

## 50 Years of Kimberlite Geophysics, A Review

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### ABSTRACT

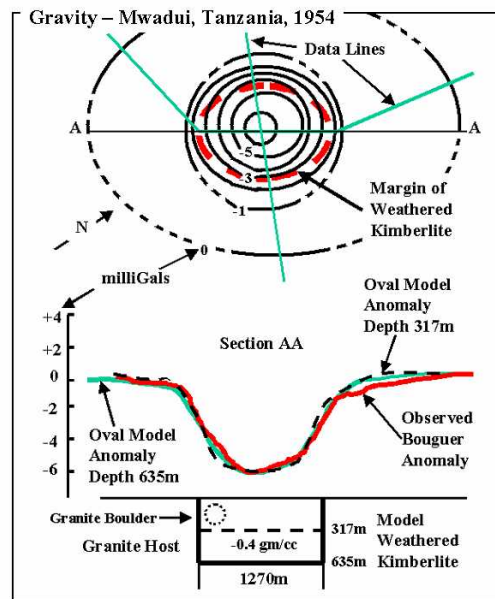
*The application of geophysical methods to exploration for kimberlites and their associated diamonds began over 50 years ago with the use of magnetic and gravity measurements. Within a decade, resistivity and later induced polarization were applied to the problem. By the 1970's both ground and airborne methods included magnetic and electromagnetic measurements. In the present decade, reflection seismic surveys have been successfully applied to imaging kimberlite intrusions. Also in the last decade, gravity gradiometry sensors mounted in aircraft have proven to have the resolution needed to detect the density contrasts useful for detecting kimberlites. It is now routine to process all types of geophysical data to produce sub-surface images that can be directly related to contrasts in lithology. During the course of this work much has been learned about the variability of the geophysical response of kimberlite. Differences in the effectiveness of techniques among kimberlites may be due to primary variations in the petrophysics of kimberlites and to their host rocks, or to local conditions. Detailed studies have shown significant variations of response within individual kimberlites. New sensor developments may advance future kimberlite exploration, but progress is more likely to come from better processing of multiparameter geophysical data and its integration with other geoscience data, both geological and geochemical.*

### INTRODUCTION

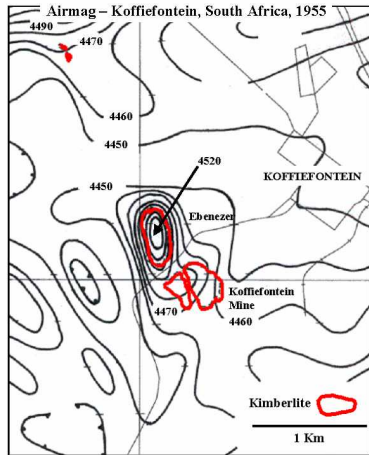
The basic principle of applying geophysical techniques to kimberlite exploration has been known for over fifty years. The purpose of this paper is to show the foundations of the application and the ways in which the application has advanced through the years. While some additions in method have been made in past decades, most of the 'new' geophysics has been refinements on the basic ideas and practices. The improvements have largely come about by learning the details of the petrophysics of kimberlite through direct application and through significant advances in the sensitivity of instrumentation as well as the manner of their use. This paper provides a brief tour through the past 50 years of application of geophysics to exploring for kimberlites and their associated diamonds, leading to the present era.

One of the seminal papers on the geophysics of kimberlite was presented at the first of the Decennial Conferences in 1967 (Gerryts, 1970). Gerryts quoted earlier papers, principally Russian in origin, dating as early as the 1950's. Gerryts presented most of the geophysical techniques in use today in the search for, and definition of kimberlite. Magnetometer, gravimetric and resistivity surveys were applied (Figures. 1, 2, 3). Induced polarization (IP) soon followed resistivity as a companion tool (Macnae, 1979). To these techniques were added electromagnetic (EM) (Macnae, 1979; Figure 4) and most recently seismic surveying (Power et al., 2004; Figure 5). Power

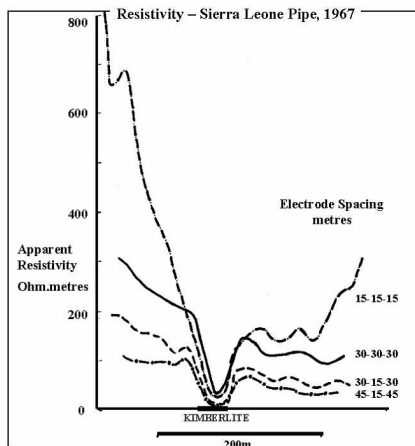
et al. also report the successful application of GPR (ground probing radar).



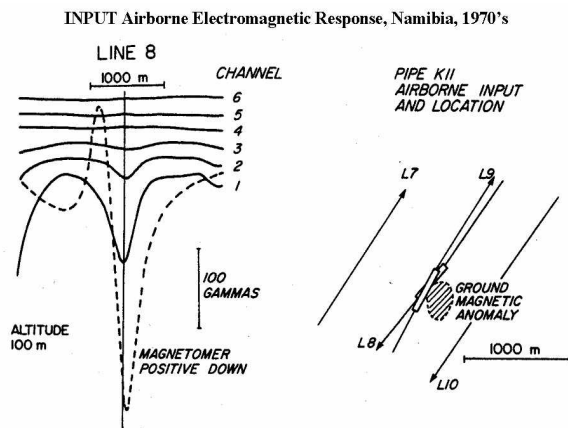
**Figure 1:** Ground gravity results over the Mwadui kimberlite pipe Tanzania, after Gerryts, 1970. Note that the model fits the field data very well at the top, but is little affected by extending the model to twice the depth.



**Figure 2:** Airborne magnetic survey from 1954 over the Koffiefontein kimberlite pipe, South Africa, after Geryts, 1970. Note that different elements of the kimberlite cluster have different magnetic response.



