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Résumé de l'article

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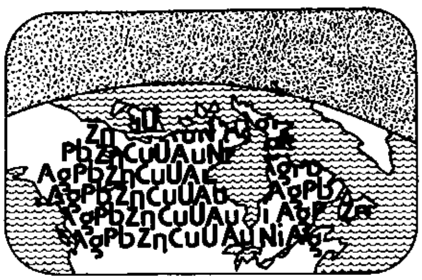
Methods used in Canada during the 24-year span have ranged from statistically dominant and geologically subordinate to the reverse, and the resulting assessments have ranged from quantitative to qualitative. Of the various methods that have been proposed, developed and tested by far the most widely used is that employing conceptual models of separate and distinct types of deposits. The models are erected by mineral deposits geologists on the basis of experience, research and examination of many examples of each deposit-type. Essential and integral parts of each conceptual model are its regional geological parameters, and it is these parameters which are sought in resource evaluation studies using the conceptual model method. This method, as presently used in Canada, usually results in an arbitrary rating of selected areas in terms of their assessed potential to contain undiscovered deposits.

Numerous examples of resource assessment using the conceptual model method recently have been published by both federal and provincial governments. These resource assessments are presented in such a manner that they can be used for government land use decisions as well as for initial phases of mineral exploration.



1. The Canadian Experience in Mineral Resource Assessment

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Summary
The first Canada-wide, non-industry resource assessment was A.H. Lang's uranium metallogenic map, published in 1958. Since then approximately two dozen resource assessments of either the entire country or various parts of it have been produced by the federal and certain provincial geological surveys. Most research in resource assessment methods, however, has been carried out in the Geological Survey of Canada; some has been done within provincial geological surveys, but little or none has emerged from Canadian universities.

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Introduction
Mineral resource assessment in Canada probably had its origins in the first years of geological study of the nation. Sir William Logan recognized the similarity in geology between Carboniferous rocks in Nova Scotia and those of the United Kingdom, and predicted that the former would therefore be favourable for the occurrence of coal. In the intervening years, most geological reports of specific areas, whether published by federal or provincial agencies, contain some comment on the perceived favourability of the area in question to contain undiscoverd mineral deposits.

On a national scale, however, the first mineral resource assessment was probably that of A.H. Lang of the Geological Survey of Canada. In 1958, Lang published a map of Canada outlining those areas of the country he felt were particularly favourable for the occurrence of undiscovered uranium deposits. In the 24 years following Lang's assessment, several methods of resource assessment have been tried by many different Canadian workers and agencies. The present paper will describe briefly selected examples of these early Canadian methods and will conclude with a description of a method in common use by the Geological Survey of Canada. As used in this report, "mineral resource assessment (or evaluation)" refers to the prognostication of undiscovered deposits; it does not refer to the geological or economic evaluation of known deposits.

Historical Review
Selected examples of various Canadian resource assessment studies carried out since Lang's initial 1958 map are listed in Table I and reveal that publications on the subject in Canada here averaged better than one a year for the past two decades. The table also shows that initial attempts to produce quantitative estimates have, in recent years, given way to increased emphasis on qualitative methods of analysis, probably reflecting a somewhat more sober and realistic approach to an extremely complex subject.

Roscoe (1966) reported on the U-Th potential of the country in terms of a map of Canada. Different map patterns outlined areas considered favourable for pegmatite, pitchblende and conglomerate deposits.

In 1970, Barry and Freyman published their assessment of the mineral endowment of the Canadian northwest and expressed their results as contoured values of tons-of-metal per square mile. The authors used a modified Delphi method to collect, on standard printed forms, the opinion of several experts supposedly knowledgeable of the geology and mineral deposits of this part of Canada.

The year 1972 saw two very different approaches to mineral resource assessment evolve within the Geological Survey of Canada. One method, developed by Agterberg and his coworkers, was geostatistical in nature and involved multi-variate analyses of individual cells of a grid superimposed on the area in question, in this case the Abitibi Belt of the Canadian Shield (Agterberg *et al.*, 1972). The product was expressed as contours of metal probability. Concurrently with Agterberg's activities, another group in the Geological Survey was developing a totally geological method of resource assessment based on the conceptual model technique. By this method, the geology of the area being assessed is compared with the diagnostic geological parameters of separate deposit-types (e.g., porphyry copper, skarn tungsten, stratiform lead-zinc, etc.). The diagnostic parameters used are those deduced by G.S.C. mineral deposits geologists as a result of direct observation of many deposits in Canada and throughout the world, and by extensive literature survey. The actual assessment is performed by a small group of individual geologists, usually 1-3 per deposit type. Carried out in this manner, the method is similar to that described as the *simple subjective* method (Singer and Mosier, 1981). Examples of this method will be described in somewhat more detail later but, in 1972, the geologically-based conceptual model method produced an estimate of Canada's undiscovered resources of Cu, Ni, Pb, Zn, Mo, U and Fe. The results of this project, known as "Operation September", constituted an unpublished internal report of the Department of Energy, Mines and Resources. Operation September, *ad hoc* though it was, firmly established the conceptual model methodology used in all subsequent official resource assessment studies performed by the Geological Survey of Canada.

