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DATA INTEGRATION AND GEOCHEMICAL EVALUATION OF MEGUMA TERRANE, NOVA SCOTIA, FOR GOLD MINERALIZATION

by

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A thesis submitted to the school of Graduate
Studies and Research in partial fulfillment of the
requirements for the degree of M.Sc. in Geology

UNIVERSITY OF OTTAWA
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ABSTRACT

Five regional geoscience datasets, from the Meguma Terrane, eastern mainland Nova Scotia, were compiled and co-registered in a digital format suitable for analysis on a micro-computer based geographic information system (GIS). The datasets are bedrock geology, surficial geology, structural data, lake sediment geochemistry and gold occurrences. The objective of this study was to develop methodology to analyze this data in a GIS environment and to integrate this data to produce a map showing areas favourable for gold mineralization.

Principal component analysis was used to determine the multi-element associations of the lake-sediment geochemistry. There were four main associations explaining a total of 70% of the total variance: 1) Zr, Ti, Li, Th, Nb, F; 2) Cu, Pb, Zn, As, Sb; 3) Au , W; and 4) Sn. The first association suggests that a major control on lake-sediment chemistry is the concentration of resistate minerals by mechanical processes. The principal component scores were mapped using catchment basins as a reference for their zone of influence. Regression experiments indicate that the bedrock and surficial geology have very little influence on the spatial patterns of the multi-element associations.

Further regression experiments, using the presence of a gold occurrence as the dependent variable and the lake-sediment geochemistry as the predictor variables, were used to find the linear combination of geochemical elements that best predict lake catchment basins containing a gold occurrence. Au in lake sediment is found to be an excellent predictor of gold mineralizaton along with As and W to a lesser extent. A predicted gold occurrence map based on the geochemistry alone was produced which showed several areas with a favourable response but no reported mineral occurrences.

Finally, a method using Bayes' rule was applied to combine other factors important for predicting gold mineralization with the lake-sediment geochemistry. A unique conditions map was generated that shows the areas with a unique combination of all the predictive factors. For each area containing a unique combination, a posterior probability was calculated. A map was then generated showing these posterior probabilities for gold mineralization. Again, areas showing a high probability for gold mineralization with no known gold occurrences were indicated.

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ACKNOWLEDGMENTS

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Dr. P. Rogers who supplied the lake sediment geochemistry data base and insight concerning their analysis,

Colette, for her love.

1. Introduction

Geologists have used maps for recording data, conceiving ideas, analyzing concepts, predicting results, and for the presentation and communication of concepts to others. Using overlays or symbols to represent two or more sets of data on a single map is a form of data integration. Relating lithologic, geophysical and geochemical factors in an attempt to define a target zone for potential economic mineralization is a form of data integration and common practice for most exploration geologists. Analysis of this spatial type of data has often been qualitative due to problems such as the nature of the data, the amount of data, lack of training in quantitative techniques and time limitations.

With the rapidly evolving computer technology, has come automated systems for efficient storage, quantitative analysis and presentation of spatial information. These systems are generally known as Geographic Infomation Systems (GIS). For the geologist who has increasing amounts of spatial data available and pressures to develop cost effective exploration programs, this tool is a great asset. The GIS allows for fast and accurate data integration and quantitative analysis of diverse and large amounts of geological data.

Nova Scotia represents a good study area to carry out computer assisted data integration techniques combined with spatial analysis techniques. This is because of the large variety of existing regional geolgical and geochemical and geophysical surveys. Geophysical surveys include magnetic gradiometer, radiometric and gravity. Geochemical surveys include lake sediment, stream sediment and till geochemistry. Geological surveys include bedrock, surficial, structural and metamorphic studies.

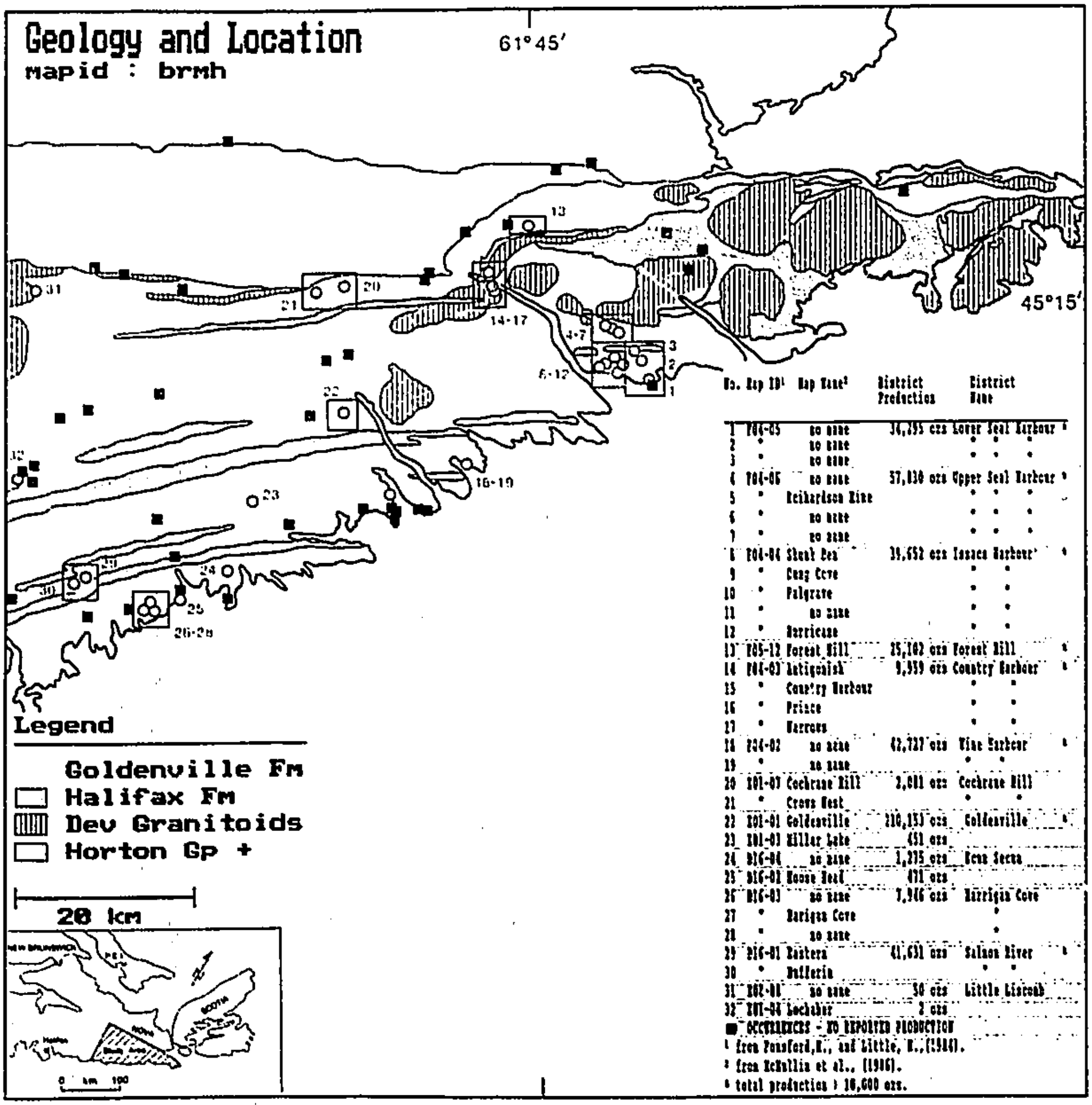
1.2 Objectives

There were three objectives for this project.

i) The first was to establish a digital data base, comprised of geological information related to gold mineralization in eastern Nova Scotia, that would be compatible with a micro-computer based geographic information system (GIS).

ii) The second was to develop methodology to analyze these spatial data bases in a generalized GIS environment. Special emphasis would be placed on handling lake sediment geochemistry and "proximity to" type data.

iii) The final objective was to apply this methodology to integrate the different data maps, to produce a final single map showing probabilities for potential gold mineralization.



Geology and Location

mapid : brmh

No.	Map ID[1]	Map Name[2]	District Production	District Name	
1	F04-05	no name	36,255 ozs	Lower Seal Harbour	*
2	"	no name		" " "	
3	"	no name		" " "	
4	F04-06	no name	37,830 ozs	Upper Seal Harbour	*
5	"	Richardson Mine		" " "	
6	"	no name		" " "	
7	"	no name		" " "	
8	F04-04	Skunk Den	39,652 ozs	Isaacs Harbour	*
9	"	Crag Cove		" "	
10	"	Palgrave		" "	
11	"	no name		" "	
12	"	Hurricane		" "	
13	F05-12	Forest Hill	25,102 ozs	Forest Hill	*
14	F04-03	Antigonish	9,559 ozs	Country Harbour	*
15	"	Country Harbour		" "	
16	"	Prince		" "	
17	"	Narrows		" "	
18	F04-02	no name	42,727 ozs	Wine Harbour	*
19	"	no name		" "	
20	E01-07	Cochrane Hill	2,081 ozs	Cochrane Hill	
21	"	Crows Nest		" "	
22	E01-01	Goldenville	210,153 ozs	Goldenville	*
23	E01-03	Miller Lake	451 ozs		
24	D16-04	no name	1,275 ozs	Ecum Secum	
25	D16-01	Moose Head	471 ozs		
26	D16-03	no name	7,946 ozs	Harrigan Cove	
27	"	Harrigan Cove		"	
28	"	no name		"	
29	D16-01	Eastern	41,631 ozs	Salmon River	*
30	"	Dufferin		" "	
31	E02-08	no name	50 ozs	Little Liscomb	
32	E07-04	Lochaber	2 ozs		

■ OCCURRENCES - NO REPORTED PRODUCTION

[1] from Ponsford, M., and Little, E., (1986).

[2] from McMullin et al., (1986).

* total production > 10,000 ozs.

Figure 1.1 Location of study area, Meguma Terrane, eastern Nova Scotia showing bedrock geology and gold occurrences.

1.3 Location of Study Area

The study area is restricted to the Meguma Terrane, mainland Nova Scotia (Figure 1.1). It comprises map sheets 11D16, 11E1, 11F4, 11F3, 11E8, 11F5, and 11F6 and has a total area of about 2,500 square kilometers.

Sheet Harbour, approximately 180 km east of Halifax, marks the south west corner. The western boundary extends along longitude 62^0 30′ and the eastern boundary is represented by the Strait of Canso and Chedabucto Bay. The Atlantic Ocean forms the southern boundary and the Chedabucto fault system forms the northern boundary.

2. GEOLOGICAL SETTING OF STUDY AREA

The study area (Figure 1.1) is underlain by the allochthonous rocks of the Meguma Terrane, predominantly a thick sequence of metamorphosed, flyschoid, Cambro-Ordovician quartz wackes and shales of the Meguma Group. The original source for the Meguma rocks has been proposed to be proximal to current north Africa (Schenk, 1971, 1973).

The Meguma Group consists of the basal Goldenville Formation and the overlying Halifax Formation. The Goldenville Formation has a minimum thickness of 16,000 m and consists of massive, thick bedded, flysh-like sandstones with thin interbeds of chloritic slate and siltstones. Sandstone beds range in thickness from a few to ten's of metres, while the slate interbeds have a maximum thickness of 2 m. The Halifax Formation has a thickness in the order of 11,000 metres and consists of grey to dark grey slate with thin interbeds of feldspathic sandstone. The slates are commonly carbonaceous and contain pyrite and/or pyrrhotite giving it a regional magnetic signature (Sangster, in press, Keppie, 1983, 1985).

The transition between the Goldenville Formation and Halifax Formation is important as it contains strata enriched in manganese (coticule), base metals, barium, arsenic and gold (Zentilli et al., 1986).

Devonian-Carboniferous granitic rocks, primarily of diorite and biotite monzogranite composition, intrude the Meguma rocks (Reynolds et al., 1981).

The Meguma Terrane was folded about northeasterly trending, subhorizontal axes during the Acadian orgeny. The folds tend to be broad and can extend along strike for over 100 km (Keppie, 1985).

The regional metamorphic grade is generally greenschist facies although grades of amphibolite facies occur in zones of plutonism (Taylor and Schiller, 1966).

Faulting is common in the Meguma Terrane. Structural trends of earlier folding are segmented by a prominent northwest trending fault system (Sangster, in press).

The surficial geology consists predominantly of quartzite till and granite till. These till sheets are generally thin (1-4 m), consist of >90% local clasts and show evidence of limited transport. Dispersion of definable till facies onto adjacent rock types is in the order of 0.8-3.0 km (Stea and Fowler, 1979). Lawrencetown till, commonly occurring as drumlins, consists of a mixture of local and "foreign" components. The matrix contains up to 25% red clay. Foreign pebbles of Carboniferous rocks and assemblages from the Antigonish Highlands and Cobequid Mountains (Stea and Fowler, 1979) comprise 10%-20% of the clast fraction. The principal ice directions are approximately to the south and southeast.

Gold Mineralization

The study area contains 68 known gold occurrences with 35 of these having an associated production. Some of the major geologic controls of these occurrences are mentioned below.

The non-placer gold in the Meguma Terrane generally occurs as hydrothermal related concordant gold vein deposits. These veins are commonly found within or on the upper margins of incompetent slate beds in the Goldenville Formation, on the domes, plunges or flanks of regional anticlines. Many of the districts are found on the steeper limb of the fold (Smith and Kontak, 1986).

Common minerals associated within the auriferous veins are quartz, arsenopyrite and carbonates (Mawer, 1986, Smith and Kontak, 1986).

Accesssory minerals found within gold bearing veins in significant amounts include pyrrhotite, galena, sphalerite, chalcopyrite and pyrite.

High levels of arsenic, tungsten, and antimony are associated with much of the gold mineralization (Kontak and Smith, 1987).

Some evidence (Mawer, 1986) has been given to suggest a positive correlation between gold occurrences and the horizontal distance from the Goldenville-Halifax Formation transition zone, the chlorite-biotite isograd and the Devono-Carboniferous granitic intrusions.

Studies of the relationship of gold occurrences to lineaments in the Meguma rocks west of the study area (Bonham-Carter et al., 1985) show lineaments oriented ENE-NE, parallel to bedding, have a statistically significant association with gold occurrences. Also, lineaments oriented in the direction NNW-NW showed a spatial association with gold occurrences.

In summary, some of the major geologic controls that may be related to gold mineralization in the Meguma Terrane include proximity to anticlines, Goldenville-Halifax contact, Devono-Carboniferous granite contact, chlorite-biotite isograd, and possibly north west trending fractures. Chemically anomalous values of arsenic, tungsten, antimony, silica and calcium would be expected. Finally the slate beds in the Goldenville Formation would be expected to be the host rock.

3. DATA SOURCES AND DESCRIPTIONS

3.1 Lake sediment geochemistry

A regional centre-lake sediment survey was conducted in the Meguma Terrane of southern Nova Scotia during 1978 and 1979 (Richardson and Bingley, 1980, Bingley and Richardson, 1978). This resulted in approximately 4000 samples collected at a density of 1 per 2 square miles. These samples were analyzed for Cu, Pb, Zn, Ag, Ni, Co, Fe, Mn, Ca, Mg, Mo, Hg, As, U, and LOI using the procedures set by the National Geochemical Reconnaissance (NGR) Program of the Geological Survey of Canada.

