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AN INVENTORY OF UNDISCOVERED CANADIAN MINERAL RESOURCES

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ABSTRACT

Unit regional value (URV) and unit regional weight (URW) are area standardized measures of the expected value and quantity, respectively, of the mineral resources of a region. Estimation and manipulation of the URV statistic is the basis of an approach to mineral resource evaluation. Estimates of the kind and value of exploitable mineral resources yet to be discovered in the provinces of Canada are used as an illustration of the procedure.

The URV statistic is set within a previously developed model wherein geology, as measured by point counting geologic maps, is related to the historical record of mineral resource production of well-developed regions of the world, such as the 50 states of the U.S.A.; these may be considered the training set. The Canadian provinces are related to this training set using geological information obtained in the same way from geologic maps of the provinces. The desired predictions of yet to be discovered mineral resources in the Canadian provinces arise as a consequence. The implicit assumption is that regions of similar geology, if equally well developed, will produce similar weights and values of mineral resources.

An example of an inventory of undiscovered, explorable mineral commodities and their probability of occurrence is given for the province of Manitoba. The value of undiscovered mineral commodities in the Yukon, Labrador, the Island of Newfoundland, Saskatchewan and Manitoba is conservatively estimated at greater than 15,000 U.S. 1967 dollars per km^2.

The URV approach is an objective, reproducible method of mineral resource assessment. Use of the technique stresses the need to operationalize or quantify geology and mineral resource variables, so that algebraic manipulation and formal hypothesis testing can be performed.

AN INVENTORY OF UNDISCOVERED CANADIAN MINERAL RESOURCES

INTRODUCTION AND OBJECTIVE

In 1967, J. C. Griffiths (1967a) proposed that the U.S. be explored for nonrenewable mineral resources by drilling the country on a 20 mile square grid. This proposal is mentioned because two of the features underlying the scheme have a direct bearing on the research presented below. First, one of the objectives of grid drilling is to obtain an inventory of nonrenewable mineral resources. Second, the economic success of the grid drilling proposal is based upon a multi-commodity search, that is all targets which are economically exploitable are considered desirable and are searched for at the same time. Continuing his research in exploration philosophy, Griffiths (1969), examined the rationale used by an explorationist to choose an area to explore. Griffiths reasoned that an input to the explorationist's decision process might be the value of the mineral resources in the area chosen for exploration. The Unit regional value (URV) approach to mineral resource evaluation, as this research has become known, has the following as its basis.[1] An estimate of the value of mineral resources to be found in large underdeveloped regions of the world is obtained by examining mineral resource production in well developed regions.[2] Thus if mineral resources of a region are considered equivalent to its past production the estimate may be obtained by cumulating the production, both weight and value, over the history of production. Since it is expected that larger regions will produce more resources, the effects in variation of region size is removed by prorating (dividing) the aggregated (summed) production by the area of the region. The resulting estimates are called the unit region value and unit regional weight. Application of the unit regional value (URV), leads to a first unconditional, albeit, because not even well developed regions are exhausted,

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[1] A more complete discussion of the Unit Regional Value philosophy as well as a summary of results from other studies can be found in Griffiths, 1978 and Missan, et al., 1978.

[2] A region is a sampling unit, politically defined, and to a first approximation is independent of the distribution of resources. A region is therefore a large political unit considered a random sample of the earth's crust. From past analysis (Griffiths, 1969; Labovitz, 1976), it was noted that political units as small as the counties of Kansas and California (approximately 5170 km^2) could be considered random samples. Therefore a region is equivalent to a state in the U.S. or a province in Canada.

conservative estimate of the value of mineral resource production to be realized from large underdeveloped regions. Calculating the URV for a large number of moderately developed to well developed regions will yield a frequency distribution and thus a more precise estimate of the expected value of production. Then, if the training regions follow a tractable frequency function, the moments (the mean, variance etc) of this distribution can be used to estimate confidence limits about the expected value. This information can be used by an explorationist to set up confidence limits on the value of mineral production to be realized from an area of a given size. Using these limits, the explorationist can decide how much to spend for exploration and development.

In this paper we present the unit regional value approach in the context of a case study, with Canada as the study location. First we derive URV estimates for the Canadian provinces and territories (provinces will henceforth include provinces and territories) and achieve a general sense of their meaning by comparison with the states of the U.S. We also show how this comparison can evolve into predictive statements.

These predictions rest upon the assumption that the states of the U.S. and the provinces of Canada are random samples of the earth's crust. Such predictions therefore may be refined by subdividing locations into geologically more similar groups or subpopulations; the implicit assumption is that regions of similar geology if equally well developed will produce similar mineral resources. So in later sections of the paper we propose a model which helps to create these subpopulations, these subpopulations are then used to examine relationships between geology and mineral resources. From these relationships we predict the number, kinds, and value of mineral commodities yet to be discovered in the provinces of Canada.

THE URV OF THE STUDY LOCATIONS

The URV's of the states of the United States are displayed in Figure 1. This figure represents the aggregation of the constant-dollar value (conversion to 1967 dollars via the wholesale price index) of annual mineral resource production for the period 1905 to 1973. For each state the