**Figure 3:** Resistivity survey over a kimberlite pipe, Sierra Leone, after Geryts, 1970.



**Figure 4:** Input airborne time domain EM and magnetic responses over a kimberlite pipe, Namibia, from Macnae, 1979.

All the basic geophysical tools used in mineral exploration, have been used in exploration for kimberlite. Magnetic, gravity and electromagnetic surveying have proven to be the most useful in detecting and delineating kimberlite rocks. There is a strong emphasis on airborne techniques followed by identification on the ground using the same parameters. While ground follow-up has been the traditional next-step, there is an increasing appearance of the direct testing of airborne results without the application of ground follow-up, as a result of the use of combining low-level high resolution surveys with global positioning system (GPS) control.

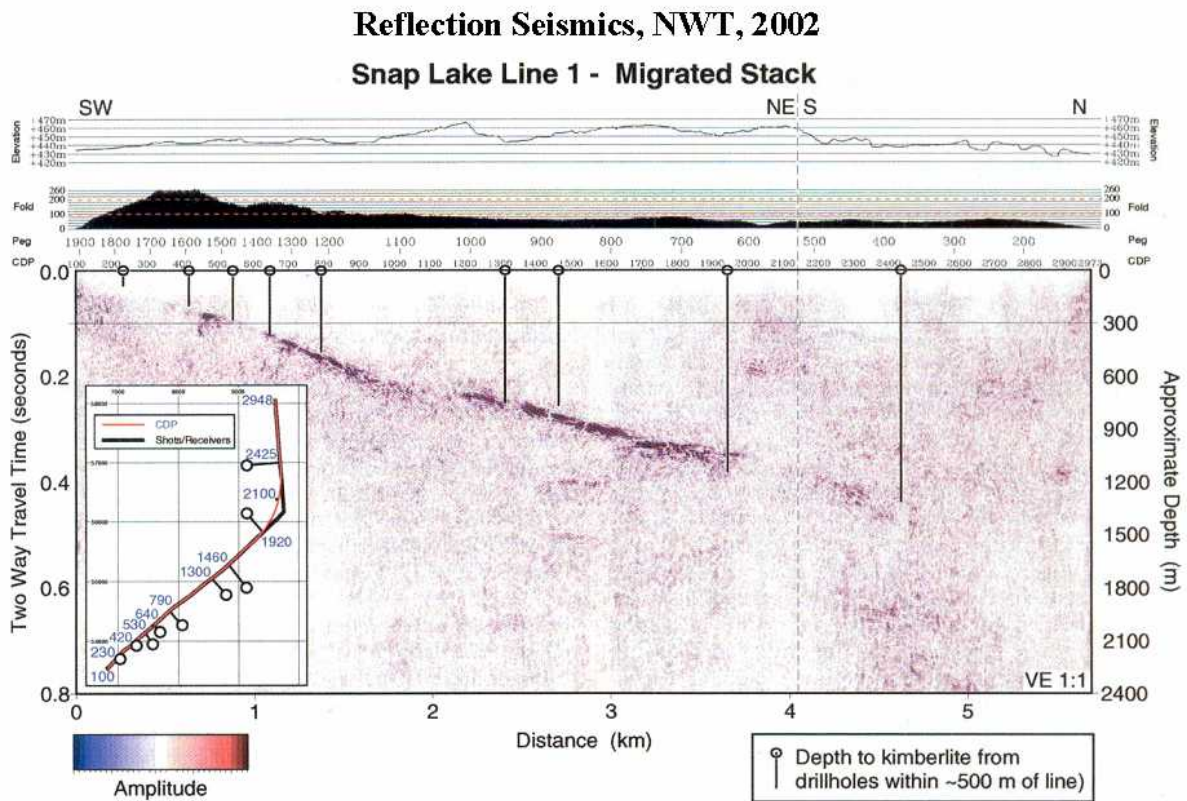
Early in the fifty plus year period, geophysical applications in kimberlite exploration were slow to be accepted and applied, as diamond exploration was narrowly defined both corporately and geographically. This pattern has changed significantly in the last 25 years, as many more companies have entered the field and exploration has expanded to favorable environments worldwide (Jenke, 1983; Smith, 1985; Reed and Sinclair, 1991; McKinlay, 1997; Guptasarma, 1989).

The discovery of kimberlite and diamonds in the Lac de Gras area of the Northwest Territories of Canada produced an explosion of geophysical information on kimberlites especially relating to the use of magnetics combined with EM. Annan et al (1996), Smith et al., 1996) and St. Pierre (1999) highlight the important role of EM in the Lac du Gras discoveries while Power et al. (2004) present a range of case histories from the NWT discoveries.

