Use of the analytic signal to identify magnetic anomalies due to kimberlite pipes

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ABSTRACT

The magnetic signature of most kimberlite pipes is, at high magnetic latitudes, a circular anomaly. At lower magnetic latitudes, it becomes asymmetric; and at the magnetic equator, the anomaly is mostly negative. The shape of the anomaly is also influenced by the presence of remanent magnetization. For a vertical cylinder, the shape of the analytic signal of the magnetic field is nearly independent of field orientation and remanence and always results in a compact, almost circular anomaly. A simple pattern recognition technique, based on a first-order regression over a moving window, between the analytic signal of the observed magnetic field and the theoretical analytic signal of a magnetic vertical cylinder is an effective tool to identify potential targets. Results where the correlation coefficient between the analytic signal and the theoretical analytic signal within a moving window are above a certain threshold are retained, and additional criteria can later be used to refine the target selection. The method’s practical utility is demonstrated by applying it to three different sites. The first is a well-documented area located at high magnetic latitude (Ontario, Canada), the second is at low magnetic latitude (West Africa), and the last one is an area where many pipes have a negative magnetization (Lac de Gras, Canada).

INTRODUCTION

Kimberlites are the major source of the world’s diamonds. Kimberlite is an ultrabasic igneous rock which can occur as sills, dikes, or pipes. Sills and dykes are rarely mined (Gerryts, 1967), and only one in a hundred pipes contains an economic deposit of diamonds (Brummer, 1978; Kamara, 1981). They are found within thick, Archean cratons and adjacent Proterozoic mobile belts (Mitchell, 1991). Pipes are carrot-shaped in cross section with steeply dipping walls, and their diameter diminishes with increasing depth (Brummer et al., 1992). The preferred geophysical model is a vertical cylinder.

Most kimberlites have a distinctive aeromagnetic signature—in general, a roughly circular anomaly. However, at ground level the anomaly is more complex, and it can have internal highs or be elongated. Typical examples are given by Brummer et al. (1992) and Macnae (1995). Kimberlites’ magnetic susceptibility is variable and can be as high as 6 × 10^-2 SI (Litinskii, 1963). Remanence may or may not be present; for instance, many of the kimberlites from the Northwest Territories in Canada have a reversed magnetization (Reed, 1993). In addition, magnetic susceptibility can vary within a given kimberlite pipe (Mwenifumbo et al., 1998). In South Africa, the apparent source dimension of the magnetic anomalies is from 100 to 1600 m (Macnae, 1979). In the Kirkland Lake area of northeastern Ontario, Canada, the diameter of the known kimberlite pipes ranges from 100 to 200 m. In the Northwest Territories, their diameter can be as small as 75 m. Brummer et al. (1992) show how aeromagnetic data can be used to identify previously unknown kimberlites in the Kirkland Lake region; their approach is to look for small, circular, isolated magnetic anomalies.

Cowan et al. (2000) review techniques that can be used to screen kimberlite magnetic anomalies. Aeromagnetic data enhancement techniques can be used to clarify the expected circular signatures. However, the results must be manually inspected to identify potential targets. Three-dimensional Euler deconvolution can be used to automatically locate circular anomalies (Paterson et al., 1991). This technique tends to generate a large number of false targets. Because it assumes that kimberlites can be represented by poles or dipoles, it does account for their finite size. A simple pattern recognition technique, based on first-order regression analysis between a window of the gridded data and a typical target theoretical anomaly, can also be used (Keating, 1995). Cowan et al. (2000) call this technique a matched filter. This approach requires some prior information about the typical target, i.e., diameters and depths. Experience...
shows that the matched filter technique does not work well at very low magnetic latitudes and does not perform well in the presence of strong magnetic remanence. In addition, it sometimes identifies magnetic lows as potential targets. Ideally, a target selection algorithm should be able to identify all known kimberlite pipes in a region and new targets with similar characteristics, i.e., diameter, depth, and range of susceptibilities. It should also be able to detect pipes that have normal or reversed magnetic polarization. Our objective is to develop a technique that performs well at all latitudes and is independent of magnetic remanence.

