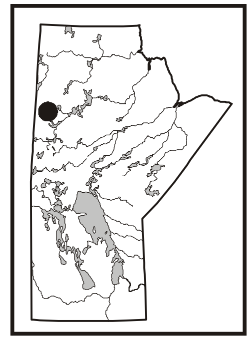
GS-16 MINERALIZATION-POTENTIAL MAPPING: A DATA-FUSION ANALYSIS

by D.M. Rogge[1], N.M. Halden[1] and C.J. Beaumont-Smith



Rogge, D.M., Halden, N.M. and Beaumont-Smith, C.J. 2000: Mineralization-potential mapping: a data-fusion analysis; *in* Report of Activities 2000, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 82-90.

SUMMARY

This project is a collaboration between the University of Manitoba and the Manitoba Geological Survey, with the objective of creating a regional database of geological and geophysical data for the Lynn Lake greenstone belt, and producing mineralization-potential maps using a GIS platform and data-fusion techniques. Data sets compiled include regional geology, lithogeochemistry, lake sediment and till geochemistry, airborne geophysics and synthetic aperture radar (SAR) data. A preliminary set of mineralization-potential maps for shear-hosted and VMS-type deposits has been completed using regional geology, lithogeochemistry and geophysical data. Spatial deposit models were developed for the two deposit types and fuzzy-logic data-fusion methods were used to integrate map layers. Preliminary results show good correlation between the potential maps, produced using theoretical principles, and known mineral occurrences throughout the southern portion of the Lynn Lake greenstone belt.

INTRODUCTION

Geographic information systems (GIS) have been developed over the years to integrate and manage large sets of diverse spatial data. These systems are also capable of manipulating the data to analyze and model the interrelations between spatial data sets (Bonham-Carter, 1994). The manipulation, or integration, of the spatial data can be accomplished using statistical weighting methods, Boolean logic, fuzzy logic, Dempster-Shafer theory, and neural-network data-fusion methods. Combinations of data can be used to locate areas of potential economic interest, define regional bedrock geology, or delineate major structural trends. However, data combination or fusion must be done in a consistent and justifiable manor; otherwise, the results will not be precise and technically accurate (Argialas and Harlow, 1990). Another important feature of this approach is that one must also understand that the integration of data is concentrated on a two-dimensional surface, even though particular data sets, such as magnetic data, are defined by three-dimensional structures (Moon, 1993). Different spatial resolution among data sets, together with the incomplete and imprecise nature of spatial data sets, requires a proper quantitative method of integration to address such problems (Moon, 1993).

Geological and geophysical data are commonly represented in the form of spatial data because a vast amount of information can be shown and understood far more easily than if the same data were presented in a written format. When spatial data sets are used together, the amount of information that can be acquired increases significantly; however, the method of integration used can give substantially different results. In the case of mineral-potential mapping, each layer of spatial data must be weighted according to the particular type of deposit being explored. It is here where simple combination does not work and the introduction of theoretical principles of geology and geophysics play a major role. Determining the various spatial data sets to be used, and the method of data fusion, is controlled by a mineral deposit model that, in turn, also determines the weighting of spatial data layers. In areas where numerous mineral occurrences are known, statistical data-fusion methods are useful. In many areas, however, previous exploration is minimal, so subjective methods are more applicable. In the case of minimal exploration, a geologist has complete control over the integration approach and weighting of the spatial data. This type of integration does not have the same quantitative accuracy as statistical methods. Subjective methods do, however, allow for flexibility, thus giving the geologist the ability to test many different scenarios, or spatial deposit models. These same methods can also be applied to less specific targets, such as regional-scale structures, by integrating aeromagnetic and SAR data.

PROJECT OBJECTIVE AND BASIC METHODOLOGY

The objective of this project is to produce structural and mineral-potential maps for the southern part of the Lynn Lake greenstone belt, specifically with respect to the Johnson Shear Zone (JSZ) and associated structures. This will be accomplished by using the theoretical principles of geology and geophysics to develop a conceptual mineral deposit model, which is then applied to a set of spatial data using fuzzy logic and Dempster-Shafer data-fusion methods. A potential map of major structural trends will be completed first. The structure map will, in turn, be applied to a number of spatial deposit models for mineralization-potential mapping.

Framework for Basic Methodology (Bonham-Carter, 1994)

1) Establish a conceptual mineral deposit model: A well defined model is key when applying theoretical principles of geology and geophysics to develop accurate mineral-potential maps. The two data-fusion methods that will be used have been developed for areas with minimal exploration. The weights applied to the various spatial data sets are not accomplished statistically, but are subjectively based on a spatial deposit model. Hence, a more defined model will result in more accurate mineral-potential maps.
2) Build a spatial database: Data sets include regional geological and structural maps, airborne geophysical data (very low frequency electromagnetics [VLF], total-field magnetics [TF], vertical-gradient magnetics [VG]), RADARSAT SAR data, regional lithogeochemistry, regional lake sediment geochemistry and regional till geochemistry. Note that the RADARSAT data, regional lake sediment geochemistry and regional till geochemistry were not integrated in the preliminary analysis.
3) Data analysis: Secondary spatial data sets will be developed to enhance or modify the usefulness of the existing spatial data sets by:
   - developing new maps based on pre-existing spatial data sets and other nonspatial data available with respect to the given mineral deposit model;
   - enhancing various maps and integrating to further define major structural features (specifically the JSZ), using the existing regional structural mapping, geophysical, and RADARSAT SAR data; and
   - producing proximity maps that can address both spatial associations and decay rates, linear or exponential, related to a particular spatial data set or group of data sets.
4) Integration of spatial data maps: This is accomplished using data-fusion methods and the given spatial deposit model.

