June 18, 2003

HEIDI WEIBE
Deh Cho Land Use Planning Committee
General Delivery
Fort Providence, NT
X0E 0L0

Dear Heidi,

**Caveats to Final Report**

Please accept this as the Final Report for the Deh Cho Land Use Planning Committee. This report meets the NWT Open File standards but has not yet gone through the critical review process required by the NWT Open File process. Once this report has been assigned an NWT Open File number, a copy will be forwarded to the Deh Cho Land Use Planning Committee.

Significant changes to the report or to the report’s conclusions and recommendations are not likely to occur as a result of the NWT Open File critical review process.

I would like to acknowledge the very significant work by Brian Eddy of GSI-GeoSystems Integration in Ottawa on the spatial analysis - mineral potential mapping and to Alan Udell of Victory Point FX in Yellowknife for outstanding GIS support. Without the contribution of these two individuals this report would not be have been possible.

Sincerely,

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Executive Summary

The mineral potential evaluation requested by Deh Cho Land Use Planning Committee (DCLUPC) is information to be considered as part of the decision making process on regional land-use planning. The C. S. Lord Northern Geoscience Centre (C. S. Lord) has been contracted to deliver the mineral potential evaluation for the Deh Cho territory in the form of a series of Mineral Potential Maps. Based on the large geographic extent of the area, combined with time, data and knowledge constraints, a ‘knowledge-driven’ mineral potential mapping approach has been taken (Eddy, et. al. 2003, Appendix E). In combination with the Geologic Survey of Canada ranking scheme, a set of Mineral Potential Maps has been produced showing geological favourability and ranking of Resource Assessment Domains (Domains) for nine (9) significant mineral deposit-types.

The nine mineral deposit-types considered here were selected from a list of twenty types thought to be have the potential to occur in the Deh Cho territory. These deposit-types were selected from an initial list of eighty-two mineral deposit-types and sub-types identified in the Geology of Canadian Mineral Deposit-types (Eckstrand, 1996). Of the nine considered in this study, the results show significant potential for:

- Sedimentary exhalitive sulphides (SEDEX) zinc-lead,
- Sediment-hosted stratiform copper,
- Mississippi Valley-type lead-zinc,
- Vein copper,
- Skarn deposits (emerald, gold, tungsten, copper, and lead-zinc).

And to a lesser extent:

- Stratiform iron, and
- Granite pegmatite (tantalum, cesium and lithium).

The most significant potential appears in the western part of the study area, within the mountainous Cordilleran geologic province. Specifically, within the Deh Cho boundary, six Resource Assessment Domains (Domains): 11, 18, 20, 21, 23, 33, reveal high to very high mineral potential for a number of deposit-types (see Resource Assessment Domain figure next page). It is these specific domains that the potential for discovery of new mineral deposits is most likely. The general conclusion is that the Deh Cho shows at least ‘some’ mineral potential (if not one type, then another) in all locations. There is nowhere within the Deh Cho territory that can be said to have ‘no potential’.

A ‘Cumulative Mineral Potential’ map illustrates this conclusion (see Resource Assessment Domain figure next page) with sum of rankings values of 22, 33, 23, 24, 40, and 33 respectively out of a maximum assigned 40.

Although the potential in the western portion is relatively higher than the central and eastern portions, it must be understood that new discoveries, data, and knowledge about the study area continue to emerge, and there may be ‘high’ potential for some commodities (e.g. Diamonds) in areas that were evaluated as relatively low in this study or not assessed.
Introduction

The Deh Cho Land Use Planning Committee’s (DCLUPC) requirement for mineral potential information is considered here as part of their regional land-use planning process. The DCLUPC have chosen to use a Geographic Information System (GIS) based mapping approach to identify land-use options for resource development, protection, and traditional use. This approach is expected to highlight locations where multiple uses may be complimentary, and/or where they may conflict. It is anticipated that this approach will contribute to an on-going optimization of land-use planning options and strategies.

Among all potential uses and land-values, the mineral potential of the Deh Cho land is a significant component. As with other places in the North, minerals represent one of the few options for substantive economic development. This project proceeded within the context of these current needs and constraints of the DCLUPC requirements, and is aimed at delivering the most accurate and meaningful information about mineral potential for the Deh Cho territory that could be made available under the given time and resource constraints.

Information Requirements

The C. S. Lord Northern Geoscience Centre (C. S. Lord) was contracted by the Deh Cho Land use Planning Committee (DCLUPC) to deliver “A Spatial Analysis and Literature Review of Mineral Potential in the Deh Cho Territory, NWT”. The C. S. Lord proposed to carry out the spatial analysis and report the results in the form of a series of Mineral Potential Maps. C. S. Lord was asked to deliver a mineral potential map within a very limited (3-4 month) time frame. The financial resources to carry out the project were only available until March 31, 2003. The products intended use is in community consultation on Land Use Planning during the spring and summer of 2003.

Approach and Methodology

The overall approach to preparing Mineral Potential Maps involves a process of synthesizing and integrating both formal and informal (global and local) knowledge and data. The output of this process (a series of Mineral Potential Maps) is an information product that is designed for specific contextual use (in this case the DCLUP). The approach used here involves a combination of methods that facilitate the transformation of primary data and knowledge into contextualized information that meets the requirements of the DCLUP. Figure 1 summarizes the main elements of the approach in four general stages or steps.
Knowledge → Data → Information → Decisions

Figure 1. General schematic outlining the approach and methodologies employed in the preparation of the Mineral Potential Maps of the Deh Cho region.

The four steps in the process are divided into two mutually interactive information streams:

A) Knowledge and Data on Mineral Deposits and Occurrences and
B) Knowledge and Data on the Geology of the Deh Cho territory (regional, general knowledge) as represented in geological maps, supporting literature, and the knowledge of local expertise.

The information content of the Mineral Potential Maps produced by this approach reflects these two information streams:

1) Geological Favourability, and
2) Mineral Occurrences Evaluation.

The four steps involve a dialogue between the two information streams and formulate the overall structure of this report. The general approach is summarized as follows.

Step 1 – Scope and Context

This step involves asking a number of important questions such as: What is the extent of the study area? Who are the users of the information and what will the information be used for? When is the information needed? What are the time and resource constraints? From here, the resource geologist consults the existing geological knowledge base to determine what knowledge and data is most appropriate for the requirement. These inputs fall into the respective minerals and geology information processing streams, which mutually interact and reinforce specific methodological operations along the processing stream.

Step 2 – Data and Knowledge

Based on the scope and context, appropriate data is gathered for preparation of Mineral Potential Map product. The choices for the selection of some data and exclusion of others must be clearly stated and justified within the context and constraints identified in the first step. The data maintains a differentiation of mineral and geological in reflection of two aspects:
1) The **mineral occurrences data** represent what is known in terms of existing or known mineral potential, and
2) The **geological data** (maps) are used to assess geographical areas for which the mineral potential is not known.

In many ways, the selection and initial preparation of the data requires detailed examination of both data types to make aware all uncertainties and limitations of the initial database in preparation for applying specific analysis and interpretation methods. There are a number of basic geographical factors that must also be considered such as the coincidence of location of specific data elements within the geographical boundaries of the study area, as well as scale differences. For example, geological maps represent generalized interpretations of primary field data and are often presented at scales significantly broader than local mineral occurrence data. All of these factors need to be taken into account in preparation of the analysis and interpretation.

**Step 3 – Analysis and Interpretation**

It is necessary to frame the analysis and interpretation of mineral potential around *mineral deposit-types*, and/or specific mineral commodities. Both the geological maps and mineral occurrence data need to be associated with knowledge about how various types of mineral deposit form. Various specific methods may be employed at this stage, most of which are dependent upon the geographic scale and extent of the study area, the scale and qualities of the data available, and the mineral deposit-types or commodities being considered. This study makes use of a modified Fuzzy Logic (Eddy et al, 2003, Appendix C) method to map geological favourability, which is evaluated in combination with known mineral occurrences, to produce mineral potential rankings of sub-divisions of the Deh Cho territory referred to as Resource Assessment Domains.

**Step 4 – Results and Recommendations**

The final step in the process involves preparing the result maps in a variety of presentation styles and formats for the intended audience(s). This involves cartographic techniques for visualizing mineral potential in map form, as well as evaluating the results and implications for intended use. In this study, the results of all deposit-types considered are presented in the form of a Cumulative Mineral Potential map. But as with all maps, there are always limitations and constraints in their use, especially for complex land-use planning processes. A series of recommendations are made to make the best use of the knowledge and data available at this time.
Scope and Context

The aim of this project is to deliver an evaluation of mineral potential for the entire Deh Cho territory, giving equal consideration to all locations so that land-use options, in conjunction with other land-use interests, can be adequately accommodated. Consideration is given to the immediate and on-going intended use of these maps as a partial input into a land-use decision-making process. This is taken into account as the primary influence in determining the most appropriate scale and resolution of both the inputs (data sources), and the outputs (Mineral Potential Maps), and the choice of method in relating the two. Within this context, the maps are intended to assist in regional land-use decision-making. They are not of a suitable resolution for identifying specific exploration target areas. Significantly higher resolution data, as well as other types of data (such as ground-based geophysics and geochemistry) would be required to conduct such a detailed assessment. The results presented at this scale represent a starting point in such a process, and should be applied under the consultation of a mineral resource assessment geologist.

The requirements for this mineral potential assessment are:

1. The whole of the Deh Cho territory must be evaluated equally.
2. The data and knowledge used must be the most recent and appropriate for application.
3. The results must be meaningful to the Deh Cho Land Use Planning process (i.e. maps must be easily readable and understood by different stakeholders)
4. The Mineral Potential Maps must be able to provide a basis for decisions among a variety of possible land-use scenarios.
5. All limitations, constraints, and uncertainties in the results must be clearly communicated.

Knowledge and Data

The primary constraint in determining which data and knowledge is appropriate for the scope and context is the geographical extent of the study area, and the requirement to map mineral potential on a relatively consistent basis throughout the Deh Cho territory. Typically, such scope would require considerable effort in compiling numerous local reports, maps, and study of local mineral occurrences in comparison to global deposit-types and models. This study benefits from the availability of three primary sources of data and knowledge that have been systematically and authoritatively compiled for this region, and lends itself appropriate for this requirement.

1) The geological base is the 1:1,000,000 scale digital map by Journey and Williams (1995), “A Window on Cordilleran Geology”.
2) The mineral occurrence information base is from NORMIN.DB, The Northern Minerals Database.
Minerals Knowledge

All mineral potential mapping exercises are based on the mineral deposit-types or -models. Mineral deposits are natural concentrations of one or more mineral commodities (Eckstrand et al, 1996). Mineral deposits having similar geological characteristics and suites of commodities occur in comparable settings at numerous locations throughout the world in rocks of different ages. Mineral deposits that are similar constitute a mineral deposit-type.

A mineral deposit-type is a collective term for mineral deposits that:

a) share a set of geological attributes, and
b) contain a particular mineral commodity or combination of commodities such that (a) and (b) together distinguish them from other types of mineral deposits.

Two important concepts that follow from this knowledge are:
1) Mineral deposits of the same type are likely to have a common or similar mode of genesis.
2) And most importantly, rock assemblages which contain the geological attributes that are characteristic of a particular mineral deposit-type have the best potential for containing mineral deposits of that type.

Each mineral deposit-type is identified on the basis of common characteristics found among deposits of a given type. These characteristics are usually descriptive in nature. Such characteristics are sometimes explained in terms of possible geological and mineralogical processes or genesis. Such explanations are regarded as mineral deposit-models. The differentiation between type and model varies considerably. For example, characteristics of some deposit-types might be significantly more descriptive, whereas others might be more genetic (or process-related).

Mineral deposit criteria is regarded as being any set of key descriptive and/or genetic characteristics that define a minimum set of criteria that are necessary for the potential of a deposit-type to occur within a particular geological setting. For many deposit-types such initial criteria often relates to regional level geological setting, tectonic or stratigraphic setting, or associated rock-types, from which the potential for a deposit-type to occur is to be considered.

However, some deposit-types (e.g. Diamonds) do not have any initial criteria that can be treated on a regional level. Although diamonds are almost universally associated with kimberlites, they can occur in any geologic environment and are difficult to detect in regional level data. The application of regional geological maps and generalized mineral deposit criteria, even with the best of local expert knowledge, remains restricted in what can be said of the potential of any large region for some types of deposits. It is primarily for this reason that any given mineral potential mapping exercise, or non-renewable resource assessment process, can never come to any final conclusion, nor identify absolute potential for a region.

All mineral potential mapping hinges on the use of some form (formal or informal, global or local) mineral deposit criteria.

The criteria used in this study were derived from The Geology of Canadian Mineral Deposit-Types (Eckstrand et al, 1996). The Geology of Canadian Mineral Deposit-Types provides...
detailed descriptions for 27 broad categories (or types) of mineral deposits, each of which may contain two or more sub-types. Together, they constitute 82 sub-types that need to be considered as part of any comprehensive Mineral Potential Mapping project. In effect, there will not be potential for all deposit-types within a given study area due to limited constraints of the geological setting. A significant sub-step at this stage is to determine which deposit-types best represent the possibilities of mineral potential for the range of geological characteristics that occur in the study area.

**Geology Knowledge**

The Deh Cho territory straddles two geologic provinces in Canada, the flat Interior Platform province in the east, and the mountainous Cordilleran Orogen province in the west (Figure 2). The Interior Platform consists of relatively flat lying sedimentary rocks of Phanerozoic age that have been deposited by sedimentary process and have remained relatively undisturbed since deposition. The Cordilleran Orogen is comprised of folded, faulted and thrusted rocks of sedimentary, volcanic, plutonic and metamorphic origin. Although the majority of the rocks within the Cordilleran portion of Deh Cho territory contain deformed equivalents of Deh Cho territory Platform rocks, there is also a significant component of rocks that span a much longer time period of deposition and a genesis (mode of deposition). An example of these different rock types are the thrusted-to-surface, sedimentary, Pre-Cambrian (1600-1000 million years old) rocks at Cap Mountain, and the Mid-Cretaceous (130-87 million years old), Selwyn plutonic suite of intrusive (volcanic) rocks adjacent to the Yukon border in the western Deh Cho territory. It is these two geological provinces that strongly influence the regional physiography, separating the mountainous Cordillera in the west, from the flat lying Interior Platform in the central and eastern portions of the study area. These differences in physiography also influence local and regional ecology, as well as human settlement patterns and interaction with the land. In spite of the more rugged terrain, the diversity of genesis, deformation and age is one of the reasons the Cordilleran may be considered ‘more interesting’ from a mineral potential point of view. It is also important to consider that one of the most significant known mineral deposits in the Deh Cho territory is the world-class, past producing Pine Point lead-zinc mine which occurs within the less-interesting Interior Platform province. The geological setting in both geological provinces offer potential for a variety of mineral deposits.
Figure 2. Physiography and geological provinces of the Deh Cho region.
Geology Data

For this study, we make use of the 1:1,000,000 tectonic assemblage (geology) map compiled by Journey and Williams (1995). A reproduction of this map is provided in Enclosure A. The geology illustrated by this compilation work provides a basis from which a selection of the most likely deposit-types from The Geology of Canadian Mineral Deposit Types (Eckstrand et al, 1996)

The use of local scale geological data, such as geochemistry, geophysics, and location specific mineral occurrence properties, are severely limited for an area this size and under the time/resource constraints of the current project. This knowledge can be brought-in to increase the resolution/evaluation at later stages, in high priority areas where deemed necessary and appropriate. For purposes of this evaluation, the data and knowledge selected for use are those that cover the entire Deh Cho area in a consistent fashion, are authoritative, and can meet the immediate needs of this type of Mineral Potential Mapping requirement.