**METHODOLOGY**

**Pattern recognition**

We propose using a simple pattern recognition technique, based on the analytic signal of the magnetic field to identify kimberlite targets. The technique attempts to identify anomalies of a given shape. A first-order linear regression between a window of the analytic signal of the grid data and a typical target anomaly is used to identify potential exploration targets. The amplitude $A$ of the analytic signal of the total magnetic field $T$ is calculated from the three orthogonal derivatives of the field according to the formula of Roest et al. (1992):

$$A(x, y) = \left[ \left( \frac{dT}{dx} \right)^2 + \left( \frac{dT}{dy} \right)^2 + \left( \frac{dT}{dz} \right)^2 \right]^{1/2}.$$  \(1\)

The derivatives of the grid data can be computed by an operator in the space domain or in the frequency domain. In our study, the vertical derivative is calculated in the frequency domain and the horizontal derivatives are calculated in the space domain by a finite-difference operator.

The amplitude of the analytic signal of the model grid is calculated by applying finite differences to the total magnetic field anomaly computed from the formulas of Singh and Sabina (1978). The vertical derivative of the magnetic field is obtained by computing the field at depths of $z + \Delta x$ and $z - \Delta x$ and dividing the difference by $2\Delta x$. The $x$ and $y$ derivatives are calculated in the same way. In practice, $2\Delta x$ should be about $1\%$ of $z$. For a depth of 100 m, this corresponds to 1 m. Model parameters are the depth, radius, length of the cylinder, and areal extent of the anomaly, i.e., the window size. The depth is taken as the flight height plus the estimated overburden thickness; the cylinder is assumed to be vertical and of infinite depth extent, and the geomagnetic field inclination and declination in the studied area are used to compute the model. The model anomaly analytic signal grid is then used as a moving window over the grid of the analytic signal of the magnetic field of the study area. Computing a simple linear regression between analytic signal of the model grid $y_i$ and of the gridded observations $x_i$ within this window gives the correlation coefficient, the standard error of fit, the slope, and the intercept of the regression line (Davis, 1986).

The equation of the regression is

$$\bar{y}_i = b_1 x_i + b_0,$$  \(2\)

where $\bar{y}_i$ is the estimated value of $y_i$ at $x_i$; $b_1$, the slope of the regressed line, is the scaling factor that relates the analytic signal of the gridded magnetic data and the analytic signal of the model cylinder; and $b_0$ is the intercept of the fitted line. The base level must be added to the analytic signal of the model cylinder to minimize the difference between the analytic signal of the model and the analytic signal of the observed magnetic field. The standard error between the estimated values of the analytic signal and the values of the analytic signal of the observed magnetic field within the moving window is calculated, as is the correlation coefficient between the analytic signal within the moving window and the analytic signal of the model. The relative error is the ratio between the standard error of fit and the maximum amplitude of the analytic signal of the anomaly.

These results are used to screen for potential targets. In practice, one first retains solutions that have a correlation greater than 75% and a relative error of less than 10%. The scaling factor $b_1$ can be used to estimate the susceptibility of the target anomaly from the susceptibility of the model anomaly. In addition, since the analytic signal is positive, targets that have negative base levels should be rejected if the base level is less than some threshold—usually the noise level of the survey data. The highest correlation coefficients are obtained over anomalies that best resemble the model. Geological factors can reduce the correlation values: deviation from a cylindrical shape, nonuniform magnetization, significant deviation from the assumed depth, and nonvertical dip. Also, other geological sources such as small gabbro plugs produce circular magnetic anomalies.

**Advantages of using the analytic signal**

Nabighian (1972) shows that the shape of the analytic signal of contacts and sheets is independent of the directions of magnetization and the local geomagnetic field. In addition, Roest et al. (1992) show that this is true for any 2D magnetic anomaly. Such is not the case for 3D anomalies. Nevertheless, the shape of the analytic signal is still nearly independent of the directions of magnetization and of the earth’s field. Agarwal and Shaw (1996) calculate the analytic signal of a single magnetic pole anomaly and conclude that, in general, the analytic signal is not symmetric for arbitrary values of inclinations and declinations. A circular symmetry is observed for a field inclination of 90°, and at an inclination of 0° the anomaly is symmetric along the axis of the declination. In general, the anomaly is nearly circular and slightly elongated along the geomagnetic field declination. Therefore, two advantages exist in using the analytic signal to identify magnetic anomalies from kimberlite pipes: first, it is independent of remanence; second, as it will be shown, it performs well at low magnetic latitudes.

