to Kearey and Brooks (1991) for a straightforward explanation of the essentials of the gravity method. Fundamentally, variations in gravitational acceleration can be used to detect differences in density in the sub-surface. From the gravity equation, it is easy to show that rocks of relatively high density cause increases in gravity (positive anomalies) and vice-versa. Also, the amplitude and wavelength of the anomaly is critically dependent on distance between the density difference and the observation point. It is important that students understand that a particular measurement of gravity is the result of not only the subsurface geology but also a number of other factors whose combined effect may be many times that of the geology. Based on this simple idea, the concept of data “reduction” of geophysical data can be introduced. Fortunately the corrections applied to gravity measurements can readily be understood in the context of the gravity equation.

Reduction of Gravity Data

The process of removing variations in the gravity field that do not result from density contrasts of interest is an essential precursor to the interpretation of the data. This “reduction” procedure consists of calculation of the corrections briefly described below. For a more complete description, the reader is referred to Kearey and Brooks (1991), or, indeed, virtually any other geophysics textbook. Note that two units of gravitational acceleration are in common use in geophysics. The gravity unit (g) is the SI unit and is equal to an acceleration of 1 m/s²; the alternative, the milliGal (mGal), is equivalent to 10 gz. The milliGal will be used throughout this paper.

- Calibration Factor. All gravity meters have an individual calibration factor to convert their readings to either gravity units or milliGals. Applying this correction is simply a matter of multiplying the instrument reading by the calibration factor. In fact the newer instruments apply this correction automatically.
- Drift Correction. Gravity meters are subject to drift. That is, the same instrument will give a different reading over time in the presence of the same gravitational acceleration. The change in reading is gradual and approximately linear and so can be monitored through repeated readings at reference (base) stations during the course of the survey. In fact, drift rates of modern gravity meters are very low, a fact not normally evident in most textbooks.
- Tidal Correction. In addition to the temporal drift of the instrument, there are effects associated with the gravitational effects of the sun and moon. These effects provide a convenient context to illustrate the applicability of the gravity equation. The cyclical nature and comparatively low amplitude of these effects can be easily explained based on the relative positions and masses of the sun and moon. More perceptive students will recognise that the earth itself will be distorted by the attractions, and hence the distance from the centre of the earth will also be modified. The validity of using drift corrections to account for tidal effects can also be discussed.
- Latitude Correction. The earth's gravitational attraction is significantly greater at the geographic poles than at the equator. The variation is caused by the centrifugal acceleration associated with the rotation of the earth and the associated fact that the equatorial radius is larger than the polar radius. This overall effect is counteracted by the associated differences in mass underlying the point of observation. The gravity equation can be used to explain the consequences of a non-spherical Earth. Variations in gravity with latitude are described by international reference formulae that determine a theoretical value for gravity as a function of latitude. A simpler approach suitable for small-scale surveys is to approximate the north-south gravity gradient with respect to latitude, remembering the sign difference in the northern and southern hemispheres.
- Elevation Correction. The results of variations in the distance of the point of observation from the centre of mass of the earth are removed by determining a correction that is effectively equivalent to vertically translating each observation to a horizontal datum surface. The correction has two components, both of which are easily explained from the gravity equation. The free-air correction only accounts for the effect of the difference in elevation between observation and datum. The correction is positive for an observation above the datum level. The second part of the correction, the Bouguer correction, accounts for the gravitational effect of the rocks between the observation point and the datum level. When the observation is made above the datum level, part of the observed gravity is due to the attraction
of these rocks. This causes the measured gravity to be "too high" and hence in this scenario the Bouguer correction is negative. The Bouguer correction is based on the approximation of the rocks between observation and datum in terms of an infinite slab whose thickness is equal to the height difference. The density of the slab must be defined.

- Because the Bouguer correction is based on the gravitational effect of a slab, it assumes that the topography surrounding the gravity station is flat. Since this is unlikely to be the case, correction should also be made for the surrounding topography. The calculation of the correction is relatively simple. However, the acquisition of the necessary details of the topography and the density of the associated rocks may be a significant task. For this reason, terrain corrections are often ignored.

The discussion of the various corrections provide ample opportunity for students to revisit basic concepts of gravity and, particularly, gain confidence that the gravitational equation really can be easily invoked to explain the reduction methodology. A simple computer program, GRAVANOM, has been developed to illustrate the affects and relative magnitudes of the different corrections in different circumstances. The program is described in more detail in the Appendix. However, GRAVANOM is fundamentally very simple. The input is a profile of observations, two base station readings, and their elevations. Various reduction and survey parameters can be changed and the affects on the final Bouguer gravity anomaly can be viewed immediately. Simply challenging students to explain the changes in Bouguer anomaly as a result of modifying the various parameters has proved to be a useful exercise. If a class contains more numerate individuals, the reduction procedure, which in fact is not at all complex, can be understood very quickly. When this occurs student interest can be maintained by making available copies of an interesting paper by Rymer (1994) that discusses reduction procedures and the use of gravity data as a precursor to volcanic activity.

