GIS (Geographic Information Systems) for kimberlite exploration

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Part 1: Kimberlite pipe models with applications for exploration

Kimberlite pipe models

The mining of kimberlite pipes for diamonds in southern Africa provided the initial basis for understanding the size and three-dimensional geometry of these bodies. Early models of kimberlite pipes presented by Dawson (1971) and Hawthorne (1975) are **composite** models, based on deeper levels of mining from "diatreme" pipes in the Kimberley area of South Africa and the high level mining of "crater" pipes in Tanzania and Botswana. This basic model was further developed by the studies of Clement (1982) and Mitchell (1986) utilizing facies analysis of the various kimberlite rock types, and resulting in the "classic model of a South African kimberlite pipe" as shown in Figure 1.

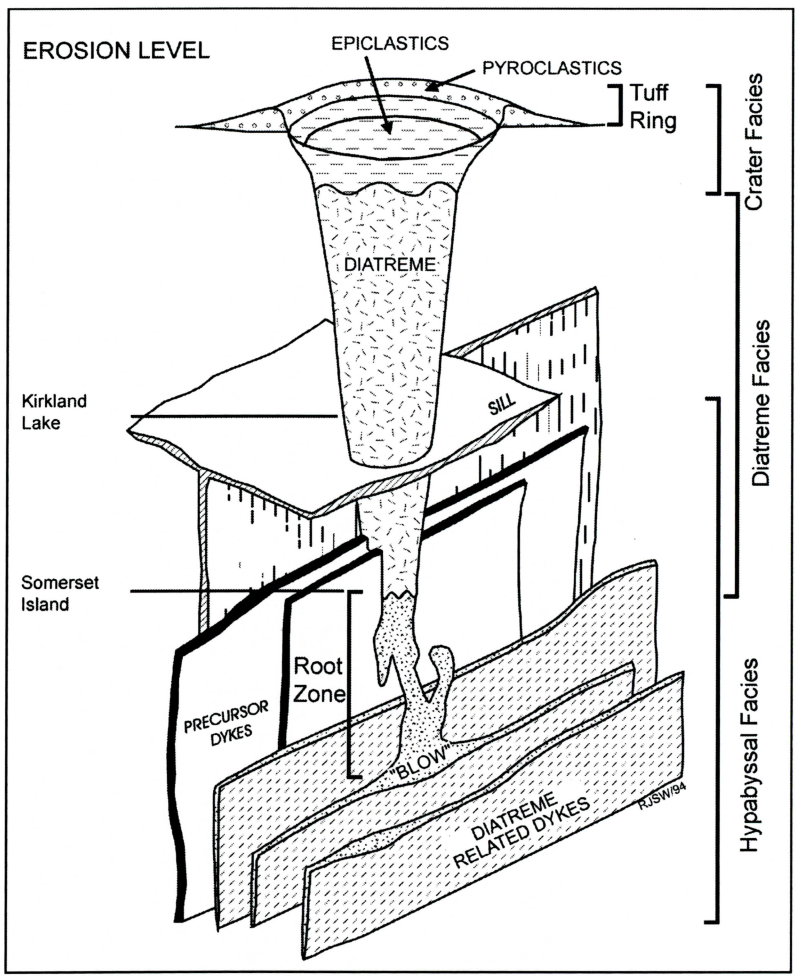

Figure 1: Classic model of a South African kimberlite pipe. Modified from Mitchell (1986), adapted after Kjarsgaard (1996).

In the past decade, a number of kimberlites that do not conform to the South African kimberlite pipe model have been discovered in Canada. Furthermore, the re-investigation of a number of kimberlites in southern Africa has revealed major deviations from the "model geometry". In Figure 2, the variation in kimberlite pipe geometry in the Lac de Gras area (NWT, Canada) is illustrated, and compared to a simplified 400 m diameter South African model kimberlite pipe. In Figure 2, also note the variation in facies or type of kimberlite which make up the Lac de Gras kimberlite pipes i.e., the kimberlite pipes are not necessarily comprised of "diatreme facies tuffisitic kimberlite". Some obvious conclusions to be drawn from the simplified kimberlite cross-sections shown in Figure 2 include:

1.) in the Lac de Gras region, most of the kimberlites are smaller than typical southern African pipes, with some LDG pipes <100 meters in diameter.

2.) in the Lac de Gras region, the country rock/kimberlite pipe contacts can be quite irregular, not the near constant 82° dips as observed in southern African pipes.

3.) in the Lac de Gras region, the kimberlite pipes can be comprised of intrusive (hypabyssal, tuffisitic) and/or volcaniclastic (pyroclastic, resedimented 'epiclastic') facies kimberlite in contrast to southern African pipes which consist of intrusive tuffisitic "diatreme" facies kimberlite.

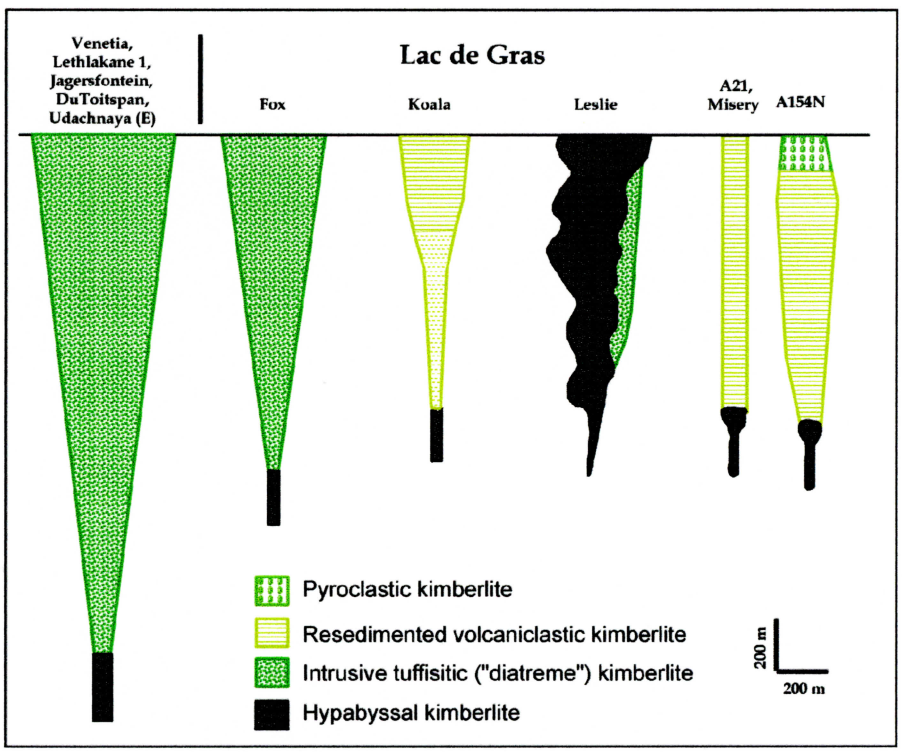

Figure 2: Simplified cross-sections of kimberlite pipes from the Lac de Gras area, illustrating the variation in geometry of the kimberlite pipes, as well as the facies of kimberlite (Kjarsgaard et al., 1998). Simplified (after Figure 1) South African pipe model is shown for comparison. All sections to scale.

In addition to the "atypical" kimberlites of the Lac de Gras area, the Fort à la Corne field (>70 pipes) in central Saskatchewan, Canada also contains kimberlite pipes which bear no resemblance to the "classic model of a South African kimberlite pipe", as shown in Figure 1. Detailed investigations of these rocks (Kjarsgaard et al., 1995; Leckie et al., 1997) has revealed that at Fort à la Corne the kimberlites form low-relief tephra cones comprised dominantly of volcaniclastic (pyroclastic and resedimented "epiclastic") facies kimberlite. It is also recognized that these volcaniclastic kimberlites are re-worked by marine and fluvial processes. More recent work (Kjarsgaard et al., 1998) has recognized discrete emplacement events, and the formation of multiple stacked tephra cones (Fig. 3), leading to highly complicated kimberlite body geometry.