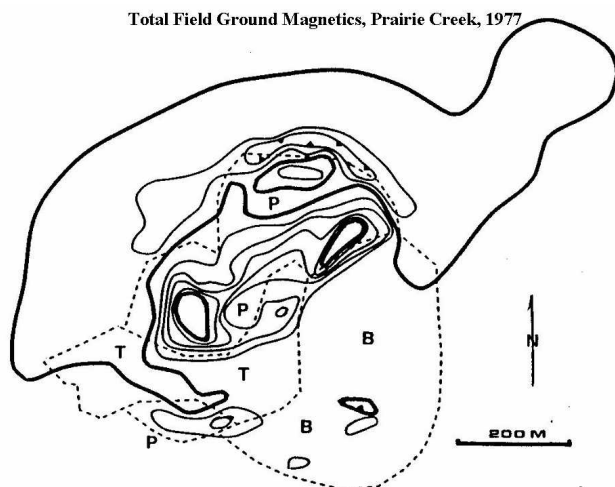
## PHYSICAL PROPERTIES

### Magnetic Susceptibilities

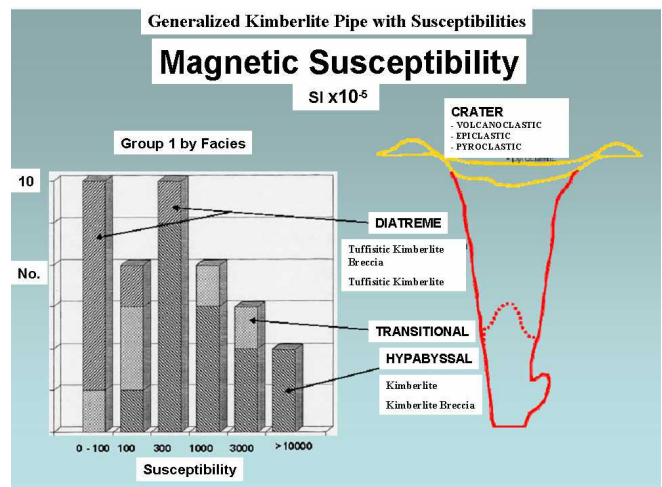
Magnetic susceptibilities of kimberlites have long been measured, so that we know that there is a significant range in the values from  $125,000 \times 10^{-6}$  SI to essentially  $0 \times 10^{-6}$  SI. There seems to be no geographical bias to the strength of susceptibilities. Samples from South Africa, Sierra Leone, Brazil, Siberia, Canada (Kirkland Lake, Saskatchewan, NWT), show a range noted above, but with a predominant range from  $1,250 \times 10^{-6}$  to  $50 \times 10^{-6}$  SI (Reed, 1993a). The very high values are observed from kimberlites in Sierra Leone (unpublished document, Selection Trust, London, 1975). The Prairie Creek lamproite in Arkansas exhibits the range of response that can occur from a polyphase intrusion complex. (Figures. 6 and 8, Lewis, 1977; and Reed, 1993b). Much of the susceptibility range suggests that weak to moderate magnetic responses may be expected from many kimberlites. Higher magnetic (and density) values such as at the Prairie Creek lamproite are attributed to peridotite phases of the intrusion. Other phases are less magnetic (and have lower gravity response). Multiple phases with different physical parameters are common and contribute to complex geophysical responses. Arnott and Köstlin (2005) (Figure 7), show magnetic susceptibilities of different phases of kimberlite. Diatreme phases are lower at  $0$  to  $3,000 \times 10^{-6}$  SI while values for hypabyssal phases range up to  $100,000 \times 10^{-6}$  SI.



**Figure 5:** Reflection seismic migrated section at Snap Lake NWT, from Power et al., 2004. The shallow dipping reflector (dark event) identifies the Snap Lake kimberlite. Note, this is a 1:1, length vs. depth representation.



**Figure 6:** Total field magnetics over the Prairie Creek kimberlite (Lewis, 1977) shows different magnetic responses over different elements of the intrusion. P is a mica peridotite, B is breccia and T is tuff. The contour interval is 100 nT with peak values of 700nT and 900nT over the mica peridotite.



**Figure 7:** Magnetic susceptibilities of various kimberlites (after Arnott and Köstlin, 2003). The idealized outline of a kimberlite pipe describes the different facies having a range of susceptibilities. Note the susceptibilities are in 10<sup>-5</sup> units SI.

Density

Kimberlites generally appear as gravity lows (for example in Figure 25), but may appear as gravity highs (Figure 8), the anomaly and its polarity being dependent on the density contrast between the kimberlite and the host rock. Most kimberlites have relatively low density. Gerrys (1970) reported density contrasts at Mwadui to range from 0.3 to 0.6 gm/cc. Arnott and Kostlin (2003) (Figure 9) report densities on a broader range of kimberlites, differentiating between diatreme and hypabyssal phases. These densities range from 1.73 to 3.51 gm/cc. The lower to mid values are in weathered and altered diatreme phases while higher values appear in the hypabyssal phases. Weathered tops of the intrusions, enhance the tendency to develop contrasting low gravity responses, but may not be solely responsible for gravity lows, as altered, unweathered phases have low densities. In contrast, the Prairie Creek example (Figure 8) shows significant gravity high responses, with differences among the three kimberlitic phases. All phases are suggested to have densities higher than their host rock.

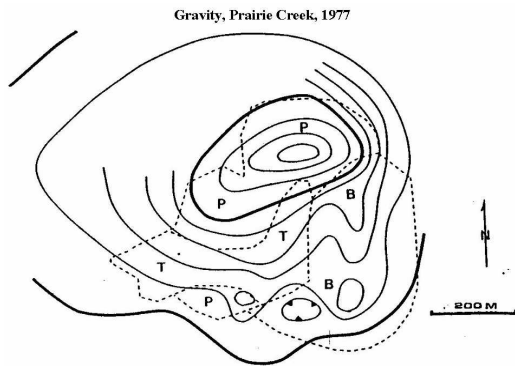


Figure 8: Gravity response over the Prairie Creek kimberlite (Lewis, 1977) shows a high density component over the mica peridotite (P), lower but somewhat elevated gravity over the breccia (B), and relatively low values over the tuff (T). Contour intervals are 0.2 milligals with the peak value at 1.4 milligals.

Resistivity and EM

The source of a low resistivity the response, as in Figure 3, (and possibly an EM response) might at first be thought to develop only from the weathered top (yellow ground) of kimberlite. This is not necessarily the case. An example of measurement of resistivity in core from kimberlite in Sierra Leone (Figure 10) (Wheildon, 1975) shows unweathered kimberlite, apparently a dyke, with low resistivities (10 to 60 ohm.metres) that in the context of the much higher resistivities in the surrounding granite would most likely develop a recognizable EM response. This analysis was designed to evaluate the potential for using EM surveying in the area. However, ground resistivity surveying (not shown) showed that EM would be unlikely to be able to identify the target kimberlites due to the presence of extensive surficial lows in the area.

Present day broad band EM technology would likely provide better discrimination in complex conductivity environments. Arnott and Köstlin (2003) (Figure 11), identify resistivities of kimberlites in South Africa, Siberia and Saskatchewan to range from 5 to 700 ohm-m, with the deepest phases having higher resistivities.