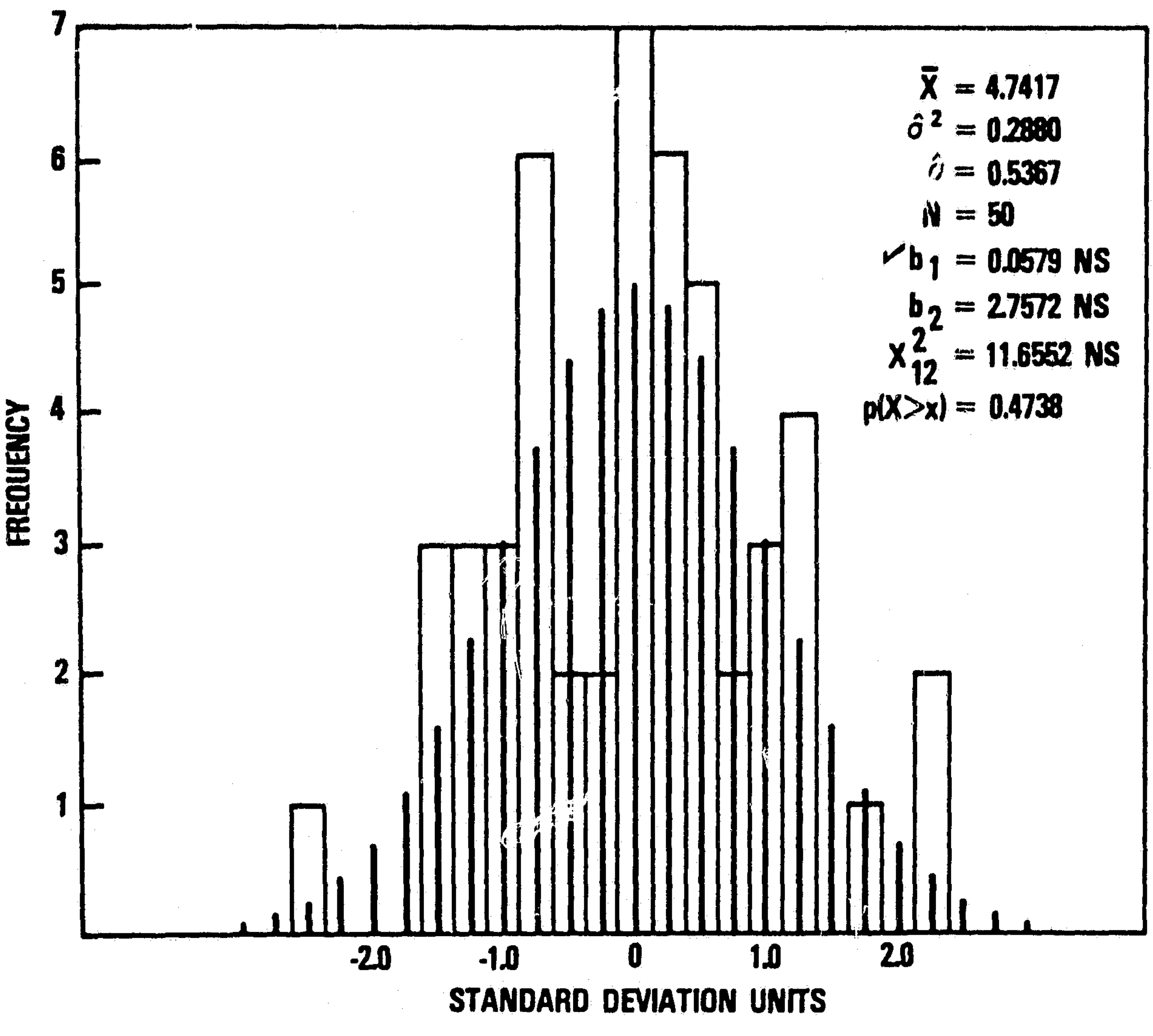

Figure 1. Comparison of observed frequency histogram of $\log_{10}$ URV (in 1967 U.S. dollars/km^2) of the U.S. states with the expected normal distribution possessing the same mean and variance. The statistics $\sqrt{b_1}$, b_2 and X^2_{12} are used in tests of the skewness, kurtosis and goodness of fit, respectively. NS means that the statistic is not significantly different from the value for a normal distribution.

aggregated value of resource production has been divided by its area (in square kilometers) and is then expressed in logarithms to the base 10. The value for the states of the U.S. is log normally distributed with a mean of 4.7417 ($55,170) per square kilometer. There are too few Canadian locations (12) to fit to a frequency distribution, but the logarithms of the URV's of the Canadian provinces (Figure 2) have a mean of 4.0420 ($11,015); the variances of the two samples 0.2880 and 0.3548 respectively are not significantly different from one another using Bartlett's test for homogeneity of variance (Bartlett, 1954), $B = 0.2009$ compared to an $\alpha = 0.05$ critical value of 3.841. Pooling the variances and testing for equality of the means, we find that the provinces of Canada have a significantly lower URV than the states of the U.S. ($t^* = 9.891$ compared to an $\alpha = 0.05$ critical value of 2.000 based on student's t distribution with 60 degrees of freedom). Comparing in greater detail, the states of the U.S. with the provinces of Canada (Figure 2), it can be seen that only one province, Nova Scotia, is above the mean of the states of the U.S. While the URV's of three provinces -- Alberta, Ontario and New Brunswick -- are within one standard deviation below the mean, three other Canadian locations -- Prince Edward Island, Yukon and Northwest Territories are more than two standard deviations below the mean of the U.S. states. Thus the indications are that the provinces of Canada are underdeveloped in mineral resources vis-à-vis the states of the U.S. While this statement would be considered almost intuitive to a great many economic geologists and mineral economists, it is based upon a measure that has not existed previously. This measure provides a quantitative, reproducible and, hence, an objective appraisal of mineral resource production which could be used in predictions and decision making. For example, one may use the stated differences in URV to note that if the URV of the Northwest Territories is raised just to the mean of the U.S. states, an additional $\$160 \times 10^9$ (1967 dollars) would be realized. When the overall totals are subdivided into totals for each resource sector, such as construction materials, fuels and nonmetals, and analyzed, the results indicate the same pattern of relative underdevelopment of the Canadian provinces (Labovitz, 1978).

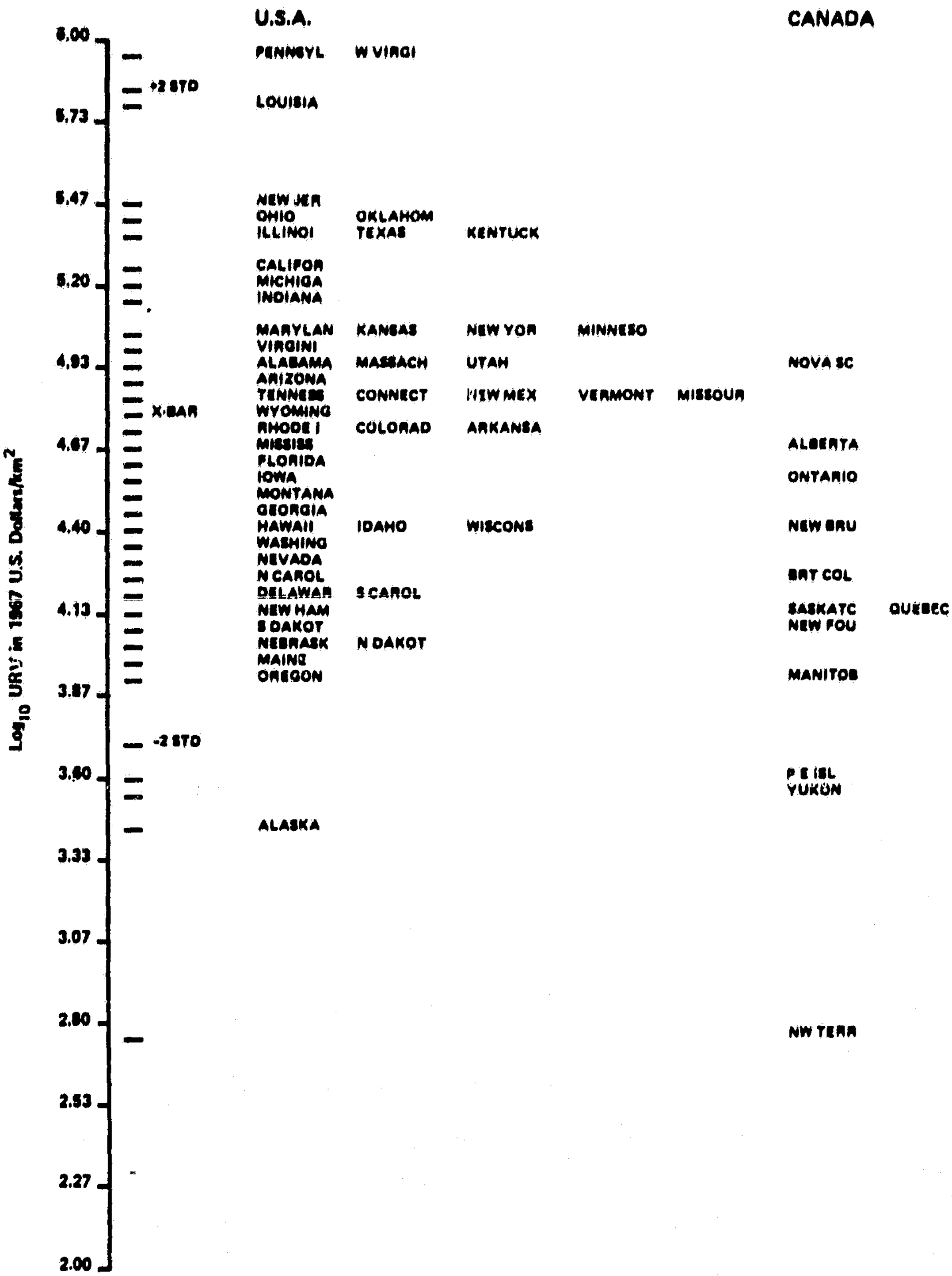

Figure 2. Comparison of total production of mineral resources in U.S. states and Canadian provinces. The mean, XBAR, and standard deviation are estimated from the U.S. states.

