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Airborne Gravity 2004

Abstracts from the ASEG-PESA Airborne Gravity 2004 Workshop

Edited by Richard Lane

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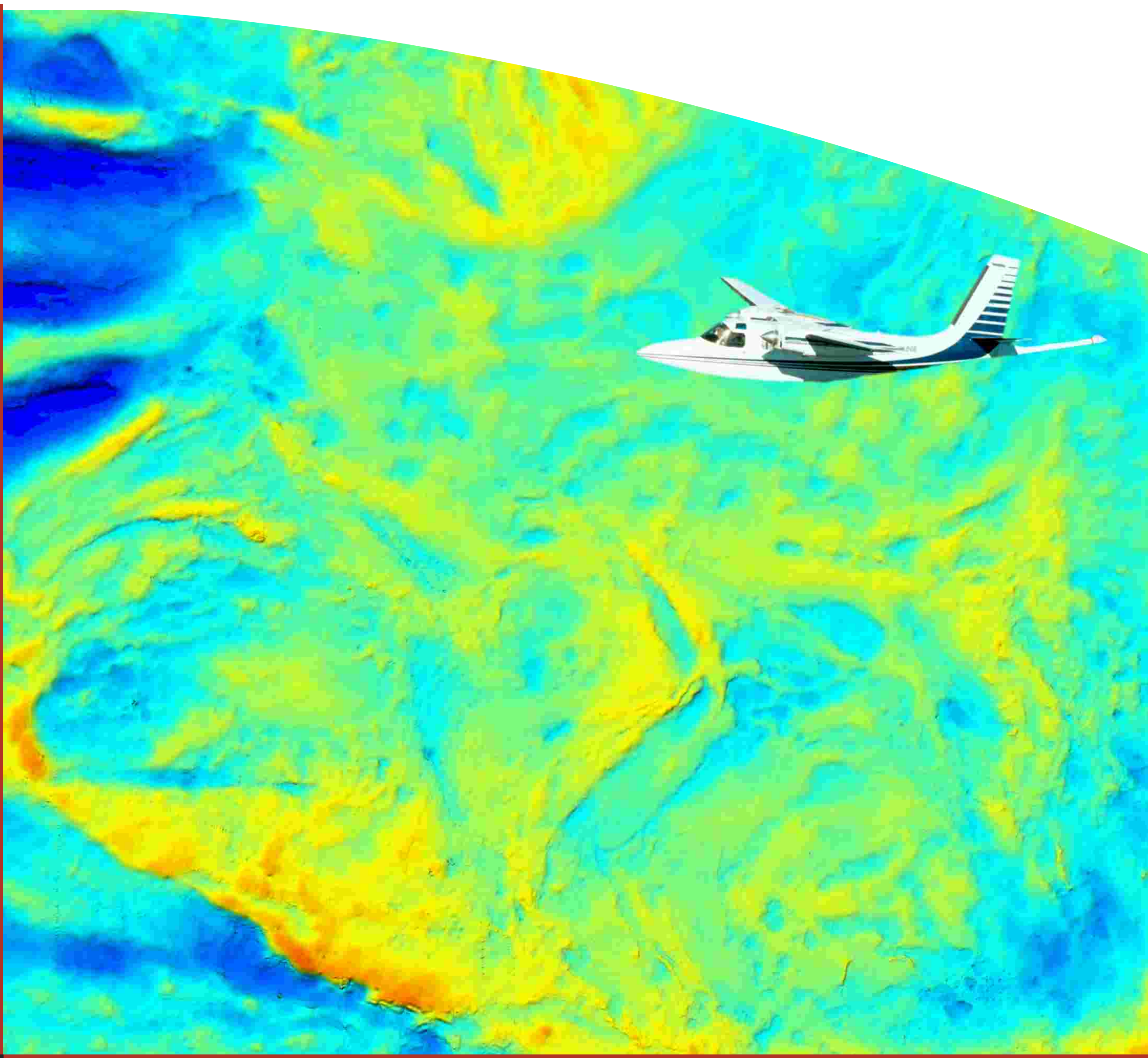

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Department of Industry, Tourism & Resources

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Preface

The "Airborne Gravity 2004 Workshop" was held in Sydney on August 15, in conjunction with ASEG-PESA Sydney 2004 (the ASEG's 17th Geophysical Conference and Exhibition). The aims of the workshop were to provide participants with a review of the current state of the art in airborne gravity instrumentation, to present case histories of the use of these methods in minerals and petroleum applications, and to distribute sample data sets. "Airborne gravity" is used in this context to include both airborne gravimeter and airborne gravity gradiometer methods.