**Influence of magnetic field orientation**

To understand the behavior of the analytic signal of the magnetic anomaly of a vertical cylinder, we present its total-field anomaly (Figure 1) and its analytic signal (Figure 2) for various field inclinations when the radius of the cylinder is equal to its depth. All cases are for sources magnetized by induction only. At high magnetic inclinations, the total-field and analytic signal anomalies are nearly circular. As the inclination is lowered, the total-field anomaly becomes more dipolar and its analytic signal is slightly elongated along the direction of the magnetic declination. At low magnetic inclination, the total-field anomaly

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is highly asymmetric and its analytic signal is nearly circular. When the field inclination is horizontal, the total magnetic field anomaly is mostly negative and elongated in the direction perpendicular to the field declination. The corresponding analytic signal anomaly tends to be slightly lozenge shaped. However, in all cases the analytic signal anomaly is spatially compact, i.e., it is almost a bull’s eye.

**Influence of cylinder radius**

The analytic signal anomalies for cylinders of various radii are shown in Figure 3. As the ratio of the cylinder radius to its depth trends to zero, the anomaly more closely resembles the anomaly of a pole. If the ratio is increased, we expect to detect the northern and southern edges of the cylinder. This is illustrated for a radius-to-depth ratio of 2, for which the analytic signal has two distinct maxima (Figure 3d). This illustrates the importance of having reliable information about source width. In fact, this is not too difficult because one generally has some knowledge of the geology of the study area. In practice, using two or three different radii is sufficient. When the radius of the cylinder is much larger than its depth, a ring-shaped anomaly outlining the edge of the cylinder is observed. This case is of less interest for kimberlite detection because this geometry generally corresponds to a large intrusive body rather than a kimberlite.

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**FIG. 1.** Total magnetic-field anomalies for a semiinfinite vertical cylinder at various magnetic-field inclinations magnetized by induction only. Field declination is 15° W, pipe radius is 100 m, and the observation plane is 100 m above the pipe. Minimum contour interval is 5 nT. Field inclinations are (a) 75°, (b) 45°, (c) 15°, and (d) 0°.
Influence of reverse magnetization

In some cases, remanence is an important factor when modeling kimberlite pipes. For example, many of the pipes in the Northwest Territories have a negative magnetic signature. These pipes, when they were emplaced, acquired a magnetization in the opposite direction of the present geomagnetic field. Some pipes are known to be of Cretaceous age (Kjaersgaard, 1996). At that time (73–75 Ma) the geomagnetic field inclination in that area was $-80^\circ$, while it is presently $84^\circ$. Based on that information, we calculated the total-field magnetic field anomaly and its analytic signal for a 100-m-radius pipe located at a depth of 100 m (Figure 4). The total-field anomaly is negative and circular, while the analytic signal is a circular positive anomaly. Although such a negative anomaly is easy to identify visually, it would be more difficult to find in real cases where both positive and negative anomalies are present. In many cases it could be confused with the negative lobe associated with a dipping body.

Influence of erroneous size selection

Selection of erroneous model parameters to model the target kimberlite pipe will influence the value of the maximum calculated correlation coefficient. To study this effect, a model target pipe having a radius of 100 m and top at a depth of 100 m is used. Field inclination and declination of $75^\circ$ N and $15^\circ$ W, respectively, typical for eastern Canada, are used. The cylinder has an infinite depth extension, and its axis is located on a gridpoint. Correlation coefficients are calculated using a

![Fig. 2. Analytic signal of the magnetic anomalies shown in Figure 1. Minimum contour interval is 0.05 nT/m. Field inclinations are (a) $75^\circ$, (b) $45^\circ$, (c) $15^\circ$, and (d) $0^\circ$.](image-url)
FIG. 3. Analytic signal of the magnetic field for a semi-infinite vertical cylinder of radii of (a) 25, (b) 50, (c) 100, and (d) 200 m, magnetized by induction only. Plane of observation is 100 m above the pipes. Magnetic field inclination is 45°, and declination is 45° W. Minimum contour interval is 0.05 nT/m.

FIG. 4. (a) Total magnetic field for a semi-infinite vertical cylinder. Field inclination is 84°; magnetization inclination is −80°. Minimum contour interval is 5 nT. (b) Analytic signal of the magnetic field shown in (a). Minimum contour interval is 0.02 nT/m. Cylinder radius is 100 m; plane of observation is 100 m above the cylinder.
window size of 500 m, with radius and depth varying from 50 to 200 m (see Table 1). We can see that the technique will fail if the radius is too large and the depth too shallow.