MINERAL RESOURCE MODEL

The above results are not explicitly conditioned upon any other variables. The remainder of this paper will set forth and apply a model which incorporates other types of information. The data cube (Figure 3) is used in this paper as the operational form of the inputs and outputs of the mineral resource model. It has three dimensions. One of these dimensions, called the characteristics of a region, consists of socio-economic, mineral commodity and geologic variables. The second dimension, location, is composed of those regions of the world under study. The third dimension – time – is composed of the periods when observation of the characteristics are made on the locations. Thus each cell of the data cube[3] represents the observation of a characteristic at a given location for a specified time. The interrelations of the characteristics given in the data cube are expressed conceptually and in their fullest generality in the model displayed in Figure 4. The model used to represent the mineral resource system is an input – output or "black-box" model (Ashby, 1971). The model has four elements – input, output, processor (black-box) and feedback. One input to the system consists of a group of socio-economic variables represented in Figure 4 by the term commitment; this includes for example, how much money we are willing to spend, how many geoscientists are to be committed to the project, how much land will be available for exploration etc. The other input to the model is a group of geologic factors. For a specific study area these would include lithological, tectonic, physiographic or metallogenic province and geophysical characteristics. The outputs of the system are functions of the production of mineral resources – the number and kinds of mineral resources produced, their value and quantity. The inputs are related to outputs through the processor or black-box. The processor is an aggregation of many phases of the mineral resource system such as exploration, development, exploitation, transportation, etc. Operationally, the relationship between the input and output is described mathematically or statistically through a variety of modeling techniques. The fourth element – feedback – is the means by which the

[3] The use of the data cube in mineral resource analysis is covered more fully in Menzie et. al., 1977 and Labovitz et. al., 1977.

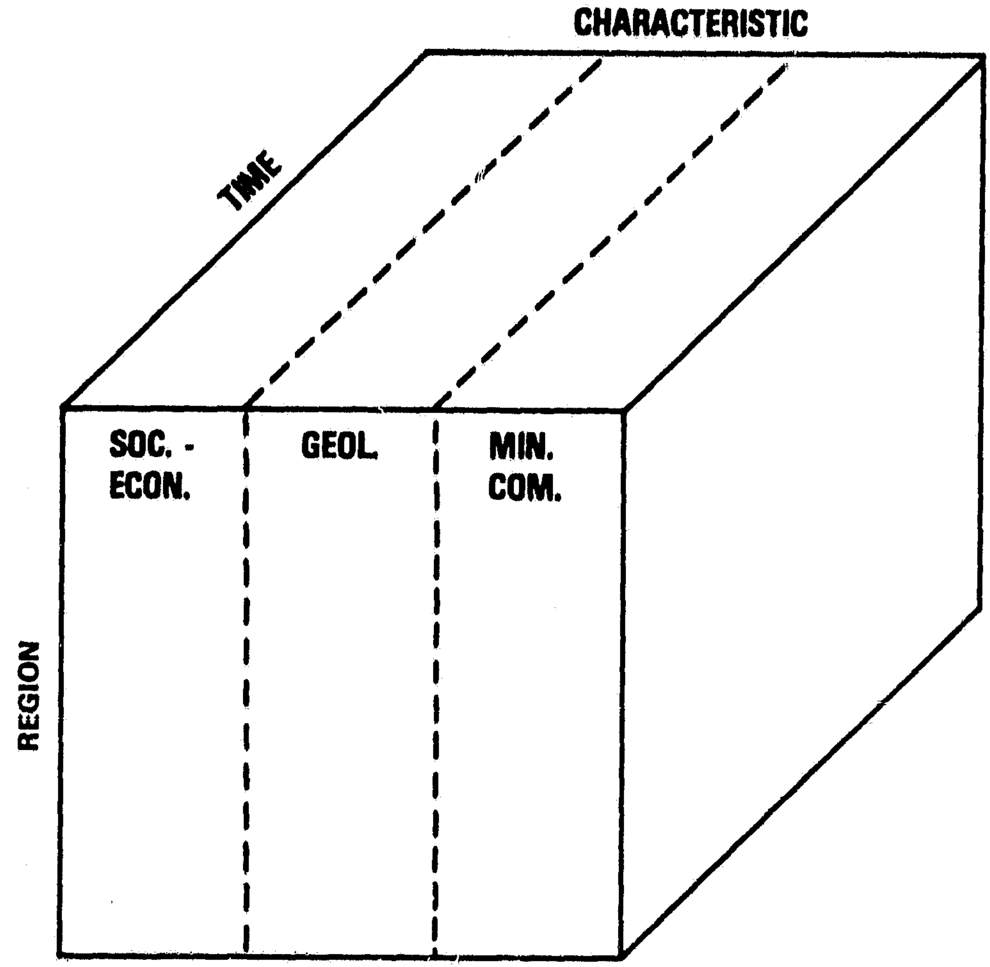

Figure 3. The data cube exhibiting the three dimensions of characteristics, time and regions.

output acts upon the input and processor. For example, the quantity of proved petroleum reserves influences the resources allocated to the search for petroleum. It is often in the feedback that the system's evolution or dynamics are displayed. Figure 4, as previously noted, presents the model in its fullest generality. We now simplify and operationalize the model for the present application. The input, processor and output portions of the mineral resource model as used in this paper are examined below.