The program was split into 2 sessions. The morning session provided a review of the systems, with presentations covering a number of systems currently in operation as well as some that are still under development. The focus shifted in the afternoon session to case histories, with examples from surveys spanning the globe; from Antarctica to the tropics of Papua New Guinea, from Africa through Australia to Canada.

To capture the essence of the day and to promote the ongoing development of airborne geophysical methods, speakers were invited to submit papers for inclusion in a workshop volume. The papers were reviewed prior to publication in this Geoscience Australia Record. Participants received a copy at the workshop, and additional copies of the Record are available on an ongoing basis from Geoscience Australia (www.ga.gov.au).

Units

Physical quantities should be expressed in SI units. The Bureau International des Poids et Mesures (BIPM) is the custodian of this system. To quote from their website (www.bipm.fr): “Its mandate is to provide the basis for a single, coherent system of measurements throughout the world, traceable to the International System of Units (SI)”.

The SI unit for acceleration is “metre per second squared” (m/s^2). The signals encountered in gravity surveys for exploration are small, and the prefix “micro” is commonly used (micrometre per second squared, $\mu m/s^2$). The gal (or Gal), equal to 1 cm/s^2, is a derived unit for acceleration in the CGS system of units. A prefix of “milli” is commonly used (milligal, mGal). In rare cases in the literature, a “gravity unit” (gu) may be encountered. In this publication, the $\mu m/s^2$ has been the preferred unit for gravity measurements, but mGal has been accepted.

$1\ \mu m/s^2 = 10^{-6}\ m/s^2$
$1\ mGal = 10\ \mu m/s^2$
$1\ gu = 1\ \mu m/s^2$

The gravity gradient is a gradient of acceleration and so the appropriate units are acceleration units divided by distance units. Thus, “per second squared” (s^{-2}) is appropriate in the SI system. Typical gravity gradients measured in exploration are extremely small, and the prefix “nano” is appropriate in most circumstances (per nanosecond squared, ns^{-2}). The eotvos unit (Eo), although not recognised in either the SI or CGS systems, is used almost universally in geophysics as the unit for gravity gradient measurements. It is equal to 1 ns^{-2}. In this publication, the ns^{-2} and Eo have both been accepted as units for gravity gradient measurements.

$1\ ns^{-2} = 10^{-9}\ s^{-2}$
$1\ Eo = 1\ ns^{-2}$

Acknowledgments

The Airborne Gravity 2004 Workshop Organising Committee would like to acknowledge the support of the ASEG-PESA 2004 Conference Organizing Committee and the Conference Secretariat. Support from Geoscience Australia, BHP Billiton and the NSW Department of Primary Industries - Mineral Resources helped to make the workshop a success. The diligence of Mario Bacchin, Katharine Hagan, Angie Jaensch, Jim Mason, Peter Milligan, Ian Hone and Roger Clifton enabled this Record to be produced in time for the Workshop, despite a tight deadline. Finally, a vote of thanks goes to the speakers who committed their time and energy to deliver presentations on the day and to compose this permanent record of the event.

Evaluation of a full tensor gravity gradiometer for kimberlite exploration

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Abstract

Test surveys of a full tensor gravity gradiometer (FTG) operated as the “Air-FTG™” system, were carried out over three sites in Botswana. The main purpose of this program was to evaluate the resolution of the system as well as the amplitude and spectral character of the noise. This information can be utilized to determine the effectiveness of the system for kimberlite exploration in other environments.

High resolution ground gravity data had previously been collected over all three of the FTG test blocks. These data were upward-continued to the level of the airborne drape surface before a first vertical derivative transformation was applied. After re-sampling at the locations of the airborne survey observations, the resultant data were subtracted from the airborne vertical gravity gradient data. Assuming that the ground gravity data are accurate and measured with sufficient sampling density, the residual provides a post-processing estimate of the noise of the airborne system data. The rms noise values obtained from the three separate tests carried out over a 10-month period progressively decreased from 15.4 Eo to 5.4 Eo as acquisition and processing methods were improved by the contractor. The airborne FTG data contain information for wavelengths down to approximately 400 m, which corresponds to a bandwidth of zero to 0.15 Hz given an average airspeed of 60 m/s. There is a significant amount of residual noise in the wavelength range of 300 m to 900 m, with longer wavelength noise also present which is thought to be due to mis-leveling of traverse lines.