An increase in depth can, however, compensate for the selection of an erroneous radius. Table 2 presents the results of computing the correlation coefficient when the axis of the target cylinder is located halfway between grid cells. Lower maximum correlations are obtained, even when the correct radius and depth are used for the model. However, this effect is reduced as the radius increases because the ratio of the location error (half a grid cell) to the radius of the model cylinder is reduced.

### Influence of wrong shape

To study the effect of departure from circularity, the analytic signal of a square and a rectangular prism with the same surface area as the previously used target model located at a depth of 100 m was used. Although a rectangular kimberlite pipe is unrealistic, it provides a good worst-case model. The ratio between the lengths of the sides of the rectangular prism is 2. The depth of the prisms varies from 25 to 200 m. Results are presented in Table 3. For a square prism, the maximum correlation coefficient is 0.92 when the depth of the prism is 25 m, reaches 0.99 at 100 m, and goes to 0.97 at 200 m. For a rectangular prism, the maximum correlation increases from 0.73 at a depth of 25 m to 0.91 at 200 m. Therefore, a square prism is seen as a cylinder as long as the ratio of the depth to the assumed radius is not too small. The anomaly of a rectangular prism will resemble the anomaly of a cylinder if the prism is at great depth.

### Influence of noise

The analytic signal is calculated from the horizontal and vertical derivatives of the magnetic field, and its noise level is higher than that of the magnetic field. For example, any small leveling problems that could not be seen in the total field will become apparent in the analytic signal. The effect of noise is studied by adding white noise to the model target anomaly used previously. The noise level is defined as the ratio of the standard deviation of the noise to the maximum anomaly amplitude of the analytic signal of the target model. Results are presented in Table 4. For low noise levels (<2.5%), results are similar to those for noise-free data, except when the radius is over-estimated (200 m). In general, results degrade with increasing noise levels as expected.

These results are for relative noise levels and should be interpreted accordingly. In fact, for a given survey, the absolute noise level will, in general, be the same over the whole survey area unless survey conditions varied during the data acquisition period. For example, varied and rugged topography can affect the noise level. Therefore, relative noise levels are smaller for higher amplitude anomalies and vice versa. Although the previous results (Tables 1 and 2) seem to indicate that the selection of a correct radius is not that important, taking noise into consideration, one must conclude that selecting a radius either too small or too large can degrade the results. This shows the importance of using model anomalies of different radii.

### ACTUAL EXAMPLES

We demonstrate the technique for three different cases. First, we use a data set from the Kirkland Lake area, Canada. Kimberlite pipes from this area are well documented, and the data are in the public domain. Second, we show the usefulness of the technique at low magnetic latitude in West Africa. Finally, we use magnetic data from the Northwest Territories to illustrate how the technique can be used in a complex magnetic area where many kimberlite pipes have a negative response because of strong remanence.

### Table 1. Maximum correlation coefficient as a function of cylinder depth and radius. Magnetic field inclination and declination are 75° N and 15° W, respectively. Target cylinder has a radius of 100 m and is located at a depth of 100 m. Cylinder has an infinite extent.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>50</th>
<th>100</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.85</td>
<td>0.98</td>
<td>0.85</td>
<td>0.43</td>
</tr>
<tr>
<td>100</td>
<td>0.96</td>
<td>1.00</td>
<td>0.94</td>
<td>0.75</td>
</tr>
<tr>
<td>150</td>
<td>0.99</td>
<td>0.99</td>
<td>0.95</td>
<td>0.85</td>
</tr>
<tr>
<td>200</td>
<td>0.99</td>
<td>0.97</td>
<td>0.94</td>
<td>0.87</td>
</tr>
</tbody>
</table>

### Table 2. Maximum correlation coefficient as a function of radius when the model cylinder is mislocated by half a grid cell (25 m). Magnetic field inclination and declination are 75° N and 15° W, respectively. Target cylinder has a radius of 100 m and is located at a depth of 100 m. Cylinder has an infinite extent.