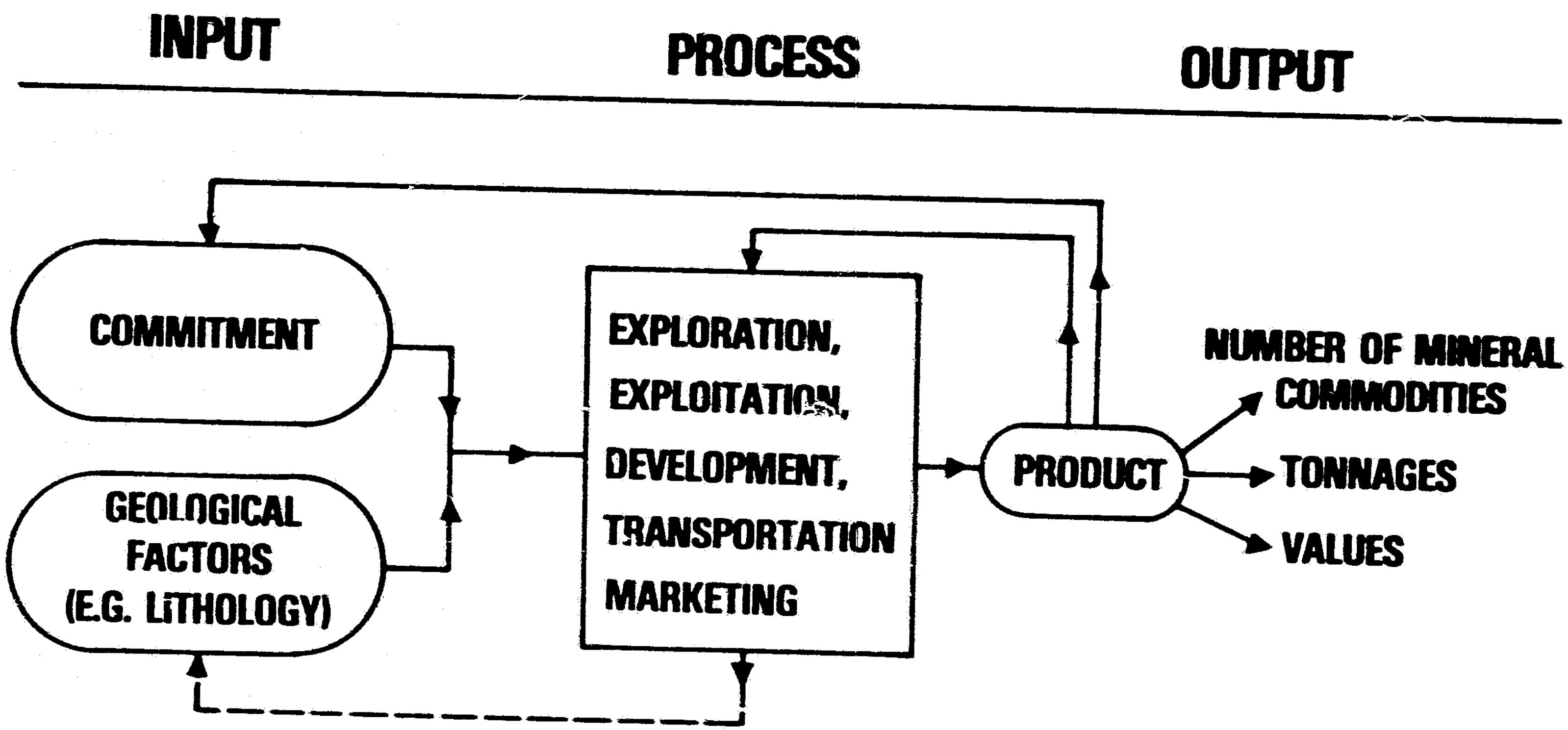

Figure 4. Generalized cybernetic input-output model of mineral resource development.

The Output[4]

The outputs of the system are functions of the mineral resource production: thus, to be able to relate production from different locations the mineral resources must be expressed in equivalent form and so a standard set of mineral resources called file 2 was created (Labovitz *et al.*, 1977) along with a set of mappings translating local names for the resources (file 1) to the file 2 commodities. Table 1 presents the file 2 names and numerical codes. There are 74 "recognizable" mineral resource commodities divided into 5 resource sectors – construction materials, fuels, metals, nonmetals and precious materials – plus 12 "accounting" codes or resource sector subtotals. Table 1 also displays the file 2 commodities discovered to date in Canada. Here, the terms discovery or occurrence (the latter is used later) of a mineral commodity means that the commodity has existed or exists in economically exploitable quantities as defined by the records of historical production.

The Input[5]

The difficulty in examining lithology as an input to the system, is in comparing a host of local names. This once again necessitated the development of a standard and operationalized geologic classification. The "time-petrographic" classification, (Menzie, 1977) Figure 5, is composed of two dimensions – age and lithology which are combined to form 70 classes.

The sedimentary classification is based on Krynine (1948) as modified by Griffiths (1974) and Menzie (1977). This classification of the detrital rocks is used for several reasons. First, it has a tectonic basis that is using the "end-members" of Krynine (1948), the rocks can be related to the tectonic settings of their formation. Second, these detrital rock types have a quantitative or operational definition given by Griffiths (1967b, 1977). The igneous rock classification is based on criteria from Hurlburt (1966) as modified by Menzie (1977). The metamorphic rocks, at the

[4]Sources for Canadian mineral commodity data are given after References.

[5]Geologic maps used in point counts are given after References.

Table 1. Standard set of mineral resource commodities which enables the comparison of mineral resources from different locations. Each of these commodities, which are collectively known as File 2, has an operational definition (given in Labovitz <u>et. al.</u>, 1977) which allows local commodity names to be assigned to the standard set.

CODE	COMMODITY	CODE	COMMODITY	CODE	COMMODITY
100	CONSTRUCTIONAL MATERIALS	308	• COBALT	410	• GARNET
101	• ASBESTOS	309	• COPPER	411	• GEM STONES
102	• CEMENT	310	• IRON ORE	412	• GRAPHITE
103	• CLAYS	311	• LEAD	413	• LIME AND LIMESTONE
104	• DIATOMITE	312	• LITHIUM	414	• MAGNESITE
105	• GYPSUM	313	MAGNETITE	415	• MINERAL PIGMENTS
106	• MICA	314	• MANGANESE	416	NITRATES
107	• SAND AND GRAVEL	315	• MERCURY	417	• PHOSPHATES
108	• STONE	316	• MOLYBDENUM	418	• POTASSIUM SALTS
200	FUELS	317	• NICKEL	[illegible]	• PYRITES
201	ANTHRACITE COAL	318	• RARE EARTHS	420	• SALT
202	• ASPHALT	319	• TANTALIUM	421	• SAND
203	• BITUMINOUS COAL	320	• THORIUM	422	• SODA
204	• LIGNITE	321	• TIN	423	• SULFUR
205	• LIQUID PROPANE	322	• TITANIUM	424	• TALC
206	• NATURAL GAS	323	• TUNGSTEN	425	VERMICULITE
207	NATURAL GASOLINE	324	VANADIUM	500	PRECIOUS MATERIAL
208	OIL SHALE	325	• ZINC	501	DIAMONDS
209	• PEAT	326	ZIRCONIUM	502	• GOLD
210	• PETROLEUM	400	NONMETALS	503	• PLATINUM
211	• URANIUM	401	• METAMORPHIC ALUMINUM SILICATES	504	• SILVER
300	METALS	402	• BARYTES	600	MISCELLANEOUS
301	ALUMINUM	403	BORATES	601	OTHERS
302	• ANTIMONY	404	BROMINE	602	NOT CONSIDERED
303	• ARSENIC	405	CARBON DIOXIDE	603	AGGREGATE BROKEN UP
304	• BERYLLIUM	406	• CLAYS	604	REMAINDER=(TOTAL-PTOTAL)
305	• BISMUTH	407	• CORUNDUM	790	TOTAL VALUE
306	• CADMIUM	408	• FELDSPAR	701	PSEUDO-TOTAL=(SUM SECTORS)
307	• CHROME	409	• FLUORSPAR		

•FILE 2 COMMODITIES OCCURING IN CANADA

ROCK TYPE	CENOZOIC	MESOZOIC	PALEOZOIC	PROTEROZOIC	ARCHEOZOIC
OTHERS		414			
REGIONAL METAMORPHIC ROCKS	513				
ULTRABASIC EXTRUSIVE ROCKS		412			
ULTRABASIC INTRUSIVE ROCKS	511				
BASIC EXTRUSIVE ROCKS		410			
BASIC INTRUSIVE ROCKS	509				
ACID EXTRUSIVE ROCKS		408			
ACID INTRUSIVE ROCKS	507				
EVAPORITE ROCKS		406			
CARBONATE ROCKS	505				
HIGH RANK GRAYWACKE		404			
LOW RANK GRAYWACKE	503				
ARKOSE		402			
QUARTZITE	501	401	301	201	101

Figure 5. "Time Petrographic" classification (from Menzie, 1977; modified by Watson, 1977).

scale of the maps used, are limited to slates, phyllites, schists, gneisses and marbles. These are all assigned to the class called Regional Metamorphic Rocks. A 14th petrographic class called "others" is available for rocks which do not belong to the first 13 classes.

Geologic time is, in this scheme, grouped into five eras. The three eras composing the Phanerozoic – the Paleozoic, Mesozoic and Cenozoic – are well defined. The Precambrian is divided into two eras – Archeozoic and the Proterozoic. The relation between the subdivisions used in the "time-petrographic" classification is given in Figure 6 (modified after King, 1977, from Labovitz, 1978). Thus, rocks of Archean age are placed in the Archeozoic and rocks of Aphebian, Helikian, or Hadrynian Ages are considered to be in the Proterozoic. The description and use of the "time-petrographic" classification is given in greater detail in Griffiths (1978).