The noise characteristics that were derived from the test surveys were used in a forward modeling exercise to determine the effectiveness of this system for kimberlite exploration. The results from modeling a range of kimberlite bodies of different sizes and depths of burial indicated that larger kimberlite bodies would be readily detected, but noise would limit the detection of smaller and more deeply buried bodies. The specifics of this result were, of course, contingent on the density contrasts assigned to the bodies and would need to be adjusted from one geological environment to another. The results of the modeling could be used as an input, along with line-km costs and a definition of the acceptable level of risk, to determine the optimal line spacing.

A number of products were calculated from the tensor components in an attempt to enhance the signals due to kimberlites. The most useful operator was found to be the determinant (I_2) of the gravity gradient tensor which incorporates information from all of the tensor components. This quantity tends to highlight kimberlite anomalies, but at the expense of a decrease in the overall signal-to-noise ratio.

Introduction

The ground gravity technique has been used successfully by De Beers in the discovery and delineation of kimberlites in a variety of geological settings around the world. However, due to the length of time required to collect ground data over large areas and the inadequate resolution and sensitivity of airborne systems in the past, the gravity technique has not been commonly used as a reconnaissance exploration tool by De Beers.

With the advent of airborne systems based on the Lockheed-Martin airborne gravity gradiometer technology (e.g., Falcon®, Air-FTG™), it appeared that the latest airborne systems might have noise levels and resolution that are suitable for reconnaissance kimberlite exploration (Liu et al., 2001). When the Air-FTG™ system was deployed on a fully commercial basis in 2003 (Hammond and Murphy, 2003), a series of test surveys were carried out to ascertain the noise levels and resolution of the system. This paper describes the results of these tests and provides modeling that demonstrates the effectiveness of the system for the detection of kimberlite bodies. The results of evaluating a number of enhanced products that can be derived from the full tensor measurements are also discussed from the perspective of improving the detection of kimberlite anomalies.

System evaluation

Typically, new geophysical systems are evaluated via a case study approach by flying test surveys over a number of economic bodies. Although such case studies are useful, economic kimberlites can have a very wide range of surface extents, shapes, depths of burial and density contrasts. Potentially economic kimberlites can range from sub-hectare bodies to over 100 Ha in size and can be intruded in Archaean basement through to Palaeozoic and Mesozoic aged sediments. The flying of orientation surveys over a small number of deposits may not provide adequate information to allow the effectiveness of a system to be predicted for a wide range of exploration scenarios.

In the role of a client, it is not always possible to obtain all of the information concerning operational noise levels and processing steps that are required to define the performance of the system without recourse to independent comparisons. By comparing airborne data from a new system with adequately sampled and accurate ground data, the character of the final data from the acquisition and processing system can be ascertained. The performance levels determined in this manner can be combined with information provided by the exploration team about the local geological environment, emplacement model, erosion level and weathering characteristics to develop a survey plan which sets out the limits of detection and balances the risks of missing an economic target balanced the survey costs.

Survey description

Three Air-FTG™ surveys were flown over blocks in Botswana during 2003 (Table 1). The surveys were carried out in different seasons; January (summer), July (winter) and November (spring). All of the surveys were within the Kalahari Desert where extreme daytime temperatures and turbulence are common in the summer months. The maximum temperature is rarely above 25 ^{o}C in winter, and the resultant lower levels of turbulence allow greater survey productivity.

Each of the Air-FTG™ test surveys covered an area approximately 25 km^2. Traverse line spacing was 200 m whilst the tie-line spacing was 2000 m. In-fill lines were occasionally flown. The flying height was a constant 80 m above ground which was controlled from radar altimeter readings. The aircraft was not equipped with a laser scanner for these surveys.

The data used to construct the digital terrain model for the test areas were acquired during the ground gravity surveys with a dual channel, differential GPS system. Since the survey areas generally possess only first order topographic variation, and given centimeter-scale accuracy from the DGPS measurement, the DTM based on these measurements more than met the 1 m accuracy required to produce a terrain correction with insignificant errors (Stone and Simsky, 2001). The terrain-corrected vertical gravity gradient (Gzz) data from the FTG survey over Test Area 3 are shown in Figure 1a.