Regional-Residual Separation

It is very likely that the area of a gravity survey contains all or part of more than one anomaly. In fact this is often the case with other geophysical methods as well, for example self-potential and magnetic surveys, and as such the problem has general applicability. The most common manifestation of this is that the local anomaly, which is the object of the survey, is superimposed on a longer wavelength anomaly (Figure 1a). The latter anomaly is often referred to as the "regional" field. The identification of this, and its subtraction to leave just the "residual" anomaly which is of interest, is known as regional-residual separation. There are a number of ways to achieve this. The easiest is simply to interpolate, by eye, the regional anomaly across the area occupied by the residual anomaly. This is often called a graphical approach. As the regional variation is usually not complex, in profile it can usually be represented by a linear or simple curvilinear form. Alternatives to this approach include fitting a low-order polynomial to the data by least-squares and wave-number filtering. The latter methods have the advantage of being entirely free of interpreter bias. However, some geological knowledge in assigning the regional anomaly is often of considerable use, and the objective choice associated with the manual approach can offer significant advantages. The residual anomaly, and hence its interpretation, is often greatly affected by the choice of regional. This last point is a key aspect of the practical exercise described below. The range of methods for regional-residual separation provides an opportunity to accommodate students with differing levels of numeracy. For example, the less numerate students can apply the graphical approach, whilst the more numerate can be invited to explore some of the more numerical alternatives which are not difficult to implement using graphing software in common use. Descriptions of suitable methods can be found in Rao and others (1975), Agarwal and Sivaji (1992), and Zeng (1989), among others.

Interpretation of Gravity Data

Having isolated the residual anomaly, its interpretation can begin. Here we are concerned only with
the interpretation of profile data, but it is important to emphasize the use of a map of the gravity anomalies to determine whether the anomaly of interest should be regarded as two- or three-dimensional. A two-dimensional anomaly is continuous perpendicular to the profile such that its length is significantly more than the wavelength seen within the profile. The scenario involved in the practical exercise is three-dimensional since the anomaly is sub-circular in plan view, and the discussion will be limited to this kind of anomaly.

Profiles of gravity data can be analysed in terms of their gradients and half-width \((x_{1/2})\) to impose limitations on the source of the observed anomaly (Figure 1b). The half-width of an anomaly is the horizontal distance over which the anomaly decreases from its maximum value to one half of this value. For a three-dimensional anomaly, if the assumption is made that its cause can be approximated by a point mass, assuming the source body is roughly spherical, then the depth \((z)\) to the point mass or centre of an equivalent sphere is given by:

\[
    z = 1.305 \times x_{1/2}.
\]  

(1)

Note that, since this is the depth to the centre of the sphere, the depth to its top will be less. A second approach uses the anomaly maximum \((\Delta g)\) and the maximum horizontal gradient \((\Delta g/\Delta x)\). In this case the maximum depth to the centre of the sphere is given by:

\[
    z < 0.86 \left( \frac{\Delta g}{(\Delta g/\Delta x)_{\max}} \right).
\]  

(2)

These are useful for initial interpretation of anomalies, since they can be quickly used to determine the depth to the source to see if it is potentially of economic significance, for example, an ore body at shallow depth. There are equivalent formulae for different source models, for example, horizontal of vertical cylinders. In the authors’ opinion, knowing formulae/ rules of thumb such as this is extremely useful for both geologists and geophysicists and, hence, is an important aspect of the practical exercise.

A second aspect of the interpretation of gravity anomalies that can be important in mineral exploration is the concept of excess mass \((M_e)\). The shape of the body responsible for a gravity anomaly cannot be uniquely determined from the anomaly itself. However, the actual addition or deficit in mass that is associated with the higher or lower density material that is replacing the “normal” country rock can be uniquely determined. The method can be useful for estimating the tonnage of ore bodies, and it is in this context that it is introduced in the exercise. The excess-mass calculation involves the surface integration of the gravity anomaly over the area in which it occurs. In applying this procedure, it is essential to correctly remove the regional field so the residual anomaly tails to zero. A simple expression exists for the excess mass associated with a point source as can be assumed in the example in the practical exercise.

\[
    M_e = \frac{\Delta g z^2}{G}.
\]  

(3)

Note that \(z\) is in metres and \(G\) is the gravitational constant \(= 6.67 \times 10^{-11} \text{ m}^3\text{kg}^{-1}\text{s}^{-2}\). Therefore gravitational acceleration in milliGals must be converted to m/s\(^2\).