"TIME-PETROGRAPHIC" CLASSIFICATION	EVENT (IN MILLIONS OF YEARS)	GEOLOGICAL SURVEY OF CANADA
Paleozoic		Cambrian
Proterozoic	Avalonian 570-650 m.y.	Hadrynian
	Grenvillian 900-1,100 m.y.	Helikian
	Elsonian 1,300-1,400 m.y.	
	Hudsonian (=Penokean) 1,700-1,800 m.y.	Aphebian
	Kenoran (=Algoman) 2,500-2,700 m.y.	
Archeozoic		Archean

Figure 6. Relationship between subdivisions of Canadian Precambrian and "time-petrographic" classification (after King 1977, and Labovitz, 1978).

Data forming the input were collected by placing a transparent square grid on the geologic map of the study area. The map symbol falling under the intersection is noted and a determination made as to which "time-petrographic" class the map symbol belonged (Griffiths *et al.*, 1979b). For Canada the objective was to observe the geology every 8 to 10 miles (12 to 16 km) and so the size of the sampling grid was adjusted to conform with the map scale (see Table 2). The Northwest Territories is the only location in Canada for which the sampling interval is greater than the targeted value and this arises because there is no compilation map of NWT at a suitable scale (a scale no smaller than 1 to 1,500,000). The point count of Canadian geology is composed of 37,475 observations (Labovitz, 1978).

The Processor

Figure 7 is an abstraction of the model given in Figure 4 and may be used to note the potential richness of the model, that is the number of potential configurations relating input to output variables. For instance, if the set of values that the 70 geologic variables and the 74 mineral commodities can take on consists of 0 or 1 (presence or absence), then there are 2^{70} possible geologic configurations and 2^{74} possible mineral resource commodity mixes; so the possible number of configurations that the system may take on is $2^{70 \cdot 2^{74}}$. Thus this model has the ability to represent a large number of system configurations even though based on presence – absence data.

The remainder of the paper will use these data to examine the relationship between the presence or absence of "time-petrographic" units and the presence or absence of mineral resources. The rationale for use of presence-absence data in this analysis is to try to see through the impact of economics upon the mineral resource system. This approach is suggested by previous research in which Labovitz (1976) and Menzie (1977) found that, while geology may set broad upper and lower bounds on the resource endowment of an area, the actual level of production is largely a function of non-geologic variables, including economic factors. Potentially then the presence-absence data and not the level of production will reflect more clearly the relationship between geology and mineral resources.

Table 2. Number of points counted and their area of influence for the provinces of Canada.

LOCATION	GRID SPACING	MAP SCALE IN. TO MI.	NO. OF POINTS	AREA OF INFLUENCE (KM^2)	GROUND DISTANCE (KM)
ALBERTA	1/2"	1 TO 20	2,508	263.63	16.24
BRITISH COLUMBIA	1/4"	1 TO 40	3,855	246.45	15.70
MANITOBA	1/2"	1 TO 20+	2,535	256.47	16.01
NEW BRUNSWICK	1"	1 TO 8	448	163.90	12.80
NEWFOUNDLAND					
– ISLAND	1/2"	1 TO 15.78	706	159.07	12.61
– LABRADOR	1/2"	1 TO 15.78	1,727	169.21	13.01
NWT	1/4"	1 TO 78.91	3,835	881.28	29.69
NOVA SCOTIA	1"	1 TO 8	331	163.16	12.97
ONTARIO	1/2"	1 TO 16	5,823	183.50	13.55
QUEBEC	1/2"	1 TO 16	8,104	174.00	13.19
SASKATCHEWAN	1/2"	1 TO 20	2,360	275.53	16.60
YUKON	1/4"	1 TO 23.67	5,243	102.29	10.11

+ SCALE FOR MANITOBA FROM MAP 65-1

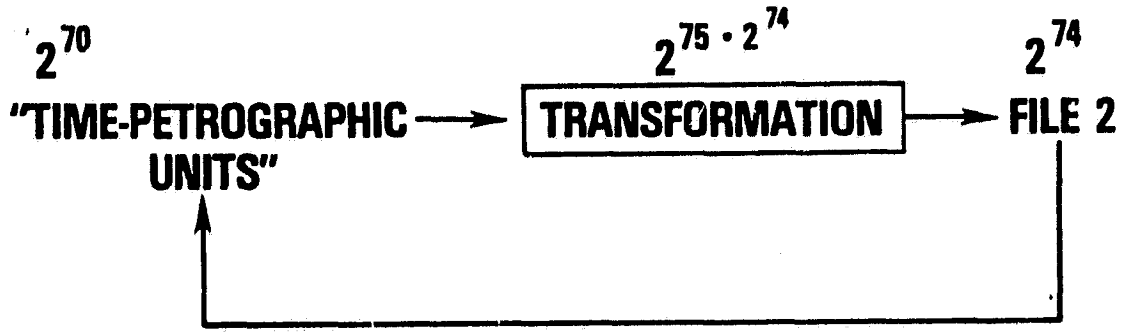

Figure 7. Input-output model of Figure 4 displaying relationships between varieties of time-petrographic inputs and mineral resource outputs.

OVERVIEW OF ANALYSIS

The analysis strategy for predicting the types of mineral commodities yet to be discovered in the Canadian Provinces and the URV of these commodities is as follows.

We first examine the hypothesis that the geologic information, as measured by the point counts, can be used to predict what kinds of mineral commodities are likely to be found. This is done in two steps.

(1) Comparison of groups of regions grouped upon the presence-absence of "time-petrographic" units versus groups of the same regions formed using the presence-absence of mineral commodities. The methodology for this comparison is based upon the assumption that the more similar the two groupings, the stronger the relationship between geology and type of commodities.

(2) Comparison of the number of "time-petrographic" units and the number of mineral commodities for a region. This is accomplished through a linear regression procedure.

Next, the Canadian provinces are assigned among the groups of regions examined in other URV studies. These groups were initially formed using the presence-absence of "time-petrographic" units and without Canadian locations. Then steps (1) and (2) provide the rationale for predicting the type and number of commodities which are likely to be present in a province. Finally, for each province, a simulation procedure is used to estimate the URV for these yet undiscovered commodities. The analysis and results are covered in greater detail below.

Analysis of the Relationship between Geology and Mineral Resources using Presence-Absence Data

The analysis was begun by examining whether or not the presence or absence of geologic units contains information about the commodity mix (i.e. the specific kinds [not amounts] of commodities). Using the states of the U.S. as a training set, two classifications were produced. First, the states were grouped using the "time-petrographic" presence-absence data (Menzie, 1977). This was followed by an independently performed classification of the states using mineral commodity presence-absence data. The classification based on commodity data yielded four groups while the classification based on "time-petrographic" data resulted in eight groups. The classifications along with proportion of the states falling within each class are given in Table 3. For example, Pennsylvania (PA) is in commodity class 2, which contains 10/50 or 20% of U.S. states, and "time-petrographic" class 5, which contains 05/50 or 10% of the states. A test of the independence of the two groupings using the contingency table techniques was deemed unsuitable because of the small number of observations vis-à-vis the number of cells in the analysis. However, another test statistic was derived under the assumption that the fewer the number of diagonal cells containing observations, or alternatively, the greater the number of off diagonal cells with no observations, the more similar are the classifications. A Monte Carlo simulation procedure was used to determine if the number of off diagonal empty cells is significantly greater in Table 3 than that which might be obtained by a random distribution of 50 objects in an 8 X 4 array, the size of Table 3. Such a table was simulated 500 times and the number of empty cells for each of these realizations was tallied in a frequency histogram, Figure 8. Table 3 has 21 observed cells containing no observations. Using Figure 8, the probability of getting 21 or more empty cells, if the classifications are independent, is 3/500 or 0.006. Using any conventional α level we must reject the hypothesis of independence between the two classifications. This affirms that contained in the geology, as measured here, is information about the kinds of commodities to be found at a given location.