The ground gravity data had been previously acquired for exploration purposes but their availability provided an ideal opportunity to compare these data with the output from the Air-FTG™ system. The ground measurements have a traverse line spacing of 100 m and station spacing of 50 m, and there are 13 600 ground stations in total. The data were collected with a CG-3 gravimeter, which has an observation error of less than 0.05 mGal. The vertical gravity gradient data derived from the ground gravity data had very little visible noise after being upward-continued to the 80 m flying height of the airborne survey (Figure 1b).

Noise and resolution analysis

In order to analyze the noise of the Air-FTG™ system, the Gzz data from the Air-FTG™ system were compared with the equivalent vertical gravity gradient data calculated from the ground gravity observations. The ground data were first upward-continued to the drape surface of the airborne survey. A first vertical derivative transformation was applied to produce vertical gravity gradient data. This response was then re-sampled at the same positions as the airborne data. The rms error between the ground and Air-FTG™ Gzz datasets was then calculated for each of the three areas (Table 1).

The improvement in rms error over time was thought to be largely due to the reduction of system noise and improvements in processing techniques. To some extent the poor result of the first survey can be attributed to the turbulent weather conditions at the time of this survey.

The results from the final test are thought to provide a reasonable estimate of what can currently be achieved on a production survey with good quality-control measures in place. A comparison of the ground and airborne data over Test Area 3 with the same sampling parameters is shown in Figure 1. The Air-FTG™ data were leveled and filtered by the contractor using proprietary algorithms without prior knowledge of the ground gravity response.

Table 1. Noise statistics for the Air-FTG™ test blocks.

	Survey Date	rms error	Maximum absolute error	Line-kms for the test block
Test area 1	January 2003	15.5 Eo	50 Eo	220 km
Test area 2	July 2003	8.5 Eo	31 Eo	410 km
Test area 3	October 2003	5.4 Eo	16 Eo	140 km

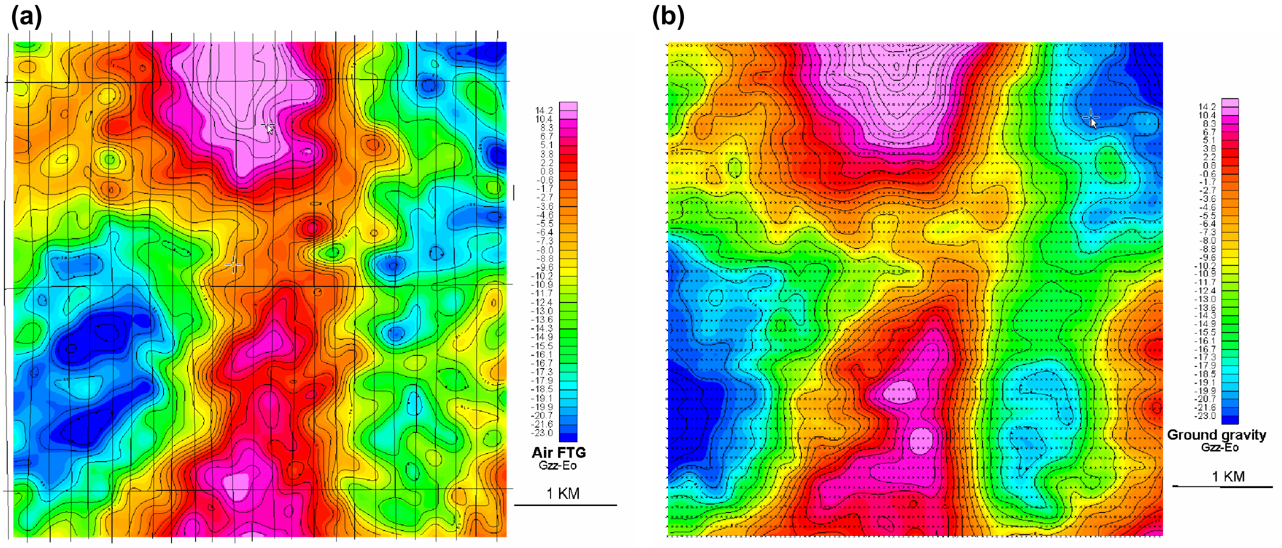

Figure 1. (a) (a) The Gzz component from the Air-FTG survey of Test Area 3, and (b) the equivalent Gzz response calculated from the upward continued ground gravity data. The flight-path of the airborne survey and locations for the ground stations are superimposed on the appropriate plots.

