

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600



Université d'Ottawa • University of Ottawa

**AN EVALUATION OF INDICATORS OF PROSPECTIVITY AND
POTENTIAL MAPPING OF PORPHYRY DEPOSITS IN MIDDLE &
SOUTHERN BRITISH COLUMBIA BY A GIS STUDY OF
REGIONAL GEOCHEMICAL AND OTHER GEOSCIENTIFIC DATA**

Bahram Daneshfar

A thesis submitted to the School of Graduate Studies in partial fulfilment of the
requirements for the degree of Ph.D. in Earth Sciences

OTTAWA-CARLETON GEOSCIENCE CENTRE

UNIVERSITY OF OTTAWA

OTTAWA, ONTARIO, CANADA, 1997

© Bahram Daneshfar, Ottawa, Canada



National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisitions et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-36770-3

ABSTRACT

This thesis presents mineral potential maps for prospecting porphyry deposits at the regional scale. The study area covers certain geological units in southern and middle British Columbia (from 48° N to 56° N) that are known for hosting major porphyry deposits. Four main types of data were used in this thesis, namely geochemical, geophysical, tectonic and distribution of known porphyry deposits. Several "evidence" maps were generated based on these data sets. These maps can indicate areas with porphyry mineralizations inside the study area. The "evidence" maps were combined to create potential maps for porphyry deposits. Such potential maps show the gradation of favourability within different areas for prospecting porphyry deposits. The fuzzy logic method was utilised for representing the relative importance of maps and map combinations.

The stream geochemical dataset showed a "boundary shift" for some elements between a number of the National Geochemical Reconnaissance (NGR) surveys map sheets. In such cases, the data for stream sediment and water samples were levelled prior to statistical or GIS analysis. For levelling the geochemical data, a method was presented to estimate the required width for the bands that must be selected at the contact of the map sheets with a "boundary shift".

The geochemical data were disaggregated based on the geological environment and univariate and multivariate analyses were performed on these subsets of data. It was noticed that the median of Cu in stream sediments was often a good predictor of porphyry deposits. In many cases parameters measuring the spatial variability of Cu and Mo, such as variance or slope (maximum first spatial derivative) of these elements in a moving cell, were good indicators of potentially mineralized zones. In addition, the results of multivariate techniques such as factor and discriminant analysis could often be used as

good indicators of mineralized areas. Residual total field magnetics and vertical derivative (gradient) of magnetics were also good indicators of porphyry Cu-Au and Cu-Mo mineralizations at the regional scale. At this scale areas with high density of faults show also strong association with the location of known porphyry deposits. Areas close to known porphyry deposits and mining camps were subtracted from the final potential maps to introduce only those areas predicted by this model, with no known porphyry deposits.

In application of GIS at the regional scale, diversity of geology along the study area must be considered. It was noticed that evidences introduced by the univariate and multivariate analysis of geochemical data can be very useful at the regional scale if the geochemical data is first separated based on the similarity of geological environment. Such a separation enhances any statistical analysis at the regional scale.

TABLE OF CONTENTS

Abstract	I
Table of Contents	III
List of Tables	VIII
List of Figures	X
Acknowledgements	XVI

CHAPTER 1

INTRODUCTION

1.1 General	1
1.2 Study Area	2
1.3 Objective	2
1.4 Methodology	4
1.5 Data Files	5
1.5.1 Regional Geology	5
1.5.2 Geochemical Data (Stream Sediment & Water Samples)	5
1.5.3 Geophysical Data	6
1.5.4 Faults	6
1.5.5 Mineral Occurrences Information	7
1.6 Thesis Format	7

CHAPTER 2

AN OVERVIEW OF TECTONIC AND PLUTONIC EVOLUTION OF CANADIAN CORDILLERA

2.1 Tectonic Evolution	9
2.1.1 Introduction	9
2.1.2 Foreland and Omineca Belts	13
2.1.3 Intermontane Belt	15
2.1.3.1 Slide Mountain Terrane	16
2.1.3.2 Quesnellia, Cache Creek & Stikinia Terranes	17
2.1.4 Coast Plutonic Belt	20
2.1.5 Wrangellia & Alexander Terranes of Insular Belt	22
2.2 Magmatic Evolution	25
2.2.1 230 to 214 Ma (During Late Triassic)	28
2.2.2 214 to 200 Ma (End of Triassic and Part of Early Jurassic)	28
2.2.3 200 to 155 Ma (Late Early to Early Late Jurassic)	29
2.2.4 155 to 140 Ma (Late Jurassic)	29

2.2.5	145 to 138 Ma (Latest Jurassic and Beginning of Early Cretaceous)	30
2.2.6	135 to 125 Ma (Early Cretaceous)	30
2.2.7	110 to 90 Ma (Middle Cretaceous)	30
2.2.8	80 to 70 Ma (Late Cretaceous)	30
2.2.9	70 to 60 Ma (Latest Cretaceous to Paleocene)	30
2.2.10	55 to 45 Ma (Latest Paleocene to Middle Eocene)	31

CHAPTER 3

REVIEW OF CHARACTERISTICS AND DISTRIBUTION OF PORPHYRY DEPOSITS IN THE STUDY AREA

3.1	Introduction	32
3.2	Classification of Porphyry Deposits	33
3.2.1	Cordilleran Classification	35
3.2.1.1	Classification Based on Morphology, Rock Association and Depth	36
3.2.1.2	Classification Based on the Chemistry of Plutons	38
3.2.1.3	Classification Based on Metal Content	40
3.3	Temporal and Spatial Distribution	44
3.4	Selection of Major Geological Units Associated with Porphyry Deposits in the Study Area	46
3.4.1	Cu-Au Porphyry Deposits Group	47
3.4.2	Cu-Mo (+/-Au) Porphyry Deposits Group	49
3.4.3	Mo Porphyry Deposits Group	50
3.5	Density of the Distribution of Porphyry Deposits	55
3.6	Exploration Model	59
3.6.1	Porphyry Cu-Au	59
3.6.2	Porphyry Cu+/-Mo+/-Au	60
3.6.3	Porphyry Mo	61

CHAPTER 4

LEVELLING GEOCHEMICAL DATA BETWEEN MAP SHEETS

4.1	Introduction	63
4.2	Methodology	64
4.3	Data Sets	67
4.4	Selection of Bands	68
4.5	Examples of Levelling	72
4.5.1	Levelling pH Values	72
4.5.2	Levelling Mo Values	78
4.5.3	Levelling Fe Values	82
4.5.4	Levelling Mn Values	85

CHAPTER 5

GEOCHEMICAL DATA ANALYSIS

5.1	Introduction	87
5.2	Univariate Analysis.....	88
5.2.1	Filtering the Data	88
5.2.1.1	Guichon Plutonic Suite (EJgG)	91
5.2.1.2	Copper Mountain (EJyCM, MJyCM), Duckling Creek (MJyCMD) plutonic suites	92
5.2.1.3	Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs), Topley (EJqT) Plutonic Suites	93
5.2.1.4	Late Cretaceous Plutonic Suite (LKg)	93
5.2.1.5	Bonanza Arc Volcanic Group (JB)	94
5.2.1.6	Hazelton Arc Volcanics (JH)	95
5.2.1.7	Takla & Nicola Arc Volcanics (TrJ & TrJN).....	96
5.2.2	Univariate Parameters Used as Indices of Potentially Mineralized Areas	97
5.2.2.1	High Median	97
5.2.2.2	High Variability of Indicator and Pathfinder Elements (Cu, Mo)	104
5.3	Multivariate Analysis.....	113
5.3.1	Introduction	113
5.3.2	Principal Components and Factor Analysis	114
5.3.3	Discriminant Analysis	116
5.3.4	Application of Multivariate Analysis Techniques on Geochemical Data of Geological Units of the Study Area.....	117
5.3.4.1	Factor Analysis on Geochemical Data of Guichon Plutonic Suite (EJgG) for Series of (Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, pH, F in water, U in water)	117
5.3.4.2	Series of (As, Au, Ba, Br, Ce, Cr, Cs, Hf, La, Lu, Na, Rb, Sc, Sm, Ta, Th, U, Yb, Zr)	126
5.3.4.3	Discriminant Analysis for the Geochemical Data of Guichon Plutonic Suite (EJgG)	135
5.3.4.3.1	Training or Control Area	135
5.3.4.4	Comparison with the Geology of Guichon Plutonic Suite	145
5.3.4.5	Factor Analysis on Geochemical Data of Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) Plutonic Suites	147
5.3.4.6	Factor Analysis on Geochemical Data of Late Cretaceous Plutonic Suite (LKg)	154
5.3.4.7	Factor Analysis on Geochemical Data of Bonanza Arc Volcanics (JB))	161
5.3.4.8	Comparison with the Geology Bonanza Arc Volcanics.....	167
5.3.4.9	Factor Analysis on Geochemical Data of Hazelton Arc Volcanics Group (JH)	169
5.3.4.10	Factor Analysis on Geochemical Data of Takla & Nicola (TrJ, TrJN) Arc Volcanics.....	175

CHAPTER 6

GEOPHYSICAL CHARACTERISTICS OF PORPHYRY MINERALIZED AREAS AND ANALYSIS

6.1 Introduction	182
6.2 Analysis of Aeromagnetic Data.....	183
6.2.1 Introduction	183
6.2.2 Porphyry Deposits and Magnetic Susceptibility	184
6.2.3 Residual Total Field Magnetics.....	189
6.2.4 Vertical Derivative (gradient) of Magnetics	197
6.3 Analysis of Gravity Data	202
6.3.1 Introduction	202
6.3.2 Relationship Between Gravity Data and Porphyry Deposits.....	202
6.3.3 Vertical Derivative (gradient) of Bouguer Gravity Anomalies.....	203

CHAPTER 7

TECTONIC CONTROL

7.1 Introduction	214
7.2 Relationship Between Faults and Porphyry Deposits in British Columbia	215
7.3 Regional Setting.....	219
7.4 District Settings	222
7.4.1 Stikinia District.....	223
7.4.2 Alice Arm District	223
7.4.3 Babine District	224
7.4.4 Tahtsa District	225
7.4.5 Highland Valley District.....	226
7.4.6 Kamloops and Copper Mountain Districts.....	228
7.5 Spatial Analysis for Distribution of Faults and Known Porphyry Deposits	230
7.5.1 Spatial Density of Faults.....	230
7.5.2 Buffer Zones Around Faults.....	234
7.5.3 Buffer Zones Around Points of Fault Intersection.....	237
7.6 Discussion.....	240

CHAPTER 8

MODELING AND INTEGRATION OF DATA

8.1 Introduction	244
8.2 Types of Models.....	245
8.3 Fuzzy Logic Method	247

8.3.1	Combining Fuzzy Membeship Values.....	249
8.3.1.1	Fuzzy “AND”.....	250
8.3.1.2	Fuzzy “OR”.....	250
8.3.1.3	Fuzzy Algebraic Product.....	250
8.3.1.4	Fuzzy Algebraic Sum.....	251
8.3.1.5	Gamma Operation	252
8.4	Integration of Maps.....	253
8.4.1	Geochemical Factor	254
8.4.1.1	Guichon Plutonic Suites (EJgG)	261
8.4.1.2	Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs), Topley (EJqT) Plutonic Suites	263
8.4.1.3	Late Cretaceous Plutonic Suites (Lkg).....	264
8.4.1.4	Bonanza Arc Volcanics (JB)	265
8.4.1.5	Hazelton Group Arc Volcanics (JH)	266
8.4.1.6	Takla & Nicola Arc Volcanics (TrJ, TrJN).....	266
8.4.2	Geophysical Factor.....	267
8.4.3	Tectonic Factor.....	271
8.4.4	Distribution of Known Porphyry Deposits Factor (density factor).....	274
8.4.5	Integration of All Factor Maps.....	276
8.4.5.1	Guichon Plutonic Suites (EJgG)	277
8.4.5.2	 Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs), Topley (EJqT) Plutonic Suites	278
8.4.5.3	Late Cretaceous Plutonic Suites (Lkg).....	279
8.4.5.4	Bonanza Arc Volcanics (JB)	280
8.4.5.5	Hazelton Arc Volcanics (JH)	281
8.4.5.6	Takla & Nicola Arc Volcanics (TrJ, TrJN).....	282
8.4.6	Most Favourable Areas for Prospecting Porphyry Deposits Inside the Study Area	283
8.5	Evaluation of Results.....	292
8.5.1	Mineral Potential Project of British Columbia	292
8.6	Conclusions.....	298

References

Appendixes

List of Tables

CHAPTER 1

Table 1. Different types of analyses and processing that are done on various input layers.....	4
Table 2. Different types of geophysical data used in this thesis and their resolution.....	6

CHAPTER 3

Table 1. Associated geological units with Cu-Au group of porphyry deposits, based on the literature and MINFILE (as explained in the text).....	48
Table 2. Associated geological units with Cu-Mo group of porphyry deposits, based on the literature and MINFILE (as explained in the text).....	50
Table 3. Associated geological units with Mo group of porphyry deposits, based on the literature and MINFILE (as explained in the text).....	51

CHAPTER 4

Table 1. Organizational summary for the geochemical map sheets considered in this chapter.....	71
Table 2. Ordinates of the normal distribution and assigned weights to quantiles.....	74

CHAPTER 5

Table 1. Percentiles and cut-off values used as the selection limit to separate extreme outliers for stream sediment and water samples inside Early Jurassic Guichon plutonic suite (EJgG).	92
Table 2. Percentiles and the selection limit used for separating extreme outliers for stream sediment and water samples inside Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites.	93
Table 3. Percentiles and cut-off values used as the selection limit to separate extreme outliers for stream sediment and water samples inside Late Cretaceous plutonic suite (LKg).	94
Table 4. Percentiles and selection limit used to separate extreme outliers for stream sediment and water samples inside Bonanza Group (JB).	95
Table 5. Percentiles and the selection limits used to separate extreme outliers for stream sediment and water samples inside Hazelton Group (JH).	96
Table 6. Percentiles and cut-off values used as the selection limit to separate extreme outliers for stream sediment and water samples inside Takla and Nicola arc volcanic Group (TrJ & TrJN). ..	97
Table 7. Results of weight of evidence analysis between the known porphyry deposits of different types located inside geological units of the study area, and maps of variance and coefficient of variation of Cu and Mo (Figure 7, 8, 10, 11).	111
Table 8. Rotated factor loadings matrix.	118
Table 9. Characteristics of 13 possible factors.	118
Table 10. Factor loadings matrix after oblique rotation.	127
Table 11. Characteristics of 13 possible factors.	128
Table 12. Factor correlation matrix for the first four factors (rotated by oblique method).	129
Table 13. Wilks' Lambda and univariate F-ratio with 1 and 58 degrees of freedom for investigating difference between means of elements for mineralized and unmineralized units (N=474).	138
Table 14. Percentages of samples of group 1, 2 and all other samples classified by the calculated discriminant function into group 1 or 2.	139
Table 15. Pooled within-groups correlations between discriminating variables and canonical discriminant functions a) for elements with significant difference for their means, b) for all elements.....	141

Table 16. Rotated factor loadings matrix for the first four factors.	147
Table 17. Eigenvalues and percent of variability.....	148
Table 18. Rotated factor loadings matrix for the first four factors.	154
Table 19. Eigenvalues and percent of variability.....	155
Table 20 a) Factor loadings for the rotated solution, b) Eigenvalues for all the possible factors, ...	162
Table 21. Eigenvalues and for all the possible factors.....	169
Table 22. Factor loadings for the rotated solution.....	170
Table 23 a) Factor loadings for the rotated solution, b) Eigenvalues for all the possible factors, ...	175

CHAPTER 6

Table 1. Silica-undersaturated plutons and the relationship between mineralogy and Cu-Au porphyry mineralization.	188

CHAPTER 7

Table 1. Contingency Coefficient, Tschuprow's T and Cramer's V for the three maps.	241
Table 2. Odds ratios and alpha values for classes of 3 maps compared as pairs with each other. .	243

CHAPTER 8

Table 1. A Classification of models used in geology. These are symbolic models as opposed to physical scale models.	245
Table 2. An example of fuzzy membership values for classes of a geochemical map.....	249

List of Figures

CHAPTER 1

- Figure 1. Geological units known as major hosts for porphyry deposits selected as the “study area”. Regions outside these units were judged to be not permissive (extracted from geology of the Canadian Cordillera at the scale of 1:1 000,000). 3

CHAPTER 2

- Figure 1. Major terranes and five tectonostratigraphic belts of the Canadian Cordillera. 12
- Figure 2. Suggested Early Permian reconstruction of the Slide Mountain ocean, arcs, and the subduction zones off the west coast of Ancestral North America (Nelson, 1993). 16
- Figure 3. Stages 1 and 2 of tectonic evolution of Quesnellia, Stikinia and Cache Creek (Mihalynuk et. al. 1994). 18
- Figure 4. Stages 3 and 4 of tectonic evolution of Quesnellia, Stikinia and Cache Creek (Mihalynuk et. al. 1994). 19
- Figure 5. Geological cross section in southern British Columbia from Pacific Ocean in west to Interior Planes in east. (from tectonic map of The Canadian Cordillera). 24
- Figure 6. Frequency of all magmatic dates of The Canadian Cordillera beside motion of Farallon plate with respect to North America and motion of North America with respect to hot spots (Armstrong, 1988) and timing of porphyry and gold mineralizations (Engelbreton et al., 1985, McMillan, 1994). 27

CHAPTER 3

- Figure 1. Relative abundance of Cu (in %), Mo (in %) x10 and Au (in g/t) for various porphyry deposits from around the world [after Cox and Singer (1988) and Sillitoe (1993)]. 35
- Figure 2. Relative abundance of Cu (in %), Mo (in %) x10 and Au (in g/t) for selected Cordilleran porphyry deposits. Pre- to syn- and post-accretion deposits are distinguished by circles and triangles respectively [after McMillan et al. (1995)]. 44
- Figure 3. Porphyry deposit mineralization epochs in British Columbia (Christopher and Carter, 1976, McMillan, 1994). 46
- Figure 4. Distribution of known porphyry Cu-Au deposits with different status. 52
- Figure 5. Distribution of known porphyry Cu-Mo deposits with different status. 53
- Figure 6. Distribution of known porphyry Mo deposits with different status. 54
- Figure 7. General procedure for creating combined density map for distribution of porphyry deposits. 56

CHAPTER 4

- Figure 1. Adjoining map sheets (A & B) that show a shift in the value of a given element at their boundary, although the geological units are similar on each side of the boundary. 64
- Figure 2. Various scenarios that may occur when quantiles are plotted for pairs of bands at the boundary between map sheets. a) No shift between two maps, b) shift by a positive constant, c) shift by a multiplier, d) shift by a constant and multiplier, e) no quantifiable relation between quantile pairs. (After Darnley et al, 1995). 65
- Figure 3. Considering geological condition in selecting length of the bands “a” and “b”. Assuming that the map sheet in the middle has a boundary shift compared to surrounding sheets. 67
- Figure 4. Different map sheets of National Geochemical Reconnaissance (NGR) with their open file numbers. 70

Figure 5. Levelling pH of water samples for 2038, 2039, 2040 and 2182, 2183, 2184 map sheets. a) before and b) after levelling c) plutonic units in the area.	73
Figure 6. Exploratory bands, which were put inside the map sheet BC RGS34.....	74
Figure 7. Variations of D with width(km) of exploratory bands inside sheets 867 and BCRGS34.....	75
Figure 8. Regression lines and their 95% confidence limits for 5, 10, 15 and 50 km exploratory bands inside BCRGS34.	76
Figure 9. Similarity of regression models derived for levelling between map sheets 2039/34 and between 2039/867.....	77
Figure 10. a) Original values of Mo in map sheets 2182, 2183, and 2184. b) Levelled map of Mo. .	79
Figure 11. Regression lines and their 95% confidence limits for 5, 10, 15 and 50 km exploratory bands inside 2039.	81
Figure 12. Similarity of regression lines derived for levelling between map sheets 2183/2039 and between 2184/867.....	82
Figure 13 a) Boundary shift for Fe between 2038, 2039, 2040 and also between 2182, 2183, 2184 and adjacent map sheets b) Fe, after separately levelling 2182, 2183, 2184 and 2038, 2039, 2040 map sheets with different levelling equations.	84
Figure 14 a) Shifted values of Mn , b) Levelled Mn after levelling 2038, 2039, 2040.	86

CHAPTER 5

Figure 1. Streams, drainage basins and location of NGR stream sediment and water samples inside the Guichon Creek batholith and the Highland Valley mining area. Samples were not taken from the streams coming directly from mines.	89
Figure 2. Probability and box plots for a) median of Cu in stream sediment samples and b) log ₁₀ of median of Cu in stream sediment samples inside 609 geological polygons that have more than 5 samples in them.	99
Figure 3. Median of Cu in stream sediment samples for all geological polygons with more than 5 samples in them. Boundaries of the study area are also shown with black lines.	102
Figure 4. Median of Cu in stream sediment samples for polygons of all the selected geological units with more than 5 samples within them.	101
Figure 5. Median of Cu in stream sediment samples for Guichon plutonic suite (EJgG). Points represent known porphyry deposits. Guichon Creek pluton is known as a highly mineralized and Wild Horse as an unmineralized pluton of EJgG.	102
Figure 6. Comparison of medians and number of known porphyry deposits in each class of median map of Figure 5.	103
Figure 7. Variance of Cu in stream sediment samples inside the geological units of the study area, calculated by moving average method.	105
Figure 8. Coefficient of variation (CV) of Cu in stream sediment samples inside the geological units of the study area, calculated by moving average method.	106
Figure 9. Slope of Cu in stream sediment samples inside the geological units of the study area, calculated by moving average method.	107
Figure 10. Variance of Mo in stream sediment samples inside the geological units of the study area, calculated by moving average method.	108
Figure 11. Coefficient of variation (CV) of Mo in stream sediment samples inside the geological units of the study area, calculated by moving average method.....	109
Figure 12. Slope of Mo in stream sediment samples inside the geological units of the study area, calculated by moving average method..	110
Figure 13. Decrease of W+ and C (contrast) with lower values of variance and coefficient of variation (CV) of Cu and Mo, indicating association of known porphyry deposits with top classes (high values) of variance and coefficient of variation (CV) of Cu and Mo in stream sediment samples.	112
Figure 14. Scree plot for 13 possible factors.....	118
Figure 15. Factor loadings and histogram for scores of factor 1.....	119
Figure 16. Factor loadings and histogram for scores of factor 2.....	120
Figure 17. Factor loadings and histogram for scores of factor 3.....	120

Figure 18. Factor loadings and histogram for scores of factor 4.....	121
Figure 19. Factor loadings and histogram for scores of factor 5.....	121
Figure 20. Factor 3 and 4 scores for samples located in the mineralized (Guichon Creek) and unmineralized (Wild Horse) plutons of Guichon plutonic suite (EJgG). Numbers are sample ID numbers from NGR data files.....	122
Figure 21. Factor 3 (Cu-Zn) scores calculated for the NGR samples located inside the Guichon plutonic suite (EJgG). Areas A and B are zoomed in the next figures for details.	123
Figure 22. Factor 3 (Cu-Zn) scores in Guichon Plutonic Suite (EJgG) in areas A and B of Figure 21 with known porphyry Cu-Mo and Cu-Au deposits. 379 samples are located in part A and 94 samples in part B.....	124
Figure 23. Factor 4 (U-Mo) scores in Guichon Plutonic Suite (EJgG) in areas A & B of Figure 21 with known porphyry Cu-Mo and Cu-Au deposits. 379 samples are located in part A and 94 samples in part B.....	125
Figure 24. Scree plot for 13 possible factors.....	128
Figure 25. Factor plot in rotated factor space for the second series of elements. Two-dimensional plots for loadings of each pair of factors are shown in Appendix B-1.	130
Figure 26. Probability plot for distribution of factor 3 scores.	131
Figure 27. Factor loadings and histogram for scores of factor 1 and 3.....	131
Figure 28. Factor loadings and histogram for scores of factor 2 and 4.....	132
Figure 29. Distribution of factor 3 scores in Guichon plutonic suite (EJgG) wherever the analysis results for the second series of elements were available.	133
Figure 30. Scatter plots for factor 3 and 4 scores and factor 3 scores of the second group of elements in Guichon plutonic suite (EJgG).....	134
Figure 31. Control area for the discriminant analysis. Guichon Creek batholith is selected as the mineralized and Wild Horse batholith as the unmineralized unit.	136
Figure 32. Histogram of calculated discriminant Z scores for group 1 and 2 and their centroids.	140
Figure 33. Probability plot for the calculated Z scores.	140
Figure 34. (a) Distribution of discriminant function score(Z), and (b)- Distribution of probability of samples related to the mineralized parts of EJgG in the training area.	143
Figure 35. Probability.....	144
Figure 36. Different phases of Guichon plutonic suite and other plutonic intrusives near Guichon Creek batholith.	146
Figure 37. Scree plot for 13 possible factors.....	148
Figure 38. Configuration of factor loadings for the first three factors. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-2.....	148
Figure 39. Factor loadings and histogram for factor 1 scores.....	149
Figure 40. Factor loadings and histogram for scores of factor 2.....	150
Figure 41. Probability plot for scores of factor 2.....	150
Figure 42. Factor loadings and histogram for scores of factor 3.....	151
Figure 43. Factor loadings and histogram for scores of factor 4.....	151
Figure 44. Distribution of factor 2 scores in Bulkely (LKgB), Francois Lake (JKgF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites.	152
Figure 45. Factor 2 scores and known porphyry deposits inside Bulkely (LKgB), Francois Lake (JKgF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites.....	153
Figure 46. Scree plot for 13 possible factors.....	155
Figure 47. Factor loadings and histogram for scores of factor 1.....	155
Figure 48. Factor loadings and histogram for scores of factor 2.....	156
Figure 49. Factor loadings and histogram for scores of factor 3.....	156
Figure 50. Factor loadings and histogram for scores of factor 4.....	157
Figure 51. Configuration of factor loadings of the first three factors. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-3.....	158
Figure 52. Distribution of factor 2 scores over the Late Cretaceous plutonic suite (Lkg).	159
Figure 53. Factor 2 scores in Late Cretaceous plutonic suite (Lkg) zoomed in A & B areas with known porphyry Cu-Mo, Cu-Au and Mo deposits..	160
Figure 54. Scree plot for all the 15 possible factors.....	162
Figure 55. Configuration of factor loadings of the first three factors. Two dimensional plots for	

loadings of each pair of factors are shown in Appendix B-4.....	163
Figure 56. Factor loadings and histogram for the scores of factor 1.....	163
Figure 57. Factor loadings and histogram for the scores of factor 2.....	164
Figure 58. Distribution of factor 2 scores over the Bonanza group.....	165
Figure 59. Factor 2 scores in Bonanza group (JB) with known porphyry Cu-Mo & Mo deposits.....	166
Figure 60. Loadings for factor 3 and histogram of its scores.	167
Figure 61. Distribution of Bonanza arc volcanics (JB) in northern Vancouver Island.	168
Figure 62. Scree plot for all the 13 possible factors.....	169
Figure 63. Factor loadings for factor 1, 2 and 3. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-5.	170
Figure 64. Factor loadings and histogram for scores of factor 1.....	171
Figure 65. Factor loadings and histogram for scores of factor 2.....	171
Figure 66. Factor loadings and histogram for scores of factor 3.....	172
Figure 67. Factor loadings and histogram for scores of factor 4.....	172
Figure 68. Location and distribution of factor 3 scores in Hazelton arc volcanics (JH)	173
Figure 69. Distribution of factor 3 scores in Hazelton arc volcanics (JH) and known porphyry deposits	174
Figure 70. Scree plot for all the 14 possible factors.....	176
Figure 71. Loadings of factor 1, 2 and 3. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-6.	176
Figure 72. Factor loadings and histogram for scores of factor 1.....	177
Figure 73. Factor loadings and histogram for the scores of factor 2.....	178
Figure 74. Factor loadings and histogram for the scores of factor 3.....	178
Figure 75. Factor 3 scores in Takla and Nicola (TrJ, TrJN). Three areas of A, B and C are plotted in more details in the Figure 76.....	179
Figure 76. Factor 3 scores for Takla and Nicola (TrJ, TrJN) on zoomed areas of A, B, and C	180
Figure 77. Factor loadings and histogram for the scores of factor 4.....	181

CHAPTER 6

Figure 1. Residual total field magnetics with boundaries of the study area and porphyry deposits.	191
Figure 2. Box plot for the residual total field magnetics in different geological units that contain more than 10 measurements.(for 95% confidence level).....	192
Figure 3. Decrease of contrast and number of known porphyry Cu-Au deposits from class 1 to 29 of the residual total field magnetics map. Class 1 is the highest and class 29 represents the lowest level of the residual total field magnetics.	194
Figure 4. Decrease of contrast and number of known porphyry Cu-Mo deposits with higher classes of the residual total field magnetics map. Class 1 is the highest and class 29 represents the lowest level of the residual total field magnetics.	195
Figure 5. Variations of contrast and number of known porphyry Mo deposits with higher classes of the residual total field magnetics map. Class 1 is the highest residual total field magnetics and class 29 represents the lowest level of residual total field magnetics.....	196
Figure 6. Vertical derivative (gradient) of magnetics with boundaries of the study area and porphyry deposits.	198
Figure 7. Decrease of contrast and number of known porphyry Cu-Au deposits with higher classes of the vertical derivative (gradient) of magnetics map. Class 1 represents the highest level and class 30 represents the lowest level of the vertical derivative (gradient) of magnetics.	199
Figure 8. Decrease of contrast and number of known porphyry Cu-Mo deposits with higher classes of the vertical derivative (gradient) of residual total field magnetics map. Class 1 represents the highest level and class 30 represents the lowest level of the vertical derivative (gradient) of magnetics.	200
Figure 9. Variations of contrast and number of known porphyry Mo deposits with classes of the vertical derivative (gradient) of residual total field magnetics map. Class 1 represents the highest level and class 30 represents the lowest level of the vertical derivative (gradient) of magnetics.	201

Figure 10. Density ranges of common rock types (Telford et al. 1990).	203
Figure 11. Vertical derivative (gradient) of Bouguer gravity anomalies with boundaries of the study area and porphyry deposits.	205
Figure 12. Area of each class of gradient of Bouguer gravity anomalies map inside the plutonic and volcanic units of the study area.	206
Figure 13. Box plot for distribution of vertical derivative (gradient) of Bouguer gravity anomalies in different geological units of the study area.	207
Figure 14. Variations of contrast and number of known porphyry Cu-Au deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the volcanic units of the study area.	209
Figure 15. Variations of contrast and number of known porphyry Cu-Au deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the plutonic units of the study area.	210
Figure 16. Variations of contrast and number of known porphyry Cu-Mo deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the volcanic units of the study area.	211
Figure 17. Variations of contrast and number of known porphyry Cu-Mo deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the plutonic units of the study area.	212
Figure 18. Variations of contrast and number of known porphyry Mo deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the volcanic units of the study area.	213

CHAPTER 7

Figure 1. Distribution of faults inside the Southern and Middle Canadian Cordillera.	217
Figure 2. Faults inside geological units of the study area and location of districts discussed in the text.	218
Figure 3. A tensional opening formed at flexure in a fault surface.	229
Figure 4. Density of faults inside rectangular grids covering different parts of the geological units of the study area, where faults at the scale of 1/250,000 exist.	232
Figure 5. Density of faults cut by the boundaries of geological units of the study area.	233
Figure 6. Original map of buffer zones around faults inside geological units of the study area.	235
Figure 7. Smoothed map of buffer zones around faults cut by the boundaries of the study area.	236
Figure 8. Buffer zones around points of fault intersection.	238
Figure 9. Smoothed map of buffer zones around points of fault intersection inside the study area.	239
Figure 10. Variation of contrast (C), a) Between porphyry deposits & fault density map. b) Between porphyry deposits & smoothed fault buffer map. c) Between porphyry deposits & smoothed fault node buffer map.	240

CHAPTER 8

Figure 1. Variations of the combined fuzzy membership values (μ combination) for different values of γ for the discussed example of $\mu_A = 0.8$ and $\mu_B = 0.4$.	253
Figure 2. Generalised inference network to create favourability maps.	254
Figure 3. The inference network to generate the geochemical factor map.	255
Figure 4. Variation of contrast (C) for different classes of Cu and Mo variance maps with a) porphyry Cu-Au deposits, b) porphyry Cu-Mo deposits, c) porphyry Mo deposits.	256
Figure 5. Combined variability of Cu and Mo in the geological units of the study area.	258
Figure 6. Combined variability of Cu and Mo zoomed in area A of Figure 5.	259
Figure 7. Zoomed variability of Cu and Mo zoomed in area B of Figure 5.	260
Figure 8. Geochemical factor for a) lower part and b) upper part of Guichon plutonic suite (EJgG).	262

Figure 9. Geochemical factor for Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs), Topley (EJqT) plutonic suites.	263
Figure 10. Geochemical factor for a) upper part and b) lower part of Late Cretaceous plutonic suites (Lkg).	264
Figure 11. Geochemical factor for Bonanza (JB).	265
Figure 12. Geochemical factor for Hazleton Group (JH) arc volcanics.	266
Figure 13. Geochemical factor for Takla and Nicola arc volcanics (TrJ, TrJN).	267
Figure 14. Inference network to create the geophysical factor map.	268
Figure 15. Geophysical factor map generated as explained in Figure 14.	269
Figure 16. Final geophysical factor map enlarged in A and B areas of Figure 15.	270
Figure 17. Inference network to create the tectonic factor.	271
Figure 18. Tectonic factor map generated by combining three “evidence” maps by fuzzy “OR”.	272
Figure 19. Tectonic factor map zoomed in the northern and southern part of the study area (A and B areas of Figure 18).	273
Figure 20. Inference network to create the distribution factor.	274
Figure 21. Density factor created by combining density of SHOWINGS and density of all other status types except SHOWINGS (with less fuzzy membership values for density of SHOWINGS).	275
Figure 22. Inference network to create the favourability maps.	276
Figure 23. Favourability maps for a) northern and b) southern parts of Guichon plutonic suites (EJgG) created by combining all factors by gamma operator ($\gamma = 0.95$).	277
Figure 24. Favourability map for Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites created by combining all factors by gamma operator ($\gamma = 0.95$).	278
Figure 25. Favourability maps for Late Cretaceous plutonic suites (Lkg) created by combining all factors by gamma operator ($\gamma = 0.95$) in a) northern and b) southern part of study area.	279
Figure 26. Favourability map for Bonanza arc volcanics (JB) created by combining all factors by gamma operator ($\gamma = 0.95$).	280
Figure 27. Favourability map for Hazleton arc volcanics (JH) created by combining all factors by gamma operator ($\gamma = 0.95$).	281
Figure 28. Favourability map for Takla and Nicola (TrJ, TrJN) arc volcanics created by combining all factors by gamma operator ($\gamma = 0.95$).	282
Figure 29. Favourability map for the whole study area, created by combining all factors by gamma operator ($\gamma = 0.95$).	283
Figure 30. Variations of contrast (C) with different classes of favourability map.	284
Figure 31. Favourability map with buffer zones around mining camps and SHOWINGS, in the northern part of the study area.	285
Figure 32. Favourability map with buffer zones around mining camps and SHOWINGS, in the southern part of the study area.	286
Figure 33. Distribution of the most favourable areas for prospecting porphyry deposits and detailed studies in the study area.	287
Figure 34. Distribution of the most favourable areas for prospecting porphyry deposits in northern part of the study area.	288
Figure 35. Distribution of the most favourable areas for prospecting porphyry deposits in southern part of the study area.	289
Figure 36. Mineral potential map from the mineral potential project of British Columbia.	296
Figure 37. Overlay of the boundaries of the most favourable areas created in this thesis on the mineral potential map of British Columbia Geological Survey.	297

Acknowledgments

First I must thank my supervisor Prof. Eion Cameron, both for his initial direction of the subject and for all his help during this thesis, and my wife, whose patience, support, and understanding, allowed me to do this thesis. Other people helped greatly during this thesis with their guidance and assistance. Dr. Graeme Bonham-Carter and Dr. Robert Garrett from Geological Survey of Canada kindly assisted me with some of my GIS and statistical questions. Mr. Warner Miles from geophysical section of Geological Survey of Canada answered some of my geophysical questions and supplied geophysical data. Dr. Eric Grunsky, Dr. William J. McMillan , Dr. Vittorio Preto, Dr. David Lefeburo, Dr. Andrejs Panteleyev from British Columbia Geological Survey Branch were very patient answering many of my questions. Mr. Martin McCurdy, Dr. John Lynch from Geological Survey of Canada, Wayne Jackaman and Dr. Ray Lett from British Columbia Geological Survey Branch supplied NGR geochemical data and information related to these data. I also wish to acknowledge Mr. Edward Hearn for helping to keep a roof over my head and introducing me to some of the foibles of English. My friends at the University of Ottawa, Mark Mihalasky, Dr. Kevin Telmer, Dr. Qiuming Cheng helped me in different forms during this thesis.

