Investigating Theoretical and Time-Dependent Corrections to Gravity Survey Data

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Abstract

To understand the basic of analysing gravity data, a code was developed in MATLAB to perform theoretical and time-dependent corrections to gravity survey data. The time-dependent corrections involved in this study are the tidal drift and instrument drift. The raw gravity data is first plotted over time to show the initial trend of the gravity over investigation period. The theoretical gravity correction is based on the International Gravity Formula (IGF) and is applied first to the raw data to account for assuming the Earth as a reference ellipsoid. Then, the time-dependent corrections are applied one by one. At each point, the contour plot of the gravity is plotted. There is very limited difference between contour plots of raw data and data that is applied to the theoretical and tidal drifts where they all have a very sharp line in the middle of the plot. The contour plot makes more sense or shows a better smooth transition across the plot after the instrument drifts are applied.

Background / Theory

Gravity method is a versatile geophysical technique used to detect and identify subsurface bodies and anomalies within the Earth. This method has been used extensively in the hydrocarbon and mineral exploration over the years. Gravity surveys exploit the very small changes in gravity from place to place that are caused by changes in subsurface rock density (Telford et al., 1990). Higher gravity values are found over rocks that are denser, and lower gravity values are found over rocks that are less dense. A buried body represents a subsurface zone of anomalous mass and causes a localized perturbation in the gravitational field known as a gravity anomaly.

The acquisition of gravity data is done using a gravity meter or gravimeters where it measures the variations in the Earth's gravitational field. Most commonly used gravimeters measured the spatial and temporal change in gravity or its gradient rather than the absolute value of gravity intensity. This is due to the high sensitivity requirement of absolute measurements, which is of the order of 10^{-8} for 0.01 mGal resolution, compared with a significantly lower sensitivity requirement for relative instruments. Virtually all modern exploration gravimeters used in this way are based on the zero-length spring principle originally developed by LaCoste (1934) where the zero-length spring is used since they have tension proportional to absolute length, rather than to extension from unstressed length.

To make accurate measurements, the instrument must be level (aligned with the vector of the Earth's gravity field), in a place quiet enough to avoid vibrations (e.g., trucks rumbling by and earthquakes). The instrument should also be brought to the specified temperature a few days or at least several hours prior to the start of the survey to remove temperature gradients within the meter and achieving thermal and mechanical equilibrium to avoid sharp changes in temperature that effect the instrument's metal parts.

Gravity data acquisition is a relatively simple task that can be performed by one person. However, two people are usually necessary to determine the location (latitude, longitude, and elevation) of the gravity stations. Surveys are conducted by taking gravity readings at regular intervals along a traverse that crosses the expected location of the target. However, in order to take into account the expected drift of the instrument, one station must be located and has to be reoccupied every half to 1 hour or so to obtain the natural drift of the instrument. These repeated readings are performed because even the most stable gravity meter will have their readings drift with time due to elastic creep within the meter springs. The instrument drift is usually linear and less than 0.01 mGal/hour.

Gravity corrections is applied to observed or measured gravity data because the gravity varied for many reasons other than lateral variations in mass in the subsurface where gravity can also vary with latitude due to the shape and rotation of the Earth, the tides, and with variations in elevation. There are two types of time-dependent corrections that must be applied to gravity survey data obtained using a relative gravimeter: tidal drift/correction and instrument drift. In order to isolate the effects of lateral variations in mass, gravity corrections are needed to reduce the effects of these features of Earth/planetary gravity by removing all known gravitational effects not related to the subsurface density changes. Tidal correction is a correction made in gravity observations to remove the effect of the Earth's tides. For any location at the surface of the Earth, the distance to the Sun and Moon change continually with time, changing the gravity field, hence, the tidal correction is needed.