Further studies (Richarson et al., 1982, Chatterjee et al., 1984) found the elements Zn, Cu, Th, Li, F, Sn, Cl and Rb significant in terms of hydrothermal mineralization. Since most of these elements were not analyzed in the 1977 and 1978 surveys, the same samples were re-analyzed for the latter suite (Rogers et al., 1985).

A summary of the analytical methods are shown in Table 3.1.

A computer tape with the results of the reanalyzed data was obtained from the NSDME. Samples that fell within the study area were selected from this tape file. A total of 438 samples were within the study area.

Table 3.1 Summary of elements and analytical methods used to analyze lake sediments. (from Rogers et al., 1985).

Elements	Method	Detection Limit
Cu, Pb, Zn, Li	Atomic Absorption Spectroscopy	1.0 ppm
Ag		0.1 ppm
F	Specific Ion Electrode	20 ppm
Sb, Rb, Sn, Zr	x-ray Fluorescence	1.0 ppm
Ti		10 ppm
As, W	Instrumental Neutron Activation	1.0 ppm
Th		0.5 ppm
Sb		0.2 ppm
Au		5.0 ppb

Quality Control

The methods used for quality control on this data were carried out according to specifications outlined by the Geological Survey of Canada in consultation with the Nova Scotia Department of Mines and Energy. Detailed descriptions of field collection and analytical methods are given in Garrett (1974) and Garrett et al., (1980).

The precision and accuracy of the analytical variance was monitored by incorporating a field duplicate, blind duplicate (a split of the field duplicate) and a control reference in every analytical block of twenty samples.

The control references, a natural sample of known approximate concentration, were used to monitor the accuracy through repeated analysis. For a block of 20 samples to be acceptable for all elements on the basis of the control reference sample, the values for each element must fall within ±2.5 standard deviations of the mean of the control reference (John Lynch, Geological Survey of Cananda, pers. comm.)

The precision was monitored by measuring the differences between the duplicate pairs. For each element in the blind duplicate pair the following expression was calculated:

$$\frac{V_1 - V_2}{V_{1,2}} \quad X \quad 100$$

where V_1 = the value of the element in the first member of the duplicate pair

V_2 = the value of the element in the second member of the duplicate pair

$V_{1,2}$ = the mean of V_1 and V_2

For a block of 20 samples to be acceptable for all elements, the percentage as calculated above must fall within the tolerances specified by the overseeing analytical geochemist. A list of tolerances used for this data is included in Appendix A.

3.2 Bedrock Geology

The lithology for the study area was taken from an unpublished geology map compiled at 1:150000 by Dr. Duncan Keppie of the Nova Scotia Department of Mines for this project.

3.3 Suficial Geology

The surficial geology was taken from maps produced by Stea and Fowler (1979).

3.4 Structure

The structure was derived from tectonic maps of Nova Scotia compiled by Keppie (1982)

3.5 Gold deposits

The gold deposit locations were taken from the Nova Scotia Department of Mines and Energy MOD (Mineral Occurrence Data base) file and from maps by Ponsford and Lyttle (1984) and McMullin et al., (1986). A total of 68 occurrences were selected. These were divided into three groups; producing mines with total production of over 10000 oz., producing mines with total prodution of less than 10000 oz. and non-producing mines (occurrences). The major deposits and gold districts are summarized on Figure 1.1.

4. DATA PREPARATION

4.1 Introduction

Five levels of data were prepared for this project. These were lake sediment geochemistry, structure, surficial geology, bedrock geology and gold deposit locations. These data bases can be generalized to fall into three types; polygon data, line data and point data.

The lake geochemistry can be initially considered as point data, but because they are represented in terms of their associated catchment basins they are grouped as polygon type data. The bedrock and surficial geology are also polygon type data bases with different geologic units represented by polygons.

The structural data base contains information related to lineaments, faults and fractures. These are linear features and so the structural data base is classed as a line type data base.

The deposit locations are considered as point data because they are represented on the map as points.

Although there are common factors in the preparation of each of the three types of data bases, there are significant differences that make it easier to describe the preparation method for each type separately.

4.2 Polygon Data

A complete description of the production of digital maps of regional stream geochemical data analyzed by catchment basin analysis is given in Ellwood et al., (1985). The steps followed in that procedure are generally the same for any polygon type data.

The basic steps involve first, to plot the sample sites on a stable base at the same scale as the topographic map showing drainage of the study area. This stable base and a second unmarked stable base are placed over the topographic map making sure the sample locations are registered correctly on to the topographic map. Using the topography, the boundaries of the sample catchment basins are then inked onto the second overlay. A "neat line" must be inked in to define the limits of the study area. The overlay with the catchment basins inked on is then digitized using a drum scanner.

The geology maps are generally easier to generate. The process usually involves a direct tracing of the geologic contacts from the geology map to a clean stable base, creating the polygon boundaries. Again, a neat line must be drawn to define the study area. The geology maps are digitized in the same manor as the catchment basin maps. The digitizing process is described in Bonham-Carter et al., (1983).

The end result is a computer file containing a raster image.

The final step is to create a lookup table that links the polygon on the map to specific information. In the case of the catchment basin map it would be the geochemical data and for the geology map it would typically be rock type. Other attributes for geology might be age, metamorphic grade or mineralization.

4.3 Line Data

Geologic structure is an excellent example of line type data and is the only type of line data used for this project. The significant difference between line data and polygon data is that the lines do not close on themselves.

Again it is a simple matter of tracing the structure onto a stable base from the lineament map and having it digitized by a drum scanner.

An alternative to the drum scanner for simple cases is to digitize the information manually using a digitizing table and the appropriate software.

4.4 Point Data

This is the easiest data to prepare. In the simplest case, no digitization is necessary. The only requirement is a file containing the location coordinates, usually UTMs, in the same projection as the other data bases. In cases where UTM coordinates are not present, they can be entered using the digitizing table. Again, a lookup or attribute file can be generated for each location containing information regarding the nature of the deposit such as tonnage, secondary mineralization, alteration and production figures.

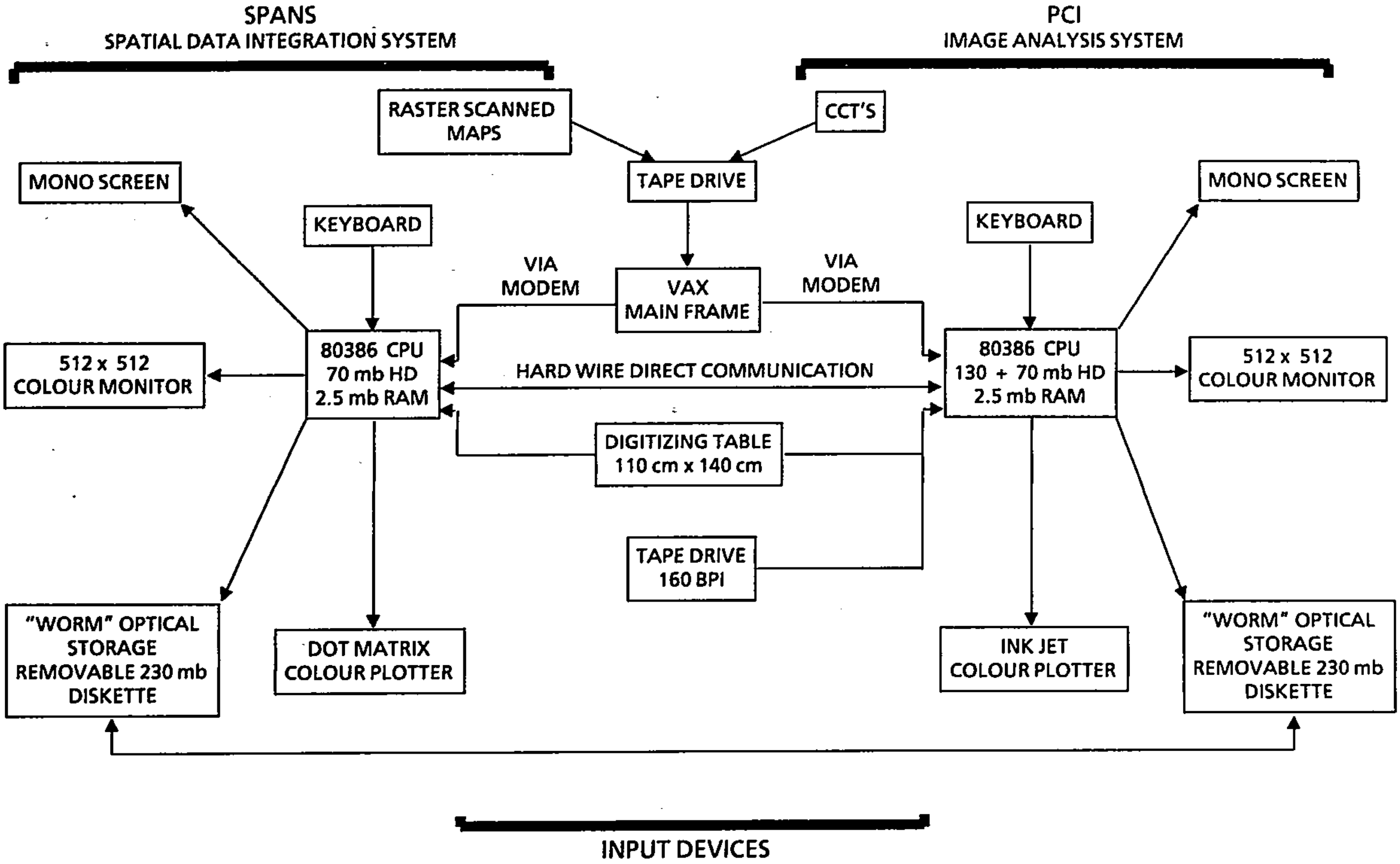
4.5 Computing Requirements

4.5.1 Software

Two commercially available software packages were used in this study to deal with analyzing and creating output from multi-layered spatial data sets.

The first package, called EASI-PACE and developed by the Toronto based company PCI, is designed for image analysis of grey-scale imagery. Remote sensing and airborne geophysical data are typical grey-scale imagery and software functions would include convolution operations for enhancement, filtering and edge detection.

The second package, called SPANS (SPatial ANalysiS) and developed by the Ottawa based company TYDAC, deals primarily with spatial data analysis and handles point, line and thematic maps more readily than the PCI software. The SPANS software stores and processes images using a "quad-tree" system. This system allows a variable pixel size so that large areas of a common theme can be stored as a single pixel thus reducing the amount of memory required.



SYSTEM CONFIGURATION

Figure 4.1 Illustration of geographic information system and image analysis system with communication links between them.

Data generated with other DOS compatable software, such as statistical packages of text-editing packages, can easily be imported into either of these two systems.

All the processing for this study was done using the SPANS system.

4.5.2 Hardware

The system is centered around two 80386 micro-computers operating with the disk operating system (DOS). The unit hosting the SPANS software has a hard disk with a memory capacity of 70 Mb and a random access memory of 2.5 Mb. The unit hosting the PCI software has a hard disk with a memory capacity of 230 Mb and a random access memory of 2.5 Mb. The larger memory is required because of the large size of the images processed by the PCI system.

Data can be input into either system from main-frame computers via a modem, floppy diskettes, digitizing table or keyboard. The digitizing table has a relatively large surface of 100 X 130 cm so that larger maps do not need to be digitized in sections and joined later through software. The PCI system also has its own 1600 bpi tape drive allowing data input directly, eliminating the need to go through the main frame.

Data from either system can be output on a 19 inch colour monitor, a monochrome monitor, a colour ribbon impact printer that permits plots of up to 17 inches wide or an inkjet plotter that permits plots of up to 11 inches wide.

In addition, each system has an optical disk drive with removeable diskettes containing 230 Mb of memory, used for backup.

5. ANALYSIS OF LAKE SEDIMENT GEOCHEMISTRY

5.1 Introduction

The goals of this section of the study were to characterize and interpret the multi-element compositional and spatial patterns in the lake sediment geochemical data and to analyze the influence of the bedrock and surficial geology on the lake sediment geochemistry.

The lake sedimemt chemistry was represented using catchment basins as described in Chapter 4. In this process each sampled lake was associated with its catchment basin, digitized as a polygon whose colour or pattern denoted element content. This provided an alternative to representing the data as symbols at sample points or as a regular grid using an interpolation method. Catchment basins have been used by Bonham-Carter and Goodfellow (1984,1986) in a study of the relationship between mapped geology and stream sediment geochemistry in the Nahanni River area, Yukon. Bonham-Carter et al. (1987) used a similar approach in the Cobequid Highlands, Nova Scotia. Some advantages of basin analysis were: 1) basins could be considered as the spatial zone of influence of samples, for display purposes: 2) basins could be used as a "grid" for sampling other maps.

Using this approach, maps of bedrock and surficial geology and mineral occurrences could be "sampled" by the lake sediment catchment basins. Data from these maps were appended to attribute tables. The attribute table consisted of a set of location identifiers with a list of descriptive variables associated with each location identifier. In this case each catchment basin was described in terms of its geochemical composition (chemical attributes), as well as geological composition (geological attributes), and evidence of mineralization (mineral occurrence attributes).

5.2 Multi-element associations - Principal Component Analysis

5.2.1 Methods

Principal components analysis was employed, outside of SPANS, to search for multi-element associations, using a commercial statistical package named SYSTAT (System for Statistics). New columns were added to the geochemical attribute file containing principal component scores on the first 4 axes. These newly derived variables could then be mapped with SPANS.

5.2.2 Results

Table 5.1 shows the varimax-rotated principal component loadings for the 16 elements. Logarithims of the analysis were used to give the data a log normal distribution. The first four component axes explained a total of 70 percent

Table 5.1 Principal component loadings for first four axes on all elements of lake sediment data.