CHAPTER 1

INTRODUCTION

1.1 GENERAL

The Canadian Cordillera is one of the world's major metallogenic provinces for porphyry deposits (Hollister, 1978; McMillan and Panteleyev, 1988). It has numerous porphyry deposits and prospects containing principally the metals Cu, Mo, Au and in the northern Cordillera, W. Over the last ten years, exploration for porphyry deposits at the regional scale has focused on geological provinces that contain producing mines and known porphyry deposits (Thompson, 1995). In 1996, porphyry deposits represented 41.5% of all exploration targets in British Columbia, more than any other deposits type (Schroeter, 1997). The diversity of targets, from large world-class deposits to smaller but profitable targets, continues to make British Columbia a good place to explore.

Computerized techniques hold considerable promise as so many of the practical applications in mineral exploration are based on accumulated knowledge and empirical rules (Garrett, 1989). Developments in Geographic Information Systems (GIS) have made it possible to assemble and integrate a variety of geo-referenced data sets representing geology, geochemistry, geophysics, etc. Outputs for the integrated data include mineral potential maps that can guide exploration and resource evaluation. GIS can be applied at any scale of exploration, from local to regional. The wide availability of

government-sponsored, regional-scale surveys, carried out to consistent standards, make these an attractive source of data for GIS studies.

At a regional scale, some deposit types which occupy small areas, such as veins, are not readily distinguished from regional datasets. Other types, occupying a larger area, or which may be associated with extensive alteration haloes, are much more suitable for regional-scale GIS studies. Included in the latter group are porphyry deposits. The study described in this thesis applies GIS methods, including fuzzy logic techniques, to regional scale data sets from middle and southern British Columbia to identify areas of interest for prospecting porphyry deposits.

1.2 STUDY AREA

For this thesis certain geological units within the Canadian Cordillera covering south and middle British Columbia (48° N to 56° N) were selected (Figure 1). These geological units contain most of the known and major porphyry deposits of this region. These geological units are introduced in Chapter 3. Different types of available regional scale datasets cover most of this study area.

1.3 OBJECTIVE

In the Canadian Cordillera, although certain geological units are known as the main hosts for porphyry deposits, not all parts of them are mineralized. The objective of this thesis is to present mineral potential maps to identify the most favourable zones for prospecting porphyry deposits within the selected geological units, by applying fuzzy logic at the regional scale.

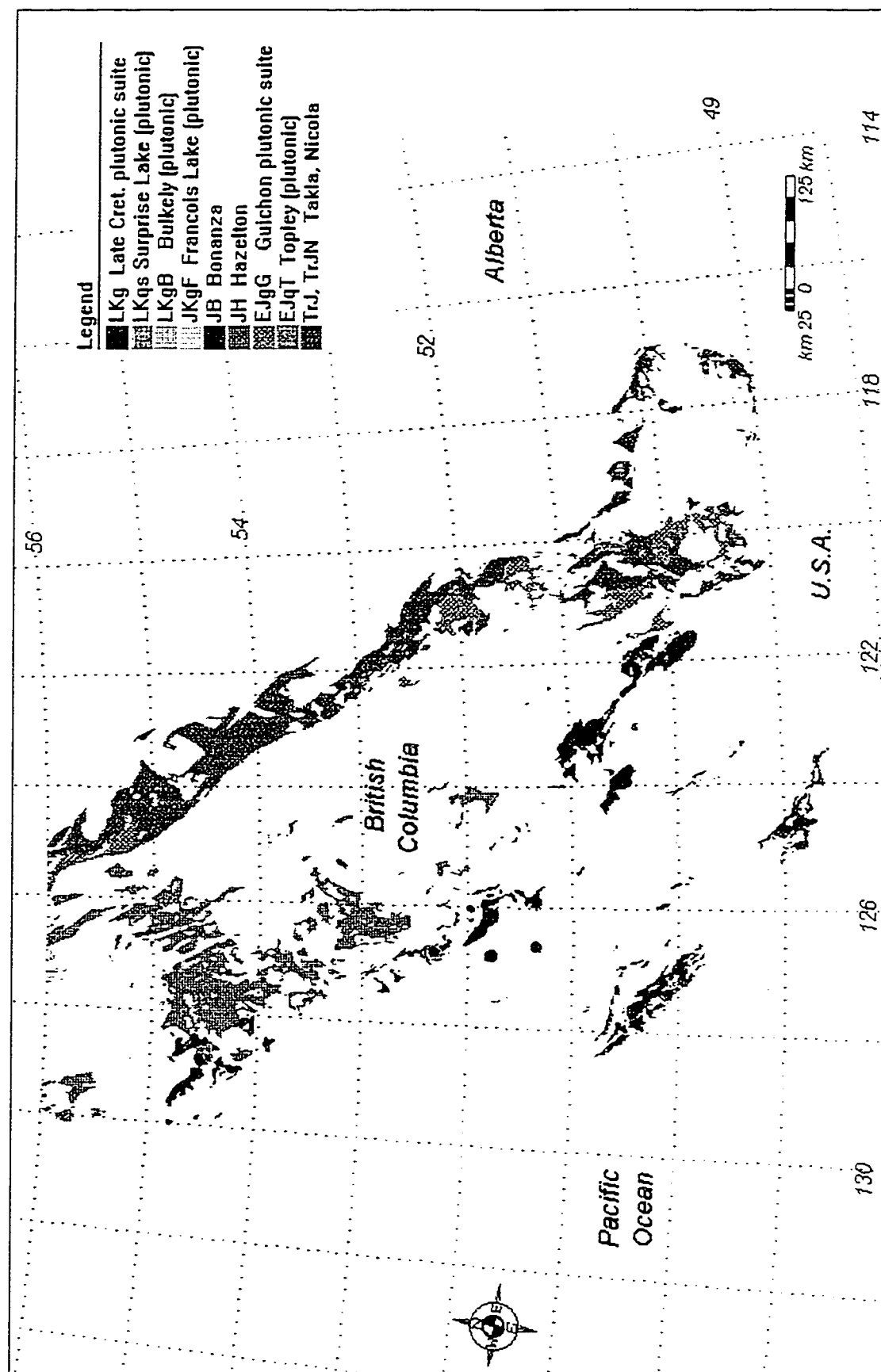


Figure 1. Geological units known as major hosts for porphyry deposits selected as the "study area". Regions outside these units were judged to be not permissive (extracted from geology of the Canadian Cordillera at the scale of 1:1 000,000).

1.4 METHODOLOGY

To create potential maps for prospecting porphyry deposits, three steps were undertaken:

- a. *Building spatial databases:* in this step, various initial data files were edited, restructured, extracted, connected and imported to the established study area. In most GIS studies, including this thesis, this step takes much time. A standardized format for different types of data can considerably reduce the amount of time and effort needed for this step.
- b. *Data analysis and processing:* in this step different data that were prepared properly in step 1 were analysed and processed. Table 1 shows the general procedures of various analyses performed on different datasets. The objective in this step was to find indicators of porphyry mineralizations within the geological units of the study area.

Table 1. Different types of analyses and processing that are done on various input layers.

<i>Type of Data</i>	<i>Type of Analysis & Processing</i>
<i>Geology</i>	- Extraction and selection of geological units that host porphyry deposits
<i>Known Porphyry Deposits</i>	- Generating density maps for distribution of different status types of known porphyry deposits
<i>Stream Sediment & Water Geochemistry</i>	- Levelling geochemical data as needed between some map sheets, - Univariate & multivariate analyses, mapping the mineralization indicators found from these analyses - Mapping elements and variability parameters of some elements as good indicators of mineralizations - Quantitative comparison between distribution of known porphyry deposits with these indicators
<i>Geophysics</i>	- Mapping geophysical parameters - Quantitative comparison between distribution of known porphyry deposits with geophysical indicators
<i>Tectonics</i>	- Selection of faults, points of intersection of faults, - Mapping density of faults, smoothed buffers around faults and buffers around faults intersections points, - Comparing these maps together, quantitative comparison between distribution of porphyry deposits and these maps

c. Combining different input layers by integration modelling: The last step consisted of combining various map layers to form predictive maps showing the relative favourability or porphyry mineralization potential. The combination process involved the weighting and 'fusing' of different suites of evidence. In this study the method of fuzzy logic was used. Fuzzy logic is a superset of conventional (Boolean) logic that has been extended to handle the concept of partial truth -- truth values between "completely true" and "completely false".

1.5 DATA FILES

1.5.1 REGIONAL GEOLOGY

The compiled digital files of geology of the Canadian Cordillera at the regional scale of 1:1, 000,000, which are prepared by the Geological Survey of Canada, were utilised for this study. In 1997 this data was published on CD-ROM for the public by the Geological Survey of Canada (Wheeler *et al.*, 1997).

1.5.2 GEOCHEMICAL DATA (STREAM SEDIMENT & WATER SAMPLES)

Geochemical data can be valuable for mineral potential studies because they may provide direct indications of mineralizations. The National Geochemical Reconnaissance (NGR) of stream sediment and water surveys have been carried out by the Geological Survey of Canada both independently and in conjunction with the provinces under various federal-provincial programs since 1970 (Friske and Hornbrook, 1991). In British Columbia, some of the regional geochemical surveys have been carried out by the British Columbia Geological Survey Branch in cooperation with the Geological Survey of

Canada. These surveys currently cover approximately 70% of British Columbia and on some map sheets contain determinations for up to 40 elements. In NGR surveys, each map sheet evaluates an area covering approximately 14,000 km². Sediment and water samples are collected from first or second order drainage basins with an average density of one sample site per 10 to 13 km².

1.5.3 GEOPHYSICAL DATA

Geophysical data are used for mineral potential analysis if there is a known or possible relationship between geophysical signature and a certain type of mineralization. Considering the regional scale of this study, the geophysical data of National Aeromagnetic and National Gravity databases from the Geophysics Division of Geological Survey of Canada were used. Table 2 shows different types and resolution of geophysical data that were used here.

Table 2. Different types of geophysical data used in this thesis and their resolution.

GEOPHYSICAL DATA	RESOLUTION (km)
Residual Total Field Magnetism	2
Vertical Gradient of Total Field Magnetism	2
Vertical Gradient of Bouguer Gravity Anomalies	6

1.5.4 FAULTS

As a part of the mineral potential project, the British Columbia Geological Survey Branch has compiled the bedrock geology for all of British Columbia at the scale of 1:250,000. In addition to the bedrock geology, they have digitized tectonic features of British Columbia at the same scale. Faults that are used in the tectonic analysis of Chapter 7 were extracted from these digital files.

1.5.5 MINERAL OCCURRENCES INFORMATION

MINFILE is the British Columbia Geological Survey Branch's computerized mineral inventory system. It is a comprehensive database for mineral deposits of British Columbia that contains over 60 megabytes of geologic, geographic location and economic information on over 11,600 documented metallic, industrial mineral and coal occurrences. Different types of porphyry deposits and their recorded information were extracted from this database. The information included geographical co-ordinates, commodities, major elements, production or exploration status and an abstract containing a description of the geology of the deposit or mine.

1.6 THESIS FORMAT

Chapters of this thesis are organised to explain how the different types of exploration datasets were prepared for the data integration step to produce favourability maps. Because of the importance of the relationship between porphyry mineralization and tectono-stratigraphic environment, chapter 2 presents a general overview of the tectonic and plutonic evolution of Canadian Cordillera. Chapter 3 outlines the principal characteristics, the different classifications of porphyry deposits, and their spatial and temporal distribution in the Canadian Cordillera. Also, in this chapter density maps for distribution of porphyry deposits are presented as well as the selection of certain geological units that are known as host for different types of porphyry deposits.

After editing and compiling the data of different NGR map sheets, some of the geochemical elements (i.e. Mo, Fe, Mn) and also pH, exhibited a “boundary shift” or levelling problem between different NGR map sheets. In Chapter 4 the data of map sheets with a boundary shift were levelled. In this chapter, the method suggested by

Garrett et al. (1995) was further developed and tested. The levelling procedure, introduced in Chapter 4, is general and could be applied to other areas and data sets with a boundary shift between map sheets. After levelling, geochemical samples were allocated to subsets based on the geological units or groups of geological units (selected in Chapter 3). These subsets were analysed by univariate and multivariate statistical methods in Chapter 5 (Table 1). The goals in Chapter 5 were to find the best univariate and multivariate predictors of deposits within each of the geological units or groups of geological units of the study area. Chapter 6 focuses on the regional geophysical characteristics of the porphyry deposits with respect to aeromagnetic and gravity measurements inside the region covering the study area. The geophysical parameters that were checked for their efficiency as indicators of mineralized areas are indicated in Table 2. In Chapter 7 some tectonic features potentially suitable for intrusion-related ore deposit mineralizations, were analysed, discussed and compared with each other. In Chapter 8, for each geological unit or group of geological units of the study area, different types of evidence maps, introduced in the previous chapters as indicators of porphyry mineralizations, were integrated to each other using the fuzzy logic method for knowledge representation and combination. Finally all of these separately generated favourability maps were joined to create one favourability map for the study area. To present the most favourable areas, all the low classes of this favourability map were removed, also buffer zones representing mining camps around the known porphyry deposits and mines were subtracted. The remaining zones in this final map can indicate the most favourable zones for finding undiscovered porphyry deposits. In the end, maps of mineral potential project of British Columbia created by the British Columbia Geological Survey which are for all metallic deposits, are compared with the favourability maps for porphyry deposits of this thesis.

CHAPTER 2

AN OVERVIEW OF TECTONIC AND PLUTONIC EVOLUTION OF THE CANADIAN CORDILLERA

2.1 TECTONIC EVOLUTION

2.1.1 INTRODUCTION

During the past decade has it been fully realised that much of the Cordillera in Western North America comprises an assembly of disparate crustal fragments, or terranes, some of which originated at distant locations. The Cordillera is a collage of pericratonic and accreted terranes welded to the western edge of the North American craton (Gabrielse *et al.*, 1991).

Five major belts (Figure 1) are recognized in the Canadian Cordillera that originated during Mesozoic to post-mid Tertiary events: the Ancient North American continental margin and miogeocline (Foreland Belt); the Omineca Belt comprising pericratonic terranes with similarities to North America; the allochthonous Intermontane and Insular superterrane, both consisting of several terranes; and the intrusive Coast Plutonic Complex, which separates, but incorporates

roof pendants of, the two superterrane (Monger *et al.*, 1991). Each of these belts show marked contrasts in physiography, metamorphism, volcanism, plutonism and structural styles which to some degree, were inherited from the original component terranes (Gabrielse *et al.*, 1991). The boundaries of the belts are somewhat arbitrary because their definition combines both geological and physiographic factors.

In particular, Monger *et al.* (1972) argued that the eastern Canadian Cordilleran consists of rocks with ties to North America, while the western Cordillera consists largely of island arc and oceanic assemblages that are generally allochthonous with respect to the continent. These ideas led to the development of tectonic models based on the accretion of numerous disparate crustal fragments known as terranes. The Canadian Cordillera can be divided into five belts based on terrane amalgamations (Monger *et al.*, 1991). Evidence from paleomagnetic (Irving and Thorkelson, 1990; Irving and Wynne, 1991), and faunal studies (Monger and Ross, 1971, Carter *et al.* 1991) suggest that in the Canadian Cordillera, some of the terranes spent part of their histories at more southerly latitudes before accretion.

Terranes are defined as parts of the Earth's crust which preserve a geological record different from those of neighbouring terranes (Gabrielse *et al.*, 1991, Monger, 1991). Terranes are differentiated primarily by their stratigraphy. In many cases, they also have distinctive structural styles and volcanic and plutonic histories. Terranes may have formed in different tectonic environments. The boundaries between terranes are faults and to some extent, are colinear with the boundaries between belts (Gabrielse *et al.* 1991). Accreted terranes are those which became incorporated with ancestral North America at a late stage in their tectonic histories. Major accreted terranes are Slide Mountain, Quesnellia, Cache Creek, Stikinia, Wrangellia and Alexander. Most of the accretions of the terranes have taken place in a relatively short period from about 200 Ma (Early Jurassic) to nearly 45 Ma (Mid Tertiary). More than 100 different terranes have been accreted to Western North America (Gabrielse *et al.*,

1991). Among these, only a few are major terranes. Each of the major terranes comprises some subterrane.

As Monger (1989) notes: "extensional tectonics dominated the evolution of the western margin of the North American continent from Middle Proterozoic through Middle Jurassic time, and compressional tectonics thereafter", and post-Middle Jurassic relative movement is very great. Engebretson (1983), using magnetic anomaly patterns and hot spot traces, calculated that more than 10,000 km of Pacific Ocean crust have been subducted beneath the western margin of North America in the last 145 Ma.

Some terranes are fault-displaced parts of the ancient continental margin (Cassiar terrane); some are pericratonic and probably originated off the edge of the North American plate (Kootenay terrane). Pericratonic terranes occur between the accreted terranes and ancestral North America and form components of the Omineca Belt. Parts have stratigraphic affinities with the ancient continental margin and thus may not have been greatly displaced from their locale of origin. Some other parts, however, have stratigraphic and structural characteristics that are not observed in the rocks of the ancient margin. An example is the Kootenay terrane. These terranes contain miogeoclinal assemblages, which were displaced northward hundreds of km from their original positions. Although it is not well constrained, strike-slip faulting probably began in the north-eastern Cordillera in the Late Cretaceous and Early Tertiary (Price and Carmichael, 1986).

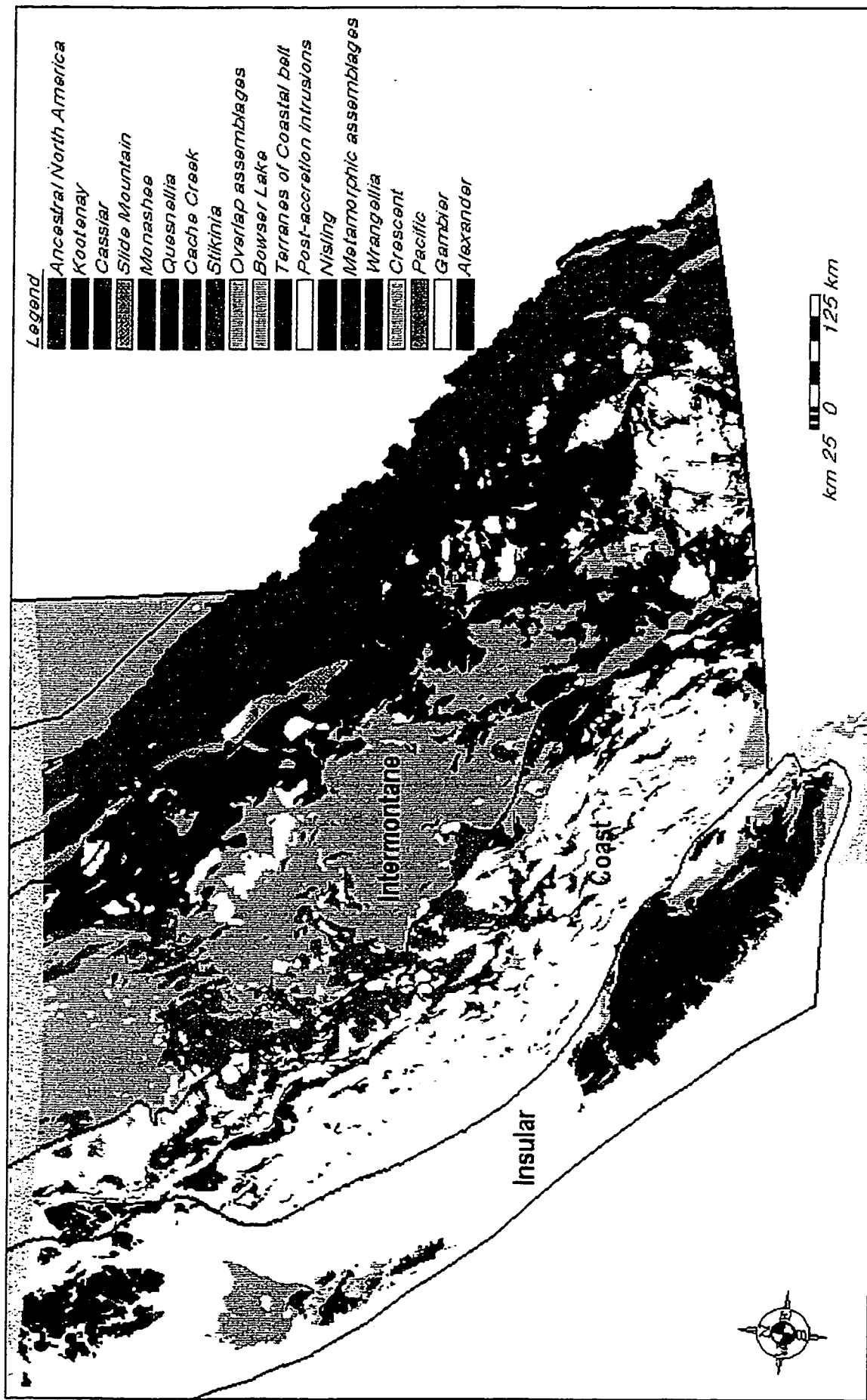


Figure 1. Major terranes and five tectonostratigraphic belts of the Canadian Cordillera.

About 150 Ma ago, the relative movement between the Pacific and North American plates was easterly. By 100 Ma it shifted to the northeast and by 50 Ma to the east-northeast (Engebretson *et al.*, 1985). Near the continental edge, at about 85 Ma, the Kula plate broke off from the Pacific plate and moved north relative to North America. At about 40 Ma the Kula plate amalgamated with the Pacific plate, when a new Farallon-Pacific-North American plate triple-junction originated off the north end of what is now Vancouver Island. Today, motion north of the triple-junction continues to be northwards relative to the North American plate (Gabrielse and Yorath, 1989). In Neogene time, Pacific-Juan de Fuca-North American plate interactions have been key to many plutonic activities. The spectacular Cascades volcanoes are one of the results (McMillan, 1994).

The timing and importance of amalgamation, the joining together of terranes to form a large compound or superterrane, and accretion, the addition of terranes or superterranes to the ancient continental margin of North America, is the source of many debates about the tectonic evolution of the Cordillera (McMillan *et al.* 1995). The Intermontane belt contains the most important terranes with regard to porphyry deposits.

2.1.2 FORELAND AND OMINECA BELTS

The Foreland Belt forms the eastern mountain ranges and foothills of the Canadian Cordillera. It is largely composed of material deposited in extensional settings and derived from cratonic sources. The rocks are divided into three stratigraphic packages based on lithology and age relationships. Beginning in Middle Proterozoic time, episodes of rifting created a thick, passive margin sequence along the edge of the North American craton. The initial, 1200 Ma, event is evidenced by two thick, clastic and carbonate sequences, the Purcell Supergroup in the south, which hosts the famous Sullivan lead-zinc-silver massive sulphide deposit, and the Wernecke Supergroup in the north. Rifting the full length of the Cordillera led to deposition of

the second sequence, the late Proterozoic (770 Ma), dominantly clastic Windermere Supergroup. Mafic dikes and flows of this age are widespread and volcanic-exhalative cherty iron formation occurs in the McKenzie Mountains (McMillan, 1994, Gabrielse *et al.* 1991). The third sequence, which is related to a mid-Devonian to Early Mississippian rifting event, led to formation of the "sedex" barite- lead- zinc massive sulphide deposits of the Kechika trough and the Selwyn basin. Rifting was accompanied by deformation, volcanism and plutonism at the craton margin (Nelson and MacIntyre, 1989). Later, during Mesozoic and Cenozoic times, the miogeocline was affected by compression and magmatic activity during accretion of island-arc terranes, and cut by Cretaceous and Cenozoic dextral strike-slip faults (McMillan, 1994).

Because of the accretions, miogeoclinal sediments are folded and faulted with thrust faults. The amount of shortening and eastward displacement over the underlying Canadian Shield is estimated to be between 50 km in the northern Foreland Belt to over 200 km in the south (Gabrielse *et al.* 1991).

Beginning of the accretions corresponds with the movement of Farallon oceanic plate. Farallon plate began to move towards the North American plate in Late Triassic to Early Jurassic time (Irving and Wynne, 1991) and caused the western margin of the North American plate to become tectonically active. The Omineca Belt is an uplifted region, extensively underlain by metamorphic and granitic rocks which straddles the boundary between the accreted terranes and Ancestral North America (Foreland Belt). From the time the accretions started, the western margin of miogeoclinal sediments was absorbing the collision and compression of accretions. This gradually started metamorphism in Omineca Belt. During all the accretions, the Omineca Belt was a centre of deformation and high metamorphism leading to many S-type granitic plutons (Gabrielse *et al.* 1991).

In the Omineca Belt, metamorphic rocks record deep structural depression during mid-Jurassic tectonism, followed by significant uplift. By Late Cretaceous time the Omineca and

Coast plutonic-metamorphic belts were well established and being uplifted (Gabrielse and Yorath, 1989). Metamorphic core-complexes in the Omineca Belt were further exhumed by mid-Cenozoic uplift and detachment faulting (Coney, 1989).

In Late Cretaceous and Early Tertiary time the belt was further disrupted by several northwest-trending dextral faults, repeated the belt along hundreds of km of overlap length (Gabrielse *et al.* 1991). During the Eocene widespread granitic magmatism and uplift occurred in the Coast and Omineca Belts. The Omineca Belt also displays up to 100 km of extension accompanied by volcanism and high heat-flow rates. Dextral strike-slip faulting continued and movement began on the Fraser-Yalakom system. Paleomagnetic studies show that the Eocene Kamloops volcanics (Symons and Wellings, 1989) and the mid-Eocene Ootsa Lake volcanics (Vandall and Palmer, 1990) have the same pole as the craton, so the Intermontane Superterrane was cratonized by mid-Eocene time.

2.1.3 INTERMONTANE BELT

The Intermontane Superterrane consists of the oceanic Slide Mountain and Cache Creek terranes and the island-arc Quesnellia and Stikinia terranes. Stikinia, the Cache Creek terrane and Quesnellia may have been linked (amalgamated) by latest Triassic time. Closing of the Slide Mountain ocean began in the late Palaeozoic and apparently ended with mid-Jurassic to Early Cretaceous thrusting of the Slide Mountain and to a lesser extent Quesnellia allochthons onto the miogeocline (McMillan, 1994). In the northern Cordillera, the Teslin suture zone, which formed during oblique Triassic-Jurassic convergence that resulted in dextral offset, now separates accreted and North American rocks (Hansen *et al.*, 1989). Closure of this ocean basin may be in part responsible for formation of the Quesnellia island-arcs. The Intermontane Superterrane collided with the North American craton in mid-Jurassic time, about 185 to 175 Ma, giving rise to the Omineca Belt (McMillan, 1994).

2.1.3.1 SLIDE MOUNTAIN TERRANE

This terrane is believed to be located at the west margin of ancestral North America, before starting of accretions. In fact in Early Mississippian to mid-Permian it was a marginal sedimentary basin (Nelson, 1993). In Figure 2, an Early Permian reconstruction of the Slide Mountain Ocean and its relationship to ancestral North America is shown.

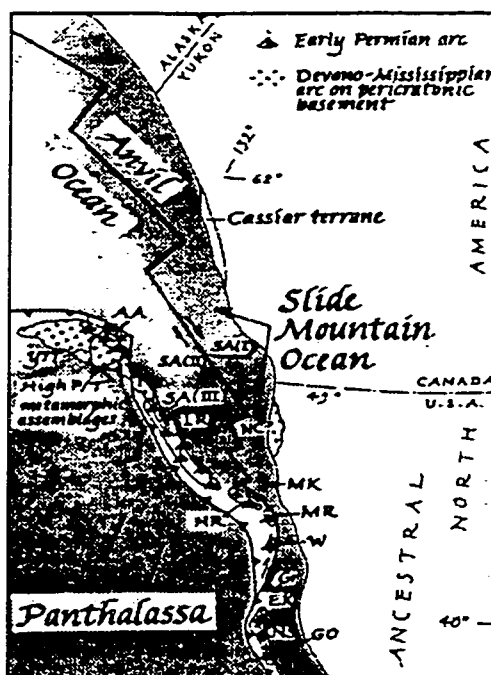


Figure 2. Suggested Early Permian reconstruction of the Slide Mountain ocean, arcs, and the subduction zones off the west coast of Ancestral North America (Nelson, 1993).

Like the Anvil Ocean, it opened in Early Mississippian time, separating the pericratonic sliver that became the Yukon-Tanana terrane from the continent. As seen from Figure 2, Nelson (1993), based on her studies has suggested that the Slide Mountain Ocean was not a vast Paleo-Pacific ocean as it is suggested by Monger et al. (1991), but it was a relatively narrow oceanic basin. It widened to the north into the Anvil Ocean, where late Palaeozoic south-westerly subduction beneath the Yukon-Tanana terrane did occur. This terrane is one of the first accreted terranes.

2.1.3.2 QUESNELLIA, CACHE CREEK & STIKINIA TERRANES

Exotic and far-travelled oceanic crustal rocks of the Cache Creek terrane are bordered by less exotic Quesnellia and Stikinia arc terranes to the east, north and west.

The oldest rocks of Stikinia, the Stikinia assemblage (Brown *et al.*, 1991) comprises Devonian to Permian volcanic and sedimentary strata. However, in most regions this assemblage is absent or poorly exposed, and Stikinia is more commonly characterised by younger and more widely distributed volcanic and sedimentary rocks of the Upper Triassic Stuhini and Lewes River groups (Anderson and Thorkelson, 1990).

On the east, Stikinia is faulted against mainly the Quesnellia and Cache Creek terranes. The Cache Creek terrane, characterised by strata of oceanic affinity, is regarded as vestiges of an ocean basin that separated Stikinia from Quesnellia and more inboard terranes (Mihalynuk *et al.* 1994)

In Early Mesozoic Quesnellia and Stikinia were joined through their northern ends as two adjacent arcs that faced south toward the Cache Creek ocean (Panthalassa?). Oceanic Plateau remnants within the Cache Creek today were transported from the Tethyan realm and collided with these arcs during subduction of Cache Creek ocean. Counterclockwise rotation of Stikinia and Nisling terranes in the Late Triassic to Early Jurassic caused enclosure of the Cache Creek terrane. Rotation continued until these terranes collided with Quesnellia as the final closure in the Middle Jurassic (Mihalynuk *et al.* 1994). Figures 3 and 4 show different stages in evolution of Stikinia, Quesnellia and Cache Creek terranes.

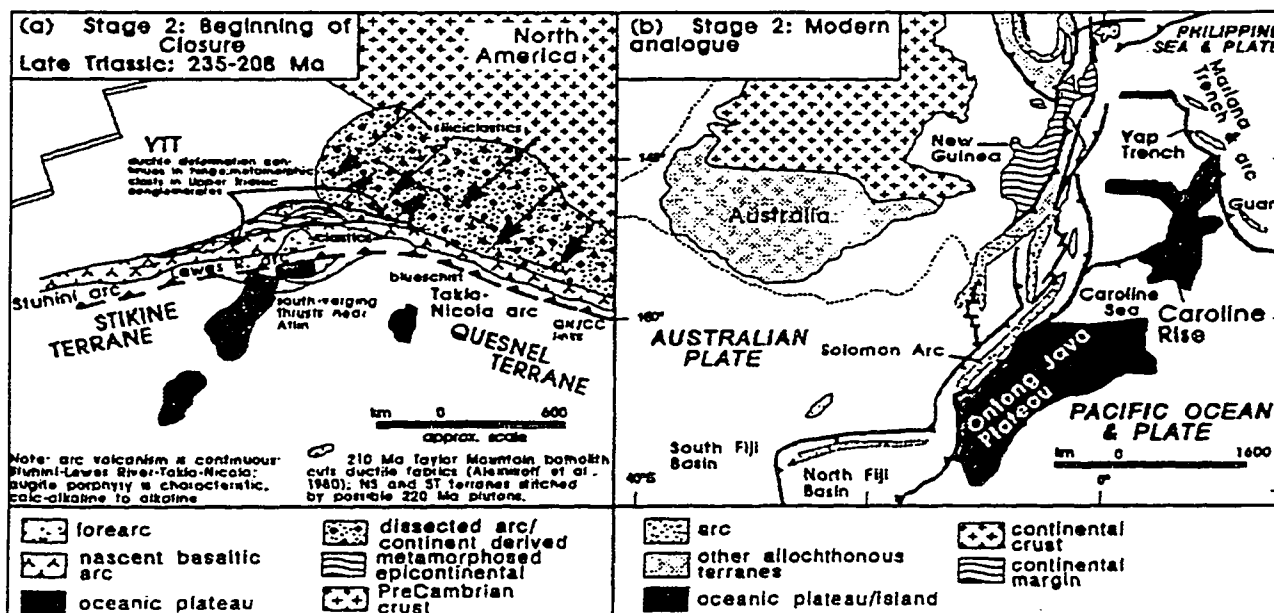
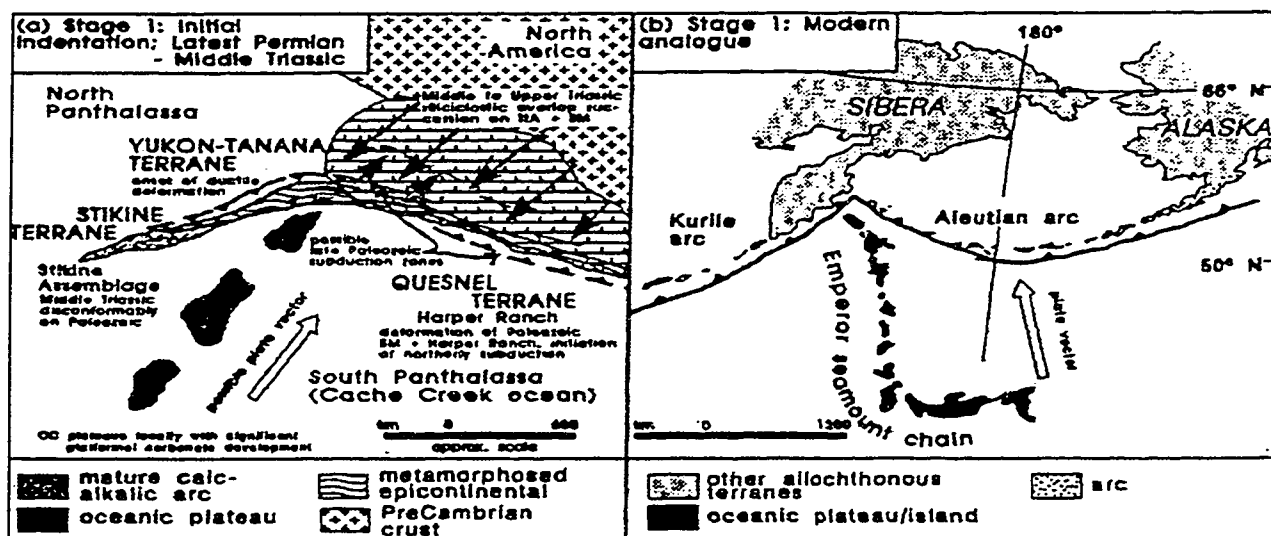


Figure 3. Stages 1 and 2 of tectonic evolution of Quesnellia, Stikinia and Cache Creek (Mihalynuk *et al.* 1994).