At the same time as resource assessment methods were evolving within the G.S.C., workers in a sister branch, now known as the Mineral Policy Sector, concluded a study in cooperation with the Manitoba Mines Branch, on the undiscovered endowment of a dozen or so commodities in the Canadian Shield of northern Manitoba. A modified Delphi method (Harris *et al.*, 1970) was used and results were expressed as units of metal weight per cell of 400 square miles (Azis *et al.*, 1972).

In the mid-1970s, two new players entered the mineral resource assessment game. Ontario (Robertson, 1975) began publication of a series of mineral potential maps in which geologically-defined areas were assigned a seven-fold rating for a variety of metallic and non-metallic commodities. The method used was geologically-based and very similar to that employed by the G.S.C. During this time also, the British Columbia Department of Mines began publishing a series of maps (McCartney *et al.*, 1974; McCartney and Matheson, 1974) depicting the geological probability of certain commodities to occur in selected, geologically-defined areas.

By 1980, a joint project of the Manitoba Department of Energy and Mines and the Geological Survey of Canada had produced a geological evaluation of the Precambrian massive sulphide potential of northern Manitoba (Gale *et al.*, 1980). Simple subjective probability was used to express potential in terms of a six-fold rating scheme. The project differed, however, from all other resource assessments in that it did not report evaluations of specific commodities (e.g., Cu, Zn, Ni) but, rather, of a deposit-type (i.e., volcanogenic massive sulphides). In one sense, therefore, this study served to re-emphasize that although most if not all assessments are reported in terms of commodities, the actual assessment is carried out in terms of geological deposit-types. Conversion of deposit-type potential into commodity potential involves several assumptions and introduces a number of errors which the Manitoba-G.S.C. study attempted to avoid.

Iron and Uranium: Special Cases

A glance at Table I reveals a long history of uranium and iron resource assessments. For this reason, and because treatment of these commodities has been somewhat different than for other metals, uranium and iron are singled out for special consideration.

Iron. Although most early surveys of Canadian iron resources were largely inventory in nature, they did contain modest prognostications of undiscovered iron deposits (e.g., Tanton, 1952, p. 340; Gross, 1970b; Table I). The iron deposits were first subdivided into distinct deposit-types and, for each, conceptual descriptive and genetic models were established (Gross, 1965; 1970a). By 1967, Canadian reserves and prognosticated resources had been calculated according to the different deposit-types, although the results were not published until several years later (Gross, 1970b; Tables 1 and 4). In spite of these prognostications, however, it is nevertheless true that the main emphasis in iron appraisals is the assessment or evaluation of known deposits rather than on the prognostication of undiscovered deposits. This emphasis on the known deposits renders iron evaluations different than those for base metals, where the emphasis is on the prognostication of undiscovered deposits.

Uranium. Following the pioneering qualitative assessments of uranium by Lang (1958) and Roscoe (1966) and the first quantitative uranium prognostications embodied in the Operation September report of 1972, the Canadian government announced in 1974 the establishment of a Uranium Resource Appraisal Group (URAG). Comprised of geologists, mineral economists and mineral treatment specialists from the Department of Energy, Mines and Resources, URAG was assigned the task of an annual audit of Canada's uranium resources and, by late 1975, had

Table I *Selected examples of Canadian resource assessment studies. The abbreviation "O.F." refers to Geological Survey of Canada Open File reports listed under references.*