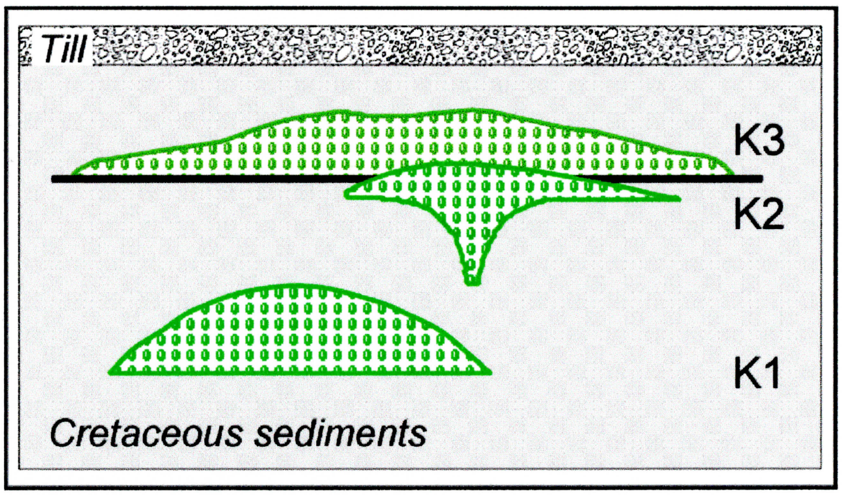

Figure 3: Simplified cross-section of a "single kimberlite" from the Fort a la Corne field, illustrating the complex body geometry which results from discrete, stacked tephra cones (Kjarsgaard et al., 1998).

Scaled cross-sections for kimberlite pipes from Saskatchewan (from Fig. 3), and Lac de Gras (from Fig. 2), are shown together with the South African kimberlite pipe model in Figure 4. The huge variation in the known geometry of kimberlite pipes in Canada has important implications for exploration methodology, particularly with respect to airborne and ground geophysical techniques and drift prospecting.

Drift prospecting

During glaciation, kimberlite is eroded and dispersed into the glacial sediments. Typically, kimberlite and indicator minerals form a dispersion train (of variable shape) from a point source (the kimberlite). Hence the size (surficial area) of the kimberlite body influences the potential amount of kimberlite which can enter the glacial sediment system. For example, the size of the indicator mineral dispersal train and the region of anomalous till geochemistry may be very different for a kimberlite of 100 m diameter (e.g., Lac de Gras), as compared to a kimberlite with a 1 km diameter (e.g., Fort à la Corne).

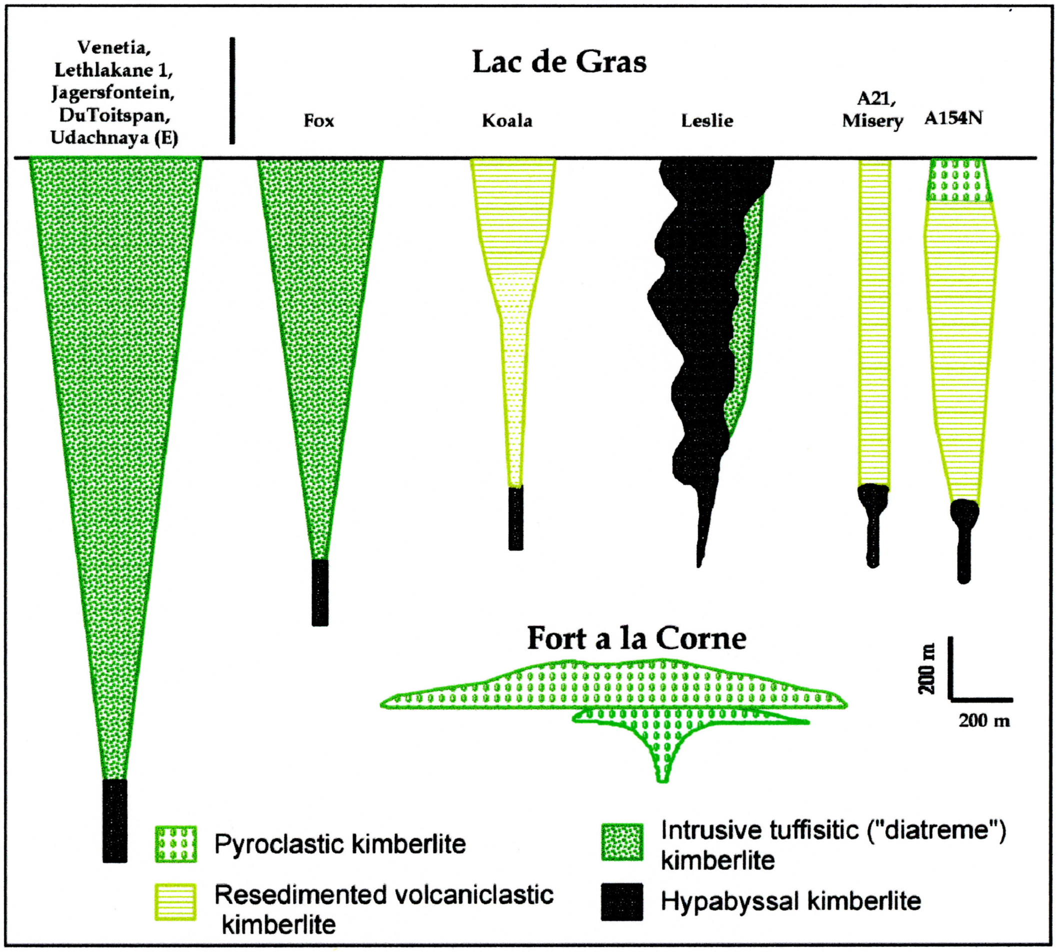

Figure 4: Simplified cross-sections of kimberlites from Lac de Gras and Fort a la Corne, compared to South African kimberlite pipe model (Kjarsgaard et al. 1998). All cross-sections to scale.

Geophysical applications

Target size is one of the fundamental parameters in the determination of line spacing for airborne geophysical surveys for the detection of kimberlite pipes. Line spacing of 200 - 300 m might be considered appropriate (Macnae 1995) when the target is 300 - 400 m in diameter (i.e. the average size of a typical southern African kimberlite pipe). This is illustrated in Figure 5a, where the two large kimberlites would have a high likelihood of being detected (provided they have a magnetic or EM response which contrasts with the host rocks), but the detection of the smaller (i.e., "Lac de Gras size") kimberlites is much more problematic. This, of course, could be rectified by closer line-spacing (Fig. 5b).