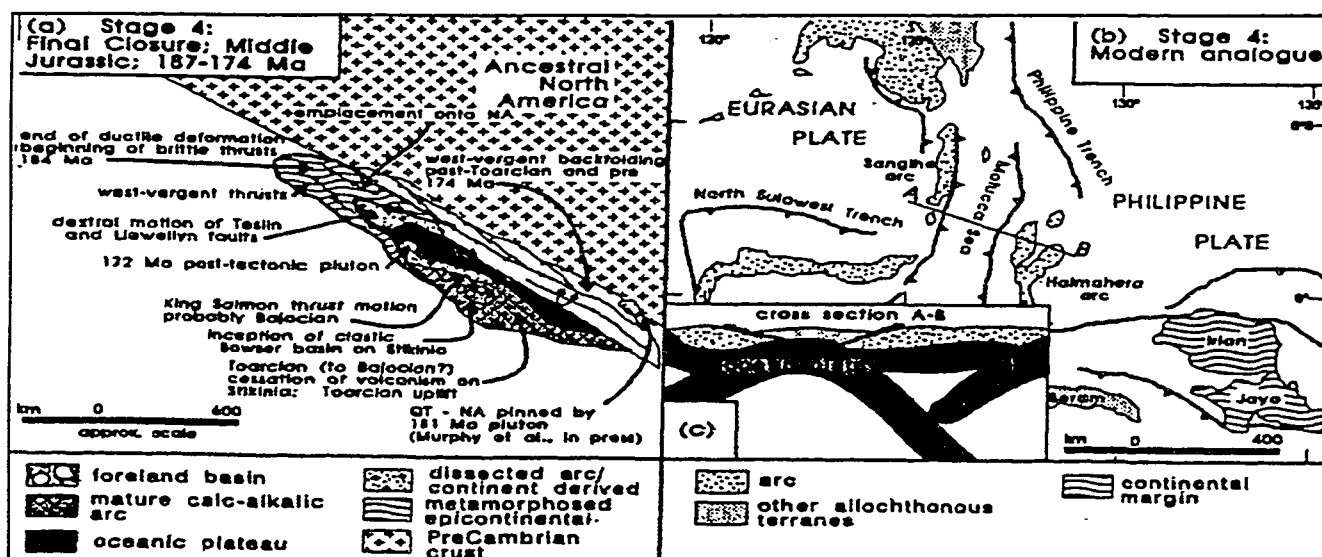
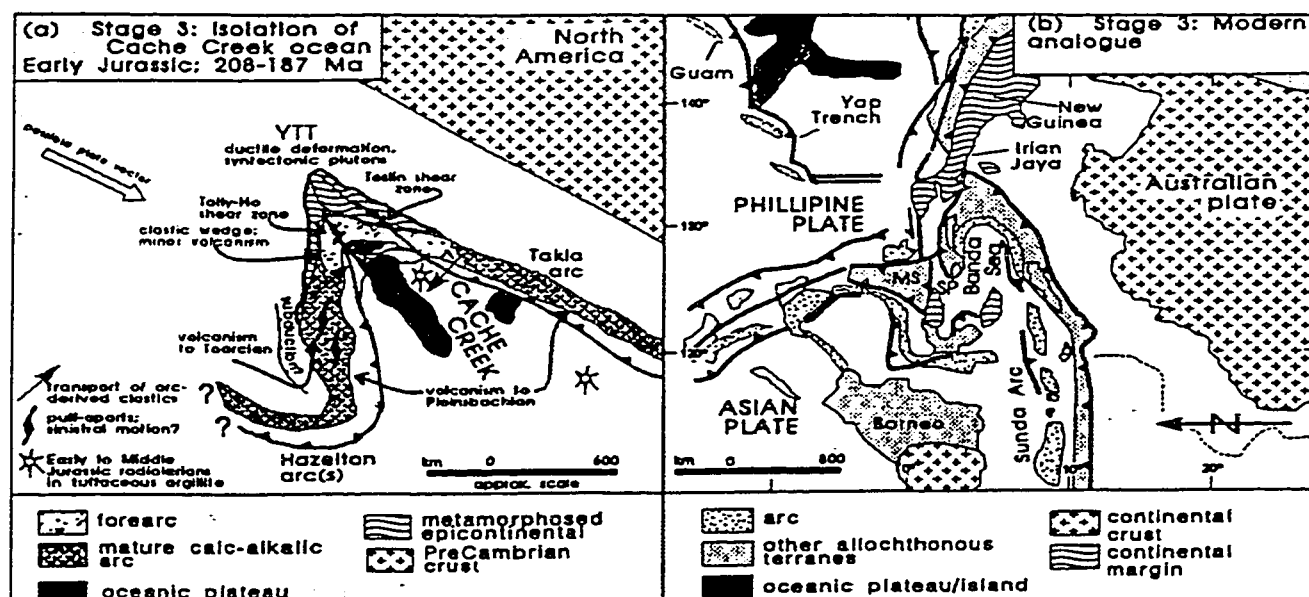


Figure 4. Stages 3 and 4 of tectonic evolution of Quesnellia, Stikinia and Cache Creek (Mihalynuk *et al.* 1994).

The earliest definite linkage between Stikinia and the Cache Creek terrane is a succession of conglomeratic rocks of the Bowser Basin which were derived from the Cache Creek terrane and deposited on Stikinia in Bajocian (Early Middle Jurassic) and younger time (Gabrielse, 1991).

There are different ideas about the tectonic evolution of the Intermontane superterrane. Based on one, the combined Intermontane and Insular superterranes were at their present relative positions by mid Cretaceous time; another is that they were against North America but farther south, as "Baja BC", at that time and did not arrive at present latitudes until Early Tertiary time. A different hypothesis is that the Stikinia 'block' originated in the Columbia embayment and began its travels northward in Middle to Late Jurassic time when the early-arriving, southern part of Wrangellia collided with continental North America (Wernicke and Klepacki, 1988).

2.1.4 COAST PLUTONIC BELT

Like the Omineca Belt, the Coast Belt is a Mesozoic metamorphic-granitic belt. The Coast Belt, spans the length of the Canadian Cordillera (Figure 1). Both of these belts are interpreted to be suture zones where the leading edges of two major composite accreted terranes—the Intermontane and Insular superterranes—crumpled into the North American plate (McMillan, 1994). Although the conclusion is not universally accepted (Price and Carmichael, 1986), Irving *et al.* (1980) and Tipper (1984) argue from paleomagnetic and paleontological data that individual elements of these superterranes originated far to the south of their present locations. Moreover, Monger *et al.* (1982) argue that as the terranes moved northward they amalgamated to form the distinct Superterranes before they docked with North America.

The Coast Belt is a high relief region composed largely of granitic and metamorphic rocks of Coastal Plutonic Complex. It contains pre- syn- and post-accretionary granitic rocks and has

been created by either or both long-term subduction and accretion of Insular Superterrane to the terranes in the Intermontane Belt (Gabrielse *et al.* 1991).

Its boundary is defined by the limit of dominantly plutonic rocks. The Coast Plutonic Complex has a regional north-westerly structural trend; individual bodies are commonly oriented with their long axes in a NW-SE direction. Overall, it is comprised of about 75% calc-alkaline granitoid material, ranging in composition from gabbro to granite. Quartz diorite, tonalite and diorite make up almost 75% of Coast plutonic Complex plutons, with hornblende and biotite as common mafic phases (Friedman and Cui, 1994).

The known age range of Coast Plutonic Complex plutons, based on U-Pb geochronology is Silurian to Miocene, with at least 95% of the bodies being of Jurassic to Eocene age. Regional U-Pb geochronology studies in the central and southern Coast Plutonic Complex indicate that the western limit and axis of magmatism moved eastward across the belt during Cretaceous time (Van der Heyden, 1989, 1992; Friedman and Armstrong, 1994)

Based on Nd and Sr isotopic data for Coast Plutonic Complex plutons in the southern Coast Belt, Friedman and Cui (1994) have found that the isotopic ratios are consistent with formation of southern Coastal Belt igneous rocks within a young magmatic arc, with minimal incorporation of old or isotopically evolved crustal material. There are no significant systematic Nd-Sr isotopic trends on the basis of geographic position or age (Friedman and Cui, 1994). The southern Coast Belt experienced 0-3.5 km of post-40 Ma uplift, increasing from southwest to northeast (Parrish, 1983), significantly less than the Coast Belt farther north.

The Nisling terrane in the northern Coast Mountains of British Columbia is a narrow terrane that could be a fragment rifted from North America and later accreted (Currie and Parrish 1993). The Nisling terrane is tectonically bounded by younger, oceanic, arc-dominated terranes on both sides (the Alexander to the west and Stikinia to the east). The Nisling terrane was accreted to Stikinia along a transpressive shear zone between 185 and 170 Ma, during or

before the accretion of Stikinia to the ancestral margin of North America (Currie and Parrish, 1993).

Along the eastern side of the Coast Range, the so-called "Coast Megalineament" originated at about 70 Ma. An incredible 800 km of the Megalineament is occupied by a foliated tonalite body. It is not certain whether this body is intrusive or a deep crustal slab, analogous to the Kapuskasing High in eastern Canada (Percival and Card, 1983).

2.1.5 WRANGELLIA & ALEXANDER TERRANES OF INSULAR BELT

The major internal elements of the Insular Superterrane—the Alexander Terrane and Wrangellia— originally defined by apparent differences in their Palaeozoic to Late Triassic histories (Jones *et al.*, 1977), were adjacent to one another by mid-Pennsylvanian time (308 +/- 6 Ma) (Gardner *et al.* 1988). In the middle Cretaceous, at about 100 Ma, the Insular Superterrane collided with the west side of the Intermontane Superterrane, initiating formation of the Coast plutonic-metamorphic belt (McMillan, 1994).

The Palaeozoic basement history of the Alexander terrane indicates that the crustal fragment evolved as an island arc complex, perhaps in proximity to the Gondwana orogenic system prior to Devonian time (Gehrels and Saleeby, 1987). Neodymium isotopic studies suggest an intraoceanic environment for the Alexander-Wrangellia terrane through Late Triassic time (Samson *et al.*, 1989, 1990).

Paleobiogeographic and paleomagnetic data suggest that the Alexander and Wrangellia terranes were considerably south of their present location with respect to North America in Late Triassic time. The Alexander and Wrangellia terranes were most likely positioned in the eastern Pacific basin, south (~30°) of the North American margin, during Late Triassic time and moved northward to near its present position with respect to cratonal North America during Late Triassic-Middle Jurassic time (McClelland *et al.*, 1992).

Regional similarities in the character and age of Late Jurassic-Early Cretaceous marginal basins common to the Alexander and Wrangellia terranes and Cordilleran margin reflect the Middle Jurassic accretion of the Alexander and Wrangellia terranes (McClelland *et al.*, 1992). Accretion of the Alexander and Wrangellia terranes was a protracted process of juxtaposition, translation, and imbrication that occurred from Middle Jurassic to mid-Cretaceous time (McClelland *et al.*, 1992). Since there is currently no evidence for a subduction complex separating the Alexander and Wrangellia and Stikinia terranes, McClelland *et al.* (1992) have concluded that the initial Middle Jurassic Alexander and Wrangellia-Cordilleran margin juxtaposition resulted from either oblique subduction along the margin south of the Stikinia terrane followed by northward displacement along a dextral strike-slip fault system or, migration of the Alexander and Wrangellia terranes along the Cordilleran margin as a forearc fragment above a coeval east dipping subduction zone. Oblique or transpressional accretion of the Alexander and Wrangellia terranes, most likely along the paleo-Oregon-Washington margin, was apparently synchronous with Middle Jurassic accretion of the Stikinia and inboard terranes (McClelland *et al.*, 1992).

Closely following accretion of the Alexander and Wrangellia terranes, arc magmatism in all but the westernmost portion of the Stikinia terrane ceased (Armstrong, 1988) and Late Jurassic arc magmatism apparently shifted westward to the Alexander and Wrangellia terranes. This westward shift likely reflects initiation or resumption of east directed subduction outboard of the Alexander and Wrangellia terranes that is recorded by the oldest accretionary complex fragments preserved in the Chugach terrane. Accretion of the Insular Superterrane, beginning in the Early Cretaceous, is interpreted to have led to deposition of the Campanian (about 80 Ma) Belly River Formation (Cant and Stockmal, 1989; Gabrielse and Yorath, 1989). Obviously, sedimentary wedges that are by-products of terrane accretion can lag accretion by several tens of millions of years (McMillan, 1994).

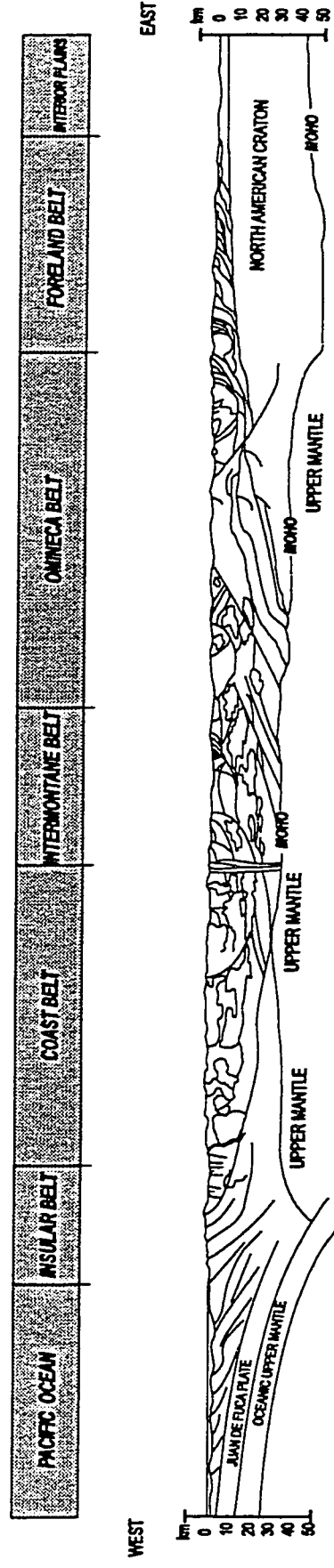


Figure 5. Geological cross section in southern British Columbia from Pacific Ocean in west to Interior Planes in east. (from tectonic map of Canadian Cordillera).

2.2 Magmatic Evolution

From Jurassic through Eocene time, episodes of deformation, plutonism and volcanism within the Cordillera correlate well with changes in velocity or movement direction of the North American Plate relative to oceanic plates (Figure 6). Relative collision vectors were often oblique to terrane boundaries during amalgamation and docking events. Consequently, timing of collision and related plutonic events varies along the length of the Cordillera. The curved to uneven shapes of the leading edges of rafting island-arcs and the North American plate border would be a major influence on variations in local stress regimes; the same movement vector could generate local compressional, extensional or transverse forces. These forces provide ground preparation for mineral deposition by producing deeply penetrating fracture systems and by generating heat flow and magmas that favour formation of large hydrothermal systems (McMillan, 1994).

Based on 3000 Ar, Sr, and Pb isotopic age determinations, the magmatic history of the Canadian Cordillera is revealed as episodic, with stable distribution patterns within episodes and distinct lulls and changes in distribution between the episodes. Distinction of episodes is based on peaks and low points of the histograms (for age distribution), on changes in geographic distribution of magmatism, and on the basis of compatibility with previous descriptions of geologic age relationships and natural grouping of rocks (Armstrong, 1988).

The episodes vary in intensity, duration, extent, and character, and they appear to be linked to major changes in plate motion. The most notable time-transgressions are the rapid continentward advances of episode inception and the gradual retreat of the magmatic front over a much longer time span than individual magmatic episodes.

During late Triassic and continuing through Jurassic time, the episodes were relatively terrane-specific, but from the Cretaceous onward, the Coast Belt was the site of Andean-type continent-margin magmatic arc (Armstrong, 1988). Sr isotopic composition of magmas is

terrane-specific but is also affected by changing thermal conditions and crustal evolution. Chemical trends across magmatic belts reveal subduction polarity as well as changing thermal conditions. Eastward-descending subducted ocean crust appears to have been the general rule through Mesozoic time (Armstrong, 1988).

Major magmatic episodes correspond to times of increased westward motion of North America with respect to hot spots or to times of increased convergence between western North America and the Farallon Plate (Armstrong, 1988). Figure 6 shows a summation of all magmatic dates of The Canadian Cordillera beside the timing of porphyries and gold mineralizations. In addition, motion of Farallon plate with respect to North America from Jurdy (1984) and motion of North America with respect to hot spots from Engebretson et al. (1985) are indicated. Based on this figure, the magmatic episodes could be defined as indicated in the following pages.

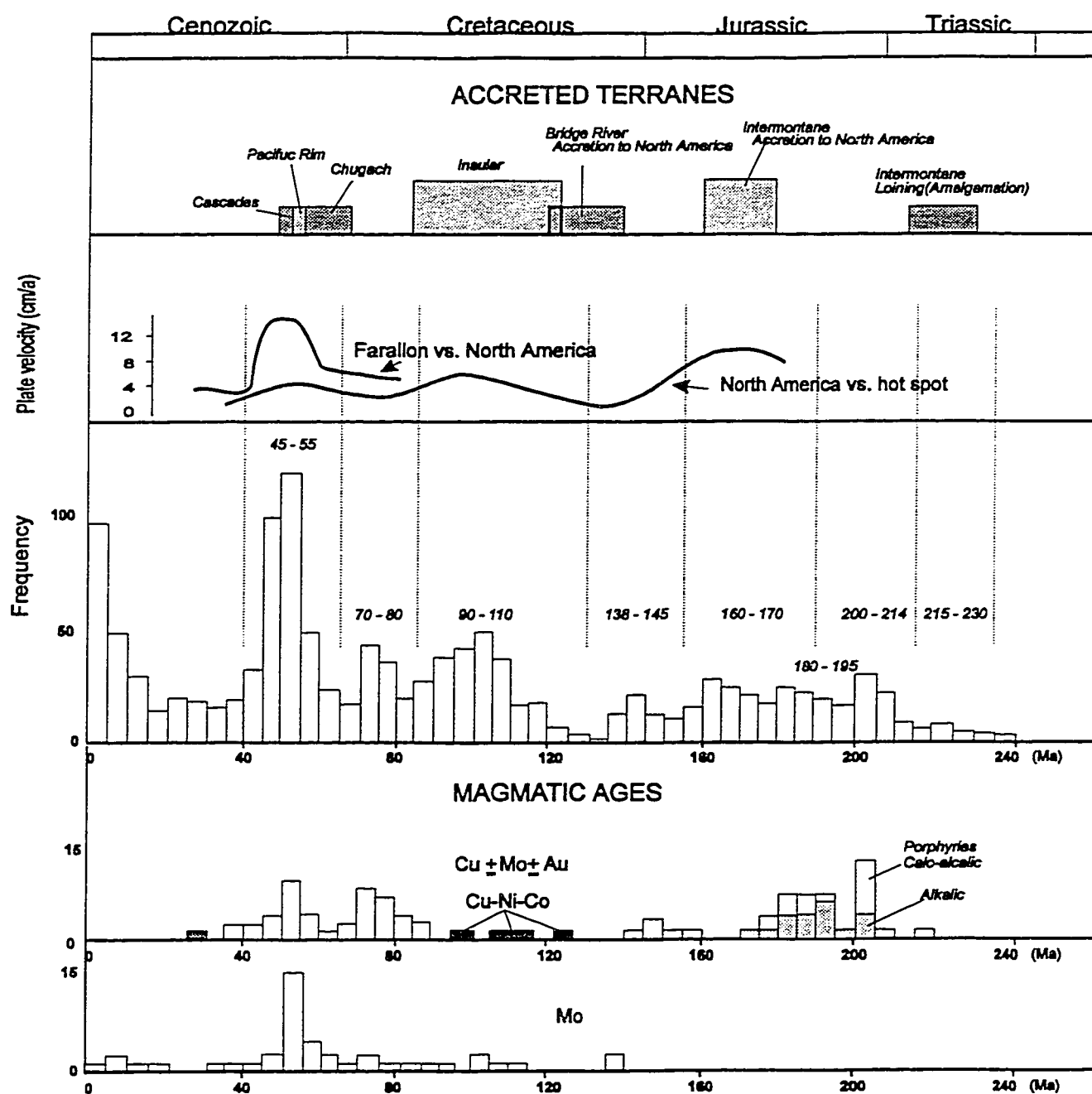


Figure 6. Frequency of all magmatic dates of Canadian Cordillera beside motion of Farallon plate with respect to North America and motion of North America with respect to hot spots (Armstrong, 1988) and timing of porphyry and gold mineralizations (Engelbreton *et al.*, 1985, McMillan, 1994).

2.2.1 230 to 214 Ma (DURING LATE TRIASSIC)

Extensive mafic volcanism occurred in the Wrangellia, Quesnellia and Stikinia terranes. Volcanic-related ultramafic complexes are found scattered through the two latter terranes (Armstrong, 1988). At this time all these island arc terranes were not accreted to ancestral North America. Blueschists formed in the Cache Creek, which was an oceanic basin between Quesnellia and Stikinia terranes.

2.2.2 214 to 200 Ma (END OF TRIASSIC AND PART OF EARLY JURASSIC)

Arc magmatism began in Wrangellia, northern Quesnellia, and Stikinia terranes. A distinct magmatic event is recognisable only in southern Quesnellia (Armstrong, 1988). There is a strong lithologic and temporal similarity between the Late Triassic augite-phyric basalts of Quesnellia and Stikinia terranes. Volcanism commenced at approximately the same time in both terranes (Mihalynuk *et al.* 1994). Additional similarities between the two terranes in Late Triassic-Early Jurassic time include alkalic and ultramafic intrusions and associated copper-gold bearing subvolcanic monzonite porphyries (Copper Mountain suite, Woodsworth *et al.*, 1991) and calc-alkalic, usually felsic volcanic centres adjacent to the Cache Creek (Mihalynuk *et al.* 1994).

During this period, Quesnellia and Stikinia terranes share a progression from felsic volcanics through augite porphyries of the main arcs, which are loosely stitched to pericratonic terranes that lie farthest from the Cache Creek (Mihalynuk *et al.* 1994).

2.2.3 200 to 155 Ma (LATE EARLY TO EARLY LATE JURASSIC)

Magmatism was extensive in the Wrangellia, Quesnellia and Stikinia. Magmatism overlapped into North America only east of southern Quesnellia after about 180 Ma (Armstrong, 1988). By the middle of this interval, the southern Quesnellia-Slide Mountain-North America linkage was complete. During this period, in Middle Jurassic, voluminous arc volcanism ceased, slightly later on Stikinia than on Quesnellia, as a result of cessation of both subduction zones of these two arcs and Cache Creek oceanic plate, signalling the rupture and westward obduction of cool Cache Creek crustal fragments and termination of Cache Creek sedimentation. At the same time, Quesnellia was transported eastward onto the North American margin, and major deformation and metamorphism had affected the Omineca Belt in British Columbia, and the formation of the Omineca Belt began. Rapid accumulation of Cache Creek derived strata within the Bowser Basin marks overthrusting and foredeep clastic deposition during final closure of the orocline (Mihalynuk *et al.* 1994).

Early to Middle Jurassic magmatism in southern Wrangellia (Vancouver island) is distinctly older than the Middle to Late Jurassic magmatism that occurred in central Wrangellia (Queen Charlotte Island)(Armstrong, 1988).

2.2.4 155 to 140 Ma (LATE JURASSIC)

A few late plutons of the late Early to early Late Jurassic episode and other rocks with partially reset 155 to 145 Ma dates occur in the Wrangellia, Quesnellia and Stikinia terranes. Late Jurassic magmatism (160 to 140 Ma) occurred in the Alexander terrane (Saint Elias region) (Armstrong, 1988).

2.2.5 145 to 138 Ma (LATEST JURASSIC AND BEGINNING OF EARLY CRETACEOUS)

Plutonism occurred in the Endako area of central British Columbia (Francois Lake suite), but is virtually unknown elsewhere (Armstrong, 1988).

2.2.6 135 to 125 Ma (EARLY CRETACEOUS)

During this period, there was a magmatic lull of major significance present throughout western North America. It corresponds to the minimum rate of movement of North America with respect to hot spots.

2.2.7 110 to 90 Ma (MIDDLE CRETACEOUS)

Widespread plutonism occurred across all terranes. Dual culmination are evident: the Coast Plutonic and Omineca Belts. Before this time all sutures except those outboard of Wrangellia had been closed (Armstrong, 1988).

2.2.8 80 to 70 Ma (LATE CRETACEOUS)

A narrow, sinuous belt of magmatism persisted, mostly in the south-eastern Coast Plutonic Belt, and scattered across the Skeena and Stikinia arches.

2.2.9 70 to 60 Ma (LATEST CRETACEOUS TO PALEOCENE)

A distinct lull in magmatism occurred. Rare plutons of this time interval are known in the Coast Plutonic Belt, on the Skeena Arch, and in the southern Intermontane Belt (Armstrong, 1988).

2.2.10 55 to 45 Ma (*LATEST PALEOCENE TO MIDDLE EOCENE*)

Widespread and voluminous magmatism occurred in all terranes. The early Cenozoic volcanic front crossed the Coast Plutonic Complex from its east side in the south to its west side in the north. Associated thermal and tectonic effects were strong even into the Omineca Belt, producing large reset metamorphic areas in the Coast and Omineca Belts. This was a short-lived event, synchronous from southern British Columbia through the Yukon. West of the volcanic front, offshore of Wrangellia, Metchosin volcano growth was underway at this time. Late in this time interval, the 50?- 45- 36- Ma Catface-Leech River event(s) of southern Wrangellia occurred (Armstrong, 1988).

CHAPTER 3

REVIEW OF CHARACTERISTICS AND DISTRIBUTION OF PORPHYRY DEPOSITS IN THE STUDY AREA

3.1 INTRODUCTION

Porphyry deposits are primary sources of Cu and Mo. They are large, low- to medium-grade deposits in which hypogene ore minerals are primarily structurally controlled and which are spatially and genetically related to felsic to intermediate subvolcanic porphyritic intrusions (Kirkham, 1972). The large size and structural control (e.g., veins, stockworks, fractures, 'crackled zones', and breccia pipes) serve to separate porphyry deposits from genetically-related (e.g. some skarns, high temperature mantos, breccia pipes, peripheral mesothermal veins, epithermal precious-metal deposits) and unrelated deposit types (Kirkham and Sinclair, 1996). Porphyry Cu deposits of the northern Cordilleran Orogen reflect geological environments that are different from those found in mineralized intrusions elsewhere in the Cordillera Orogen, both to the south in the United States and Mexico and to the north west in Alaska (Hollister, 1978). This may be because of the complex and different tectonic history of

geological terranes in the Canadian part of the Cordillera.

In this chapter, different classifications for porphyry deposits of the Canadian Cordillera, their characteristics, and both their spatial and temporal distribution are briefly discussed. Next, major geological units associated with porphyry deposits, used as the study area, were selected. Finally density maps were created to show the spatial distribution of porphyry deposits inside the study area so that they could be used in combining all evidence maps to prepare favourability or potential maps of chapter 8.

3.2 CLASSIFICATION OF PORPHYRY DEPOSITS

A variety of criteria have been used to classify porphyry deposits. The simplest breakdown is based on the principal commodities, Cu versus Mo. The importance of Au to the economics of porphyry deposits allows for further subdivisions in cases where Au is present in these deposits.

Porphyry Cu deposits have been subdivided on the basis of the correlation between their tectonic environments of formation or crustal association, and enrichment in Mo versus Au (Sillitoe, 1972; Kesler, 1973; Titley and Heinrich, 1978). Titley and Beane (1981) and Barr *et al.* (1976) have used the petrology of related intrusions to subdivide porphyry Cu deposits. In general, petrological associations correlate well with tectonic settings and metal abundance. Cox and Singer (1988) demonstrated a number of general relationships between metal abundance, tectonic setting, crustal environment, petrological association, mineralogy, and depth of emplacement. Unfortunately, none of these characteristics provide an unambiguous classification of porphyry Cu+Mo+Au deposits, and there are exceptions to the generalisations (McMillan, 1995). Sillitoe (1979 and 1993) described various features that are common to Au-rich porphyry Cu deposits, but again noted that no single feature provides a clear

discriminant for the classification or explanation for Au-rich deposits.

Similarly, different classification schemes for porphyry Mo deposits have been proposed, based on the character of related intrusions, into granodiorite or granite types (Mutschler *et al.*, 1981), or into calc-alkaline, alkali-calcic and alkalic types (Westra and Keith, 1961). Porphyry deposits have also been grouped into fluorine-rich and fluorine-poor varieties (Theodore and Menzie, 1984), which correspond roughly to the granite and granodiorite classes, respectively. White *et al.* (1981) proposed a widely accepted separation, based on petrology, into deposits related to either granite porphyry or alkali rhyolite, and those related to quartz monzonite. The former is commonly referred to as Climax-type deposits after the Climax mine. Carten *et al.* (1996) modified this scheme to define three groups of deposits: a high-silica rhyolite-alkaline suite, a differentiated monzogranite suite, and a granite-related Mo-Cu suite with Mo>0.05%. Known porphyry Mo deposits in the Canadian Cordillera fall in the differentiated monzogranite suite (McMillan, 1995).

The compositions of major porphyry deposits throughout the world are plotted in Figure 1 and divided into groups by principal commodities. Some of the general tectonic and petrological associations and correlations are depicted, there are many examples of deposits whose relative metal abundance differ from these typical associations (McMillan, 1995). Classification of deposits by features other than relative metal abundance is possible for porphyry Mo deposits, and may be possible in the future for some porphyry Au deposits (McMillan, 1995).

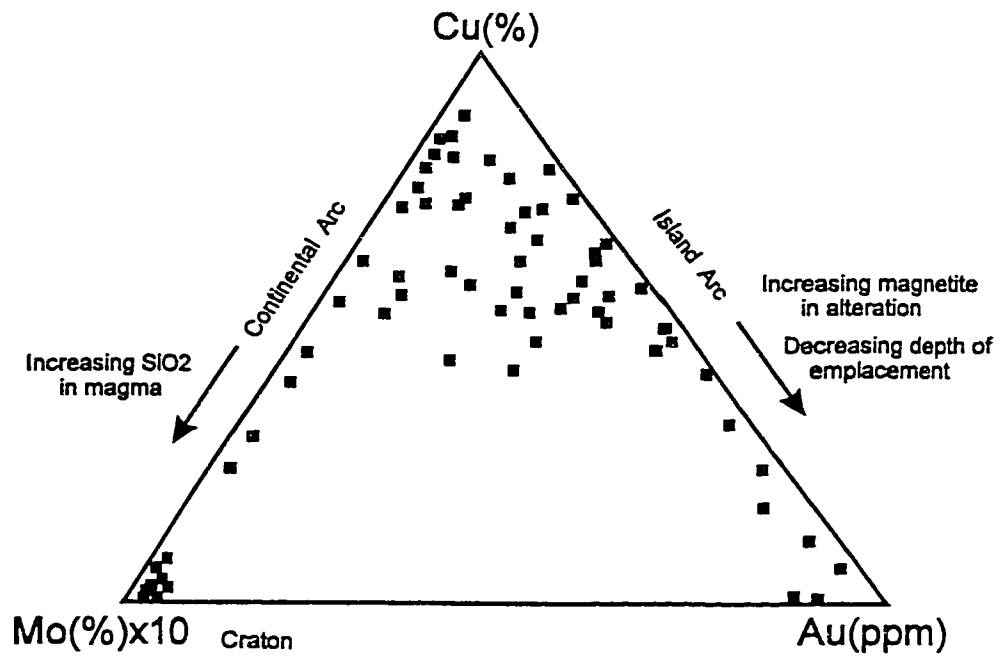


Figure 1. Relative abundance of Cu (in %), Mo (in %) x10 and Au (in g/t) for various porphyry deposits from around the world [after Cox and Singer (1988) and Sillitoe (1993)].

3.2.1 CORDILLERAN CLASSIFICATION

Three main types of classification are proposed for Cordilleran porphyry deposits, which are based on:

- Morphology, rock association and depth,

Which comprise three broad types of plutonic, volcanic and classic (stock)

- Chemical classification,

Calc-alkalic and alkalic classes

- Metal content,

Cu-Au, Cu-Au $\pm$ Mo, Cu-Mo, Cu-Mo $\pm$ Au, Mo $\pm$ Cu, Mo, W-Mo, and Au $\pm$ Mo $\pm$ W

3.2.1.1 CLASSIFICATION BASED ON MORPHOLOGY, ROCK ASSOCIATION AND DEPTH

Three end-members of "plutonic", "volcanic" and "classic (stock)" types to describe porphyry deposits in the Canadian Cordillera are based on a morphological, depth-zoning classification. This classification has been developed by Sutherland Brown (1976). They represent variations caused by tectonic setting and depth of pluton emplacement.

Plutonic deposit types are Cu-Mo deposits that occur within plutons; examples are the Highland Valley, Brenda and Gibraltar deposits (Figure 5). These deposits form at relatively deep levels. Dikes and breccia bodies may be abundant (McMillan, 1994). Alteration patterns are similar to those described for deposits in the southwest United States by Lowell and Guilbert, (1970); and Guilbert and Lowell, (1974). They tend to be Cu-Mo deposits with low Au grades (McMillan, 1994). With the possible exception of Brenda mine, no plutonic type of porphyry deposits have been found with dates appreciably younger than the intruded calc-alkalic volcanic rocks (Hollister 1978). All appear to occur in the 205-170 Ma range (except Brenda).

The very large granitic pluton types are usually old (Triassic to Mid-Jurassic) porphyry deposits that have been deeply eroded. Consequently, their alteration zoning and geometric pattern may not fit the typical Lowell-Guilbert model (Hollister 1978).

Volcanic deposit types are Cu-Mo-Au and Cu-Au deposits that formed in the root zones of ancient calc-alkalic and alkalic volcanoes in association with subvolcanic stocks, plugs, sills and dike swarms; examples include Island Copper, Galore Creek and Mt. Milligan. (McMillan, 1994). The country rocks, which host most of the ore, are largely volcanic rocks, breccias and dikes. Early developed biotite, which McMillan and Panteleyev (1988) argue may be hornfelsing, is typical. Propylitic alteration can extend up to several hundreds of meters or more into the country rock from the deposits. Calc-alkalic Cordilleran examples are Island Copper and Schaft

Creek; alkalic examples are Galore Creek, Afton, Copper Mountain-Ingerbelle and Mount Milligan. It is important to note that calc-alkalic phases often occur within the suites of intrusive rocks that contain both alkalic members and alkalic porphyry deposits (Hollister, 1978).