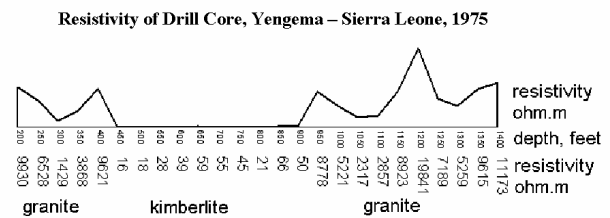


Figure 10: Resistivity of samples of kimberlite drill core from Sierra Leone. The rocks expressing the low values are identified as unweathered kimberlite.

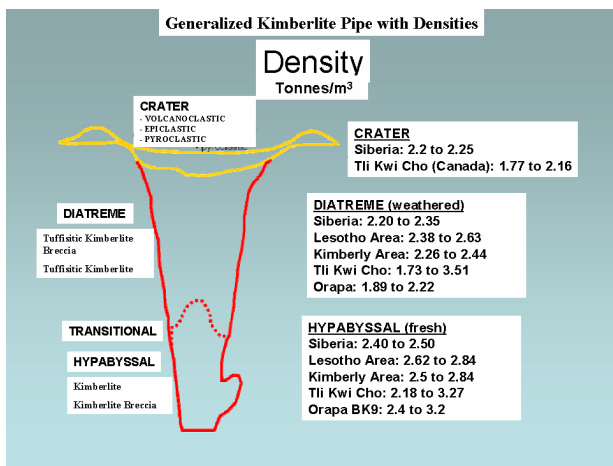


Figure 9: Densities of various kimberlites (after Arnott and Köstlin, 2003). The idealized outline of a kimberlite pipe describes the main characteristics that may be observed.

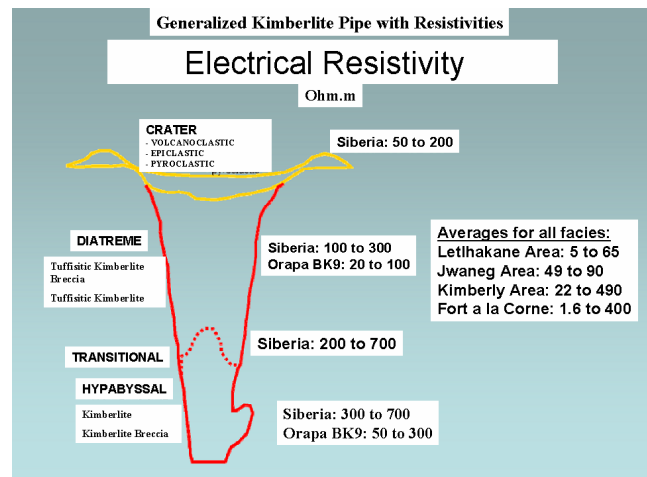


Figure 11: Resistivities of various kimberlites (after Arnott and Köstlin, 2005). The idealized outline of a kimberlite pipe describes the main characteristics that may be observed.

**RECENT DEVELOPMENTS**

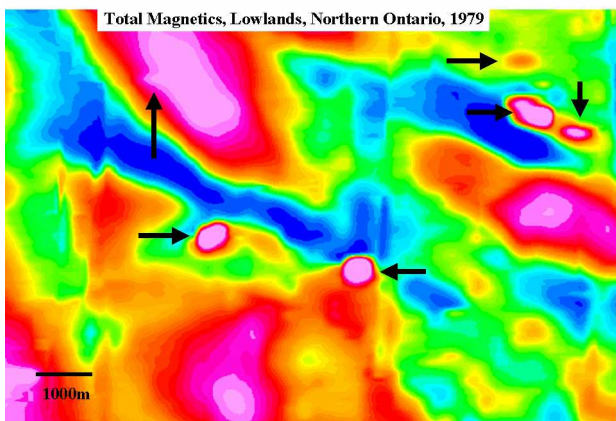
The basic parameters measured have not changed significantly over time, but the sophistication of measuring, resolution, processing and anomaly recognition has moved forward as instrumentation and experience have pushed the barriers.

**Surveying**

Magnetic and EM Surveying

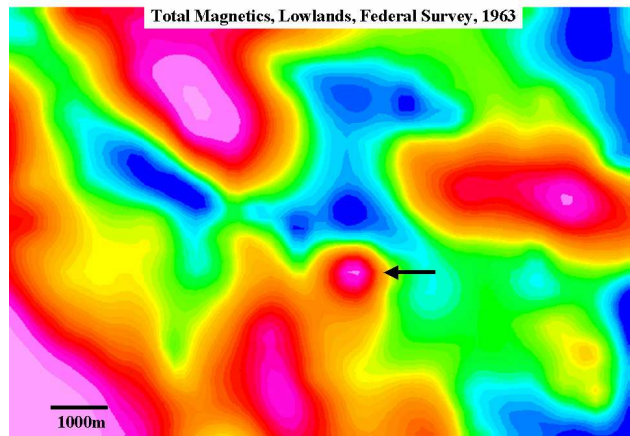
Fixed wing and helicopter airborne magnetic and electromagnetic surveying is standard kimberlite exploration practice. Improved understanding of target size and required definition details have caused re-thinking that line spacing and height above ground surface needs to be closer and lower than simple detection parameters might indicate. This is especially true for magnetic parameters. Costs and appropriate use of resources remain important, but the opportunity to miss an intrusive body rises rapidly with increased line spacing and flying height.

An example showing the effect of line spacing is presented from the James Bay lowlands of Ontario. (Reed and Sinclair, 1991). Surveying at 100 meters altitude and 250 meters line spacing found over 50 pipe-like intrusive bodies in the area. Figure 12 shows pipe-like source magnetic anomalies from this survey. The tops of the magnetic bodies are 50 meters below ground surface and are generally easily separated from the 300 meter deep magnetic basement. The wider line spacing of the previous Geological Survey of Canada surveying (Figure 13, within Smoky Falls sheet, NTS area 42J 4/5, 1:250,00 scale) in this area identified 3 of the 50 bodies and one of the six identified in the sub-set shown. The magnetic response in Figure 13 indicates the low recovery of the smaller pipe-source anomalies. Current survey design uses closer line spacings. 100 meter and 50 meter separations are of value in areas of known or high kimberlite probability.