Mineral Data

The mineral occurrence data is taken from the NORMIN.DB, The Northern Minerals Database 2003/05/01 (http://www.nwtgeoscience.ca/normin, CS Lord Northern Geoscience Centre, Yellowknife, Northwest Territories). A summary list of mineral occurrences in the study area, (indexed by deposit-type) is provided in Appendix A. The processing and selection of records and fields from this database are described below in the Analysis and Interpretation section. Additional fields were added to the tables in Appendix A as part of this study. These Mineral Occurrence locations are shown in Enclosure A.

NORMIN.DB data are provided without warranty of any kind, either expressed or implied. The information may be used with the strict understanding that neither the federal nor territorial governments nor their ministers, employees, or agents shall be liable to any persons for any loss or damage of any nature, whether arising out of negligence or otherwise, which may be occasioned as a result of use of this information.

Data in NORMIN.DB are translated from public records. The federal Department of Indian Affairs and Northern Development and the Government of the Northwest Territories cannot guarantee the accuracy of the public records or of the data recorded in NORMIN.DB. The NORMIN.DB website or CS Lord Northern Geoscience Centre staff should always be consulted for the latest data or for assistance in using the data. Data do not represent every mineral deposit in an area or every reference to an area. Data are not necessarily the most recent available or the most relevant for a user's needs.
Analysis and Interpretation

The analysis and interpretation (Step 3) of this study proceeded through a series of sub-processing stages. Figure 3 provides an information-processing path of the sequence of sub-steps taken between Steps 3 and 4 (in reference to Figure 1).

![Figure 3. Stages of processing involved in the preparation of the Mineral Potential Maps.](image)

**Geological Interpretation and Deposit-type Selection (3a)**

As noted above, the first step in the analysis is an interpretation of the geological setting of the Deh Cho territory to assess which deposit-types are most likely to occur in the study area. Enclosures A (Geological Map) provides the most recent synopsis of the geological characteristics of the study area.

Information associated with the geological units provide the basis from which a sub-set of deposit-types was selected as those more likely (3a) to occur within the region, due to the limited geological constraints that are required for certain types of deposits to occur. The rationale for selection is based partly on a cross comparison of deposit-type criteria and geological setting, local knowledge of known deposits and occurrences, as well as active exploration interests. The selected deposit-types are listed in Table 1. The selected deposit-types represent those that are known to occur or most likely to occur given the geological constraints of the study area. Primary diamonds are included in the selected list. Diamond potential in the Deh Cho territory presents a unique challenge in representing its potential and is included here to illustrate not only its significance, but some of the limitations in mapping mineral potential on regional scales (see discussion under Limitations and Constraints and Appendix B).
Table 1. Selected Deposit-types Considered for Mineral Potential Map in this Study.

<table>
<thead>
<tr>
<th>Type # *</th>
<th>Deposit-type Name</th>
<th>Mineral commodities</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Sedimentary exhalitive sulphides (SEDEX)</td>
<td>Copper-lead-zinc</td>
</tr>
<tr>
<td>8.3</td>
<td>Sedimentary-hosted stratiform copper</td>
<td>Copper</td>
</tr>
<tr>
<td>10.0</td>
<td>Mississippi Valley-type lead-zinc</td>
<td>Lead-zinc</td>
</tr>
<tr>
<td>17</td>
<td>Vein copper</td>
<td>Copper</td>
</tr>
<tr>
<td>20.1</td>
<td>Skarn lead-zinc-silver</td>
<td>Lead-zinc-silver-gold</td>
</tr>
<tr>
<td>20.3</td>
<td>Skarn gold</td>
<td>Gold, bismuth, tellurium</td>
</tr>
<tr>
<td>20.5</td>
<td>Skarn tungsten</td>
<td>Tungsten, gold, silver, molybdenite</td>
</tr>
<tr>
<td>21.0</td>
<td>Granitic pegmatite</td>
<td>Beryllium, lithium, cesium, talanum, muscovite mica, feldspar, etc.,</td>
</tr>
<tr>
<td>25.0</td>
<td>Primary diamonds</td>
<td>Diamonds</td>
</tr>
</tbody>
</table>

*(Eckstrand et al, 1996)

Note that other deposit-types also have the potential to occur such as, but not limited to, those identified in Table 2. However, it was not possible to model all of these types under the limited time constraints of this project.

Table 2. Deposit-types with potential to occur but not analyzed/assessed.

<table>
<thead>
<tr>
<th>Type #</th>
<th>Deposit-type Name</th>
<th>Mineral commodities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>Placer Gold</td>
<td>Gold</td>
</tr>
<tr>
<td>7, 12, 13</td>
<td>Three types of uranium deposits</td>
<td>Uranium</td>
</tr>
<tr>
<td>16</td>
<td>Clastic metasediment-hosted vein Ag-Pb-Zn</td>
<td>Silver, Lead, Zinc</td>
</tr>
<tr>
<td>18</td>
<td>Vein-stockwork Sn/W</td>
<td>Tin-Tungsten</td>
</tr>
<tr>
<td>19</td>
<td>Porphyry copper</td>
<td>Copper, Gold, Molybdenum, Tungsten, Tin, Silver</td>
</tr>
<tr>
<td>20.2</td>
<td>Skarn copper</td>
<td>Copper</td>
</tr>
<tr>
<td>22</td>
<td>Kiruna/Olympic Dam (Iron Oxide Copper-Gold (IOCG))</td>
<td>Gold, Copper, Iron, Silver</td>
</tr>
<tr>
<td>23</td>
<td>Peralkaline Rock-Associated Rare Metals</td>
<td>Niobium, Tantalum, Beryllium, Zirconium, Yttrium and Rare Earth Elements (REE)</td>
</tr>
</tbody>
</table>

Geological Favourability Mapping (3b)

The next step involved using the geological data and the selected mineral deposit criteria to map the geological favourability component of the Mineral Potential Map for each selected deposit-type. Geological knowledge of each deposit-type, aided by an understanding of its genesis, allows us to identify geological areas most likely to contain undiscovered deposits of that type. The key linkages between data and expert knowledge are the relationships expressed in mineral deposit-type model criteria. As with all geoscientific-mapping applications, the ability to relate data (representations of our observations in the real world) with our knowledge (our understanding of those observations) cannot always be achieved with absolute certainty. In other words, the method must provide room for geologists to accommodate varying degrees of certainty or uncertainty in inferring such relationships.
For this component, a Fuzzy Logic method is used. Fuzzy logic is defined as “reasoning involving fuzzy sets, that is, where elements do not fit within compact boundaries. Involves probability concepts” (Jackson, 1997).

Using a scaleable, relative-favourability legend, the geological favourability component of mineral potential for multiple commodities/deposit-types can be portrayed in map form in a style that can be easily digested by people of diverse disciplines and roles in a multi-stakeholder land-use decision environment. This is a well-grounded scientific method (Eddy, 1996, Bonham-Carter 1994, An et. al. 1991) and can be used in later stages of assessment in combination with other Mineral Potential Map methods as newer and higher-resolution data (mapping, geochemistry, geophysics) become available. The specific aportia approach applied here is based on that in Eddy, et. al. (2003, Appendix C). The legend presented in Figure 4 is to be used to reference the colour schemes representing the geological favourability component in each Mineral Potential Map and also to convey the assessment of mineral potential for all deposit-types collectively (a Cumulative Mineral Potential map).

To simplify, the fuzzy logic method presents geological favourability on a gradational scale that represents a range of answers to a general question “Is there potential for Z at location x, y”? In applying this approach for Mineral Potential Mapping, we simply replace ‘Z’ with the deposit-type, then seek to justify the geological favourability by inferring the linkages between the definitive criteria for each deposit-type, with data provided in the geological map. The choice of colours represents a gradational ‘hot’ (very high potential), to ‘cold’ (no potential, or low potential).

Example Logical Propositions:
Form: Is there ‘Z’ (condition) at location (x,y).
Are there Diamonds here?  
Is the water safe here?  
Does it snow at this location? 
Is this soil good for corn?  
Is the habitat for Caribou favourable at this location?

The answer given, in numerical form on the [0,1] interval corresponds to the respective evaluations.

Figure 4. The modified Fuzzy Logic legend used for representing geological favourability.
The fuzzy geological favourability legend is scaled numerically on a 0.0-1.0 interval, where 1.0 equals Yes (with certainty – there is potential), and 0.0 equals No (with certainty - there is no potential). In this method (Eddy, et. al., 2003, Appendix C), the middle value (0.5) represents complete uncertainty for cases where the geologist cannot give a clear yes or no answer to the question. The intermediate values (ranging from 0.1 to 0.5 and 0.5 to 0.9) provide a gradational scale for answers in between these extents (for answers such as maybe, not likely, etc.). The certainty of the answer to the question “Is there potential for deposit-type or commodity Z?” depends on the scale of the data used to support the answer. Small-scale data pertains to regional-national level data (i.e. 1:5,000,000 maps), and large-scale pertains to very local scale data (i.e. actual occurrences, ground-truth information). For each Mineral Potential Map presented, this legend represents the geological favourability component. This is why as can be seen in some of the results, yellow areas only show up in the immediate vicinity of known occurrences. The range of colours surrounding the known occurrences reflects the general scale of data used to map the geological favourability for each deposit-type.

**Mineral Occurrence Classification and Ranking (3c-3d)**

Parallel to mapping geological favourability, the selection of deposit-types permits an evaluation of the known occurrences for comparison with the results of the geological favourability mapping (3c-3d). Not all mineral occurrences can be treated with equal certainty with respect to their associations with a specific deposit-type. This process involves another level of interpretation by examining the descriptive information of each occurrence and assessing potential association to selected deposit-types. In some cases, mineral occurrences (especially known deposits) have been studied in great depth, and their classification against one of the Canadian Mineral Deposit-types (Eckstrand et al, 1996) has been verified. But for the majority of occurrences, there is not enough information to draw firm conclusions. This can be problematic in mapping some occurrences for comparison against different deposit-types that contain the same commodities (i.e. Pb-Zn, or Au). To accommodate this problem, the fuzzy favourability legend was also used to indicate the degree of confidence in classifying each mineral occurrence according to one of the selected deposit-types. This is illustrated in Figure 5, which is a sample of records taken from the tables presented in Appendix A.

**Figure 5. An example table of mineral occurrences (see Appendix A)**

<table>
<thead>
<tr>
<th>GISID</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Name</th>
<th>Commodities</th>
<th>DevStage</th>
<th>DepType</th>
<th>FAV</th>
<th>SigRank</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>62.1889</td>
<td>-128.8992</td>
<td>Cali Li</td>
<td>Li</td>
<td>Local Examin</td>
<td>Gran Peg</td>
<td>0.75</td>
<td>2</td>
</tr>
<tr>
<td>53</td>
<td>62.1997</td>
<td>-123.4386</td>
<td>Camsell Mountain</td>
<td>Zn-Pb</td>
<td>xTo Be Assig</td>
<td>MVT</td>
<td>0.80</td>
<td>3</td>
</tr>
<tr>
<td>54</td>
<td>63.1167</td>
<td>-123.5000</td>
<td>Camsell Range (Pb-Zn)</td>
<td>Pb-Zn</td>
<td>xTo Be Assig</td>
<td>MVT</td>
<td>0.80</td>
<td>3</td>
</tr>
<tr>
<td>231</td>
<td>61.9528</td>
<td>-128.2625</td>
<td>Cantung Mine W-Cu-Bi-Zn</td>
<td>W-Cu-Bi-Zn-Producer</td>
<td>xTo Be Assign</td>
<td>W Skarn</td>
<td>0.90</td>
<td>1</td>
</tr>
<tr>
<td>223</td>
<td>63.4222</td>
<td>-123.2250</td>
<td>Cap Mountain</td>
<td>Cu</td>
<td>xTo Be Assig</td>
<td>Sed-host Cu</td>
<td>0.85</td>
<td>3</td>
</tr>
<tr>
<td>225</td>
<td>63.4167</td>
<td>-123.1667</td>
<td>Cap Mountain (Eastern Slo)</td>
<td>Fe</td>
<td>xTo Be Assig</td>
<td>Strat Fe</td>
<td>0.80</td>
<td>4</td>
</tr>
<tr>
<td>132</td>
<td>60.9803</td>
<td>-126.5681</td>
<td>Chuck Au</td>
<td>Au</td>
<td>Reconnaissance</td>
<td>Placer Au</td>
<td>0.75</td>
<td>3</td>
</tr>
</tbody>
</table>
Each occurrence was classified according to one of the selected deposit-types (recorded in the DepType field). The ‘FAV’ (for Fuzzy Assignment Value) records the assessed level of confidence that the occurrence matches the deposit-type. For example, the Cantung Mine is assigned a value of 0.90 to indicate the high degree of confidence that it is a Tungsten Skarn deposit-type. In other cases (e.g. Stratiform Iron), a lower confidence level indicates that more information is required to make an assessment.

The result of this analysis provides a ranking of significance factor to the occurrences to aid in their interpretation with the geological favourability. A known deposit or operating mine (e.g. Cantung) is obviously more significant than an occurrence for which only little information is available (or is significantly smaller in size). A four class ranking scheme is applied here as follows:

1 – Very significant, known deposit, well understood.
2 – Significant, not a deposit, but a significant occurrence.
3 – Moderately significant, potentially a given deposit-type, but limited information.
4 – Low Significance, limits and uncertainties in descriptive information, and confidence of classification.

Resource Assessment Domains (3e)

A comprehensive Mineral Potential Map provides a ranking of different sub-areas based on an evaluation of the combination of geological favourability and the known occurrences. This is the basis for the modified Geological Survey of Canada’s Mineral and Energy Resource (MERA) ranking scheme (Scoates et. al., 1986) provided in Table 3.

A modification to the Geological Survey of Canada (GSC) ranking scheme applied in this study is the assignment of numerical score values to each ranking (from 0 to 7 with each rank). As will be seen below, this scoring is used partly as a basis in preparing a Cumulative Mineral Potential map, and as a ‘Sum of Rankings’ component to that map. Notice also that the mineral occurrence ranking (along the column axis in Table 3) shows a number of fields that are not likely or possible in a Mineral Potential Map. The highest score of 7 (Very high – Rank A) is not possible if there are no known deposits, or if the quality of information for those deposits is suspect. Likewise, it is also not possible to assign a score of 1 (Very Low – Rank G), if the quality of information is poor. Additionally, it is also not likely to assign a score of 0 (not assessed) for areas where there is good quality information available.
Table 3. Mineral potential ranking based on GSC MERA ranking system.