Classic deposit types are Cu-Mo and Cu-Au $\pm$ Mo deposits related to multi-phase subvolcanic plutons emplaced into older, unrelated host rocks; examples are Granisle, Morrison, Bell, Fish Lake, and Poison Mountain in British Columbia, and Casino and Mount Nansen in Yukon. Deposits of Classic type have also been labelled simple, cylindrical, phallic (Sutherland Brown, 1976) and hypabyssal.

These deposits are related to multiple subvolcanic plutons. Host-rocks may be volcanic or sedimentary; dikes and breccias are common (McMillan, 1994). The mineralized pluton may be quartz diorite to quartz monzonite in composition, but quartz monzonite is the most common igneous stage intruded close in time to ore (Hollister, 1978). Early developed biotite is characteristic and the change of biotite colour from green in the aureole to brown in the ore zone may provide a "vector to guide exploration (Carson and Jambor, 1974). These deposits are close analogues of Tertiary porphyries in the southwest United States (Lowell and Guilbert, 1970; Guilbert and Lowell, 1974). Late Cretaceous to Tertiary deposits in British Columbia are mainly of the classic (stock) type (McMillan, 1994). At Granisle, for example, Fahrni *et al.* (1976) associate the porphyry Cu deposit with multiple porphyry intrusions of Eocene age that cut Jurassic volcanic and sedimentary country rocks. Copper mineralization is centred on the contact between biotite-feldspar porphyry and an earlier quartz diorite porphyry. The main zone consists of chalcopyrite and bornite in quartz-filled fractures and is enclosed in a pyritic halo. Alteration zoning is well developed, from a potassic core, with secondary biotite, through a flanking phyllic zone, characterised by quartz-sericite-carbonate-pyrite assemblages, to a propylitic fringe with chlorite, carbonate and epidote alteration (McMillan, 1994). The majority of stock-type porphyries are under 83 Ma and only a few (e.g. Island Copper) are older. The

tendency of these mineralized intrusions to occur during periods of time when formation of batholiths was minimal suggests that they may have a magmatic origin distinct from, what gave rise to the large intrusive masses associated with rapid subduction. This negative correlation also suggest that each may occur under differing conditions of plate movement (Hollister, 1978).

The intrusion mostly associated with porphyry Cu mineralization of the stock-type is commonly close to quartz monzonite in composition. The injection of a stock frequently results in development of a circular fracture pattern which may be mineralized Au-enhanced porphyry deposits fall within the volcanic and classic (stock) deposit types, whereas the Au-poor deposits fall in the plutonic deposit type (McMillan, 1994 and Preto, personal communications, 1996).

3.2.1.2 CLASSIFICATION BASED ON THE CHEMISTRY OF PLUTONS

In British Columbia, a second major distinction in classification is made between porphyry deposits related to calc-alkalic versus those related to alkalic intrusive rocks (McMillan, 1995, Soregaroli, 1975, Sutherland Brown, *et al.*, 1971). Calc-alkalic deposits include plutonic, volcanic and classic (stock) types. Alkalic deposits (Barr *et al.*, 1976; Fox, 1989) are dominantly volcanic types, although some might be variations on the classic (stock) type. The distinction is important because, although they tend to be smaller, Cu and Au grades are generally higher for known deposits in the alkalic class of porphyries (McMillan, 1994).

Mineralization in the alkalic model porphyry deposits tends to occur most commonly in spatial association with monzonite or syenite phases of zoned diorite-monzonite-syenite intrusions. Copper sulphide is accompanied only rarely by Mo but commonly by abnormally high Au:Cu ratios. Sulphur accompanying the Cu is insufficient to consume the iron present in the host intrusion, and the altering mineralizing process leaves large amounts of magnetite accompanying chalcopyrite. Magnetite may be as important a hydrothermal mineral in

dissemination in alkalic model porphyries as is pyrite in calc-alkalic model deposits, occurring as a dissemination in the potassic and propylitic zones (Hollister, 1978). The alkalic suite is well defined in terms of metal content, petrology and alteration (Lang *et al.*, 1994).

According to Fox (1989) common characteristics of many alkalic porphyry deposits are: association with high level stocks and dike complexes for example at Mount Milligan, Mount Polley (Cariboo Bell), Ingerbelle, Galore Creek and Afton; association with zoned stocks, such as at Shiko, Kwun and QR (all in the Quesnel); or association with cumulates, such as at Mount Polley, Cantin Creek and perhaps the Tulameen ultramafic complex, north of Copper Mountain (McMillan, 1994). The dikes are generally felsic and may be coeval to accumulations of felsic breccia; some of the breccias are intrusive, although they may carry extrusive clasts, such as Preto (1977) described at Afton. The stocks are zoned from cores of diorite through to syenite; differentiates may be sodic (McMillan, 1994). Associated volcanic rocks may be alkalic rocks of basic to intermediate composition in which basalt members are nearly saturated in SiO₂ but have high total alkalis, Al₂O₃, Fe³⁺ / Fe²⁺, CO₂ and F (McMillan, 1994). Generally, these rocks are also enriched in Ba, Rb, Sr, Pb, REE, Th, U, Cu and Pt group elements (Mutschler *et al.*, 1990).

The calc-alkalic type of porphyry is most commonly Cu-Mo with relatively low Au values, although Cu-Au types are also known. The calc-alkalic suite is not as well defined and includes a range of petrological associations and deposit types and based on the metal content classification may be subdivided into Cu-Mo, Cu-Mo-Au, Cu-Au or Au types (Hollister, 1978).

3.2.1.3 CLASSIFICATION BASED ON METAL CONTENT

Generally the following groups are introduced for porphyry deposits of the Canadian Cordillera: Cu-Au, Cu-Au $\pm$ Mo, Cu-Mo, Cu-Mo $\pm$ Au, Mo $\pm$ Cu, Mo, W-Mo, and Au $\pm$ Mo $\pm$ W (McMillan *et al.*, 1995; Kirkham and Sinclair, 1996, Preto, personal communication, 1996).

Based on metal content and chemistry of associated intrusions, porphyry deposits of the Canadian Cordillera can be separated into Cu-Au deposits associated with calc-alkaline plugs, stocks and batholiths, and Mo deposits associated with leucocratic acidic intrusions. The Cu-Au deposits all fit Sutherland Brown's volcanic class; Mo deposits are in the plutonic and classic(stock) classes; and Cu and Cu-Mo deposits are represented in all three classes.

Sillitoe (1989) arbitrarily defined a Au-rich porphyry as one with greater than 0.4 g/t Au. Gold values range to greater than 2 grams per ton. These deposits possess all the characteristics of their Au-poor counterparts, albeit intensity of development of these features varies (McMillan, 1994). Retrogressive alteration, usually to intermediate argillic sericite-clay-chlorite assemblages, partly overprints the early alteration, and phyllic alteration is poorly developed. The Au zones may be overprinted or flanked by intense argillic alteration developed both in the intrusions and the volcanic country rocks (McMillan, 1994).

The related intrusions are I-type, magnetite-series hypabyssal and generally emplaced in the epizone. Typically the stocks are composite and 1 to 2 km across with steep, cylindrical outlines. In well-documented studies in the southwest Pacific and in South America, the stocks intrude coeval volcanic rocks in stratovolcano settings (McMillan, 1994). Stocks range in composition from calcic, to low potassium through high potassium calc-alkalic to potassic alkalic; few are in alkali-calcic rocks (Keith 1983). Most related stocks are magnetite-rich (McMillan, 1994, Hollister, 1978). Leveille *et al.* (1988), who studied alkalinity-oxidation states, and Keith and Swan (1987), concluded that relatively reduced oxidation states are characteristic of Au-enriched intrusions. Cox and Singer (1988) not only stress the importance of high

magnetite content, but also the relatively high magnetite to pyrite ratio, which implies high oxygen relative to sulphur fugacity in the Au-enriched porphyries.

At the local scale, metal-zoning patterns around these deposits can be striking. Peripheral base metal deposits with precious metal values are both indicators to possible porphyries. Epithermal Au mineralization with quartz alunite or pyrite-native sulphur-enargite acid sulphate type alteration may occur nearby (McMillan, 1994). Most are located above the Au rich porphyries. They present an attractive, under explored potential target in British Columbia (McMillan, 1994). Some deposits have a Cu-As-Au association. Sillitoe (1987) stresses that Au-rich porphyries occur along discrete linear belts that he relates to the convergent plate margins. In compilations on a global scale, deposits of this class are relatively rare (Cox and Singer, 1988; Sillitoe, 1991) but they are vitally important in British Columbia. Subalkaline to alkaline, arguably shoshonitic, affiliations result from a conjunction of tectonic events. Yet these deposits occur along the length of the Canadian Cordillera, in two accreted tectonic terranes—Quesnellia and Stikinia, and during a very restricted period of time —late Triassic to Early Jurassic. The event was large scale and has not been repeated (McMillan, 1994).

Cordilleran alkalic porphyries relate to alkalic magmatic centres in the early Mesozoic island-arcs of Quesnellia and Stikinia. Host volcanic packages are predominantly pyroxene-bearing basaltic rocks of the Nicola, Takla and Stuhini Groups. These arcs began forming in Late Triassic (Carnian) time, magmatism ended in latest Triassic time in Quesnellia, and in Early Jurassic (Sinemurian) time in Stikinia (Nelson, 1991).

Hydrothermal breccias are prominent at deposits such as Copper Mountain, Afton and Mount Milligan. Overlapping alteration and mineralization events disrupt annular patterns and locally disseminated mineralization can exceed fracture-controlled ores. Phyllic alteration zones, and quartz veins and stockworks are uncommon in this setting (McMillan, 1994).

Alkalic porphyry deposits relate to relatively evolved, often late phases of multiphase

intrusions (Fox, 1989). The intrusions penetrate evolving volcanic edifices and breccia phases blast out to the surface where "boulder tracing of felsic clasts in extrusive breccias can lead to intrusive centres and mineralization (Barr *et al.*, 1976). At Afton the main deposit is hosted in brecciated, late stage Cherry Creek micromonzonite and microsyenite. The 1.9 km long Mount Milligan hydrothermal system (Rebegliati and Copeland, 1989; Harris, 1991) has annular shells of potassium silicate and propylitic alteration centred on the dike-like MBX and Silver Star porphyry stocks and related prominent breccias (McMillan, 1994). For this type of Au-rich porphyries, where alkalic metasomatism is intense, Albitization, rather than potassic feldspar, may occur. This sodic alteration produces albite, calcite, chlorite and epidote with associated pyrite and chalcopyrite (Fox, 1989). In the Iron Mask batholith, the series of alkalic porphyry deposits, including Afton and Ajax, have pervasive and vein-controlled albite. Albitization is also reported from Mount Milligan's 66 Zone (McMillan, 1994).

In Stikinia, in north-western British Columbia, the unusual Galore Creek alkalic porphyry deposit apparently formed in the throat of an ancient, 212 million year old (Logan and Panteleyev, 1991), volcano. Ten intrusive phases comprise the Galore Creek syenite complex and four have been related to porphyry-type mineralization. Ten Cu deposits currently known are hosted in biotite, garnet and potassic feldspar-altered volcanic rocks and pipelike breccia bodies (Allen *et al.*, 1976; Logan and Panteleyev, 1991).

Mineralized volcanic rocks are genetically related shoshonitic basalts to alkali-enriched pyroclastic rocks that have been converted to skarns and coarse-grained fenitic porphyroids near mineralized zones (Allen *et al.*, 1976). Copper and Au generally correlate positively, but while the Au is hosted in the Cu-enriched zones, the highest Au grades are not necessarily coincident with the highest Cu grades. Molybdenum content is negligible in this type of porphyry deposits (McMillan, 1994).

In the Canadian Cordillera precise tectonic reconstruction for deposits that were emplaced in

the early Mesozoic is difficult, and in many cases the composition of the associated crust or basement is uncertain McMillan *et al.*, (1995). Recent understandings of the tectonic history of Canadian Cordillera have been also applied into the classification of porphyry deposits. McMillan *et al.* (1995) have divided these deposits into pre- to syn-accretion and post-accretion groups, which were formed before or during, or after addition of the composite terranes to North America. The pre-accretion porphyry deposits are probably genetically linked to subduction-related tectonic processes in discrete island arcs, although there is evidence that at least some of these arcs had older continental basements. Some Jurassic deposits, like Mt. Milligan, may have formed during accretion of the Intermontane superterrane. The post-accretion deposits were emplaced during Cretaceous and Tertiary time and are hosted by several of the older terranes. Consequently, the composition of their basement rocks varies considerably. The relative metal abundance of porphyry Cu deposits, Mo:Cu and Cu:Cu ratios do not correlate with terrane or timing of emplacement (pre- or syn- versus post-accretion) but several generalisations can be made (McMillan *et al.*, 1995):

- Porphyry Cu-Au deposits of the unusual alkalic suite (Barr *et al.*, 1976) were emplaced in two different terranes prior to or during (e.g., Mt. Milligan) accretion.
- Porphyry Mo, Sn and W deposits are restricted to the post-accretion setting.

Post-accretion deposits are divided by principal commodity into Cu-Mo, Cu-Au $\pm$ Mo, Mo, Mo-Cu, W-Mo, and Au $\pm$ Mo $\pm$ W types. The petrology and characteristics of the post-accretion deposits are variable but no distinct type equivalent to the alkalic suite is defined.

This approach differs from that employed by Sutherland Brown (1976), who developed a three end-member classification of "plutonic", "volcanic" and "classic (stock)" deposit types. The general characteristics of these types are listed in McMillan and Panteleyev (1988) and McMillan (1991). Sutherland Brown's classification scheme is compatible with that employed by (McMillan *et al.*, 1995).

Plutonic and volcanic deposits are exclusively pre- to syn-accretion. Classic deposits are exclusively post-accretion; hence their occurrence is in a variety of older host rocks (McMillan *et al.*, 1995).

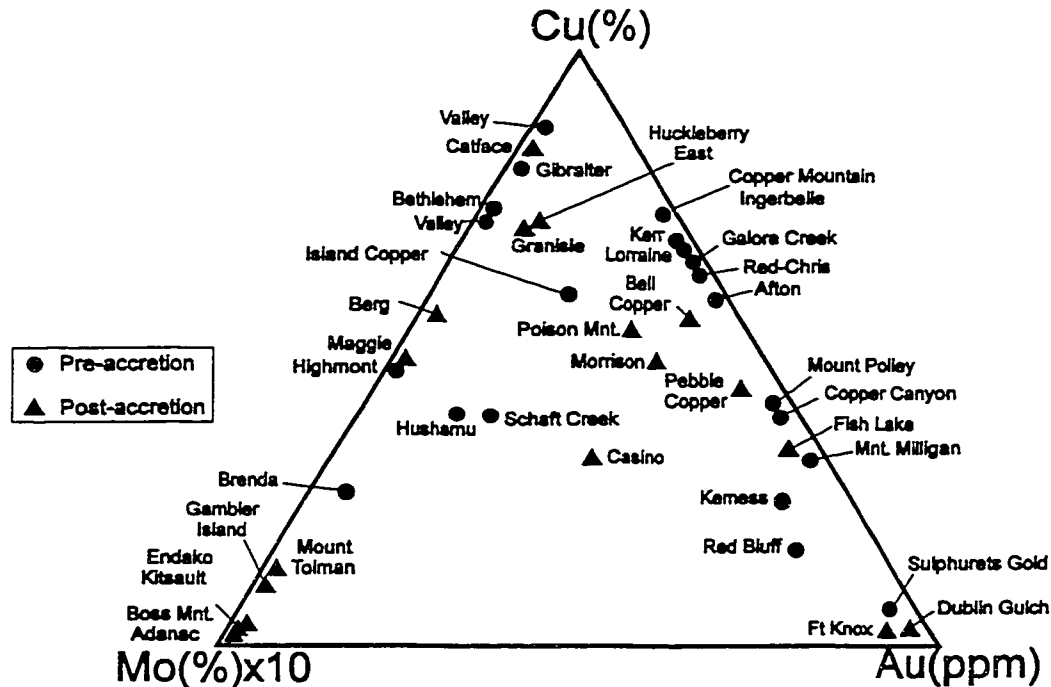


Figure 2. Relative abundance of Cu (in %), Mo (in %) x10 and Au (in g/t) for selected Cordilleran porphyry deposits. Pre- to syn- and post-accretion deposits are distinguished by circles and triangles respectively [after McMillan *et al.* (1995)].

3.3 TEMPORAL AND SPATIAL DISTRIBUTION

Multiple magmatic events characterise porphyry districts. Mineralization often follows one or more pulses of magmatism and may be followed by barren magmatic pulses; more than one pulse can have related mineralization (McMillan, 1994).

Metallogenic provinces and epochs in the Canadian Cordillera reflect an uneven distribution of mineral deposits in space and time (Figure 3). The existence of metallogenic provinces for

porphyry deposits of the Canadian Cordillera is apparent from the distribution of deposits within the Insular, Coast, Intermontane and Omineca belts. The concept of metallogenic epochs as it applies in porphyry mineral deposits of the Canadian Cordillera is demonstrated by the correlation between age of porphyry mineral deposits and the silicate and sulphide chemistry of the related intrusive rocks. Porphyry mineral deposits of the Canadian Cordillera are spatially and genetically related to Mesozoic and Tertiary intrusions that can readily be dated by the K-Ar method (Christopher and Carter, 1976).

In the Canadian Cordillera there is a direct relationship between velocity of plates motion, magmatic events, and timing of amalgamation and accretion of the major terranes that comprise the Canadian Cordillera and the timing of Cu and Mo mineralising events (Armstrong, 1988, Christopher and Carter, 1976, McMillan, 1994) (refer also to the Figure 3 of chapter 2).

Several authors (White *et al.*, 1968; Moore *et al.* 1968; Fyles *et al.*, 1973) have demonstrated the close association of intrusion and mineral deposition in Cordilleran porphyries by age determination. Multiple magmatic events characterise porphyry districts. Mineralization often follows one or more pulses of magmatism and may be followed by barren magmatic pulses; more than one pulse can have related mineralization (McMillan, 1994).

In the Canadian Cordillera most porphyry deposits are in island arc rocks of the accreted Intermontane superterrane. Deposits associated with calc-alkalic intrusions are of Mesozoic to Tertiary age; those related to alkalic intrusions are Early Jurassic and generally have related shoshonitic volcanism. However porphyry deposits that are post-accretionary are related to calc-alkalic intrusions along traverse structural zones like the Stikinia and Skeena arches, or are in Tertiary extensional settings. Examples are Bell and Granisle in central British Columbia (McMillan, 1994). Porphyry Mo deposits occur mainly near the boundaries of the Intermontane Belt, with deposits in central British Columbia extending into the Intermontane Belt. Porphyry Cu-Mo deposits are distributed throughout the four western belts, with concentrations of distinct

types related to the Bulkley, Nanika and Babine intrusions in the central part of the Intermontane Belt (Carter, 1974) and -to the Guichon Creek batholith in the southern part of the Intermontane Belt (McMillan, 1976). Metallogenic epochs are based on a review of chemical and geological settings of a mineralized porphyry system, with emphasis on K-Ar data (Christopher and Carter, 1976). Metallogenic epochs for porphyry mineral deposits are demonstrated by plotting histograms (Christopher and Carter, 1976) (refer also to the Figure 3 of chapter 2).

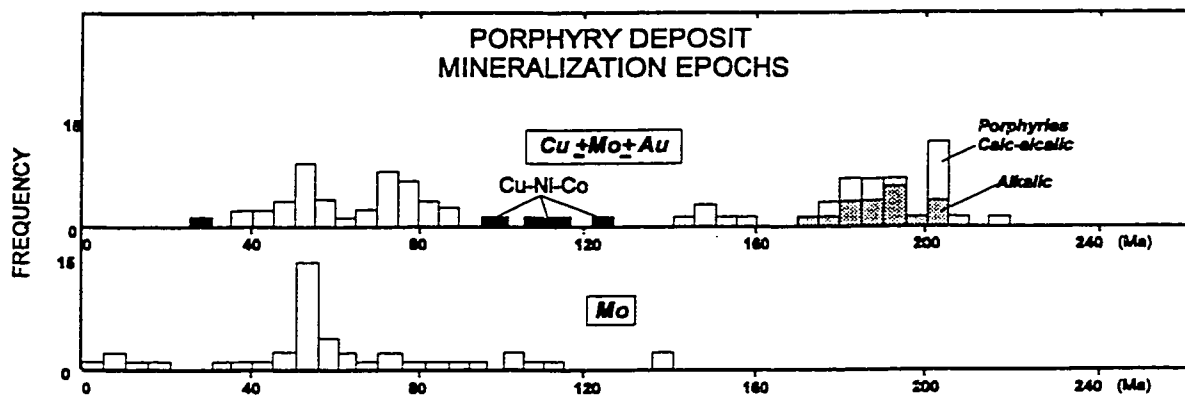


Figure 3. Porphyry deposit mineralization epochs in British Columbia (Christopher and Carter, 1976, McMillan, 1994).

3.4 SELECTION OF MAJOR GEOLOGICAL UNITS ASSOCIATED WITH PORPHYRY DEPOSITS IN THE STUDY AREA

Here geological units that are either spatially or genetically most closely related to different types of porphyry deposits are selected. These selected geological units are utilised to extract samples and separately analyse the geochemical data. Together they form the study area of this thesis.

To select geological units that are associated with 3 groups of porphyry deposits discussed above, the following sources are used:

1- From the literature, those geological units acting as host rock to or plutonic intrusions associated with porphyry mineralizations were selected.

2- From MINFILE, those geological units that are introduced as host rock for known porphyry deposits or genetically associated with mineralization, were selected.

The major references used for selecting appropriate geological units, are two, the CIM (Canadian Institute of Mining and Metallurgy) special volumes No.15 and 46, "Porphyry Deposits of Canadian Cordillera" and "Porphyry Deposits of the northwestern Cordillera of North America", but in some cases other references were also used. From the MINFILE, "capsule geology" option in the extracted report for the searched deposits provides the abstract for geology of the deposit.

For selection of porphyry deposits in the category of SHOWINGS, only those reported as SHOWINGS in MAP-A of CIM special volume 46 were selected, and not all SHOWINGS extracted from MINFILE.

3.4.1 Cu-Au PORPHYRY DEPOSITS GROUP

Spatial distribution of this group of is more limited to certain geological units than Cu-Mo and Mo groups (Figure 4, 5, 6). This is because of their genesis conditions, which was indicated very briefly earlier and is completely documented in the references.

In general, most of this group of and their related intrusions occur in the Intermontane belt (Figure 4). They are mainly related both spatially and genetically, to the Upper Triassic Nicola, Takla, and Stuhini volcanic assemblages and comagmatic plutonic intrusions related to 175-200 Ma (Barr et. al., 1976, Christopher & Carter, 1976) (Figure 3). These plutonic intrusions range from plugs and stocks to small batholiths and are associated with linear structures of regional extent. They have chemical compositions identical to their volcanic host rocks and were evidently emplaced in the volcanic centres (Barr et. al., 1976).

For this selection of geological units based on the MINFILE, only units containing known Cu-Au porphyries with the status of "PAST PRODUCER", "PRODUCER", "DEVELOPED PROSPECT", and "PROSPECT" are considered.

Examples of this group are Iron Mask and Hogem batholiths of Early Jurassic calc-alkalic intrusions of EJgG unit which host well known porphyry deposits of this group such as Ajax East & West, Afton, Comet and Lorraine. Table 1 shows the selected geological units based on both literature and MINFILE.

Table 1. Associated geological units with Cu-Au group of porphyry deposits, based on the literature and MINFILE (as explained in the text).

MAIN HOSTS & INTRUSIONS	AGE	DEPOSIT (example)
Copper Mountain Intrusions (MJyCM), (EJyCM)	Middle Jurassic (155-187 Ma)	Copper Mountain, Ingerbelle
Duckling Creek Complex (a phase of Hogem intrusions)(MJyCMD)	Middle Jurassic (155-187 Ma)	Lorraine
Iron Mask intrusions (of EJgG)	Early Jurassic (200-217 Ma)	Ajax East & West, Afton, Comet
Nicola (TrJN)	Upper Triassic- Lower Jurassic	Copper Mountain, Ajax, Mount Polley
Stuhini Group (TrS)	Upper Triassic	Red-Chris, Galore Creek
Takla (TrJ)	Upper Triassic- Lower Jurassic	Lorraine, Mnt. Milligan

Below a small explanation for each of the selected geological units is presented.

- Copper Mountain intrusions (EJyCM): Early Jurassic, high level, alkaline, syenite, syenodiorite, monzonite, pyroxene-hornblende diorite and gabbro and Middle Jurassic phases of Copper Mountain suite comprising MJyCM & MJyCMD , Duckling Creek syenite. Although highly associated with porphyry Cu-Au deposits; due to the small area of these geological units, they were not included in the study area. They contain only 35 NGR geochemical samples.
- Iron Mask (of EJgG): The Iron Mask batholith lies in the southern part of the Quesnellia. The batholith is a subvolcanic, multiple intrusion which is comagmatic and coeval with the Nicola rocks. It is situated along the southwest side of a regional northwest trending fracture zone and is cut by numerous northwesterly faults. The batholith comprises two major northwest trending plutons separated by 6 km of Eocene Kamloops Group volcanic and sedimentary rocks. The

larger pluton, the 18 km long southern part of the batholith, is called the Iron Mask pluton.

- Nicola (TrJN): Upper Triassic Nicola Group, which is in the Quesnellia, is dominated by arc volcanics (volcanic flows and volcanoclastic sedimentary rocks) associated with alkaline intrusions. The intrusions vary from diorite to monzonite in composition and are thought to be comagmatic with the Nicola Group, ranging in age from Late Triassic to Early Jurassic.
- Stuhini (TrS): Upper Triassic Stuhini Group comprises arc volcanics and sediments with some calc-alkaline intrusions. Stuhini (TrS) was not selected as a geological unit of the study area because most of it is not covered by the NGR geochemical samples.
- Takla (TrJ): Upper Triassic to Lower Jurassic Takla Group is comprised of sedimentary and arc volcanic rocks. Takla Group sediments are intruded by various phases of mesozonal plutonic rocks assigned to the Late Triassic to Early Cretaceous Hogem Intrusive Complex.

3.4.2 Cu-Mo (+/-Au) PORPHYRY DEPOSITS GROUP

Porphyry Cu and Cu-Mo deposits in different tectonic belts reflect the variable chemical and physical properties of related calc-alkaline batholiths, stocks and plugs that range in age from Late Triassic to mid-Tertiary, with metallogenic epochs indicated at 200-195 Ma (deposits related to Guichon Creek batholith, and that at Gibraltar), 185-175 Ma, 155-140 Ma, 80-65 Ma (Bulkley intrusions), 50 Ma (Babine & Nanika intrusions), 40-35 Ma and 26-18 Ma (Christopher & Carter, 1976).

The same method applied for Cu-Au group of porphyry deposits explained earlier, was utilised to find major geological units associated with Cu-Mo group of porphyry deposits. The result of this selection is indicated in Table 2.

Table 2. Associated geological units with Cu-Mo group of porphyry deposits, based on the literature and MINFILE (as explained in the text).

MAIN HOSTS & INTRUSIONS	AGE	DEPOSIT (example)
Bonanza (JB)	Lower & Middle Jurassic	Island Copper, Hushamu
Bulkley Intrusions (LKgB)	Late Cretaceous (64-87Ma)?	Huckelberry, Whiting Creek
Babine Intrusions (EtgB)	Early Tertiary (40-64 Ma)	Bell, Granisle
Guichon Intrusions (EJgG)	Early Jurassic (200-217 Ma)	Highland Valley deposits
Hazelton (JH)	Lower & Mid. Jurassic	Berg, Huckelberry, Bear, BigOnion
Nicola (TrJN)	Upper Triassic- Lower Jurassic	IronMask, CopperMnt., Brenda
Takla (TrJ)	Upper Triassic- Lower Jurassic	Endako, Kerness,
Stuhini (TrS)	Late Triassic	Kerr

Below a brief explanation for each of the selected geological units is presented.

- Bonanza (JB): Lower Jurassic Bonanza Group in the Wrangellia is an island arc sequence of basaltic to rhyolitic volcanic rocks. These rocks have been intruded by stocks of the Jurassic Island Plutonic Suite intermediate to felsic volcanic flows and pyroclastics.
- Bulkley (LKgB): Bulkley intrusions of the Late Cretaceous are high level and calc-alkalic (mainly granodioritic) in composition. In addition to Bulkley (LKgB), the entire Late Cretaceous plutonic suite (LKg) was also selected as a part of the study area.
- Babine (EtgB): Eocene Babine intrusions include granodiorite, quartz monzonite and biotite hornblende quartz diorite and associated biotite-feldspar porphyry plugs and dykes.
- Guichon (EJgG): Early Jurassic-Late Triassic Guichon intrusions are calc-alkaline, mainly granodiorite, quartz monzonite and quartz diorite.
- Hazelton (JH): The Hazelton rocks are volcanic arcs complexes comprised of massive andesite, tuff, lapilli tuff, agglomerate, flow breccia with narrow bands and interbedded argillite.

3.4.3 Mo PORPHYRY DEPOSITS GROUP

Porphyry Mo deposits are exclusively post-accretionary. These deposits are widely distributed in the Cordillera and partially overlap in time and space with porphyry Cu-Mo-Au deposits (McMillan *et al.* 1995). Metallogenic episodes are recognised at about 140 Ma

(Endako, Francois Lake intrusions), 110 to 100 Ma (Boss Mountain), 80 to 60 Ma (Bulkley intrusions, Adanac) and 50 Ma, with local events occurring at 54 Ma to 48 Ma (Alice Arm intrusions) and 8 Ma (Salal Creek) (Christopher & Carter, 1976). In general, Porphyry Mo deposits in Canadian Cordillera are associated with leucocratic acidic intrusions and based on the geomorphological classification, are in the plutonic and phallic (classic (stock)) classes (Christopher & Carter, 1976).

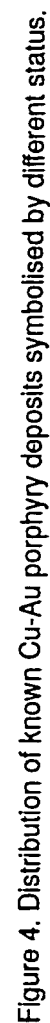
The selected geological units for Mo group of porphyry deposits are shown Table 3.

Table 3. Associated geological units with Mo group of porphyry deposits, based on the literature and MINFILE (as explained in the text).

MAIN HOSTS & INTRUSIONS	AGE	DEPOSIT (example)
Bulkely Intrusions (LKgB)	Late Cretaceous (64-87Ma)	Fog, Bear, Glacier Gulch
Francois Lake Intrusions (JKgF)	Late Jur.-Early Cret. (130-155Ma)	Endako, Mac
Surprise Lake (LKqS)	Late Cretaceous (64-87Ma)	Adanac
Topley Intrusions (EJqT)	Early Jurassic (187-214Ma)	Babs, Chris

Below a brief explanation for each of the selected geological units is presented.

- Francois Lake (JKgF): Late Jurassic Francois Lake intrusions are calc-alkaline, quartz diorite, quartz monzonite and granodiorite.
- Surprise Lake (LKqS): Late Cretaceous Surprise Lake intrusions are mainly granite and quartz monzonite.
- Topley intrusions (EJqT): Early Jurassic Topley intrusions are mainly granitic, usually with diorite or syenite border phases.



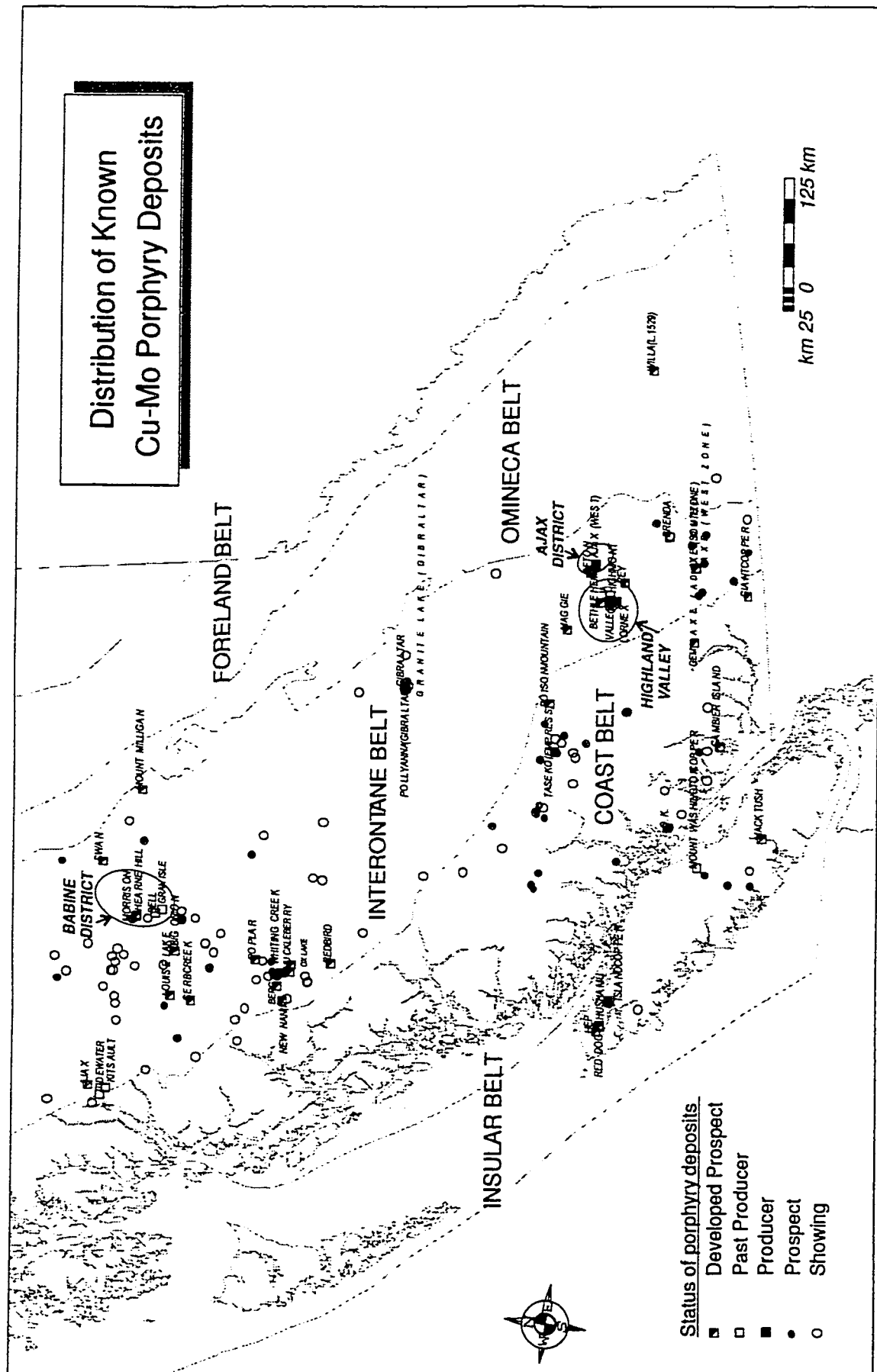


Figure 5. Distribution of known Cu-Mo porphyry deposits symbolised by different status.