Normal (theoretical) gravity, g_t, is an approximation of the true gravity on Earth's surface by means of a mathematical model representing Earth. The most common model of a smoothed Earth is a rotating Earth ellipsoid of revolution. The International Gravity Formula (IGF) is the standard formula for the variation of gravity with latitude, θ, where it gives the variation on the surface of the reference ellipsoid. The first IGF that was proposed by the International Association of Geodesy and was in use from the 1930s up to the 1980s (Equation 1) where g_e is the gravity at the equator, A is a parameter characterizing the "gravitational flattening" effect causing increased gravity effect at the poles and B is a parameter related to the ratio of the centrifugal acceleration to the gravitational acceleration at the equator causing a decrease in gravity effect. From Telford et al. (1990), the most recent and commonly used version of the IGF (Equation 2) is that based on the GRS80 geodetic reference system (the parameters for the reference spheroid are a_e = 6378137 m and the flattening factor f = 1/298.257222101).

$$g_t = g_e[1 + A\sin^2\theta - B\sin^2 2\theta] \tag{1}$$

$$g_t = 9.780327[1 + 0.0053024\sin^2\theta - 0.0000058\sin^2 2\theta] \tag{2}$$

Methods / Algorithm

A set of gravity survey data file, **'goph_547_lab_2_data.mat'**, contains four arrays (**grav_survey_data**, **Xt**, **Yt** and **Zt**). The columns of **grav_survey_data** contain the following information (**base_point**, **day**, **time**, **total_time**, **x**, **y**, **z**, **g** and **dg_tide**) where the description of each information is given in Table 1. The other arrays **Xt**, **Yt** and **Zt** contain terrain survey data over a much wider region (±50 km to each side of the gravity survey region). The **Xt** and **Yt** matrices contain the eastings and northings, respectively, of each survey point in km and **Zt** contains the elevation data in metres ASL. Terrain survey points in **Xt**, **Yt** and **Zt** overlapping with the gravity survey region contain identical data. This data comes from a survey that was performed over a 50 km × 50 km region centred on a latitude of 49.1286°N where the presence of an ore deposit with significant density contrast to the surrounding rock at a depth of approximately 750 m was revealed by a prospecting borehole.

Table 1 Description of the information contained in the columns of **grav_survey_data**.

Column	Information	Description
1	**base_point**	An integer indicating whether that survey point was at the base station. If **base_point==1**, the point was at the base station at the beginning of a loop. If **base_point==2**, the point was at the base station at the end of a loop. Otherwise, the point was not at the base station.
2	**day**	A number indicating the day of the survey operation.
3	**time**	The time (in hours) on a given day.
4	**total_time**	The running time (in hours) of the survey starting at midnight on day 1. Note that operations began at just after 8:30AM on day 1, so the first survey point is not at **total_time == 0**.
5	**x**	The easting of the survey location in km.
6	**y**	The northing of the survey location in km.
7	**z**	The elevation (relative to sea level) of the survey point in km.
8	**g**	The measured gravity effect (in μGal) at the survey point. The first data point **g(1)** is the value of absolute gravity at the base station for the first survey measurement, calibrated to a measure of absolute gravity obtained using an absolute gravimeter used to occupy the base station. All subsequent values in column 8 are Δg values relative to the first data point. That is for each data point $i > 1$, $g_i = g_1 + \Delta g_i$ where g_1 is the value in the first row of column 8 and Δg_i is the value in row i of column 8.
9	**dg_tide**	The tidal variation (in μGal) obtained from regular measurements with an absolute gravimeter occupying the base station. The values are calibrated so that when the measured value of absolute gravity matches that from the IGF (i.e. $g_{abs} = g_t$), $\Delta g_{tide} = 0$. That is, these are tidal variations relative to g_t.

To observe the time variation of the relative gravity measurements (**g**) and the tidal variation (**dg_tide**), both measurements are plotted against **total_time** on a single set of axes. Since the relative reading of **g(1)** to itself is zero, the value of **g(1)** is set to zero only for this plot. MATLAB function **polyfit()** is used to estimate the best fit line for the **g** against **total_time** data plot.

MATLAB function **contourf()** is used to build a contour plot of the terrain survey data (**Xt**, **Yt** and **Zt**) so that the elevation in the survey area can be visualize. The mean elevation is calculated using MATLAB function **mean()** while the range of elevations (minimum and maximum elevations) are found using MATLAB function **min()** and **max()**. The minimum elevation in the survey area is selected as the datum elevation for the survey corrections and saved as **z_datum**.

A new three-column matrix (**x_sort**) with the **x**, **y** and **z** data in the columns is created. The matrix is sorted first by x-coordinate and then by y-coordinate using MATLAB function **sortrows()**. The sorted indices (the second output from **sortrows()**) are saved as **ind_sort**, which can be used later in sorting the gravity data. The unique entries from **x_sort** is then extracted using MATLAB function **unique()** and the unique indices (the second output from **unique()**) are saved as **ind_uniq**.