<table>
<thead>
<tr>
<th>Offset (m)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>150</th>
<th>175</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.93</td>
<td>0.96</td>
<td>0.98</td>
<td>1.00</td>
<td>0.98</td>
<td>0.94</td>
<td>0.87</td>
</tr>
<tr>
<td>25</td>
<td>0.87</td>
<td>0.90</td>
<td>0.93</td>
<td>0.94</td>
<td>0.94</td>
<td>0.92</td>
<td>0.86</td>
</tr>
</tbody>
</table>

### Table 3. Maximum correlation coefficient as a function of depth when the target anomaly is a square or a rectangle. The sides of the rectangle have a ratio of 2. Surface area in both cases is the same for a 100-m-radius cylinder. Magnetic field inclination and declination are 75° N and 15° W, respectively.

<table>
<thead>
<tr>
<th>Anomaly shape</th>
<th>Depth (m)</th>
<th>25</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>125</th>
<th>150</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square</td>
<td>0.92</td>
<td>0.97</td>
<td>0.98</td>
<td>0.99</td>
<td>0.99</td>
<td>0.98</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>Rectangle</td>
<td>0.73</td>
<td>0.80</td>
<td>0.84</td>
<td>0.88</td>
<td>0.90</td>
<td>0.91</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Maximum correlation coefficient as a function of radius for various noise levels. The model cylinder is mislocated by half a grid cell (25 m). Magnetic field inclination and declination were 75° N and 15° W, respectively. Target cylinders have a radius of 100 m and are located at a depth of 100 m. Cylinder has an infinite extent.

<table>
<thead>
<tr>
<th>Noise (%)</th>
<th>0</th>
<th>1</th>
<th>1.5</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius (m)</td>
<td>50</td>
<td>100</td>
<td>150</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>0</td>
<td>0.90</td>
<td>0.94</td>
<td>0.92</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.90</td>
<td>0.95</td>
<td>0.92</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>0.89</td>
<td>0.94</td>
<td>0.91</td>
<td>0.78</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.88</td>
<td>0.93</td>
<td>0.90</td>
<td>0.77</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.82</td>
<td>0.88</td>
<td>0.86</td>
<td>0.74</td>
<td></td>
</tr>
</tbody>
</table>
Kirkland Lake

The proposed methodology is first demonstrated for the Kirkland Lake area located in northern Ontario, Canada. Seven known kimberlite pipes are in this area, and their discovery is described by Brummer et al. (1992). The pipes are covered by between 30 and 125 m of overburden that consists mainly of till, sand, gravel, and clay whose thickness averages 40 m and whose diameter varies from 75 to 350 m. All were drilled on the basis of aeromagnetic data (Ontario Geological Survey, 1979), and all have a distinct positive magnetic anomaly. In the aeromagnetic data their shape is roughly circular; however, this is not always the case: for ground magnetic data, they can be circular, oval, or even irregular (see Brummer et al., 1992, their Figure 3).

The data used here are from a combined magnetic and time-domain electromagnetic (EM) survey flown along 200-m spaced flight lines oriented north–south. The magnetometer was located in a bird at a mean terrain clearance of 70 m (Geological Survey of Canada, 1993). The same data set was used to test a similar methodology based on the use of total-field magnetic data (Keating, 1995). Data were gridded at a 50-m interval. An apparent conductivity map calculated from the EM data is also available (Geological Survey of Canada, 1993). The vertical derivative of the magnetic field used to compute the analytic signal was calculated in the frequency domain, while the horizontal derivatives were calculated in the space domain with a three-point operator. Two kimberlite pipe models were used. First, a vertical cylinder with a radius of 100 m located at a depth of 40 m (i.e., 110 m below the magnetometer) was used; window size was 600 × 600 m. All known kimberlite pipes but one, known as A1, were found. Pipe A1 has a diameter of about 80 m and is buried under more than 100 m of water-saturated sand and gravel of the Munro Esker (Brummer et al., 1992). Use of a 75-m-radius model located at a depth of 40 m resulted in the positive identification of that previously unidentified pipe. In that case the window size was reduced to 500 × 500 m. In both cases only solutions with a correlation coefficient of more than 0.8 were retained. The magnetic anomaly from this pipe is difficult to detect because it is located within a north–south magnetic anomaly that corresponds to the Munro Esker.

A total of 149 solutions cluster into 60 groups (see Figure 5). The number of potential targets can be reduced by using the apparent conductivity. In the Canadian Shield, kimberlites are associated with a thickening of the overburden (McClenaghan, 1996). Over known kimberlites, this results in an increase of the apparent conductivity. By rejecting the solutions located where the apparent conductivity is lower than 5 mS/m, the number of solutions is then reduced to 100, clustered in 40 groups (Figure 6). This may seem a high number of targets to investigate, but it is interesting to note that this survey was specifically flown to detect discrete conductive targets, such as massive sulfides, and that 32 EM targets were detected in the studied area. In both cases, final target selection for ground investigation is based on geological knowledge of the area and other constraints.