MINERAL DEPOSIT MODEL

Known gold deposits within the southern portion of the Lynn Lake

[1] Department of Geological Sciences, University of Manitoba, 125 Dysart Road, Winnipeg, Manitoba R3T 2N2

belt are characterized by intensive silicification and are associated with the JSZ. In order to locate new areas of economic interest, one must define a deposit model that best represents a particular target orebody. Deposit models can be quite simple and incorporate more that one specific target; however, a more defined model will produce a more accurate potential map. The model will also determine which spatial data sets should be incorporated, and how they should be used during integration. Many of the ideas defined by a deposit model cannot be treated in a spatial sense. Once a deposit model has been chosen, it must be utilized to represent the data available, so a spatial deposit model is developed. Nonspatial data, such as timing of structural and intrusive events, can also be incorporated into the spatial deposit model, but their influence is indirect and applied primarily in the weighting of the spatial data. Representation of a deposit model in a spatial sense is a major objective of this project. The spatial deposit models defined in this report are preliminary, and modifications are ongoing to develop more accurate potential maps. A detailed discussion of the major theoretical components related to the two deposit models will not be given here. For a more complete discussion, please refer to Roberts (1988), Bursnall (1989), Hodgson (1993) and Bonham-Carter et al. (1993) for the shear-hosted model; and Lydon (1988a, b), Franklin (1993) and Wright and Bonham-Carter (1996) for the VMS model.

Shear-Hosted Magmatic Hydrothermal Deposit Model

Thrust and strike-slip faults are common structural features associated with shear zones, commonly located at or close to the transition from brittle to ductile regions in the crust (between 7 and 12 km in depth). Within shear zones, a hydrous component typically extracts elements from adjacent wall rocks and transfers them to areas where they precipitate in greater concentration. Fluids liberated during magmatic solidification or during metamorphic dehydration usually make up the hydrous component. Spatial association to source rocks is common, although zones of mineralization are not necessarily specific to a particular rock type. Some rocks tend to be more susceptible to alteration or fracturing, and are therefore more probable sites for element concentration. The key components of this model then become, with respect to degree of decreasing importance, structural control, source of the hydrous component, and source of the mineral component.

Volcanic-Hosted Massive Sulphide (VMS) Deposit Model

Hydrothermal fluids circulating through a package of subaqueous mafic and felsic volcanic rocks is the basic environment for the formation of VMS deposits. The key components for this model include a heat source, which drives the hydrothermal system, a fluid source and an impermeable cap to the hydrothermal reaction zone. High fluid temperatures are required to dissolve a sufficient amount of metals for later deposition. The source of the heat is usually attributed to intrusive complexes and associated dykes and sills. This heat source must be great enough to overcome cool seawater, the major source of the fluids, circulating through the permeable subaqueous volcanic rocks. Magmatic fluids are considered to be a minor component. Precipitated metals associated with the subaqueous volcanic rocks are sealed in with an impermeable cap, commonly massive pyroclastic ash or rhyolitic flows. Faulting within the region may act as a trap for the precipitating sulphide minerals, although structural control is a minor component in the formation of a VMS deposit. Alteration is a key spatial component in both VMS and shear-hosted deposits; however, a complete spatial data set is not available, so alteration is not discussed here.

SPATIAL DATA SET

Development of a spatial data set will be accomplished using GIS and will include spatial and point data. Data sets acquired for this preliminary study include regional geology maps, lithogeochemistry and regional geophysics (Table GS-16-1). The extent of the individual data sets varies and they do not cover the entire greenstone belt; however, the problems associated with missing or incomplete data will be addressed during map integration.

Table GS-16-1: Spatial data sets used in preliminary mineralization-potential maps.

1:50 000 scale geological map, Lynn Lake greenstone belt; Manitoba Geological Survey.
1:250 000 scale geochemical units, Lynn Lake greenstone belt; Manitoba Geological Survey, OF99-13 (Zwanzig et al., 1999).
Airborne TF, VG, VLF-EM, Project 10500, Barrington Lake; Canada–Manitoba joint agreement, 1983.
Airborne TF, VG, VLF-EM, Project 13800, Lynn Lake; Canada–Manitoba joint agreement, 1982.
Airborne TF, VG, VLF-EM, Project 18201, Barrington Lake; Canada-Manitoba Mineral Development Agreement (MDA), 1985.

DATA ANALYSIS

Shear-Hosted Model

Structural control is the major component of the shear-hosted model. Therefore, a structure (lineament) map has been produced by combining known major fault and shear zone features, compiled during regional mapping, and geophysical data. Synthetic aperture radar (SAR) data have been acquired for this project, but have not yet been integrated into the structure mapping. Lineaments were defined from the vertical-gradient magnetic map by applying directional and gradient filters, and by adjusting the image threshold value. Lineaments were divided into four categories based on their length. Proximity maps, at 100 m intervals to a maximum of 5 km, were created for each of the lineament maps and the known structure map.

Heat can be attributed to intrusive units, whereas the fluid sources can be related to fluid loss during magmatic crystallization. 'Proximity to heat source' maps were created by selecting intrusive units from the geological map. Proximity maps were created for both mafic and felsic intrusive units with 100 m intervals to a maximum of 5 km.

Reclassification, or map recoding, is the reassignment of the classes of a spatial data layer to produce a new map. Reclassification is not used to change spatial relationships within a particular map layer, but instead to simplify or make integration between maps possible. Geology has been reclassified to combine similar lithological units. It has also been reclassified to represent relative rheological characteristics of intrusive, volcanic and sedimentary units. The lithogeochemical map has been reclassified into two maps, 'MgO content' and 'primitive versus evolved', based on the average MgO and rare-earth element (REE) data, respectively, for each of the defined geochemical units.

VMS Spatial Model

'Proximity to heat source' maps for the VMS spatial model were derived from the shear-hosted model 'proximity to heat source' maps; however, weighting of the maps is different to reflect the given model. Structure is a minor component for this model, so lineament maps and known structure have been combined into a single 'proximity to structure' map. Additional stratigraphic, or 'proximity to volcanic rocks', maps have be created for the VMS model using the geological map. The lithogeochemical data for volcanic units have not been applied in this preliminary analysis.