The sorted unique entries from **x_sort** is saved in three separate column vectors, **Xg**, **Yg** and **Zg**, where the number of grid points in these lists is verified to be a square number. The number of points in the x and y direction is computed as **Nx** and **Ny** where both are equal to the square root of the number of grid points in **Xg** and **Yg**. MATLAB function **reshape()** is used to convert each of **Xg, Yg** and **Zg** into a grid with the number of rows and columns in the output equal to **Nx** and **Ny** respectively.

A vector of corrected gravity data (**g_corr = g**) is initialized and then the raw data is saved (**g_raw = g_corr**). The absolute readings are computed by adding **g_raw(1)** (the initial base station reading) to the relative readings in **g_raw(2:end)**. The sorted and unique data is extracted by overwriting **g_raw** with **g_raw(ind_sort)** and then with **g_raw(ind_uniq)**. Next, the raw data (**g_raw**) is converted into a grid with the number of rows and columns in the output equal to **Nx** and **Ny** respectively using **reshape()**. A countour plot of **g_raw** on the grid defined by **Xg** and **Yg** is created using **contourf()**.

The theoretical gravity (**gt**) is computed using Equation 2. **g_corr** is the updated by subtracting **gt** from **g_corr(1)**. The current value of **g_corr** is saved as **g_norm**. **g_norm** are updated by adding **g_norm(1)** to **g_norm(2:end)**. The sorted unique data is extracted by overwriting **g_norm** with **g_norm(ind_sort)** and then with **g_norm(ind_uniq)**. Next, **g_norm** is converted into a grid with the number of rows and columns in the output equal to **Nx** and **Ny** respectively using **reshape()**. A countour plot of **g_norm** on the grid defined by **Xg** and **Yg** is created using **contourf()**.

g_corr is updated by subtracting **dg_tide** (tidal variation) from **g_corr** and the current value of **g_corr** is saved as **g_tide**. **g_tide** are updated by adding **g_tide(1)** to **g_tide(2:end)**. The sorted and unique data is extracted by overwriting **g_tide** with **g_tide(ind_sort)** and then with **g_tide(ind_uniq)**. Next, **g_tide** is converted into a grid with the number of rows and columns in the output equal to **Nx** and **Ny** respectively using **reshape()**. A countour plot of **g_tide** on the grid defined by **Xg** and **Yg** is created using **contourf()**.

The rate of instrument drift may vary over time, so, corrections are performed using linear interpolations in each loop (loop over the survey data using a for loop). Each time the end of a survey loop is reached (where base_point == 2), the value in **g_corr** at this point is saved as **drift**. The average **drift_rate** on this loop is then calculated as **drift / dt** where **dt = t_2 – t_1** is the difference in total_time between the end of the current loop (where **base_point == 2**) and the beginning of the current loop (where **base_point == 1**). The instrument drift only on this loop is corrected by subtracting **drift_rate * (t – t_1)** from each point for which **t_1 < t < t_2**. **drift** is subtracted from this and all future points in the survey. After this correction, the value of **g_corr** at the current point should be zero. Each time the beginning of a survey loop is reached (where **base_point == 1** except for the beginning of the first survey loop), the value of **g_corr** at that point is saved as **drift**. **drift** is subtracted from this and all future survey points. After this correction, the value of **g_corr** at the current point should be zero.

The value of **g_corr == 0** is verified for all points where **base_point == 1** or **base_point == 2** using a for loop. Then, the value of **g_corr(1)** is added to all other points in **g_corr**. A time series plot of **g_corr** against **total_time**. Finally, **g_corr** is sorted and reshaped into a grid following the same procedure that used for **g_raw**, **g_norm** and **g_tide**.