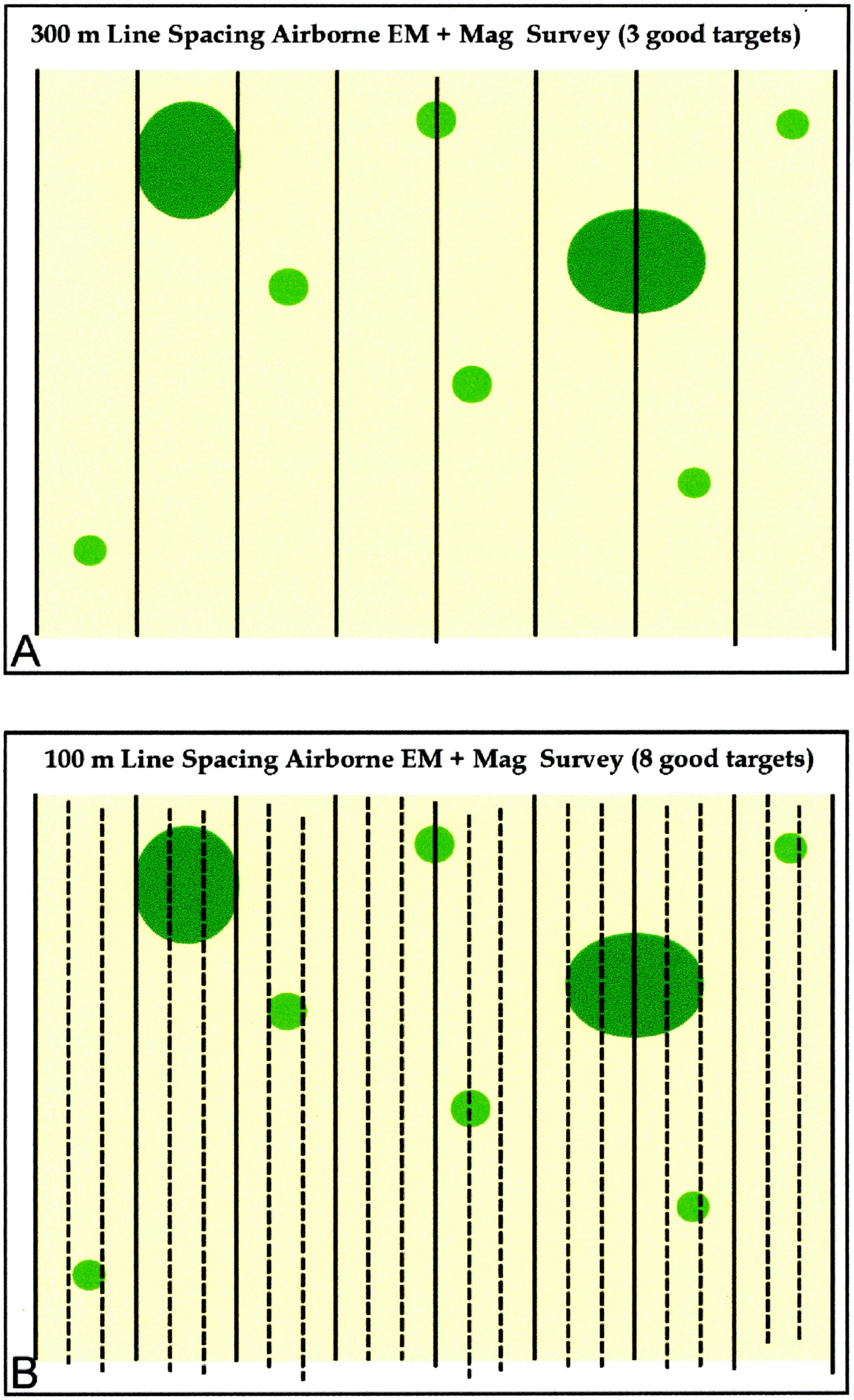

Figure 5: Relationship between kimberlite target size (showing two target sizes - typical Lac de Gras and typical South Africa), and line-spacing for airborne geophysical surveys. Map A demonstrates 300 m line-spacing, while Map B demonstrates a 100 m line-spacing.

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Part 2: Introduction to GIS

What is GIS?

A GIS (Geographic Information System) is a system of computer hardware, software, and procedures designed to support the capture, management, manipulation, analysis, and display of spatially referenced data for solving complex planning and management problems (Fig. 6). The GIS is thus a system that not only contains spatially referenced data, but contains the tools necessary to allow the analysis and conversion of information for a specific set of purposes, or application. The key feature of a GIS is the analysis of data to produce new information. The user becomes part of the GIS whenever complicated analyses, such as spatial analyses and modeling have to be carried out. These usually require skill in selecting and using tools from the GIS toolbox and intimate knowledge of the data being used. At present, and for year to come, general purpose GIS will rely on users to know what they are doing, pushing a button is not enough.

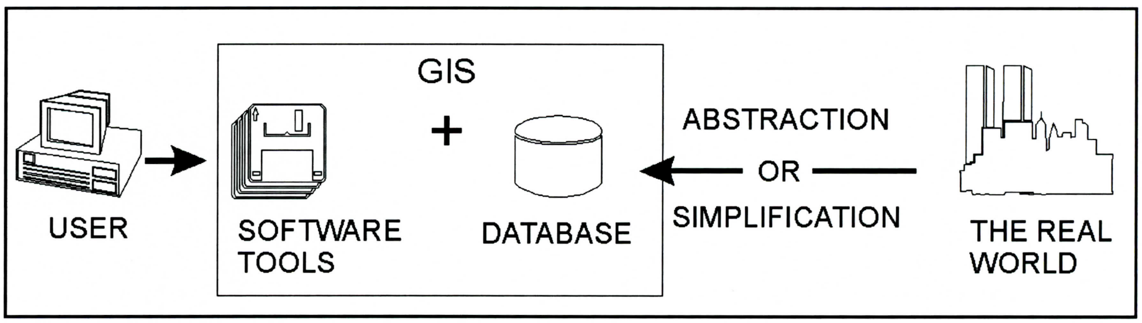

Figure 6: Schematic representation of the GIS analysis process.

Geographic information systems rely on the integration of three distinct aspects of computer technology: database management (of graphic and non-graphic data); routines for manipulating, displaying and plotting graphic representations of the data; and algorithms and techniques that facilitate spatial analysis (Fig. 7).

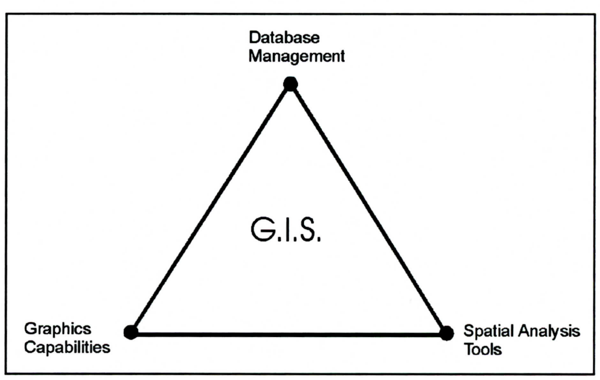

Figure 7: Three components of a GIS.

What can a GIS do?

For any application, there are five generic questions that a sophisticated GIS can answer:

1) LOCATION – What is at…?
   This question seeks to find out what exists at a particular location. A location can be described in many ways using, for example, a place name, a postal code, or a geographic reference such as latitude and longitude.

2) CONDITION – Where is it?
   This is the converse of the first question and requires spatial analysis to answer. You want to find a location where certain conditions are satisfied (e.g., an area of high magnetic trends and low topography).

3) TRENDS – What has changed since…?
   This question involves both of the first two and seeks to find the differences within an area over time.

4) PATTERNS - What spatial patterns exist?
   This question is more sophisticated. You might ask this question to determine whether structural features are strongly related to kimberlite emplacement. Just as important, you might want to know how many kimberlites do not fit this pattern, and where they are located.

5) MODELING - What if….?
   "What if…" questions are posed to determine what happens, for example, to our exploration favourability map, if topographic depressions hide preferentially eroded kimberlite pipes? Answering this type of question requires geographic, geologic and exploration knowledge.