Year	Author(s)	Area	Commodities Reported	Method	Form of Results
1958	Lang	Canada	Uranium	Geological	Qualitative
1966	Roscoe	Canada	Uranium Thorium	Geological	Quantitative
1969	Kelly and Sheriff	British Columbia	Various	Geostatistical	Quantitative
1970	Gross	Canada	Iron	Geological	Quantitative
1970	Barry and Freyman	Northern B.C. and Yukon	Various	Subjective probability (Delphi)	Quantitative
1970	De Geoffrey and Wu	Canadian Shield	Various (Dollar values)	Probabilistic	Quantitative
1971	De Geoffrey and Wignall	Grenville Province	Various	Probabilistic	Quantitative
1972	Agterberg et al.	Abitibi District	Copper, zinc	Geostatistical	Quantitative
1972	Azis et al.	N. Manitoba	Various	Subjective probability (Delphi)	Quantitative
1973	Derry	Arctic and Sub-Arctic	Cu,Pb,Zn,Au,Fe	Geological	Quantitative
1974	McCartney et al.	British Columbia	Various	Geological	Qualitative
1974	McCartney and Matheson	British Columbia	Various	Geological	Qualitative
1975	Robertson	Ontario	Various	Geological	Qualitative
1977a	E.M.R.	Canada	Cu,Pb,Zn,Mo,Ni	Geological	Quantitative
1977b	E.M.R.	Canada	Fe	Geological	Quantitative
1977	Ruzicka	Canada	Uranium	Geological	Qualitative
1977	O.F. 492	Western Arctic	Various	Geological	Qualitative
1978	Agterberg and Divi	Appalachians	Cu,Pb,Zn	Geostatistical	Quantitative
1978	Sinclair et al.	British Columbia	Various	Geological	Qualitative
1980	O.F. 716	N. Yukon, NWT (Parts of) and Arctic Islands	Various	Geological	Qualitative
1980	O.F. 691	N. Yukon and NWT (Parts of)	Various	Geological	Qualitative
1980	Gale et al.	Manitoba	Massive sulphides	Geological	Qualitative
1981	Findlay et al.	Arctic Islands	Various	Geological	Qualitative
1981	Agterberg et al.	S. District of Keewatin, NWT	Various	Geostatistical	Qualitative
1981	O.F. 760	N. Yukon	Various	Geological	Qualitative
1981	O.F. 786	N. Ellesmere Is.	Various	Geological	Qualitative
1982	Labovitz and Griffiths	Canada	Various (Dollar values)	Geostatistical	Quantitative
in prep.	Sinclair et al.	Yukon	Various	Geological	Qualitative

published a preliminary uranium assessment as of 1974 (E.M.R., 1975). The geological principles used in these assessments were described by Ruzicka (1977), and Martin *et al.* (1977) outlined the quantification procedures used. The basis of URAG's assessments was conceptual models of geological deposit-types, the same principle as that used in base metal and iron prognostications. An important point to note here is that URAG's annual reports (e.g., E.M.R., 1981) present not only prognostications of undiscovered deposits but also evaluations of Canada's known uranium resources in terms of three resource categories (measured, indicated and inferred). Uranium appraisals, in terms of this emphasis, therefore lie between those for base metals (emphasis on prognostication) and those for iron (emphasis on evaluation of known deposits). These annual uranium reports (to be published biennially beginning in 1983), represent the most sophisticated and methodical mineral resource assessment program in Canada.

Current G.S.C. Method—the Conceptual Model

Since 1977, the Geological Survey of Canada has issued a number of Open File publications on the resource potential of several large areas of northern Canada (Fig. 1). These assessments, originated in response to requests from native peoples' organizations and government agencies such as Parks Canada, were prompted by a number of northern land assignment studies. More recently, the G.S.C. has continued this work in the belief that it has potential usefulness in identifying areas for exploration by industry.

The resource evaluation method most widely used in the G.S.C. is based on the principle of conceptual models of selected deposit-types. By this method the common and obvious geological parameters of many deposits of the same type are combined to erect a hypothetical or ideal descriptive and genetic model for each deposit-type. Both regional and local geological features are an integral part of the conceptual model, but it is the former which are used most extensively in mineral resource evaluations. The conceptual models used are usually a combination of those published by other workers plus modifications based on G.S.C.'s mineral deposits geologists' extensive Canadian and world-wide examinations and studies of a variety of deposit-types. Drawing upon this experience, together with information from files of mineral deposits data compiled over many decades (the first G.S.C. Economic Geology Reports, on talc and iron, were pubished in 1926), composite conceptual models are established and then compared with the geology of the area(s) being assessed. The conceptual model approach, the basis of all current