<table>
<thead>
<tr>
<th>MINERAL POTENTIAL RANKING</th>
<th>MINERAL OCCURRENCE RANKING</th>
<th>Confidence Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rank 1: Abundant reliable information</td>
<td>Rank 2: Moderate amount of information</td>
</tr>
<tr>
<td>Rank A - Very High – Score = 7:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geologic environment is favourable.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant deposits/accumulations are known. Presence of undiscovered deposits/accumulations is very likely.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank B - High – Score = 6:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geologic environment is favourable.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occurrences are present but significant deposits/accumulations may not be known to be present. Presence of undiscovered deposits/accumulations is likely.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank C - Moderate to High – Score = 5:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate between moderate and high potential.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank D - Moderate – Score = 4:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geologic environment is favourable.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Occurrences may or may not be known. Presence of undiscovered deposits / accumulations is possible.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank E – Low to Moderate – Score = 3:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermediate between low and moderate potential.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank F - Low – Score = 2:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Some of the aspects of the geological environment may be favourable but are limited in extent. Few if any occurrences are known. Low probability that an undiscovered deposits/accumulations are present.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank G- Very Low – Score = 1:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geologic environment is unfavourable.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No occurrences are known. Very low probability that an undiscovered deposit/accumulations are present.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rank H- Not Assessed – Score = 0:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposit-types unknown, overlooked, beyond the scope of the assessment, or not worth mentioning at the time the assessment was done (could be a higher ranking in the future).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>

Notes: The X denotes fields that are unlikely to be used. The criteria for assessing mineral potential follows the Geological Survey of Canada’s Mineral and Energy Resource assessment ranking scale (Scoates et al, 1986).
This ranking scheme is applied on an aerial basis using Resource Assessment Domains (Domains). Domains are used as a sub-regional geographical framework that reveals contrasting patterns of geological favourability and mineral occurrence clusters. There are a number of methods for delineating Domains in a study area. They may be based on geological unit groupings, on physiographic domains, metallogenic domains, or possibly ecological units if desired. In this study, they were mapped from contrasting potential patterns in the set of geological favourability maps. The Domains for the Deh Cho study area are shown in Figure 6.

Domains 6 and 7 are not assessed for geological favourability due to lack of geological information. The Journey-Williams (1996) base map does not show geology for this area, which demonstrates limitations on the base information. Sub-Domains (39-43) were added because of the very significant mineral occurrences in this region related to the Pine Point lead-zinc past producing mine.

As can be seen in the following Mineral Potential Maps, these Domains contrast geological favourability patterns as well as clusters of known mineral occurrences, and therefore provides a fair representational framework for the entire Deh Cho region. These Domains are used as the basis for assigning the ranking values, and the calculation of a ‘sum of rankings’ as part of the Cumulative Mineral Potential map.
Figure 6. Resource Assessment Domains (Domains) used in this study.
Results and Recommendations

Reading the Maps

The results are presented as Mineral Potential Maps for each selected deposit-type and as a Cumulative Mineral Potential map encompassing all deposit-types selected for analysis. This section summarizes the symbology used in each Mineral Potential Map. The maps take into account the mineral occurrence, geology, and Domain ranking elements. There are three layers of information in each map:
1) Geological Favourability,
2) Mineral Occurrences (and rankings), and
3) Resource Assessment Domain rankings.

An example of each of these elements is provided in the example map in Figure 7.

Figure 7. Example Mineral Potential Map showing the symbology for geological favourability, mineral occurrences, resource assessment domains, and ranking values.
(Note: example taken from Deposit Type 10.0 – MVT Pb-Zn Mineral Potential Map.)
The results for each deposit-type are presented in map form, with a brief summary of each of the three elements:

**Geological Favourability** – is presented according to the Fuzzy Favourability legend presented in Figure 4. Recall that pinkish to red areas are the positive potential areas, and the light to dark bluish areas are the ‘negative’ potential areas for the given deposit-type. Greyish-white colours indicate areas of uncertainty, which often occur in transition between the blue and red end-members of the spectrum of colours.

**Mineral Occurrences** – are presented as point locations. Mineral occurrence rankings are provided in Appendix A.

**Ranking of Resource Assessment Domains** – are presented as empty polygon areas (i.e. not filled or coloured) with labels of the assigned ranking values (or scores as indicated in Table 3).

This presentation approach permits a combination of Mineral Potential Map elements to be viewed simultaneously in one map. This is expected to aid in discussion about the results (as part of land-use planning options) as well as convey as clearly as possible the range of certainty and uncertainty in the assessment. Readers can see that although a Resource Assessment Domain may have received a high score (e.g. 6), not all areas within that a Domain is equally a 6 ranking. The geological favourability underlay reveals more specific locations for which these values apply. Therefore, it can be seen that in cases where there may be conflicting land-use interests, delineating these areas within a Domain may help reduce the possibility of perceived conflicting land-values.
CMDT 3.0 – Stratiform Fe

Geological Favourability

Geological favourability for Stratiform Fe is quite limited within the Deh Cho territory. Most units were assigned very low values (below 0.40), except those with chemical sedimentary rocks (Enclosure A), which are restricted to units in the northwest and south-central portions of the study area.

Mineral Occurrences

There are only two known occurrences in proximity to higher ranked areas.

Ranking of Resource Assessment Domains

The sparse geological favourability and sparse mineral occurrences results in rankings score of 1 (very low favourability) for most of the study area. Only four Domains receive a ranking score of 3 (low to moderate) or 4 (moderate) in the northwest (Domains 16, 17, 18), while two Domains receive a score of 2 (Domains11, 24). Only two of these (11, 18) fall within the Deh Cho boundary.
CMDT 3.0 – Stratiform Fe Mineral Potential Map
CMDT 6.1 – SEDEX

Geological Favourability

Higher values are assigned to units associated with documented rift-related packages or non-passive sedimentary sequences in the west. Unit descriptions do not provide enough detail to differentiate active volcanic related sedimentary sequences from passive ones. This is illustrated by values ranging from 0.50-0.57 (pinkish) assigned to acknowledge the possibilities.

Mineral Occurrences

There are 37 mineral occurrences that correspond well with SEDEX model characteristics, and they all occur in the westernmost portion of the study area. These are dominantly Zn and V bearing occurrences. Several Pb-Ag-Cu bearing occurrences are included in this set, although their correspondence with SEDEX model criteria is not as strong.

Ranking of Resource Assessment Domains

Most Domains are assigned a very low (1) to low (2) ranking score, with the exception of some regions showing increased geological favourability (Domains 17, 18, 21, 29, 34-36, Figure 6), but with few known occurrences. High geological favourability combined with a cluster of known occurrences in Resource Assessment Domain 23 results in a ranking of 6 for this area, the most significant potential area that falls within the Deh Cho boundary.
CMDT 6.1 – SEDEX Mineral Potential Map
CMDT 8.3 – Sediment-hosted Cu

Geological Favourability

High geological favourability is restricted to the western and northwestern interior. Units associated with rift settings are considered more favourable, as well as the presence of volcanic rocks, red beds and evaporites. Higher values (0.58-0.61) are given for units indicating the presence of these environments, lower positive values (0.51-0.57) are given for units that may possibly contain ox-redox exposed units. Negative values correspond to the plutonic rocks (blue) in the west.

Mineral Occurrences

The 49 occurrences classified under this deposit-type all fall within the northwest area in what is locally referred to as the ‘copper belt’. Although only two of these occurrences fall within the Deh Cho territory, they are an extension of the copper belt from the north.

Ranking of Resource Assessment Domains

Most Domains are assigned a very low (1) to low (2) ranking. Values of 4 and 5 correspond with areas where the geological favourability is considered reasonably high (in the northwest outside of the Deh Cho boundary), but few or no occurrences are known. Domains 17 and 18 receive a ranking of 6 because of both the high geological favourability and the number of known occurrences that match this deposit-type in that area.
CMDT 8.3 – Sediment-hosted Cu Mineral Potential Map
CMDT 10.0 – MVT Pb-Zn

Geological Favourability

Of all deposit-types considered Mississippi Valley-type lead zinc (MVT Pb-Zn) is considered to be of most significant potential in both the west and east. Low values are assigned to volcanic and plutonic units highlighted in blue in the west, and moderate values (0.48-0.55) assigned to units that might contain platform carbonates and shales in the central platform region. Higher positive values (0.58-0.63) are assigned to units with known platform carbonate and shale sequences. Values increase with proximity to mapped faults. The assessment of the eastern and western areas is elaborated further in conjunction with a review of the known mineral occurrences and warrants a separate view of these two areas.

Mineral Occurrences

The western half of the Deh Cho territory contains seventy-five known occurrences that show a correlation with MVT Pb-Zn deposit-type criteria. The majority of these occurrences coincide with moderate to high geological favourability. Occurrences in the southeast portion of this area (Prairie Creek occurrences) are also tentatively classified as MVT-type occurrences. Jefferson, et al. (2003) have suggested that these occurrences might better fit under an alternative deposit-type (Manto-Pb-Zn Skarn). (Note: we have tentatively retained the MVT classification until further investigation. The ‘total’ mineral potential evaluation is not affected by this discrepancy).

The southeast Deh Cho area (adjacent to Pine Point deposits) contains 10 very significant MVT Pb-Zn occurrences. The geological favourability for this area was not assessed due to the eastern limits of Journeay’s (1995) map. However, these occurrences are deemed significant enough to warrant a ranking and evaluation as part of this analysis. All 10 occurrences, including one past producing mine, Pine Point, are ranked very significant, and have been confirmed to be MVT Pb-Zn occurrences.

Ranking of Resource Assessment Domains

Many areas in the west receive moderate to high values supported by the moderate to high geological favourability and numerous known mineral occurrences. Three Domains 19, 30, 31 (Figure 6) receive a score of 5, and three other Domains 17, 18, 20 (Figure 6) receive a score of 6. Note that the ranking of Domains 19 and 20 (Figure 6) are pending a possible reclassification as another deposit-type, but would simply transfer this ranking to that other deposit-type (Manto-Pb-Zn Skarn).

The ranking of Domains 39-43 (Figure 6) in the east is warranted on the basis of the locally and globally known significance of these occurrences. Three of these areas receive a ranking of 6, and two areas receive a ranking of 7. Those with a value of 7 are those with known deposits. (Note also that this is the only deposit-type for which a ranking of these specific domains is needed. All other deposit-types are ranked as 0 for Not assessed in domains 39-43).
CMDT 10.0 – MVT Pb-Zn Mineral Potential Map
CMDT 17.0 – Vein Cu

Geological Favourability

The assignment of values to geological units for Vein-Cu is particularly difficult primarily because of their general nature of occurrence. While there are some primary sedimentary sequence correlations, these types of deposits are not necessarily constrained by geological settings or rock types. Therefore, all units are given a base value of 0.55 and increased values are assigned for Proterozoic sedimentary rocks, especially if they are associated with igneous intrusions or are interpreted to be rift-related sequences.

Mineral Occurrences

The study area is sparse of known Vein-Cu occurrences. One occurrence correlates with high geological favourability, however, this area also corresponds with the ‘copper belt’ of high Sediment-hosted Cu potential. As with some of the MVT occurrences mentioned previously, in either case, these domains are viewed to have high Cu potential.

Ranking of Resource Assessment Domains

All domains, with the exception of those not assessed, are assigned a base 3 ranking score indicating a minimum of low to moderate potential. Scores of 4 and 5 are assigned to a number of domains in the west coincidental with higher geologically favourable environment environments.
CMDT 17.0 – Vein Cu Mineral Potential Map
CMDT 20 – Skarn (20.1 – Pb/Zn, 20.3 – Au, 20.5 – Skarn W and Emeralds)

Note: Because of the strong similarities of the Skarn-type deposit characteristics, the results of these three deposit sub-types are presented together. While there is only subtle difference in geological favourability, the individual rankings for each sub-type is affected more by the differences of the known occurrences for each sub-type.

Geological Favourability (all sub-types)

In each of the three Skarn sub-types, the geological favourability is relatively the same with a few minor differences. The similarities are strongest at locations where carbonate rocks (Skarn host rocks) have been, or may have been affected by either contact (close to plutons) or regional metamorphism. The differences for each of the three sub-types pertain to known age or lithological host constraints associated with the different commodities of the sub-types. In these cases, base values are assigned to geological units according to sub-type criteria. In all cases, the geological favourability is significantly higher in the west, especially in the vicinity of the known plutons (Enclosure A). Carbonate-bearing units in the interior (at some distance away from plutons) are considered moderately favourable based on the possibility that they may have been affected by regional metamorphism (to varying degrees). Note however, such differentiation (between degrees of regional metamorphism) is not documented in Journeay’s (1995) map, nor possible to represent at that scale. Therefore, all carbonate-bearing units are considered as initially potentially favourable for Skarn mineralization.

Mineral Occurrences

- CMDT 20.1 – Skarn Pb-Zn (also Manto). Eighteen occurrences of this sub-type have been identified in the western portion of the study area. Several of these are derived from advanced exploration investigation, while the remainder are reconnaissance or have yet to be verified as Skarn Pb-Zn occurrences. All occurrences intersect with areas of moderate to high geological favourability.

- CMDT 20.3 – Skarn Gold (Au). There are only four known occurrences that correspond to this sub-type, two of which have a low internal ranking in terms of their correspondence to this specific sub-type. However, as with Skarn Pb-Zn, they coincide with areas of high geological favourability.

- CMDT 20.5 – Skarn Tungsten (W). Of the three sub-types, Skarn (tungsten) W is the most significant. Of the fifteen known occurrences, one is a producing mine (Cantung Mine), and three others have reached advanced exploration stages. Many of these occurrences cluster within the vicinity of the Cantung Mine, which increases the likelihood that significant Skarn W potential is high in this area.
Ranking of Resource Assessment Domains

Note: As with the geological favourability discussed above, the base rankings applied to the resource assessment domains reflect similarities among the three sub-types. At the scale of applying the modified Geological Survey of Canada ranking scheme, the subtle differences in geological favourability for each sub-type (especially in the central platform areas) become diffused. In most cases, all eastern, central, and mid-western domains (those favoured only for their carbonate-bearing significance) are scored very low (1) or low (2). A ranking score of 3 (low to moderate) is assigned for domains that intersect with areas where carbonates may have possibly been regionally metamorphosed. The distinct differences among the three sub-types occur in the western portion where differences in the known occurrences have significant bearing on the rankings.

- CMDT 20.1 – Skarn Pb-Zn (lead-zinc). The higher geologically favourable areas (as indicated by the concentric patterns in the vicinity of known plutons) are ranked as either moderate (4) or moderate to high (5). Domains 20 and 25 receive a low-moderate score (3). More significantly, Domains 33 and 36 each receive a score of 6 (High) because of the coincidence of both high geological favourability and significant known occurrences.

- CMDT 20.3 – Skarn Au (gold). Two significant occurrences are known in Resource Assessment Domain 36, which is assigned a high ranking (6). Other occurrences, although potentially significant, have yet to be validated as this specific sub-type, and therefore their respective Domains (23, 28, 30) retain a ranking of moderate to high (5).