Spatial data models

Maps represent real world, geographic information using points, lines, surfaces (raster/images) and areas (polygons) (Fig. 8). Points define discrete location information, of features too small to be depicted as lines or areas, as well as locations that have no area. Likewise, lines are used to represent the shapes of geographic areas too narrow to depict as an area, or linear features that have length but no area (e.g., contour lines). Areas on the other hand, represent the shape and location of homogeneous features such as bedrock units, while surfaces describe things that have a value for every point on the Earth (e.g., elevation). The storage of these various representations of the real world, is done in the GIS using a data model.

Model	Definition	Geological example
POINT	Zero-dimensional spatial object that specifies geometric location (x,y, {z})	Positions of field observations (e.g. structural measurements)
LINE	One-dimensional spatial object defined by two or more ordered and interconnected points	Faults
AREA	Two-dimensional spatial object that is bounded and continuous	Lithologic units
RASTER	One or more overlapping layers for the same digital image	Elevation, magnetics, etc.

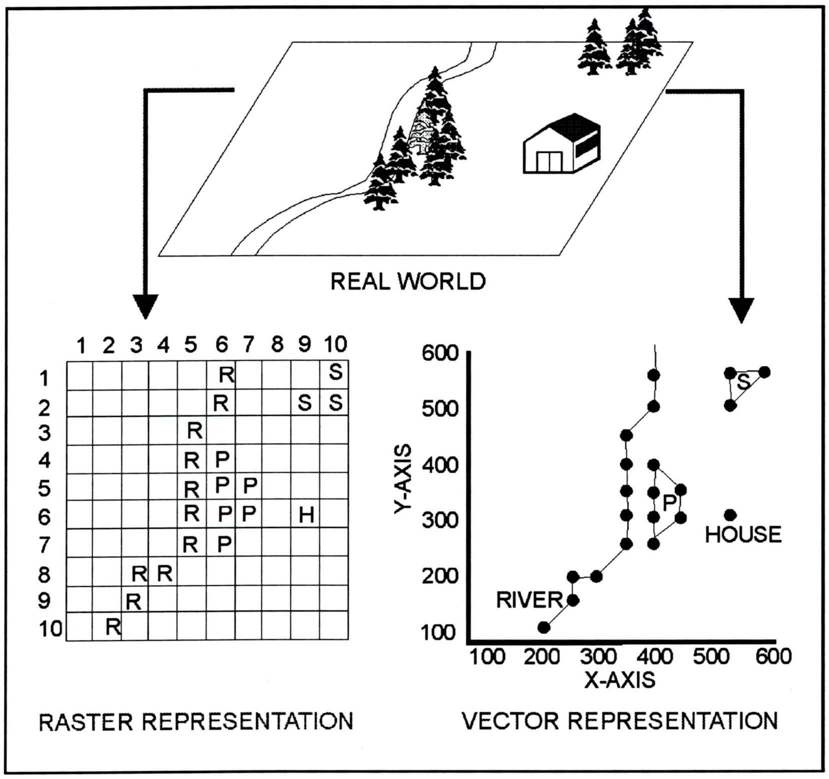

Figure 8: Types of map data and their representation in the vector and raster data models.

The vector data model represents geographic features similar to the way maps do. Points represent geographic features too small to depict as lines or areas; lines represent geographic features too narrow to depict as areas; and areas represent homogeneous geographic features. An x,y (Cartesian) coordinate system references real-world locations. With these x,y coordinates, points, lines and polygons can be represented as a list of coordinates, rather than as a picture or graph (Fig. 8).

In the raster model, the focus is on location, resulting in data that is more like a photograph than a map. The raster model works as a regular grid of cells, or pixels, filled with values. Each location is thus represented as a cell. The matrix of cells, organized into rows and columns, is called a grid. Like the vector mode, the raster data model can represent discrete points, lines and area features. Where a point is represented by a single cell, a line is represented by a series of connected cells that portray length, and an area by a group of connected cells portraying a shape (Fig. 8). This has important implications on accuracy in that the larger the area a pixel represents, the lower the resolution of the data.

Since a common Cartesian reference system can be used for both data models, it is possible to ensure that each coordinate represents the same location in each model. This allows us to use the optimum data model for representing each particular aspect of the Earth and permits greater flexibility for analyzing and displaying data (Fig. 9).

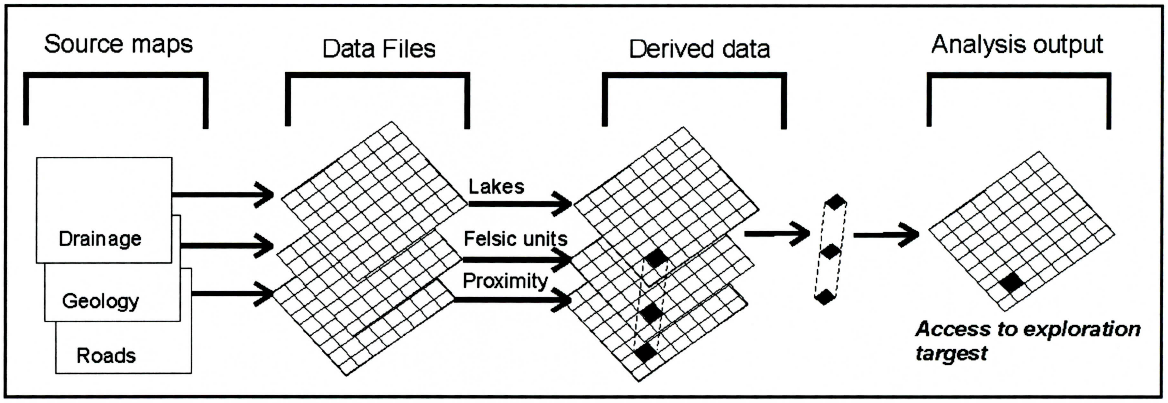

Figure 9: Schematic representation of multi-layer, multi-data model spatial analysis process.

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Part 3: GIS modeling strategies

Modeling types

One of the major strengths of a GIS, is to combine geologic data in order to analyze spatial relationships, or to make predictions using deposit models. The primary objective is to use the spatial analysis capabilities of the GIS to produce a derivative map from the input data, which will give an indication of mineral potential or favourability. From a philosophical point of view, mineral potential is a double-edged sword, as an area labeled as low potential may only be low potential until more detailed data is collected, and/or specific deposit models change. The results that can be obtained from the GIS, are dependent on the scale and quality of the data input, as well as the expertise of the geologist and the associated assumptions that he or she makes on the deposit modeling being used. Since there are many modeling techniques, all of which can produce generally similar results, these assumptions become very important. If the deposit model is in error or is unrealistic, then the results obtained by the GIS can't be expected to lead to the correct decisions being made.

Many spatial modeling techniques exist which combine geologic data to produce a mineral favourability map. However, these methods can be divided into two basic categories: knowledge- and data-driven techniques. Data-driven approaches require a prior knowledge of the area under study, for example, a database of known mineral occurrences or deposits. This allows for spatial relationships between the input maps (predictor maps) and the spatial location of known mineral occurrences to be established and to guide the modeling procedure. Furthermore, training areas can be established over each mineral deposit, allowing predictive information to be gathered from the data input around the deposit. Methods such as *logistic regression*, *weights of evidence*, and *decision tree analysis*, are examples of data-driven approaches. In contrast, knowledge-driven approaches rely on the geologist's input to weight the importance of each data input layer (predictive map), as it relates to a particular deposit model being used. Thus, this approach is more subjective, but has the advantage of incorporating the knowledge and expertise of the geologist in the modeling process. Examples of knowledge-driven approaches include *simple Boolean logic*, *index overlays*, *analytical hierarchy process*, *fuzzy logic*, and *Bayesian probability*. Table 1 summarizes these various methods and provides appropriate references, however, an excellent review of the various modeling methods can be found in Bonham-Carter (1994).