On visual inspection, the long wavelength features of the two data sets are similar including those that are of relatively low amplitude. However, there are a number of shorter wavelength anomalies, mainly present in the FTG data, which do not correlate between the two datasets. This is more easily seen by subtracting the ground response from the airborne data (Figure 2). Assuming that the ground data are accurate and adequately define the geologic signal, the difference grid represents the residual noise that is left after processing of the Air-FTG™ data. In addition to the expected single-line anomalies that would be due to short-period turbulence effects, there are several coherent trends and larger anomalies that are visible across several lines.

Average spectra of the differences between the processed FTG and ground gravity data calculated in the east-west and north-south directions are shown in Figure 3. A curve of scaled white noise that has been upward-continued to survey altitude has also been plotted for reference. The difference grid has spectral response similar to that of white noise at longer wavelengths (i.e., wavelengths greater than 700 m). The spectra show rapid attenuation, however, for wavelengths less than 400 m. Several factors combine to ensure that the upward continued ground data have very low spectral amplitude at short wavelengths; low noise levels in these data, the presence of relatively homogenous flat-lying geological cover units across the test area, and upward continuation (i.e., low-pass filtering) of these data to a terrain clearance of 80 m. To suppress noise in the raw FTG data, the contractor applies several proprietary processing algorithms. Although this low-pass filtering has been restricted to preserve kimberlite signatures, it is felt that there is little signal remaining following processing for wavelengths less than 400 m. The absence of response in either the ground or airborne data for wavelengths less than 400 m ensures that the difference grid between these two datasets also shows very low amplitude and these wavelengths.

Another feature of the difference grid is the presence of relatively long-wavelength anomalies (i.e., greater than 2000 m) that are elongated in the north-south direction. Variations in aircraft altitude and topography were eliminated as possible causes of these long wavelength anomalies. As proper tide, drift and loop procedures were employed during acquisition of the ground gravity data, the regional component of these data was thought to be accurately defined and unlikely to contribute to the difference grid. Some of the long wavelength variations are elongated parallel to the flight-direction, suggesting errors in the line leveling as being a possible cause. The anisotropy in the difference grid is also apparent in the amplitude spectra, which shows that amplitude variations in the east-west (i.e., across-line) direction are twice as large as those in the north-south (i.e., along-line direction.

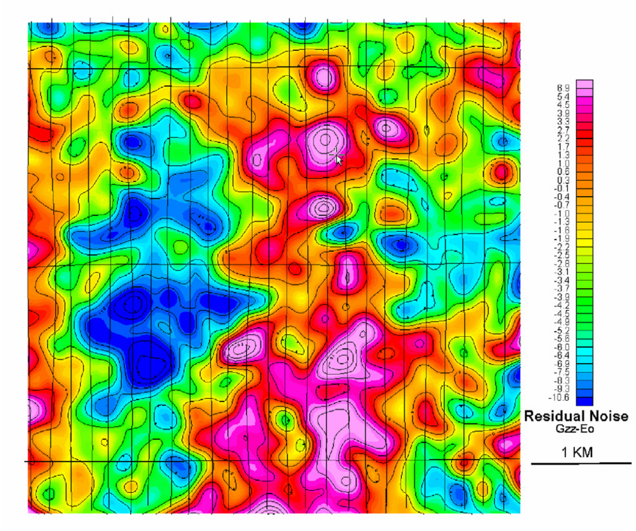

Figure 2. Image of the residual noise grid for Test Area 3 calculated by subtracting the Gzz derived from ground data from the Air-FTG Gzz data.