![Figure 5](image_url)  
**Fig. 5.** Analytic signal of the magnetic field in the Kirkland Lake area. Known kimberlite pipes are indicated by arrows. The model cylinders are located at a depth of 40 m and have radii of 75 and 100 m. The value of the correlation coefficient is proportional to circle diameter. All coefficients above 0.8 are shown.
The second example is from an area located at low magnetic latitude (West Africa), where the field inclination is about 3°. The magnetic survey was flown at a nominal terrain clearance of 120 m along flight lines oriented north–south and spaced 100 m apart. Because of the rugged topography in the southern part of the area, flight height varies from 58 to 430 m above ground. Data were gridded at a 25-m interval. Eight known alluvial diamond deposits are in the area, and two are located over kimberlite pipes (Figure 7). The matched filter technique (Keating, 1995) was applied to the total-field anomaly. Solutions with an absolute value of the correlation coefficient larger than 0.75 are shown in Figure 7. A radius of 60 m was used, as this is the mean radius of the known pipes in the area. Depth to the top of the model cylinder was 250 m. No solutions are located near the south pipe. Some solutions are near the north pipe, but they extend over a length of about 2 km and do not constitute a good exploration target. Solutions tend to be located along east–west-oriented magnetic anomalies because at low magnetic latitude the magnetic anomaly of a model pipe is elongated in the east–west direction and therefore correlates well with any magnetic anomaly that has that orientation. Furthermore, at such latitudes, structures parallel to the magnetic meridian become almost undetectable in the total magnetic field, enhancing east–west striking structures.

We applied our technique to the analytic signal. Processing parameters were the same as for the total field test. Solutions that have a correlation higher than 0.75 and a relative error of less than 5% are presented in Figure 8. Both known kimberlite pipes are now identified by isolated solutions. The analytic signal produces more compact anomalies, greatly improving the performance of the matched filter technique. The number of targets with a correlation coefficient greater than 0.75 is also greatly reduced. For the total field, 5263 potential targets are identified; that number is reduced to 424 for the analytic signal of the magnetic field. These solutions are clustered in 87 groups. The number of targets can be reduced further to 54 groups if solutions located on topographic highs are excluded. In that area, all known kimberlite pipes are found in topographic lows; radiometric data could be used to better define exploration targets. No such data, however, are available.

Euler deconvolution of the total magnetic field was also performed, as it is independent of field inclination and declination (Reid et al., 1990). This technique is one of the methods used to identify kimberlite magnetic anomalies (Cowan et al., 2000). A structural index of 2, corresponding to a magnetic pole, was used. For Euler deconvolution, the relative error is defined as the ratio of the standard deviation of the calculated depth to the calculated depth, expressed in percent. Only solutions that had a relative error of less than 0.5% for their calculated depths were retained (Figure 9). More than 16,000 solutions exist in the area. Although there is a small group of Euler solutions over one of the known kimberlite pipes, it would be nearly impossible to correctly select the solution without prior knowledge of the location of the pipe.

![Fig. 6. Analytic signal of the magnetic field in the Kirkland Lake area. Known kimberlite pipes are indicated by arrows. The model cylinders are located at a depth of 40 m and have radii of 75 and 100 m. Only solutions where the apparent conductivity is higher than 5 mS/m are shown. The value of the correlation coefficient is proportional to each diameter. All coefficients above 0.8 are shown.](image-url)
Therefore, there is a clear advantage in using the analytic signal of the magnetic field to identify kimberlite pipes at low magnetic latitude. This is also true if one is to visually inspect total magnetic field analytic signal maps. Ease of identification also depends on the geological context and flight height of the magnetic surveys. If the data used in the previous example had been acquired at a lower height (50 m would be typical for a helicopter survey), magnetic anomalies from kimberlite pipes would likely be easier to identify in the total magnetic field, but their signature would still be more apparent in the analytic signal.