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MODEL TYPE	***METHOD***	***MODEL PARAMETERS***	***CRITERIA FOR COMBINING INPUT DATA***
Data-driven	Weights of Evidence (Bonham-Carter 1984)	Training area (knowledge of existing mineral deposits)	Establish spatial relationship between known occurrences and input data (use of Bayesian probabilities).
	Logistic Regression (Chung and Agterberg,1980)		Use of training areas around each deposit to gather statistics from each of the input layers - used to predict the presence or absence of a mineral deposit
Knowledge-driven	Boolean Operations (Harris,1989)	Estimated by geologist	Summing of binary maps.
	Index Overlay (Rencz et al., 1994)		Summing of weighted input binary maps.
	Fuzzy Logic (An et al.,1991)		Each input predictor map assigned a fuzzy weight - all predictor maps combined using a fuzzy operator (and, or, gamma).
	Analytical Hierarchy (Harris et al., 1997)		Summing of weighted favourability (continuous maps)

Table 1: Summary of modeling methods, including basic parameters, input criteria and references.

Part 4: Case Study

SEARCHING FOR KIMBERLITE: PRELIMINARY EXPLORATION MODEL FOR THE LAC DE GRAS AREA, NWT*

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Abstract

Diamond exploration in Canada's north is hampered by thick, extensive till cover and small exploration targets, making the development of pipe-specific predictive maps difficult. In the Lac de Gras area, GIS analytical techniques are used to test the spatial relationship between known kimberlite pipes and exploration criteria, such as structural trends, till geochemistry anomalies, circular and cold lakes, surficial geology and circular magnetic anomalies, using a "*weights of evidence*" technique.

Ni, Sr, Na, Mg, Cr, and Ba anomalies in the clay fraction of till geochemical data, circular magnetic anomalies, Proterozoic diabase dykes older than 2.0 Ga, bedrock contacts, circular magnetic anomalies and small, cold lakes show a positive spatial association with known kimberlite pipes.

Introduction

Although a theory to predict the location of kimberlite fields within a craton is lacking, many identified fields show a preferred orientation suggesting that pre-existing, deep-seated structures (e.g. dykes, lineaments, lithologic contacts) may be an important factor in the distribution of kimberlite magmatism. Kimberlites are also often characterized by unique electromagnetic and magnetic responses, producing circular anomalies. Since many kimberlites are soft, and easily eroded, pre-glacial and glacial erosion of kimberlite could lead to the preferential development of small, deep, circular and cold lakes or preferentially deeper tills over kimberlite bodies. In addition, the pre-glacial erosion of kimberlite bodies can also lead to the development of related till chemistry anomalies. Recent bedrock mapping, till chemistry surveys, regional magnetic data and an abundance of known kimberlite occurrences make the Lac de Gras area of the Northwest Territories (Fig. 1) an ideal study area for the use of the "*weights of evidence*" (hereafter referred to as WofE) technique to identify key kimberlite exploration parameters and thresholds, and for the generation of a kimberlite favourability map. It is likely that results from the Lac de Gras area can be extrapolated to similar areas where the kimberlite potential is unknown.

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Regional geology

The Lac de Gras area is dominated by low pressure/high temperature metamorphosed Archean metasedimentary rocks and granitoids, deformed by two phases of folding and regional cleavage development. High strain zones parallel regional lineaments and are associated with fold limbs (Kjarsgaard and Wyllie 1994). Over 100 kimberlites are scattered throughout the Lac de Gras region (Pell 1997) (Fig. 1).

The entire area is overlain by a thin (<2 m) to very thick (30 m) till unit attributed to Late Wisconsinan Laurentide Ice (Dredge et al. 1994). Ice flow indicators suggest an early ice flow direction to the southwest followed by a progressive rotation of ice flow through west and northwest with dominant ice flow, in terms of glacial transport and definition, to the northwest (Fig. 1) (Ward et al. 1996). Transport distances in the area are variable, with 40% of source rocks being retained in the till at distances of 5 to 20 km (Ward et al. 1996).

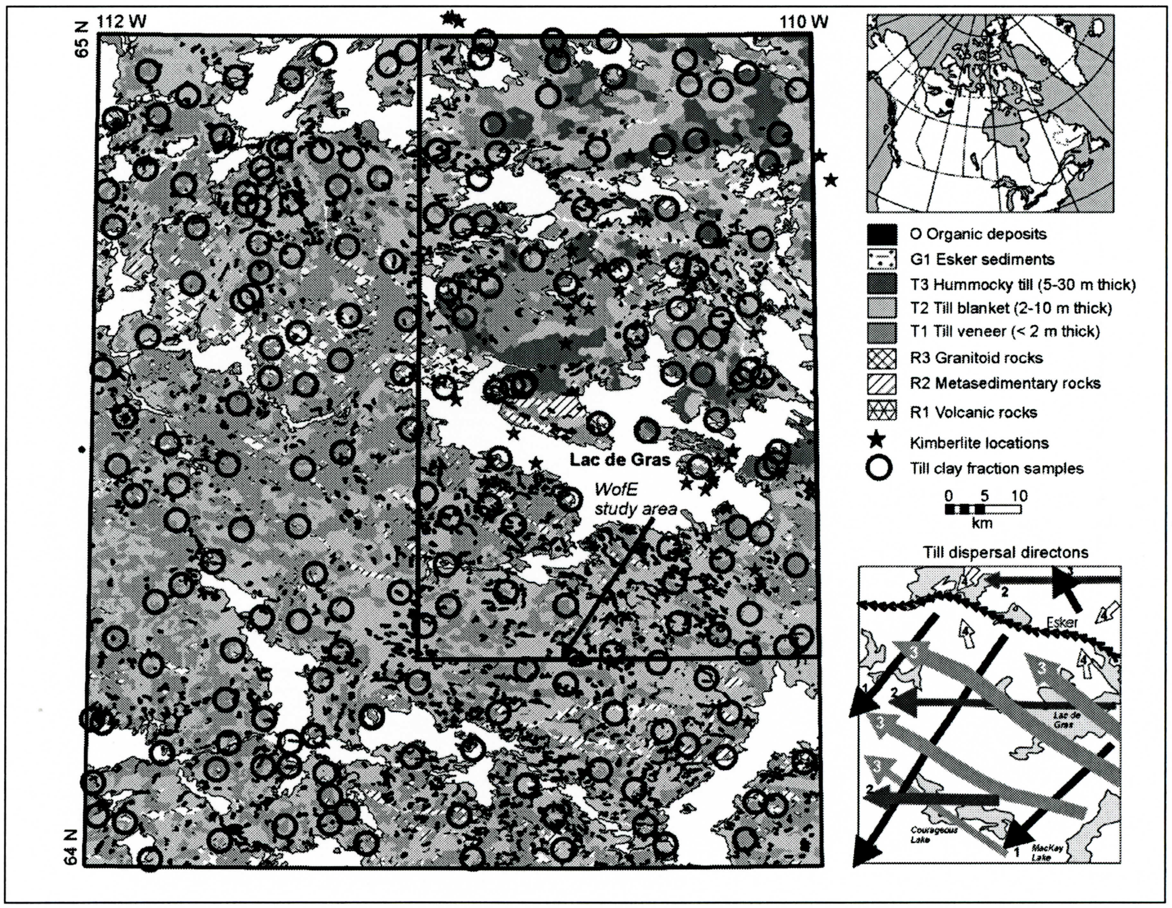

Figure 1 : Location and surficial geology of the Lac de Gras study area. Clay fraction geochemical sample and kimberlite locations are indicated. Local till dispersal directions are also indicated (see inset figure bottom right).