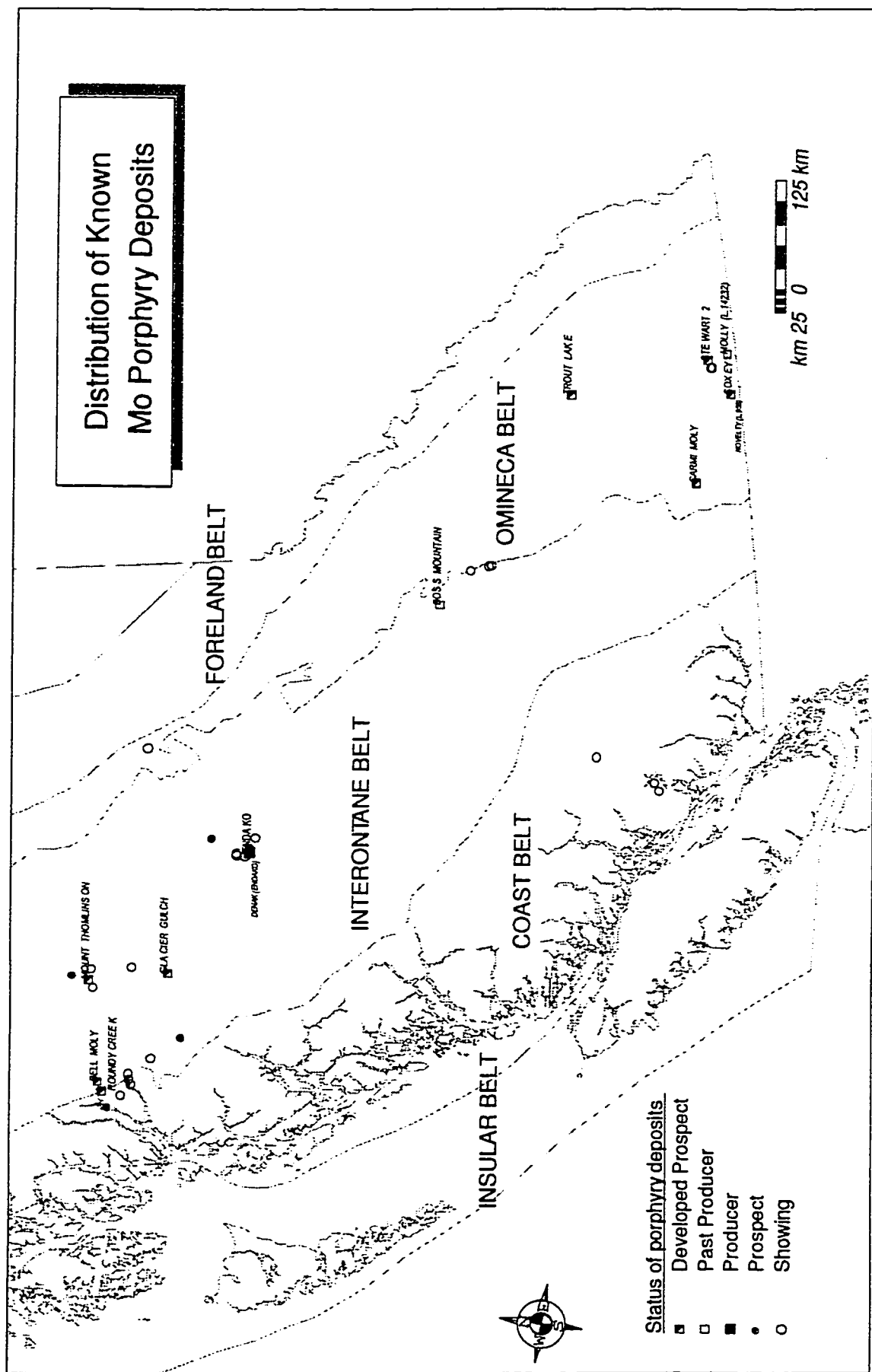


Figure 6. Distribution of known Mo porphyry deposits with different status.

3.5 DENSITY OF THE DISTRIBUTION OF PORPHYRY DEPOSITS

One of the methods used in exploration for porphyry deposits at the regional scale and in the “area selection” stage is the study of the location and distribution of known deposits of this type (Thompson, 1995). These areas have been the focus of exploration for porphyry deposits. Areas with known porphyry deposit mineralizations and porphyry affinity are important because the potential for extensions to known mineralizations is high. Also, there is a possibility that deposits occur in groups or clusters. Considering these facts, maps were generated to show the spatial density for distribution of discovered porphyry deposits. Areas with high density of porphyry deposits were given high scores in the final integration of all input maps.

Different types of status of porphyry deposits extracted from the MINFILE, are PRODUCER, PAST PRODUCER, DEVELOPED PROSPECT, PROSPECT and SHOWING. All those porphyry deposits with the status of PRODUCER, PAST PRODUCER, DEVELOPED PROSPECT and PROSPECT were considered as one group and all SHOWINGS as another. This separation was done because in general there is less certainty in the classification of SHOWINGS as porphyry deposits than other status categories (personal communications, Larry Jones, 1996). To take this into account, smaller fuzzy membership values were assigned to comparable classes of the density map of SHOWINGS than the density map of all other status categories in the integration of these two maps which is performed in the last chapter.

To generate density maps of Figures 7 and 8 moving average method was used. Twenty five km was selected for the radius of the moving cell with maximum 8 points for consideration and with decay rate of 0.05 for weighting function inside the moving cell. No density values are calculated for areas lying outside of any sampling radius (moving cell). Figure 7 shows generally the combining procedure. Appendix E shows scores given to different classes of these maps as fuzzy membership values, for combining them with the fuzzy logic method.

*Density Map of
Producers, Past Producers,
Developed Prospects & Prospects*



*Fuzzy Logic
Method*

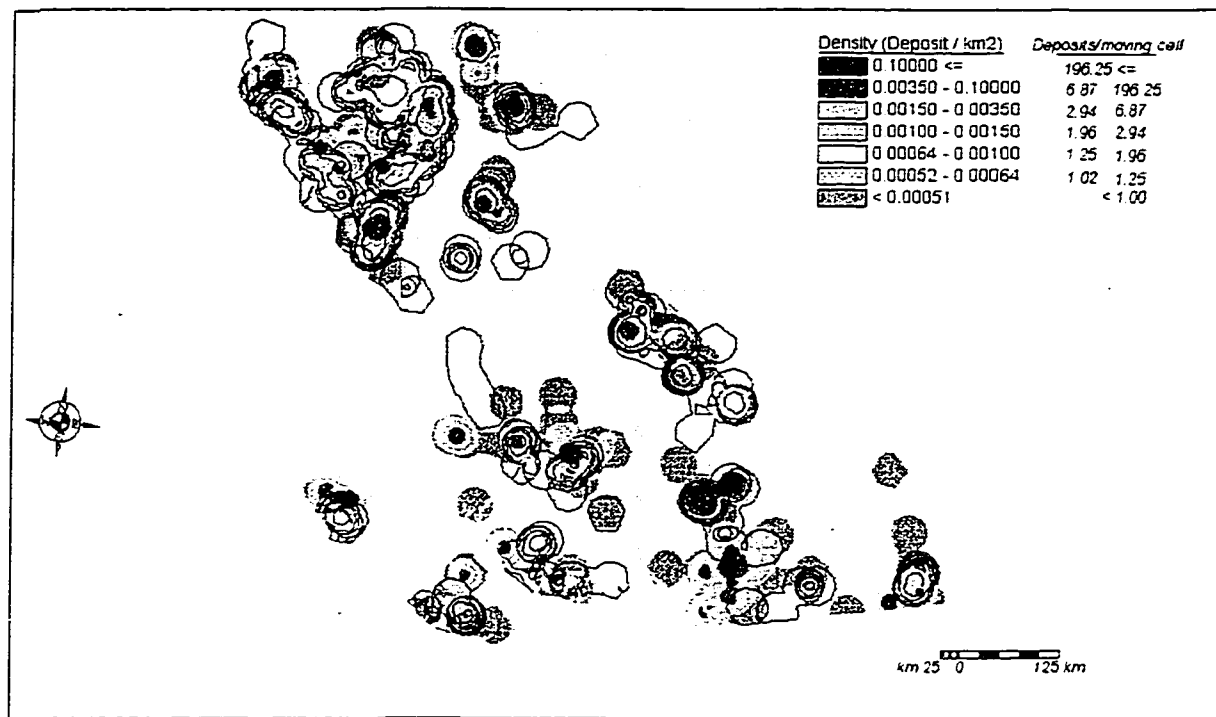
*Density Map
of
Porphyry Deposits*



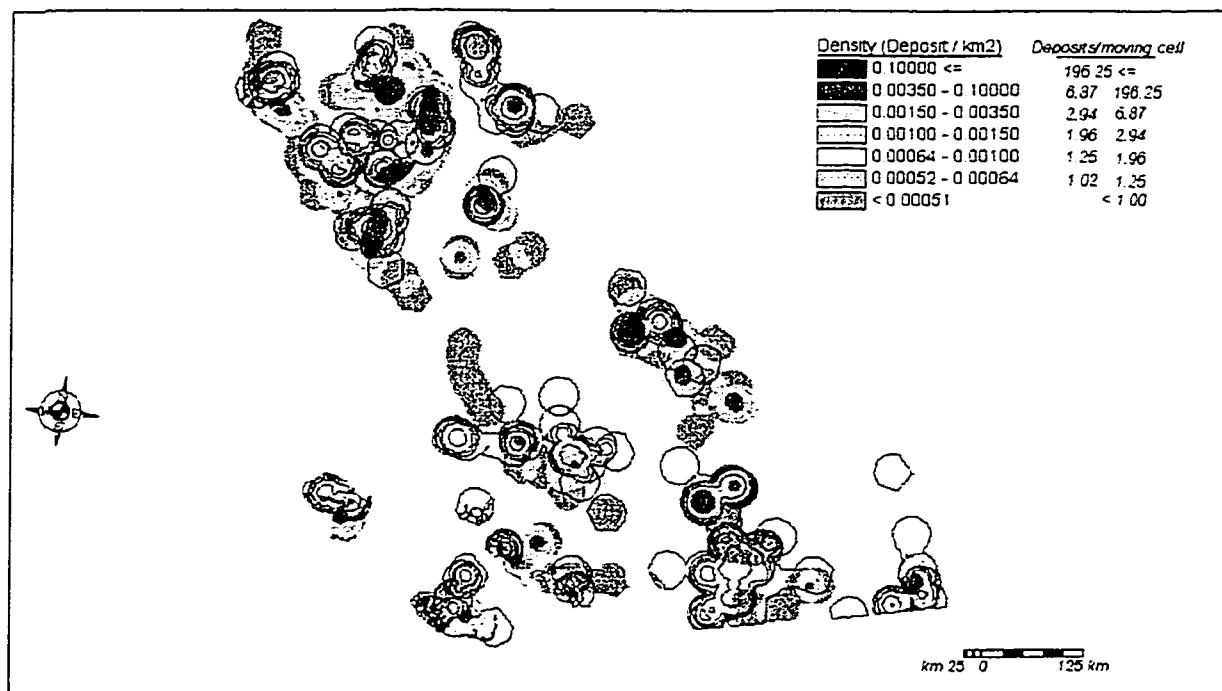
*Density Map of
Showings*

Figure 7. General procedure for creating combined density map for distribution of porphyry deposits.

In order to compare the maps for density of porphyry deposits of Figure 8, contour lines of each map were created and overlaid on the other density map. As Figure 8a and 8b show, generally in many location contours of densities match with classes of the other map. In addition, these contour lines are overlaid on the terrane map (Figure 9). As Figure 9a and 9b show, obviously most of areas of high density of porphyry deposits are located inside the Intermontane belt. In Omineca, locations of high densities are mainly associated with Quesnallia terrane. In Intermontane Belt, Quesnellia and Stikinia show the highest densities for porphyry deposits. Plutonic suites located within Intermontane Belt in some localities also have associations with high densities of both SHOWINGS and all other categories. In Coast Belt high densities of porphyry deposits are located in the southern parts of this belt. They are mainly associated with plutonic bodies of pre, syn and post accretion intrusions. In Insular Belt, Wrangellia terrane in Vancouver Island show high densities of porphyry deposits (Figure 9a and 9b).

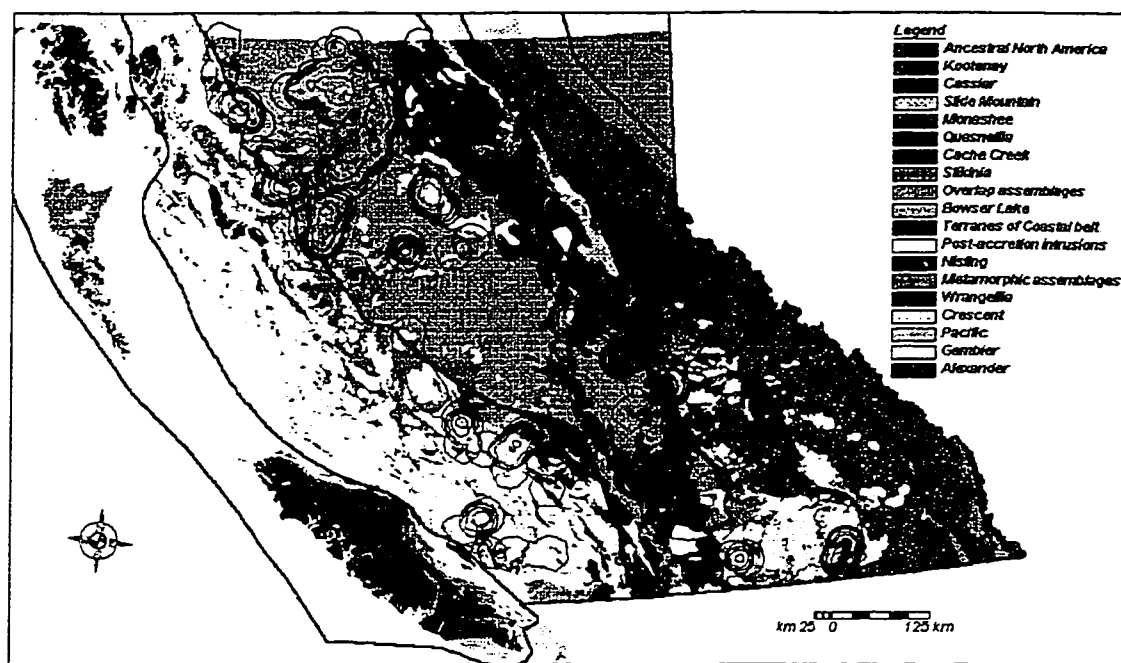


(a)

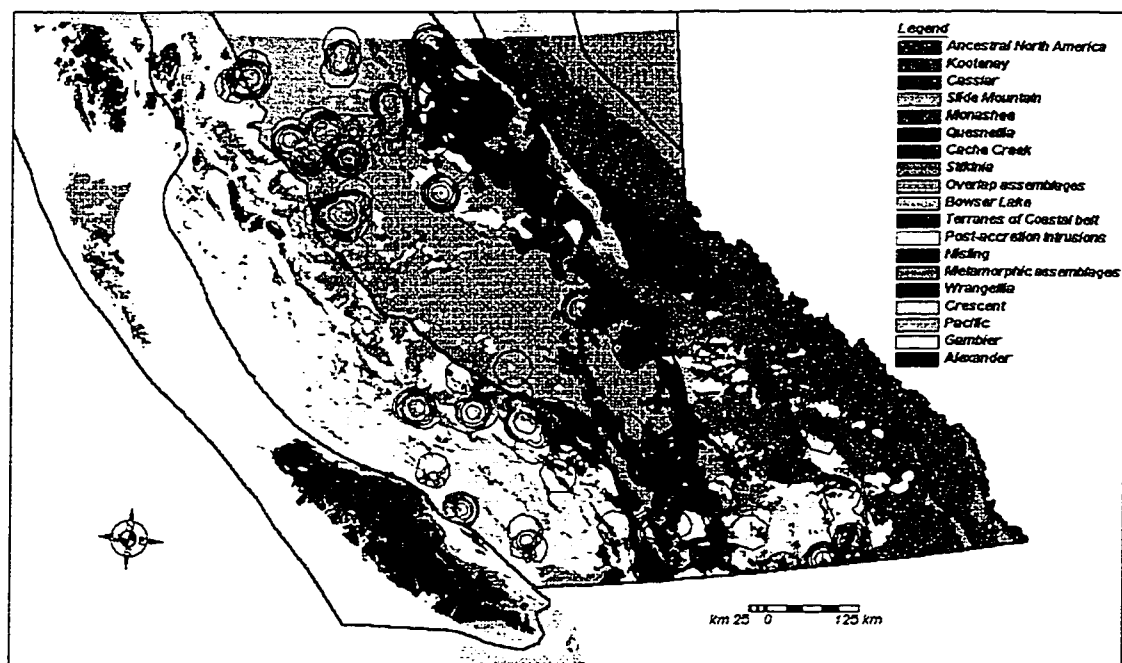


(b)

Figure 8. Spatial density of all porphyry deposits that are a) PRODUCER or PAST PRODUCER or DEVELOPED PROSPECT or PROSPECT, b) SHOWING. Contour lines in map (a) represent contours of map (b) and in map (b) represents the contours of map (a).



(a)



(b)

Figure 9. Comparison between terranes and contours of density of all porphyry deposits that are a) PRODUCER or PAST PRODUCER or DEVELOPED PROSPECT or PROSPECT, b) SHOWING.

3.6 EXPLORATION MODEL

Here exploration model for three types of porphyry deposits considered in this thesis is explained. Some of the points indicated below can be considered as an exploration tool at the regional scale. Sections for porphyry Cu-Au and Cu+/-Mo+/-Au are from Panteleyev (1995a) and Panteleyev (1995b). Section for porphyry Mo is based on Sinclair (1995).

3.6.1 PORPHYRY Cu-Au

TECTONIC SETTING(S): In orogenic belts at convergent plate boundaries, commonly oceanic volcanic island arcs overlying oceanic crust. Chemically distinct magmatism with alkalic intrusions varying in composition from gabbro, diorite and monzonite to nepheline syenite intrusions and coeval shoshonitic volcanic rocks, takes place at certain times in segments of some island arcs. The magmas are introduced along the axis of the arc or in cross-arc structures that coincide with deep-seated faults. The alkalic magmas appear to form where there is slow subduction in steeply dipping, tectonically thickened lithospheric slabs, possibly when polarity reversals (or 'flips') take place in the subduction zones. In British Columbia all known deposits of this type are found in Quesnellia and Stikinia terranes.

DEPOSITIONAL ENVIRONMENT/GEOLOGICAL SETTING: High level (epizonal) stock emplacement levels in magmatic arcs, commonly oceanic volcanic island arcs with alkalic (shoshonitic) basic flows to intermediate and felsic pyroclastic rocks. Commonly the high-level stocks and related dikes intrude their coeval and cogenetic volcanic piles.

GEOCHEMICAL SIGNATURE: Alkalic cupriferous systems do not contain economically recoverable Mo (< 100 ppm) but do contain elevated Au (> 0.3 g/t) and Ag (>2 g/t). Cu grades vary widely but commonly exceed 0.5 % and rarely 1 %. Many contain elevated Ti, V, P, F, Ba, Sr, Rb, Nb, Te, Pb, Zn, PGE and have high CO₂ content. Leaching and supergene enrichment effects are generally slight and surface outcroppings normally have little of the copper remobilized. Where present, secondary minerals are malachite, azurite, lesser copper oxide

and rare sulphate minerals; in some deposits, native copper is economically significant (e.g. Afton, Kemess).

GEOPHYSICAL SIGNATURE: Ore zones, particularly those with high Au content, are frequently found in association with magnetite-rich rocks and can be located by magnetic surveys. Pyritic haloes surrounding cupriferous rocks respond well to induced polarization surveys. The more intensely hydrothermally altered rocks produce resistivity lows.

OTHER EXPLORATION GUIDES: Porphyry deposits are marked by large-scale, markedly zoned metal and alteration assemblages. Central parts of mineralized zones appear to have higher Au/Cu ratios than the margins. The alkalic porphyry Cu deposits are found exclusively in Later Triassic and Early Jurassic volcanic arc terranes in which emergent subaerial rocks are present. The presence of hydrothermally altered clasts in coarse pyroclastic deposits can be used to locate mineralized intrusive centres.

3.6.2 PORPHYRY Cu+/-Mo+/-Au

TECTONIC SETTINGS: In orogenic belts at convergent plate boundaries, commonly linked to subduction-related magmatism. Also in association with emplacement of high-level stocks during extensional tectonism related to strike-slip faulting and back-arc spreading following continent margin accretion.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level (epizonal) stock emplacement levels in volcano-plutonic arcs, commonly oceanic volcanic island and continent-margin arcs. Virtually any type of country rock can be mineralized, but commonly the high-level stocks and related dikes intrude their coeval and cogenetic volcanic piles.

GEOCHEMICAL SIGNATURE: Calcalkalic systems can be zoned with a cupriferous (or Mo) ore zone having a 'barren', low-grade pyritic core and surrounded by a pyritic halo with peripheral base and precious metal-bearing veins. Central zones with Cu commonly have coincident Mo,

Au and Ag with possibly Bi, W, B and Sr. Peripheral enrichment in Pb, Zn, Mn, V, Sb, As, Se, Te, Co, Ba, Rb and possibly Hg is documented. Overall the deposits are large-scale repositories of sulphur, mainly in the form of metal sulphides, chiefly pyrite.

GEOPHYSICAL SIGNATURE: Ore zones, particularly those with higher Au content, can be associated with magnetite-rich rocks and are indicated by magnetic surveys. Alternatively the more intensely hydrothermally altered rocks, particularly those with quartz-pyrite-sericite (phyllic) alteration produce magnetic and resistivity lows. Pyritic haloes surrounding cupriferous rocks respond well to induced polarization (I.P.) surveys but in sulphide-poor systems the ore itself provides the only significant IP response.

OTHER EXPLORATION GUIDES: Porphyry deposits are marked by large-scale, zoned metal and alteration assemblages. Ore zones can form within certain intrusive phases and breccias, or are present as vertical 'shells' or mineralized cupolas around particular intrusive bodies. Weathering can produce a pronounced vertical zonation with an oxidized, limonitic leached zone at surface (leached capping), an underlying zone with copper enrichment (supergene zone with secondary copper minerals) and at depth a zone of primary mineralization (the hypogene zone).

3.6.3 PORPHYRY Mo

TECTONIC SETTING(S): Subduction zones related to arc-continent or continent-continent collision.

DEPOSITIONAL ENVIRONMENT / GEOLOGICAL SETTING: High-level to subvolcanic felsic intrusive centres; multiple stages of intrusion are common.

GEOCHEMICAL SIGNATURE: Mo, Cu, W and F may be anomalously high in hostrocks close to and overlying mineralized zones; anomalously high levels of Pb, Zn and Ag occur in peripheral zones as much as several km distant. Mo, W, F, Cu, Pb, Zn and Ag may be

anomalously high in stream sediments. Mo, W and Pb may be present in heavy mineral concentrates.

GEOPHYSICAL SIGNATURE: Magnetic anomalies may reflect presence of pyrrhotite or magnetite in hornfels zones. Radiometric surveys may be used to outline anomalous K in altered and mineralized zones. Induced polarization and resistivity surveys may be used to outline high-pyrite alteration zones.

OTHER EXPLORATION GUIDES: Limonitic alteration of pyrite can result in widespread gossan zones. Yellow ferrimolybdate may be present in oxidized zones. Ag- Pb-Zn veins may be present in peripheral zones.

CHAPTER 4

LEVELLING GEOCHEMICAL DATA BETWEEN MAP SHEETS

4.1 INTRODUCTION

In regional compilations of geochemical data, where the surveys have been carried out at different times and/or by different organizations, a boundary shift may be observed at the join between the surveys. Even where the same sampling medium has been used, there may be variations in technique employed by different sampling crews. However, the major source of differences is usually in the analytical methods. The exact same procedures may not have been used during sample preparation and analysis, or the analytical instruments or settings may not have been identical. Even where the analytical methods were the same, there may have been an absence of standardization, or imperfect standardization between laboratories. Procedures to minimize such problems have been discussed by Darnley et al. (1995).

In this chapter a method is described that adjusts the data between surveys that show a "shift" along their boundary. The method is based on a suggestion for parametric levelling by R.G. Garrett and N. Gustavsson (in Damley et al., 1995). Bands are selected on either side of the shifted border(s) and quantiles of the data for a given element are calculated for each band. A line is then fitted to quantiles pairs, which provides an equation relating the data for the element between surveys. This equation may then be used to adjust or "correct" the data of the two surveys so that the boundary shift is reduced or eliminated. This procedure may then be sequentially applied to all surveys within the compiled area where such problems exist.

4.2 METHODOLOGY

Assume that there is a shift for the value of a certain element at the border of two surveys, A and B (Figure 1). As a first step, data in the bands "a" and "b" of maps A and B are extracted and quantiles of the data for each band are calculated. Calculated quantiles could be 0.05, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 0.95. The quantile is the value corresponding to a given fraction of the data and is an alternative expression for percentile when the result is expressed in fractions. For example, the 0.5 quantile is the 50th percentile or the median.

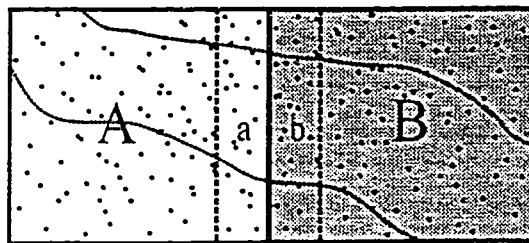


Figure 1. Adjoining map sheets (A & B) that show a shift in the value of a given element at their boundary, although the geological units are similar on each side of the boundary.

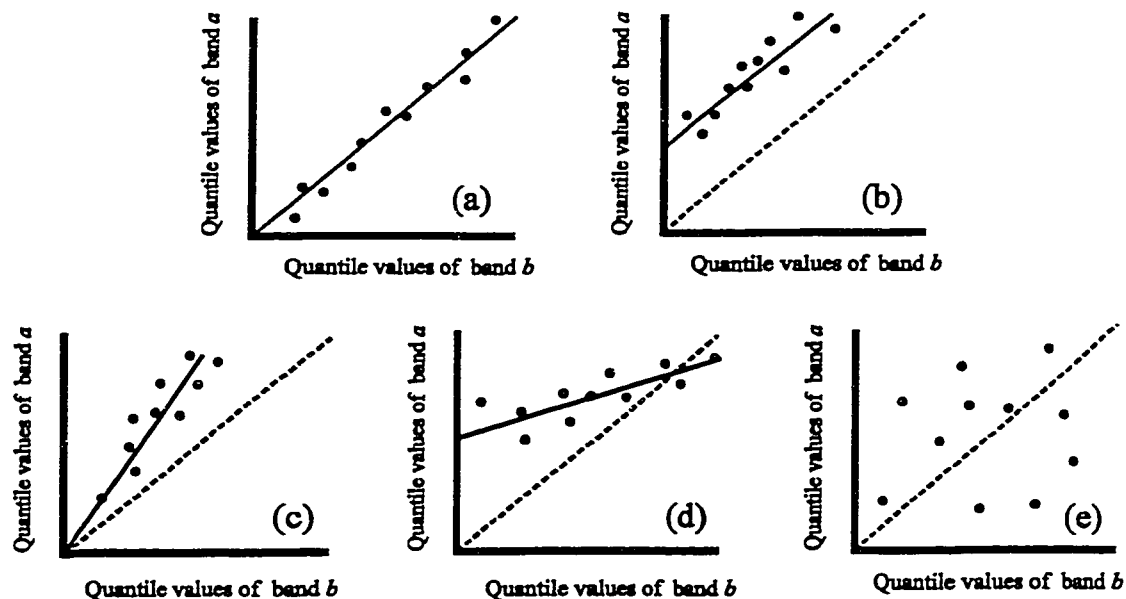


Figure 2. Various scenarios that may occur when quantiles are plotted for pairs of bands at the boundary between map sheets. a) No shift between two maps, b) shift by a positive constant, c) shift by a multiplier, d) shift by a constant and multiplier, e) no quantifiable relation between quantile pairs. (After Darnley *et al*, 1995).

Figure 2 shows alternative scenarios for the relationship of quantiles between bands “a” and “b”. In most cases the data will be plotted on logarithmic scales in order to meet homogeneity of variance considerations important in the analysis of trace element data. In Figure 2a there is a 1:1 relationship between quantiles, indicating that the data are fully consistent between the two surveys. If such data extended over 2 or more orders of magnitude and were plotted without logarithmic transformation, the points would fan out at higher concentrations. Figure 2b indicates that the data from band “b” is consistently high by a constant amount. The distributions shown in Figure 2c require a multiplier to correct the data from one survey to the other, while Figure 2d shows a situation where both a multiplier and a constant are required. In situations like (e), levelling is not possible because there is no quantifiable relationship between the quantile pairs.

In all three scenarios requiring a correction, a regression equation is calculated between quantiles for bands “a” and “b”. In this chapter band “a” plotted along the y axis, is taken to be the “true” set of data and band “b” and the remaining area of sheet B are corrected to be consistent with band “a” and sheet A. It is assumed that those features that might affect the geochemical distributions, such as rock type or the physiographic environment, are broadly similar in the bands being compared, for example, that the survey boundary is not a geological boundary. The choice of which sheet or data set to consider “true” is a matter of judgment. In general, the data that have the best analytical standardization and quality control should be selected. If these do not provide a clear criterion, data sets that are consistent over the largest part of the total area should be chosen.

Should initial X-Y quantile plots exhibit non-linearity, transformations can be used to improve the linearity. If a logarithmic rule or a Poisson counting process is involved, a logarithmic or square root transformation may be adequate. If a logarithmic transformation is required, then all calculations need to be completed in logarithms, with a final conversion back to the original scale. In calculating a levelling line that best fits the X-Y distribution of quantile pairs, the precision of quantiles as estimators should be considered, since this is a function of the number of samples used to calculate individual quantiles. The central quantile (0.5) is estimated with greatest precision, and the precision then falls off to the outer quantiles (Wilks, 1962). It may thus be prudent to use a weighted regression so the outer quantiles, which have the greater error, have less influence in estimating the regression coefficients. In some cases it may also be desirable to compute confidence intervals around the regression line.

4.3 SELECTION OF BANDS

One of the most important considerations is that the geology be reasonably similar for bands that are being compared. This affects the selection of the length and width of the bands. Figure 3 shows four map sheets with dotted lines as their boundaries. Boundaries between numbered geological units are shown as solid lines. In this figure the central map sheet is considered to have a shift for element x relative to the other three sheets. For the bands shown, (a-W, b-W) are the best pair, since the areas of different geological units are approximately equal. In contrast, bands (a-N, b-N) are poor, because the geological units are different on either side of the border. Bands (a-, b-E) provide an intermediate case in terms of suitability. In the case of the E band pairs, the length of the bands may be decreased (Figure 3) to assure better representivity.

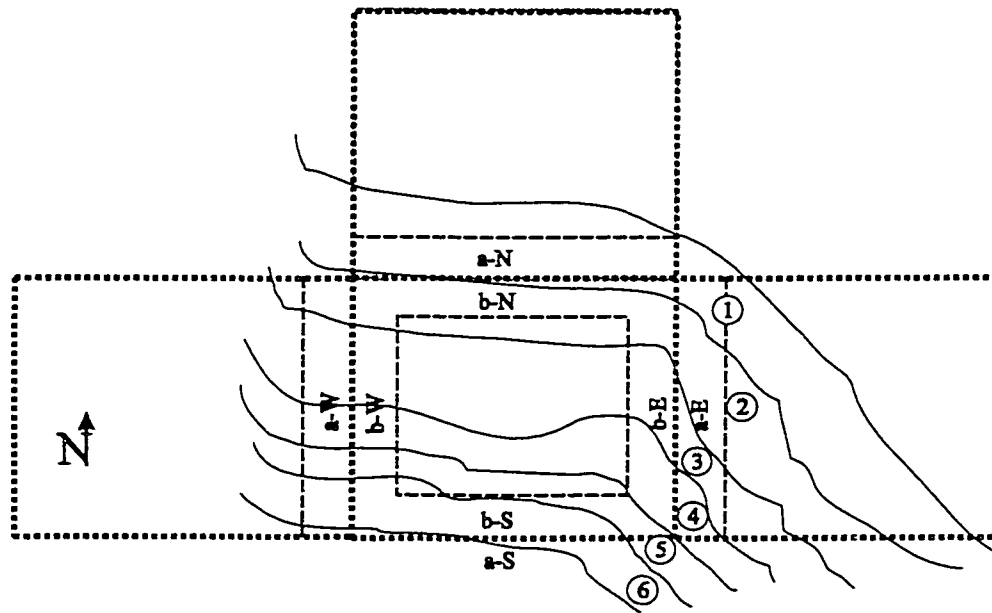


Figure 3. Considering geological condition in selecting length of the bands "a" and "b". Assuming that the map sheet in the middle has a boundary shift compared to surrounding sheets.

Choice of an appropriate width for the bands is also important. If the width is too small, then there will not be enough samples; if too wide the areas included may be too diverse in geology or physiography.

In the following example for levelling, a quantitative method is tested and applied to estimate a width needed for bands “a” and “b”. Then maps with a boundary shift are leveled.

4.4 DATA SETS

The data sets used here are Mo in stream sediments and moss mat samples and the pH of stream water taken from National Geochemical Reconnaissance (NGR) Surveys in British Columbia. The NGR stream sediment and water surveys in British Columbia have been carried out jointly by the Geological Survey of Canada (GSC) and the British Columbia Geological Survey (BCGS). For the first several years the survey program was managed by the GSC, with sample collection, sample preparation and chemical analysis carried out under contract by private companies. Quality control was the responsibility of the manager (Friske and Hornbrook, 1991). From 1987 the manager changed from GSC to BCGS. The initial survey sheets managed by BCGS were given NGR Open File numbers. Later, the surveys were given the designation BCRGS (British Columbia Regional Geochemical Survey). Table 1 shows the managers and contractors involved in the survey sheets (Figure 4) discussed in this chapter.

For map sheets 865, 867 and all others managed by the Geological Survey of Canada, Mo was determined by reacting a 0.5 gm sample with 1.5 ml concentrated HNO_3 and allowing it to stand at room temperature for overnight (Lynch, 1992). Then, sample test tubes were placed in a hot water bath at room temperature, heated to 90° C and allowed to digest at 90° C for 30 minutes. Another 0.5 ml of concentrated HCl was

added and the digestion continued at 90° C for an additional 90 minutes with gentle mixing every 30 minutes. After removing the test tubes from the water bath and cooling to room temperature, 8 ml of 1250 µg/ml Al solution was added, and the sample solution was diluted to 10 ml and mixed well using a vortex mixer. Solids in the test tube were allowed to settle for two hours. Molybdenum was determined by atomic absorption spectrophotometry (AAS) using single element molybdenum hollow cathode lamp and a laminar flow nitrous oxide-acetylene burner. During the analysis a standard solution was analyzed after every tenth sample. Different standard solutions were used throughout the run so that the concentration range of a batch of unknown samples is represented by replicate standard readings.