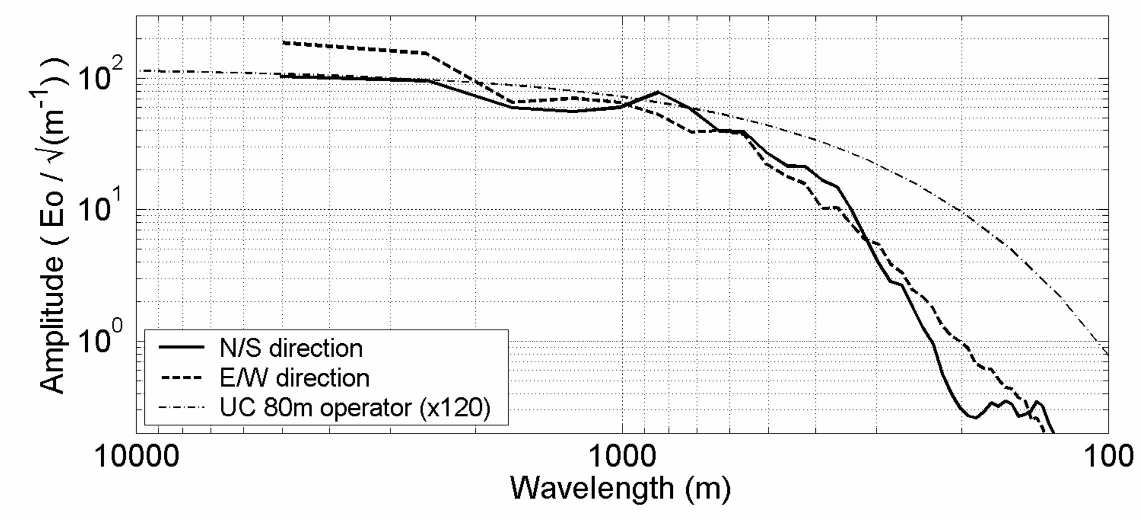

Figure 3. Averaged spectra for E/W and N/S directions from the residual noise grid calculated by subtracting the Gzz derived from the ground data from the Air-FTG™ Gzz data. A curve corresponding to scaled white noise that has been subject to an 80 m upward continuation operator has been plotted for comparison.

Assuming that virtually the entire signal has been eliminated for wavelengths shorter than 400 m and that the airspeed was roughly 60 m/s, the bandwidth of the measurements is zero to 0.15 Hz. The rms noise of 5.4 Eo is thus equivalent to a spectral density of 14 Eo/√Hz.

Of importance for kimberlite exploration, the difference grid and associated spectra show that the noise has relatively high energy for features with wavelengths of 300 m to 900 m. Noise in this bandwidth will have an impact on the detection of smaller kimberlites.

Detection of kimberlites

With an understanding of the noise that is present in the processed data from the Air-FTG system, it is possible to investigate the effectiveness of kimberlite detection in different environments with various survey parameters. Figure 4a shows the Gzz response calculated with ModelVision over a number of kimberlites with a range of surface areas (2 Ha, 6 Ha and 10 Ha) and depths of burial (20 m, 60 m and 100 m) sampled with a line spacing of 50 m. For this example, the model used was a simple disk with a density contrast of -0.3 g/cm^3 and a thickness of 100 m, representing the weathered cap and crater facies component of a kimberlite intrusion. To provide a realistic scenario, noise with an amplitude and spectral content as determined from the Air-FTG test has been added (Figure 4b). To test the effect of varying the line spacing, the data were re-sampled to simulate surveys with line spacing of 100 and 200 m (Figures 4c and 4d).