Data processing

Figure 2 presents a generalized flow chart summarizing the data used and processing of the data using GIS and other assorted statistical analysis and interpolation software. The general methodology involves processing the raw data using a number of spatial analysis techniques to produce binary anomaly (evidential theme) maps that are compared to known the kimberlite distribution using the WofE technique. Kimberlite exploration favourability maps are produced in the final stage of analysis.

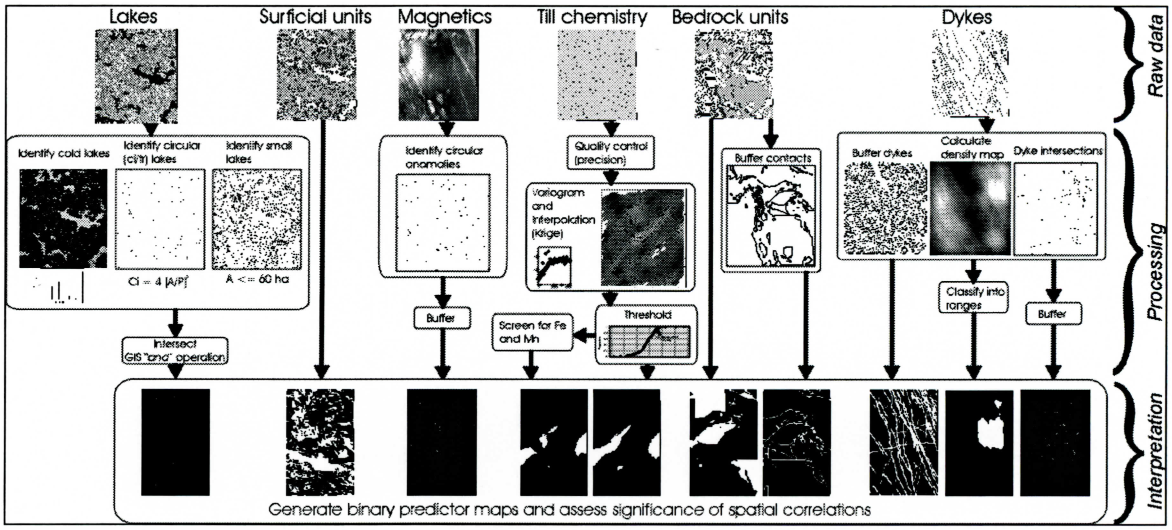

Figure 2: Data processing steps for kimberlite WofE favourability map generation.

Structural control

Contacts between bedrock units of contrasting rheology provide a potential point of weakness in the crust for kimberlite intrusion. All contacts were buffered in 50 m increments to a maximum distance of 500 m and tested for spatial relationships to known kimberlite pipe occurrences.

Five dyke swarms, ranging in age from 1.27 to 2.23 Ga, have been identified in a recent geological compilation using field mapping and total field airborne magnetic data (LeCheminant 1994). For each dyke swarm, buffer maps were constructed in intervals of 50 m to a maximum distance of 1100 m. Each buffered dyke map was then compared to the known kimberlites using the WoFe technique to determine whether individual dyke swarm trends are spatially associated with known kimberlites (see Fig. 3). Since the convergence of dykes also provides a structural control, a dyke density map was calculated and classified into percentile ranges, while dyke intersections were digitized as discrete points and then buffered in 50 m intervals to a distance of 1100 m. Both the dyke density percentile classes and the buffered dyke intersections were tested for spatial association to the known kimberlites using the WofE technique.

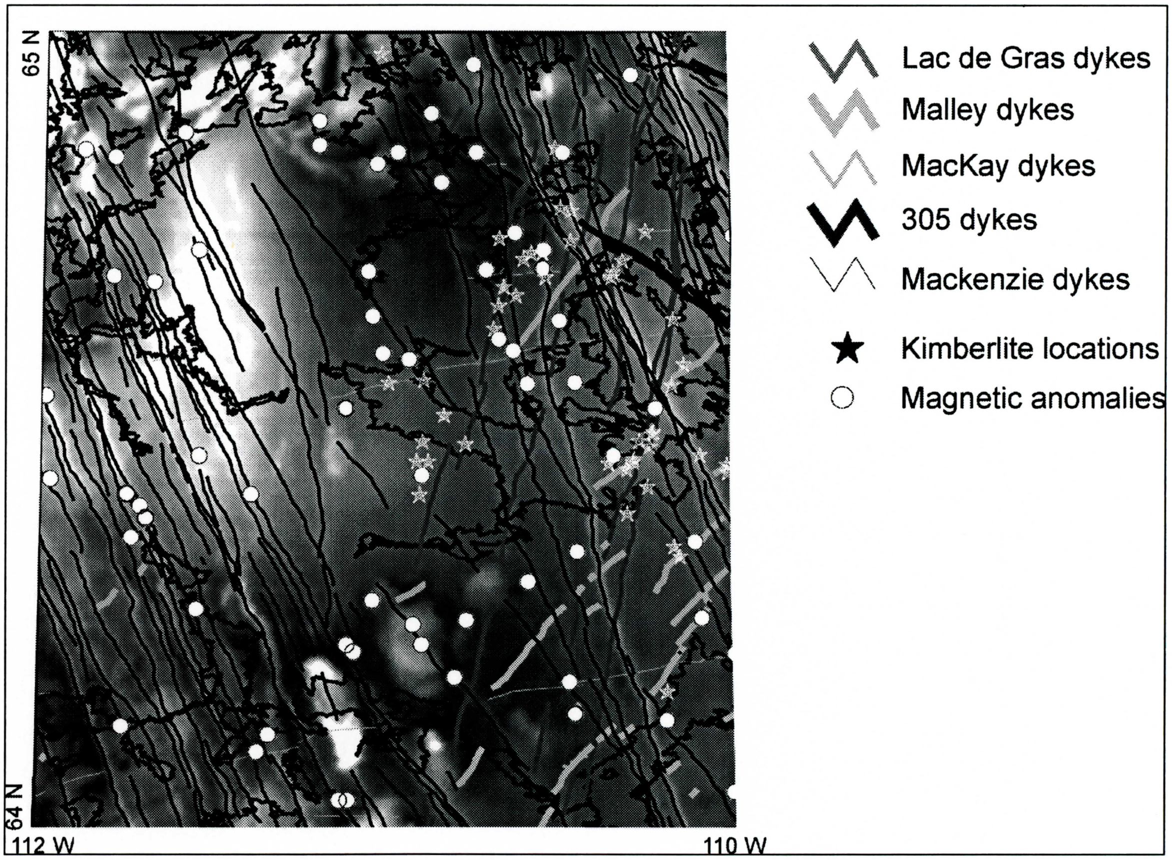

Figure 3: Dyke distribution (by swarm) and circular magnetic anomalies overlain on regional total field magnetics data.

Topography

Kimberlite bodies, being relatively soft, would be expected to form relatively deep depressions, often occupied by cold, circular lakes, due to preferential recessive weathering and erosion compared to surrounding more resistant granitoid and metavolcanic rocks (e.g. Dilabio et al. 1992). All lakes present on digital 1: 250 000 scale hydrography data from Geomatics Canada, were tested for association to known kimberlites. In addition, since known kimberlites in the Lac de Gras area have pipe diameters in the range of 141 to 346 m (Pell 1997), small lakes < 60 ha in size were also tested separately with the WofE technique. All lakes and lakes < 60 ha, were divided into classes based on degree of circularity ($CI = 4[Area/Perimeter]^2$), and into temperature classes based on lake temperatures extracted from Landsat TM thermal band 6 (July 26, 1989). All circularity and lake temperature classes were then tested for spatial association with the known kimberlites using the WofE technique.