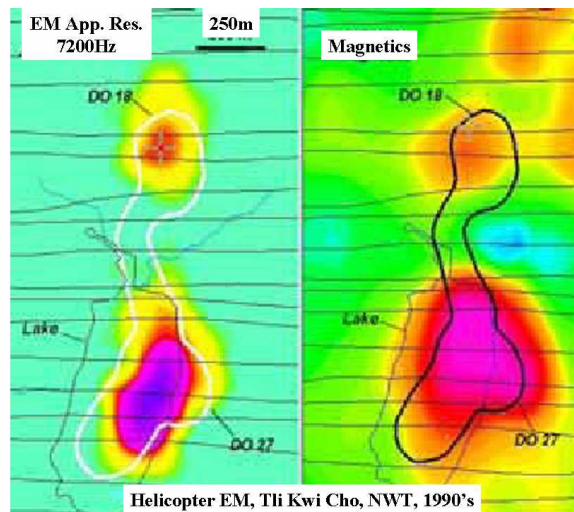
**Figure 12:** Total field magnetics in the Lowlands area flown with 250 meter line separation and 100m terrain clearance (after Reed and Sinclair, 1991). Shallow magnetic intrusions which have vertical cylindrical shapes like kimberlites. These bodies identified by the arrows

are hosted in non-magnetic Paleozoic limestone over deeply buried variably magnetic Precambrian basement rocks. The relatively shallow magnetic bodies are Alnoites of Jurassic age, and while related to kimberlites, carry no diamonds.



**Figure 13:** Total field magnetics (same area as Figure 12) flown with 880 meter line spacing and 300 meter terrain clearance. One clearly identified anomaly from a shallow pipe-like source is indicated. The identification is hit and miss. The identified body lies under a flight line while most bodies lie between flight lines and were missed.

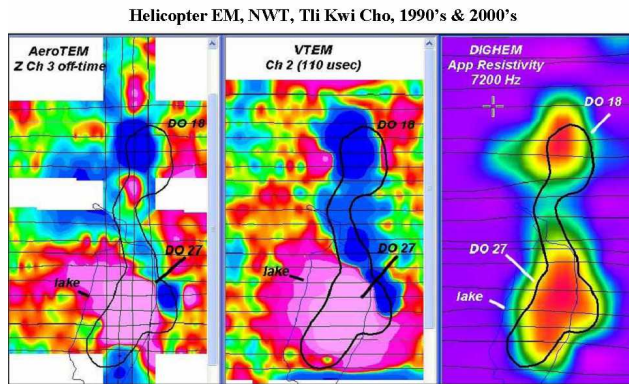
Figure 14 shows magnetic and frequency domain electromagnetic responses over the Tli Kwi Cho pipe in the Northwest Territories (Jansen and Witherly, 2004). Both parameters detect the dual nature of this kimberlite residing under a lake. The southern member is stronger in both magnetic and EM response.



**Figure 14:** Helicopter Frequency EM (left) and magnetic responses (right) identify two parts of the Tli Kwi Cho kimberlite in the NWT of Canada.

Figure 15 shows more recent versions of the EM response along with a calculated resistivity from the survey above. The helicopter time domain EM surveys have different transmitter characteristics, but both see the southern response as positive

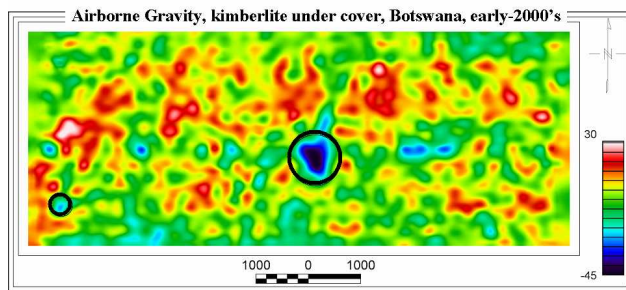
and the northern response as negative. The explanation for the negative response is problematic and must be left for discussion and resolution to a different venue. This frequency EM system identifies the bodies as resistivity lows (or conductivity highs).



**Figure 15:** Three different helicopter EM surveys at the Tli Kwi Cho kimberlite pipe, NWT (Time domain, left and center, frequency domain, right, shown in Figure 14 with different colour contrast), showing variability of response from the different systems. All detect the kimberlite intrusions, but with different characteristics.

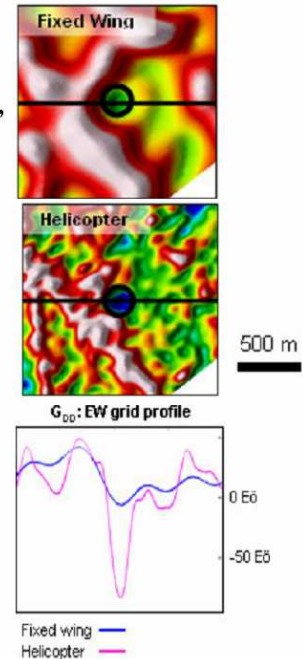
#### Airborne Gravity

Airborne gravity, especially airborne gravity gradiometry (AGG) has been added to the tools use in the kimberlite search (van Leeuwen, 2000; Liu, et al, 2001; Lee et al, 2006). Figure 16 shows a kimberlite in Botswana identified under cover as a distinct gradient low. The airborne gravity method was first applied using fixed wing aircraft. Presently helicopter borne gradiometer instruments are being employed to reveal more sharply defined responses over kimberlite (Figure 17).



**Figure 16:** Airborne gravity gradiometer Falcon Gzz survey identifies (negative, center) a buried kimberlite under 90 meters of sediments on the Kukong Test Block, Botswana (Hinks, et al., 2004). The other circled feature (SW corner) also identifies a kimberlite. (Image collected from [http://www.Orion.bhpbilliton.com/falcon/case\\_studies](http://www.Orion.bhpbilliton.com/falcon/case_studies)). Amplitude units are in Eötvös.