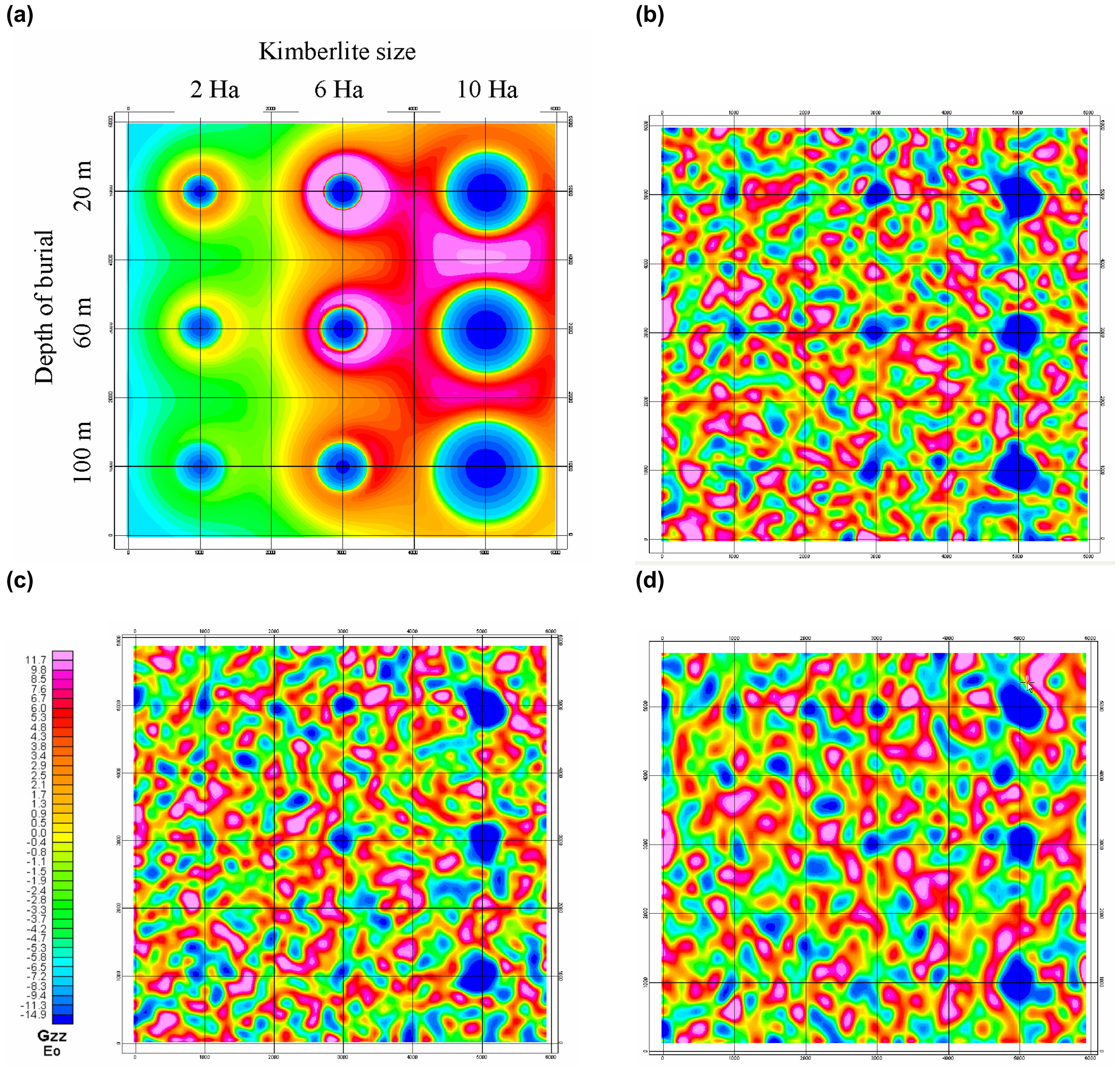

Figure 4. (a) Noise-free forward model response for kimberlites of different sizes at various levels of burial sampled with a line spacing of 50m. (b) Noise with an amplitude and bandwidth representative of the Air-FTG™ system has been added to the response shown in (a). The line spacing has been broadened to 100 m in (c) and 200 m in (d). A 1 km graticule is used with each image.

With 50 m line spacing, all of the modeled kimberlites can be seen but the amplitude of the response from the smaller and more deeply buried bodies is close to the noise level. It would be unlikely that an interpreter would be able to distinguish some of these anomalies from the residual noise, particularly with a geological background signal also present. Increasing the line spacing to 100 m and 200 m reduces the number of kimberlites that can be reliably interpreted, with only the 10 Ha bodies being readily visible at 200 m line spacing. Further modeling runs could be carried out to examine the effect of a more complex kimberlite model and changes to other variables such as the density contrast.

The selection of line spacing in a particular area is a balance between close line spacing to detect anomalies from economically viable targets and cost constraints. Given noise levels for the Air-FTG system, density models for the target body and host, survey costs per line km and a profile of the acceptable exploration risk, modeling can be used to select an appropriate line spacing that will provide an optimal cost-benefit. In areas where the density contrast is not well known or where higher levels of geologic noise are likely, the survey line spacing can be reduced (with a cost penalty) to mitigate the risk of missing potentially economic bodies.

Interpretation techniques for kimberlite exploration

Schmidt and Clark (2000) provide an overview of the advantages of utilizing the magnetic gradient tensor for interpretation, many of which are also applicable to gravity gradients. One of the main advantages of FTG data is that it can be used to highlight directional features and edges which are useful for geologic and structural mapping. Of paramount importance in kimberlite exploration is the identification of discrete anomalies thought to be derived from intrusive bodies. In practice, only the Gzz component can be used to visually select kimberlite targets because the other tensor elements have complex anomaly forms such as quadrupoles.