For map sheets 2038, 2039, 2040, 2182, 2183, 2184, and BCRGS 34, Mo was determined in stream sediment samples as follows. A 3 ml aliquot of HNO₃ was added to a 0.5 gm sample and allowed to sit overnight. Then 1 ml HCl was added and the sample was left at 90° C in a water bath for 2 hours, then cooled. Aluminum solution were added and the whole left for 2 hours. The resulting solution was aspirated into an atomic absorption spectrophotometer (AAS) using an air-acetylene burner and standard solutions for calibration, with 1 ppm as the detection limit. The quality control procedure for these map sheets were also similar to those indicated above.

For all surveys, water samples were collected into 250 ml polyethylene bottles and were sent to the contractor's laboratory. The measurement of pH was done in the laboratory with a glass-calomel electrode system. For pH measurement an aliquot was poured into a separate container and pH determined using a glass-calomel system, and reported to the nearest 0.1 pH unit.

Since the procedure for sampling and pH measurement for all surveys is similar, the major reason for the existing shifts for pH may be because of slightly different instrumental calibrations.

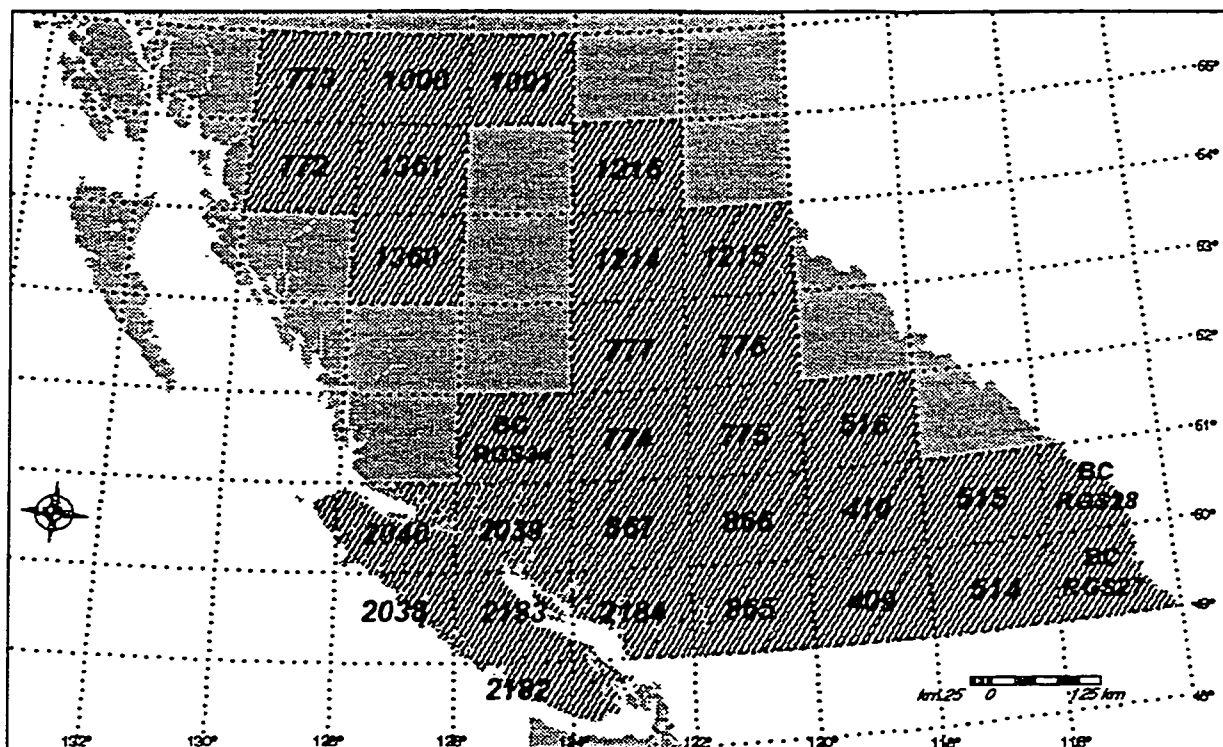


Figure 4. Different map sheets of National Geochemical Reconnaissance (NGR) with their open file numbers.

Table 1- Organizational summary for the geochemical map sheets considered in this chapter.

Map sheet	Year	Sample Collection	Sample Preparation	Sample Analysis	
2038*				Sediments	Water
2039*	1988	McElhanney Engineering Services Ltd.	Kamloops Research and Assay Ltd.	Chemex Laboratories	Barringer Magenta Ltd.
2040*					
BCRGS 34*	1991	McElhanney Engineering Services Ltd.	Rosbacher Laboratory Ltd.	Barringer Magenta Ltd.	
2182*					
2183*	1989	MPH Consulting Ltd.	Rosbacher Laboratory Ltd.	Barringer Magenta Ltd.	
2184*					
865 & 867**	1981	ROOI Enterprises Ltd.	Kamloops Research Assay and Laboratory Ltd.	Chemex Labs Ltd.	Bondar-Clegg & Co. Ltd.

* Managed by the British Columbia Geological Survey.

** Managed by the Geological Survey of Canada.

4.5 EXAMPLES OF LEVELING

4.5.1 LEVELLING pH VALUES

The first example is for shifts in the pH of stream water between the group of NGR sheets 2182, 2183 and 2184, which were sampled and pH measured in the same year (1989) and between the adjacent sheets BC RGS 34 and NGR 867 that were sampled in 1991 and 1981 respectively. Figure 5a shows that there is a sharp change in pH value at the boundary between sheets 2039 and 34 and between 867 and 2039.

To estimate the appropriate width of bands that should be constructed at the boundary between 2039/34 and 867/2039, bands of variable width (exploratory bands) were created within sheets 34 and 2039. Those within sheet 34 are 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 km wide and are shown in Figure 6.

Since these bands are taken from one map sheet, quantiles should plot close to a line where $Y=X$. Two methods were used to assess whether the quantile plots were close to the line $Y=X$. In the first, a parameter is defined that can estimate the range of optimal widths based on the differences between the quantile pairs. The parameter D as defined here, can help only as a guide to estimate the range of width for levelling bands. If the distribution of data between each band of the pair is identical, then the quantile pairs will be the same value. The value D is calculated:

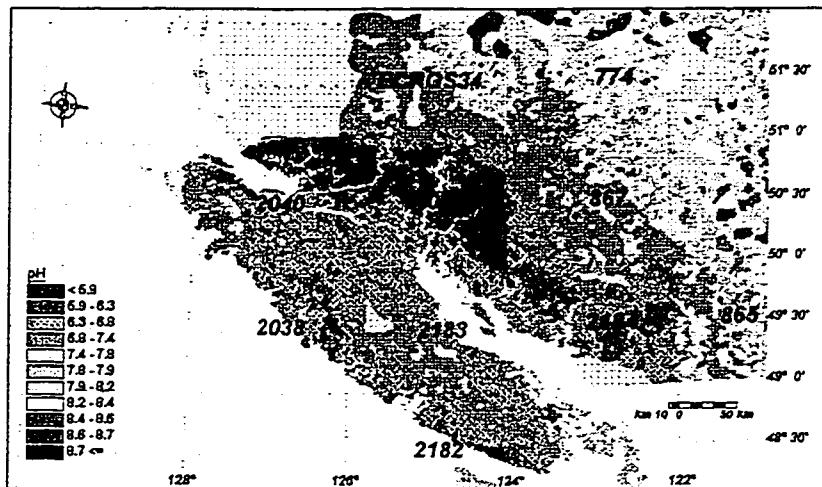
$$D = \sum w_i [(q_i)_e - (q_i)_{e'}]^2$$

where

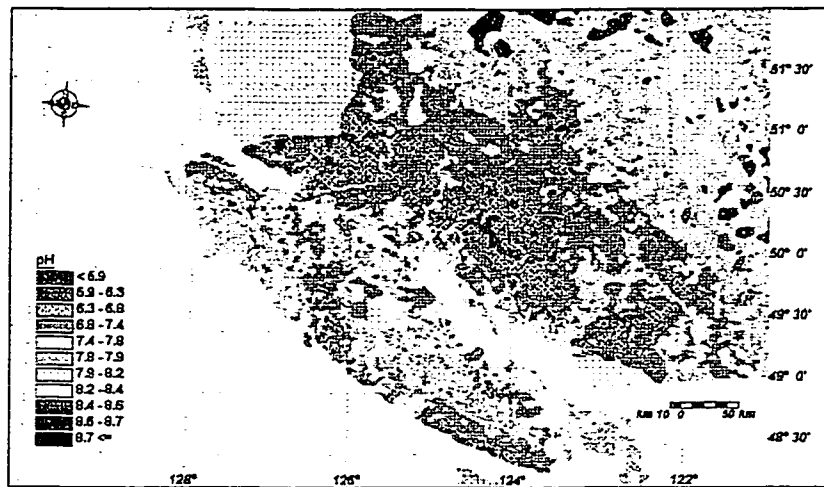
w_i = assigned weight to i th quantile

$(q_i)_e$ = i th quantile in band e

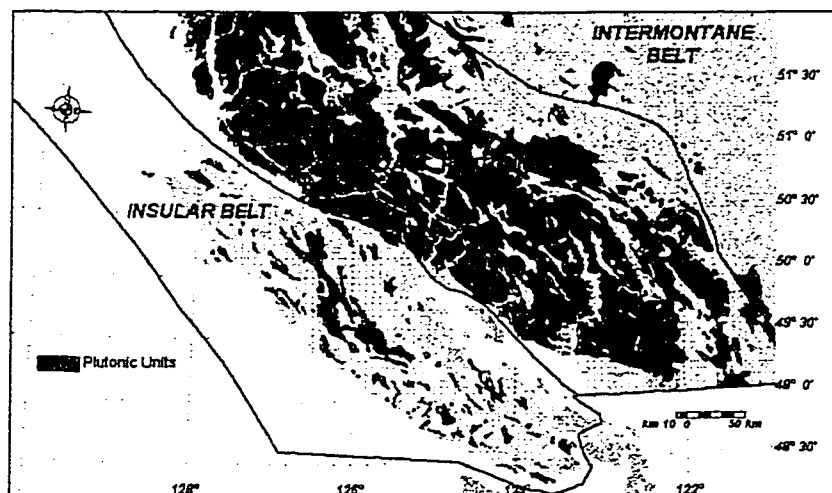
$(q_i)_{e'}$ = i th quantile in band e'



(a)



(b)



(c)

Figure 5. Levelling pH of water samples for 2038,2039,2040 and 2182, 2183, 2184 map sheets.

a) before and b) after levelling c) plutonic units in the area.

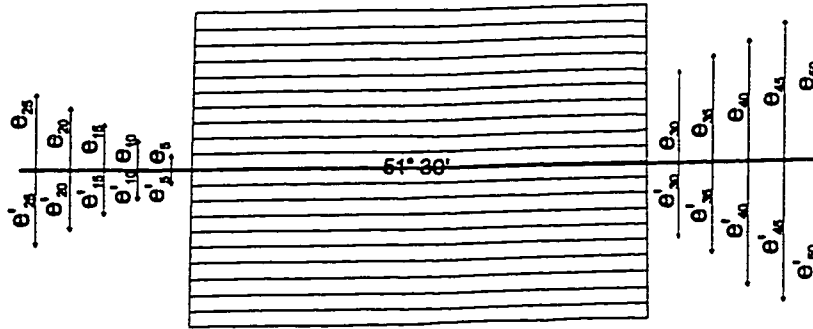


Figure 6. Exploratory bands, which were put inside the map sheet BC RGS34.

Weights are introduced to favor quantile pairs at or near the median based on the ordinates of the normal distribution (Krumbein & Graybill, 1965). The ordinate of a normal distribution for the 0.5 quantile (median) is 0.399, and the others were scaled relative to 0.399 (Table 2).

Table2. Ordinates of the normal distribution and assigned weights to quantiles.

Quantiles	Ordinates of the normal distribution	Weight
0. 50	0.399	1
0.40 & 0.60	0.386	0.97
0.30 & 0.70	0.348	0.87
0.20 & 0.80	0.280	0.70
0.10 & 0.90	0.175	0.44
0.05 & 0.95	0.103	0.26

Variations of D with width of exploratory bands within sheets 34 and 867 are shown in Figure 7. A quadratic polynomial curve is fitted to these D values. The range of widths consistent with low values for D are considered most appropriate as the initial estimate. A study of Figure 7 shows that 10 to 30 km can be an initial estimate for the width of the levelling bands, because in this range both sheets have low values for D. Among the minimum D values, smaller ones are preferred because as the dimensions of the bands increase, the geology becomes more dissimilar.

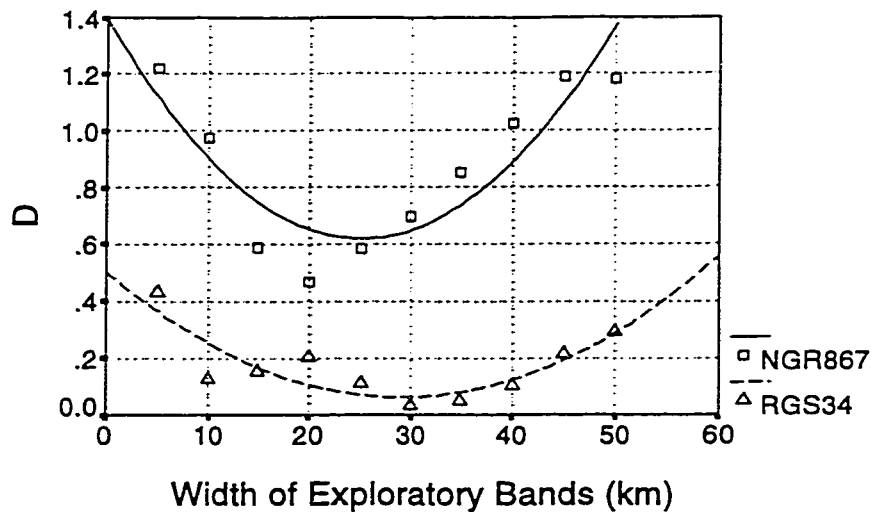


Figure 7. Variations of D with width(km) of exploratory bands inside sheets 867 and BCRGS34.

In the second method, to assess the optimal width more precisely, regression lines were fitted to the quantile plots for each pair of exploratory bands and 95% confidence limits were drawn on either side of the regression line. Using this approach, only exploratory bands of 5, 10 and 15 km width had confidence limits that covered the $Y=X$ line (Figure 8) and for example the bands of 20, 25 and 50 km width did not meet these criteria. The statistical estimate of quantiles improves as the number of samples used in their calculation increases, which affects the estimate of confidence limits. Note in Figure 8 that the width of the confidence limits for the 15 km bands is less than either the 5 or 10 km bands. By considering the above discussions, for this map sheet, 15 km bands can be considered as optimal. Larger widths increase the number of samples used to estimate quantiles, but the increased widths introduce differences in geology between the band pairs. Similar analysis within sheet 867 also showed the 15 km width to be optimal.

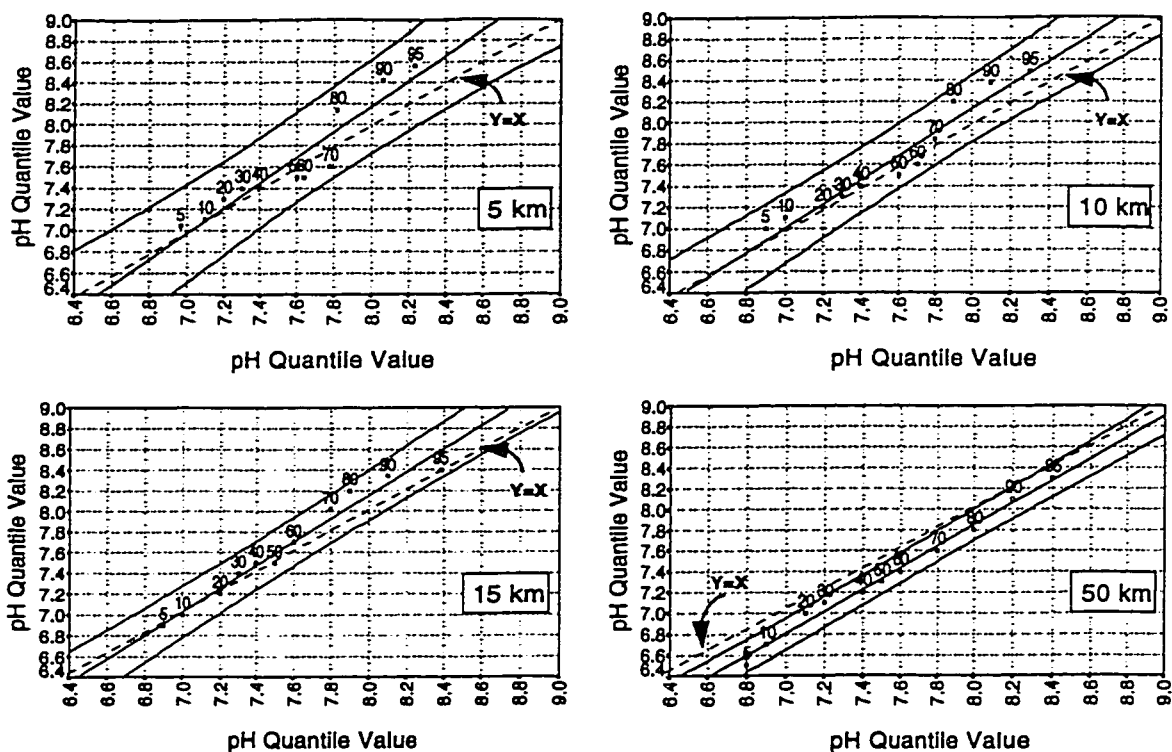


Figure 8. Regression lines and their 95% confidence limits for 5, 10, 15 and 50 km exploratory bands inside BCRGS34.

Thus in constructing bands to assess the boundary shifts at 34/2039 and 867/2039, widths of 15 km were used and sheets 34 and 867 were considered to have the “true” values, i.e., they are the “a” bands. These calculations show that the pH of samples within sheet 2039 can be corrected by:

$$\text{pH}_{(34)} = 0.77 \text{ pH}_{(2039)} + 1.87$$

$$\text{pH}_{(867)} = 0.89 \text{ pH}_{(2039)} + 1.14$$

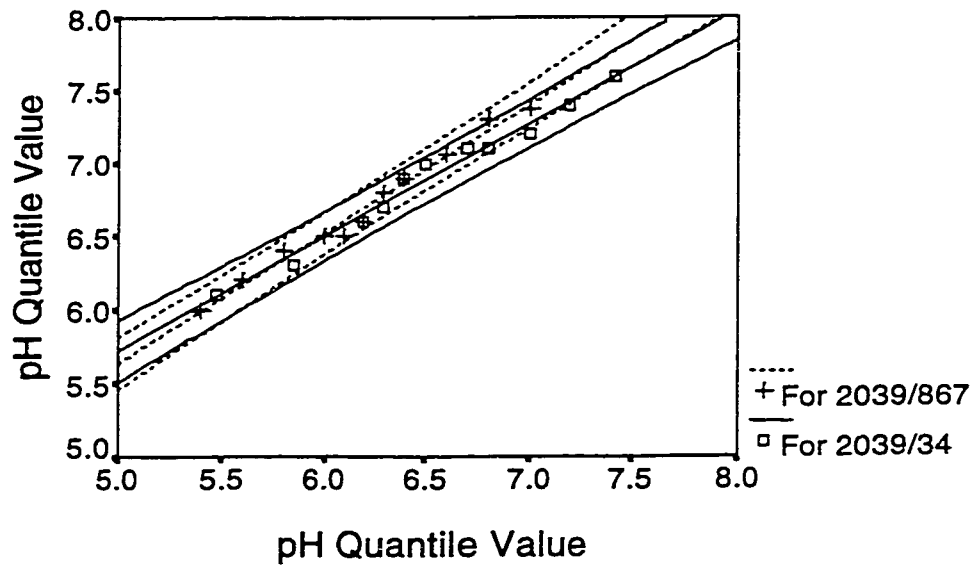


Figure 9. Similarity of regression models derived for levelling between map sheets 2039/34 and between 2039/867.

These values are similar and suggest that the pH within sheets 34 and 867 are similar, which is also apparent in the lack of shifts in the area occupied by sheets 34, 774 and 867 (Figure 5). To assess this similarity, confidence limits were plotted for each of these regression lines (Figure 9). As Figure 9 shows, each of these lines are located within the confidence limits of the other line and could be considered indistinguishable at the 95% confidence level. Thus a final stage was to combine the bands flanking 34 and 867 with 2039 and estimate the corrections using both data sets simultaneously:

$$\text{pH}_{(34 \text{ and } 867)} = 0.84 \text{ pH}_{(2039)} + 1.93$$

It was also considered that, since sheets 2038, 2039 and 2040 were sampled and

measured in the same year, this correction should be applied to all three sheets.

Sheets 2182, 2183 and 2184 were sampled and measured in the same year. Bands of 15 km width between sheets 867 and 2184 were used for estimating quantile pairs and produced the equation:

$$\text{pH}_{(867)} = 0.94 \text{ pH}_{(2184)} + 1.13$$

This correction was then applied to sheets 2182, 2183 and 2184.

When all of the above corrections are made, the map is replotted (Figure 5b). The boundary shifts that were apparent in Figure 5a are no longer present. The resulting trends in pH follow the geology of the region, with the lowest pH values corresponding to the Coast Plutonic Complex and additional smaller areas of felsic rock in the Insular Belt of Vancouver Island (Figure 5c).

4.5.2 *LEVELLING Mo VALUES*

Figure 10a shows the same area first discussed for levelling pH in south western British Columbia. Here a shift exists for Mo in stream sediments and moss mat samples between map sheets 2182, 2183, 2184 and all the adjacent sheets. As Table 1 shows, map sheets 2182, 2183 and 2184 were sampled and analyzed in the same year (1989) by the same company and laboratory, which are both different as compared to adjacent sheets.

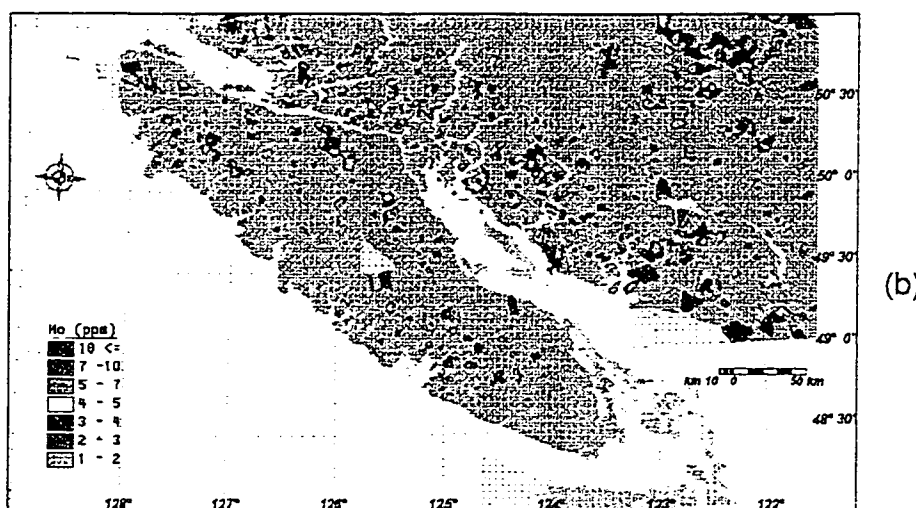
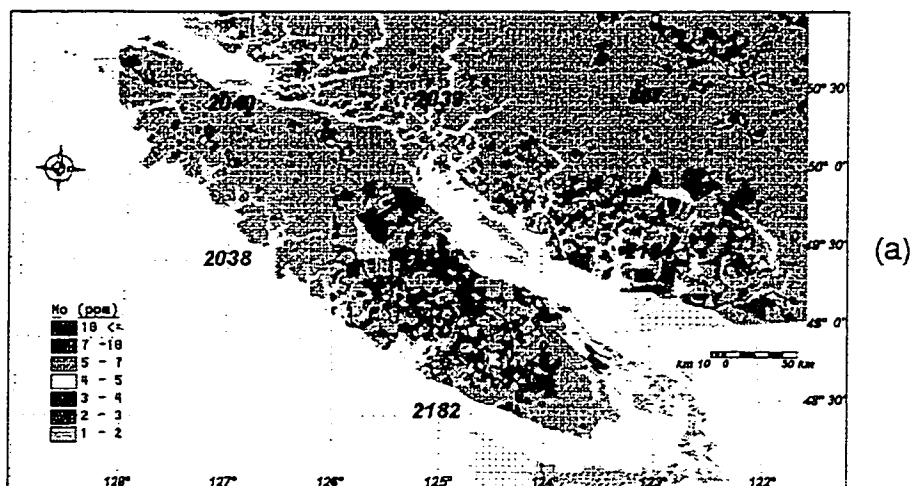


Figure 10. a) Original values of Mo in map sheets 2182, 2183, and 2184. b) Levelled map of Mo.

For levelling Mo values, a $\log_{10}$ transformation was first carried out prior to the regression modeling. Set of exploratory bands were selected from inside sheet 2039 of width 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 km. Figure 11 shows the regression lines and their confidence limits for the 5, 10, 15 and 50 km exploratory bands. For all exploratory bands, $Y=X$ locates inside the confidence limits of regression lines. For the

10 and 30 km bands the estimated quantiles of $\log_{10}(\text{Mo})$ were equal. Therefore their regression lines did not have any confidence bounds, and the D value for the 10 km and 30 km bands is 0, which is the minimum possible value. Here, 10 km was judged the best estimate for the width of bands “a” and “b” which would result in a successful levelling. Only the northern borders of 2183 and 2184 were selected for levelling with the southern border of 2039 and 867 using 10 km bands.

To check whether there is any significant difference if bands “a” and “b” are selected only between 2183 and 2039, or only between 2184 and 867, the following analysis was undertaken.

The regression model appropriate for correcting the Mo of samples within sheet 2183 to sheet 2039 equivalent values was estimated as:

$$\log(\text{Mo})_{(2039)} = 0.62 \log(\text{Mo})_{(2183)} - 0.15$$

The correction between sheets 2184 and 867 is:

$$\log(\text{Mo})_{(867)} = 0.57 \log(\text{Mo})_{(2184)} - 0.08$$

These values are similar and suggest that the Mo measurement levels within sheets 2039 and 867 are similar, which is also apparent in the lack of shifts in the area occupied by sheets 2038, 2039, 2040 and 867 (Figure 10). To check the similarity of these two regression models, their confidence limits were plotted (Figure 12), each regression line is located within the confidence limits of the other. So these lines could be considered indistinguishable at the 95% confidence level.

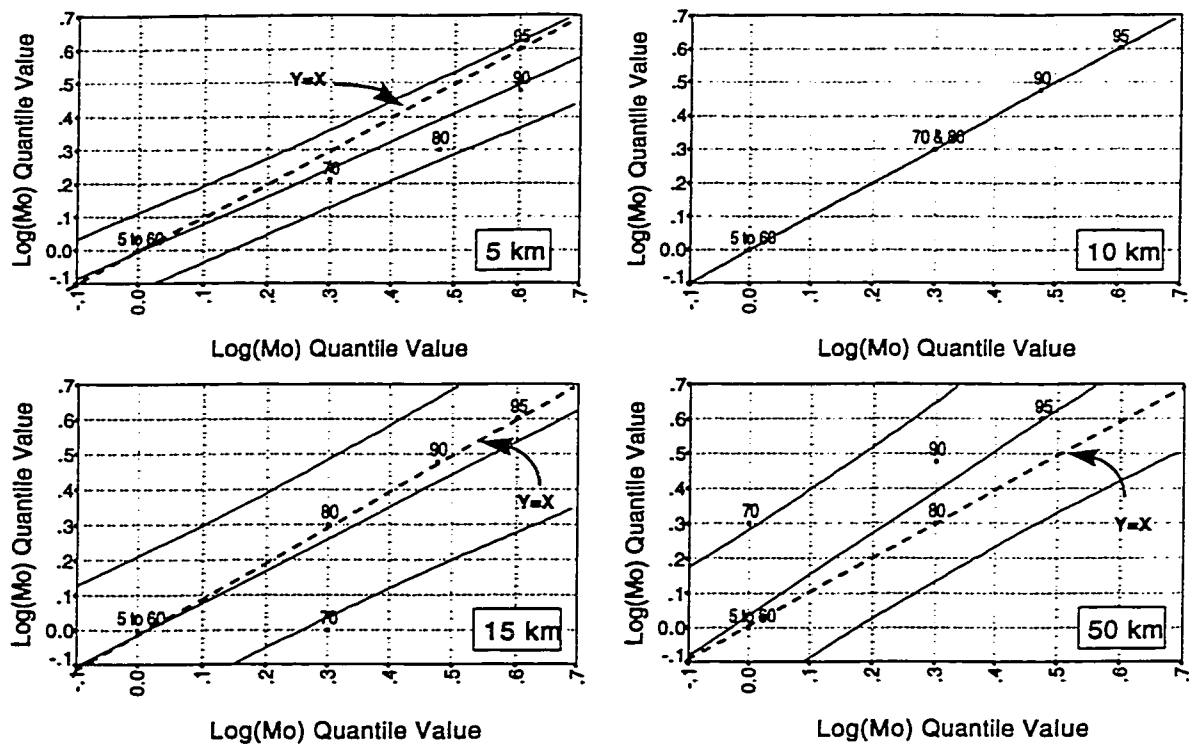


Figure 11. Regression lines and their 95% confidence limits for 5, 10, 15 and 50 km exploratory bands inside 2039.

Here a final stage was to combine the bands “a” and “b” flanking 2184/867 and 2183/2039:

$$\log(\text{Mo})_{(2039,867)} = 0.97 \log(\text{Mo})_{(2183,2184)} - 0.24$$

It was also considered that, since sheets 2182, 2183 and 2184 were sampled and analyzed in the same year, this correction should be applied to all three sheets.

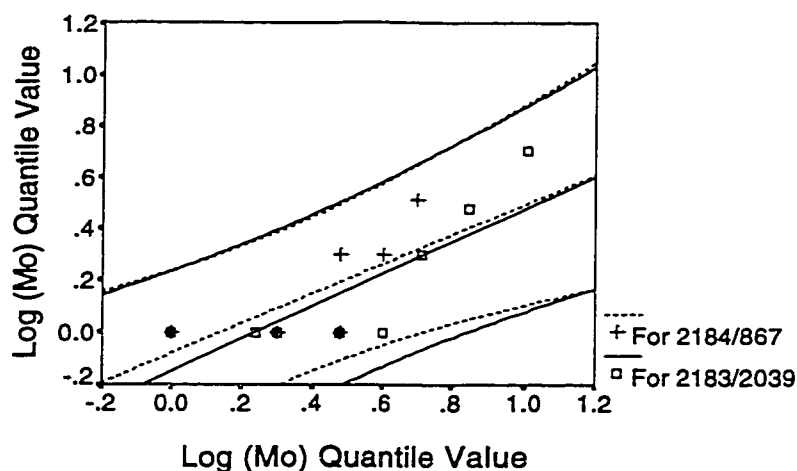


Figure 12. Similarity of regression lines derived for levelling between map sheets 2183/2039 and between 2184/867.

After levelling by this last equation, all of $\log(\text{Mo})$ values are then transformed from log scale into the original scale and all the leveled Mo values that were less than 1 were assigned to 1 which is the minimum reported value for Mo.

By using these leveled values, and the original values of Mo for the adjacent balanced map sheets, the map of Figure 10b is created which does not show the boundary shift that were apparent in Figure 10a. To make this map, the same imaging levels of Figure 10a, were applied.

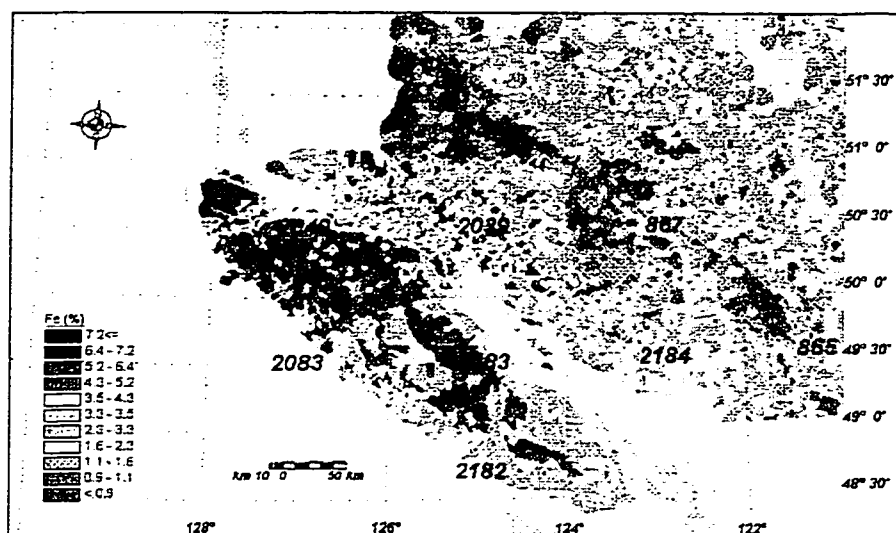
4.5.3 LEVELLING Fe VALUES

Iron is another element which has a boundary shift between 2038, 2039, 2040 and the adjacent map sheets (Figure 13a). Also there is another boundary shift for Fe between 2182, 2183, 2184 map sheets and adjacent map sheets which is smaller than the first mentioned one. As Table 1 shows, samples of map sheets 2182, 2183 and

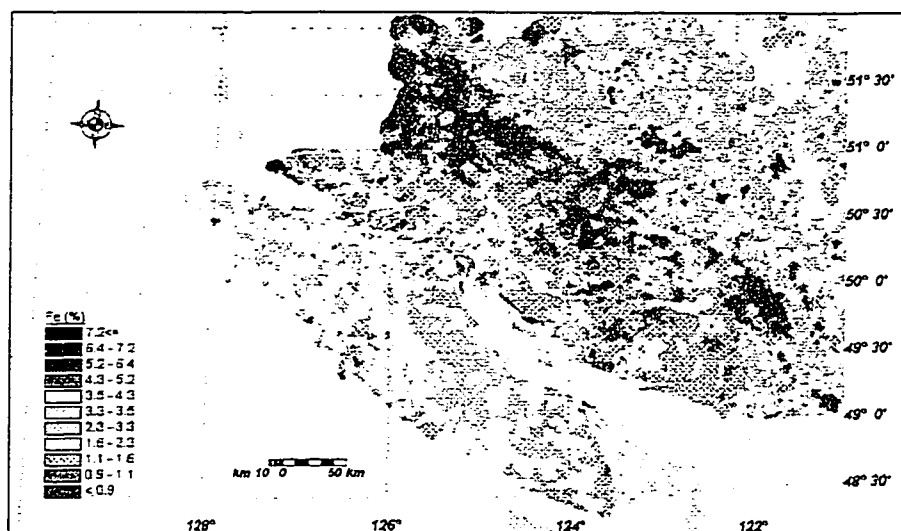
2184 are collected and analysed in the same year (1989) and those of 2038, 2039 and 2040 were collected and analysed in 1988 and by another company and laboratory which is different as compared to adjacent sheets. Most likely, this change of companies and laboratories is the reason to have such a boundary shift for Fe. Here Fe has a positively skewed distribution close to lognormal. To calculate the levelling equation, first log10 of original Fe values were calculated. Based on the above discussions, here for Fe a width of 15 km is selected for bands “a” and “b”. Samples inside bands “a” and “b” between 2039/867 map sheets were extracted and the quantile pairs were calculated. The levelling line that Fe of samples within sheet 2039 can be corrected is calculated as:

$$\log(\text{Fe})_{(867)} = 0.76 \log(\text{Fe})_{(2039)} - 0.25$$

Similar to pH, this correction should be applied to all three sheets of 2038, 2039 and 2040, since these sheets were sampled and measured in the same year and by the same companies.