VAIABLES	PC-1	PC-2	PC-3	PC-4
Zr	0.903*	0.101	0.015	0.107
Rb	0.893*	0.179	0.149	0.202
Ti	0.881*	0.202	0.062	0.002
Li	0.732*	0.306	0.086	0.378
Th	0.732*	0.409	0.115	0.127
Nb	0.716*	0.027	.080	-0.082
F	0.629*	0.299	0.240	0.393
Cu	0.033	0.774*	0.132	0.059
Zn	0.098	0.770*	0.032	0.386
As	0.208	0.699*	-0.162	-0.282
Pb	0.358	0.569*	0.184	0.019
Sb	0.390	0.534*	0.167	-0.019
Au	0.011	0.031	0.890*	0.055
W	0.270	0.159	0.795*	0.025
Sn	0.171	-0.007	0.034	0.844*
TOTAL VARIANCE	32.04%	18.33%	10.95%	8.803

* Multi-element grouping for each principal component

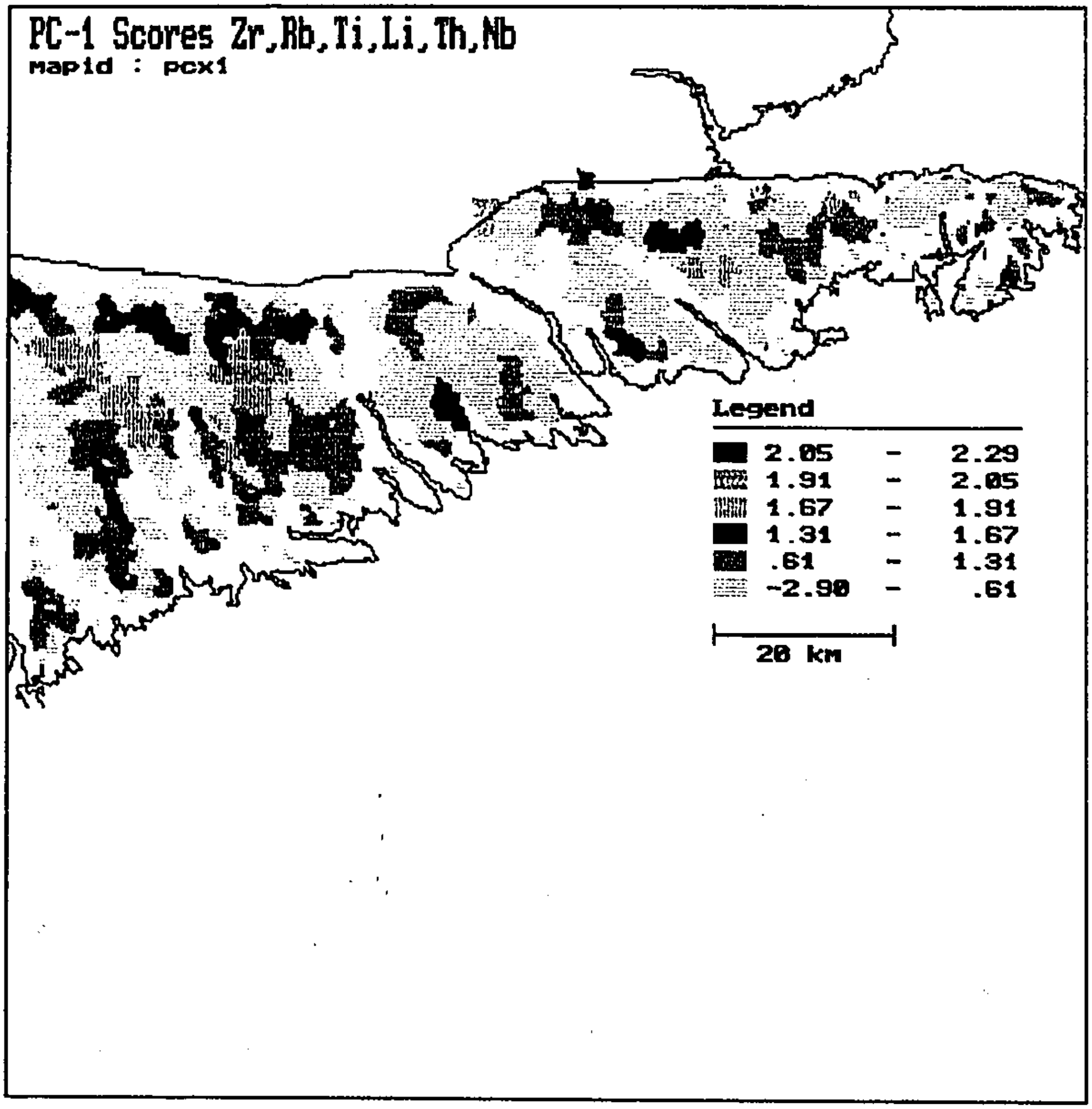

PC-1 Scores Zr,Rb,Ti,Li,Th,Nb
mapid : pcx1
Legend
2.05 - 2.29
1.91 - 2.05
1.67 - 1.91
1.31 - 1.67
.61 - 1.31
-2.90 - .61
20 km

Figure 5.1 Map showing spatial distribution of principal component 1 scores. Shows association of Zr, Rb Ti, Th, Nb, and F and explains 32.04% of total variance. The legend values are the scores calculated for each sample using the loadings from Table 5.1. They are grouped by percentile. The descending values of the percentile cutoffs are 98th, 95th, 90th, 80th, 70th, and 60th.

of the total variance. Component scores for each sample on each component axis were calculated and plotted in Figure 5.1 to 5.4 to facilitate interpretation.

PC1 was a strong association of Zr, Rb, Ti, Th, Nb, and F and explained 32.04% of the total variance in the data. Figure 5.1 indicated that, except for a weak NW trending zone in the most westerly portion of the study area, PC1 did not exhibit a distinctive spatial pattern nor correlate strongly with any particular rock type.

This element association was similar to that found by Fortescue and Stahl (1987) from lake sediments in the Sturgeon Lake area of Ontario. Based on low LOI/element ratios, they suggested that this group reflected the mineral matter content of the lake sediments rather than the variations in the geochemistry of the bedrock and/or Quaternary deposits. This means that sediments were not a simple representation of the lithologies immediately underlying them, but represented a mixing and sorting of the regional lithologies and surficial deposits.

One possible mechanism for producing the strong association, which persisted after several additional PC analyses were carried out on various data partitions, was that it is caused by resistate minerals concentrated by mechanical transport. Giles (pers. comm.) has suggested this mechanism for a similar suite of elements in lakes from the Liscomb area.

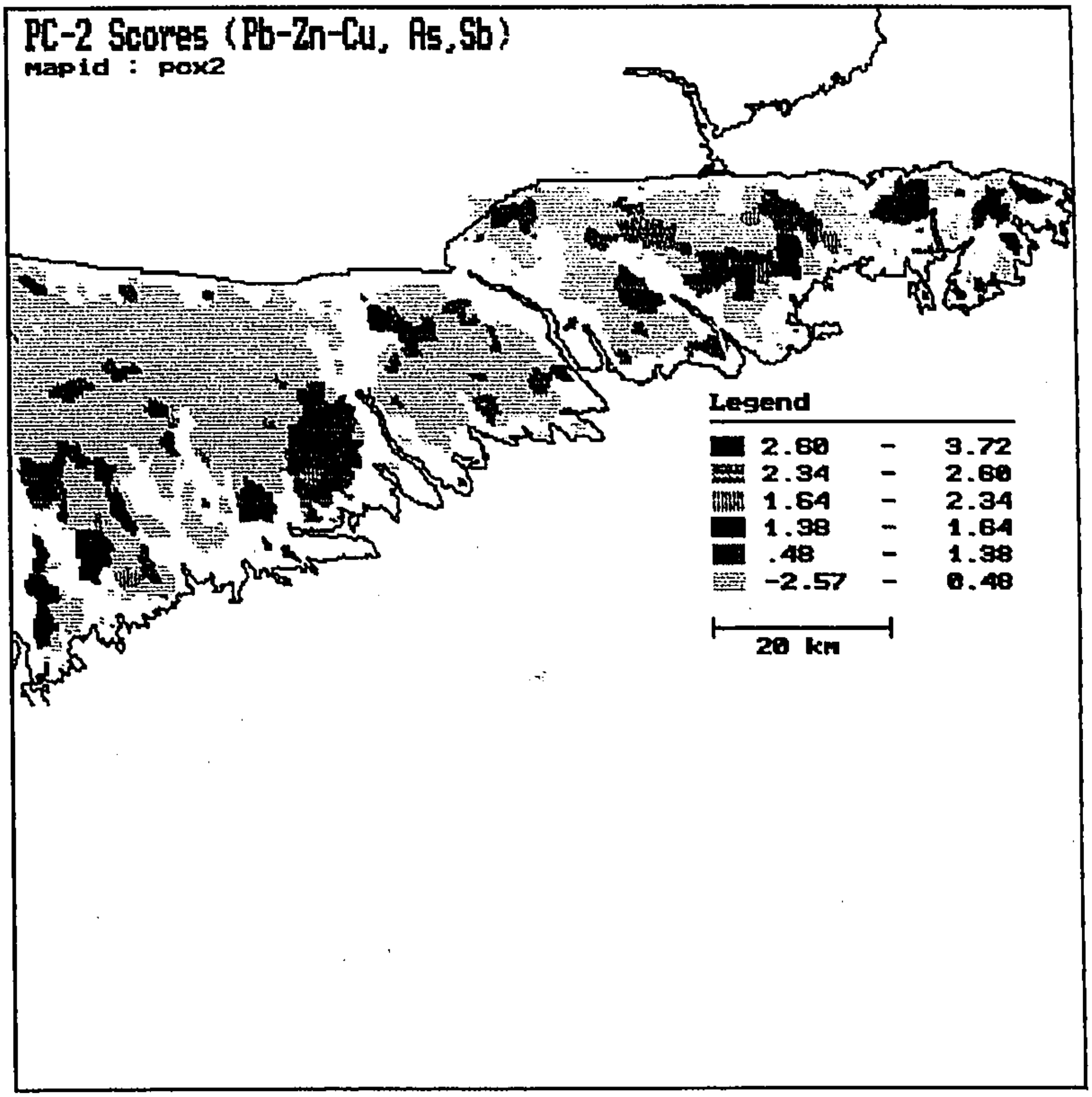
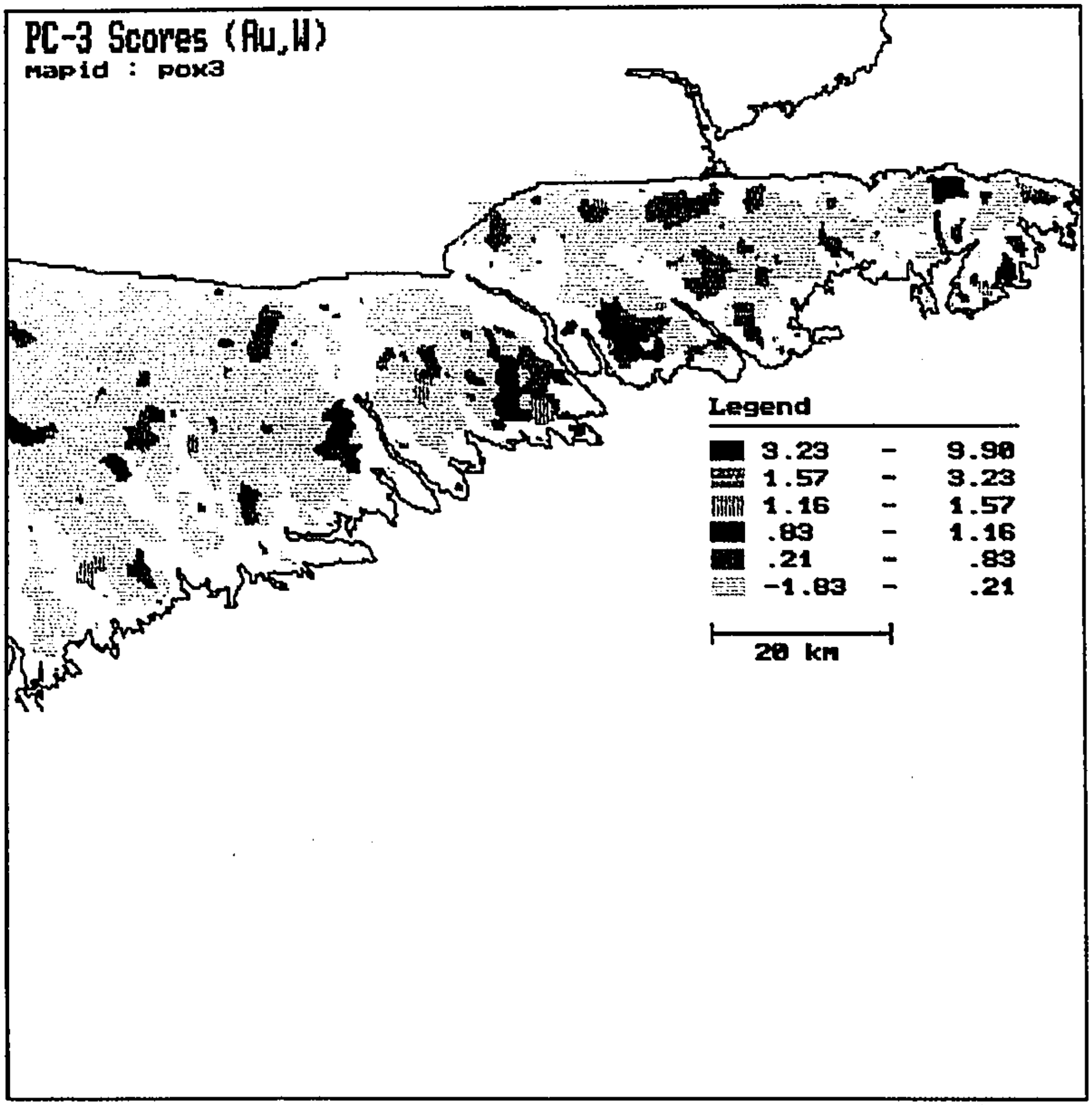

PC-2 Scores (Pb-Zn-Cu, As,Sb)
mapid : pox2
Legend
2.60 - 3.72
2.34 - 2.60
1.64 - 2.34
1.38 - 1.64
.48 - 1.38
-2.57 - 0.48
20 km

Figure 5.2 Map showing spatial distribution of principal component 2 scores. Shows association of Cu, Pb, Zn, As, and Sb and explains 18.32% of total variance. The values in the legend are scores calculated using the loadings in Table 5.1. The scores are grouped by percentile. The descending order of the percentile cutoffs are 98th, 95th, 90th, 80th, 70th and 60th.

Rogers (1987), identified zircon, monazite, ilmenite, and fluorapatite from Meguma Terrane lake sediments on the Halifax Peninsula. These minerals could explain the Zr, Th, Ti and F in the association, although the Rb, Li and Nb remained problematic. The strong NW grain in the western part of the area was partly an artifact due to the drainage pattern, but was also strongly influenced by a strong NW Zr trend that appeared to terminate in the Liscomb pluton. This may represent the influence of glacial transport SE from the granite, carrying zircon-rich debris.

PC2 was a strong base metal association of Cu, Pb, Zn and of As and Sb. It explained 18.32% of the total variance. Again, a weak NW trending zone appears in the western part of the study area as shown in Figure 5.2.

This association may reflect sulphide mineralization, although there is no hard evidence to support this. The NW trend may again be an artifact of the drainage pattern, reflect the ice direction patterns , or may be related to NW fractures which are associated with base metal mineralization in other parts of Nova Scotia. Fortescue and Stahl (1987) found a somewhat similar association in the Sturgeon Lake area, but in conjunction with Fe and Mn. Their interpretation was that of scavenging by Fe and Mn hydroxides in the surficial environment. The present suite of analyses did not include Fe and Mn, so this hypothesis could not be tested.



PC-3 Scores (Au,W)
mapid : pox3
Legend
3.23 - 9.90
1.57 - 3.23
1.16 - 1.57
.83 - 1.16
.21 - .83
-1.83 - .21
20 km

Figure 5.3 Map showing spatial distribution of principal component 3 scores. Shows association of Au and W and explains 10.94% of total variance. The values in the legend are scores calculated using the loadings in Table 5.1. and are grouped by percentiles. The descending order of the percentile cutoffs are 98th, 95th, 90th, 80th, 70th, and 60th.