Results and Discussion

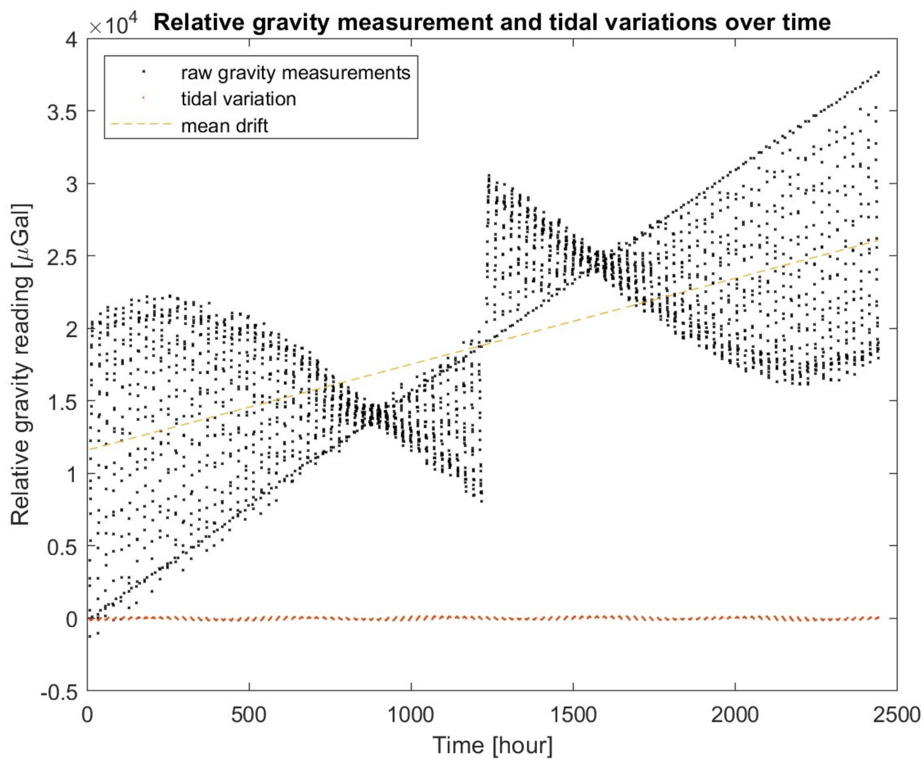

Figure 2 Relative gravity measurements and tidal variations plotted over time.

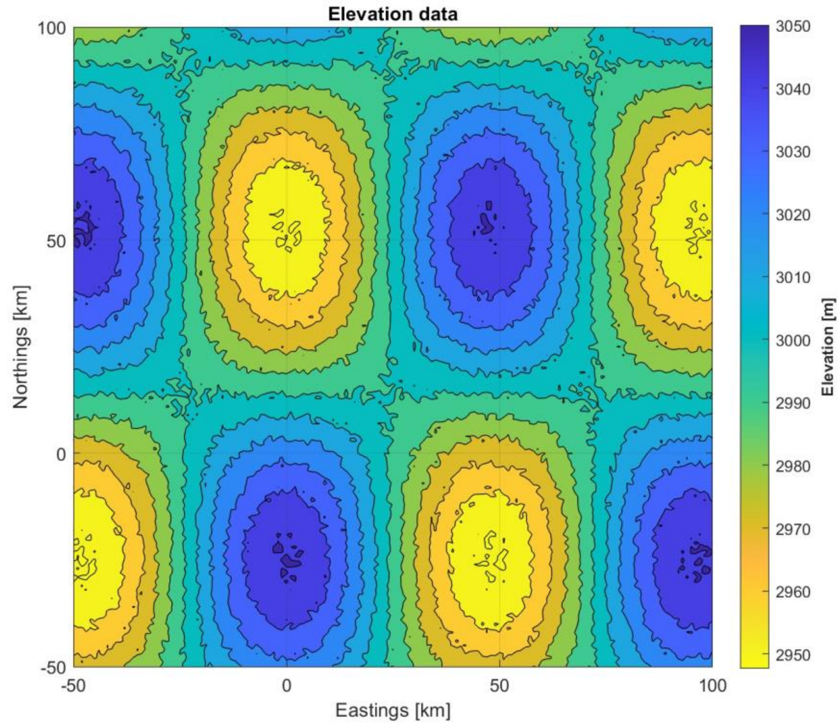

Figure 2 Contour plots of the elevation of the survey area.