(a)



(b)

Figure 13 a) Boundary shift for Fe between 2038, 2039, 2040 and also between 2182, 2183, 2184 and adjacent map sheets b) Fe, after separately levelling 2182, 2183, 2184 and 2038, 2039, 2040 map sheets with different levelling equations.

To find the equation for levelling Fe for 2184 map sheet, samples were extracted from 15 km bands between 2184/867 sheets. The levelling line between sheets 2184 and 867 is calculated as:

$$\log(\text{Fe})_{(867)} = 0.77 \log(\text{Fe})_{(2184)} + 0.10$$

Because of the classification intervals used for the map of Fe, a “fined tuned” levelling was necessary. In this case, it was also possible to increase the class intervals in the classification used for creating Fe map to generate a completely levelled map, but here the same classification and contour intervals were used. Here selecting the upper limits of the 95% confidence intervals of the calculated levelling line will result in a better levelling:

$$\log(\text{Fe})_{(867)} = 0.69 \log(\text{Fe})_{(2184)} + 0.05$$

This correction was applied to all three sheets of 2182, 2183, 2184. Figure 13-b shows the levelled map for Fe.

4.5.4 LEVELLING Mn VALUES

As Figure 14a shows, there is a small boundary shift for Mn between 2039 and the adjacent map sheets. Samples that are located in boundaries of 2039/RGS34 and 2039/867 were extracted from 15 km bands “a” and “b”. The distribution of Mn is positively skewed and is very close to a lognormal distribution. Therefore first $\log_{10}(\text{Mn})$ is calculated and is used to find the levelling equation. Then all the levelled values of Mn are transformed back from logarithmic to original scale. The levelling line between sheets 2039/867 and 2039/867 is calculated as:

$$\log(\text{Mn})_{(867, \text{RGS34})} = 1.41 \log(\text{Mn})_{(2039)} - 1.32$$

Similar to the previous cases, this correction was applied to all three sheets of 2038,

2039 and 2040, since these sheets were sampled and measured in the same year (1988) and by the same companies. Figure 14b shows the levelled map of Mn.

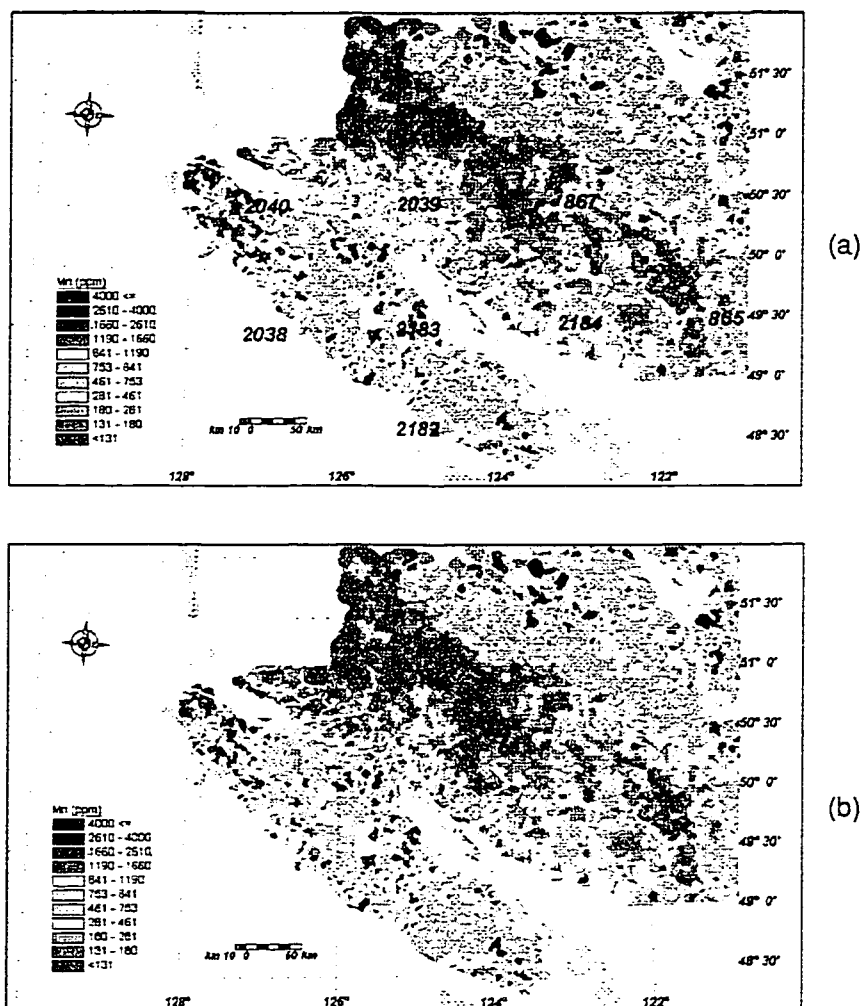


Figure 14 a) Shifted values of Mn , b) Levelled Mn after levelling 2038, 2039, 2040.

CHAPTER 5

GEOCHEMICAL DATA ANALYSIS

5.1 INTRODUCTION

The geochemical data sets that were used in this thesis are from stream sediment and stream water samples of National Geochemical Reconnaissance (NGR) Surveys in British Columbia. In order to carry out the geochemical data analysis, the geological units that are either spatially or genetically most closely related to different types of porphyry deposits were selected (Chapter 3). In some cases, geochemical data analysis was performed on the data set related to a single geological unit and in other cases groups of geological units. The selected arc volcanic units were studied separately from plutonic units. In some cases, those geological units that have similarity in their dominant rock types and host similar types of porphyry deposits were studied together. If the area of a selected plutonic unit is large enough, it was studied separately. Univariate and multivariate data analyses were done on separately extracted subsets of the original NGR data. Before starting any geochemical data analysis, statistical distribution of different elements were checked for the presence of extreme outliers. If needed, for different elements, these extreme outliers were removed.

In this chapter, it is shown that in certain polygons of geological units that have porphyry mineralizations, the median of Cu is higher than the units without porphyry mineralizations. It is also shown that the variability of indicator elements of porphyry deposits (Cu, Mo) can be used to display the presence of geochemical provinces of porphyry deposits. In addition, it was shown that calculating principal component scores for geochemical samples, is a very useful tool to indicate areas of porphyry mineralizations. Such principal component scores can also help to distinguish different geological environments or phases of plutonic activities inside the geological units of interest.

By a distinct example from Guichon plutonic suite (EJgG), it is shown that the discriminant analysis, is an efficient multivariate analysis method to differentiate the areas with high potential for mineralization from barren zones within the same geological environment. The results obtained by the discriminant analysis were similar to the results of the certain selected factors from factor analysis.

5.2 UNIVARIATE ANALYSIS

5.2.1 FILTERING THE DATA

To reduce the effect of different geological environments and different background levels, samples located within the selected geological units were extracted and each individual data set was statistically analysed. In the surveys of NGR, samples were not taken from streams coming directly from mining camps (Jackaman, 1996, personal communication). As an example, Figure 1 shows this for the Guichon Creek batholith and the Highland Valley mining camp.

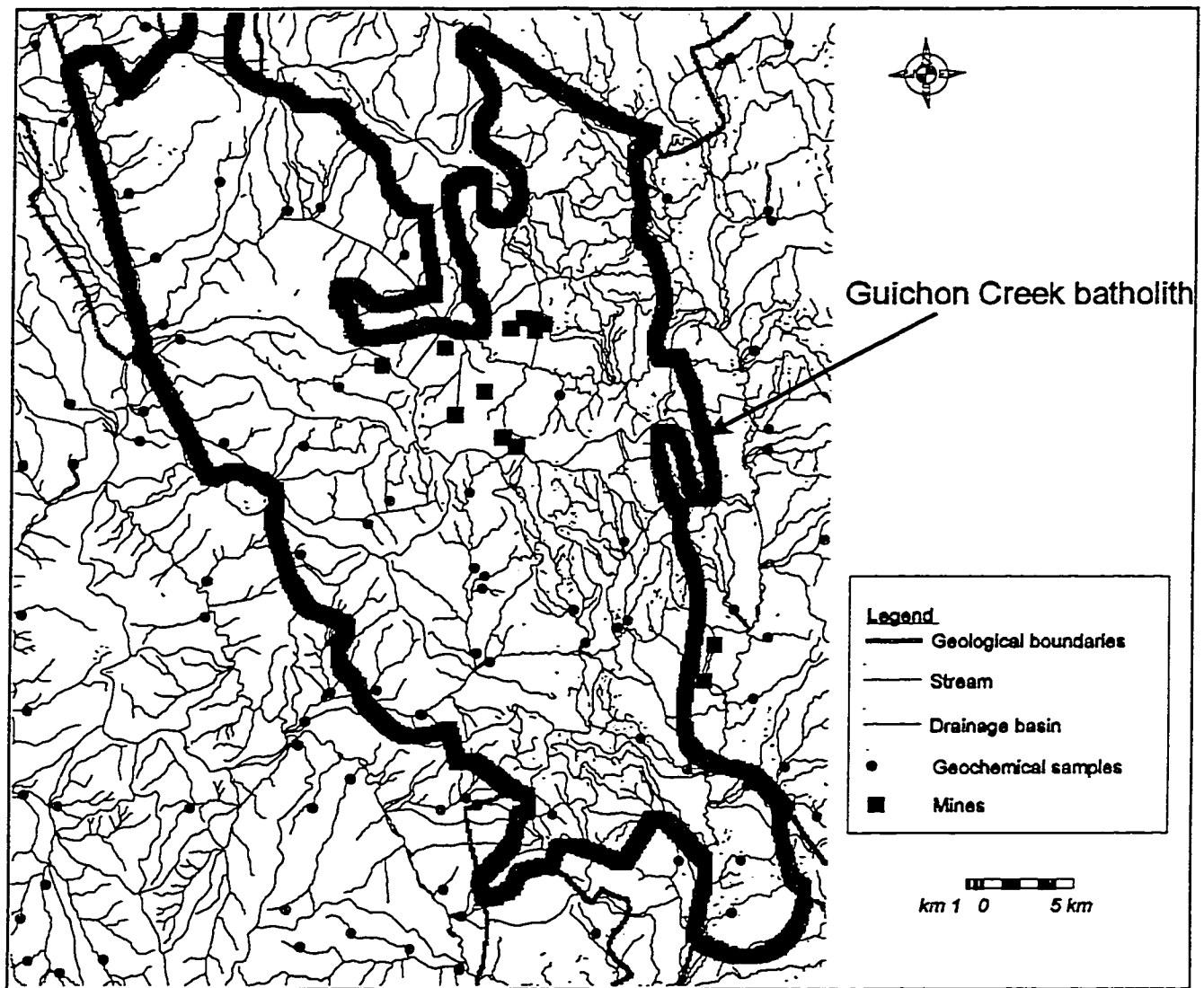


Figure 1. Streams, drainage basins and location of NGR stream sediment and water samples inside the Guichon Creek batholith and the Highland Valley mining area. Samples were not taken from the streams coming directly from mines.

An outlier is an individual result drawn from some other statistical population than the one being investigated. Therefore, when they are compared with the remainder of the data they lie at a notable statistical distance from the main mass of the data (Garrett, 1995, personal communication). Estimation of statistical parameters can be distorted by including the extreme outliers in the data set. Therefore, before analysing these subsets of data, the distributions of

elements and presence of extreme outliers were checked. Where needed, these extreme outliers were removed from data subsets. Two useful tools that help to identify such extreme outliers are Tukey box-plots and normal probability plots (Garrett, 1991 and personal communication). The box-plot provides a quick and simple graphical summary of the data (Systat, 1992), and normal probability plots provides detailed information on the statistical distribution of the data and existing subgroups. In different commercial statistical packages, probability plots are called by a variety of names e.g., normal probability plots, normal quantile plots, Q-Q plots, p-plots, etc. The advantage of these graphs is that they simply describe the data the way they are with no assumptions about number or width of classes as is needed for a histogram.

In a box plot, the median is marked by the centre line. The lower and upper hinges comprise the edge of the central box. The median splits the ordered batch of numbers in half, and the hinges split the remaining halves in half again (Systat, 1992). In the Systat box-plots, the outlier values are shown by asterisks and circles. The circle is used for extreme outlier values. In the probability plots if the data are from a normal distribution, the plotted values fall along a straight line extending from the lower left corner of the display towards the upper right corner. The observed data values are plotted along the horizontal axis. The expected normal values for each observation are plotted on the vertical axis (Systat, 1992). If the frequency distribution of the sample population is skewed or the population is polymodal, then the probability plot will be curved or discontinuous (Grunsky, 1991). To separate the extreme outliers, the element distribution was considered. The location of gaps separating the very end members of the anomaly population from the other samples related to the anomaly population were used to do this filtering (Garrett, 1996, personal communication). In cases where no distinct gap existed, all the data for that element were selected. When a gap was located, it was usually in the interval of the 98 to 99 percentile.

Cut-off values to disaggregate the extreme outliers are presented in the following tables for different discussed geological units. In each case, 95, 98 and 99 percentiles of the data are also reported for comparison with the selected cut-off values that separate the extreme outliers.

5.2.1.1 GUICHON PLUTONIC SUITE (EJgG)

There are 518 samples of stream sediment inside the EJgG Guichon plutonic suite that have analytical results for Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, pH, F in water (F-wat) and U in water (U-wat) and 256 samples with analytical results for As, Au, Ba, Br, Ce, Cr, Cs, Hf, La, Lu, Na, Rb, Sc, Sm, Ta, Th, U, Yb and Zr. The probability and box plots for all of the discussed elements and pH are shown in Appendix A-1.

Table 1 shows the calculated percentiles and the selected cut-off value (selection limit) between the extreme outliers and the rest of the data for different elements. Among the first group of elements (Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, pH, F in water (F-wat) and U in water (U-wat) only the distribution of pH is close to normal. Since pH has nearly a uniform and continuous distribution (Appendix A-1) and there are no extreme outliers, all the data for pH were selected. For U, the anomaly population is continuous and there is no large gap between points of high value, therefore all the values were selected (Appendix A-1). For other elements, it is possible to find such gaps by the box and probability plots at the very end parts of their distributions. For Ni and U in water (U-wat), it is possible to distinguish more than one group of anomalies (Appendix A-1). Barium and Na follow a normal distribution (Appendix A-1). Distribution of Rb is also very close to normal, but its careful study reveals that there might be two populations with normal distributions that mix with each other, and a smaller anomaly population. Scandium has also a distribution close to normal but not as close as Ba, Na and Rb.

Table 1. Percentiles and cut-off values used as the selection limit to separate extreme outliers for stream sediment and water samples inside Early Jurassic Guichon plutonic suite (EJgG).

	95%tile	98%tile	99%tile	selection limit	No. of valid cases
Co	15.0	18.6	21.0	25	518
Cu	135.1	249.3	488.1	800	518
Fe	3.8	5.2	6.1	6.5	518
F in water	250.0	339.0	399.0	450	504
Hg	150.0	228.2	250.0	260	408
Mn	2251.5	3100.0	4240.5	3500	518
Mo	5.0	8.6	20.6	30	518
Ni	38.0	95.8	140.5	150	518
Pb	10.0	15.0	31.4	40	518
pH	8.3	8.5	8.5	all selected	504
U	15.1	25.6	38.2	20	509
U in water	3.7	8.9	11.5	11	504
Zn	90.1	155.0	330.6	300	518
As	13.2	20.4	43.6	50	256
Au	23.2	110.8	258.1	100	256
Ba	1515.0	1700.0	1900.0	all selected	256
Br	41.2	61.8	83.1	100	256
Ce	101.5	130.0	144.3	all selected	256
Cr	310.0	562.9	867.1	700	256
Cs	4.5	5.9	10.0	10	256
Hf	18.2	31.0	40.9	50	256
La	75.6	98.3	110.0	100	256
Lu	0.5	0.7	0.9	1	256
Mo	7.0	15.7	40.7	35	256
Na	3.2	3.4	3.5	all selected	256
Rb	96.0	100.0	114.3	all selected	256
Sc	22.4	27.7	29.7	all selected	256
Sm	10.7	12.7	14.2	14	256
Ta	2.5	3.6	5.2	all selected	256
Th	20.1	28.1	35.3	35	256
U	16.2	27.1	42.2	30	256
Yb	3.2	4.0	5.9	all selected	256
Zr	824.5	1186.0	1886.0	1800	256

5.2.1.2 COPPER MOUNTAIN (EJyCM, MJyCM), DUCKLING CREEK (MJyCMD) PLUTONIC SUITES

A total of 36 stream sediment and water samples are located inside the Copper Mountain plutonic suites (EJyCM, MJyCM, MJyCMD). Because of the few geochemical samples, for this set of geological units, multivariate analysis was not undertaken.

5.2.1.3 BULKLEY (LKgB), FRANCOIS LAKE (JKgF), SURPRISE LAKE (Lkqs), TOPLEY (EJqT) PLUTONIC SUITES

Here 116 samples are located inside the polygons of these plutonic units. These samples have the analysis results for Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, pH, F in water (F-wat) and U in water (U-wat). Table 2 shows cut-off values used to remove the extreme outliers. Here in cases like Fe, Pb, pH, U and U in water (U-wat) all samples were accepted. Appendix A-2 shows the probability and box plots for all of the discussed elements and pH. Among these, Fe and pH follow a normal distribution. For Zn it is possible to distinguish 3 to 4 normally distributed populations. F in water (F-wat) also shows 3 distinct populations. Excluding pH, all the elements show a positively skewed distribution.

Table 2. Percentiles and the selection limit used for separating extreme outliers for stream sediment and water samples inside Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites.

	95%tile	98%tile	99%tile	selection limit	No. of valid cases
Co	23.2	36.0	59.6	60	116
Cu	114.7	201.2	359.4	300	116
Fe	3.8	4.1	4.3	all selected	116
F-wat	65.8	84.6	155.7	150	116
Hg	130.0	163.2	244.7	200	116
Mn	1402.4	1807.6	5789.5	6000	116
Mo	10.0	41.8	56.3	50	116
Ni	230.6	384.1	449.9	400	116
Pb	15.0	22.0	26.3	all selected	116
pH	7.9	8.2	8.2	all selected	116
U	24.7	53.1	63.6	all selected	115
U-wat	0.7	1.1	1.2	all selected	116
Zn	115.2	153.0	220.3	200	116

5.2.1.4 LATE CRETACEOUS PLUTONIC SUITE (LKg)

There are 598 geochemical samples inside LKg plutonic suite within the study area. Table 3 shows the calculated percentiles and the selected cut-off value (selection limit) between the extreme outliers and the rest of the data for Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, pH, F in water (F-wat) and U in water (U-wat). The probability and box plots for all of these are

presented in Appendix A-3. Here pH has almost a normal distribution (Appendix A-3). All other elements have a positively skewed distribution. Cu shows 2 populations for anomalies with a break in the slope and a gap in the distribution. For Fe, by excluding the anomalies, it is possible to consider the distribution of the rest of the samples close to a normal distribution.

Table 3. Percentiles and cut-off values used as the selection limit to separate extreme outliers for stream sediment and water samples inside Late Cretaceous plutonic suite (LKg).

	95%tile	98%tile	99%tile	selection limit	No. of valid cases
Co	15.0	20.0	24.0	all selected	598
Cu	72.0	90.0	105.8	400	598
Fe	3.0	3.5	4.0	all selected	598
F-wat	160.0	261.6	300.8	400	591
Hg	70.0	105.4	198.1	400	572
Mn	820.3	1101.2	1403.0	3000	598
Mo	3.0	10.0	23.0	50	598
Ni	28.1	55.1	122.0	300	598
Pb	11.0	24.2	62.1	200	598
pH	7.9	8.1	8.3	all selected	591
U	14.1	27.0	32.0	50	595
U-wat	0.6	1.3	2.4	4	591
Zn	90.0	120.1	430.3	all selected	598

5.2.1.5 BONANZA ARC VOLCANIC GROUP (JB)

There are 466 samples in this arc volcanic unit. Elements that were used for the sediment and water samples located inside Bonanza Group (JB) are Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, and LOI from stream sediment data and pH, F in water (F-wat) and U in water (U-wat) from water samples. The probability and box plots for all of these are presented in Appendix A-4. Table 4 shows the high percentiles for different elements and the selected cut-off limit to disaggregate the extreme outliers from other samples. Among these, pH shows a normal distribution and Fe very close to normal. Cobalt shows 2 populations in its anomaly group. Other elements show a positively skewed distribution.

Table 4. Percentiles and selection limit used to separate extreme outliers for stream sediment and water samples inside Bonanza Group (JB).

	<i>95%tile</i>	<i>98%tile</i>	<i>99%tile</i>	<i>selection limit</i>	<i>No. of valid cases</i>
Co	30.0	38.0	43.7	50	466
Cu	105.7	120.0	204.0	400	466
Fe	2.8	3.2	3.4	all selected	466
F-wat	46.0	62.4	73.6	120	439
Hg	796.0	2696.0	5625.0	5000	466
LOI	24.1	31.6	37.2	50	465
Mn	1917.6	2689.1	3983.3	6000	466
Mo	3.0	4.0	5.7	10	466
Ni	43.0	47.7	59.0	150	466
Pb	11.0	18.7	30.3	30	466
pH	8.7	8.9	9.0	all selected	439
Sb	1.2	1.9	3.3	5	466
U	2.7	3.8	4.2	6	466
U-wat	0.1	0.1	0.2	0.4	439

5.2.1.6 HAZELTON ARC VOLCANICS (JH)

Hazelton Group (JH) is an arc volcanic complex in Stikinia terrain. There are 1332 stream sediment and water samples located inside Hazelton Group (JH) in the study area. Analytical results are reported for Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, and LOI for stream sediment samples and pH, F in water (F-wat) and U in water (U-wat) for water samples. As Table 5 shows, there are no data available for 25 water samples. In addition, 406 stream sediment samples have no record for Sb and 570 stream sediment samples for LOI. Therefore Sb and LOI were not entered into the multivariate analysis. Here also pH shows a normal distribution. For most of the other elements, the distribution is positively skewed and is close to lognormal (Appendix A-5). In some cases, it is possible to distinguish more than one group in anomaly population.

Table 5. Percentiles and the selection limits used to separate extreme outliers for stream sediment and water samples inside Hazelton Group (JH).

	95%tile	98%tile	99%tile	selection limit	No. of valid cases
Co	22.0	28.0	31.7	50	1332
Cu	104.0	150.0	328.1	900	1332
Fe	4.8	5.7	6.4	10	1332
F-wat	60.0	84.0	129.2	300	1307
Hg	120.0	210.0	353.6	1000	1331
LOI	13.6	17.3	19.3	30	762
Mn	1900.0	2667.0	4167.0	7000	1332
Mo	5.0	8.7	15.0	40	1332
Ni	41.0	53.3	63.3	150	1332
Pb	28.0	46.0	65.3	100	1332
pH	8.3	8.5	8.6	all selected	1307
Sb	2.7	3.9	5.6	15	926
U-wat	0.1	0.2	0.3	0.5	1307
U	5.4	9.0	13.7	25	1326
Zn	203.4	301.7	359.3	500	1332

5.2.1.7 TAKLA & NICOLA ARC VOLCANICS (TrJ & TrJN)

Takla and Nicola (TrJ & TrJN) have the largest area of arc volcanic units in the study area. They were formed under similar tectonic environments. Here Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, and Zn from stream sediment data and pH, F in water (F-wat) and U in water (U-wat) from water samples were used for data analysis. The probability and box plots for them are presented in Appendix A-6. Iron shows 2 populations, which are close to normal. The metallic elements show distributions close to lognormal. Similar to previous cases, pH has a close to normal distribution (Appendix A-6).

Table 6. Percentiles and cut-off values used as the selection limit to separate extreme outliers for stream sediment and water samples inside Takla and Nicola arc volcanic Group (TrJ & TrJN).

	95%tile	98%tile	99%tile	selection limit	No. of valid cases
Co	20.0	24.0	30.0	50	1841
Cu	84.9	110.8	143.6	300	1841
Fe	3.8	4.5	5.1	7	1841
F-wat	160.0	256.2	422.4	850	1718
Hg	240.0	338.6	499.4	1000	1757
Mn	2395.0	3874.0	5804.4	10000	1841
Mo	4.0	6.0	8.0	20	1840
Ni	91.0	140.0	180.0	all selected	1841
Pb	9.0	14.0	18.6	32	1841
pH	8.4	8.5	8.7	all selected	1718
Sb	1.4	2.4	3.3	4.2	1568
U	5.0	8.1	13.0	30	1819
U-wat	1.1	2.3	4.4	6.5	1718
Zn	131.8	180.0	241.6	450	1841

5.2.2 UNIVARIATE PARAMETERS USED AS INDICES OF POTENTIALLY MINERALIZED AREAS

5.2.2.1 HIGH MEDIAN

A geochemical province is defined as a segment of earth's crust in which the chemical composition is significantly different from the average (Rose *et al.*, 1979). Geochemical provinces are most clearly manifested by suites of igneous rocks, all members of which are relatively enriched or relatively impoverished in certain chemical elements. One of the criteria of a bona fide geochemical province is that the characteristic chemical peculiarities should be recognisable in rocks covering a substantial period of time (Rose *et al.*, 1979).

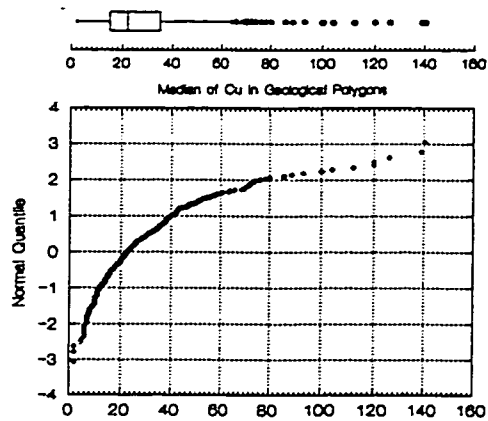
The formation of ore may be promoted by an unusually rich source operated on by a process, or by the operation of unusually efficient ore-forming processes on a normal source, or by some combination of these. Following this model, a metallogenic province with many orebodies can be either (I) a geochemical province, where the absolute concentration of metal

is higher than normal, or (II) a region where the physical and chemical environment promoted concentration of ore elements into deposits. A metallogenic province formed by the first process is simply one manifestation of a geochemical province. Such provinces can be detected and delineated by wide-spaced rock or drainage sampling. Particularly in inaccessible or poorly explored terranes, the delineation of geochemical provinces can provide useful guidance in the reconnaissance stages of exploration (Rose *et al.*, 1979).

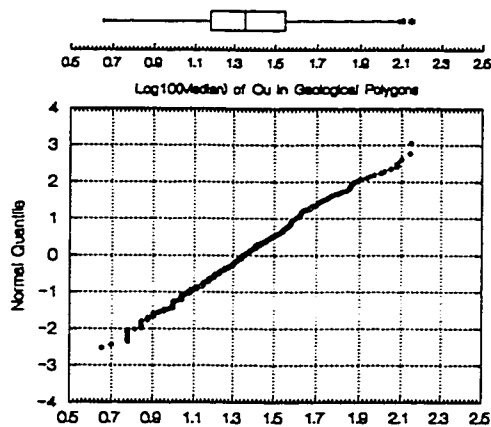
In this study, it was shown that many of the selected geological units have higher median for Cu in stream sediment samples than other geological units. The median was used here because it has the advantage that is almost not sensitive to extreme values in a distribution so it can be a good estimator of central tendency of the data. In GIS, a polygon is defined as a closed boundary. Each geological unit comprises several polygons in a geological map. Median of Cu in stream sediment samples was calculated for only those geological polygons that have more than 5 samples in them. Figure 2-a shows the probability and box plots for medians of Cu in stream sediment samples. It shows that the data do not fall on a straight line; so medians of Cu in stream sediment samples are not normally distributed. Furthermore, it appears that more than one single distribution exists. The probability plot for logarithm of medians is close to a straight line (Figure 2b), suggesting that medians of Cu in stream sediment samples follow a lognormal distribution. Figure 2a helps to find the natural breakpoints of medians. Based on these breakpoints, a classification was made and used to generate the map of Figure 3.

Median can be considered as an estimator of the generalised background. By considering geological units composed of similar rock types, it is possible to see that most of geological units selected in the study area have medium to high medians for Cu (Figure 3). However, Karmutsen Volcanics (TrK) in Vancouver Island, which has a distinctly high median for Cu is not considered by geologists as a known host for porphyry deposits (Panteleyev, personal communication, 1996). The high background for Cu in Karmutsen Volcanics (TrK) is mainly due

to minor scattered Cu mineralizations along a basaltic bed and some minor stratiform mineralizations along some sedimentary beds (Panteleyev, personal communication, 1996).



(a)



(b)

Figure 2. Probability and box plots for a) median of Cu in stream sediment samples and b) $\log_{10}$ of median of Cu in stream sediment samples inside 609 geological polygons that have more than 5 samples in them.

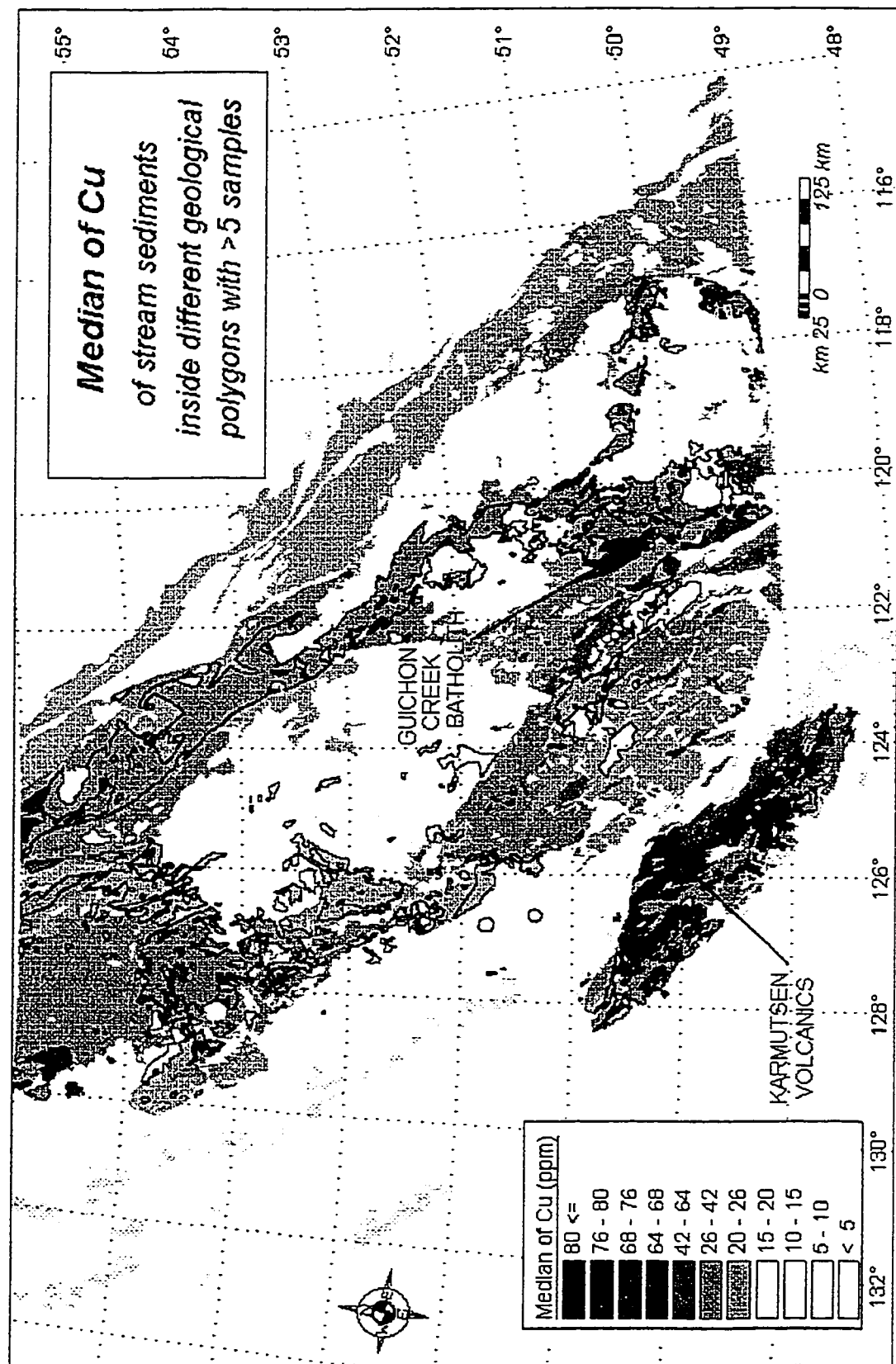


Figure 3. Median of Cu in stream sediments for all geological polygons with more than 5 samples in them. Boundaries of the study area are also shown with black lines.

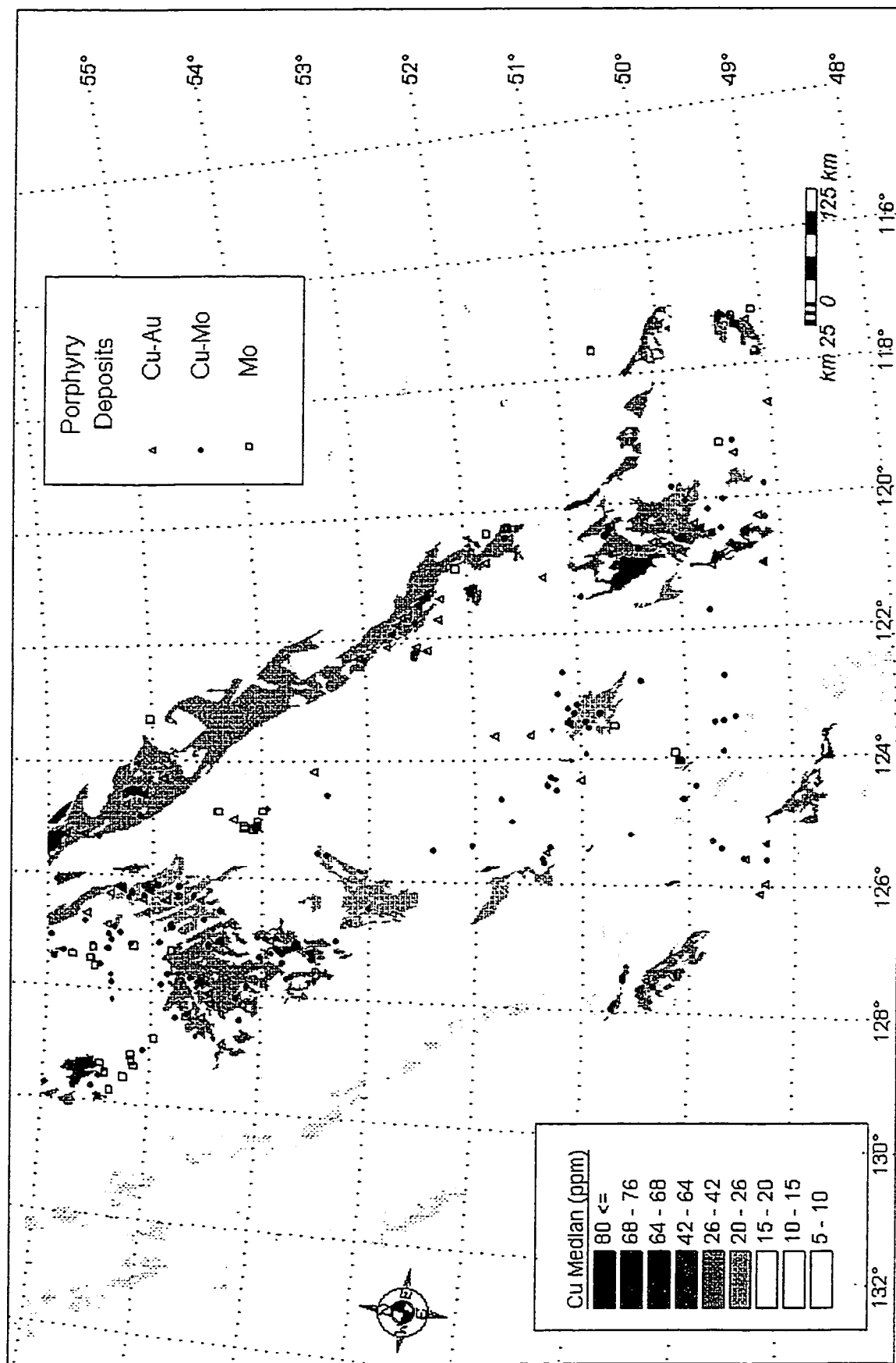


Figure 4. Median of Cu in stream sediments for all geological polygons with more than 5 samples within them.