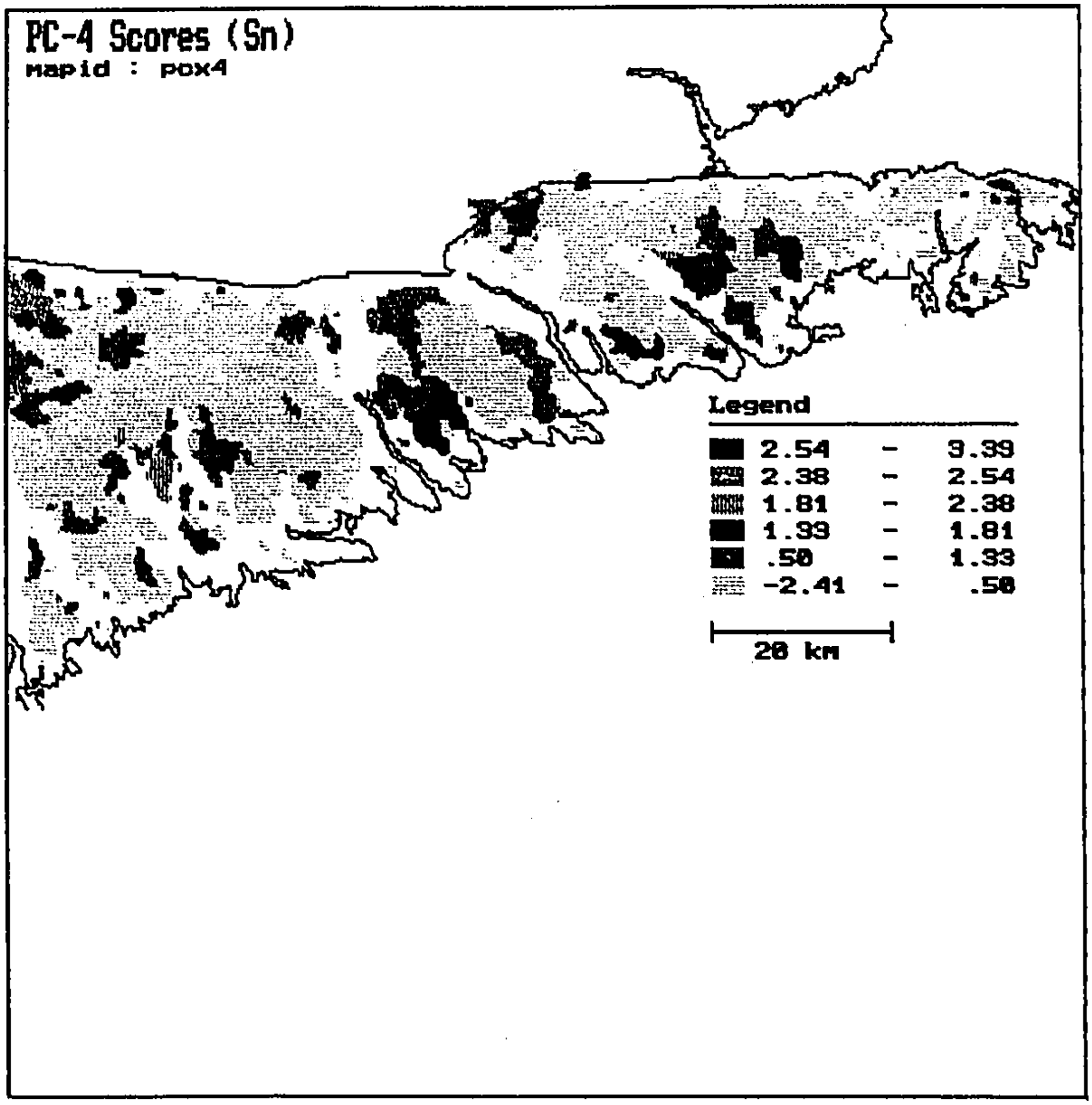

PC-4 Scores (Sn)
mapid : pcx4
Legend
2.54 - 3.39
2.38 - 2.54
1.81 - 2.38
1.33 - 1.81
.50 - 1.33
-2.41 - .50
20 km

Figure 5.4 Map showing spatial distribution of principal component 4 scores. Shows Sn standing on its own and explains 8.03% of total variance. The values in the legend are scores calculated using the loadings in Table 5.1 and are grouped by percentiles. The descending order of percentile cutoffs are 98th, 95th, 90th, 80th, 70th and 60th.

PC3 was almost solely an Au - W association and explained 10.94% of the total variance. Figure 5.3 shows that there is a strong relationship between the high PC3 scores and known gold districts. The high scores indicated on the map as red zones, from west to east, correlate with the easterly extension of the Fifteen Mile Stream deposit area, Goldenville district and the Seal Harbour district respectively. It was recognized that this association may be strongly related to contamination and that this possibility should be further investigated.

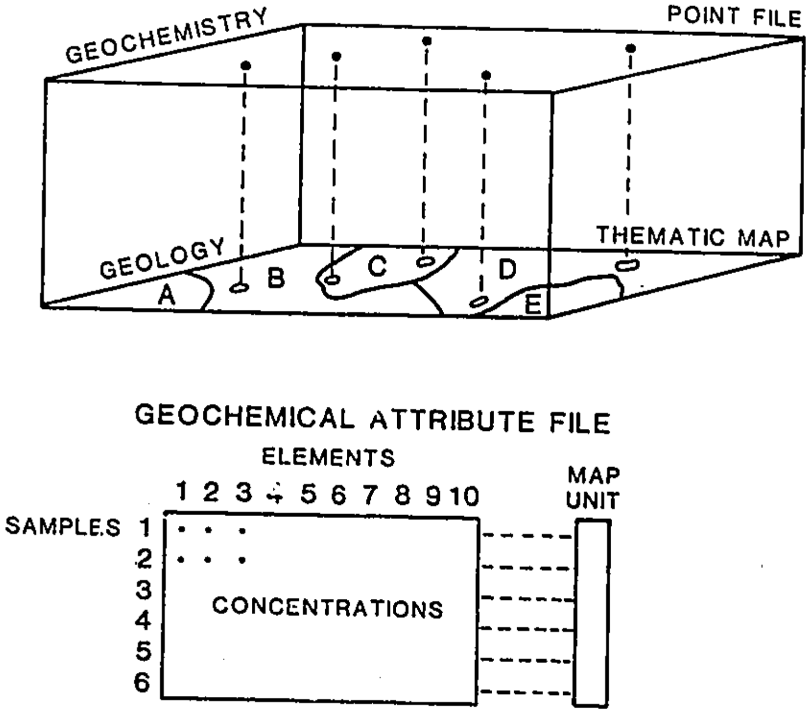
Finally, Sn stood out on its own in PC4, and showed some affinity with granites (Liscomb pluton in the far NW, and Sherbrooke pluton in the centre of the area, Figure 5.4).

5.3 Relation to geology

5.3.1 Methods

Figure 5.5 illustrates two possible methods for analyzing the influence of the geology on the geochemical signature. Because the lakes were sampled at points, and the geological map consisted of mutually exclusive regions, or geological units, either the map unit actually occurring at each sample site could be used, or the sample points could be converted to regions (the catchment basins), and then overlain onto the geological units. In SPANS these two functions are called point select and two-map overlay, respectively.

A. POINT SELECT.



B. TWO-MAP OVERLAY.

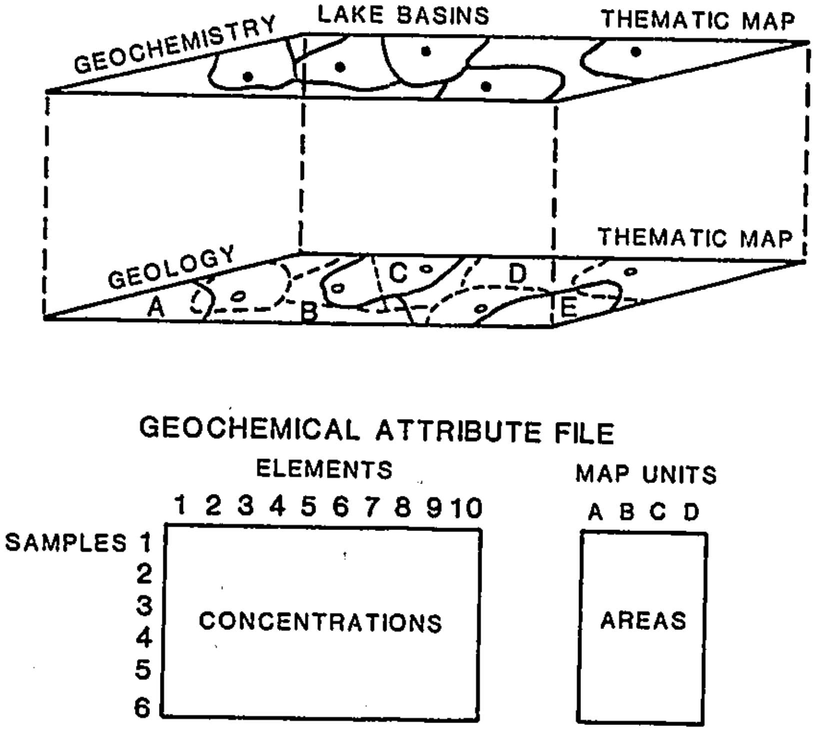


Figure 5.5 Illustration of two possible methods to evaluate the relationship between a regional geochemical survey and the geology. Method A illustrates the procedure for when the geochemical data is considered as point data; while Method B illustrates the procedure for when the geochemical data is considered as polygon data (eg. catchment basins).

In the point select method, the geological unit is selected for each sample site, and added as an extra column to the attribute table, Figure 5.5. In the two-map overlay method the area of each geological unit is measured for each catchment basin, and a new column added to the attribute table for each geological unit. The advantage of the latter method, used in this study, is that the geology of the catchment area as a whole is represented, not just the geology at the sample site.

Using the mixing model described by Bonham-Carter and Goodfellow (1984), a regression equation was solved for each element in turn which found a set of coefficients, one for each rock unit. These coefficients were determined by minimizing the sum of squared differences between observed concentrations and those predicted by the mixing model. The success of this model was measured by the squared multiple correlation coefficient R^2; $100R^2$ gave the percentage of total sum of squares 'explained' by the mixing model.

5.3.2 Results

Each of the 16 elements (using logarithms) was regressed on the lithologic units underlying the catchment basins, represented as areal proportions, (Bonham-Carter and Goodfellow, 1984). Table 5.2 summarizes the proportion of the total variation explained by the regression for each element. It was seen that lithology only accounted for .3%

Table 5.2 Proportion of total variance of each element accounted for by areal proportions of a) bedrock geology units, b) surficial units, within catchment basins.

ELEMENT	BEDROCK	SURFACE
	$100R^2$	$100R^2$
Cu	3.0	2.7
Pb	3.4	7.3
Zn	2.6	9.4
Ag	1.3	1.9
F	2.7	7.6
Li	11.6	14.0
Nb	4.5	8.8
Rb	8.9	12.6
Sn	0.7	3.3
Zr	1.6	9.3
Ti	0.8	9.4
Au	0.3	2.8
Sb	2.6	9.1
As	3.8	6.0
Th	0.9	7.7
W	3.0	3.7

to 11% of the variation in the chemical concentrations. Based on similar studies in the Cobequid Higlands (Bonham-Carter et al., 1987) and the Selwyn Basin (Bonham-Carter et al., 1984) where the lithology explained between 30 and 60 percent of the variance, the results from this study indicated that the mapped bedrock units had very little influence on the spatial distribution of the element concentrations.

Similar regression experiments were conducted regressing the 16 elements on the areal proportions of the surficial units that underlie the catchment basins, also shown in Table 5.2. Again the variation in the chemistry accounted for by the surficial deposits was very low having a maximum of 14%.

This was in marked contrast to other lake sediment studies (Friske, 1985) which have shown a very strong correlation of lake sediment geochemistry to underlying bedrock and related tills. The main reason for this difference is likely related to the similarity of the geochemistry of the major lithological units within the study area. Another possibility may be a mixing of the sediments from all sources resulting in a masking of the influence of each individual lithologic or surficial unit.

Only three major bedrock units are present in the Meguma Terrane, and the background concentrations of many elements do not show a strong partition between the units.

5.4 Conclusions

Principal component analysis suggested that a major control on the lake sediment chemistry was the concentration of resistate minerals by mechanical processes. A second major control may have been due either to scavenging by Fe, Mn hydroxides, or possibly to sulphide mineralization. A third control, producing the Au-W association, was related to gold mineralization.

The use of areal proportions of the mapped geological units (Goldenville Formation, Halifax Formation and Devonian Granites) and the surficial deposits are not successful in explaining the variance in the concentration of the elements in the lake sediments or indicating a strong partition between element concentrations and the different units. The geochemical similarity of the major lithological units within the study area was the reason for the lack of correlation.

6. PREDICTING GOLD OCCURRENCES - REGRESSION ANALYSIS

6.1 Introduction

The goal of this section was to investigate the relationship between known gold mineralization and the lake-sediment geochemistry, and then determine whether new areas for exploration follow-up were indicated. As in Chapter 5, the lake-sediment geochemistry was represented using catchment basins which were then used to sample the mineral occurrence map.

6.2 Method

In the GIS environment, the problem was how to measure the association between two point datasets - mineral occurrences on the one hand, and geochemical samples on the other. Again the catchment basin map was used to 'sample' the mineral occurrences file.

Regression outside SPANS was then employed to determine the best linear combination of geochemical elements for predicting basins containing a known occurrence. Ordinary and stepwise multiple linear regressions were employed, although logistic regression might have been more appropriate (Bonham-Carter and Chung, 1983).The ordinary least squares method produced readily interpretable results. Again, new columns for predicted scores were added to the basin attribute file, for display with SPANS.