MAP INTEGRATION

The integration of the various data sets in this preliminary analysis has made use of the fuzzy-logic data-fusion method. The fuzzy-logic method utilizes the continuous scale from 0 to 1, or fuzzy membership function, which represents the full nonmembership (0) and full membership (1) function, respectively, of a fuzzy set. The initial advantages of the fuzzy-logic method are its straightforward implementation and its ability to develop mineralization-potential maps in areas that are not well explored. Fuzzy-set theory enables the user to develop a set of attributes for a particular spatial data set, whereby membership functions can be expressed as linear or nonlinear, depending on the problem at hand (Bonham-Carter, 1994). Defining a fuzzy set, A in X, as the set of ordered pairs

$$A = \{ x , u(x)\}$$

where x is a member of X and u(x) is the membership function, we can now develop a series of fuzzy sets for our geology, geochemistry, 'proximity to heat source', 'proximity to volcanic rocks', 'proximity to structure' and geophysical spatial data.

Five methods of map integration, fuzzy AND, fuzzy OR, fuzzy algebraic product, fuzzy algebraic sum and the gamma operation, have been defined for the fuzzy-logic method (Bonham-Carter, 1994). The first two methods are not used in this project, and the algebraic product and sum methods are only used in combination with the gamma operation. The algebraic product is defined as

$$\text{Ucombination } (x_1, x_2, \dots , x_n) = (x_1)\,(x_2) \dots (x_n)$$

Its output is less than or equal to the smallest contributing membership value and therefore represents the minimum probability. The algebraic sum, on the other hand, results in a maximum probability that is equal to or greater than the largest contributing factor:

$$\text{Ucombination } (x_1, x_2, \dots , x_n) = 1 - \{(1 - (x_1))\,(1 - (x_2)) \dots (1 - (x_n))\}$$

The last method is the gamma operation, where a parameter, gamma (γ), is used to ensure a flexible compromise between the maximum probability of the algebraic sum and the minimum probability of the algebraic product (Bonham-Carter, 1994). The value of γ can range between 0 and 1, where 0 would result in the output being equal to the algebraic product, and 1 would result in the output being equal to the algebraic sum. With a γ value of 0.75 used in this project, the gamma operation can be defined as:

$$\text{Ucombination } (x_1, x_2, \dots , x_n) = ((\text{fuzzy algebraic sum})\ \gamma)\ ((\text{fuzzy algebraic product})\ 1 - \gamma)$$

Before map integration can take place, weighting of the various maps must be completed. Weighting is completed at two levels: first between the individual maps, and second with regard to classes within the individual maps themselves. Tables GS-16-2 and -3 list the fuzzy-set membership functions for each of the given spatial data sets for the shear-hosted and VMS deposit models, respectively. Between individual maps, a maximum possible membership value is given to a particular map based on the degree of evidence of that map. Weighting of the various classes for each map has been applied differently with respect to the lithological unit map, geochemical maps, geophysical maps and proximity maps. The lithological and 'primitive versus evolved' maps are subjectively weighted. The 'MgO map' is based on the relative MgO values for the given volcanic units. Geophysical maps are reclassified relative to the original image data values. 'Proximity to heat' and 'proximity to structure' maps are weighted with an exponential decay function from proximal to distal, whereas a linear decay function is applied to the 'proximity to volcanic rocks' maps.

Figure GS-16-1 is an integration flow chart representing the preliminary shear-hosted spatial deposit model. The model is separated into two major components, the source zone probability and deposition zone probability. The source zone probability relates to the source of the mineral component and is dependent on primary lithology and geochemistry, whereas the deposition zone probability is dependent on structural control and source of the hydrous component, primarily magmatic in this case. Structural control is directly related to the rheology of a particular rock type and the spatial associations between rock types. Geophysical data represent present geophysical characteristics of the regional geology. Therefore, both rheology and geophysics have tentatively been included in the depositional zone probability.

Figure GS-16-2 is the integration flow chart for the VMS spatial deposit model. This model has been separated into source zone probability, geophysical factor and deposition zone probability. The geophysical data again represent present geophysical characteristics of the regional geology; however, because of the magnetic nature of VMS deposits, the geophysical factor is considered as a separate component.

Figures GS-16-3 and -4 are the resulting mineralization-potential maps produced for the two deposit models, where the grey-scale range is relative probability. Only the top 20^{th} percentile is shown, with grey-scale values being further stretched to highlight local variations. Three geophysical surveys were completed in the area, but they have not been levelled relative to one another. Therefore, each mineralization-potential map comprises three individual maps, each with its own relative potential scale that represents the special limits of the particular geophysical survey.

PRELIMINARY RESULTS

Preliminary spatial deposit models have been completed and the resulting maps were used during the 2000 summer field season. Shear-hosted and VMS deposit models were integrated using the fuzzy-logic data-fusion method. Initial analysis shows that high-potential sites, specifically within the top 20^{th} potential, show good agreement with known mineralization in this part of the Lynn Lake greenstone belt. It must be stressed here that these mineralization-potential maps are based on spatial deposit models defined by theoretical principles of geology and geophysics, and are not defined by known occurrences within the region. The initial analysis was based on known occurrences compiled in the Mineral Deposit Series and from ground-truthing completed during the 2000 field season. A detailed analysis of the preliminary and subsequent maps will be completed over the winter (2000–2001) and will include further ground-truthing. Analytical data from geochemical and assay samples collected during the 2000 field season have not yet been received, but will be included in the subsequent analysis. Shear-zone potential maps were completed for vein-type and disseminated-type occurrences. The two shear-hosted potential maps are similar (disseminated-type potential map is shown in Fig. GS-16-3), suggesting that either rheology plays a minor role or that the application of rheology is incorrect. Further work is necessary to address this issue. A number of high-potential zones have been located where there has been no known major exploration. These areas, if truly unexplored, could represent new areas of interest and would be the focus of subsequent work.