- CMDT 20.5 – Skarn W (tungsten). As discussed previously, this sub-type represents the only active producing mine in the region, hence, domain 23 is assigned a Very High (7) ranking. Fourteen other occurrences in adjacent Domains (33, 34) warrant a High ranking (5) for these areas.
CMDT 20.1 – Skarn Pb-Zn Mineral Potential Map
CMDT 20.3 – Skarn Au Mineral Potential Map
CMDT 20.5 – Skarn W Mineral Potential Map
CMDT 21.0 Pegmatites

Geological Favourability

The geological setting for pegmatite occurrence is primarily associated within and in close proximity to known plutons (Enclosure A). However, areas affected by regional scale faults (and other deformational features) also present possibilities for pegmatite occurrence. The generally uncertain values associated with these faulted areas illustrates this evaluation. For the most part however, geological favourability is increased within and near known plutonic rocks.

Mineral Occurrences

All eleven occurrences have been reasonably confirmed as pegmatite-type, however, only coincides with an area of high geological favourability. A significant cluster of occurrences exists within a faulted region at a considerable distance away from known plutons.

Rankings of Resource Assessment Domains

All domains outside of the known pluton-rich domains are assigned a Very Low ranking (1) or Low (2). The domains coincident with plutons in the west are assigned Moderate to High (4-5).
CMDT 21.0 Pegmatites Mineral Potential Map
CMDT 25.0 – Primary Diamonds

Geological Favourability

The potential for primary diamond occurrences requires the occurrence of deep-seated igneous intrusions, such as kimberlites or lamproites. Although these are primarily known to occur within Shield areas (such as the Slave Province, north of Yellowknife), they are known to occur in a wide range of geological environments and ages. It is possible that these intrusions occur within the Interior Platform or Cordilleran as they do elsewhere in the world (Eckstrand et al, 1996). However, their nature of occurrence (small size) makes it very to represent potential on a regional scale. As a result, the geological favourability component has been mapped at 0.50 (or a poria (Eddy, 2003), complete uncertainty) it cannot be said whether or not diamonds occur in the study area.

Mineral Occurrences

None known.

Rankings of Resource Assessment Domains

It was not possible to assess diamond potential, so all domains received a value of 0 (Table 3).
CMDT 25.0 – Primary Diamonds Mineral Potential Map
Cumulative Mineral Potential (CMP) Map

In the previous sections, the mineral potential for each deposit-type was represented by mapping relative favourability of the geological setting, combined with ranking of areas using the modified Geological Survey of Canada ranking scheme (Table 3). Each deposit-type representation revealed a range of potential, and it can be said that the potential for some deposit-types (e.g. Stratiform Fe) are consistently low across the study area, while the potential for others (e.g. Vein Cu) are consistently moderate to high. Other deposit-types (e.g. SEDEX, MVT, Skarn) reveal a range of Low to Very High potential depending on the correspondence between geological favourable settings and geographical location. Individually, they provide important information for land-use decision makers, however they may also be combined collectively to provide another layer of information as an aggregate of all types considered. In this section, a Cumulative Mineral Potential (CMP) map is represented as a composite of the individual Mineral Potential Maps presented above.

Geological Favourability

The calculation of cumulative geological favourability is based on combining all of the geological favourability maps for all deposit-types considered in this study. This layer uses the same relative favourability legend as in all other maps (Figure 4). It was calculated by taking the maximum potential of all deposit-types and increasing the net value for locations where there is high potential for more than one type. For example, if in one location, the geological favourability for a deposit-type was given a value of 0.65, and there is no other high potential deposit-types for that same location, then this map shows that location as 0.65 (the maximum of all types). But in some locations, the geological favourability is high to very high for more than one type (as is seen in SEDEX, MVT, and Skarn for similar locations). The geological favourability in the Cumulative Mineral Potential map takes into account the possibility that there is good potential for more than one type in some locations. Therefore, the calculation shows an increased affect for locations where there is high potential for more than one type.

This combination results in relatively higher cumulative favourability values in the range of 0.80 to 0.96. In reference to the favourability legend presented in Figure 4, such values represent a relatively confident answer to the more general question “Is their mineral potential at location x-y”? The range of colour from medium red to dark red on this map indicates a geologic favourability assessment of Likely to Very Likely (Figure 4). In some locations (i.e. where there are validated occurrences and known mineral deposits), the answer is “Yes” (significantly higher values than 0.65-0.75). The redness of this map indicates that no location within this region can be said to be of low cumulative mineral potential.

Sum of Rankings (Resource Assessment Domains)

It can be seen that some areas have relatively higher potential than others. The ranking scheme applied to each deposit-type individually is incorporated here as a ‘Sum of Rankings’ information layer. All ranking values are presented in Table 4. Note that the resulting numerical scale (to values as high as 40) does not equate to the corresponding evaluations of the modified Geological Survey of Canada ranking scheme. The sum of rankings simply reflects
the overall relative cumulative potential of all deposit-types considered in this study. The sum of rankings values in the western interior are significantly higher than those in the central and interior platform areas.

Specifically, within the Deh Cho boundary, six Domains (11, 18, 20, 21, 23, 33, Figure 6) reveal high to very high mineral potential for a number of deposit-types, with sum of rankings values of 22, 33, 23, 24, 40, and 33 respectively. It is these specific domains that the potential for discovery of new mineral deposits is most likely.

The sum of rankings and geological favourability shown here are calculated from all nine deposit-types selected for this study. The inclusion or exclusion of specific deposit-types from this type of calculation will inevitably affect how cumulative mineral potential is viewed in terms of the relative ranking of potential for different locations across the Deh Cho territory. It is for this reason that mineral potential information must always be considered relative and contextual depending on the selection of deposit-types or commodities of interest, as well as the limitations of data, knowledge, and methodologies employed in the analysis and interpretation of potential. These are just a few significant aspects that are important to consider when applying this information for examining land-use options.
Table 4. Individual Rankings and Sum of Rankings Values by Resource Assessment Domain.

(Not: ‘light blue cells’ indicate ‘Not assessed’).

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Cumulative Mineral Potential Map (CMP)
Simplified (Four Class) Cumulative Mineral Potential Map
Limitations and Constraints

The use of any modeling criteria derived from local and global knowledge, as well as formal and informal knowledge of what constitutes “mineral potential” must be treated in the context that new knowledge and new discoveries continue to be made, which at times, may alter the assumptions and conclusions built into existing models. These results are presented within the context of a pre-cautionary approach. This is to say that it is not wise for resource geologists to assess any given location as having no mineral potential or even low mineral potential. Only that for specific deposit-types, some locations are relatively lower or higher depending on the geological characteristics and supporting evidence.

Where potential is identified as relatively higher it does not preclude the potential for relatively lower areas being ranked higher in the future, with the use of different data, knowledge, or in consideration for other types of commodities.

For example, the potential for Diamonds in the Interior Platform is being given significant attention. Over six (6) million hectares (~25,000 km$^2$) has recently (Feb. 2003) been permitted by Diamondex in Inuvialuit, Sahtu and Gwich’in Territories (see Appendix D) on the basis of favourable sampling results in the summer of 2003. Diamondex is the same group who made the Snap Lake diamond discovery northeast of Yellowknife, now being developed by DeBeers into Canada’s first underground diamond mine. Diamondex is planning to spend $2,000,000 in the summer of 2003 on exploring for diamonds in the Interior Platform.

The geology underlying these areas presently being explored is similar to that which underlies the Deh Cho territory, and by extrapolation it could be said that portions of the Deh Cho territory have similar potential for the occurrence of diamonds.

Based only on the geology, and what we know about primary diamond deposits in Canada, this area (Interior Platform) would be considered low for diamond potential. Although exploration for diamonds has been going on in the Interior Platform for over 30 years by DeBeers and others (Blackwater Lake area) and significant diamond indicator minerals have been found: no kimberlite (host for diamonds) nor diamonds have been discovered. Therefore, conclusions based only on geology and known diamond/kimberlite occurrences would not suggest potential for diamonds in this geologic environment. However, because of the degree of industry interest and level of investment this region can be considered to be of some significant potential.

This is much the same as the Lac de Gras area appeared before the discovery of diamonds. Prior to 1985 no one recognized the diamond potential in the area. The Northwest Territories is now supplying 10% of the world’s diamonds by value (Appendix D). Diamonds represent one commodity for which there may be significant potential but cannot be adequately conveyed within the mapping approach applied here. The Mineral Potential Maps presented here represent a minimum of potential commodities but cannot conclude that some areas are low or no potential.

These results also do not take into account economic, social, political, environmental and engineering factors that play a significant role in bringing a potential area into the status of
actuality. Another level of assessment would need to be undertaken for these factors to be considered. The implications of these constraints are discussed further in the conclusions and recommendations section below.

It is possible to portray mineral potential for the entire Deh Cho territory through the application of this specific approach. But this study is based on 1:1,000,000 scale mapping which is too coarse for the level of detail that may be required in the land-use decision making process in some areas. The results presented here are highly generalized. The Deh Cho would benefit from more detailed Mineral Potential Map and assessment in some sub-regions, perhaps for specific commodities of interest, and in locations where greater clarity and resolution is required.
Conclusions

1. The most significant potential appears in the western part of the study area, within the mountainous Cordilleran. Both the individual Mineral Potential Maps and the Cumulative Mineral Potential Map illustrate this conclusion. In particular, this region is regarded as high to very high for Skarn, SEDEX and MVT Pb-Zn.

2. The general conclusion is that the entire Deh Cho area contains at least some mineral potential, if not because of one mineral deposit-type, then another, or some combination of types. There is nowhere within the Deh Cho area that can be said to have no potential or low potential.

3. Although not assessed for geological favourability during this study, significant MVT Pb-Zn occurrences within the eastern portion of the Deh Cho boundary (Pine Point) show high to very high potential. The proximity of these occurrences to existing infrastructure and resources warrants significant attention and future study.

4. The Cumulative Mineral Potential portrayed by these maps: to be relatively higher in the west relative to the central and eastern portions may change based on new information. New discoveries, data, and knowledge about the study area continue to emerge, and there may be high potential for some commodities (e.g. Diamonds) in areas that are evaluated as relatively low in this study.

Recommendations

1. It is recommended that no decisions regarding the promotion, development or withdrawal of areas should be made on the basis of the Mineral Potential Maps presented here without the guidance of a resource assessment geologist.

2. It is recommended that a second phase of Mineral Potential Mapping be carried-out at 1:500,000 to 1:250,000 for selected deposit-types, and in locations where the DCLUPC consider important for their planning purposes.

3. In conjunction with Recommendation 2, a fieldwork component (new data collection) may necessary to augment the rankings applied here. While it is not possible to conduct fieldwork at the same level of detail for the entire Deh Cho region, specific sub-areas considered important by the DCLUPC should be given attention.
References


Appendix A - Mineral Occurrences Data
NORMIN Mineral Occurrences Data Table

Note: The fields provided in these tables are a summary selection of those available in the NORMIN database. The last three fields pertain to classification and rankings for application in this study only.

Field Descriptions

{Numeric ID}
GID – GIS ID {note: used for DC MPM GIS application only}

{General Information from NORMIN}
Latitude – Latitude
Longitude – Longitude
Name – Occurrence Name
Commods. – Commodities
DevStage – Development Stage*

? Note: Development Stage pertains to stage of development of deposits, as well as the level of investigation of occurrences.

{Analytical Information – Added for this study only}
DepType – Deposit Type Classification
FAV – Fuzzy Assignment Value (indicates strength of association with Deposit Type)**
SigRank – ‘Significance’ Ranking**

** Note: See text for explanation of the relationship between the FAV and SigRank.
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### DT 20.1 - Skarn Pb-Zn

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Appendix B – Media Releases of Diamond Exploration Interests
Lena West Property, Northwest Territories

Location:
The Lena West project is located approximately 310 kilometers north of Norman Wells, Northwest Territories.

Size:
139 prospecting permits encompassing 6.15 million acres

Ownership:
Diamondex 100%

Budget Expended/Projected:
To date: C$220,000
2003 C$2.0 million

Assets:

- The Lena West Project area was selected for evaluation on the basis of the region's geologic and tectonic similarities to the important diamond producing regions of the East Siberian kimberlite province.
- Dr. Nikolai Pokhilenko, the Chief Research Geologist for the Russian Diamond Company (Almazy Rossii -- Sakha Co. Ltd.) and overseer of the program, theorized that the Phanerozoic sediments of this portion of the Interior Platform are underlain by stable crustal material similar in areal extent to the Slave Province.
- Dr. Pokhilenko's study of Tertiary river drainages and Quaternary glaciation cycles affecting the region indicated that the Lena West Project area was the primary source for numerous alluvial
diamonds previously reported from the Yukon River basin located to the west. The same study negates the possibility that these diamonds were transported from the Slave Craton kimberlites, which are located 1,400 kilometers to the east.

**Overview:**

These permits were acquired following a heavy mineral concentrate sampling program undertaken during the 2002 field season. Evaluation of stream sediment samples produced significant concentrations of pyrope garnet, picroilmenite, and more rarely, chromite.

Consultant Dr. Nickolai Pokhilenko, who has over 35 years experience exploring for diamonds in various parts of the world stated that, "the nature of the recovered indicator minerals (IM) and their distribution in the prospective area is typical for IM halos of kimberlite regions of the Siberian Diamond Province." Dr. Pokhilenko reports that the Lena West Project area overlies a new kimberlite province and probably hosts several kimberlite clusters and that "the multiple finds of coarse diamond crystals made through gold placer mining operations in the upper Yukon River basin (several finds of diamonds up to 8 mm in size and up to 28 diamonds recovered in the Klondike and 60 Mile River areas) is excellent evidence for the presence of high grade pipes (such as the Udachnaya, Aikal, and Mir pipes of Yakutia) in the Lena West Project area."

Early reconnaissance work by the Company in the 25,000 square kilometer permit area could represent the discovery of one of the most significant new kimberlite fields since the Lac de Gras discovery of 1991.

**Forecast 2003:**

The Company has approved a $2.0 million budget for 2003, which includes a major sampling program and geophysical surveys for the delineation of drill targets.

Dr. Pokhilenko will continue to provide technical guidance for the Lena West Project. A team of Russian geoscientists will work alongside
Diamondex personnel through the current exploration season. Further details concerning the Lena West exploration program will be announced in the near future.

Maps and Photos

Lena WestFall 2002 Sampling Program
61 KB, approx. 33 seconds at 28.8Kbps

Lena WestFall 2002 Sampling Program
75 KB, approx. 40 seconds at 28.8Kbps

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For more information, send questions and comments to diamonds@diamondex.net

This page was created on Wed Jun 18, 2003 at 2:48:51 PM Pacific Time.
Total Acreage 6,154,748 acres

Lena West
Prospecting Permit Areas

http://www.diamondex.net/i/maps/lena-west.jpg

07/05/2003
DIAMOND MINING IN CANADA’S NORTH

Diamond mining in Canada’s North is growing. The Ekati Diamond Mine in the Northwest Territories (NWT) currently produces 3 per cent of the world’s diamonds by value.

Operated by BHP Diamonds Inc. and opened in 1998, the Ekati Diamond Mine in the NWT is now producing slightly over 7,200 carats per day. According to BHP, total sales in 2000 were approximately $430,000,000. Preparatory work to begin mining another pipe (i.e., deposit) in October 2001 is well underway.

The Ekati mine currently employs 700 full time workers of whom almost 70 per cent are Northerners (33 per cent are Aboriginal). The company also purchases approximately $356,000,000 worth of goods and services each year with almost 80 per cent of these purchases made in the North.