A second investigation explored the relationship between the number of commodities and the number of "time-petrographic" units observed for a given location. This problem has an ana-

Table 3. Classification of U.S. states[+] based on presence-absence of mineral commodities (columns) compared classification of U.S. states based on presence-absence of "time-petrographic" units (rows).

TIME PETROGRAPHIC GROUPING	COMMODITY GROUPING					
Class	1	2	3	4	N	N/50
1	AZ CO NM SD TX UT WY				7	.14
2	CA				1	.02
3	MT			ID	2	.04
4	NV			OR	2	.04
5		MD NY NC PA VA			5	.10
6		AL GA MA SC VT	AR CN DE FL HA IL IN IO KA KY LA ME MI MO NB NH NJ ND OH OK RI TN WV WI		29	.58
7			MI MN		2	.04
8				AK WA	2	.04
					Totals	
Number in Class (N)	10	10	26	4	50	
Proportion (N/50) =	.20	.20	.52	.08		1.00

[+]STATE ABBREVIATIONS BASED ON U.S. POSTAL CODES

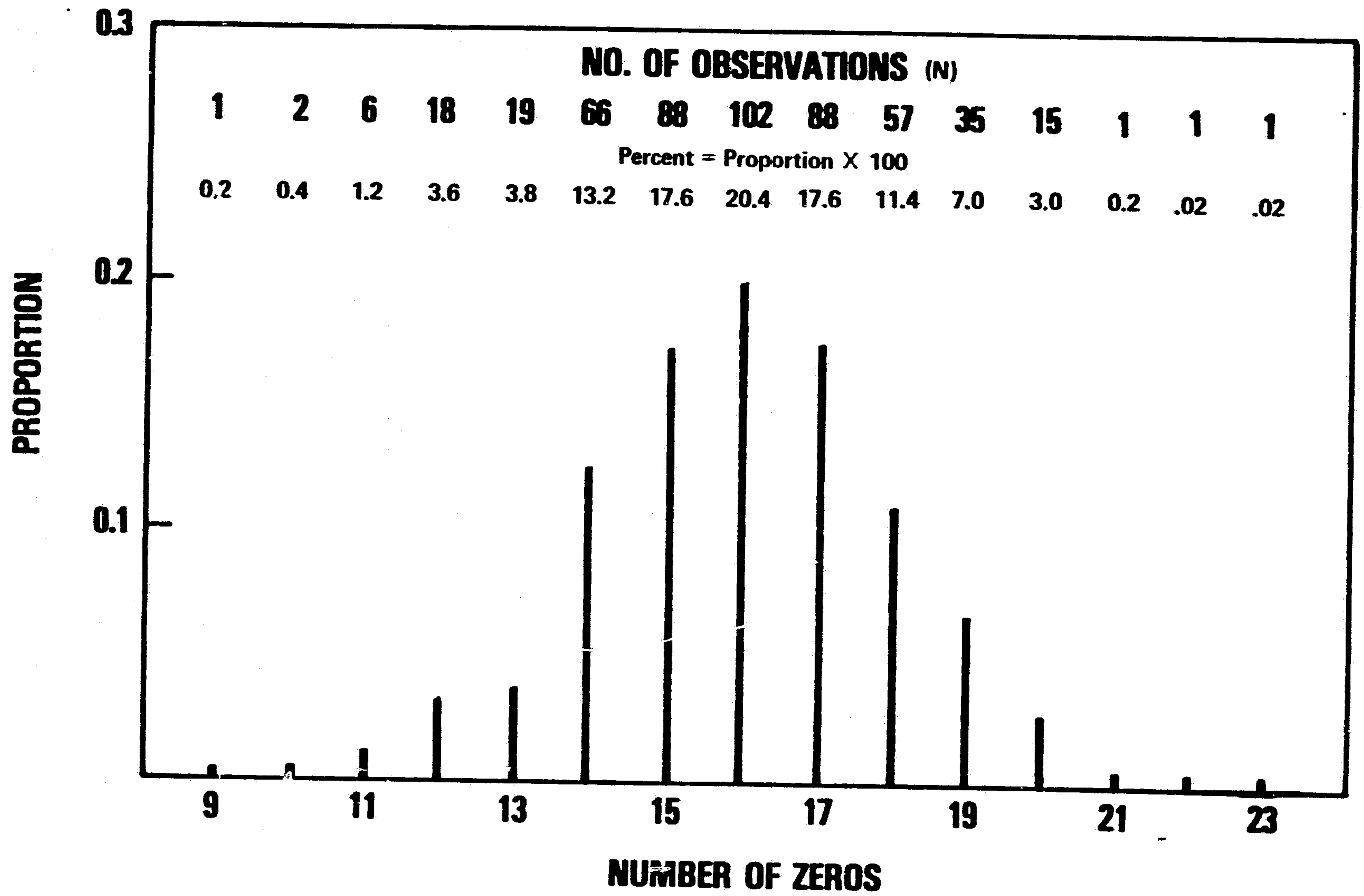

Figure 8. Frequency distribution of the number of empty cells in an array of size 8 X 4 to which 50 observations had been assigned randomly according to the marginal proportions given in Table 3. This frequency distribution was generated using a "Monte Carlo" procedure the number of empty cells which would arise if the factors on each margin (1. classification of U.S. states by mineral commodity; 2. classification of U.S. states by "time-petrographic" unit) are independent of one another.

logue in the determination of species diversity for a population. Since we were interested in any and all mineral commodities, the measure of species diversity called richness was used.[6] Richness is the number of species (number of "time-petrographic" units or mineral commodities) minus one. Figure 9 is a plot of the relation of the richness of geologic units on the abscissa versus the richness of mineral commodities on the ordinate. The dashed line is a graph of the function Y = 11.277 + 1.846 X. This relationship was established by Griffiths *et al.* (1979) and is based upon analysis of locations which have previously undergone URV studies, these include the states of the U.S., Puerto Rico, South Africa, Zimbabwe, Australia, United Kingdom, Ireland, New Zealand, Mexico, Venezuela. As can be seen, with the exceptions of Ontario and British Columbia, the locations of Canada fall well below their expected mineral richness based upon their geologic endowment.

The estimates of the number of mineral commodities were refined by using information from geologically similar regions outside of Canada. To do this, the "time-petrographic" presence-absence data was used to assign the Canadian locations to a previously developed classification[7] composed of regions from other URV studies. Therefore, the locations in each group in Figure 10 are geologically similar.

For each group containing Canadian locations, the non-Canadian locations were used to estimate a linear model relating geologic richness and mineral resource richness. This model was used in turn to reestimate the expected number of mineral commodities for the Canadian location. Table 4 contains these refined estimates as well as a $\pm 2\hat{\sigma}_e$ range. Quebec and NWT formed their own group; there are no other locations in the training set with similar geology and hence the estimates, given in Table 4, for the number of commodities to be found at these two locations are based on the initial estimates using the linear regression given above. Initial estimates are

[6]The use of measures of species diversity for analyzing mineral resource endowment is more fully discussed in Griffiths et al. (1979, 1980).

[7]The classification was performed with the computer program CLUS (Rubin and Friedman, 1967) using the Rodgers and Tanimoto (1960) coefficient of association to create the similarity matrix.