One of the major problems of integration when using the fuzzy-logic data-fusion method is areas of no data, because all subsequent integration must be multiplied by zero. This problem was overcome by giving areas of no data a non-zero value of 0.01. The results showed that, even with the non-zero value, the method does not represent these areas sufficiently. Subsequent analysis will make use of the Dempster-Shafer method, which can represent missing or zero data values.

Table GS-16-2: Fuzzy set membership function for shear-hosted spatial deposit model.

Metres	PXL5	PXL2	PXL1	PXL0	PXHF	PXHM
0-100	0.80	0.60	0.50	0.40	0.60	0.40
100-200	0.77	0.58	0.48	0.38	0.58	0.38
200-300	0.74	0.55	0.46	0.37	0.55	0.37
300-400	0.71	0.53	0.44	0.35	0.53	0.35
400-500	0.68	0.51	0.42	0.34	0.51	0.34
500-600	0.65	0.49	0.41	0.32	0.49	0.32
600-700	0.62	0.46	0.39	0.31	0.46	0.31
700-800	0.59	0.44	0.37	0.30	0.44	0.30
800-900	0.56	0.42	0.35	0.28	0.42	0.28
900-1000	0.54	0.40	0.34	0.27	0.40	0.27
1000-1100	0.51	0.38	0.32	0.26	0.38	0.26
1100-1200	0.49	0.37	0.30	0.24	0.37	0.24
1200-1300	0.46	0.35	0.29	0.23	0.35	0.23
1300-1400	0.44	0.33	0.27	0.22	0.33	0.22
1400-1500	0.41	0.31	0.26	0.21	0.31	0.21
1500-1600	0.39	0.29	0.25	0.20	0.29	0.20
1600-1700	0.37	0.28	0.23	0.18	0.28	0.18
1700-1800	0.35	0.26	0.22	0.17	0.26	0.17
1800-1900	0.33	0.25	0.20	0.16	0.25	0.16
1900-2000	0.31	0.23	0.19	0.15	0.23	0.15
2000-2100	0.29	0.22	0.18	0.14	0.22	0.14
2100-2200	0.27	0.20	0.17	0.13	0.20	0.13
2200-2300	0.25	0.19	0.16	0.13	0.19	0.13
2300-2400	0.23	0.17	0.15	0.12	0.17	0.12
2400-2500	0.22	0.16	0.14	0.11	0.16	0.11
2500-2600	0.20	0.15	0.13	0.10	0.15	0.10
2600-2700	0.18	0.14	0.12	0.09	0.14	0.09
2700-2800	0.17	0.13	0.11	0.08	0.13	0.08
2800-2900	0.15	0.12	0.10	0.08	0.12	0.08
2900-3000	0.14	0.11	0.09	0.07	0.11	0.07
3000-3100	0.13	0.10	0.08	0.06	0.10	0.06
3100-3200	0.12	0.09	0.07	0.06	0.09	0.06
3200-3300	0.10	0.08	0.06	0.05	0.08	0.05
3300-3400	0.09	0.07	0.06	0.05	0.07	0.05
3400-3500	0.08	0.06	0.05	0.04	0.06	0.04
3500-3600	0.07	0.05	0.05	0.04	0.05	0.04
3600-3700	0.06	0.05	0.04	0.03	0.05	0.03
3700-3800	0.05	0.04	0.03	0.03	0.04	0.03
3800-3900	0.05	0.03	0.03	0.02	0.03	0.02
3900-4000	0.04	0.03	0.02	0.02	0.03	0.02
4100-4200	0.03	0.02	0.02	0.02	0.02	0.02
4200-4300	0.03	0.02	0.02	0.01	0.02	0.01
4300-4400	0.02	0.02	0.01	0.01	0.02	0.01
4400-4500	0.02	0.01	0.01	0.01	0.01	0.01
4500-4600	0.01	0.01	0.01	0.01	0.01	0.01
4600-4700	0.01	0.01	0.01	0.01	0.01	0.01
4700-4800	0.01	0.01	0.01	0.01	0.01	0.01
4800-4900	0.01	0.01	0.01	0.01	0.01	0.01
4900-5000	0.01	0.01	0.01	0.01	0.01	0.01
5000+	0.01	0.01	0.01	0.01	0.01	0.01

TF	VLF
0.40	0.40
0.39	0.39
0.38	0.38
0.38	0.38
0.37	0.37
0.36	0.36
0.35	0.35
0.34	0.34
0.34	0.34
0.33	0.33
0.32	0.32
0.31	0.31
0.30	0.30
0.30	0.30
0.29	0.29
0.28	0.28
0.27	0.27
0.26	0.26
0.26	0.26
0.25	0.25
0.24	0.24
0.23	0.23
0.22	0.22
0.22	0.22
0.21	0.21
0.20	0.20
0.19	0.19
0.18	0.18
0.18	0.18
0.17	0.17
0.16	0.16
0.15	0.15
0.14	0.14
0.14	0.14
0.13	0.13
0.12	0.12
0.11	0.11
0.10	0.10
0.10	0.10
0.09	0.09
0.08	0.08
0.07	0.07
0.06	0.06
0.06	0.06
0.05	0.05
0.04	0.04
0.03	0.03
0.02	0.02
0.02	0.02
0.01	0.01

Unit	Fuzzy
1	0.00
2	0.60
3	0.60
4	0.50
5	0.40
6	0.20
7	0.20
8	0.05
9	0.10
10	0.01
11	0.01
12	0.01
13	0.01
14	0.45
15	0.45
16	0.45
17	0.10
18	0.10
19	0.45
20	0.10
21	0.10
22	0.10
23	0.10