BHP Diamonds Inc. is also looking to expand its mining activities by seeking regulatory approval to mine 3 additional kimberlite pipes.

In 2003, the Diavik mine is scheduled to begin production. Construction of this mine, by Diavik Diamond Mines Inc., is proceeding well. By June 2001, almost 1000 people were working in the NWT on the Diavik Project at Lac de Gras and in Yellowknife. Approximately 40 per cent of these workers are Northern residents from the NWT and Nunavut's West Kitikmeot region. In addition, over $600 million or approximately 75 per cent of the construction contracts and purchase orders have been awarded to Northern companies. The project remains on schedule to begin diamond production in the first half of 2003.

As building strong partnerships with Aboriginal people is important to the success of the Diavik mine, there is ongoing community participation including site visits by Aboriginal community members and elders and the establishment of joint committees with Diavik Diamond Mines Inc.'s neighbouring communities (Dogrib First Nation, Yellowknife's Dene First Nation and the North Slave Metis Alliance) to monitor the success of participation agreements negotiated between the company and the communities. Discussions with the Lutsel K'e Dene First Nation and the Kitikmeot Inuit Association with respect to similar agreements are also underway.

In February 2001, De Beers Canada Mining Inc. submitted its licence applications to begin the environmental assessment process for its proposed SnapLake Diamond Project in the NWT. Production is tentatively scheduled to begin in 2006.

http://www.ainc-inac.gc.ca/nr/prs/s-d2001/01223bkb_e.html

4/17/2003
The Tahera Corporation is also in the environmental assessment process for its Jericho Diamond Project, in Nunavut, which is anticipated to begin production in 2004.

By 2006 when both DeBeers Canada Mining Inc.'s Snap Lake project and Tahera Corporation's Jericho project are in production, Canada will produce about 12 per cent of the world's diamonds by value.

October 2001

Back to News Release

Last Updated: 2002-12-30

http://www.aicn-inac.gc.ca/nr/prs/s-d2001/01223bkb_e.html

4/17/2003
Appendix C – “Mineral Potential Analyzed and Mapped at Multiple Scales - A Modified Fuzzy Logic Method Using Digital Geology”
Mineral Potential Analyzed and Mapped at Multiple Scales - A Modified Fuzzy Logic Method Using Digital Geology

Eddy, B.G\textsuperscript{1}. Bonham-Carter, G.F.\textsuperscript{2} and Jefferson, C.W.\textsuperscript{2}

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\textsuperscript{2} Geological Survey of Canada, 601 Booth St., Ottawa, Ontario CANADA K1A 0E8 bonham-carter@nrcan.gc.ca cjeffers@nrcan.gc.ca

The following paper has been submitted to and accepted by the Geological Association of Canada for publication in a Special Volume on GIS Applications in the Earth Sciences. A copy of the submitted version of this paper is provided here with the permission of the first author and the GAC Volume Editor, on the condition that it is used only as a technical reference only for the Deh Cho Land Use Planning Committee. A formal formatted published version of this paper will be available soon through the GAC. In the interim, the material presented in this paper is not for reproduction or distribution, in whole or in part, but only as a technical reference for the DCLUP committee members to augment the existing report prepared by the C.S. Lord Northern Geoscience Centre on the Mineral Potential Mapping of the Deh Cho Territory. Any use beyond the DCLUP must be authorized by permission of the first author. Copyright, Brian G. Eddy, 2003.
Abstract

Data-driven statistical methods used in Mineral Potential Mapping (MPM), such as weights-of-evidence (WofE), are usually constrained to study areas where there is a sufficient number of known mineral occurrences, complemented by multi-thematic geoscience data sets. However, vast geographical areas remain deficient of this quality and quantity of data; areas for which MPMs are required for regional economic and land-use planning, and mineral exploration. In Canada, such areas of data deficiency constitute over 70% of the land area, including the Canadian High Arctic and other less explored frontier regions. Requirements often call for MPM at multiple scales, and for different commodities and deposit types. Resource geologists are constrained by data deficiency, and further challenged to adequately accommodate 'uncertainty' in the presentation of results, with a presentation style that is consistent across scales, and concisely informative for multi-disciplinary audiences.

A knowledge-driven, 'modified' fuzzy logic method is presented for MPM at multiple scales using only geological maps (as data) and mineral deposit criteria (as knowledge). Previous applications of fuzzy logic use a 'base 0' approach that restricts application to multi-scale mapping, and conflates areas with rankings of low potential with areas of missing data. This modified method uses a 'base 0.5' approach as an uncertainty 'hinge line' upon which Fuzzy Membership Values may diverge toward the pure end members (where 0=No, and 1=Yes) with increasing certainty depending on the data and knowledge available in a variety of geographical scales. A mock WofE example is used to demonstrate how this 'possibilistic' knowledge-driven method is empirically consistent with the 'probabilistic' data-driven approach. The method is demonstrated using an application mapping MVT Pb-Zn potential on Bathurst Island, Nunavut, and surrounding areas, at four scales of
representation, using four different geological maps. This illustrates the use of fuzzy logic to create MPM in an objective manner that also permits review and iterative modification of the logical steps taken, using different model criteria and assumptions.
INTRODUCTION

GIS-based analysis for mineral exploration and research has increased significantly in the past decade. A variety of methods have been developed for preparing mineral potential maps (MPM) with digital geoscience data sets (An, et.al, 1991; Agterberg, et. al, 1993; Bonham-Carter, 1994; Cheng, 1994; Chung and Fabbri, 1993; Constanza and Hale, 2001; Eddy, 1996; Harris, et. al., 2001; Mihalasky, 2001; Wright, 1996). The choice of method often depends on the data available, the scale and scope of the requirements, the commodities or deposit types being modelled, and the type of mineral potential information required. The location and geographical extent of the study area will often influence the choice of method due to the limitations of the data available. It is now known that some methods are generally more successful for more localized study areas for which multi-thematic data are available, and for which modelling the potential for a specific deposit type is the primary objective.

MPMs are also needed for larger regions, such as for reconnaissance exploration, research or land-use planning. In contrast to localized studies, regional geologists are often confronted with sparse, disparate, or fragmented data as well as a paucity of known mineral occurrences from which any consistently inductive analysis might be based. Regional studies may need to assess multiple deposit types or commodities, such as is required in the Mineral and Energy Resource Assessment (MERA) process (Scoates, et. al., 1986).

Exploring and analyzing mineral potential at regional scales requires reconciling constraints imposed by limitations in data and knowledge available for these scales. The ability to conduct detailed field studies and generate new data is often not possible. One means of overcoming these constraints is a modified fuzzy logic approach that can be applied at many scales, to one or many commodities and with as little input data as a single geological map used in combination with
deposit model criteria. This approach is introduced in comparison with the weights-of-evidence (WofE) method.

A comprehensive vocabulary describes the two approaches compared herein. The fuzzy logic approach is variously described as knowledge-driven or based (KD); deductive, possibilistic, hermeneutic, and theoretical. The WofE approach is described as data-driven or based (DD); inductive, statistical, heuristic, and probabilistic. Both are effectively rendered in GIS. Throughout this paper, the terms KD and fuzzy logic are used interchangeably, as are DD and WofE.

Outline

This paper is presented in three sections. In the first section, a general context and approach is presented to exemplify some of the more common constraints in producing mineral potential information on regional levels, especially for frontier regions such as in the Canadian High Arctic. We explore general relationships of data to knowledge, and DD to KD MPM as originally outlined by Bonham-Carter (1994). Geographical scale, as well as logistic, political, and other constraints are also explored. The second section presents the basis for a modified fuzzy logic approach using a comparative analysis with a mock WofE example. This comparison demonstrates the principles by which the modified fuzzy logic method is internally consistent with DD approaches. The third section presents a case study that applies the modified fuzzy logic method to mapping MVT Pb-Zn potential in the Canadian High Arctic, using four different geological maps at four different geographical scales, with the same set of deposit criteria. We conclude by discussing potential further development and application of this method.

CONTEXT AND CONSTRAINTS IN REGIONAL MINERAL POTENTIAL MAPPING

The Use of Geoscientific Information in MPM
In many mineral potential studies the context is critical. The choice of method is often constrained not only by technical or scientific factors relating to data and scale, but also by politics, economics and logistics (Figure 1). Inter-relationships among these factors vary considerably, and it may be necessary to reconcile conflicting or contradictory information. The differentiation of data and knowledge is not always apparent. This has important bearing on the overall methodology, especially in GIS, so that the choice of method best suits the study requirements. It is therefore necessary to examine more closely how the terms ‘data’ and ‘knowledge’ are implied in some GIS-based MPM.

**Data-Driven (DD) and Knowledge-Driven (KD) Methods**

Bonham-Carter (1994) discussed distinctions between DD and KD approaches to GIS modelling. In the context of MPM, DD approaches make use of known deposits and occurrences within the study area as training sites. KD methods utilize the opinions or judgement of experts who assign weights to various model input factors, and also control the model construction and processing. DD methods are often regarded as more heuristic, objective, or empirical, whereas KD methods are regarded as more theoretical, or subjective. Hybrid methods are those that combine some element of both DD and KD elements, such as when an expert assigns the relative weights based on the results of a weights-of-evidence analysis (Bonham-Carter, 1994).

DD methods are sometimes favoured over KD methods because they are perceived to be more objective (observer independent), whereas KD methods, being more subjective, are generally perceived to be more prone to bias and error. Such crisp distinctions between subjectivity and objectivity, or the theoretical and empirical dimensions in methodology, begin to dissolve upon a closer examination of data and knowledge flows in both DD and KD methodologies. This has been a source of debate on resource assessment methodology among many resource geologists (IAMG,
Based on the original framework of KD and DD methods (Bonham-Carter, 1994), we here elaborate their mutual relationships so that both can be considered equally valid approaches to MPM.

This framework presented here (Figure 2) treats data as factual, objective, empirical evidence, and knowledge as subjective, theoretical, or deduced from data. The intrinsic relationship between data and knowledge is viewed here as an iterative cycle. With any methodology, both data and knowledge must be employed, and, neither is considered purely objective or subjective. DD and KD methods are thus distinguished on the basis of which direction the primary information flows during modelling. DD methods rely predominantly on inductive information derived from statistical relationships among locations of known mineral deposits and geological patterns - this is considered here as ‘bottom-up’ information flow (exploratory, discovery = heuristic). KD methods rely predominantly on deductive information influenced by the degrees of association between geological attributes in the study area that are assigned by an expert to deposit model criteria, and are considered here as a ‘top-down’ information flow (interpretation = hermeneutic) that requires specialized expertise for each deposit type. Hybrid methods incorporate both inductive (statistical/heuristic) and deductive (interpretive/hermeneutic) information flows.

In this context, all mineral potential maps are outputs of some combination of data and knowledge. In this hierarchy, knowledge supercedes data, and is therefore considered higher or more abstract than data. DD approaches are often preferred because local empirical elements (e.g. WofE statistics) as well as broader theoretical elements (e.g. global mineral deposit models) can be jointly considered. Comparisons of DD and KD approaches have revealed strong agreement (Wright, 1996; Harris, et. al. 2001) when the same modelling criteria and data are used.
Examining Regional Level Constraints

Rigorous DD approaches can rarely be employed in regional mineral potential studies. DD approaches are more likely to be successful in regions where there are a statistically sufficient number of known mineral occurrences of similar type within a defined study region. In Figure 3, such regions correspond to the darker tones (more dense regions). Depending on the commodity and relative spatial density, DD methods might be successful in some of the less dense regions, but less so in regions of sparse known occurrences (less than 1 occurrence per 1000 km$^2$).

Sparsity of mineral occurrences constitutes only one constraint in DD modelling. The distribution and resolution of other geoscientific data, such as geochemistry, multi-parameter geophysics, and mineralogy generally coincides with the density of mineral occurrences. It is expected that studies conducted on more local scales, in areas of higher known occurrence density, will also benefit from the availability of multi-thematic geoscience datasets. Multi-thematic geoscience data tend to be sparse in regions of few mineral occurrences. This results in part from the logistical and economic constraints of distance and climate on speculative data collection and exploration.

It is often within regions of sparse data where mineral assessments are required, especially for regional land-use planning, or grass roots exploration. Discovery of diamonds in the Northwest Territories and the Ni-Cu deposit at Voisey’s Bay in Labrador are recent examples of previously unrecognized high mineral potential in both well explored (dense) and relatively less explored (sparse) regions of Canada. Assessment of mineral potential of these regions is critically constrained by the non-uniform mineral occurrence and availability of multi-thematic data sets. Generally, the only consistently available information is reconnaissance level geology. Such maps, when used in combination with specific data compilations, and written reports for the region, often constitute the
starting point in estimating mineral potential of frontier regions, by comparison against provincial to
global criteria for each commodity or deposit type being assessed.

In the case of the MERA process (Scoates, et. al., 1986), all deposit types in the Geology of
Canadian Mineral Deposit Types (Eckstrand, et. al., 1995) must be considered, as well as any
additional types or commodities that may be known locally but are not formally included in the
literature. A number of complex inter-relationships within the information base must be iteratively
analyzed for each commodity and each location under question. Such a task can become laborious
for geologists working under tight project constraints. Whether or not mineral potential can be
mapped depends very much on the key criteria that characterize a deposit type (i.e. if they are
mappable criteria), as well as whether any evidence for these criteria can be derived from geological
maps and reports available for the study region. The use of the term ‘potential’ will have different
meanings in different contexts, and the geologist must state the context in which potential is
assessed. This is especially true for results directed at non-geologists such as land-use planners,
local communities, policy analysts, educators and politicians.

Defining study area boundaries is particularly important in calibrating DD methods such as
weights- of- evidence, because statistics derived from area measurements are sensitive to
configuration and areal extent. In the early stages of a mineral potential study, it may not be known
which specific locations, commodity types, policy or economic interests will be of interest. For
example, in the MERA process, planning new national park boundaries has frequently shifted
attention between different proposed sub-regions within the national plan or within a park region.
For reconnaissance exploration, a company may change its interests in exploring one or more sub-
areas of a larger region.
For these reasons, requirements for a strong GIS method for frontier MPM differ significantly from those of local, information-rich areas. The level of requirements and methodology are, in general, inversely related to map scale (Figure 4). Regional level mineral resource studies may examine multiple commodities (MERA) or single commodities (Policy economic analysis or commodity-focused industry), but generally use few input layers. In both situations, geological compilation maps, and their derivatives (e.g. metallogeny, proximity measures, etc.), combined with deposit criteria, are the primary data for regional mineral potential analysis. Conversely, local mineral potential studies tend to focus on fewer commodities and benefit from multi-thematic geoscientific data sets. These inverse relationships also reflect the natural tendency for a greater diversity of deposit types to occur over larger regions, versus more limited diversity within smaller metallogenic domains (although diversity is also related to other factors such as lithological diversity (Griffiths, et. al. 1980, Mihalasky and Bonham-Carter, 2001).

Reconciling these inverse relationships is paradoxical and challenging. Sparse regional data sets force simplicity and use of national to global models. Complex and dense local data sets provide more spatial evidence in relation to specific deposit model criteria, and provide more latitude in experimenting with data, leading to a higher number of possible outcomes (e.g. Harris, et. al. 2001). Regional mineral potential maps may provide a more reproduceable portrayal of mineral potential than what might be expected in local assessments.