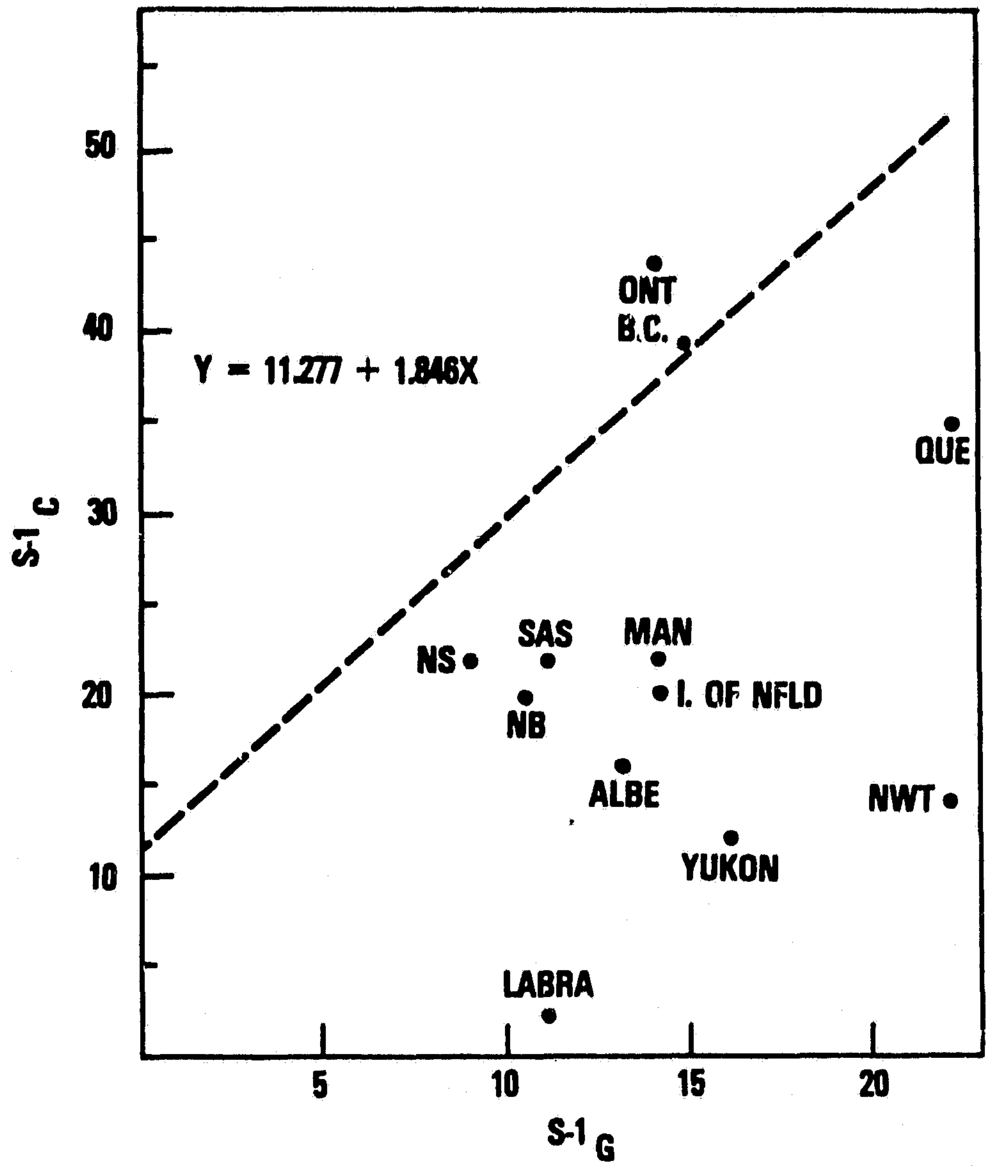

Figure 9. Scatter plot of richness of mineral resources ($S - 1_C$) and richness of "time-petrographic" units ($S - 1_G$) in Canadian provinces. Dashed line is due to Griffiths' *et al.*, (1979) and represents this relationship for other locations which have undergone URV studies.

GROUP 1 = IDAHO AND MONTANA

2 = CALIFORNIA AND NEVADA

3 = GEORGIA, MAINE, MASSACHUSETTS, NEW HAMPSHIRE, NORTH CAROLINA, RHODE ISLAND, SOUTH CAROLINA, VERMONT, NEW BRUNSWICK, NEWFOUNDLAND, AND NOVA SCOTIA

4 = ALABAMA, ARKANSAS, CONNECTICUT, DELAWARE, FLORIDA, ILLINOIS, INDIANA, IOWA, KANSAS, KENTUCKY, LOUISIANA, MARYLAND, MISSISSIPPI, MISSOURI, NEBRASKA, NEW JERSEY, NEW YORK, NORTH DAKOTA, OHIO, OKLAHOMA, PENNSYLVANIA, TENNESSEE, VIRGINIA, WEST VIRGINIA, WISCONSIN, ALBERTA, MANITOBA, AND SASKATCHEWAN

5 = MICHIGAN, MINNESOTA, CAPE, NATAL, ORANGE FREE STATE, TRANSVAAL, RHODESIA, ONTARIO, AND LABRADOR

6 = WASHINGTON, MALAYSIA, AND YUKON

7 = HAWAII, OREGON, PUERTO RICO, AND BRITISH COLUMBIA

8 = ARIZONA, COLORADO, NEW MEXICO, SOUTH DAKOTA, TEXAS, UTAH, AND WYOMING

9 = NEW ZEALAND

10 = ALASKA

11 = NORTHWEST TERRITORIES AND QUEBEC

Figure 10. Groupings based on "Time-Petrographic" units.

Table 4. Expected richness of mineral commodities ($S - I_C$) for locations in Canada.

	$S - I_C$		
LOCATION	OBSERVED	EXPECTED	RANGE
[1]NEW BRUNSWICK	20	32	23 - 41
[1]NEWFOUNDLAND (ISLAND)	16	42	32 - 52
[1]NOVA SCOTIA	22	27	19 - 35
[1]ALBERTA	16	34	24 - 44
[1]MANITOBA	22	35	25 - 45
[1]SASKATCHEWAN	21	31	21 - 41
[1]LABRADOR	2	27	17 - 34
[1]ONTARIO	44	36	28 - 44
[2]BRITISH COLUMBIA	40	39	28 - 50
[2]YUKON	12	41	30 - 52
[2]NWT	14	52	40 - 64
[2]QUEBEC	35	52	40 - 64

[1]Refined estimate (see text).

[2]For these provinces and territories no refinement of the regression parameters based upon membership in a geologic class could be obtained. Estimates for these locations are based on the function described in text attributed to Griffiths et al., 1979.

also given for British Columbia and the Yukon Territory, because there were an insufficient number of non-Canadian locations in their respective geologic groups to fit a linear model. British Columbia and Ontario have been dropped from further consideration as they have already exceeded their expectations. However, most locations in Canada have not achieved even the lower bound on their expected number of commodities. Having estimated the number of commodities to be found in locations in Canada, and having found that the locations are underproduced, the next question is what additional specific commodities can be expected.

PREDICTING UNDISCOVERED MINERAL COMMODITIES AND THEIR URV

For each Canadian location under study, a list was compiled of the (file 2) commodities not discovered there but which are present in non-Canadian locations of the geologic group to which the study area belongs. The probability of occurrence of these commodities is then estimated as the number of locations possessing the commodity over the total number of non-Canadian locations in the geologic group. Table 5 gives the potentially occurring mineral commodities and the probability of their occurrence in Manitoba. Based on these estimates of the probabilities of occurrence, the URV (1967 U.S. dollars per km^2) of undiscovered mineral commodities were estimated. The estimated URV came from a frequency distribution created by repeatedly generating realizations using the following conditions;

(1) only those commodities with a probability of occurrence of .375 or better were used in the estimation procedures;

(2) a realization from a joint multivariate log normal distribution was created using estimates of the mean vector and variance – covariance matrix generated from the data;

(3) the values in the realization were exponentiated, summed, and logged (base 10).