6.3 Results

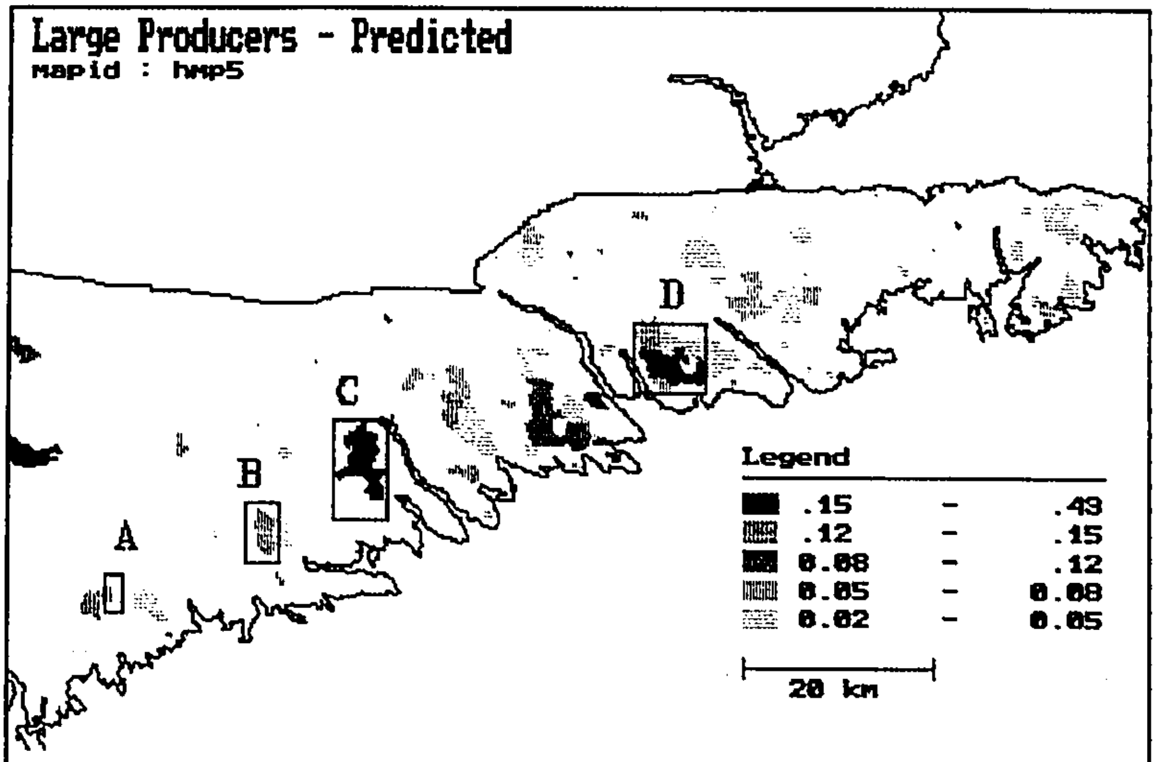
Table 6.1 shows the results of regression experiments that predict those lake catchment basins containing reported Au mineralization, in terms of the best linear combination of the logarithms of lake-sediment Au, As, W and Sb. The first experiment shows the results for all Au-occurrences ; the second for all occurrences with known Au production; the third for all Au occurrences with more than 10,000 ozs. production. The suite of elements was selected partly on statistical evidence, and partly on geological reasoning.

The prediction became more reliable using data from the larger producers, as was indicated by the R^2 values as they increased from 6.9% (all occurrences including mines) to 13.0% (all mines) to 25.3% (larger mines). In each case, the logarithm of Au concentration was the strongest predictor of Au mineralization. Log W was not a good predictor for all occurrences, but becames more important for mines. Log As was a good predictor of occurrences, but was less important for predicting the Au mines. Log Sb was not a strong predictor of Au-mineralization, based on these results.

In regression terms, the ability of lake sediment Au to predict Au-mineralization was perhaps surprisingly strong, and the predictive map based on the regression scores, Figure 6.1, confirmed that most of the major gold districts that fall into catchment basins showed a favourable response.

Table 6.1 Regression coefficients for predicting presence/absence of Au mineralization in catchment basins, a) all mines and occurrences, b) all mines (producers), c) mines > 10000 ozs. total production. The F-test and squared multiple correlation coefficient (R^2) are included to indicate the overall goodness of fit and amount of variance explained.

	ALL MINES + OCC		ALL MINES		LARGE MINES	
PREDICTORS	COEFF	STD ERR	COEF	STD ERR	COEF	STD ERR
CONSTANT	-.135	.054	-.110	.036	-.128	.024
ln Au	.209	.047	.185	.031	.196	.021
ln As	.046	.020	.020	.014	.009	.009
ln W	-.009	.066	.042	.044	.037	.029
ls Sb	.006	.051	.025	.034	.005	.022
F-Test	8.008		16.144		36.464	
R^2	.069		.130		.253	



A - Salmon River
B - Miller Lake
C - Goldenville
D - Seal Harbour/Issacs Harbour

Figure 6.1 Prediction of lake drainage basins that will contain Au mineralization. The prediction was based on regression analysis using lake sediment geochemistry from catchment basins that contain gold mines with greater than 10,000 ozs. The values in the legend indicate a favourability index where the higher values indicate a higher chance for gold mineralization.

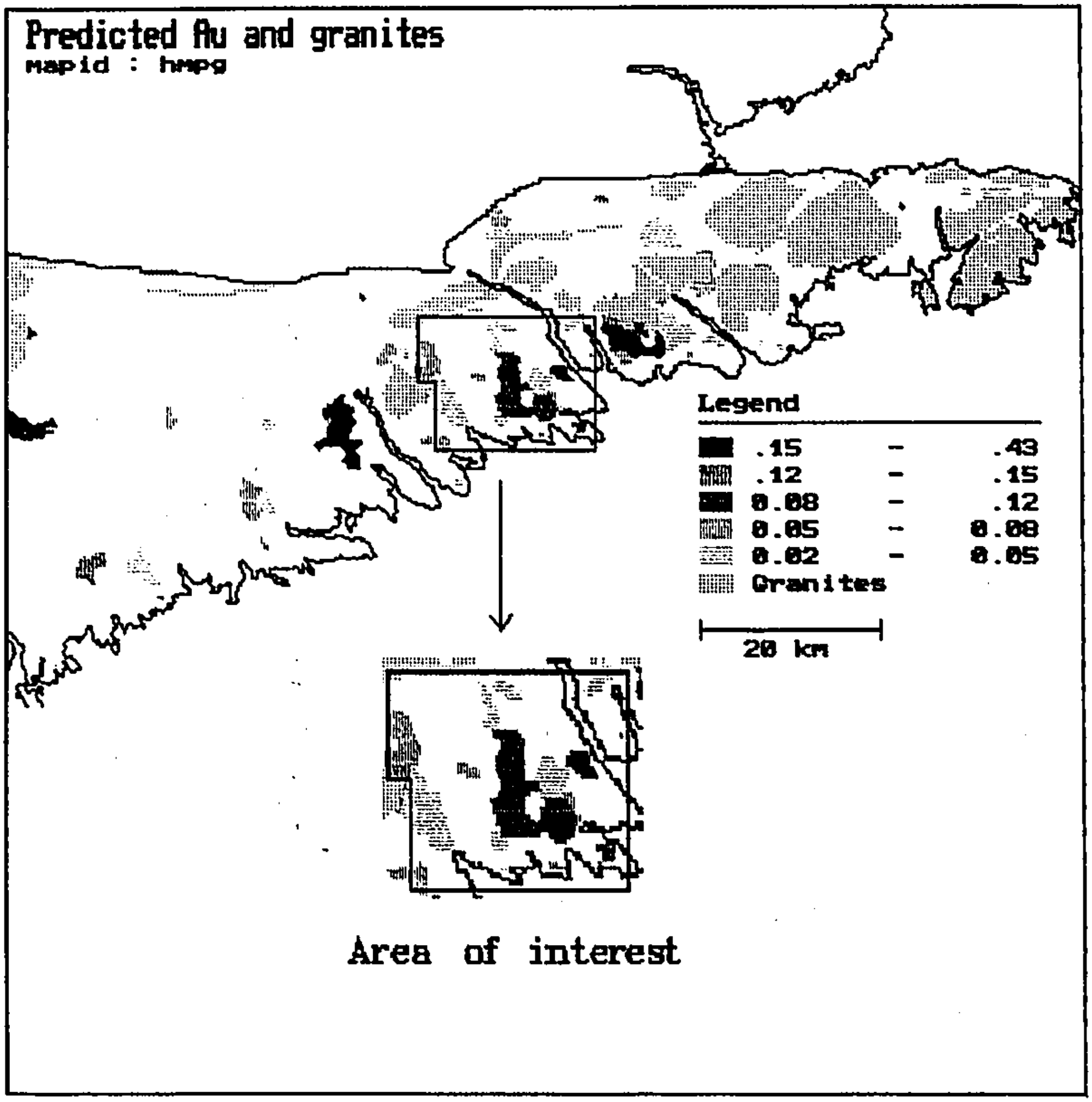

Predicted Au and granites
mapid : hmpg
Legend
.15 - .43
.12 - .15
0.08 - .12
0.05 - 0.08
0.02 - 0.05
Granites
20 km
Area of interest

Figure 6.2 Same as Figure 6.1 with Devonian granites and mineral occurrences overlain, where they occur in sampled catchment basins. Note favourable regions with no reported mineralization.

In Figure 6.2, the results of Figure 6.1 were overlain by the Devonian granites, because granites do not host the typical Meguma gold mineralization. This elminated basins that showed good potential for gold mineralization but were underlain by granites. Several additional areas were suggested for exploration follow-up, particularly in the area east of the Sherbrooke pluton, between the Goldenville and Seal Harbour districts. Lakes in this area showed a generally favourable potential for Au mineralization.

The lake sediment signature associated with large gold producers was almost certainly influenced to some extent by erosion of mine tailings, and Au may have moved quite large distances due to the relative mobility of the Au-Hg amalgam produced during the extraction process. Unfortunately, Hg was not one of the elements analyzed so this hypothesis could not be checked. Nevertheless, one may argue that the multi-element geochemical signature associated with Au-mine tailings will be a good estimate of the signature associated with unworked mineralization. It may differ, however, from the signature to be expected from buried deposits, where no mechanical erosion was involved and transport was only hydromorphic. Therefore the areas with a relatively strong signature, Figure 6.2, where no workings have been reported certainly suggested the presence of near-surface mineralization, exposed to mechanical erosion.

6.4 Conclusion

Direct prediction of Au mineralization using known gold mines with greater than 10,000 ozs. production showed that lake sediment Au was an excellent predictor, and that a multi-element suite (Au, As, Sb and W) could sucessfully explain about 25% of the total variance, certainly all the larger gold districts. Although this signature was probably affected by contamination from mine tailings, several areas were shown to be favourable for Au mineralization where no known workings were reported.

7. Predicting Gold Mineralization using Conditional Probability Techniques

7.1 Introduction

In the previous section, regression analysis was used to combine the multi-element lake sediment geochemical data into a single variable and resulted in a map predicting gold occurrences. Although this map was successful in predicting gold occurrences, it could have been more effective if other factors were included. As mentioned in Chapter 2 some of these factors were host rock, structures, distance from Devonian granite contacts, distance from Goldenville/Halifax contacts and distance from Acadian anticline axes.

Dealing with these factors in a regression analysis approach would have been difficult for several reasons; 1) large memory requirements are required to handle " distance from point to line " type data. This is because the study area must be broken down into a very large number of small sampling cells in order to capture this information adequately, and results in huge attribute files and unique condition files. Those large files cannot be accommodated in a micro-computer environment. 2) In regression analysis one must either assume mean values for those missing observations or simply omit those regions with incomplete data. 3) Regression coefficients are difficult to interpret (Bonham-Carter et al., 1988)

In order to overcome these problems and make a more effective use of the GIS environment, a new method using conditional probabilities was used. This method is discussed in detail by Agterberg et al. (1988). A summary of the methods are discussed below.

7.2 Method

In general, this process involved taking features that were considered important for predicting a mineral occurrence and reducing each of these features to a map of relatively few discrete states. Typically, the simplest pattern would be a binary one, representing presence or absence of the feature, or a ternary one representing presence/absence/unknown conditions for the feature. The maps were then divided into a sampling grid with a unit cell of a scale small enough to capture the necessary information. A 1 km^2 square grid may be considered for a 1:250,000 scale map.

A prior probability and posterior probability for a unit cell to contain an occurrence was calculated. Weights w+ and w- were computed using expressions which involved the logarithms of ratios of conditional odds. The log odds of the unit cell's posterior probability was obtained by adding w+ or w- for presence/absence of the feature to the log odds of the prior probability. The weight was zero for a feature that was unknown (no data).

If a factor was positively correlated with a deposit, w+ was positive. A negative value for w+ indicated a negative correlation. The measure $c = w+ - w-$, called the contrast, provided a measure of the strength of the correlation. This measure was theoretically zero if the mineral deposits were randomly distributed in the region without preference for presence or absense of the feature. The contrast was used to assist in the determination of the optimum cut-offs for classifying features into binary patterns of presence/absence conditions. This was done by computing the weights w+ and w- for a series of different areas and the area with the maximum c indicated the optimum cut-off for which the predictive power of the resulting pattern was maximized.

The equations for the values discussed abcve for map pattern analysis are given below:

The prior probability, P_{pr} of an occurrence occurring within the unit cell was defined as:

$$P_{pr} = A_{dt} / A_t$$

where

A_{dt} = the number unit cells containing an occurrence in the total study area.
A_t = the number unit cells in the total study area

The prior probability of an occurrence occurring within the unit cell was expressed in terms of prior odds as

$$O_{pr} = P_{pr} / (1 - P_{pr})$$

The posterior odds, the odds that an occurrence will occur within a unit cell after considering all the features, was be expressed as

$$O_{po} = \exp \{ \ln(O_{pr}) + \Sigma \underset{j=1}{\overset{m}{W_j}} \}^{k}$$

where the weights were

$$w_j^k = w_j^+ \text{ if pattern j is present}$$

$$w_j^k = w_{\bar{j}} \text{ if pattern j is not present}$$

$$w_j = 0 \text{ if pattern j is unknown}$$

The weights for the jth pattern were computed as

$$w_j^+ = \ln \{p(j|d) / p(j|\bar{d})\}$$

$$\bar{w}_j = \ln \{p(\bar{j}|d) / p(\bar{j}|\bar{d})\}$$

The conditional probability terms in the above equation were calculated from

$$p(j|d) = A_{dj} / A_{dt}$$

$$p(j|\bar{d}) = (A_j - A_{dj}) / (A_t - A_{dt})$$

$$p(\bar{j}|d) = 1 - (A_{dj} / A_{dt})$$

$$p(\bar{j}|\bar{d}) = 1 - ((A_j - A_{dj}) / (A_t - A_{dt}))$$

where

A_{dt} = number of unit cells containing a deposit in the total study area

A_{dj} = number of unit cells containing a deposit in pattern j

A_j = number of unit cells in pattern j

A_t = number of unit cells in total study area

The posterior probability was then computed as

$$P_{po} = O_{po} / (1 + O_{po})$$

Weights for presences or absences of features obtained from different map patterns could be added if the theoretical condition of conditional independence was satisfied. A statistical test has been devised (Agterberg et al., 1988) to compare the theoretical frequencies with their corresponding observed frequencies for sub areas with the same probabilites on the final integrated map.