This paper focuses on methods for sparse regional data sets, but their application to local multi-thematic data sets is not precluded. In fact, the method is devised such that it must also function at more local levels. To summarize, the principal aims for this methodology include:
Application to MPM of sparse data sets at regional to global scales, but amenable to incorporate additional data.

Capability to inter-relate geological features and patterns presented in geological maps (data) with deposit model criteria (knowledge).

Application at different scales, such as for a compilation of geological maps at different original scales, using the same set of deposit model criteria.

Provision of a cartographic presentation style that allows geologists to generate appropriate contexts in the portrayal of mineral potential to different audiences.

Consistency, both theoretically and empirically, with DD methods.

**APPROACH AND METHODOLOGY**

Although the requirements and constraints for regional level MPM appear diametrically opposed to those on the local level, it is important that approaches to each are consistent. This will facilitate integration of local studies nested within regional studies ('zooming in'), as well as expanding local studies across larger regions ('zooming out'). As discussed previously, it is necessary to ensure the compatibility of the fuzzy logic (KD) and weights-of-evidence (DD) methods.

The starting point in any MPM study is a question such as: "What is the potential for commodity 'Z' at all locations within the study area?". In cases where mineral occurrences are known, there is an *a priori knowledge of potential*, but without such knowledge, the initial response would be complete uncertainty, perplexity. It is not until data and knowledge are collected that geologists can begin to answer the question. MPM aims to reduce the uncertainty of the answer.

The fuzzy logic method produces a relative favourability map both within the study area. The weights-of-evidence method aims to produce probabilities of occurrence per unit area that identify
areas of higher and lower chances of success in locating a deposit, in relation to a prior probability that is calculated using the known deposits within the study area.

The KD (fuzzy logic) and DD (WofE) methods thus have similar beginnings. These two approaches use different information flow paths, and the 'types' of starting point uncertainties are different. Figure 5 illustrates some of these relationships using terms derived from the fuzzy logic and WofE methods as reference. The initial WofE calculation is a prior, unconditional probability (representing an 'a priori' argument), and all subsequent probability calculations are updates on the prior, conditional on the spatial evidence. The method adds various geo-data layers to analyze statistical relationships between occurrences and geological patterns, and where similar relationships exist in the areas without occurrences by producing a 'posterior probability'. There can be both increasive (higher relative potential) and decreasive (lower relative potential) posterior probabilities relative to the prior, and the response map provides the statistical chances of finding a deposit at each location in the study area.

It follows that in a KD methodology, the aim is similar, only in this instance, there may not be a sufficient number of occurrences within the study area to derive a satisfactory statistical relationship, and therefore, there is no a priori basis to use as a starting point. Even if there are several known deposits, projecting the mineral potential for the remainder of the study area is problematic for both DD and KD methods because the representativeness of those few occurrences in a large region may be poor.

The KD starting point is a different form of uncertainty, or perplexity, referred to here as 'aporia', which is a Greek term meaning 'perplexity, complete uncertainty, or two diametrically conflicting truth claims' (Crisp, R. 1999). The terms 'certainty' and 'uncertainty' take on different contexts in deductive and inductive reasoning processes, and therefore the notions of 'a priori' and
'aporia' further distinguish the starting points in the DD from KD methods. In comparison to WofE, fuzzy logic aims to reduce aporia by discerning between increasive and decreasive 'Fuzzy Membership' of the locations in the response map, to assess the potential for 'Z' at each location.

To address the multi-scale requirement, and to illustrate the inversion between requirements and scale (Figure 4), we first examine the effects of scale and information detail on the results for each method. Increasing scale tends to improve geological detail, enabling geologists to reduce uncertainty about the spatial evidence. Improved detail will have similar effects on both KD and DD methods by providing some degree of certainty at the starting point (i.e. not aporia). The following WofE experiment illustrates the effect of detail. We then show how the level of detail is incorporated in the modified fuzzy logic approach.

A Multi-Scale Experiment in WofE

A WofE experiment was created using a set of random mineral occurrences, and geological maps at three different scales (Figure 6, Table 1). Map A (Figure 6) represents a 1:1,000,000 compilation with three primary geological units at the Group level (Gp), Map B represents 1:250,000 geology sub-dividing units at the Formation level (Fm), and Map C represents 1:100,000 geology sub-divided to the Member level (Unit). WofE provides two types of weights (W+ and W-) (Bohnam-Carter, 1994), and associated variances. For the purpose of this experiment, the W+ values will suffice. W+ is the strength of positive association between occurrences and geological units. The full range of W+ values for each map is presented, which provides an indication of the range or variance of W+ values for each of the three maps. The W+ values are centered upon 0.0, which on this logit scale represents neutral evidence that is neither positive nor negative (i.e. lacking predictive power).
For Map A, the weights indicate a strong positive association for Gp 3, a strong negative for Gp 2, and a weaker negative association for Gp 1. The results for Maps B and C illustrate the effect of increasing map scale on differentiating positive and negative associations and their W+ and range values. In Map B for example, the subdivided values for Gp 1 differentiate the moderate negative influence of Fm 11 from the weak positive influence of Fm 12 that produce the overall weak negative association of Gp 1. Further detail in Map C differentiates moderate and weak positive associations for Units 121 and 122 from moderate and weak negatives for Units 111, 112, and 123. Similar analyses can be made for Gp 2 and 3.

This experiment reveals the effect of increasing map scale on WofE results (Figure 6). First is the general increase in the strength of the weights as indicated by increasing individual W+ values, which is also reflected in the total range values progressively through maps A to C. Second, sub-units differ spatially and in the increasing values of their relative weights. The strongest positive associations are in Fm 32 (1/3 of Gp 3) and subsequently in units 321 and 323. Although a weak negative association was revealed for Gp 1 in Map A, its Unit 121 has a moderately strong positive correlation (Map C).

To summarize, in the logit scale of W+ values, a zero (0.0) value represents the prior probability (a priori). Empirical evidence reveals the ability to better differentiate between positive and negative associations relative to the prior. A similar effect would need to be considered in KD approach. The following section discusses how the fuzzy logic method can be used similarly to map mineral potential at various scales.
A Multi-Scale Approach Using Fuzzy Logic

A brief introduction to the fuzzy logic method is provided as background to its multi-scale application. Fuzzy theory is traced back to Zedah (1965) as a means of accommodating uncertainty in computation and information representation, notably with respect to decision support systems (DSS). Elements of DSS contain embedded knowledge in programming scripts that incorporate many types of ‘If, then, else’ statements. For example, the general structure of such a script is expressed as:

\[
\text{If \{condition\} (is 'Yes')} \\
\text{Then \{do something\}} \\
\text{Else (if condition is 'No/False')} \\
\text{\{do something else\}} \\
\text{End.}
\]

In many decision support environments, it is not always easy to determine with certainty the conditions of the statement. For example, consider the data for a group of trees presented in Table 2. Suppose a script Is needed to perform a classification of each tree according to whether or not it was ‘tall’, based on reading the height values in the table. Tallness, can be a subjective judgement and difficult to program depending on how it is defined in the DSS. This can be resolved by assigning additional values for each tree record (e.g. Table 2). In one column of Table 2, a binary value, \(\mu_b(x)\), is used to indicate whether or not each tree is tall. Although it is generally more obvious for the tallest and shortest trees in the list, trees with moderate height values are more problematic to resolve. In this binary representation, a 23 ft. tree is classified the same as a 10 ft tree, a clearly unsatisfactory representation for this subject matter.

In contrast to the classical, or binary form of representation, where objects must be either ‘0’ or ‘1’, fuzzy theory allows a gradation of values in the [0,1] interval, to indicate for example, the
degree to which the height of each tree corresponds to the notion of tallness. The [0,1] interval represents a range from non-membership (0) to full-membership (1). As illustrated in Table 2, \( \mu_0(x) \) provides a more flexible means of representing tallness.

Furthermore, data might be missing for some trees, (e.g. height for Fir). In the \( \mu_0(x) \) set of values, the Fir is assigned 0.00 (it could be another value such as a weighted mean of the set). This approach to assigning fuzzy membership values was introduced for MPM by An. et al. (1991) and incorporated by Bonham-Carter (1994), Eddy (1996) and Wright (1996) among others. Generally, a value of ‘0’ (non-membership) is equated with low favourability, or low compliance with the proposition, whereas a ‘1’ (full membership) is equated with high favourability. If a linear model is applied, a value near 0.5 would be considered moderately favourable (Figure 7). This approach is valid for applications where the data are relatively similar in scale and quality. However, it is constraining for applications that require the analysis and presentation of mineral potential at multiple scales and contexts.

The modified fuzzy logic approach (also Figure 7) considers the end-members of the [0,1] interval as pure certainty (non-aporia). The mid-point, 0.5, represents aporia - high uncertainty with no answer. The ‘0’ and ‘1’ end-members correspond to either a ‘No’ or a ‘Yes’, (False or True) with respect to the proposition “There is potential for commodity Z at location x,y”. In other words, values approaching ‘0’ do not just indicate low favourability, they further indicate the certainty of ‘No potential’, and conversely, values approaching ‘1’ strongly indicate ‘Yes, there is high potential’. The modified fuzzy logic evaluation scale thus rates favourability as a continuum of values, as well as representing uncertainty. In this scheme, low favourability falls in the 0.5 to 0.65 range, because favourability in the positive sense is in the 0.5-1 range. The values in the 0.0-0.5 range, do not represent low favourability per se. Instead, they represent non-favourability, or no
potential with varying degrees of confidence. This approach is represented in Table 2, where the fuzzy membership values assigned to each tree using the Base 0.5 approach ($\mu_{0.5}(x)$) are different than those for the Base 0 ($\mu_0(x)$), with respect to the proposition tallness.

The benefits of this approach for multi-scale application are two-fold. First, setting a 0.5 value as maximum uncertainty (*aporia*) provides an anchor point from which geologists can assign fuzzy membership values to spatial evidence, in both positive and negative directions. Geologists can determine an appropriate range of values that are permissible with each source map used, following the general guideline that with increasing spatial evidence (associated with factors relating to scale and information quality), and the range of fuzzy membership values can expand accordingly. *Apora* provides a common starting point for each piece of evidence, and makes it easier to assign values with greater consistency.

Second, missing data can be represented with the 0.5 value, as opposed to a 0.0 value, or a relative weighted mean value. In the Base 0 approach, attributes that are judged as low potential can be conflated with instances of missing data. In this modified method they are more clearly differentiated (Table 2). Approaches that use a relative weighted mean value are problematic for multi-scale data sets because these values will vary from one scale (or source map) to another. Hence, the 0.5 value can be used consistently with maps of multiple scale (and information detail), and as a starting point for both missing data, and for data that remains completely uncertain.

This modified approach to fuzzy logic is ideally suited to mineral potential mapping (MPM) in consideration of the various types, levels of resolution and scales of available data. The inverted relationship between data and scale (Figure 4) is combined with the empirical results of the WofE experiment (Figure 6) to guide the assignment of fuzzy membership ranges at different scales (Figure 8). As in the WofE (DD) approach, the horizontal scale represents a relative favourability
legend for the results. Values assigned to features derived from regional geoscience data, such as compilation maps, can be narrowly confined within the middle range of the [0,1] interval. If higher resolution data are used, values can be assigned to broader range in the [0,1] interval to indicate a better match between the proposition (knowledge) and the evidence (data). It is worth noting that spatial scale is only one factor that affects the detail of information on geological maps. Geologists will need to consider other factors (such as lithological diversity, cartographic detail, etc.) while establishing appropriate scale ranges for each source map used.

To help illustrate the scale effect, Table 3 provides fuzzy membership values that correspond to the maps used in the above WofE experiment. The effects of increasing scale on empirical results are incorporated. The values for Map A range from 0.37 to 0.63, Map B: 0.26 to 0.68, and Map C: 0.14 to 0.83. Some values in Map C remain very close to the 0.5 zone of *aporia*, reflecting the relative uncertainty of the values for these units in Figure 6. This illustrates that increasing resolution, while improving differentiation and certainty in many cases, may not do so for some units, even at local scales.

The assignment of fuzzy membership values using the Base 0.5 approach represents only the first step in the fuzzy logic method. The next steps involve: (i) more detailed analysis of multiple criteria; (ii) analysis of evidence derived from geological data represented at multiple scales, and (iii) calculation of a map result based on a combination of all evidence available through the use of an inference model. These elements of the method are presented in more detail below. To summarize, the Base 0.5 approach presented here allows empirical (DD) and theoretical (KD) approaches to be more easily aligned, and to be applied at multiple scales. This is similar to others approaches that treat the mid-point on the [0,1] interval as a hinge-line (Burrough and McDonnell,
1998). The following section describes in more detail how this method is applied in mapping MVT Pb-Zn potential in the Canadian High Arctic.

APPLICATION TO MULTI-SCALE MPM

The modified Fuzzy Logic method was applied in mapping the potential for MVT Type Pb-Zn in the Canadian High Arctic using four different geological maps compiled at four scales. The principles of the three-step process are first illustrated for part of the larger study area, then employed at four scales.

Step 1. Setting the Context – Model Criteria

A small sub-set of data were extracted from a digital geological map from Bathurst Island, Nunavut, in the Canadian High Arctic (Harrison and de Freitas, 1998). This subset is presented in Figure 9, with corresponding map results, to illustrate one specific representation of mineral potential for MVT-Type Pb-Zn, using a criteria statement simplified from Sangster (1995) as follows: ‘The mineral potential for MVT Type Pb-Zn will occur in locations occupied by platform carbonate rocks, and especially where these rock types exist in close proximity to unconformities or faults’.

Step 2. Building Content – Providing the Evidence

Four sub-themes were extracted from the source geological map: 1) rock units, 2) proximity to unconformities, 3) proximity to faults associated with the Cornwallis Fold Belt (CFB), and 4) proximity to faults associated with the Parry Islands Fold Belt (PIF). The weighting for each evidence theme is represented by the columns of fuzzy membership values assigned to the class categories (Figure 9). Each geological unit, and each proximity class interval is assigned a membership value, following the Base 0.5 approach outlined above. Geological units that are
determined to be not carbonate, or not platform carbonate related, are assigned values close to 0.0, whereas geological units that are carbonates, or especially identified as platform carbonates, are assigned weights closer to the 1.0 end of the scale. Units for which such a clear distinction cannot be made are assigned values near the 0.5 value. For example, the value of 0.85 assigned to the Irene Bay and Thumb Mountain units indicates that these units are highly likely to contain platform carbonates suitable for hosting MVT Pb-Zn deposits. Conversely, the value assigned to the Bird Fiord Fm. (0.25) indicates this unit is not likely to include favourable strata. No pure values are assigned to any unit because the modeller judged that uncertainties exist between the criteria statement and the map unit description. For example, some units might be described as simply carbonates, some as platform succession rocks, some as carbonates within shales, or shales associated with platform carbonates. These words and their connotations do not exactly match the words “platform carbonate rocks” in the criteria statement. At most, the modeller can infer an association between the criteria and the geological descriptions provided in maps and reports, but such units are generally assigned moderate values in the 0.60-0.70 range to indicate the degree of association.