G-unit	f_{MgO}	f_{prim}
1a	0.25	0.30
1b	0.36	0.30
1c	0.29	0.30
1d	0.21	0.30
2a	0.60	0.10
2b	0.58	0.10
2c	0.35	0.10
2d	0.19	0.10
3a	0.35	0.25
3b	0.16	0.25
3c	0.23	0.25
3d	0.21	0.25
4a	0.24	0.25
4b	0.23	0.25
4c	0.22	0.25
5a	0.56	0.01
6a	0.28	0.35
6b	0.00	0.01
6c	0.21	0.35
7a	0.32	0.50
7b	0.13	0.50
7c	0.33	0.50
8a	0.42	0.60
8b	0.26	0.60
9a	0.73	0.01
10a	0.06	0.01
10b	0.08	0.01
11a	0.00	0.01
11b	0.03	0.01
11c	0.06	0.01
11d	0.04	0.01
11e	0.03	0.01
11f	0.01	0.01
11g	0.01	0.01
12	0.01	0.01
13	0.01	0.01
14	0.01	0.01
15	0.01	0.01
16	0.01	0.01
17	0.01	0.01

Unit	R_{vein}	R_{diss}
1	0.00	0.00
2	0.10	0.10
3	0.10	0.10
4	0.10	0.10
5	0.10	0.10
6	0.10	0.10
7	0.10	0.10
8	0.05	2.00
9	0.05	2.00
10	0.05	2.00
11	0.05	2.00
12	0.05	2.00
13	0.05	2.00
14	0.20	0.05
15	0.20	0.05
16	0.20	0.05
17	0.20	0.05
18	0.20	0.05
19	0.20	0.05
20	0.20	0.05
21	0.20	0.05
22	0.20	0.05
23	0.20	0.05

Explanation of abbreviations:

PXL5, proximity to lineaments ‡ 5 km in length
PXL2, proximity to lineaments 2–5 km in length
PXL1, proximity to lineaments 1–2 km in length
PXL0, proximity to lineaments 0.5–1 km in length
PXHF, proximity to heat, felsic intrusive units
PXHM, proximity to heat, mafic intrusive units
TF, total-field magnetics
VLF, very low frequency electromagnetics
Unit (lithological units): 1, undivided; 2, aphyric basalt; 3, porphyritic basalt; 4, mafic and intermediate volcanic rocks, amphibolite; 5, intermediate and felsic volcanic rocks; 6, dacite; 7, rhyolite; 8, conglomerate; 9, sedimentary rocks, paragneiss; 10, conglomerate, greywacke; 11, Burntwood Group greywacke, siltstone, mudstone; 12, Sickle Group conglomerate; 13, Sickle Group sandstone; 14, gabbro, diabase; 15, hornblende diorite, quartz diortite; 16, gabbro, norite, diorite, ultramafic rock; 17, granodiorite-diorite; 18, granite-granodiorite; 19, mafic intrusions; 20, granodiorite-tonalite; 21, granite-granodiorite; 22, granitoid rock; 23, quartz porphyry
Fuzzy, fuzzy membership value
G-unit (geochemical units): 1, arc tholeiite; 2, calc-alkaline basalt to andesite; 3, enriched arc tholeiite; 4, depleted arc tholeiite; 5, komatiitic basalt; 6, weakly depleted arc tholeiite; 7, arc tholeiite transitional to E-MORB; 8, MORB-like basalt; 9, ocean-island basalt (OIB)-ultramafic rock; 10, dacite; 11, rhyolite; 12, volcanogenic sedimentary rocks; 13, Zed Lake greywacke; 14, Ralph Lake conglomerate; 15, Burntwood Group (1.86–1.84Ga); 16, Sickle Group; 17, intrusive rocks (1.82–1.96Ga)
f_{MgO}, fuzzy membership value for 'MgO'
f_{Prim}, fuzzy membership for 'primitive versus evolved'
R_{Vein}, rheology vein type
R_{diss}, rheology disseminated type

Table GS-16-3: Fuzzy set membership function for VMS spatial deposit model.

Metres	PXL	PXHF	PXHM
0-100	0.20	0.40	0.40
100-200	0.19	0.38	0.38
200-300	0.18	0.37	0.37
300-400	0.18	0.35	0.35
400-500	0.17	0.34	0.34
500-600	0.16	0.32	0.32
600-700	0.15	0.31	0.31
700-800	0.15	0.30	0.30
800-900	0.14	0.28	0.28
900-1000	0.13	0.27	0.27
1000-1100	0.13	0.26	0.26
1100-1200	0.12	0.24	0.24
1200-1300	0.12	0.23	0.23
1300-1400	0.11	0.22	0.22
1400-1500	0.10	0.21	0.21
1500-1600	0.10	0.20	0.20
1600-1700	0.09	0.18	0.18
1700-1800	0.09	0.17	0.17
1800-1900	0.08	0.16	0.16
1900-2000	0.08	0.15	0.15
2000-2100	0.07	0.14	0.14
2100-2200	0.07	0.13	0.13
2200-2300	0.06	0.13	0.13
2300-2400	0.06	0.12	0.12
2400-2500	0.05	0.11	0.11
2500-2600	0.05	0.10	0.10
2600-2700	0.05	0.09	0.09
2700-2800	0.04	0.08	0.08
2800-2900	0.04	0.08	0.08
2900-3000	0.04	0.07	0.07
3000-3100	0.03	0.06	0.06
3100-3200	0.03	0.06	0.06
3200-3300	0.03	0.05	0.05
3300-3400	0.02	0.05	0.05
3400-3500	0.02	0.04	0.04
3500-3600	0.02	0.04	0.04
3600-3700	0.02	0.03	0.03
3700-3800	0.01	0.03	0.03
3800-3900	0.01	0.02	0.02
3900-4000	0.01	0.02	0.02
4100-4200	0.01	0.02	0.02
4200-4300	0.01	0.01	0.01
4300-4400	0.01	0.01	0.01
4400-4500	0.01	0.01	0.01
4500-4600	0.01	0.01	0.01
4600-4700	0.01	0.01	0.01
4700-4800	0.01	0.01	0.01
4800-4900	0.01	0.01	0.01
4900-5000	0.01	0.01	0.01
5000+	0.01	0.01	0.01