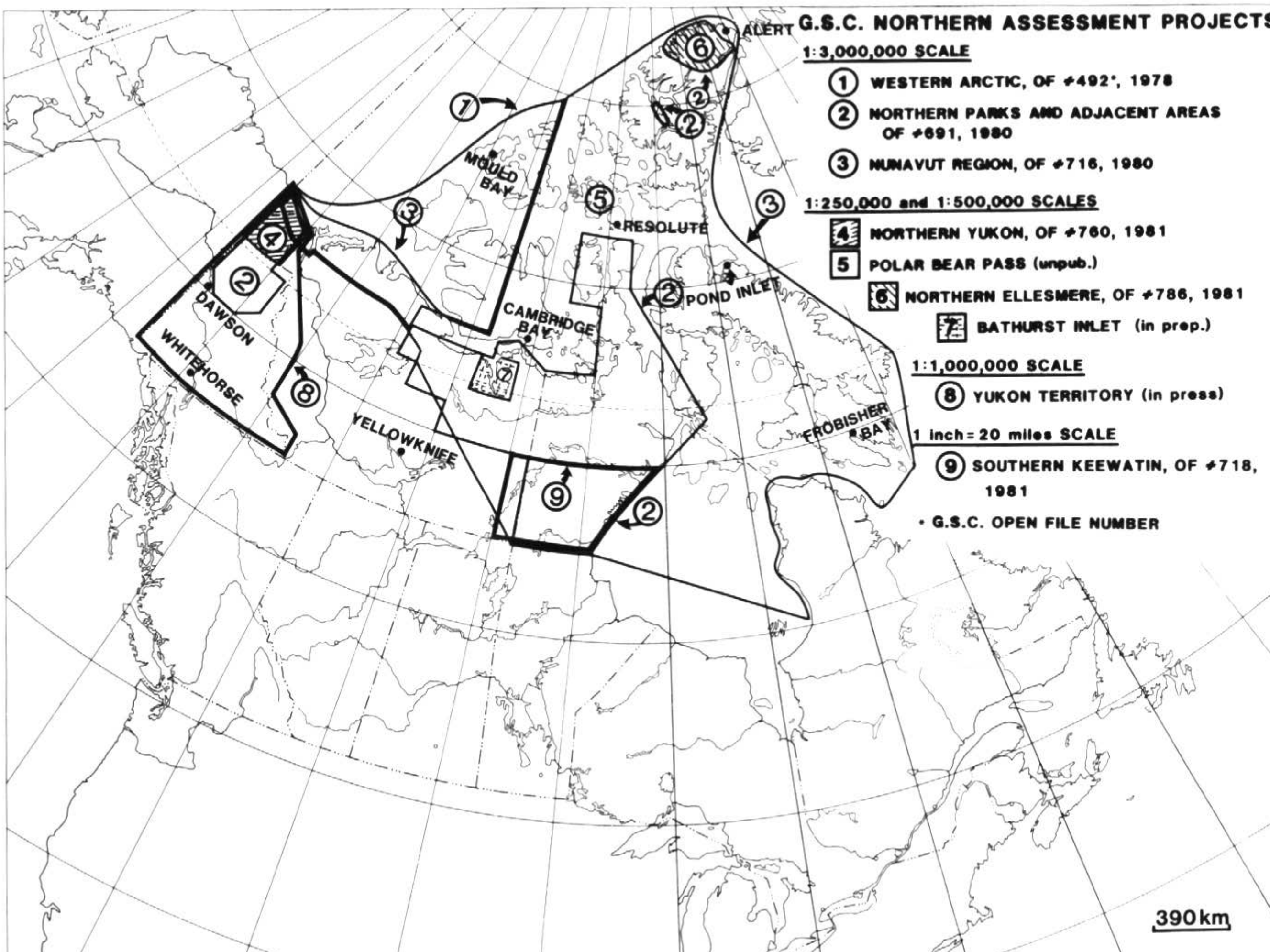

Figure 1 *Recent Geological Survey of Canada regional resource assessment projects in northern Canada.*