#### Airborne Gravity, BHP, Ekati, fixed wing vs. helicopter, 2006



**Figure 17:** Comparison of fixed wing and helicopter airborne gravity gradiometry over the Ekati kimberlite pipe, NWT. Both methods detect the pipe, but the helicopter system shows higher resolution. ([http://www.orion.bhpbilliton.com/news/june\\_2006.asp](http://www.orion.bhpbilliton.com/news/june_2006.asp)).

#### Seismic

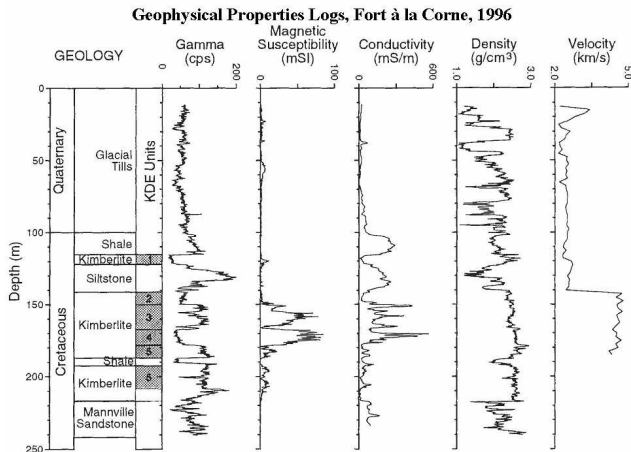
Reflection seismic surveying is now developing useful images of the sub-surface in special cases. Figure 5 shows the seismic response from a gently dipping kimberlite dyke at Snap Lake in the Northwest Territories. A combination of Vibroseis and explosive sources has allowed this dyke, which thins to 2 meters at depth, to be imaged to a depth of 1200 meters. The explosive sources with their higher frequency content, have in this case significantly assisted the detection of the thin dyke at depth. Urosevic and Evans (1998) have shown in a case from Australia, that special processing of reflection seismic data can resolve steep walls of kimberlite pipes.

#### Radar

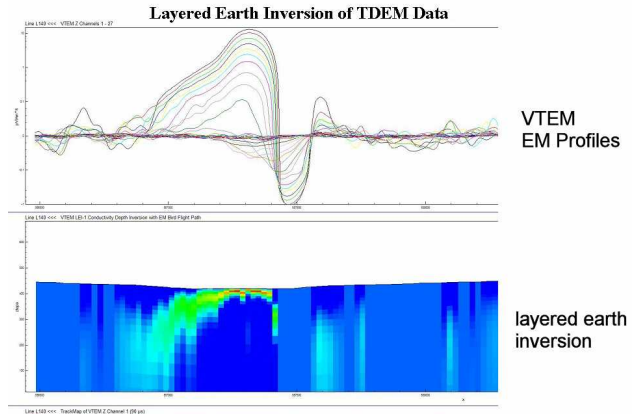
Ground Probing Radar (GPR) has been employed as a tool to define kimberlite (Power et al., 2004). One of us (Reed) however, has observed the use of this method is restricted where low resistivity clays, derived from kimberlite or other sources limit the ability of the GPR signal to penetrate the ground.

#### Borehole Physical Properties Logging

Physical properties logging has provided useful information of the properties of kimberlite in place (Mwenifumbo, et al., 1996). Figure 18 shows a log with six elements describing a kimberlite in the Fort à la Corne, Saskatchewan cluster. Note that the physical responses from within the kimberlite are not consistent, showing that the kimberlite here has various phases having different physical parameter values.



**Figure 18:** Generalized geological log, total count gamma, magnetic susceptibility, electrical conductivity, density and P wave acoustic velocity through a kimberlite, Fort à la Corne, Saskatchewan.



**Figure 19:** Layered earth inversion of the Tli Kwi Cho DO-27 pipe suggesting a conductive top (red-yellow) of shallow depth extent, surrounded by more resistive rocks (blue). The deep blue under the conductive top does not represent a resistive body, but reflects the blocking of the EM fields by the conductor at surface.

**ADVANCED PROCESSING**

Major strides have been made in the last decade in the advanced processing of most types of geophysical data; this has been referred to as value-added or more recently, Ternary processing (Witherly, 2005). The term Ternary processing is used to differentiate this more model-driven processing from the normal data-reduction style processing performed by survey contractors.

**Potential Field Data**

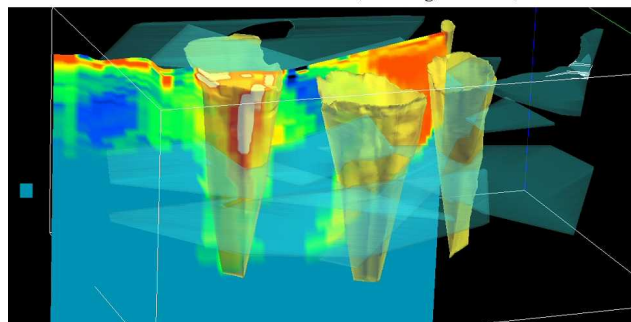
Ternary processing of magnetic and gravity data has taken on a variety of forms from developing derivatives (Hogg and Munro 2000), to regional/residual separations (Dentith et al. 2000) and two-three-dimensional (2D-3D) inversions (Li and Oldenburg, 1996). The major focus with these efforts being to separate the likely kimberlite signatures (residuals) from the background (regional) without removing too much of the residual in the regional component nor alternatively enhancing noise to the level it is deemed to be signal.

Keating (1995) and Cowan et al (2000) have both put forward relatively simple signal processing techniques to apply to large amounts of often noisy aeromagnetic data.

Practical inversion of EM is still limited to 1D or 2D models, (Macnae et al, 1998) but such outcomes can be gridded into 3D volumes with surprisingly good effect. An example of the 1D model displayed in 2D is shown in Figure 19. These data are from an airborne EM survey over the Tli Kwi Cho pipe (Jansen and Witherly, 2004).