Metres	PXR	PXIF
0-100	0.80	0.70
100-200	0.72	0.63
200-300	0.65	0.57
300-400	0.58	0.51
400-500	0.51	0.45
500-600	0.45	0.39
600-700	0.39	0.34
700-800	0.34	0.30
800-900	0.29	0.25
900-1000	0.24	0.21
1000-1100	0.20	0.18
1100-1200	0.16	0.14
1200-1300	0.13	0.11
1300-1400	0.10	0.09
1400-1500	0.07	0.06
1500-1600	0.05	0.04
1600-1700	0.03	0.03
1700-1800	0.02	0.02
1800-1900	0.01	0.01
1900-2000	0.01	0.01
2000+	0.01	0.01

Unit	Fuzzy
2	0.70
3	0.70
4	0.65
5	0.60
6	0.55
7	0.55
8	0.20
9	0.40
10	0.20
11	0.20
12	0.20
13	0.20
14	0.25
15	0.25
16	0.25
17	0.20
18	0.20
19	0.25
20	0.20
21	0.20
22	0.20
23	0.20

TF	VLF
0.50	0.70
0.49	0.69
0.48	0.67
0.47	0.66
0.46	0.64
0.45	0.63
0.44	0.62
0.43	0.60
0.42	0.59
0.41	0.57
0.40	0.56
0.39	0.55
0.38	0.53
0.37	0.52
0.36	0.50
0.35	0.49
0.34	0.48
0.33	0.46
0.32	0.45
0.31	0.43
0.30	0.42
0.29	0.41
0.28	0.39
0.27	0.38
0.26	0.36
0.25	0.35
0.24	0.34
0.23	0.32
0.22	0.31
0.21	0.29
0.20	0.28
0.19	0.27
0.18	0.25
0.17	0.24
0.16	0.22
0.15	0.21
0.14	0.20
0.13	0.18
0.12	0.17
0.11	0.15
0.10	0.14
0.09	0.13
0.08	0.11
0.07	0.10
0.06	0.08
0.05	0.07
0.04	0.06
0.03	0.04
0.02	0.03
0.01	0.01

Explanation of abbreviations:

PXL, proximity to lineaments 0.5–5 km in length

PXHF, proximity to heat, felsic intrusive units

PXHM, proximity to heat, mafic intrusive units

PXR, proximity to rhyolite

PXIF, proximity to intermediate and felsic volcanic rocks

Unit (lithological units): 1, undivided; 2, aphyric basalt; 3, porphyritic basalt; 4, mafic and intermediate volcanic rocks, amphibolite; 5, intermediate and felsic volcanic rocks; 6, dacite; 7, rhyolite; 8, conglomerate; 9, sedimentary rocks, paragneiss; 10, conglomerate, greywacke; 11, Burntwood Group greywacke, siltstone, mudstone; 12, Sickle Group conglomerate; 13, Sickle Group sandstone; 14, gabbro, diabase; 15, hornblende diorite, quartz diortite; 16, gabbro, norite, diorite, ultramafic rock; 17, granodiorite-diorite; 18, granite-granodiorite; 19, mafic intrusions; 20, granodiorite-tonalite; 21, granite-granodiorite; 22, granitoid rock; 23, quartz porphyry

Fuzzy, fuzzy membership value

TF, total-field magnetics

VLF, very low frequency electromagnetics

Shear-Hosted Magmatic-Hydrothermal Spatial Deposit Model

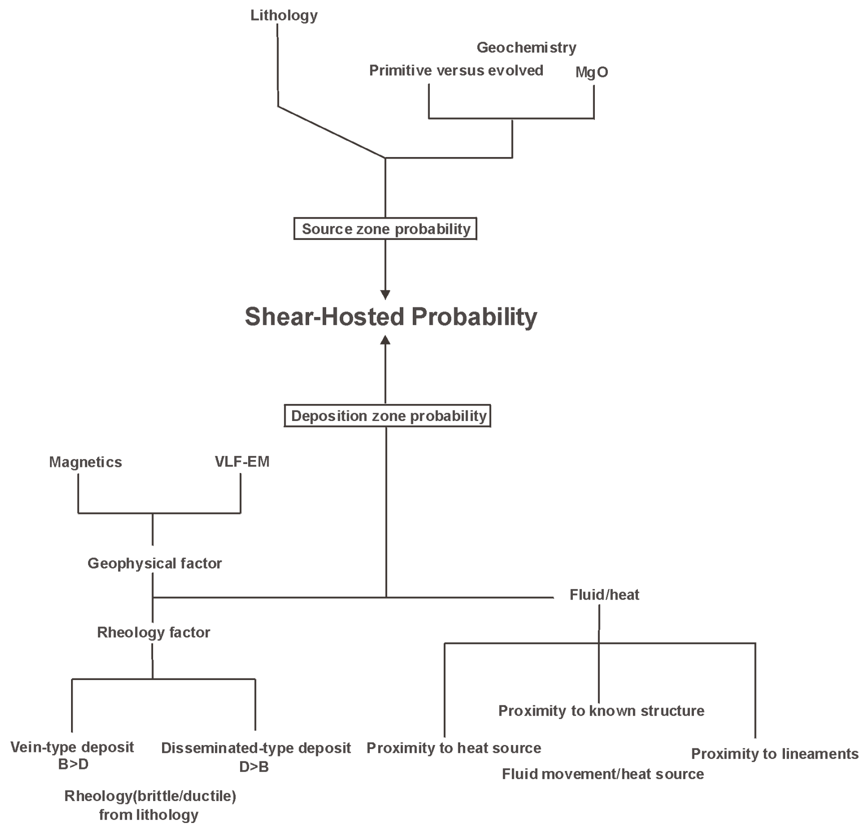


Figure GS-16-1: Integration flow chart for the shear-hosted magmatic hydrothermal spatial deposit model. The fuzzy-logic gamma operation is used at each stage of integration to minimize the increasive and decreasive effects of the algebraic product and algebraic sum.