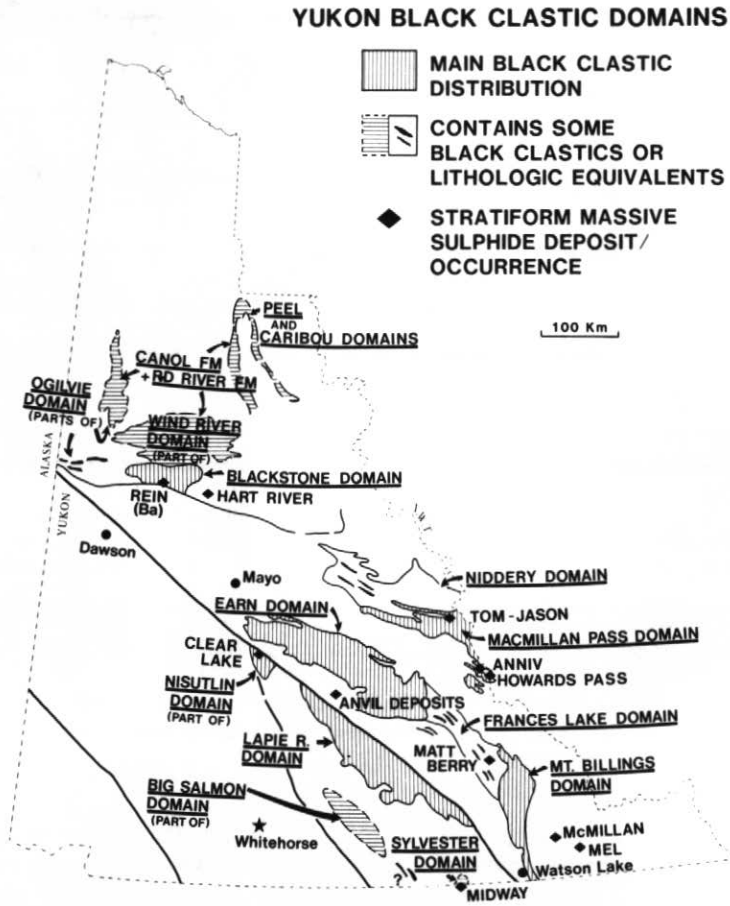

Figure 2 *Yukon assessment domains containing Black Clastic and equivalent lithologies.*

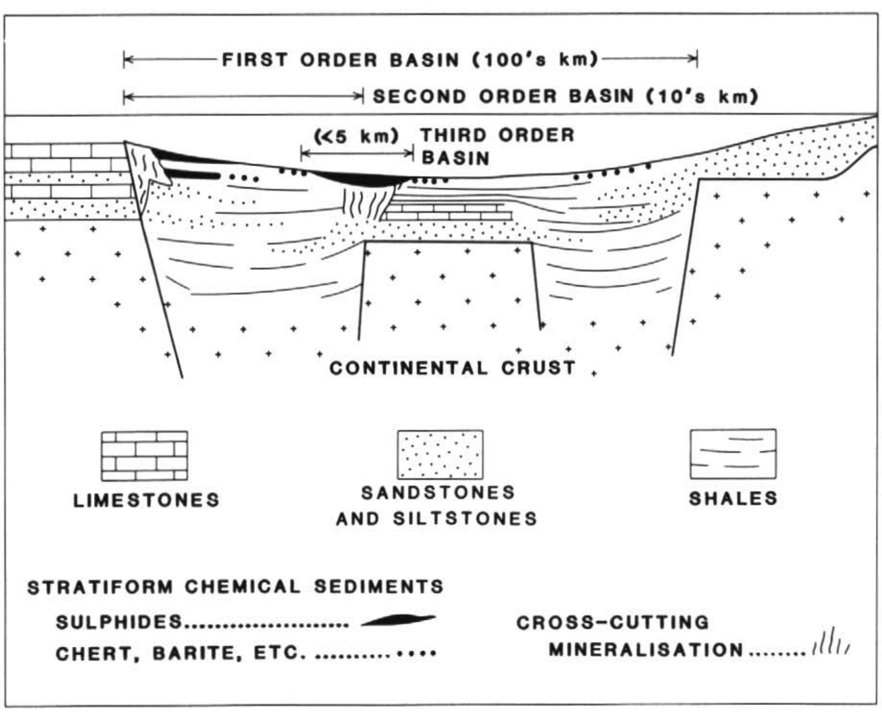

Figure 3 *Composite model of a sediment-hosted submarine exhalative sulphide-barite deposit (modified slightly from Large, 1980).*

G.S.C. base metal, uranium and iron assessments, resembles most closely the *simple subjective* method of Singer and Mosier (1981). Described (Singer and Mosier, 1981, p. 1008) as a method whereby "estimates (are) made directly by one or more individuals based on their experience and knowledge", the *simple subjective* method makes the best use of available expertise, time and data. Furthermore, the resultant product can be easily reported in a manner to suit its ultimate use. In a sense, then, the method probably differs little from the initial phase of many mineral exploration programs, most of which are also the result of intuitive deduction by experienced personnel.