Magnetic signature

Circular anomalies present on airborne regional, airborne magnetics data (Geological Survey of Canada), possibly representing kimberlite pipes, were extracted using an algorithm developed by Keating (1995). This process involves using a vertical cylinder to model a synthetic magnetic response which is then compared to the magnetic data by calculating the correlation between the modeled and true magnetic response over a user specified moving window. Areas that show a positive or negative correlation are then extracted from the magnetic data as possible kimberlite locations. For this study, a diameter of 200 m was used to model kimberlite bodies. Figure 3 shows circular magnetic anomalies extracted using this algorithm. A total of 69 candidate circular anomalies were found over the entire study area (NTS 76D), of which 32 fell within the area used for "weights of evidence" testing (see Fig. 1). Although the modeled pipe diameter was 200 m, visual inspection of the total field magnetics data indicates circular anomalies, at or near known kimberlites, of much larger radii. Each magnetic anomaly, originally identified as a point, was therefore buffered in 50 m increments to 1100 m and these buffer distances were tested for spatial association with known kimberlite pipes using the WofE technique.

Till geochemistry

Recently acquired till geochemistry data provides 177 clay (<0.002 mm) fraction samples over the Lac de Gras area (Ward et al. 1996) (Fig. 1). Elements naturally higher (or lower, although these elements are not discussed in this paper) in kimberlite than in the surrounding bedrock in the Lac de Gras area, were identified by a comparison of whole rock element concentrations in kimberlite with whole rock element concentrations in the surrounding bedrock lithologies. Kimberlite pathfinder elements identified in this comparison and available in the clay fraction of the till geochemical data with sufficient precision include major elements Na, K, Al, Fe, Mg, Mn and Ca and trace elements Ni, Ba, Co, Sr, La and Cr. Na, K and Al however, are much lower in kimberlite than in the surrounding bedrock lithology and represent negative pathfinder elements. Semi-variograms, calculated on log-transformed data were used to determine the maximum distance and direction of correlation between samples. This information was then used to interpolate the data using kriging. Anomalous concentrations were identified using thresholds determined by breakpoints in population indicated on normal probability plots of each element. Binary anomaly maps were then produced for each pathfinder element, and then used for comparison to known kimberlite pipes using the WofE technique.

A comparison of clay fraction element concentrations by mapped surficial unit indicates that the thickest till unit in the area (T3, Fig. 1) is preferentially enriched in Cr, Ba, Fe, Mg, Ni and Mn and depleted in Na and La. The T3 till unit occurs only in the northeast of the study area, coincident with the majority of known kimberlite occurrences. This suggests that the thick till unit has locally derived components from the preferential erosion of relatively soft kimberlites. The WofE technique was used to test the degree of spatial association between mapped surficial units and the known kimberlite occurrences.

In Fe and Mn-rich environments, certain elements can be scavenged from solution by adsorption onto Fe- or Mn-oxides, or by formation of Fe or Mn compounds. Since kimberlite is enriched in Fe and Mn, this process may play a role in concentrating kimberlite pathfinder elements. Continuous surface maps for Fe and Mn were generated and binary anomaly maps produced using the method described above. The anomaly map for Fe and Mn was then subtracted from each pathfinder element anomaly map thus eliminating areas where scavenging may be occurring (e.g. Fe and Mn anomalies co-occur with pathfinder element anomalies).

Weights of evidence modeling

Although we generate a favourability map for the entire Lac de Gras area (NTS 76D), the weights assigned for each input map are calculated over a 4300 square kilometer sub-area of relatively uniform known occurrences (Fig. 1). This is to ensure that the statistics are representative of the area of known kimberlite pipes. Of the 73 pipes, 44 pipes fall within this sub-area and are used in the calculation of the WofE statistics.

The WofE technique is discussed fully in Bonham-Carter (1994). The locations of known kimberlite pipes, each of which is assigned an area of 250 m^2 in this case, are used to assess the degree of spatial association between known kimberlites and each evidential theme map. A pair of weights, W^+ and W^- are determined from the degree of overlap between the known kimberlite pipes and the evidential theme pattern. W^+ will be higher if there are more kimberlite pipes occurring on the evidential theme pattern, than would be expected based on a random distribution of kimberlite pipes. The degree of spatial association of the pattern with the kimberlite pipes is indicated by the contrast, C, which is the difference between the weights W^+ and W^-. Only evidential theme maps with a positive spatial association to the known kimberlites are used in the final probability map.

Results are summarized in Table 1 for data used to build the kimberlite favourability map (Fig. 4). Positive contrast or "C" values indicate a positive correlation between the known pipes and the evidential theme map pattern. A measure of the reliability of this value is provided by the C/SD column in the table which calculates the ratio of contrast to it's standard deviation. Values of less than 1.5 indicate a lack of significance with respect to the C value and suggest caution be applied when using this result. Given that the number of pipes is constant, the weight, and hence C, will vary depending on the total area of the evidential theme map. In general, C will be large when the ratio of the proportion of pipes on an evidential theme pattern to the proportion of the study area occupied by the evidential theme pattern is large. Although C values for Ba, Mg and Na were acceptable, these maps were strongly correlated and thus violated the assumption of conditional independence for all map input layers (see Bonham-Carter 1994). These maps were combined to produce a single map of Ba, Mg and Na anomalies.

Predictor map	Area (km^2)	No. of pipes	W^+	W^-	C	C/SD	Rank	Threshold
MacKay dykes	61	2	1.19	-0.03	1.22	1.68	9	350 m
Lac de Gras dykes	243	8	1.20	-0.14	1.34	3.42	6	350 m
Malley dykes	23	2	2.18	-0.04	2.22	3.04	4	100 m
Dyke density	322	9	1.08	-0.16	1.24	3.29	7	> 3 std. dev.
Dyke intersections	9	2	3.10	-0.04	3.14	4.26	1	200 m
Cold/small lakes	30	3	2.32	-0.06	2.39	3.95	3	< 60 ha; DN < 117
Magnetic anomalies	8	1	2.49	-0.02	2.51	2.45	2	250 m
Ni (screened)	172	4	0.87	-0.06	0.93	1.76	12	110 ppm
Sr (screened)	74	2	1.02	-0.03	1.05	1.44	(11)	30 ppm
Cr (screened)	19	1	1.66	-0.02	1.68	1.65	5	174 ppm
Ba/Mg/Na (screened)	716	17	0.89	-0.34	1.22	3.89	8	245 ppm/650 ppm/7.5%
All contacts	201	6	1.10	-0.10	1.20	2.72	10	50 m

Table 1: Summary of input maps and their weights used for conservative threshold kimberlite favourability map. Rank is based on C (Contrast) value and ranks shown in brackets indicates a low C/SD (Constrast/Standard deviation of Contrast) value. Rank is based on C values.