The test required computing the χ^2 statistic

$$\chi^2 = \frac{\sum_{j=1}^{m} (O_i - E_i)^2}{E_i}$$

where

O_i = observed frequency of deposits for pattern with the posterior probability i

E_i = the theoretical frequency of deposits with the posterior probability i

j = the number of classes (8) calculated by grouping the posterior probabilites by percentile (eg. 98th, 95th, 90th, 80th, 70th, 60th, 50th)

The theoretical frequency was calculated as

$$E_i = [(A_i * P_i) / (\Sigma A_i*P_i)]$$

where

A_i = Area of pattern i

P_i = Average probability of pattern i

7.3 Results

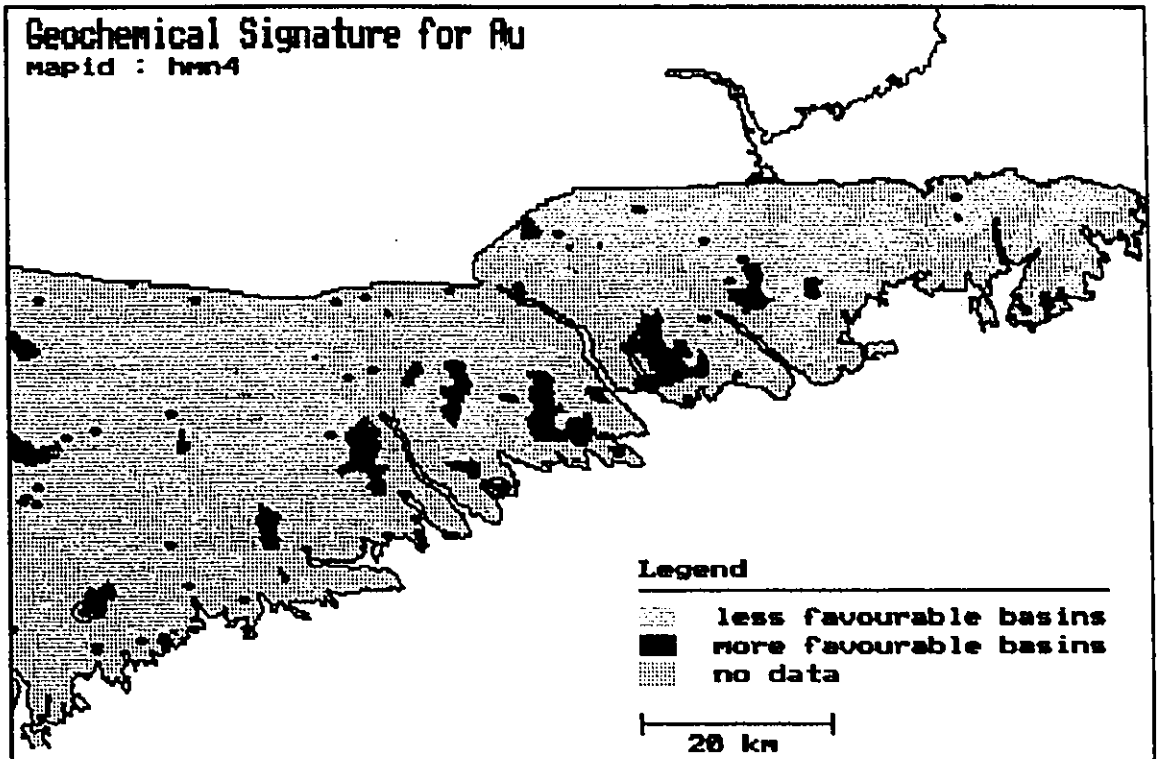
Geochemical Signature

The predicted gold occurrence map, Figure 6.1, generated using the lake sediment geochemistry was used to represent the geochemical influence in this model. This map was converted to a ternary pattern map. Weights for the presence/absence of basins associated with increasingly higher values of predictive scores were computed. These are shown in Table 7.1. The maximum C value, indicating the strongest correlation of deposits with a particular set of basins was 1.8150 and occurs for basins that have a predictive score of > .123. However, the total area covered by basins having this score was only 69.1 km2 (2.3% of sampled area). Although most of the large producing mines were included, several basins associated with known occurrences were left out. Basins that had a predictive score of > .045 had a C value of 1.1084, which was only slightly less than the maximum value. Lowering the threshold for presence of the favourable geochemical signature to

Table 7.1 Weights and contrasts for geochemical signature. The ability of the lake sedimemt geochemistry to predict gold mineralization is represented by scores and associated with catchment basins.

BASIN SCORE	BASIN AREA km^2	OCC. IN BASINS	W^+	W^-	CONTRAST $C=W^+-W^-$
> .150	47.1	5	1.6146	-.0616	1.6763
> .123	69.1	8	1.7112	-.1037	1.8150
> .080	110.0	8	1.1992	-.0891	1.2883
> .045	164.9	10	1.0047	-.1037	1.1084*
> .024	284.9	11	.5299	-.0764	0.6063
> .015	434.1	12	.1846	-.0355	0.2201
>- .001	797.5	19	.0320	-.0121	0.0442
>-1.04	1765.8	24	-0.5396	.4946	-1.0342
NO DATA	1179.2	44	0	0	

Total area sampled = 2945 km^2
Total no. of occurrences = 68



Weight for feature present w+ = 1.0047

Weight for feature absent w− = −0.1037

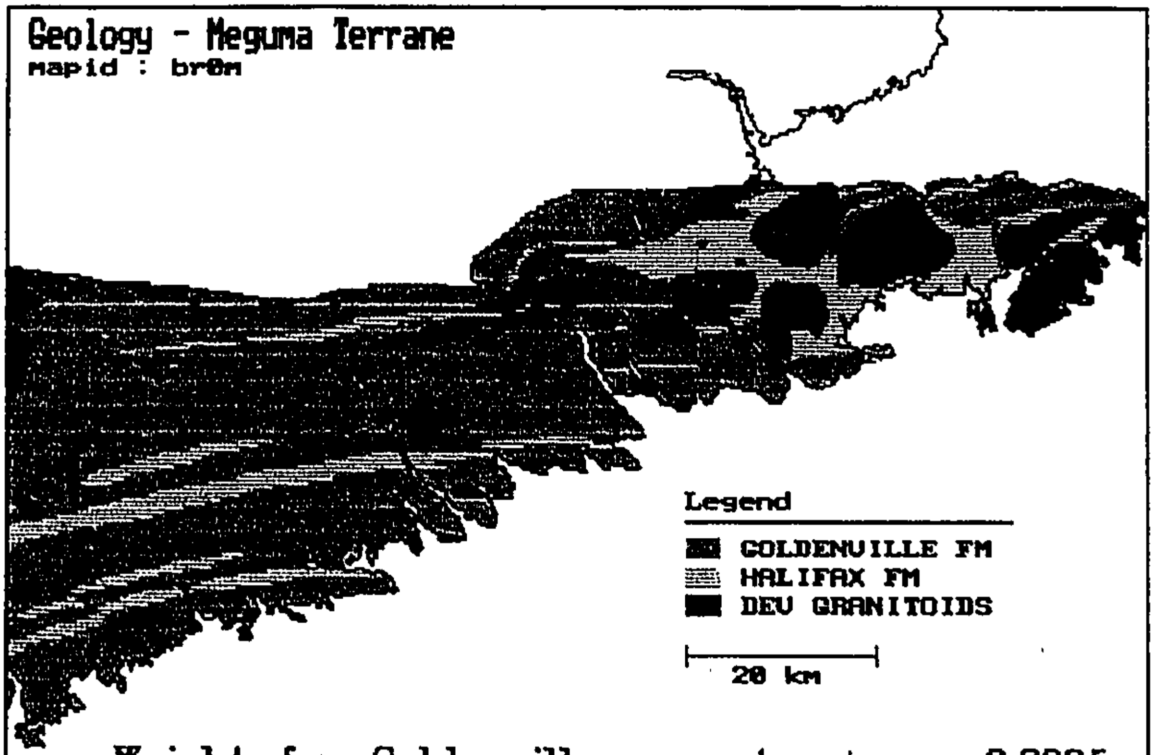
No data for feature w = 0

Figure 7.1 Geochemical signature represented as a ternary pattern map. Zero weight is assigned to parts of the study area with no data.

Table 7.2 Weights and contrasts for bedrock geology. The geology is treated as a ternary map and the w-values are not used.

ROCK UNIT	UNIT AREA km^2	OCC. IN UNIT	W^+	W^-	CONTRAST $C=W^+-W^-$
GOLDV	2020.9	63	.3085	-1.4689	1.7774
HALFX	441.9	3	-1.2041	.1204	-1.3164
DEV GRN	482.2	2	-1.7361	.1528	-1.8889

Total area sampled = 2945 km^2
Total no. of occurrences = 68



Weight for Goldenville present w+ = 0.3085

Weight for Halifax Fm present w+ = −1.2041

Weight for granites present w+ = −1.7361

Figure 7.2 Bedrock geology represented as a ternary pattern map. No W- weights are used as these patterns are mutually exclusive and together cover the whole study area.

include these basins increased the area covered to 169 km^2 and most of the occurrences were included. Based on this reasoning the cut-off was determined to be basins with a predictive score of >.045. The resulting w+ and w- values were 1.0047 and -.1037 respectively (Table 7.1). Figure 7.1 shows the geochemical signature thresholded to a binary pattern.

The area where no survey was done, and hence classed as unknown, was given w=0 as a third weight.

Geology

The geology was also represented as a ternary map. Table 7.2 shows the weights calculated for the three bedrock units. The combination of the three units covers the entire study area leaving no area where the "geology" feature is not present or unknown. It is noted, however, that w+ weights for the Halifax Formation and granites were actually negative indicating that they had a negative correlation with the deposits. Figure 7.2 shows the distribution of the geology and their associated weights.

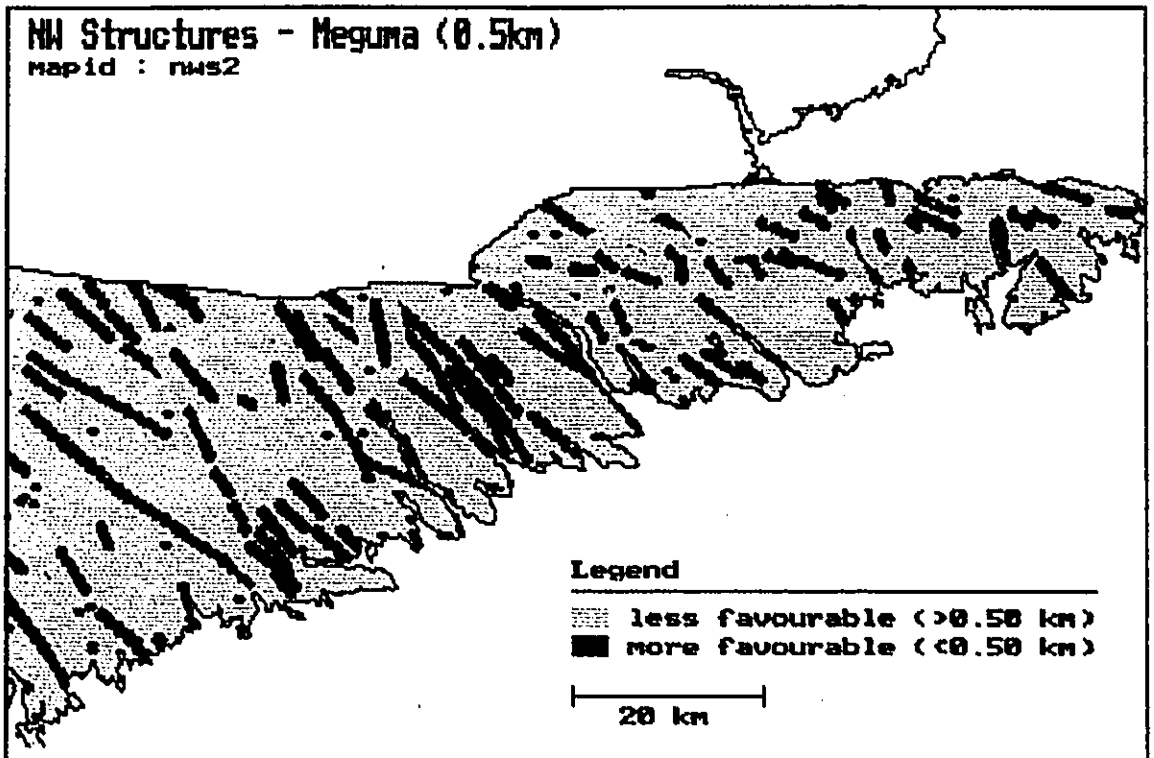
Proximity features

The next series of maps that contributed to the model may be considered as "distance to" or proximity to linear or curvilinear features. These included distance to NW trending

Table 7.3 Weights and contrasts for distance to north west trending structures represented as a binary pattern.

CORRIDOR WIDTH	CORRIDOR AREA km^2	OCC. ON CORRIDOR	W^+	W^-	CONTRAST $C=W^+-W^-$
.25 km	403.1	9	-.0344	.0054	-0.0398
.50 km	749.7	17	-.0185	.0062	-0.0247*
.75 km	1046.3	20	-.1930	.0928	-0.2859
1.00 km	1315.1	22	-.3286	.2059	-0.5346
1.25 km	1616.4	28	-.2933	.2726	-0.5659
1.50 km	1800.2	30	-.3327	.3734	-0.7060
1.75 km	1986.6	35	-.2761	.4114	-0.6874
2.00 km	2196.4	42	-.1926	.4203	-0.6129
2.25 km	2323.5	46	-.1572	.4400	-0.5971
2.50 km	2437.8	51	-.1009	.3834	-0.4843
2.75 km	2537.1	54	-.0833	.4080	-0.4913
3.00 km	2661.3	58	-.0591	.4357	-0.4948
3.25 km	2734.4	60	-.0521	.5131	-0.5652
3.50 km	2789.8	64	-.0066	.1124	-0.1190
3.75 km	2848.5	64	-.0280	.6043	-0.6322
4.00 km	2875.2	64	-.0375	.9448	-0.9823
4.25 km	2894.6	64	-.0443	1.2929	-1.3373
4.50 km	2914.3	64	-.0513	1.8463	-1.8976
4.75 km	2921.0	67	-.0068	.6095	-0.6163
5.00 km	2926.1	67	-.0086	.8580	-0.8665

Total area sampled = 2945 km^2
Total no. of occurrences = 68



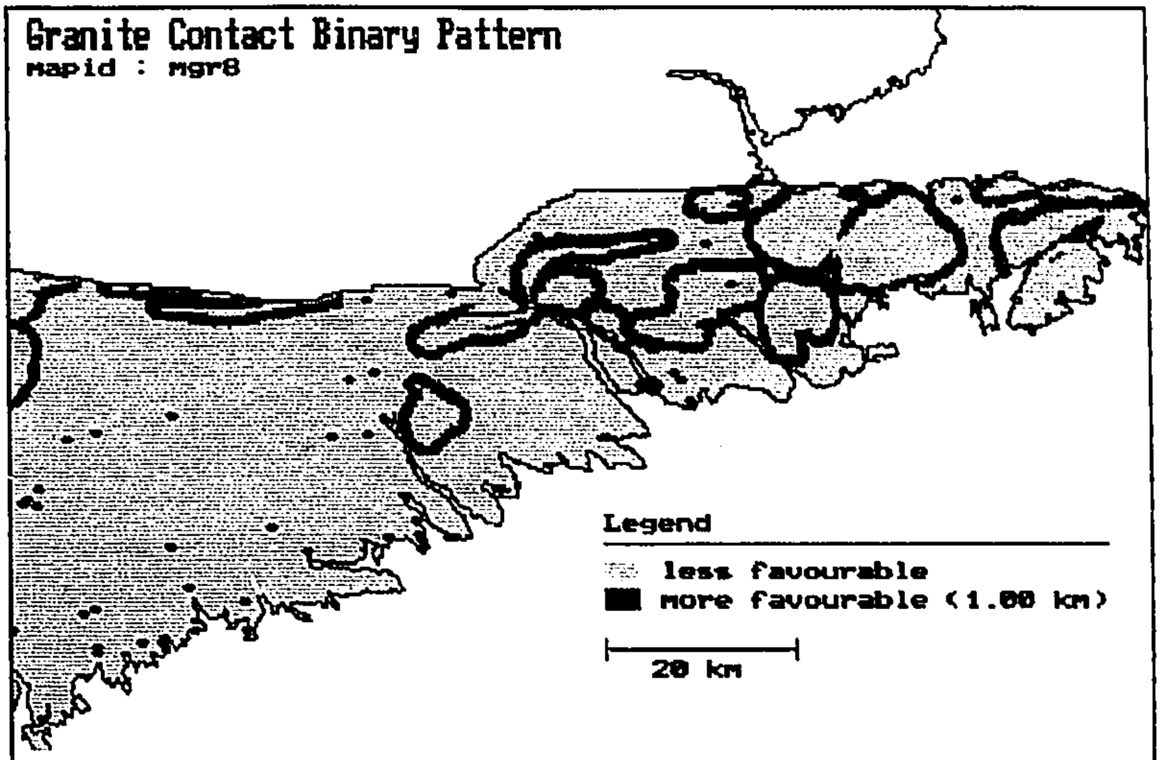
Weight for feature present w+ = -0.0185
Weight for feature absent w- = -0.0062

Figure 7.3 Binary patterns of corridors (half-width = .5 km) for northwest trending structures.