To illustrate the conceptual model method of resource evaluation as currently employed in the G.S.C., the author has selected one deposit-type (sediment-hosted, stratiform lead-zinc type) as it was evaluated in three areas: 1. Yukon Territory; 2. northern Ellesmere Island; 3. northern Baffin Island. These three areas illustrate the range of geological data-bases normally available to geologists performing resource assessments. For example, Yukon Territory is covered by geological maps on several scales, it contains many known deposits of the sediment-hosted type and several large areas within it have been covered by regional geochemical programs. Northern Ellesmere and Baffin Islands have good geological maps only; no mineral occurrences of the type in question have been reported and no regional geochemistry has been done.

Yukon Territory. The first phase of the assessment was to divide the area into geological domains based mainly on structure and stratigraphy. Those domains containing the Devono-Mississippian Black Clastic assemblages (or equivalents) were selected for special study (Fig. 2). The Black Clastic assemblage is known to contain several sediment-hosted stratiform lead-zinc(-barite) deposits, so it is a readily identified target assemblage (e.g., Tom, Jason; see Fig. 2).

Within the Black Clastic assemblage, the

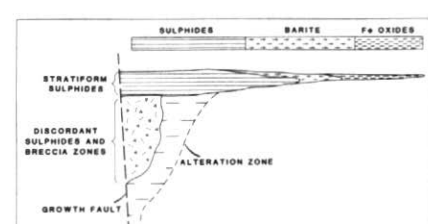

Figure 4 *Typical regional setting of sediment-hosted submarine exhalative sulphide deposits (modified from Large, 1980).*

main geological characteristics of the target deposit-type (Fig. 3) were sought. Only a few of these characteristics can reasonably be expected to be portrayed on the 1:50,000 to 1:250,000 scale data-base maps normally used in assessing areas this large. For example, large syn-sedimentary faults and evidence of exhalative activity (e.g., stratiform barite and/or iron-manganese oxides, chert, etc.) are regarded as positive metallotects. Current knowledge and understanding of this deposit-type (Large, 1980; 1981) indicates that these deposits would fit into a regional pattern in a manner schematically illustrated in Figure 4. Consequently, evidence of the possible existence of second- or third-order basins is sought in geological criteria portrayed on existing geological maps, such as direct observation of syn-sedimentary faults or indirect indicators of the same such as rapid sedimentary facies changes, abrupt variations in thickness of sedimentary units, peculiar breccias which may indicate a fault-scarp talus or sudden changes in depositional environment (e.g., a rapid

Table II *Explanation of mineral potential rating categories used in a recent G.S.C. assessment study of Yukon Territory (from Sinclair and Leech, 1982)*

Rating	Criteria
Very high	Geological environment very favourable. Significant deposits present. Additional undiscovered deposits very likely.
High	Geological environment very favourable. Mineral occurrences present but no significant deposits known.
Moderate	Geological environment favourable. Mineral occurrences may or may not be present.
Low	Aspects of the geological environment may be favourable, but limited in scope. Few, if any, mineral occurrences known. Undiscovered deposits unlikely.
Very low	Geological environment unfavourable. No mineral deposits or occurrences known. Undiscovered deposits very unlikely.

change from shallow- to deep-water sediments which may indicate graben-like movements).

Combining all geological and geochemical features in a subjective fashion, a rating is assigned to the domains being assessed. The rating categories range from "very low" to "very high" depending on the number and kinds of metallotects identified in the domain (Table II).

By this method, a subjective assessment of the potential occurrence of stratiform lead-zinc(-barite) deposits in the Black Clastic-bearing domains is achieved and is expressed graphically as shown in Figure 5. Note that the rating categories are more logarithmic than arithmetic in nature, as suggested by the curve in the lower right portion of Figure 5. That is to say, the difference in potential between categories 1 and 2 is much greater than the difference between categories 6 and 7.

Northern Ellesmere Island. For assessment of a proposed national park in this region, (G.S.C., 1981, O.F. 786) the geological base used was that published by Trettin (1971). From the point of view of sediment-hosted lead-zinc deposits, the Hazen Formation was particularly interesting for several reasons: 1. it occurs in an intracratonic basin, the Franklinian Basin (Trettin and Balkwill, 1979); 2. it has been described as having formed in a starved basin during Early and Middle Ordovician time (Trettin, 1971; Trettin and Balkwill, 1979); 3. the lithologic sequence is very similar to that containing the Howard's Pass, Yukon, stratiform lead-zinc deposit which is also contained in a lower Paleozoic restricted basin facies (Gordey, 1980; Gordey *et al.*, 1981). The gradual upward decrease in carbonate and increase in chert content in the Hazen Formation (Trettin, 1971, p. 40) is very similar to that recorded in the Active Member of the Howard's Pass Formation (Morganti, 1981, p. 72). Furthermore, Trettin (1971, p. 40, 44) noted two isolated occurrences of breccia in the Hazen Formation. The sudden appearance of angular, locally-derived breccia within the otherwise fine-grained clastic and chemical sedimentary rocks of a low-energy starved basin regime was regarded by the assessor not only as anomalous but also as possibly indicative of syn-sedimentary faulting. As a consequence of these interpretations, domains containing the Hazen Formation in northern Ellesmere Island were assigned a very high rating potential for sediment-hosted lead-zinc deposits (Sangster, 1981).