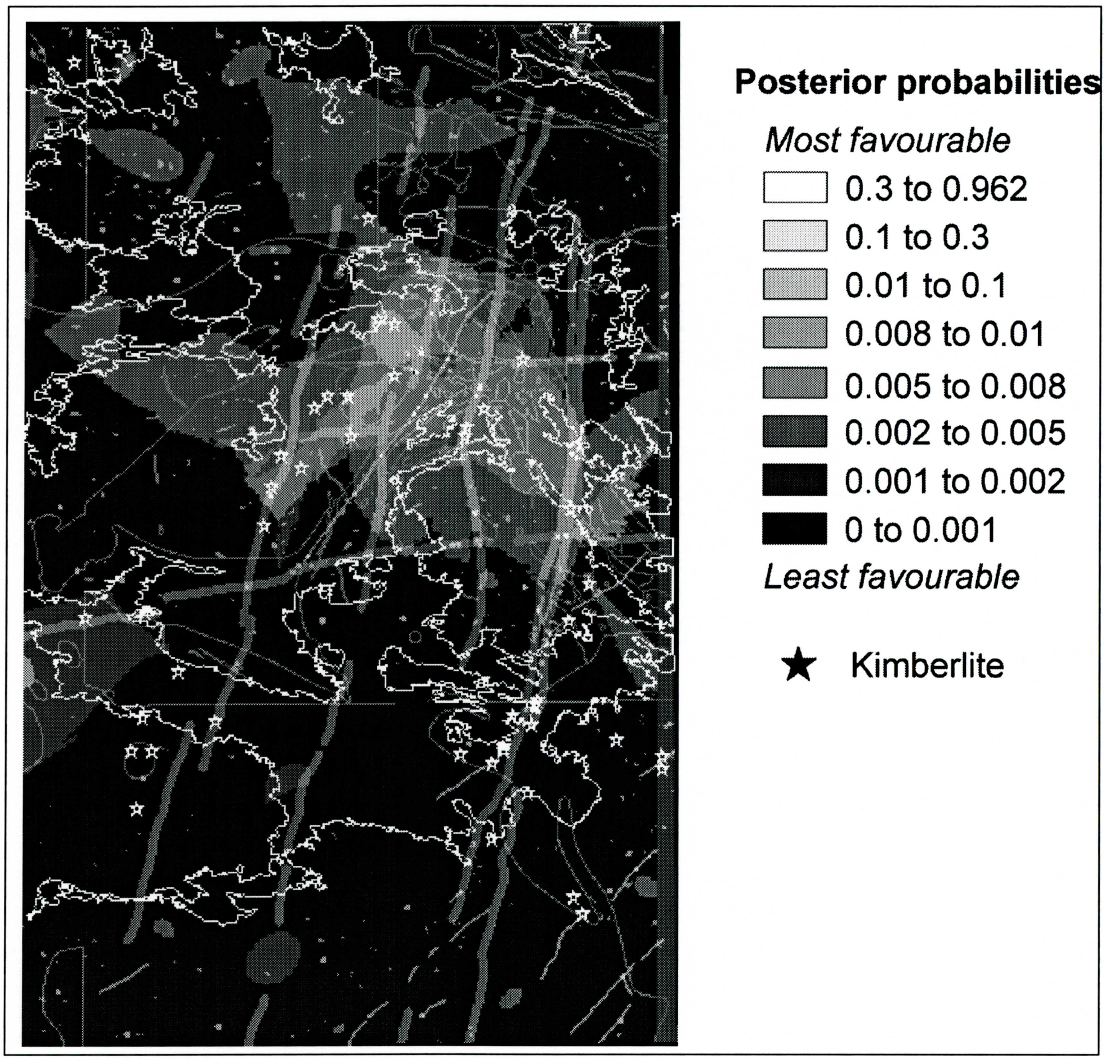

Figure 4: Kimberlite favourability map.

Discussion

Results of WofE testing indicate that all lakes are spatially related to known kimberlites. However, highest correlation was obtained for small (< 60 ha in size), cold (DN < 117) lakes, suggesting a model of small, circular and recessively weathered kimberlite bodies is appropriate for the Lac de Gras area.

The older dyke trends (Lac de Gras, Malley and MacKay) are more strongly spatially correlated with the known kimberlites than the younger dykes (305 and Mackenzie) (see Table 1). At this time, we are not aware of a tectonic theory to explain this relationship, although it is possible that the older dykes are deeper structures. Significant thresholds for the older set of dykes ranges from 100 m to 450 m, and may reflect the presence of dyke parallel fractures or smaller satellite dykes which are unique to the older sets of dyke trends. A strong positive association between kimberlite pipes and dyke density and dyke intersections suggests that the dykes are in fact, acting as a structural control on the emplacement of kimberlite pipes. This is supported by a strong association between bedrock contacts and kimberlite pipes (see Table 1). Future work will look at other possible crustal scale zones of weakness, interpreted from bedrock mapping and satellite imagery (Landsat TM and RADAR).

The strongest association between kimberlite pipes and magnetic anomalies resulted from using a 200 m diameter pipe model, resulting in the identification of one pipe within 250 m of a magnetic anomaly. Calculation of the circular magnetic anomalies is highly dependent on the resolution of the magnetics data, diameter of pipe being modeled, size of model search window, degree of correlation between model and actual data and level of acceptable error of fit. This is further complicated by the fact that the size of magnetic anomalies of known pipes tend to be much larger than the pipe itself and by the fact that not all pipes generate circular magnetic anomalies.

Positive association between elements Cr, Sr, Mg, Na, Ni and Ba anomalies in the clay fraction of the till data with kimberlites suggests that this fraction may be useful in the search for kimberlite. It also suggests that these elements may effectively be used as kimberlite pathfinders in clay fraction till data, at least in the Lac de Gras area. The lack of correlation between other kimberlite pathfinder elements such as Co and La indicates that glaciation and secondary weathering processes have a heterogeneous effect on the spatial distribution of the kimberlite pathfinder elements. This may be due to the variable effects of scavenging. Spatial correlations of Cr, Sr, Mg, Na, Ba, and Ni with known kimberlite pipes improved with removal of Fe and Mn scavenging effects, and the screened predictor maps were used in generation of the kimberlite favourability map (Table 1). Fe and Mn scavenging is therefore an important factor controlling element concentrations in the clay fraction of till, potentially controlling the concentration of other elements that were not found to be spatially associated with known kimberlite occurrences.

Individual areas of the high probability (i.e. high kimberlite potential) are quite small (see Fig. 4) due to the small size of the model target and the resultant small magnetic anomalies and lakes, and narrow buffer zones used in the predictor maps. Relaxing of the thresholds used to produce the binary predictor map results in larger areas of high potential and possibly lower C values but can also increase in the number of known kimberlites identified. This can lead to larger and more numerous high potential areas on the favourability map but also increases the potential for false anomalies.

By definition, the WofE approach to the calculation of a mineral favourability map is dependent on the number, distribution and location of the known occurrences. Poorly located occurrences can lead to errors on the final favourability maps. However, the identification of an exploration criteria using the WofE technique should not be negated with the discovery of new deposits. Like all model methods, the WofE technique assumes that the unknown mineral occurrences will have characteristics similar to the known (e.g. similar geologic/tectonic setting, geophysical signatures etc.). If this is not the case, neither objective data-driven methods such as the WofE technique, nor subjective knowledge-driven models will be fully successful in targeting unknown deposits.

Conclusions

- Localization of known kimberlite occurrences along bedrock contacts and dykes indicates the importance of pre-existing structural zones of weakness in kimberlite emplacement. This is reinforced by positive association with dyke intersections and dyke density. The stronger association between kimberlite occurrences and older dykes may indicate an unsuspected tectonic control.

- Cr, Ni and Ba geochemical anomalies in the clay fraction of till are spatially related to known kimberlites. This suggests that the clay fraction of till is a useful medium for kimberlite exploration, particularly once the effects of Fe/Mn scavenging are removed.

- An apparent lack of a statistically significant positive association between known kimberlites and the thick, kimberlite-enriched T3 till unit emphasizes the need for an adequate scale of surficial mapping and a good understanding of ice flow directions.

- Kimberlites in the Lac de Gras area are spatially related to lakes, and particularly to small, cold lakes.

- Circular magnetic anomalies are positively associated with known kimberlite occurrences. Circular magnetic anomalies are more numerous and widespread than the known kimberlite occurrences and may represent unknown kimberlite occurrences.

- Given that high probability areas are necessarily small in modeling kimberlite pipes, a more liberal favourability map may result in more high potential areas but an increase in the risk of false anomalies.

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