The spatial relationships between the geological units and linear features, such as faults and contacts, are established using three proximity maps. The values assigned to the proximity intervals increase with closeness to the respective feature, and also follow the Base 0.5 approach. Values higher than 0.50 represent increasing closeness, whereas values less than 0.50 represent increasing ‘not closeness’. The distance interval used to represent aporia generally depends on the opinion of the geologist but might be derived empirically. The actual values assigned among the three maps indicate the relative importance of each type of linear feature based on the model criteria. In this example the values assigned to the PIF faults are significantly less than those assigned to the CFB
faults which were differentiated by orientation and location. CFB faults occupy the eastern portion of the area and are predominantly N-S oriented, whereas PIF faults occupy the western portion of the area and are mostly E-W oriented. The intersection between the two belts is structurally complex (north-south zone at the centre of maps in Figure 9). Some CFB faults may be syngenetic to uplift of the platform carbonate units, an important local factor for Pb-Zn mineralization (Anglin and Harrison, 1999). The PIF faults are associated with a later event, and are considered to be less important for MVT Pb-Zn, but not exclusive.

**Step 3. Modelling Mineral Potential**

The evidence themes are now combined so that they accurately reflect the criteria statement. In Fuzzy Logic and expert systems, this is termed inference modelling. Figure 9 illustrates a three part inference net for the calculation of Map C from Maps A and B. Fuzzy Combination (inference) rules (Table 4) combine themes in different ways to reflect different contexts. For example, a given deposit model may state that certain critical factors must be combined at one location. Here the fuzzy AND operator would apply the minimum value of the set at each location. Other factors may be present unconditionally, in which case the fuzzy OR operator would apply the maximum value at each location. Where the co-presence of two or more favourable factors is desired, their combination would be modelled using the fuzzy SUM operator, to produce values higher than any individual value in the set. Conversely, net values maybe decreased using the fuzzy PRODUCT operator that combines negative evidence. If conflicting evidence is recognized, the fuzzy GAMMA rule is used, where the value of $\gamma [0,1]$, operates as a sliding scale between the increasive effects of the fuzzy SUM and the decreasive effects of the fuzzy PRODUCT.

Each sub-theme that is used as an evidence layer is considered a factor in the net calculation. In this example, the first calculation combines favourabilities according to proximity to linear
features (Map B), as set out in the criteria statement. Map B represents the ‘best of’ (Fuzzy OR) combination of the three linear feature maps. A grey-scale legend indicates the net value calculated at this node. Map C displays increased values (using the Fuzzy SUM operator) assigned to the geological units where favourable rocks are proximal to unconformities or faults. The range of values in the legend has increased from 0.85 in Map A and 0.80 in Map B to 0.95+ in Map C, which represents net favourability with respect to the selected criteria.

This example is only part of a larger inference modelling process. Usually, the criteria used are taken from deposit model literature, and/or provided by experts. The inference modelling process provides critical factors to the net calculation of relative mineral potential. It also produces an audit trail to which the geologists can return for discussion, experimentation and refinement. The following section discusses how these three steps are applied using evidence derived from four different geological maps.

**Application for Mapping MVT Pb-Zn in the Canadian High Arctic**

**Step 1. Setting the Context – Model Criteria**

Parks Canada held a multi-disciplinary workshop in 1992 to consider representation for Natural Region 38 of the Canada Parks System Plan (CHPC, 1997) (Figure 10). The fuzzy logic project reported here was initiated in 1993 to provide an early analysis of the Parry Islands Fold Belt and thus influence selection of a park study area with relatively low mineral potential. Although the primary area of interest was on northern Bathurst Island, the planners were also considering other sites throughout Region 38, including northeastern Melville Island (west of Bathurst Island in Figure 10). The park study area was, nevertheless, finally centred on the zone of highest potential that had been outlined by the first author in preliminary maps (refined in Eddy, 1996). The MERA process for this region was then initiated in 1994. The subsequent 1:100,000 scale MERA project (Anglin
and Harrison, 1999) collected substantial geoscience data, discovered Pb-Zn occurrences and confirmed Eddy’s assessment. Nevertheless the sequence of events unfolded much as exemplified by the experiment presented in Figure 6, with the second assessment providing more detail and higher confidence in locally reduced or increased potential for many commodities including hydrocarbons. The consistency of the sequential assessments contributed to a recent intergovernmental agreement that has now excluded the highest mineral and energy potential from the park proposal, subject to public consultation. As discussed above, until a final boundary is legislated, the boundary of the study area may still change in response to new information or other considerations, thus changing the context for MPM.

Among the many deposit types and commodities were under consideration, the potential for MVT Pb-Zn was critical because of the existing Polaris Mine on Little Cornwallis Island, immediately east of Bathurst Island (Figure 10). With an existing workforce and infrastructure in place in the region, the potential for a similar deposit on Bathurst Island was considered a strong possibility, and played an important consideration in negotiating the final boundary. Whereas potentials for many commodities were presented in the final MERA report (Anglin and Harrison, 1999), here we focus on MVT Pb-Zn potential. The context includes both global and local criteria used to define MVT Pb-Zn potential for the Cornwallis and Parry Islands fold belts. The global criteria were derived from Sangster (1995), and the local criteria from Anglin and Harrison (1999).

Global MVT Pb-Zn Criteria (from Sangster, 1995)

♦ Predominantly galena-sphalerite in brecciated carbonates
♦ Host rocks are platform carbonates ranging in age from Neoproterozoic to lower Carboniferous, most in Canada being lower-mid Paleozoic in age.
♦ Most deposits occur below unconformities/disconformities
Host platformal carbonates were deposited contemporaneously with distal orogeny.

Deposits are discordant in detail, but form stratabound clusters of 1-10 Mt with 5-10 % Pb-Zn.

Ore filled spaces in dolomite, brecciated through dissolution collapse.

Ore comprises primarily Pb, Zn and Fe sulphides; with associated Cd, Ge, Ba, and F, and local minor Cu, Ni, Co and Ag.

Associated minerals include pyrite, marcasite, sparry dolomite.

Zn/(Zn+Pb) ratios are commonly > 0.5, but range between 0.1 to 1.0.

Compositional zoning is common around many deposits.

Local Criteria (direct observations, Anglin and Harrison, 1999)

Known deposits and occurrences are within and associated with the Thumb Mountain and Irene Bay Fms, and Blue Fiord Beds.

Occurrences are associated with N-S oriented faults in the CFB domain.

Most of the local characteristics are consistent with the global, with the added association of N-S faults. Although faults are not considered to be a major global characteristic (Sangster, 1995), they are considered to be significant in the Bathurst Island locale, as syngenetic with the Boothia Uplift. They may have provided channels for fluid migration through the platformal carbonates. E-W faults of the Parry Island Fold Belt domain may have provided similar, though less significant, fluid pathways. The above criteria were used to construct the following criteria statement (knowledge proposition), to guide inference modelling of MVT Pb-Zn potential using Fuzzy Logic:

"MVT Pb-Zn potential is mainly associated with the Thumb Mtn/Irene Bay Fms, and the Blue Fiord beds, for which significant MVT-type deposits or occurrences are known. Other Paleozoic strata that contain dolostones or platform carbonates have lower, but still favourable potential. For these
favourable bedrock units, mineral potential tends to increase near unconformities that are overlain by less permeable shaly units. Known occurrences are spatially related to N-S faults that are mainly within the CFB structural domain. The influence of E-W faults in the PIF domain is weakly favourable and uncertain.”

Step 2. Building Content – Providing the Evidence

Four different geological maps were used at different levels of mapping and assessment (Figures 11 and 12). These include (in order of increasing scale):

2. Map B - Bedrock Geology of the Parry Islands Fold Belt (Eddy, 1996 – 1:1M synthesis of Map C with a regional 1:1M compilation by Okulitch (pers. comm., 1993),
3. Map C - Geology of Bathurst Island Group (Eddy, 1996 - 1:250K synthesis of Kerr, 1974 and Okulitch, ibid), and

Map B covers Bathurst, Byam Martin and Melville Islands. The geometry and location of geological units on Bathurst Island, as represented by Kerr (1974) at 1:500,000, are incorporated in the 1:1,000,000 compilation, using a revised stratigraphic model to reconcile the two scales and currencies of data. Map B retains the geometric resolution of Kerr for the Bathurst Island portion, but uses Okulitch’s generalized legend (pers. comm. 1993) for the Parry Islands Fold Belt.

Each map was used independently to extract evidence for MVT-Type Pb-Zn criteria. The ability to extract evidence from each geological map depended upon spatial resolution of maps, legend descriptions and accompanying reports. Table 5 summarizes the key model criteria (based on the above knowledge proposition) and their correspondence to the evidence from each map. Although Map A does not provide enough detail to map MVT Pb-Zn potential with confidence, it does provide information on the geological age and rock types which permits some differentiation between geological units that are either carbonate, or potentially contain carbonate of appropriate
ages. Map B provides significantly more information that addresses more criteria, and Maps C and D provide enough information to consider all of the major criteria.

The modelling process for each map depended on the criteria that could be considered. For Maps B through D, multiple criteria were considered, including proximity to unconformities and faults, as well as stratigraphic relationships, but the strongest influence on the model results is in the assignment of fuzzy membership values to geological units. Figure 11 shows the fuzzy membership values for each geological unit of each map that intersects the area of interest on Bathurst Island. For comparison, geological unit boundaries are displayed for a common area in central Bathurst Island to illustrate the changes in resolution with scale. Values were assigned to each map unit based primarily on the legend description for each map. In some instances, cross comparisons and visual correlations among units were made to enhance the interpretation. However, each map is best treated separately because it cannot be assumed that information from one portion of one map can be augmented with more detailed information from another map at the same locality.

The assignment of values to geological units is used as a means to represent the value of locations that are transected by those map units. The uncertainties considered in the assignment process arise from both the limits of the legend description (whether carbonates are explicitly listed, or need to be inferred through a tectono-stratigraphic association, e.g. miogeoclinal rocks), and the limits of representation of the geological map polygons at different scales. A geological unit that is explicitly defined as a platform carbonate might receive a moderate value (e.g. 0.72) if the resolution of the map is relatively coarse, and therefore mineral potential is considered less certain than for the same unit on larger scale map (e.g. 0.85).

In compiled geological maps, legend descriptions often contain a synthesis of lithological descriptions from two or more sources. In some cases the synthesis is straightforward; in others it is
problematic without conducting additional field work. Such uncertainties in legend descriptions are just one example of the elements that must be considered in assigning individual fuzzy membership values at different map scales, and different levels of stratigraphic resolution. Another element of uncertainty is the subjectivity of the geologist(s) doing the modelling.

The values assigned to Map A range from 0.35 to 0.65. Values lower than 0.50 were applied to all of the units corresponding to the Sverdrup Basin succession, as these units are interpreted to be deficient in platform carbonates. The only other value lower than 0.50 is assigned to Upper Devonian non-marine strata in the Franklinian Succession (inferred from age, rock type and geographical location). Comparison with the other maps reveals that this unit likely corresponds with the Hecla Bay Fm., which is an extensive, thick sequence of clastic sedimentary rocks that exhibit no evidence of the presence of carbonates. Values at, or near, 0.50 were assigned to units that are described as ‘undivided sedimentary rocks’ of Ordovician to Devonian age, with a slight increase (0.52, 0.53) in value for units that are lower to mid-Devonian age. These values exemplify aporia that results from the relatively equal possibilities that these units may be carbonate or ‘not carbonate’. The only two units that were assigned relatively higher positive values are the undivided Ordovician-Silurian sedimentary (0.60) and offshelf miogeoclinal (0.65) units that are here inferred to be equivalent to the Cape Phillips and Thumb Mtn./Irene Bay Fms. Respectively, that have prior known potential for MVT Pb-Zn.

The values assigned in this model iteration to Maps B and C are identical and range from 0.27 to 0.75 (a greater range than for Map A). This increase in range of values reflects greater certainty in the ability to differentiate between units that contain carbonates and those that do not. More detail is also provided in their legend descriptions and associated reports also provide more detail than those of Map A. For the Sverdrup succession, the assigned values range from 0.27 to
0.35, whereas the values for the Franklinian succession range from 0.27 to 0.75. Although most units have been correlated from Maps B and C to A, two additional units are not represented on Map A (Awingak and Ringnes formations, highlighted in grey in Figure 11). As with the assignment of values to the units in Map A, the lower (< 0.50) values represent locations that do ‘not likely’ contain carbonates, and units with higher (> 0.50) values represent locations that likely, or very likely contain carbonates. Some units in this legend were mentioned specifically in the model criteria, including the Blue Fiord, Cape Phillips and Thumb Mtn./Irene Bay formations. These units received significantly higher values because they are known to contain platform carbonates, and are capped by less permeable strata and are close to unconformities.

For Map D, fuzzy membership values are assigned to 58 geological units. Many units in this legend are not represented in Maps A to C. This is partly because some units in the previous maps fall outside of the area covered by Map D (exclusively Bathurst Island), but also, new units were discovered as a result of more detailed mapping during 1995 to 1998 (1:125,000, Harrison and DeFreitas, 1998). The additional units are highlighted in grey (Figure 11). Where units contain no platform carbonates, and are not an appropriate age, a value of 0.05 was assigned. Slightly larger values (i.e. 0.15 to 0.30) were assigned to units that contain some carbonates, but are not considered significant for MVT potential. The slight increase in assignment value indicates a lesser degree of certainty, in that such units are 'not likely' to host potential.

Members of the Bathurst Island and Stuart Bay beds were assigned values that range from 0.05 to 0.57. These units contain interbedded deep water siltstones and fine-grained sandstone, with some limstone, chert, and organic shale. Members that contain carbonate olistostromes or limestones were assigned values of 0.50 or 0.60 to indicate the higher degree of uncertainty as to whether these particular carbonate units could host MVT Pb-Zn-type mineralization. In some
locations, the geological map does not differentiate among the members, and these areas are given a value of 0.55 to reflect this uncertainty. The Disappointment Bay and Unnamed Formations were both assigned a value of 0.68 to indicate their favourable lithology. Although no Pb-Zn occurrences are known in these units, their lithologic and stratigraphic qualities fit reasonably well with global criteria.

The highest values were assigned to the Blue Fiord beds (0.75) and Thumb Mountain and Irene Bay Fms (0.85). These values reflect their distinctly favourable lithology and stratigraphic position, as well as the knowledge of MVT-type Pb-Zn occurrences hosted by them. In the case of the Blue Fiord beds where sub-members are differentiated on the geological map, different values were assigned to reflect the individual qualities of each member. The lower member (DBL1) received the highest value because it contains a known Pb-Zn occurrence. Relatively higher values were also assigned to the Cape Phillips Fm. (0.65) and Bay Fiord Fm (0.63). Although these units are not considered directly favourable, their bounding stratigraphic relationship with the Thumb Mtn. and Irene Bay formations provides the possibility, due to the complex deformation in some areas along the CFB, that the latter might be nearby, either at surface or in the near sub-surface.