Borden Basin, northern Baffin Island. Initiated as an aulacogen in the north Baffin Rift Zone, Borden Basin is regarded as one of several rift, fault-controlled basins developed along the northwestern edge of the

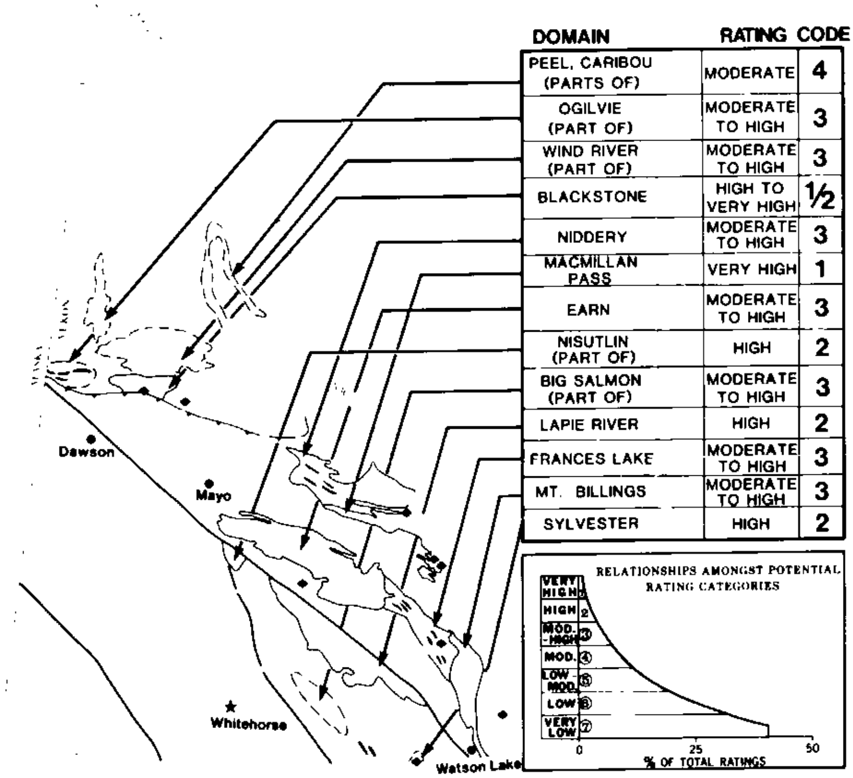

Figure 5 *Summary of assessment ratings derived for the various Yukon domains containing Black Clastic assemblages and equivalent lithologies.*

Canadian-Greenlandic Shield (Jackson and Iannelli, 1981). Within Borden Basin, syndepositional faulting has had a profound effect on sedimentation resulting in numerous facies changes and wide ranges in thicknesses of all formations (Jackson *et al.*, 1978; Iannelli, 1979). Particularly significant with regard to the perceived potential for stratiform lead-zinc deposits is the faulting which took place during deposition of the Arctic Bay Formation, a locally pyritic shale ranging in thickness from 100 m near the western end of the Rift to more than 1200 m near the eastern end.

Features within Borden Basin, and in particular within the Arctic Bay Formation, considered to be relevant to the possible occurrence of sediment-hosted stratiform lead-zinc deposits are 1) the abundant evidence of syn-sedimentary faulting, particularly during Arctic Bay time; 2) the presence of a series of horsts and grabens in the Basin, equivalent to the second-order basins illustrated in Figure 4 and suggesting, in turn, the possibility of third-order deposit-size basins; 3) a local anomalous geothermal gradient as evidenced by the presence of basalts extruded in the early stages of rifting in the west end of the Basin. All these features combined to impart a very high potential to the Arctic Bay Formation (Sangster, 1981), even in the absence of known mineral occurrences in the unit.