**Lac de Gras**

The last example is from the Lac de Gras region in the Northwest Territories, Canada. There are over 150 reported kimberlite pipes in this area (Armstrong, 1998), and their locations are given by Kjarsgaard et al. (2002). Diamondiferous kimberlites have been found in the area, and one mine is now in production. The discovery pipe, Point Lake, is located within the study area. Radiometric and magnetic data from a subarea of this region are available (Shives and Holman, 1995). Flight lines were oriented east–west, spaced 250 m apart, and flown at a mean terrain clearance of 120 m. Sampling intervals along flight lines average 60 m. The magnetometer was located in a stinger attached to the tail of the survey aircraft. Magnetic data were gridded at a 50-m interval. Microleveling (Minty, 1991) was applied to remove residual leveling error. Because this survey was flown as a radiometric survey, magnetic data are noisier than for standard magnetic survey. However, this is the only data set in the public domain for that area.

There are 15 known kimberlite occurrences in this area; their locations (Kjarsgaard et al., 2002) are shown in Figure 10. Note that only the location of the kimberlites in the public domain are given. Eight are pipes associated with circular anomalies, two are associated to dyke-like features, one has a very weak response, and four do not have any magnetic signature. Remanence may or may not be present; for instance, many of the kimberlites from the Northwest Territories have a reverse magnetization (Reed, 1993). The magnetic anomaly due to a kimberlite could be very weak, maybe undetectable, if the remanence is of about the same magnitude but is in the opposite direction to the induced magnetization. Two pipes (Grizzly, Misery) are located within or near dyke-like anomalies; both have a strong analytic signal response, and Grizzly has a reversed magnetization. Most pipes located in the northeast of the area do not show any magnetic response in this data set. In the Lac de Gras region, the analytic signal is more pronounced than in the total magnetic field.
Fig. 9. Euler solutions for a structural index of 2 superimposed on a map of the total magnetic field. Minimum contour interval is 25 nT; shading is from the north. Circle diameter is proportional to depth. Known kimberlite pipes are indicated by arrows. Locations of known alluvial diamonds are indicated by an asterisk.

de Gras area, pipe diameters range from 140 to 345 m (Pell, 1997). The area has a thick till cover, and most pipes are located under lakes (DiLabio et al., 1992).

We applied our methodology to the analytic signal. Depth to the top of the model cylinder was 130 m below the survey height. A radius of 100 m was used, as this is the mean radius of the known pipes in the area. Window size was 500 m. Solutions with a correlation coefficient greater than 0.8 and a relative error less that 10% are presented in Figure 10. The eight kimberlite pipes that have a known circular magnetic response are identified correctly. Of the remaining seven kimberlites, one (Fox) is located at the intersection of two dykes, and another one (ECH-95-20) is within a dyke; obviously, their shape is not circular and cannot be detected by the proposed technique. The others five dykes do not show any magnetic response in the tested data set. However, it is possible that they would show a magnetic response if the survey had been flown at a lower altitude and smaller line spacing. The Point Lake and Willy Nilly show rather weak magnetic responses. On the other hand, they have stronger responses in the results presented by Smith et al. (1996). In that case line spacing was 200 m, and the magnetometer was located 70 m above ground.

CONCLUSION

A simple pattern recognition technique can be used to locate kimberlite pipes that have a magnetic response. The technique uses the analytic signal of the magnetic field because its shape is much less dependent on the direction of the magnetic field and remanent magnetization of the kimberlite than total magnetic field anomalies. Although some knowledge of expected pipe diameters and depths is needed, this is not a major handicap. In practice, pipes are at the surface or are located beneath the overburden, and it is easy to search for various pipe diameters. Targets identified by this technique are still too numerous to generate specific exploration targets, and further screening is needed. This can be done by using other geophysical and geological criteria. For example, many kimberlite pipes have a conductivity response; conductivity maps, if available, can be used to reduce the number of targets (Keating, 1995). Radiometric data can also be very useful in their identification (Jenke and Cowan, 1994). Obviously, noneophysical criteria—geological context, geochemical information, and topography—can be very useful in discriminating exploration targets. Our technique is expected to fail if the studied pipes depart from the model or if their magnetic anomalies are superimposed directly on other anomalies. Nevertheless, the technique performs better than techniques such as Euler deconvolution because it produces a substantially smaller number of potential targets.

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REFERENCES

Fig. 10. Shaded relief map of the analytic signal of the magnetic field for the Lac de Gras area. Shading is from the east. Solutions with a correlation coefficient larger than 0.8 are shown by circles. Known kimberlite pipes are indicated by asterisks. Names of specific pipes are shown.