Table 7.4 Weights and contrasts for granite contact binary pattern as a function of corridor width.

CORRIDOR WIDTH	CORRIDOR AREA km^2	OCC. ON CORRIDOR	W$^+$	W$^-$	CONTRAST C=W$^+$-W$^-$
.25 km	120.8	3	.0740	-.0033	0.0773
.50 km	247.1	6	.0515	-.0048	0.0563
.75 km	318.6	7	-.0507	.0059	-0.0567
1.00 km	382.5	12	.3150	-.05628	0.3982*
1.25 km	478.4	13	.1669	-.0357	0.2027
1.50 km	528.4	13	.0649	-.0148	0.0797
1.75 km	581.6	14	.0427	-.0108	0.0535
2.00 km	670.0	14	-.1021	.0283	-0.1304
2.25 km	714.6	14	-.1679	.0486	-0.2165
2.50 km	756.3	14	-.2258	.0679	-0.2987
2.75 km	798.8	15	-.2111	.0688	-0.2799
3.00 km	864.9	17	-.1695	.0614	-0.2260
3.25 km	899.6	17	-.2047	.0787	-0.2834
3.50 km	932.8	19	-.1279	.0544	-0.1823
3.75 km	987.8	19	-.1866	.0829	-0.2695
4.00 km	1017.1	20	-.1641	.0772	-0.2414
4.25 km	1046.3	20	-.1929	.0929	-0.2858
4.50 km	1097.2	24	-.0554	.0315	-0.0869
4.75 km	1123.7	24	-.0797	.0463	-0.1260
5.00 km	1151.9	27	.0153	-.0099	0.0252

Total area sampled = 2945 km^2
Total no. of occurrences = 68



Weight for feature present W+ = 0.3150

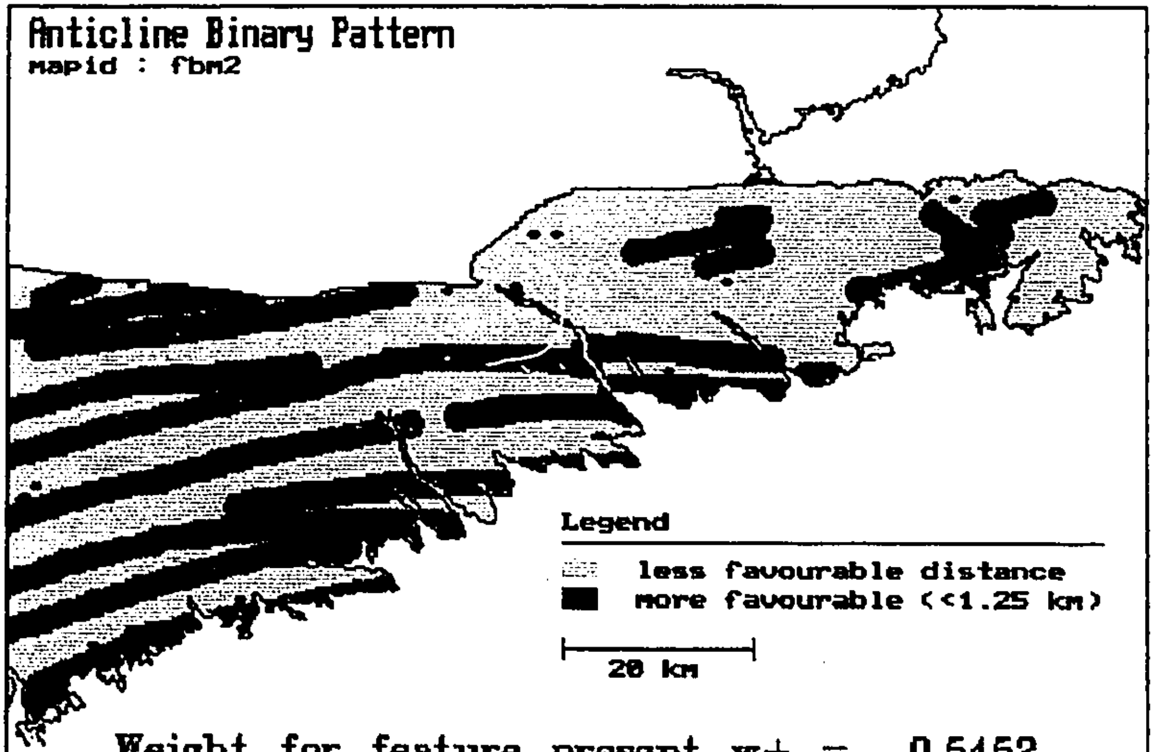
Weight for feature absent W− = −0.0562

Figure 7.4 Binary pattern of corridors (width = 1.25 km) for Devonian granite contacts.

Table 7.5 Weights and contrasts for anticline binary patterns as a function of half-corridor widths.

CORRIDOR WIDTH	CORRIDOR AREA km^2	OCC. ON CORRIDOR	W^+	W^-	CONTRAST $C=W^+-W^+$
.25 km	257.0	16	1.0327	-.1807	1.2134
.50 km	614.2	31	.8104	-.3821	1.1925
.75 km	809.1	37	.7068	-.4730	1.1798
1.00 km	995.1	43	.6475	-.5988	1.2462
1.25 km	1276.4	50	.5452	-.7735	1.3187*
1.50 km	1487.8	51	.4077	-.6943	1.1009
1.75 km	1641.4	54	.3641	-.7780	1.1422
2.00 km	1837.5	57	.3034	-.8569	1.1604
2.25 km	2007.3	59	.2478	-.8916	1.1394
2.50 km	2127.9	60	.2051	-.8715	1.0765
2.75 km	2225.7	61	.1758	-.8776	1.0534
3.00 km	2341.3	61	.1238	-.7005	.8243
3.25 km	2399.4	61	.0987	-.5986	.6974
3.50 km	2436.8	61	.0828	-.5261	.6089
3.75 km	2490.2	61	.0606	-.4319	.4925
4.00 km	2522.1	61	.0775	-.3398	.3873
4.25 km	2549.7	61	.0366	-.2726	.3092
4.50 km	2599.0	61	.0167	-.1351	.1518
4.75 km	2623.5	62	.0239	-.2189	.2429
5.00 km	2651.9	62	.0131	-.1262	.1393

Total area sampled = 2945 km^2
Total no. of occurrences = 68



Weight for feature present w+ = 0.5452

Weight for feature absent w− = −0.7735

Figure 7.5 Binary pattern of corridors (half-width = 1.25 km) for anticline axes.

structures, Acadian anticline axes, granite contacts and Halifax/Goldenville contact.

The procedure involved creating a map with 20 increasingly wide corridors spaced at 0.25 km intervals around the linear feature. Deposits were then located on the same map. To determine the number of deposits that fell within a certain distance from the linear feature, say for example 1 km (= 4 X 0.25 km), the number of deposits that occurred within the first four corridors would be counted.

Binary patterns were generated from these corridors for each of these situations after computing the weights and contrasts for the different distances. Distances that showed the maximum contrast (c = w+ - w-) indicating the strongest correlation between the occurrences and feature were selected.

Table 7.3 shows the weights and contrasts for distances to NW trending structures. It can be seen that w+ and c is negative for all distances up to 5km. This suggests that the importance of the NW trending structures, from a statistical point of view, is zero. However, NW structures are related to gold occurrences in the Meguma Terrane further to the west (Bonham-Carter et al., 1985). The value C is greatest at .5 km with weights of w+=-.0185 and w-=.0062. The binary map for this feature is shown in Figure 7.3.

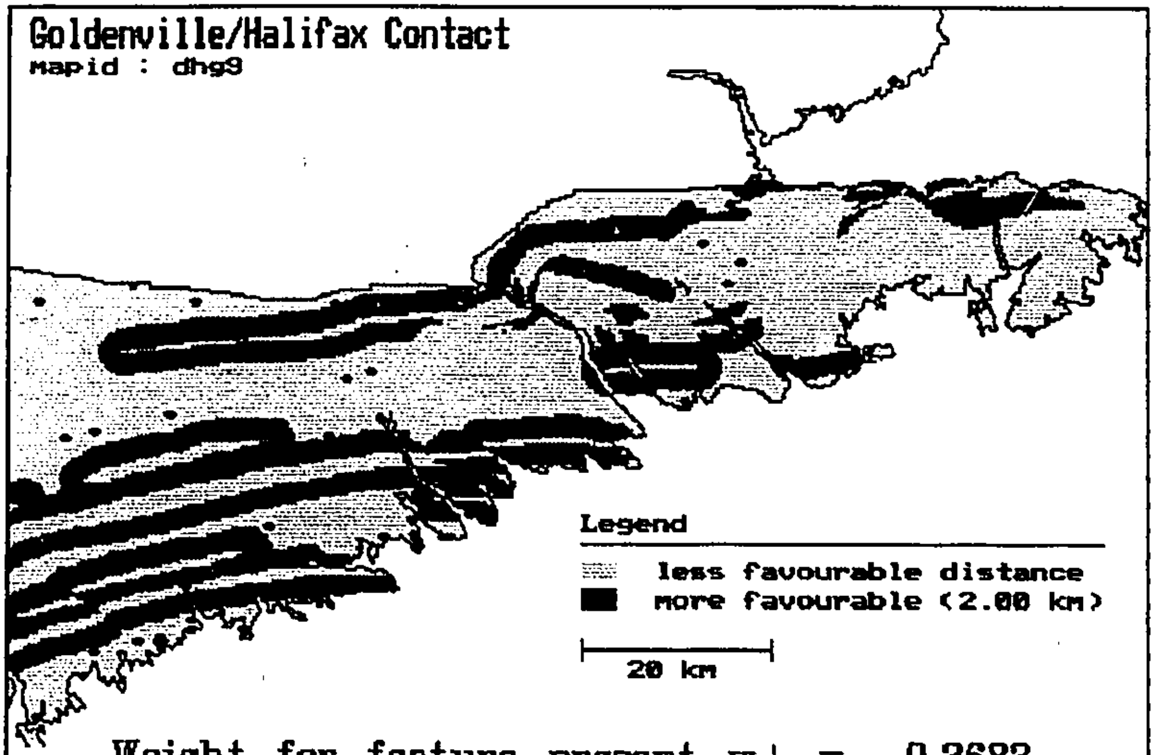
Table 7.6 Weights and contrasts for Halifax-Goldenville contact binary pattern as a funciton of width.

CORRIDOR WIDTH	CORRIDOR AREA km$^+$	OCC. ON CORRIDOR	W^+	W^-	CONTRAST $C=W^+-W^-$
.25 km	157.7	4	.1009	-.0060	0.1068
.50 km	358.7	8	-.0352	.0048	-0.0404
.75 km	462.8	11	.0296	-.0056	0.0353
1.00 km	556.5	13	.0118	-.0028	0.0498
1.25 km	712.4	19	.1479	-.0519	0.1998
1.50 km	804.7	21	.1256	-.0514	0.1769
1.75 km	891.4	27	.2787	-.1486	0.4273
2.00 km	1029.4	34	.3683	-.2685	0.6368*
2.25 km	1107.3	35	.3228	-.2567	0.5794
2.50 km	1180.8	37	.3138	-.2787	0.5925
2.75 km	1248.9	38	.2835	-.2721	0.5555
3.00 km	1347.4	42	.3084	-.3568	0.6652
3.25 km	1402.9	43	.2909	-.3606	0.6516
3.50 km	1451.4	44	.2797	-.3697	0.6494
3.75 km	1534.5	51	.3747	-.6614	1.0360
4.00 km	1578.1	54	.4048	-.8259	1.2307
4.25 km	1621.3	58	.4509	-1.1330	1.5839
4.50 km	1694.7	61	.4572	-1.4345	1.8917
4.75 km	1731.1	62	.4521	-1.5599	2.0120
5.00 km	1768.6	62	.4298	-1.5283	1.9581

Total area sampled = 2945 km^2
Total no. of occurrences = 68

Goldenville/Halifax Contact

mapid : dhg9



Weight for feature present w+ = 0.3683

Weight for feature absent w− = −0.2685

Figure 7.6 Binary pattern showing relationship between Goldenville-Halifax Formation contact (corridor width = 2.0 km) and location of gold occurrences.

The weightings and contrasts for different distances of occurrences from granite contacts are shown in Table 7.4. The maximum contrast is .3982 for the distance of 1.00 km. The binary map for granite contacts is shown in Figure 7.4.

Table 7.5 shows the weights and contrasts for distance of occurrences from anticline axes. The optimum distance for this feature was 1.25 km with values of w+ = .5452, w- = -.7735 and C = 1.3187. The binary map showing this feature is seen in Figure 7.5.

Examination of the weights and contrasts for the Goldenville/Halifax contact in Table 7.6 , indicated that the value of w+ reached a local high at 2.00 km and stayed at about this level until a distance of 3.75 km. At this point w+ again began to increase more rapidly until it reached a maximum at about 5 km. Similarly the C values reached a high at 2 km then returned below that value until a distance of 3.00 km where it increased again reaching a maximum at 5 km.

A possible reason for this behaviour is that after 3 km the relation of the occurrences to the contacts becomes obscured by the relation of the occurrences to the Goldenville Fm. It is noted that from the total 2020 km2 of Goldenville Fm. in the study area that the amount of Goldenville Fm. underlying the corridors is 1347 km^2 at a 3 km corridor width and 1768 km^2 at a 5 km corridor width.