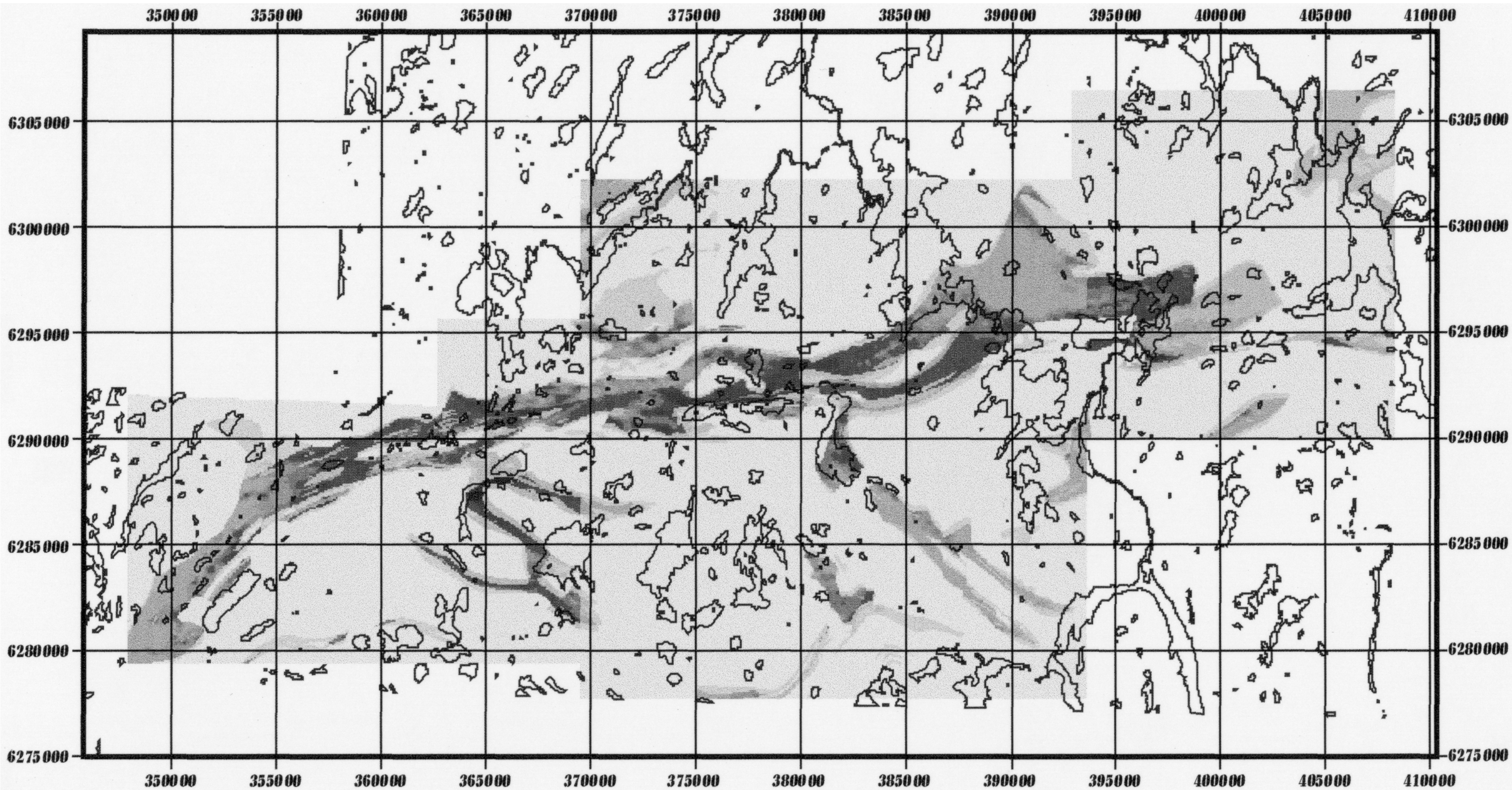


Figure GS-16-3: Mineralization-potential map for shear-hosted magmatic hydrothermal spatial deposit model. Grey-scale levels represent only the top 20th percentile, with relative scale being linear. White indicates low relative probability; black indicates high relative probability. Map base is UTM Zone 14, NAD83.