A number of products were derived from the tensor measurements to evaluate whether these products could enhance the Gzz component or bring components other than Gzz into the visual interpretation process. Higher-order derivatives, upward continuation and band pass filtering of Gzz data were all trialed, with the results confirming the well-understood advantages and disadvantages of these transformations.

The measurement of the full tensor allows the direct calculation of a number of scalar operators on a point-by-point basis. Pedersen and Rasmussen (1990) describe rotational invariants that do not change under coordinate transformation. Of particular interest is the invariant that they term "I_2" (Equation 10c in Pederson and Rasmussen, 1990) which is simply the determinant of the gravity gradient tensor. This quantity has the properties of increasing the resolution of anomalies over shallow sources while preserving the correct sign of the anomalies. An analysis of the rotational invariants was made by Dransfield (1994) and he found that these operators can reveal different and useful information contained within the gravity gradient tensor while avoiding the complex, and possibly misleading response of the individual tensor components. Dransfield demonstrated that the I_2 quantity responds best to point sources; this is a desirable characteristic in the context of exploration for kimberlites.

As anticipated, the invariant I_2 (Figure 5) increases the amplitude of the high frequency anomalies compared to longer wavelength features. There are some features that are more clearly visible in the I_2 plot which correlate with anomalies in the ground gravity data. However, there are a large number of high amplitude anomalies in the I_2 map which do not correlate with ground gravity responses. These features are suspected to be due to noise in the airborne data. Some of these noise anomalies are not visible in the Gzz plot and are therefore thought to originate from other tensor components. Although the I_2 operator appears to show some promise, it has a lower signal-to-noise ratio than the Gzz component and could draw attention to anomalies that are not of a geological origin.

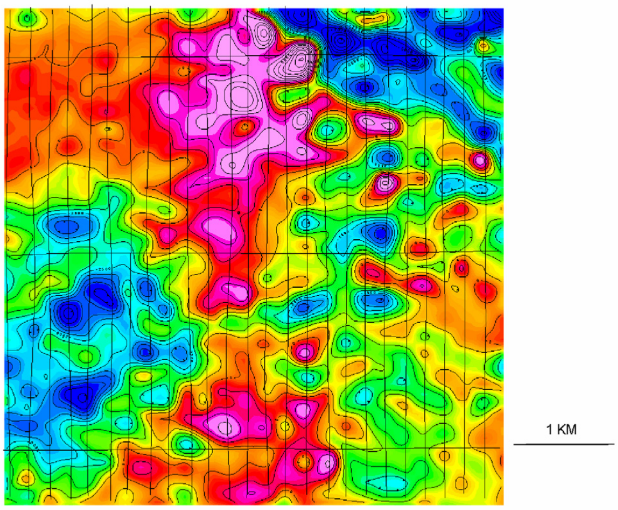

Figure 5. Image of the rotational invariant I_2, which is the determinant of the gravity gradient tensor measured by the Air-FTG system.

Conclusions

The Air-FTG system was trialed over three areas in Botswana. The FTG data were compared with ground gravity data which allowed noise levels for the final processed data to be estimated. The lowest rms error observed for the Gzz component was 5.4 Eo and this is thought to be a reasonable estimate for the noise in this component for the current implementation of the system. Filtering applied by the contractor to improve the signal-to-noise ratio removes most of the wavelengths less than 400 m, so this noise level is equivalent to a noise spectral density of 14 Eo/√Hz, assuming airspeed of 60 m/s.

A significant amount of the residual noise that remains after processing is in the range of 300 m to 900 m, which would impact on the detection of anomalies associated with kimberlites.
A long wavelength component was observed in the residual noise data and this was thought to be associated with errors in line leveling.

When integrated into a forward modeling exercise so that both signal and noise levels are considered, the noise estimated for the Air-FTG system would appear to significantly limit the detection of smaller and more deeply buried kimberlites. This could be mitigated somewhat by decreasing the flight line spacing. Larger kimberlites should be easily detected. Due to variability in host and target densities and depth of burial, forward modeling would be required in new exploration environments to derive an optimal cost-benefit for a planned survey.

For all practical purpose, the Gzz component was found to be the only single tensor component that was suitable for visual selection of anomalies thought to be associated with kimberlites. The rotation invariant I_2, the determinant of the gravity gradient tensor, was investigated and found to highlight some anomalies of geologic origin but overall reduced the signal to noise ratio of the data.

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