In Figure 20, a 2D model derived from inversion of magnetotelluric natural field electromagnetic (MT) data over the Jwaneng pipe is shown (McMonnies 2005). This type of complex visualization of inversion facilitates the assessment of geophysical outcomes with other geoscience data and is now important in seeing the interpretative products. Images of three pipe-like bodies appear in this inversion.

**3D Visualization of 2D MT inversion, Jwaneng, Botswana, 2005**



**Figure 20:** 2D inversion of MT data over Jwaneng kimberlite Botswana (McMonnies 2005). Three pipes from geology are presented (pale tan colour) along with responses from conductive elements in two of the pipes (yellow-green, extending through red to white in the pipe to the left).

**Gradients and Derivatives**

Cross-line, along-line and vertical gradients may be measured or calculated. Calculated First Vertical Derivatives (1VD) have been used to good effect in many kimberlite exploration settings. Figure 21 shows the total magnetic field over the Guigues kimberlite in Quebec. Figure 22 shows that the 1VD response enhances the identification of the kimberlite. Occasionally natural separation of responses from pipe-like sources (Figure 12) achieves a result that may be better for detection than the 1VD product (not shown).

The 1VD example in Figure 22 derives from some older processing of total field magnetics. Hogg (2004) and Fitzgerald and Holstein (2006) provide some recent ideas on processing gradiometry data to further enhance these data.

Total Magnetics, Guigues, Quebec, 1990

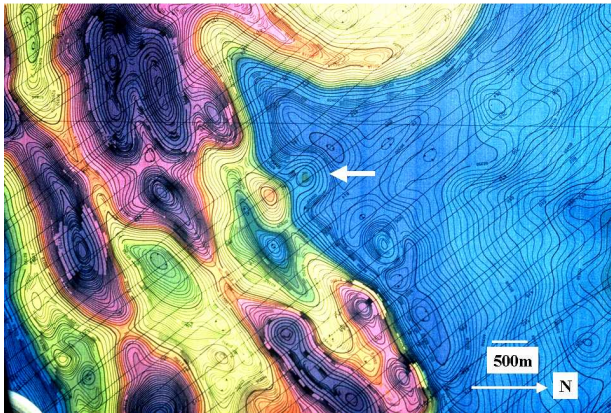


Figure 21: Total field magnetic survey detects the Guigues kimberlite pipe (arrow) in northwestern Quebec.

1VD Magnetics, Guigues, Quebec, 1990

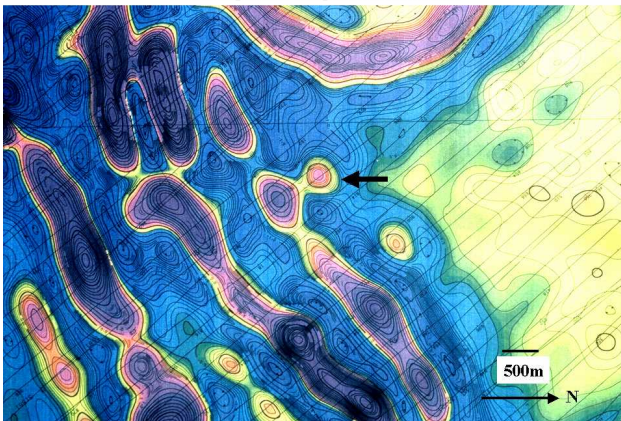


Figure 22: First vertical derivative of the same area as Figure 17 shows better resolution of the Guigues pipe (arrow).

### 3D Inversion and Modeling

Processing of magnetic and gravity data has taken a variety of forms, from developing derivatives as above, to regional/residual separations (not shown here) to 3 dimensional inversions (Li and Oldenburg, 1996, and 1998). Figures 23 and 25 show ground magnetic and gravity data collected in 1983 over the Zero kimberlite pipe in South Africa (unpublished data from African Selection Trust Exploration). This pipe, identified in an airborne magnetometer survey and hidden on surface by sand and dolomite nodules, was defined on the ground by the magnetic and gravity surveying. These data have been recently digitized (Figures 23 and 25) to permit 3D inversions of the data. The magnetic description of the pipe suggests a fissure with “blows” or widenings, with a more confined gravity low within one of these.

The uncontrolled 3D magnetic inversion (Li and Oldenburg, 1996), (Figure 24, seen in shades of purple) shows a varied body extending to 300 meters in the northwest and a larger body in the center extending deeper than 425 meters. The continuation to the southeast suggests a deeply extending body.

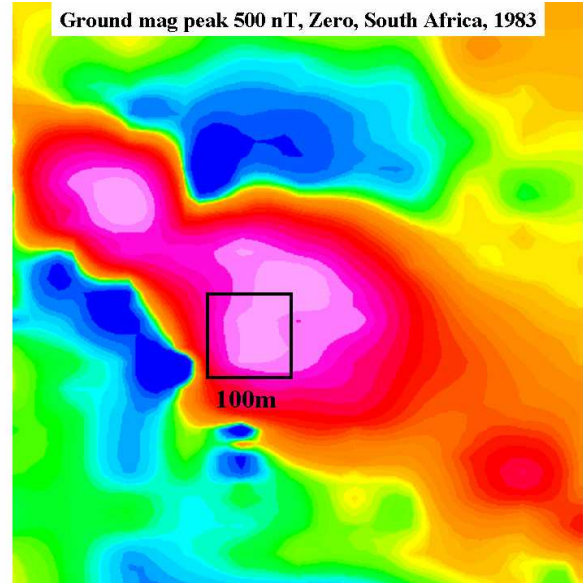


Figure 23: Ground magnetic survey over the Zero kimberlite pipe in South Africa. The survey recorded data along 100 meter interval survey lines. Peak amplitude is about 500nT over background. The 100 meter box is identical in location and ground co-ordinates to the gravity low identified by the box in Figure 25.