To compute the actual mass of the body \((M)\) requires knowledge of the densities of the anomalous (ore) body \((\rho_1)\) and the country rocks \((\rho_2)\).

\[
    M = \frac{\rho_1 M_e}{\rho_1 - \rho_2}.
\]  

(4)

Note that the density of the country rocks \((\rho_2)\) should be that used in the Bouguer correction.

It is also possible to estimate the dimensions of the sphere that is approximating the body and hence the maximum depth of drill hole needed to test the anomaly. This is simply a matter of converting the density and mass of the body to a volume and hence determining the radius of the sphere. Since the depth to its centre is known, the depth to its top is easily determined.

**Manganese Mineralisation in the Pilbara Region, Western Australia**

Western Australia is not a large producer of manganese on a world scale, but mining of a number of deposits occurs in the eastern Pilbara area in the northwest of the State. At Woodie Woodie in the northeast of the region, manganese mineralisation occurs as cavity fillings in the Proterozoic dolomite and chert. Geophysical exploration for such manganese deposits has been described by Dentith and others (1994). Gravity surveys are an important exploration tool, taking advantage of the density contrast between ore (density \(13.8 \text{ g/cm}^3\)) and host rocks (density between 2.0 and 2.7 \text{ g/cm}^3\)). Typically, gravity measurements are made on a 50 m grid, since the deposits are quite small, and areas of positive anomalies are selected for follow-up drilling. The practical exercise is based on the example of the Lox prospect described by Dentith and others (1994), which in turn is based on open-file exploration reports made to the Western Australian Department of Mines by Preusse Ag Australia Pty Ltd. Note however, that the real data have been modified to facilitate the exercise.

At the Lox prospect there are outcrops of massive ferruginous manganese together with iron-stained chert breccia. Gravity surveys showed the former to coincide with sub-circular positive gravity anomalies with amplitudes of 0.5 to 1.4 mGal (Figure 2). However, these anomalies are obscured by an approximately east-west gravity gradient. Calculations of excess mass on the southern of the two anomalies indicated a deposit of about 2.0 Mt. However, the problems of removing the regional gravity gradient made this figure uncertain. Drilling intersected between 9 and 36 m of massive manganese beneath a haematite cap 10 to 20 m in thickness (Figure 3). Unfortunately the deposit was found to consist of a high-grade core surrounded...
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Figure 2. Gravity and geological maps of the Lox manganese prospect, Western Australia. a) observed gravity, b) regional gravity, c) residual gravity. The location of the section in Figure 3 is indicated by the horizontal line at 1000N.

Figure 3. Gravity profile and geological cross section across the Lox prospect at 1000N. See Figure 2 for location. From Dentith and others (1994).

by shells of mixed iron-manganese oxides, haematite, and limonite. The result was that of the 2.0 Mt calculated excess mass; only a nucleus estimated at between 0.5 and 0.6 Mt contained commercial-quality manganese oxides.

Practical Exercise
At the beginning of the exercise, the students are given a), a description of the manganese deposits in the Pilbara region, b) an outcrop map of the Lox prospect, c) a map of Bouguer gravity across the Lox prospect, and d) a set of gravity observations which cross the centre of the anomaly associated with the manganese mineralisation. The exercise consists of reducing the data, isolating the residual anomaly, and then some basic interpretation. The specific aims of the exercise are to 1) illustrate the significance and nature of the different causes of variations in gravity observations, 2) introduce the concept of overlapping anomalies of different wavelength and the problems of isolating the feature of interest, and 3) introduce simple methods for assessing gravity anomalies to the extent that an explorationist can quickly determine whether the observed feature is of significance and consistent with their geological knowledge/hypothesis.

Having familiarised themselves with the local geology and exploration philosophy, that is, the association of manganese mineralisation with positive gravity anomalies, the first task is to reduce the observed gravity to Bouguer anomaly. This is easily achieved using standard spreadsheet software. Alternatively a partially completed spreadsheet can be provided and the gaps filled by manual calculation. In the latter case, the length of the exercise can be varied according to the number of entries left to be filled to complete the reduction process. Note that a concept that often gives students problems is whether to add or...
subtract particular corrections. It is considered particularly important for students to recognise the relative magnitudes of the different corrections, how they vary across the survey area, and how they are related to effects such as topography. To assist in the understanding of the reduction of the data, the GRAVANOM program can be used.

Reducing the gravity observations and plotting the Bouguer anomaly make it clear that there is a significant regional gradient. The students must make a decision as to how the regional is interpolated across the residual anomaly that is associated with the mineralisation. They then estimate the regional effect, by one or more means, and must plot the residual anomaly. This anomaly is then interpreted using the equations given above, since the description of the mineralisation shows it can reasonably be approximated by a sphere. The residual anomaly is then used to calculate the excess mass using equation 3 and also the total tonnage (equation 4) and depth to the ore body. Of course, if time permits, the gravity anomaly could also be modelled using standard software packages.