Conclusion

Nation-wide resource assessment studies in Canada probably began in 1958 with Lang's uranium map. Since then various agencies have experimented with a variety of techniques and on a variety of scales. Within the Geological Survey of Canada, however, with more than fifteen years' experience in resource assessment methodologies, the most widely used technique is that of the conceptual model. This technique is versatile in that it can be readily adapted to suit a wide range of data bases, time constraints, commodities and presentation formats. It makes extensive use of composite geological models of deposit-types against which is compared the geology of the area being assessed. Some of these assessments are currently being published in the form of Open File assessment reports which typically might contain information such as that listed in Table III. Presented in this manner, the assessment reports may be used for government land use decisions as well as for mineral exploration.

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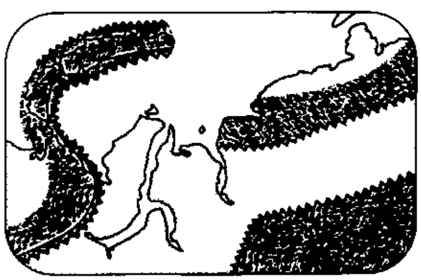

2. Methods of Predictive Metallogeny in the USSR

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Methods of Prediction

Nowadays one of our main geological tasks is prediction of the development of a program for supplying the country with mineral resources. This includes outlining and evaluating promising areas and discovering new types of deposits and ores for rational distribution of mining industries.

There are two main trends in the prediction of mineral deposits in the USSR: predictions based on the results of regional metallogenic studies, and predictions based on statistical-empirical investigations, aided by information about the deposits (data banks) and regional geology with the aid of computers.

The first trend is a traditional one in the USSR. Its fundamentals were laid down by S.S. Smirnov, Yu. A. Bilibin, V.I. Smirnov, P.M. Tatarinov, V.G. Grushevoy, A.I. Semenov, V.A. Kuznetsov, G.A. Tvalchrelidze, I.G. Magakyan and other Soviet scientists. The second trend is now being worked out in various scientific and industrial geological institutions throughout the country. Among well known developments in this latter trend is the "Region" prediction system (devised in the International Scientific Research Institute of Control Programs, Moscow), comparable both in terms of the problems solved and the software of the system to that employed in the "Appalachians" project in Canada. In the "Region" system interaction between the geologist and the computer is of primary importance, as is the choice of prediction variants made on the basis of genetic hypotheses. We shall concentrate here upon the first, metallogenic, trend developed in VSEGEI, the head institution of the USSR Ministry of Geology dealing with regional and predictive metallogenic studies.

Studies in the prediction of mineral resources are carried out in different ways, depending on the final aim. The aims and analytical methods of "special" and "regional" predictive-metallogenic studies are quite distinct. "Special" predictive-metallogenic studies are determined by the necessity to supply the mining and processing industries with ores of a particular composition. This scientific trend of investigation is based on the analysis of distribution patterns of the deposits discovered, on the establishment of the controlling factors of mineralization and, hence, the criteria for prediction (Fig. 1). The above initial data, summarized from all the deposits of the type under consideration, are later employed in the analysis of new territories. As a result, the local areas of promise are outlined and the quantitative evaluation of predictive resources is made. This method has been employed in several areas, e.g., the systems of prediction directed toward supplying the industry of the Kola Peninsula with ferruginous quartzites, manganese oxide ores and copper-nickel ores, supplying the Ural smelters and the copper-molybdenum industrial enterprises of Kazakhstan with copper sulphide ores and supplying Siberian areas with potash salts, etc. The principles and methods of special predictive metallogenic studies are summarized in the book "Kriterii prognoznoi otsenki" (1978).

"Regional" or "combined" predictive metallogenic studies are carried out during the planned geological investigation of Soviet territory. The targets of investigation in this case are areas of various scales: provinces, zones, districts. By these investigations, we hope to determine the whole complex of economic minerals that may be found in the particular territory, to define the main deposit types and to outline and evaluate the promising areas. Predictive-metallogenic studies of this character are based on regional geological research, i.e., geological, geophysical and geochemical survey data. The analysis is based on a classification of zones; established regularities (metallotects) are widely used, e.g., the association of ores with particular zone types, their period of evolution and their geological formations. Accordingly, predictive metallogenic studies presuppose in this case metallogenic division, accompanied by the outlining of types of zones (in space) and stages (in time), subsequent detailed formational analysis and, after the promising mineralization types are defined, the employment of the whole complex of methods of special metallogeny (Fig. 1).