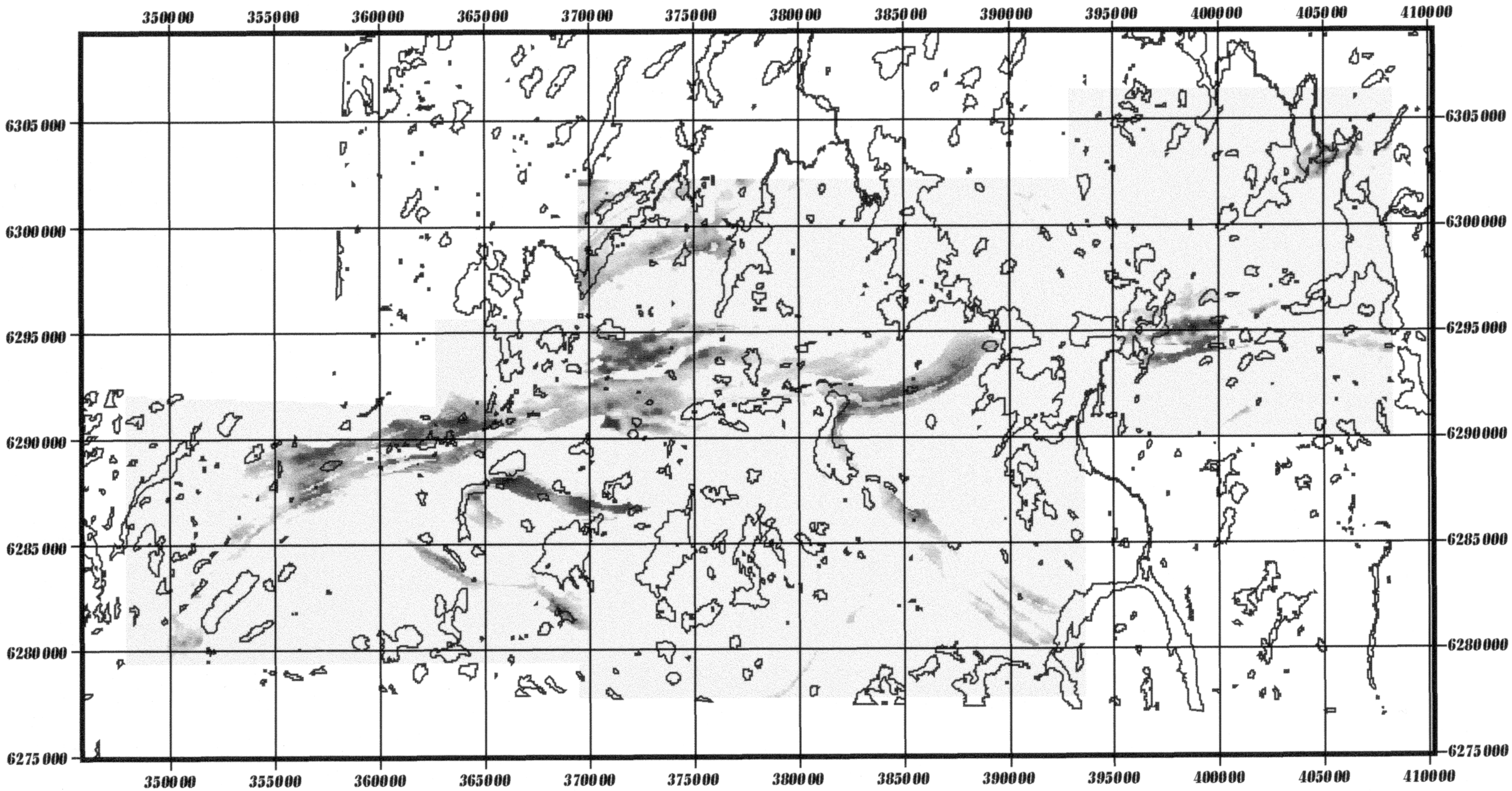


Figure GS-16-4: Mineralization-potential map for VMS spatial deposit model. Grey-scale levels represent only the top 20th percentile, with relative scale being linear. White indicates low relative probability; black indicates high relative probability. Map base is UTM Zone 14, NAD83.

REFERENCES

Argialas, D.P. and Harlow, C.A. 1990: Computational image interpretation models: an overview and a perspective; Photogrammertry Engineering and Remote Sensing, v. 56, p. 871–886.

Bonham-Carter, G.F. 1994: Geographic Information Systems for Geoscientists: Modelling with GIS; Pergamon Press, Oxford, United Kingdom, 398 p.

Bonham-Carter, G.F., Reddy, R.K.T. and Galley, A.G. 1993: Knowledge-driven modeling of volcanic massive sulphide potential with a geographical information system; *in* Mineral Deposit Modeling, (ed.) R.V. Kirkham, W.D. Sinclair, R.I. Thorpe and J.M. Duke; Geological Association of Canada, Special Paper 40, p. 735–749.

Bursnall, J.T. 1989: Mineralization and shear zones; Geological Association of Canada, Short Course Notes, v. 6, 299 p.

Franklin, J.M. 1993 Volcanic-associated massive sulphide deposits; *in* Mineral Deposit Modeling, (ed.) R. V. Kirkham, W.D. Sinclair, R.I. Thorpe and J.M. Duke; Geological Association of Canada, Special Paper 40, p. 315–335.

Hodgson, C.J. 1993: Mesothermal lode-gold deposits; *in* Mineral Deposit Modeling, (ed.) R.V. Kirkham, W.D. Sinclair, R.I. Thorpe and J.M. Duke; Geological Association of Canada, Special Paper 40, p. 635–678.

Lydon, J.W. 1988a: Volcanogenic massive sulphide deposits, part 1: a descriptive model; *in* Ore Deposit Models, (ed.) R.G. Roberts and P.A. Sheahan; Geoscience Canada, Reprint Series 3, p. 145–154.

Lydon, J.W. 1988b: Volcanogenic massive sulphide deposits, part 2: genetic models; *in* Ore Deposit Models, (ed.) R.G. Roberts and P.A. Sheahan; Geoscience Canada, Reprint Series 3, p. 155–182.

Moon, W.M. 1993: On mathematical representation and integration of multiple spatial geoscience data sets; Canadian Journal of Remote Sensing, v. 19, p. 63 – 67.

Roberts, R.G. 1988: Archean lode gold deposits; *in* Ore Deposit Models, (ed.) R.G. Roberts and P.A. Sheahan; Geoscience Canada, Reprint Series 3, p. 1–20.

Wright, D.F. and Bonham-Carter, G.F. 1996: VHMS favourability mapping with GIS-based integration models, Chisel Lake–Anderson Lake area; *in* EXTECH I: A Multidisciplinary Approach to Massive Sulphide Research in the Rusty Lake–Snow Lake Greenstone Belts, Manitoba, (ed.) G.F. Bonham-Carter, A.G. Galley and G.E.M. Hall; Geological Survey of Canada, Bulletin 426, p.339–376, 387–401.

Zwanzig, H.V., Syme, E.C. and Gilbert, H.P. 1999: Updated trace element geochemistry of ca. 1.9 Ga metavolcanic rocks in the Paleproterozoic Lynn Lake belt; Manitoba Industry, Trade and Mines, Geological Services, Open File Report OF99-13, 46 p.