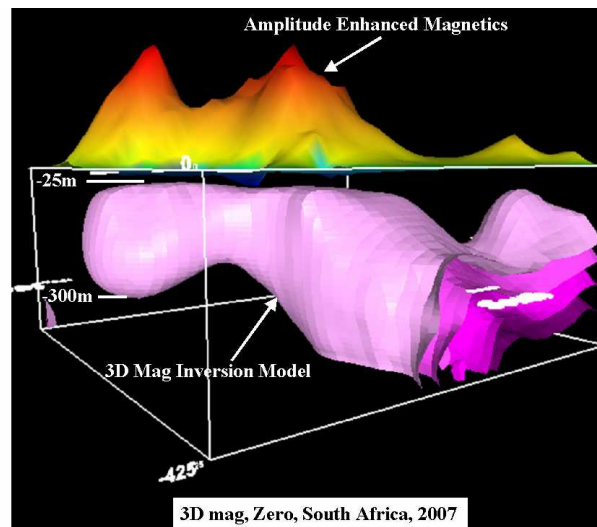
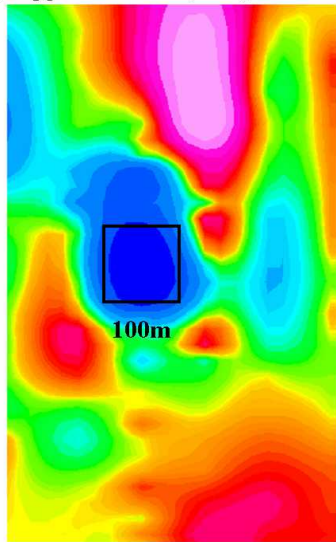


Figure 24: Three dimensional inversion product of the ground magnetic data on the Zero pipe (lower part of the image). The view looks horizontally toward the north-northeast. The highest value isosurface or shell (deep purple) describes constant susceptibilities of  $30,000 \times 10^{-6}$  SI. The lowest value shell (light purple) describes susceptibilities of  $12,500 \times 10^{-6}$  SI. Note that this outer shell has a depth of to top of 25 meters, suggesting the main magnetic body may have its top at this depth. The peak of the amplitude enhanced magnetics over the kimberlite is about 500nT.

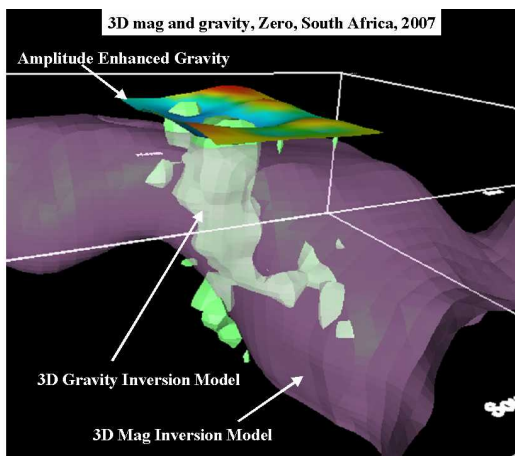


Gravity neg peak -1.1 mGal, Zero, South Africa, 1983



**Figure 25:** Ground gravity survey over the Zero kimberlite. The peak amplitude (in box) is 1 milliGal below the local background. This survey along the 100 meter lines is more limited than the magnetic survey, and may contain some reading errors. The gravity low (marked by the 100 meter square) is sufficiently clear to develop a 3D inversion model.

Figure 26 shows a more confined gravity inversion model (Li and Oldenburg, 1998) in green, extending through the magnetic model in an apparently pipe-like form. This is suggesting a low density phase of kimberlite within the larger magnetic intrusion. A caution here is that both inversions were uncontrolled and would need to be constrained in a second 3D process by drill information if it is available.



**Figure 26:** Combined 3D inversions of the magnetics (purple and transparent) and the gravity (green). The view is oblique from above the model surface, looking north-northeast. The gravity model extends through the magnetic model to a depth close to 400 meters from surface. The negative gravity shell displayed is for a density contrast of 0.4 gm/cc. The top of the gravity body lies above the magnetic body closer to surface. The gravity appears to identify a low density weathered feature at the top of the pipe that is not as magnetic as the deeper parts. The enhanced amplitude surface shows the depression of the gravity values over the pipe.

## CONCLUSIONS

Almost all of the basic geophysical tools used in mineral exploration have been applied to the search for kimberlites since the 1950's. Much has been learned about the geophysics of kimberlite and its settings to enhance the successful application. Significant advances in instrumentation and data processing have extended our ability to search for and find and define kimberlites with their associated diamonds, in a wide variety of geologic and geographic settings. In the future, continued advances in sensors are expected to lower the cost of data acquisition but may not significantly improve diagnostic use of the data. The major advances in exploration effectiveness are expected to be derived from enhanced data processing and integration of geophysical, geological and geochemical/mineralogical data.

## ACKNOWLEDGEMENTS

The authors are indebted to those pioneers from early as well as recent days who led and are leading the way in the application of geophysics to the exploration for kimberlite. Some, although not all of these, have been acknowledged in the references.

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## APPENDIX

New instrumentation is being applied to kimberlite detection.

As an innovative alternative to either a fixed-wing or rotary wing aircraft to transport the AGG sensor, one group has mounted the sensor on an airship (Figure 27). The users state that such a platform can operate lower and slower than other types of aircraft thus producing superior quality data.

Magnetic gradient measurement techniques have advanced considerably over the last decade, with much of the initial application focused at kimberlite exploration. While much of the current gradient measuring technology relies on traditional magnetic sensors, a new generation of SQUID sensors offers major advances in sensitivity of gradient measurements (Figure 28). Foss (2006) has identified processes to improve magnetic products developed by the SQUID sensors.

Currently, both the new instrumentation and carriers are being run with the intent of increasing signal to noise of responses in the search for kimberlite. Successful applications are awaited with interest.



**Figure 27:** AGG sensor deployed in airship (courtesy of Bell Geospace Inc.)



**Figure 28:** Exterior view of a cryogenic magnetometer mounted in a stinger on a fixed wing aircraft (Killeen, 2006).