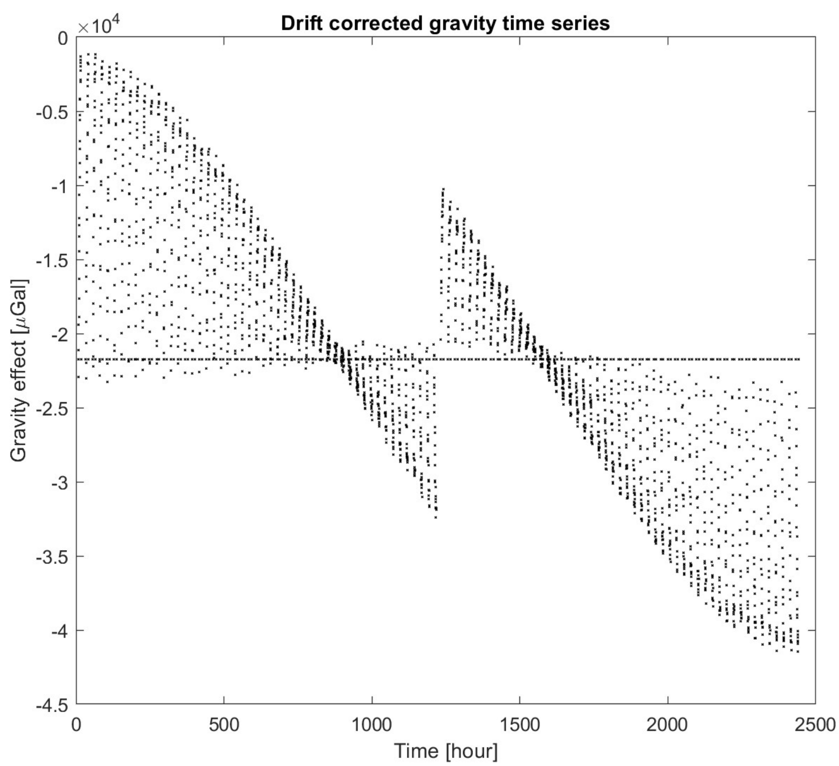

Figure 3 Drift corrected gravity plotted over time.