Step 3.3. Model and Presentation

The lithological factor comprises only a portion of the evidence used in modelling the results. As outlined in Table 5, three other evidence themes were used in combination with lithological favourability, depending on the scale of the map, and the ability to derive the different evidence from each map. Eddy (1996) provided several inference nets that represent various iterations for experimenting with different combinations of evidence themes, and combination rules. An example of one iteration for each of the four maps is presented here (Figure 12).
The same legend is used for all four maps so that results can be compared visually for different map scales. This legend was designed to provide a gradational fuzzy effect, whereby the medium grey tones represent greater uncertainty, or *aporia*, and the more pure shades as decreasing uncertainty in positive (increasing membership, black) and negative (decreasing membership, white) directions. Lighter tones are used for small-scale maps where the certainty of information presented is rarely as strong (or intense) as information presented on larger scale maps. Additionally, this legend is uses a 20 class interval scheme, which segments the [0,1] range of fuzzy membership values at 0.05 intervals. Other class intervals and colour schemes may be used depending on the number of output maps required, their respective scale ranges, and the level of precision used in the assignment and calculation of fuzzy membership values and results (i.e. a 0.001 precision would allow up to 1000 class intervals with as many colours).

Map A shows results that fall within the 0.35-0.65 range. The overall tone of the map is relatively subdued which reflects the higher degree of uncertainty in the results. However, the map succeeds in differentiating broad regional geological domains that are more likely carbonate-bearing versus those that are not likely carbonate bearing. Comparison to the other maps (B-D) reveals internal consistency in the results with increasing scale. The slightly darker grey areas on eastern Bathurst Island correspond with geological units described as Ordovician-Silurian sedimentary and miogeoclinal rocks as described in Figure 11. The effect of increasing the resolution on the Parry Islands is revealed in Map B where a better differentiation is presented with values in the 0.27-0.75 range of values. Map C shows the same results for the Bathurst Island portion, with a scale representation of 1:500,000. Table 5 illustrates how some stratigraphic factors and proximity to faults were influential in the modelling of Map B (Parry Islands compilation). These factors had a more significant effect in modelling the Bathurst Island portion (Map C) because the resolution of
the 1:500,000 scale map produced greater certainty in the mapping of boundaries and linear features than the 1:1,000,000 regional compilation map (Eddy, 1996). The increase in tone (and value range) in Map C relative to Map B reflects the influence of these additional factors.

Although Map C succeeds in differentiating MVT Pb-Zn potential from non-potential areas on Bathurst Island, Map D provides a significantly more refined representation using the 1:125,000 map prepared by Harrison and DeFreitas (1998). The reasons for the significant difference in representation are two-fold. First, there is a greater range or intensity of certainty in the results of Map D over Map C. The values represented in Map D range from as low as 0.05 to as high as 0.95. The increase in the net value is due to the use of the fuzzy SUM and GAMMA operators where high lithology values (e.g. 0.85) are combined with close proximity to favoured faults, unconformities, and/or shale units, which were mapped with considerably greater detail and accuracy. The second reason is the increased resolution of the map units, many of which were differentiated on a sub-unit level, thereby narrowing the spatial extent over which the values are represented, while simultaneously differentiating between relative potential and non-potential sub-units. Some differences are due to the additional geological units mapped at the 1:125,000 resolution. The impact of using the 1:125,000 map over the 1:500,000 map is a significant reduction in the aerial extent over which potential for MVT Pb-Zn is inferred.

**DISCUSSION**

A modified Fuzzy Logic method for generating MPM at multiple scales uses only digital geological maps and deposit model criteria. This specific KD method is developed upon similar principles as the WofE (DD) method, and both methods reveal the degree to which deductive (KD) and inductive (DD) information flow patterns influence each approach. Several guidelines apply to the Fuzzy Logic approach.
The first guide is that evidence themes used in modelling mineral potential must match reasonably well with deposit model criteria. The relative degree of confidence in the results (subjectively-judged) hinges on how well the criteria match the evidence themes used, as well as how the evidence themes are combined to reflect the deposit model as a whole. If the criteria used are more descriptive, there may be a need for considerable iteration and experimentation because the author of the criteria may not explicitly state which criteria are more important than others. If the criteria are derived from a genetic or process-oriented model, the logical constructs of the model can more directly be applied (and tested), which requires less iteration. However, a genetic model may not provide sufficient empirical information to link readily with map data, and descriptive may be mixed with genetic criteria, whether working with formal, informal, global, or local knowledge sources. This issue must be considered in both KD and DD methods. Whereas the chosen criteria influence the strength of the assignment values in the Fuzzy Logic method, as well as how the evidence is combined, the same guideline must be used in considering which mineral occurrences should be included or excluded in driving a DD model. The qualification of individual occurrences, in itself, is a subjective (deductive) element of the modelling process that may also require considerable iteration and input from experts.

The benefit of both KD and DD approaches is that iterative experimentation can proceed effectively, and most importantly, objectively. Exposing the reasoning processes in the construction of MPMs positions the methodological framework on an objective footing. However, all MPM exercises remain to some degree subjective and open to change. Absolute potential can never be determined because any iterative expression of mineral potential is nested within the context of the study, the data used, and the relative judgements applied by the modeller(s). Through iteration and experimentation, in testing model criteria and assumptions, as well as testing various representations
of evidence used in a model, reproducibility should emerge at some point. The overall degree to
which results may or may not be reproducible will ultimately determine the strength of the model for
a specific application.

In this multi-scale application, reproducibility is considered in both uni-scale (reproducibility
of each individual theme), as well as in the multi-scale context (internal consistency and similarity of
results across map scales). Various expressions of potential are possible at each scale, however, by
subjecting the reasoning process to iteration and refinement, and by applying the same general
principles to data across scales, it is demonstrated how reproducibility does emerge across scales,
even with varying degrees of certainty (which is objectively made explicit). The result is that
mineral potential maps can be presented at a variety of scales for a variety of contexts for different
purposes as suggested in Table 6.

A remaining limitation of the fuzzy logic method for MPM, for both the Base ‘0’ and Base
‘0.5’ approaches, is the lack of a secondary quantitative measure of uncertainty associated with
individual fuzzy membership values. Although the term uncertainty is used in a different context in
this modified approach, numerically, a primary uncertainty measure is indicated by the difference
between a fuzzy membership value and *aporia*. A means for developing a secondary uncertainty
measure associated with individual fuzzy membership values has yet to be explored. The handling
of secondary uncertainty would need to be consistent with DD approaches. In DD methods, the
variance of weights, and variance due to missing data provide a basis for a measure of uncertainty.
If this approach could somehow be adapted for the fuzzy logic method, multiple fuzzy membership
values, for each spatial evidence, would be required. An individual modeller may want to
experiment with assigning multiple values, perhaps at intermittent periods under a quasi-blind
assignment approach, as a means of capturing different ranges of judgement of criteria.
Alternatively, values may be solicited from more than one geologist in situations where multiple perspectives are required. In either situation, variances on the range of multiple values (for the same evidence) may serve as a starting point for developing a secondary uncertainty measure.

The development of a secondary uncertainty measure for fuzzy logic might reveal new understanding about the confidence of geological knowledge in relation to map scale (and data resolution, complexity and other factors). Experimental WofE results for multi-scale mapping reveals an increase in variance of individual weights, with increasing scale (represented in Figure 6 and Table 1 as the increase in the range of W+ values). This suggests that although a higher contrast in relative weights is achieved with increasing resolution, there is a corresponding increase in the relative uncertainty of those results. It would be worth experimenting with the assignment of multiple fuzzy membership values, at multiple scales, using two or more geologists, to examine if a similar affect is produced using fuzzy logic.

If the relation holds for both methods (and this is not assumed), it appears there may be inverted trade-off between the resolution of the data used, and confidence in the response maps with increasing scale. In both the WofE experiment, and the fuzzy logic application, the trade-off appears as an increase in the localized delineation of higher potential areas, at the expense of mathematical certainty. It remains to be seen if there is an optimal resolution at which a specific deposit or commodity type might best be modelled to maximize the contrast in the relative values across a study area, while maintaining minimal uncertainty in the results.

The modified Fuzzy Logic method presented here succeeds in addressing some of the multi-scale requirements, as demonstrated using the application for MVT Pb-Zn modelling for Bathurst Island. This analysis demonstrates the noticeable benefit of 1:100,000 to 1:250,000 geological maps to provide the level of detail required by many mineral deposit model criteria. The ultimate aim of
most MPM projects is to assist in land-use planning or exploration programs, which optimally operate within this scale range in the frontier regions of Canada. However, significant portions of the frontier regions of Canada have yet to be mapped at these scales, and the results presented here reinforces the value and need for mapping programs at this level.

Acknowledgements

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Figure and Table Captions:

Figure 1. Subject relations for geological information in mineral potential mapping (MPM).

Figure 2. Some of the main elements relating data and knowledge in producing mineral potential maps (MPMs).

Figure 3. Density contoured mineral occurrences for Canada from the CANMINDEX database (Picklyk et al. 1978; R. Laramée, pers. comm., 2000). Mineral potential estimation approaches are suggested relative to density. Note: legend shows occurrence density as the number of occurrences per km$^2$ (e.g. 1e-3 = .001 occurrences/km$^2$).

Figure 4. Relationships between resource assessment requirements, methodology and map scale.

Figure 5. Relationships between knowledge driven and data-driven methods of MPM, exemplified by fuzzy logic and WofE respectively. The horizontal line represents the MPM plane. See text for discussion.

Figure 6. A multi-scalar experiment in WofE using random mineral occurrences sampled by geological maps at three scales. Data generated for the graphs is listed in Table 1.

Figure 7. Classification of membership for fuzzy logic applications, using Base ‘0’ (dashed line) vs Base ‘0.5’ (heavy solid line, modified fuzzy logic).

Figure 8. Guideline for the assignment of fuzzy membership ranges at various scales.

Figure 9. Example of a fuzzy inference modelling process using a sub-area of Bathurst Island.

Figure 10. Location map for the Natural Region 38, Canada Parks Systems Plan (CPSP), and the different boundaries of areas where subsequent MERA work was focused.

Figure 11. Fuzzy membership values assigned to geological units for Maps A – D (see Figure 12 for results of one iteration). *Note: Eddy (1995) compilation derived from Okulitch (pers. comm.) and Kerr (1974).

Figure 12. Mineral potential map results, for MVT Pb-Zn potential, for each of Maps A-D representing scales of 1:5,000,000, 1:1,000,000, 1:500,000, and 1:125,000 respectively.

Table Captions:

Table 1. Numerical results for a multi-scale experiment in WofE using random mineral occurrences sampled by geological maps at three scales. See Figure 6 and discussion in text.

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Table 3. An example of fuzzy membership values assigned to W+ values used in the WofE experiment (Figure 6, Table 1).

Table 4. Five fuzzy combination rules commonly used in MPM. After An, et. al. (1991), and Bonham-Carter (1994).

Table 5. Illustration of the relative strength of evidence derived from each geological map (A-D) used in the application for mapping MVT Pb-Zn potential on Bathurst Island.

Table 6. Some suggestions for use and appropriate contexts for map results A-D and corresponding scale.
Geological Maps:
- Lithology
- Rock Types
- Age
- Chronology
- Stratigraphy
- Structures
- Boundaries

Known Mineral Occurrences

Correlate with geological units and features. Provide a partial basis for ranking geological units in terms of relative mineral potential.

Known Mineral Deposits

Are often indicators of some mineral deposit types and models.

Mineral Potential

Are evidence of mineral potential

Mineral Deposit Types and Models

Are an actualization of Mineral Potential

Signature Data:
- Geochemistry
- Geophysics
- Geospectral (Remote Sensing)

Mineral Potential

May be used as partial evidence of mineral potential, and also as substantive evidence in combination with favourable geological settings.

Mineral Deposit Types and Models

Provide Criteria for 'Potential' - which may be extracted from geological maps and/or signature data.

Economic / Technological Factors

Critical factors that determine 'deposit' or 'non-deposit' status, but not of immediate concern in mapping mineral 'potential'.

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Fig. 2. Some of the main elements relating data and knowledge in producing mineral potential maps (MPMs).
Data-Driven Knowledge-Driven?

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<table>
<thead>
<tr>
<th>Primary Data</th>
<th>Knowledge ('tallness')</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree</td>
<td>Height (x)</td>
</tr>
<tr>
<td>Maple</td>
<td>23 ft.</td>
</tr>
<tr>
<td>Poplar</td>
<td>~10 ft.</td>
</tr>
<tr>
<td>Pine</td>
<td>4'6-1/2&quot;</td>
</tr>
<tr>
<td>Shrub</td>
<td>2 ft</td>
</tr>
<tr>
<td>Fir</td>
<td>{missing}</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Rule</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>AND</td>
<td>$\mu_c = \text{Min}(\mu_i)$</td>
</tr>
<tr>
<td>OR</td>
<td>$\mu_c = \text{Max}(\mu_i)$</td>
</tr>
<tr>
<td>PRODUCT</td>
<td>$\mu_c = \prod(\mu_i)$</td>
</tr>
<tr>
<td>SUM</td>
<td>$\mu_c = 1 - \prod(1 - \mu_i)$</td>
</tr>
<tr>
<td>GAMMA</td>
<td>$\mu_c = 1 - \prod(1 - \mu_i)^\gamma \ast \prod(\mu_i)^{1-\gamma}$</td>
</tr>
<tr>
<td>Model Criteria</td>
<td>Map Relation</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-------------------------------------</td>
</tr>
<tr>
<td>1. Carbonate Rocks</td>
<td>Attribute</td>
</tr>
<tr>
<td>2. ‘Platform’ Carbonate rocks</td>
<td>Extended Attribute</td>
</tr>
<tr>
<td>3. Overlain by Shale</td>
<td>Spatial/Temporal Adjacency</td>
</tr>
<tr>
<td>4. Close to Unconformities</td>
<td>Proximity</td>
</tr>
<tr>
<td>5. Faults/fractures</td>
<td>Proximity</td>
</tr>
</tbody>
</table>

Table 5. Illustration of the relative strength of evidence derived from each geological map (A-D) used in the application for mapping MVT Pb-Zn potential on Bathurst Island.
<table>
<thead>
<tr>
<th>Map Result</th>
<th>Scale</th>
<th>Suggested Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Map A</td>
<td>1:5,000,000</td>
<td>- Backdrop to highlight Pb-Zn districts and occurrences,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Mapping metallogenic domains,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- National / regional level representation of relative favourability</td>
</tr>
<tr>
<td>Map B</td>
<td>1:1,000,000</td>
<td>- First phase regional assessment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Identifying target areas for more detailed investigation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Regional land-use planning (early stage)</td>
</tr>
<tr>
<td>Map C</td>
<td>1:500,000</td>
<td>- Backdrop for more detailed geological information (e.g.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>geochemistry, geophysics)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Planning tool for reconnaissance exploration or field work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Local land-use planning</td>
</tr>
<tr>
<td>Map D</td>
<td>1:125,000</td>
<td>- Late-stage mineral resource assessment input</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Delineating specific exploration targets</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Detailed land-use planning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Quantitative analysis with other geoscientific data (e.g.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>geochemistry, geophysics)</td>
</tr>
</tbody>
</table>

Table 6. Some suggestions for use and appropriate contexts for map results A-D and corresponding scale.
Enclosure A – Geology and Mineral Occurrences of the Deh Cho territory
Enclosure B – Cumulative Mineral Potential Map of the Deh Cho territory