Up to this point, the complication of the varying grades (and thus density) of manganese has not been raised but can easily be incorporated into the exercise by giving the students the results of drilling the anomaly. Also, the subjective nature of the regional-residual separation is responsible for significant variations in the estimated size of the manganese deposit, as is illustrated by the different results obtained by the students. These uncertainties were actually considered in some detail during the original exploration process after the final tonnage of ore was found to be significantly less than expected. This is a convenient vehicle for initiating a discussion on uncertainties in the whole reduction and interpretation exercise. Alternatively, it can be used as the basis for a follow-up assignment.

Concluding Remarks

The above description is intended to share some ideas about teaching geophysics to geologists. Also, a "real-life" example is presented that can be used as the basis for an introductory practical class. The exercise is continually being developed, but what has been described has proved to be a useful first introduction to geophysical exploration, especially in terms of building confidence to work with numerical concepts and data.

The GRAVANOM program is one of a suite of geophysical programs currently being developed specifically for teaching purposes and hence is designed to be easy to use without being particularly sophisticated. These programs convert exercises that involve hand calculations to computer-based exercises. This allows the students far greater time to explore the implications of a particular aspect of geophysics within the time constraints of an undergraduate practical class. Another program in the suite, SEISRESP, was described previously (Dentith and Wheatley, 1996). Both these programs are on the Department of Geology and Geophysics’ WWW site, address http://www.geol.uwa.edu.au/geology.html. The gravity data for the above exercise is also available at this location.

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References


About the Authors

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Mike Wheatley is senior analyst/programmer with the Development Unit for Instructional Technology at The University of Western Australia. He gained a PhD in the area of geochemical mineral-exploration techniques from Imperial College of Science and Technology, London. Since then he has specialised in the use of computers in scientific applications. Currently he is involved in the commercial development of multimedia CD-ROMs for training, promotion, and information dissemination.
Appendix – Program GRAVANOM

GRAVANOM performs drift, latitude (approximate), free-air, and Bouguer corrections for a traverse of gravity observations and displays the gravity profile after each correction has been applied. The user can change the trend of the traverse, the datum level, and the elevations and rock types (density) to assess their effect on the corrections. The program makes use of the menu-based Macintosh user interface enabling the program to be quickly and easily mastered. The program runs on any Macintosh running System 7.0 or later that supports Color-Quickdraw. It requires approximately 500 kBytes of RAM and does not require a co-processor.

Figure 4 shows an example of the program’s model window after data have been loaded. The upper part of the window shows the gravity profiles; the lower shows a cross section of topography and geology with different rock types assigned various patterns. The vertical scaling is automatically adjusted so that the model fits within the bounds of the window. At the lateral location of each station the topography is defined by a series of nodes. These nodes can be dragged to change the elevation at that point, with the gravity correction automatically recalculated. Where more than one rock type is present in the section, the contacts may also be dragged laterally. Lastly, the trend of the traverse can also be dragged with automatic recalculation of the latitude corrections.

The main menu has three options, file, edit and model, plus the apple menu. Choosing the latter simply displays information about the program.

File menu

The file menu contains the import function which is used to create a new model file from a data file of gravity and elevation values along a traverse. A new window is created to display the model, which then becomes the selected model. Data files can be created in Excel – four columns are required, with the horizontal position in the first column, the elevation (in metres) in the second column, the gravity meter reading in the third column, and the time in the fourth column (expressed as hr.min). The first and last entry in the file are the two base (reference) station readings. The Excel file must be saved as text format (this is an option in the Excel save as command).

Figure 4. Model window from the program GRAVANOM. In the top of the window are profiles of gravity after the application of various corrections. The lower part of the window shows the topography along the profile and the outcropping rock type.
in ascending distance. A warning is issued if the first and last stations are not at the same range and elevation. Once these checks are satisfied and the data read in, the edit survey parameters dialogue is displayed (see below). Once a model file has been created and saved, it can be accessed on subsequent occasions via the open option. The revert option restores the selected model to its previously saved condition; that is, the effects of dragging the elevation profile and so forth are removed. The save table option is used to save the reduced data from the selected model. The output worksheet contains seven columns: the station number, the position along the traverse, elevation, raw gravity data, drift-corrected data, latitude-corrected data, and combined free-air/Bouguer corrected data. Finally, the file menu also contains a series of

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**Model menu**

Four options are available under the model menu, edit survey parameters, layer properties, number of layers, and axis ticks. The first is used to define the trend of the traverse, the reference latitude used in the approximate latitude correction, and the instrument calibration factor. The number of layers option allows different rock types to be added to the cross section; note that contacts are assumed to be vertical and reach the surface. The pattern and density of these rock types is changed via the layer properties option. The axis ticks option is simply used to change the axis-tick interval on any of the three axes displayed in the model window.

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