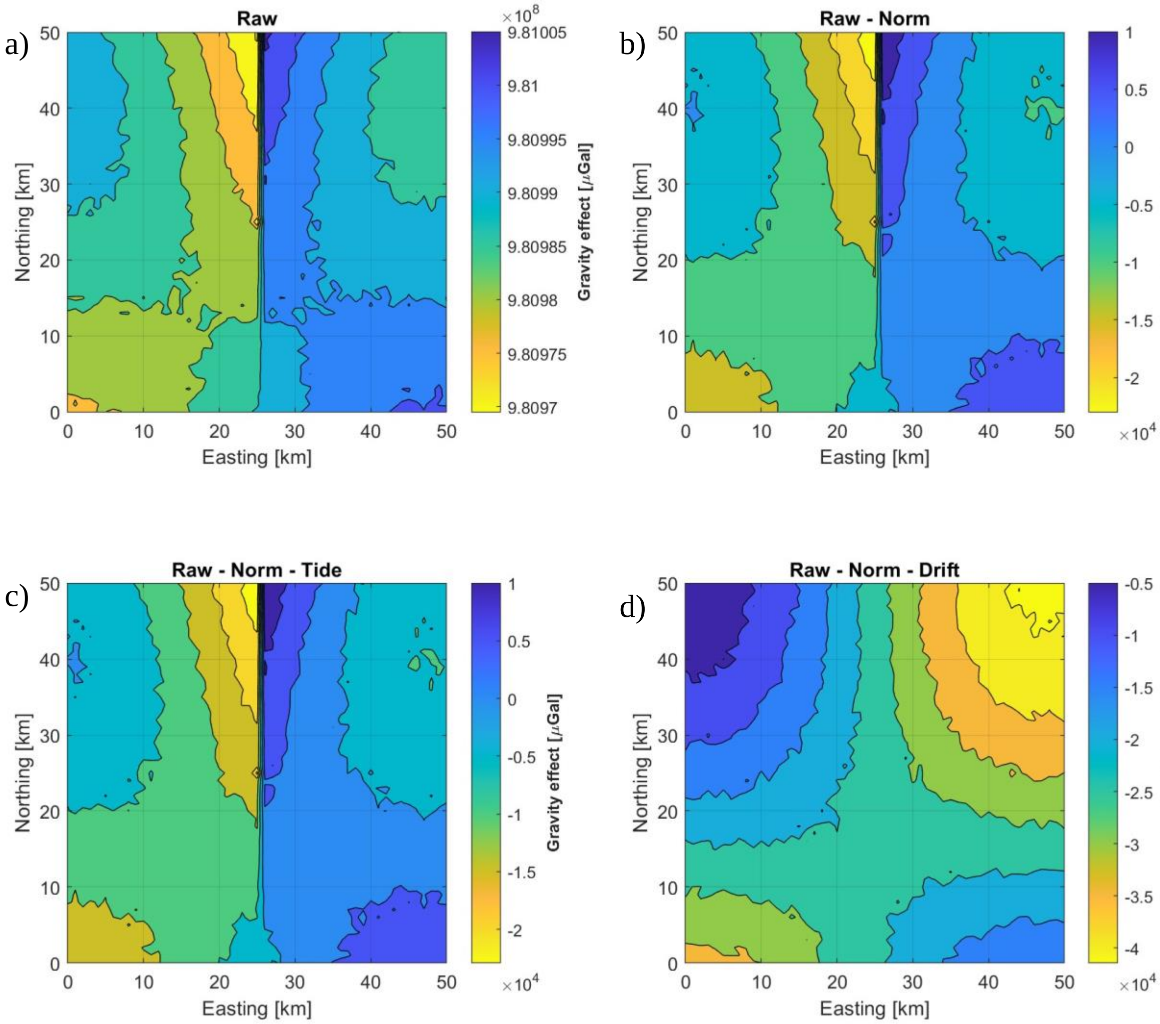

Figure 4 Contour plots of the raw gravity data (a), and the corresponding contour plots after corrections in the order due the theoretical gravity (b), tidal drifts (c) and instrument drifts (d).

From Figure 1, the raw gravity measurements over the survey period are plotted together with the tidal variation and mean drift. Over time, the gravity measurements generally decreased over time till around 1250 hours after the survey started and abruptly increases at that point and then decreased. However, the trend is not very clear as the ranges of some part of the plot are big and some parts are small. The tidal variations vary over the survey duration, following a sinusoidal shape. This does agree with the fact that the tidal effect is caused by the position of the moon (or time of the day) during the survey. The mean drift best fit line can be observed as a linear positive (increasing) line.

In Figure 2, the elevation contour plot of the survey area is plotted. The mean elevation is found to be 2965 m while the range of elevation is from 2948 m to 3052 m. The minimum elevation in the contour plot is chosen as the datum elevations for the survey corrections.

A regular grid built like in Figure 4 is unlikely to occur in a typical gravity survey due to the terrain of the survey area and differences in elevation making it hard to measure the real spacings between survey points. If the survey points are irregularly spaced, different MATLAB function has to be used to account for that.

Figure 3 is different than Figure 1 where it has a horizontal line where the values started on each time across the period. The trend is easier to be described since there is no overlapping areas of values because the values are either above or below the horizontal line.

Figure 4 shows the contour plot of the raw data before (Figure 4a) and after certain corrections. After applying the theoretical gravity correction, the contour plot (Figure 4b) does not look very differently than the raw contour plot where only small values changes occurred at certain part of the plot. The same happened when we applied the tidal drift or correction after that where there is only a very minor change in a small area of the plot (Figure 4c). All the three contour plots have roughly the same contour plots area and a very unsmoothed dividing vertical line between two very different values of the gravity in the middle of the plot (where the changes in values are very sharp or dramatic). However, as the instrument drift is applied at the end, the contour plots started making a huge difference. The sharp dividing line in the middle are now disappearing and making the final contour plot (Figure 4d) much smoother overall. From the figure, the biggest gravity corrected measurements is in northwest and some part southeast of the plot while the smallest gravity corrected measurements is in northeast and some part southwest of the plot.

Conclusion

Gravity surveys are incomplete without further consideration of other variables affecting gravity measurements. The raw gravity data cannot tell the complete information about the subsurface. The results of the investigation define the importance of correction to the data. Multiple consideration must be taken into account into correcting the raw data such as the duration or time of the day of the survey and the instrumental drift over time. The effect of the Earth as an ellipsoid also has to be taken into account. Only after applying the theoretical and tidal corrections, the data contour plot showed a much smooth transition in values across the plots.

References

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A. (1990) Applied Geophysics (2nd edn), Cambridge