Considering this, the distance of 2 km where the contrast reaches its first high, was chosen as the optimum distance. The binary contact map for the Goldenville Fm./Halifax Fm. contact is shown in Figure 7.6 .

Posterior probability map

Using the optimum weights from these six previous maps, summarized in Table 7.7, a map showing the posterior probabilities was generated (Figure 7.7).

For the final probability map to be correct, the assumption of conditional independence needed to be verified. It was expected that the possibility of conditional independence would decrease with the number of features being added. If conditional independence was not present it would be expected that there would be significant differences between the observed frequencies and the theoretical frequencies of deposits on the final probability map. Using the technique described by Agterberg et al., (1988) (see methods) the observed and theoretical frequencies for occurrences were determined and used to to conduct a $\chi 2$ test. The results are shown in Table 7.8.

$$\chi 2 = \frac{\Sigma (fo - fe)^2}{fe} = 9.786$$

Table 7.7 Summary of weights for modelling posterior probability of a gold deposit occurring in a 1 km^2 area.

MAP FEATURE	W^+	W^-	CONTRAST C
Geochemical Signature	1.0047	-0.1037	1.1084
Anticline Axes	0.5452	-0.7735	1.3187
N.W. Lineaments	-0.0185	0.0062	-0.0247
Granite Contact	0.3150	-0.0562	0.3982
Goldenville-Halifax Contact	0.3683	-0.2685	0.6368
Bedrock Geology*			
Halifax Formation	-1.2406	0.1204	-1.3164
Goldenville Formation	0.3085	-1.4689	1.7774
Granite	-1.7360	0.1528	-1.8889

* A ternary pattern where units are mutually exclusive, and weights W^- are not used.

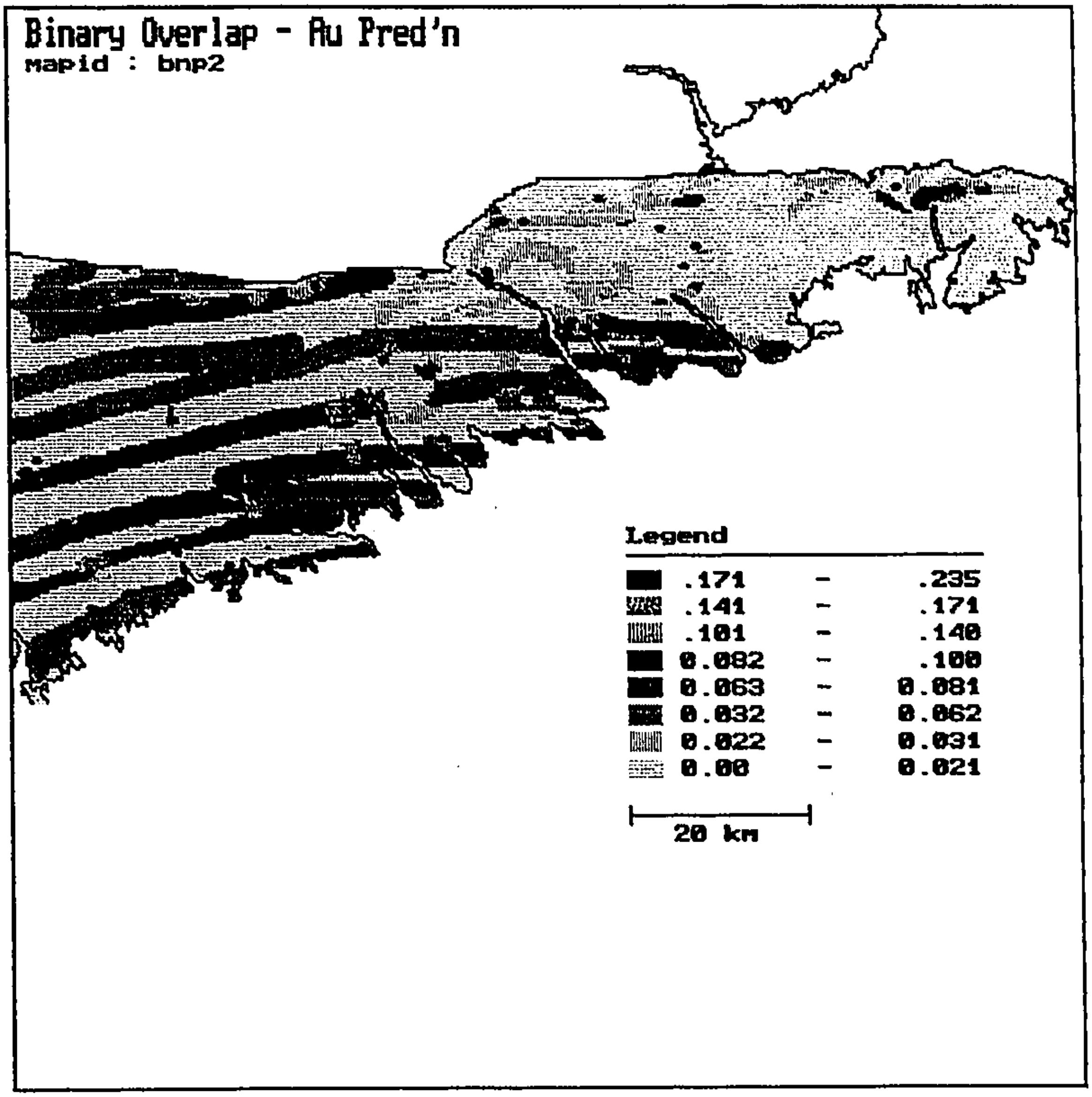

Binary Overlap - Au Pred'n
mapid : bnp2
Legend
.171 - .235
.141 - .171
.101 - .140
0.082 - .100
0.063 - 0.081
0.032 - 0.062
0.022 - 0.031
0.00 - 0.021
20 km

Figure 7.7 Integrated map pattern showing posterior probability of a gold deposit occurring in a 1 km^2 area. Legend shows posterior probabilities.

Table 7.8 Comparison of observed and expected frequencies of gold occurrences for final integrated pattern of Figure 7.7.

CLASS NO	CLASSES - POSTERIOR PROBABILITES	OBSERVED FREQ	EXPECTED FREQ	$\frac{(O - E)^2}{E}$
1	0.171 - 0.235	4	1.1	
2	0.141 - 0.171	3 7.0	4.3 5.4	0.474
3	0.101 - 0.140	1	2.7	
4	0.082 - 0.100	1 2.0	4.3 7.0	3.571
5	0.063 - 0.081	17	23.9	1.992
6	0.032 - 0.062	23	16.7	2.377
7	0.022 - 0.031	5	3.3	0.875
8	0.000 - 0.021	14	11.6	0.497
			SUM =	9.786

The number of degrees of freedom ν was set at 5 (number of classes - 1) giving the theoretical $\chi^2(5) = 11.1$ for a level of significance of $\alpha = 0.05$. It is noted that the number of degrees of freedom was uncertain as the number of estimated parameters was uncertain. The estimated value of χ^2 was less than 11.1 suggesting a good fit of the model and that the hypothesis of conditional independence was approximately satisfied. Comparison of observed and expected frequencies in Table 7.8 suggested that observed values tended to exceed expected values in the upper part of the table where the posterior probabilty was relatively large and that the reverse held in the lower part of Table 7.8. If two or more patterns were conditionally dependent with positive "partial association" (cf. Bishop et al. 1975, p. 32), the expected frequencies would exceed the observed frequencies when the posterior probability was relatively large, whereas they would be smaller when the posterior probability was small Agterberg et al., (1988).

7.4 Conclusion

The larger probabilities in the posterior probability map correlated well with known gold districts. The strong negative weights of W+ for the granites and the Halifax Formation effectively reduced the probability of gold mineralization. The w+ values were largest for the presence of the favourable geochemical signature and for the presence of the 1.25 km corridor for the proximity to the anticline axes indicating that these two features were important for predicting gold mineralization. The presence of Goldenville Formation, the presence of the Goldenville Formation close to the Halifax Formation contact and proximity to granites were all moderately important features for prediction of gold mineralization. The proximity to NW lineaments have little effect on the probability map.

Several areas indicating high probability for the presence of gold mineralization exist where no known gold occurrences occur. These represent interesting target areas for follow-up.

Interpreting the results from testing for conditonal independence must be done with caution because an upper bound for the number of degrees of freedom was used. Decreasing the number of degrees of freedom decreases the critical value of theoretical χ^2. Since the calculated value of χ^2 must be less than the theoretical χ^2 for condititonal independence to exist, decreasing the number of degrees of freedom and thereby decreasing the theoretical χ^2 may change interpretation of the presence of conditional independence.

8. SUMMARY AND CONCLUSIONS

Five digital geoscience data bases, from the Meguma Terrane, eastern mainland Nova Scotia, were compiled and co-registered in a format suitable for analysis on a micro-computer based GIS system. These were lake-sediment geochemistry represented as catchment basins, bedrock geology, surficial geology, structure, and gold occurrences.

Principal component analysis was used to characterize the multi-element compositional associations of the lake-sediment geochemistry and the results were displayed using SPANS to investigate the spatial patterns of these associations. The major control on the lake-sediment geochemistry is the concentration of resistate minerals by mechanical processes. A second major control may be due to either scavenging by Fe, Mn hydroxides , or possibly to sulphide mineralization. A third control is related to gold mineralization.

Regression analysis was used to investigate the influence of bedrock and surficial geology on on the lake-sediment geochemistry. Neither the bedrock geology nor the surficial geology were successful in explaining the variance in the concentration of the elements in the lake sediments or indicating a strong partition between element concentrations and the different units. The geochemical similarity between major lithological units and the small number of major lithological units within the study area is the reason for the lack of correlation. Mixing of the sediments may also mask the influence of the geology.

Regression analysis was used to combine the geochemical variables into a weighted sum that best predicts whether a basin contains a known occurrence. It was found that Au was an excellent predictor, and that a multi-element combination of Au, As, W and Sb can successfully explain about 25% of the total variance. Several areas are shown to be favourable for Au mineralization where no known workings are reported.

The resulting predictive map produced by the regression technique is useful only for areas where lake-sediment geochemistry is available and does not include any other factors that may be useful guides to gold mineralization.

A new method developed by Agterberg et al., (1988) involving Bayesian statistics was used to combine map patterns representing factors favourable to gold mineralization. This was carried out by the addition of weights w+ of w- representing the presence or absence of the features. The addition of weights was based on the assumption of conditional independence of the corresponding map patterns with respect to the mineral deposits. This asssumption was tested by comparing the posterior probabilites shown on the final integrated map pattern with observed frequencies of gold deposits.

A technique was developed for the construction of optimum binary patterns for linear features in order to represent the relationship between these features and the occurrence of mineral deposits. This was done by generating a sequence of increasingly wide corridors around the linear features. The choice of the optimum width was made on the basis of the contrast C which measures correlation between a binary pattern and a point pattern.

The use of a generalized GIS system in association with other software packages was more than suitable for use in spatial data integration for mineral resource assessment.

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Appendix A

Quality control of lake sediment geochemistry: List of tolerances for differences in duplicate pairs.

Element	Range V_1,V_2	Tolerance
Zn (ppm)	2 - 5	±100%
Zn (ppm)	5.1 - 20	± 50%
Zn (ppm)	20.1 - 100	± 25%
Zn (ppm)	100.1 - 300	± 20%
Zn (ppm)	+300	± 25%
Cu (ppm)	2 - 5	±100%
Cu (ppm)	5.1 - 20	± 50%
Cu (ppm)	10.1 - 30	± 30%
Cu (ppm)	30.1 - 200	± 20%
Cu (ppm)	+200	± 25%
Pb (ppm)	2 - 10	±100%
Pb (ppm)	10.1 - 20	± 50%
Pb (ppm)	20.1 - 100	± 30%
Pb (ppm)	100.1 - 1000	± 25%
Pb (ppm)	+1000	± 30%
Ni (ppm)	2 - 5	±100%
Ni (ppm)	5.1 - 10	± 50%
Ni (ppm)	10.1 - 20	± 40%
Ni (ppm)	20.1 - 100	± 25%
Ni (ppm)	100.1 - 300	± 20%
Ni (ppm)	+300	± 25%
Co (ppm)	2 - 10	±100%
Co (ppm)	10.1 - 20	± 50%
Co (ppm)	20.1 - 100	± 25%
Co (ppm)	100.1 - 300	± 20%
Co (ppm)	+300	± 25%
Ag (ppm)	.2 - 1.0	±100%
Ag (ppm)	1.01 - 5.0	± 50%
Ag (ppm)	5.01 - 10.0	± 25%
Ag (ppm)	10.1 - 100	± 25%
Ag (ppm)	100.1 - 200	± 20%
Ag (ppm)	+200	± 25%
Mn (ppm)	5 - 10	±100%
Mn (ppm)	10.1 - 100	± 50%
Mn (ppm)	100.1 - 500	± 30%
Mn (ppm)	500.1 - 1000	± 25%
Mn (ppm)	1000.1 - 2000	± 20%
Mn (ppm)	+2000	± 25%

Element	Range V_1,V_2	Tolerance
As (ppm)	1 - 2	±150%
As (ppm)	2.1 - 5	±100%
As (ppm)	5.1 - 10	± 50%
As (ppm)	10.1 - 20	± 30%
As (ppm)	+20	± 35%
Mo (ppm)	2 - 4	±100%
Mo (ppm)	4.1 - 6	± 50%
Mo (ppm)	6.1 - 10	± 40%
Mo (ppm)	10.1 - 25	± 30%
Mo (ppm)	25.1 - 100	± 25%
Mo (ppm)	+100	± 30%
Fe (%)	0.02 - 0.10	±100%
Fe (%)	0.11 - 0.5	± 50%
Fe (%)	0.51 - 1.0	± 40%
Fe (%)	1.01 - 3.0	± 30%
Fe (%)	3.01 - 10.0	± 20%
Fe (%)	+10	± 25%
F (ppm)	40 - 80	±100%
F (ppm)	80.1 - 125	± 50%
F (ppm)	125.1 - 200	± 40%
F (ppm)	200.1 - 500	± 30%
F (ppm)	+500	± 25%
LOI (%)	1 - 5.0	±120%
LOI (%)	5.1 - 10	±100%
LOI (%)	10.1 - 20.0	± 50%
LOI (%)	20.1 - 100	± 25%
U (ppm)	.5 - 3.0	± 70%
U (ppm)	3.1 - 5.0	± 50%
U (ppm)	5.1 - 10.0	± 40%
U (ppm)	10.1 - 25.0	± 30%
U (ppm)	+25.0	± 20%
V (ppm)	5 - 10	±100%
V (ppm)	10.1 - 20	± 50%
V (ppm)	20.1 - 50	± 40%
V (ppm)	50.1 - 100	± 30%
V (ppm)	+100	± 25%
Hg (ppm)	10 - 20	±100%
Hg (ppm)	20.1 - 50	± 50%
Hg (ppm)	50.1 - 100	± 40%
Hg (ppm)	100.1 - 1000	± 30%
Hg (ppm)	+1000	± 25%

(from John Lynch, Geological Survey of Canada, pers. comm.)