Estimates of the mean and median of these distributions is given in Table 6. As can be seen, the Yukon, Newfoundland, Labrador, Saskatchewan and Manitoba are expected to produce more than 10,000 1967 U.S. dollars per km^2 from mineral resources *not yet discovered.*

Table 5. Commodities not occurring in Manitoba but found in other locations of the geologic group of which Manitoba is a member.

COMMODITY	PROBABILITY OF OCCURENCE	COMMODITY	PROBABILITY OF OCCURENCE
ASBESTOS	0.1600	FLUORSPAR	0.1200
+CLAYS CM	1.0000	GARNET	0.1200
+DIATOMITE	0.6800	+GEM STONES	0.9600
+MICA	0.3200	GRAPHITE	0.2000
ANTHRACITE COAL	0.0400	+MINERAL PIGMENTS	0.7600
+ASPHALT	0.3600	PHOSPHATES	0.2400
LIGNITE	0.3400	+POT SALTS	0.6800
+LIQUID PROPANE	0.4800	PYRITES	0.5600
+GASOLINE	0.5600	SODA	0.0400
+PEAT	0.6000	+TALC	0.3200
URANIUM	0.1600	VERMICULITE	0.0400
ALUMINUM	0.1600		
ANTIMONY	0.0400		
ARSENIC	0.0800		
BERYLLIUM	0.1600		
CHROME	0.0400		
+IRON ORE	0.6800		
+MAGANESE	0.4000		
MERCURY	0.0800		
MOLYBDENUM	0.0800		
RARE EARTHS	0.0400		
THORIUM	0.0800		
TIN	0.0800		
TITANIUM	0.2000		
VANADIUM	0.0800		
ZIRCONIUM	0.0400		
Mt Al Si	0.1200		
+BARYTES	0.3600		
BROMINE	0.2400		
+CLAYS NM	0.8800		
CORUNDUM	0.1200		

+ COMMODITY USED TO ESTIMATE VALUE OF UNDISCOVERED MINERAL RESOURCES.

Table 6. Estimated URV (in U.S. 67 $) of undiscovered natural resources in selected Canadian locations.

LOCATION	10^{MEAN}	10^{MEDIAN}
ALBERTA	9,528	8,147
MANITOBA	15,560	14,355
NEW BRUNSWICK	4,481	3,327
NEWFOUNDLAND (I.)	17,298	12,853
LABRADOR	17,258	12,589
NWT	6,310	5,212
NOVA SCOTIA	3,524	2,667
SASKATCHEWAN	16,866	14,488
YUKON	20,045	17,824

Alberta, for instance, will experience large increases in its URV from exploitation of fuels, however, those commodities were not included among the undiscovered commodities and so its URV does not reflect the value of the fuels. Quebec was used as the training set for estimating the URV of NWT, because Quebec was the only other geologically similar location among the locations used (see Figure 10) and clearly it is the better developed of the two locations. However, all indications are that Quebec itself is underdeveloped so the estimated URV for NWT is likely to be very conservative. Even so, NWT would be worth an additional $\$2.132 \times 10^{10}$ (1967 dollars).[8]

[8] Arguments have arisen concerning the validity of any estimation of the mineral resource of a remote region like NWT. Such arguments point to the added costs of production in the region, the inaccessibility of the area and the inhospitable climate. These perceptions ignore many historical examples where such problems did not stop the exploitation of natural resources; examples include California in the mid 19th century, the deserts of the Middle East, the North Slope of Alaska, the North Sea and, in the future, the MacKenzie Delta. Furthermore, as we look increasingly to the possibility of mining the moon and asteroids to meet resource needs, perception of the magnitude of the problems in exploitation of the NWT must also diminish.

We believe that estimated URV's given in Table 6 are based on mineral commodities that will occur in exploitable quantities. This is because:

(1) occurrence in the training set was based on the commodity having been present in economic concentrations, and

(2) the commodity was included in the URV only if it occurred in 37.5 percent of the non-Canadian locations possessing geology similar to the Canadian location.

CONCLUSIONS

This research represents a case study using the unit regional value technique of mineral resource evaluation. The procedure has been used to estimate the number, kinds and value of the mineral resources that will be discovered in the Canadian provinces and territories. Since the URV's and mineral production of other locations are used as a training set for the Canadian estimates, the Canadian estimates are likely to be conservative. This is because the URV estimates are based on the historical records of production of members of the training set and 1) no region is as yet completely exhausted of mineral resources, 2) technologies have changed economic concentration cutoffs. However, conservative resource estimates are not solely the province of URV estimates. Indeed, the use of single valued resource estimates has been consistently unsatisfactory. The URV estimates are meant to be viewed within a probabilistic framework and as an element of a set of estimates that incorporates the concept of uncertainty as a factor. Richard Sinding-Larsen (1981) has suggested that URV estimates represent a proportion of the upper half of the McKelvey Box, (McKelvey, 1973), that is the economically recoverable resources. The proportion of the total estimate represented by URV estimates, according to Sinding-Larsen, is the $(1-\hat{p}) \cdot 100$ percentile where $\hat{p}$ is the probability estimated from the training set.

More generally, through the URV approach, we have created a reproducible, objective method for evaluation of a region's mineral resources. Operational definitions of geologic factors and mineral resources are stressed. In this way we have created a methodology for translating concepts and subjective observations into a form which is amenable to algebraic manipulation. Formal testing of subjective geologic hypotheses about the relationship between lithology and mineral resources is possible. Further, since geologists often disagree over interpretations, the translation procedure is such that any objective observation can be modified in turn to reflect the range of alternative opinions.

The system as illustrated here could be extended to allow the input of geologic expertise and information other than that presented. For example the probability of occurrence could be modified by expert opinion of other geologists. This approach presents the decision maker or explorationist with a global view of the potential for mineral resource exploration and development over large areas of Canada. There are several points in the analysis where inputs by a decision maker could be included. The outcome of the analysis would then be a test of the sensitivity of the procedure to the incorporated changes and in this way the explorationist could "game-out" the decision to explore areas.

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FIGURE CAPTIONS

Figure 1. Comparison of observed frequency histogram of $\log_{10}$ URV (in 1967 U.S. dollars/ km^2) of the U.S. states with the expected normal distribution possessing the same mean and variance. The statistics of $\sqrt{b_1}$, b_2 and X^2_{12} are used in tests of the skewness, kurtosis and goodness of fit, respectively. NS means that the statistic is not significantly different from the value for a normal distribution.

Figure 2. Comparison of total production of mineral resources in U.S. states and Canadian provinces. The mean, XBAR, and standard deviation are estimated from the U.S. states.

Figure 3. The data cube exhibiting the three dimensions of characteristics, time and regions.

Figure 4. Generalized cybernetic input-output model of mineral resource development.

Figure 5. "Time-Petrographic" classification (from Menzie, 1977; modified by Watson, 1977).

Figure 6. Relationship between subdivisions of Canadian Precambrian and "time-petrographic" classification (after King 1977 and Labovitz, 1978).

Figure 7. Input-Output model of Figure 4 displaying relationships between varieties of time-petrographic inputs and mineral resource outputs.

Figure 8. Frequency distribution of the number of empty cells in an array of size 8 X 4 to which 50 observations had been assigned randomly according to the marginal proportions given in Table 3. This frequency distribution was generated using a "Monte Carlo" procedure the number of empty cells which would arise if the factors on each margin (1. classification of U.S. states by mineral commodity; 2. classification of U.S. states by "time-petrographic" unit) are independent of one another.

Figure 9. Scatter plot of richness of mineral resources ($S - I_C$) and richness of "time-petrographic" units ($S - I_G$) in Canadian provinces. Dashed line is due to Griffiths *et al.* (1979) and represents this relationship for other locations which have undergone URV studies.

Figure 10. Groupings based on "Time-Petrographic" units.

TABLES