Within most geological units of the study area, polygons that contain more known porphyry mineralizations have higher medians or generalised backgrounds for Cu. The Guichon Plutonic Suite (EJgG) is a good example. The Guichon Creek batholith of Guichon plutonic suite, which hosts the Highland Valley Cu deposits, is known as one of the highly mineralized plutons for porphyry deposits in the Canadian Cordillera (McMillan, personal communication, 1996). It has a higher median for Cu than other polygons of Guichon plutonic suite (EJgG) (Figure 2, 5). In the same plutonic suite, Wild Horse is known as an unmineralized pluton of porphyry deposit and as Figure 3 shows it has a low Cu median.

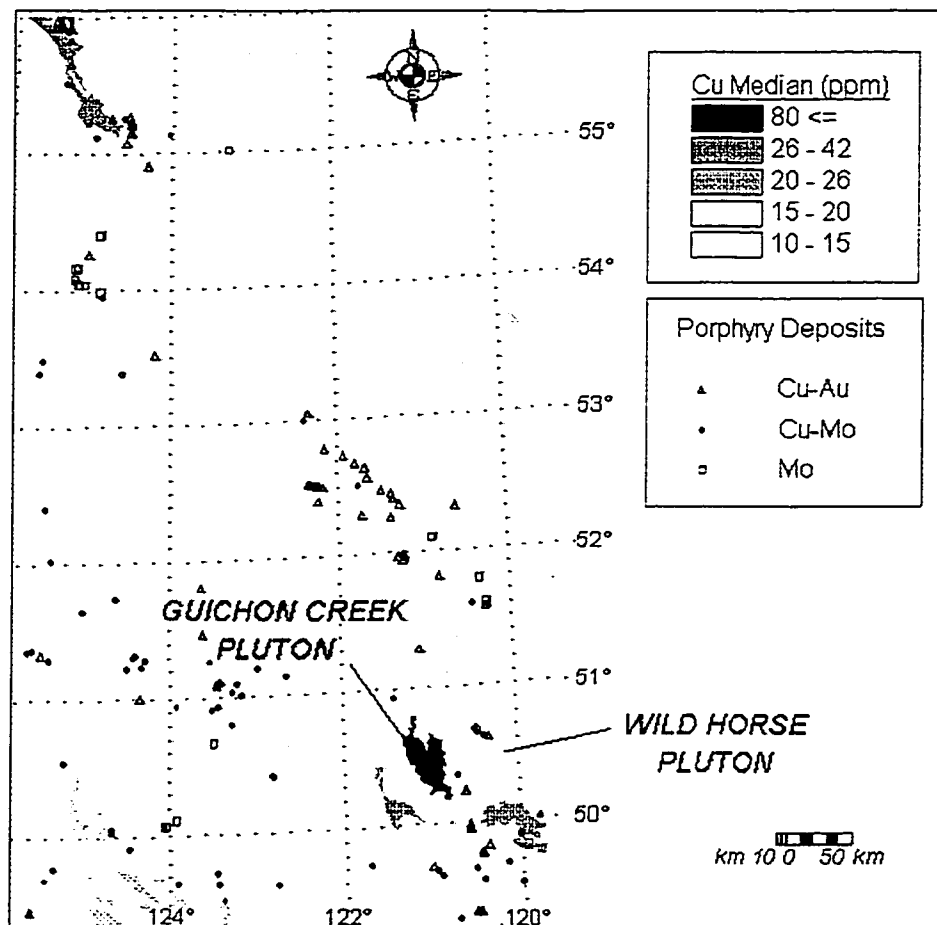


Figure 3. Median of Cu in stream sediments for Guichon Plutonic Suite (EJgG). Points represent known porphyry deposits. Guichon Creek pluton is known as a highly mineralized and Wild Horse as an unmineralized pluton of EJgG.

In Figure 6, the number of known porphyry deposits inside each class of median map is shown. As Figure 6 shows, for Guichon plutonic suite (EJgG), most of the known porphyry deposits are located inside the high classes of median of Cu.

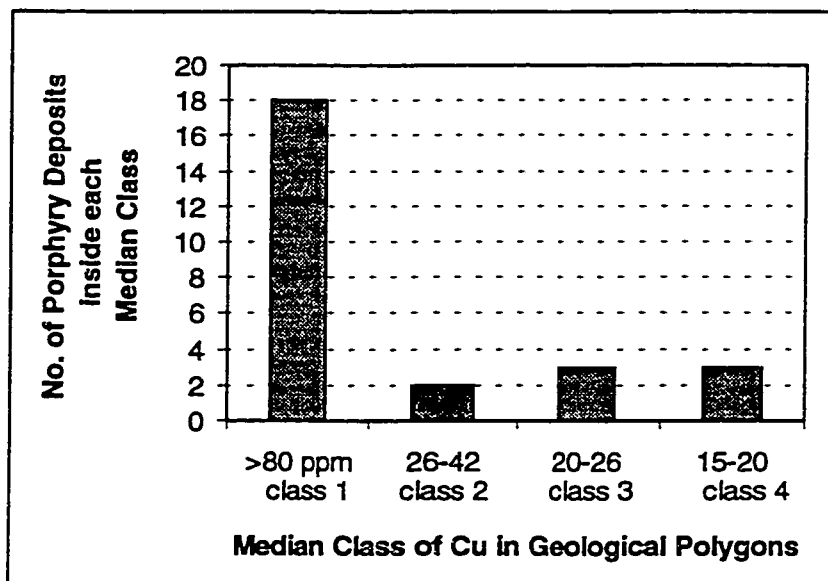


Figure 6. Comparison of medians and number of known porphyry deposits in each class of median map of Figure 5.

Unfortunately the number of geochemical samples inside different polygons of other plutonic units in the study area is small and in many cases, they do not contain more than 5 samples. Therefore with this condition, such comparison of medians in different polygons is not possible for all plutonic units.

5.2.2.2 HIGH VARIABILITY OF INDICATOR AND PATHFINDER ELEMENTS (Cu, Mo)

Higher than normal variability in the content of the indicator elements is a characteristic of many metallogenic provinces. This may be expressed qualitatively as geochemical "relief". Because of this variability, some systems of regional averaging may help to outline the limits of regional anomalies (Rose *et al.*, 1979).

The variance and coefficient of variation (CV) of indicator elements such as Cu and Mo were calculated to estimate this variability (Figure 7, 8, 10,11). A moving average method was used to calculate the variance and coefficient of variation (CV). In these maps, high amounts of variability usually correspond with the location of major areas of porphyry mineralizations. Slope maps were also generated to check the variability of Cu and Mo in stream sediment samples (Figure 9 and 12). These maps were generated by a moving average method with a circular moving cell with the radius of 14 km, 8 points as nearest neighbours were selected. For the decay rate of weighting function, 0.05 was selected. This is the same size used to create variance maps. Inside the moving cell, the slope of Cu in stream sediment samples was calculated. Similarly, a slope map was calculated for Mo in stream sediment samples.

Weights of evidence (Appendix D-1) were calculated to quantify the spatial association of porphyry deposits and classes of variance and coefficient of variation (CV) maps. Table 7 shows the calculated W^+ , W^- and C (contrast) for classes of the discussed maps and known porphyry deposits inside the study area.

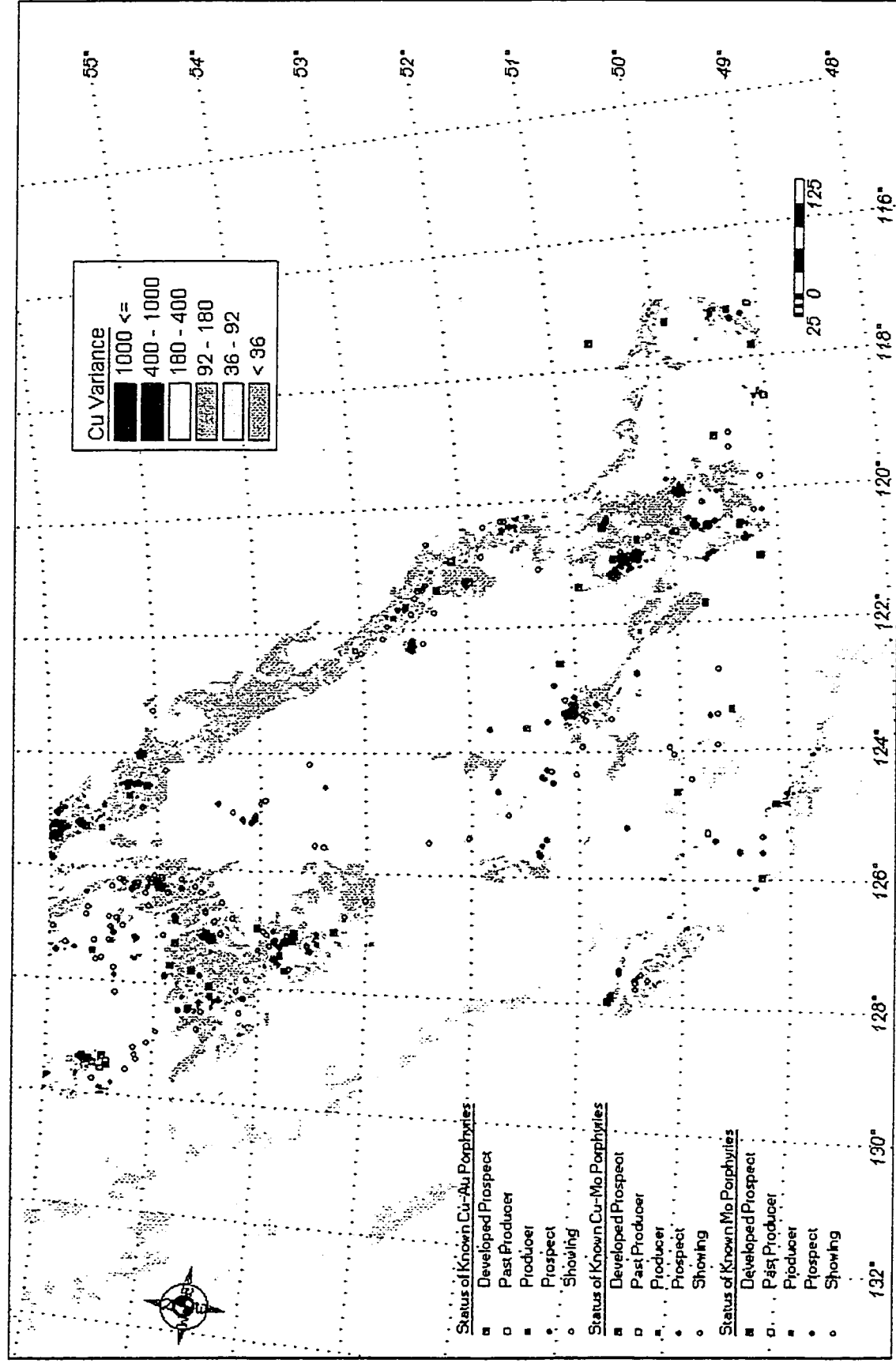


Figure 7. Variance of Cu in stream sediments inside the geological units of the study area calculated by moving average method.

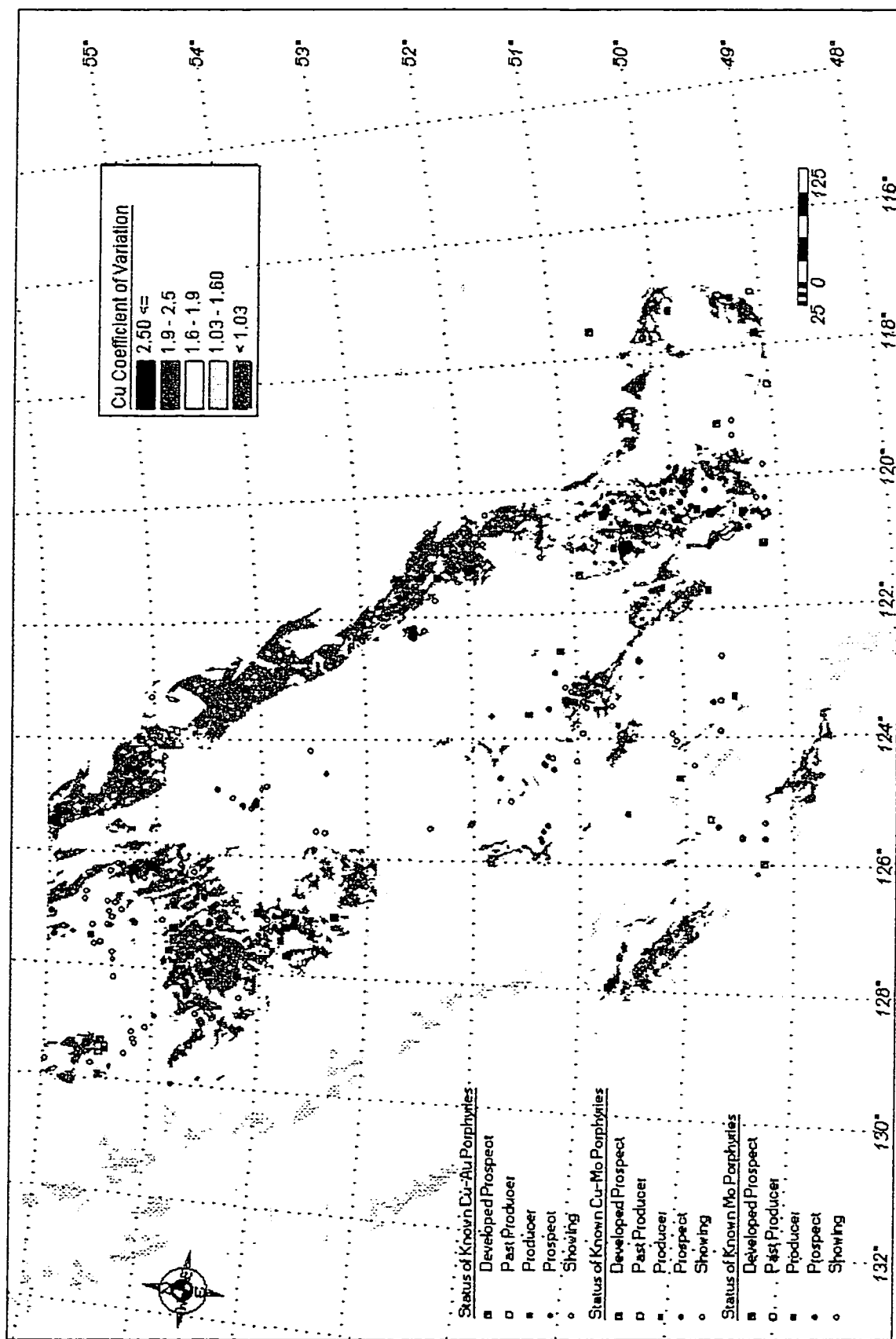


Figure 8. Coefficient of variation (CV) of Cu in stream sediments inside the geological units of the study area calculated by moving average method.

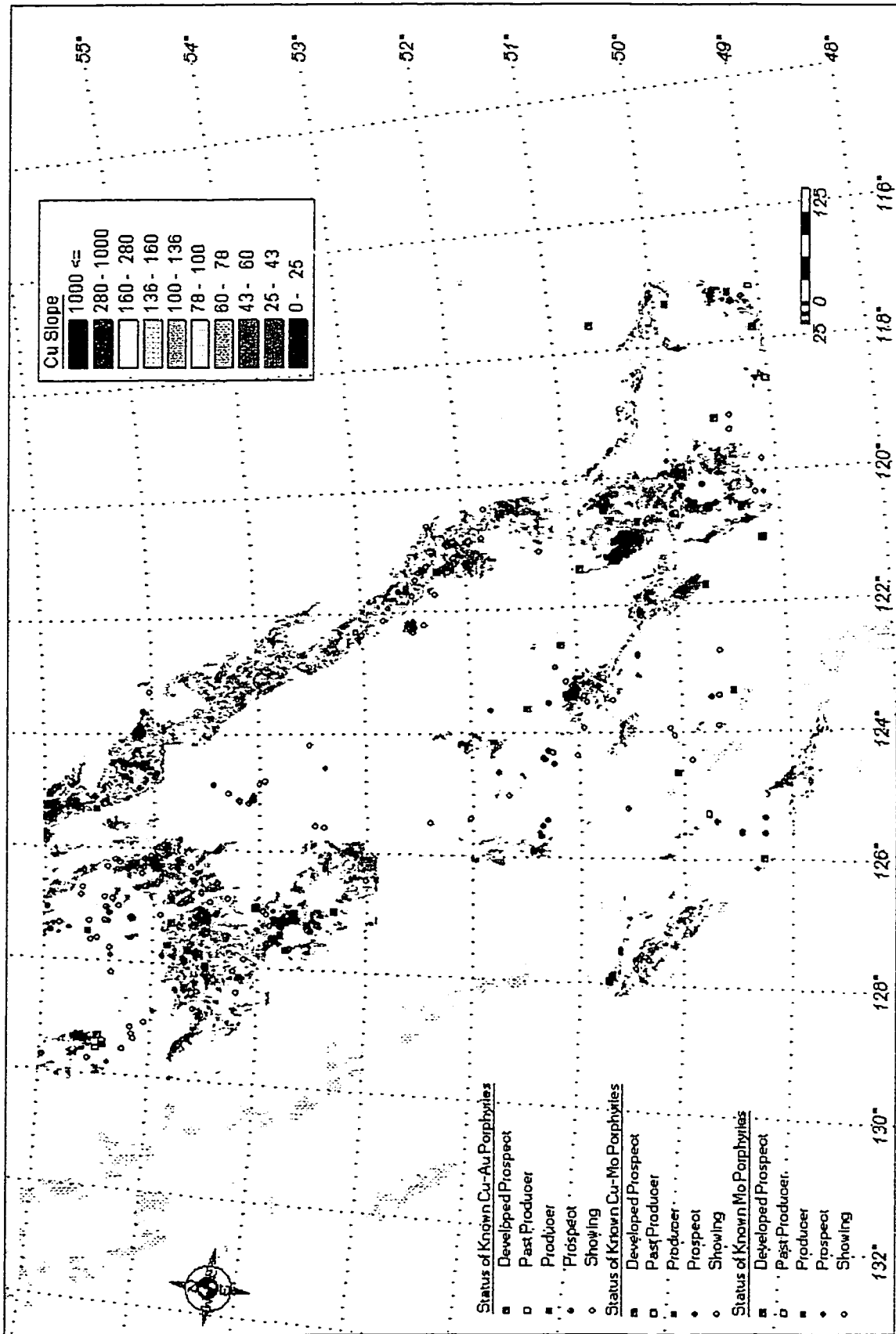


Figure 9. Slope of Cu in stream sediments inside the geological units of the study area, calculated by moving average method.

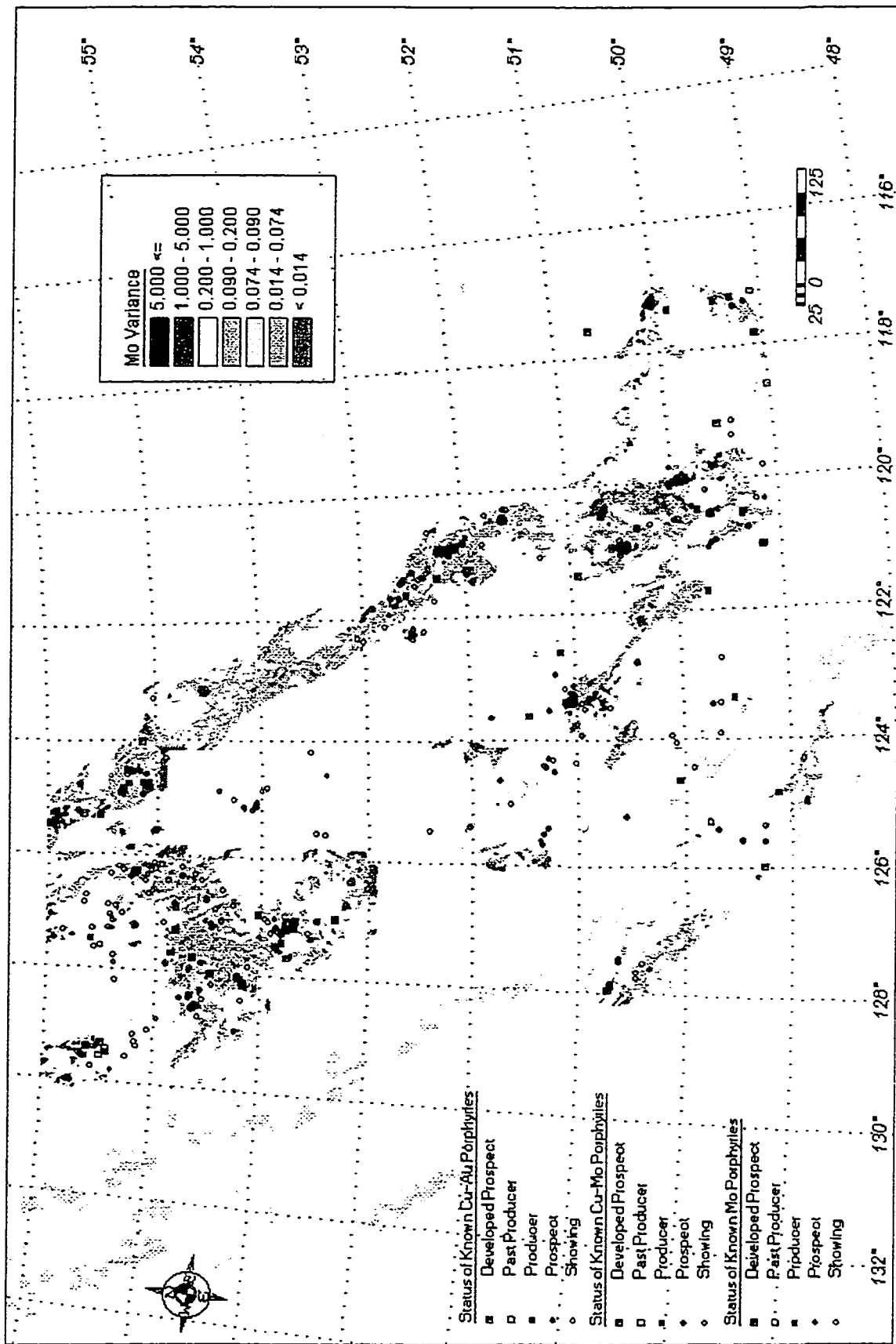


Figure 10. Variance of Mo in stream sediments inside the geological units of the study area calculated by moving average method.

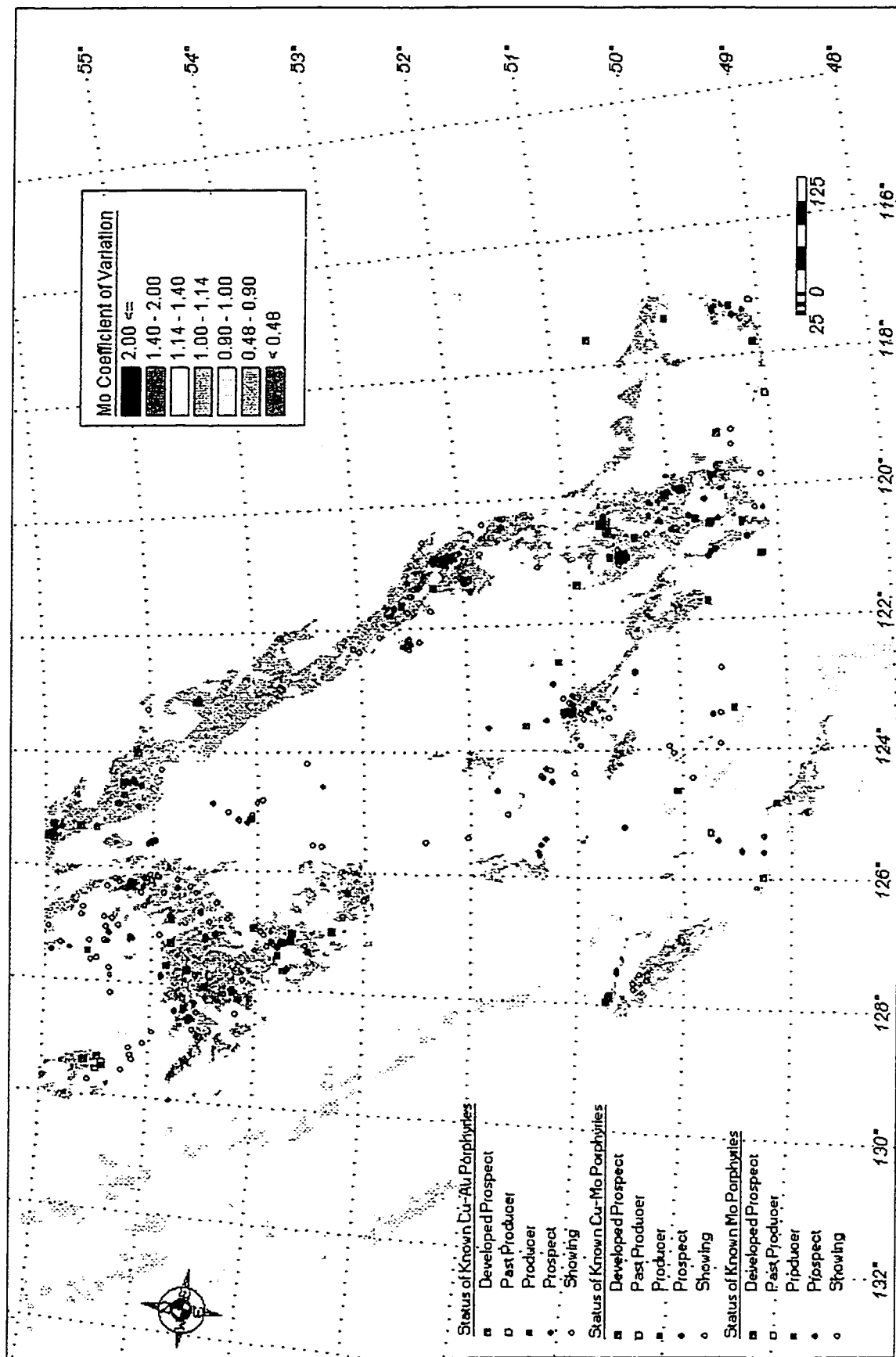


Figure 11. Coefficient of variation (CV) of Mo in stream sediments inside the geological units of the study area calculated by moving average method.

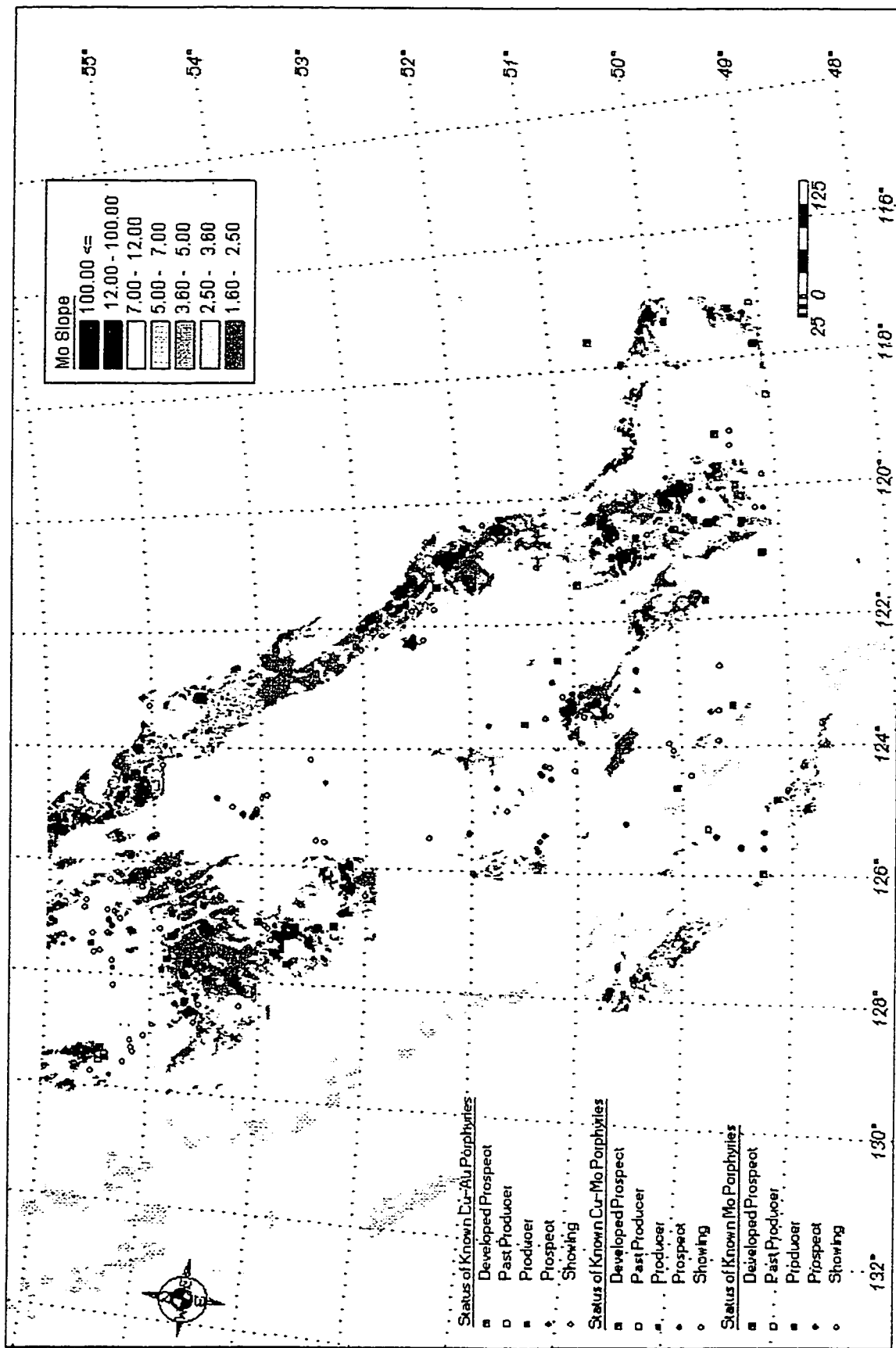


Figure 12. Slope of Mo in stream sediments inside the geological units of the study area calculated by moving average method.

Table 7. Results of weight of evidence analysis between the known porphyry deposits of different types located inside geological units of the study area, and maps of variance and coefficient of variation of Cu and Mo (Figure 7, 8, 10, 11).

(a) Between known porphyry deposits & variance of Cu map

Map class	Class area(km ²)	No. of deposits	W+	s(W+)	W-	s(W-)	C	s(C)	Stud(C)
1	2544	28	1.63	0.19	-0.14	0.08	1.76	0.21	8.57
2	2926	20	1.15	0.22	-0.08	0.08	1.23	0.24	5.19
3	5552	17	0.35	0.24	-0.03	0.08	0.38	0.26	1.47
4	7923	24	0.34	0.20	-0.04	0.08	0.38	0.22	1.72
5	16146	48	0.32	0.14	-0.10	0.09	0.41	0.17	2.44
6	47049	41	-0.91	0.16	0.59	0.09	-1.50	0.18	-8.42

(b) Between known porphyry deposits & coefficient of variation (CV) of Cu map

Map class	Class area(km ²)	No. of deposits	W+	s(W+)	W-	s(W-)	C	s(C)	Stud(C)
1	251	6	2.40	0.41	-0.03	0.08	2.43	0.42	5.86
2	1410	12	1.37	0.29	-0.05	0.08	1.42	0.30	4.75
3	1898	14	1.22	0.27	-0.06	0.08	1.28	0.28	4.61
4	14319	37	0.18	0.16	-0.04	0.08	0.22	0.18	1.18
5	64246	109	-0.24	0.10	0.58	0.12	-0.82	0.15	-5.34

(c) Between known porphyry deposits & variance of Mo map

Map class	Class area(km ²)	No. of deposits	W+	s(W+)	W-	s(W-)	C	s(C)	Stud(C)
1	2794	22	1.29	0.21	-0.10	0.08	1.39	0.23	6.09
2	5264	17	0.40	0.24	-0.03	0.08	0.43	0.26	1.70
3	14715	40	0.23	0.16	-0.06	0.09	0.28	0.18	1.58
4	12275	21	-0.24	0.22	0.04	0.08	-0.27	0.23	-1.17
5	3155	9	0.27	0.33	-0.01	0.08	0.29	0.34	0.84
6	33928	53	-0.33	0.14	0.18	0.09	-0.51	0.16	-3.09
7	9998	16	-0.30	0.25	0.04	0.08	-0.34	0.26	-1.29

(d) Between known porphyry deposits & coefficient of variation (CV) of Mo map

Map class	Class area(km ²)	No. of deposits	W+	s(W+)	W-	s(W-)	C	s(C)	Stud(C)
1	1761	20	1.63	0.22	-0.10	0.08	1.72	0.24	7.26
2	5206	23	0.68	0.21	-0.07	0.08	0.75	0.22	3.37
3	6862	23	0.41	0.21	-0.05	0.08	0.45	0.22	2.03
4	6285	14	0.00	0.27	0.00	0.08	0.00	0.28	-0.01
5	5916	18	0.31	0.24	-0.03	0.08	0.34	0.25	1.36
6	43036	65	-0.39	0.12	0.32	0.09	-0.71	0.16	-4.58
7	10648	15	-0.46	0.26	0.06	0.08	-0.52	0.27	-1.91

As Figure 13 shows, W^+ and C (contrast) have a decreasing trend from class 1, 2, 3 (High variances and CV) toward class 5 (low variances and CV). This indicates the spatial affinity of known porphyry deposits with high values of variance and coefficient of variation (CV) of Cu and Mo. Class 1, 2, and 3 of variance maps of Cu and Mo contain more porphyry deposits than the same classes of coefficient of variation (CV) maps of Cu and Mo (Table 7). Here, variance maps of Cu and Mo were selected as an indicator of geochemical provinces.

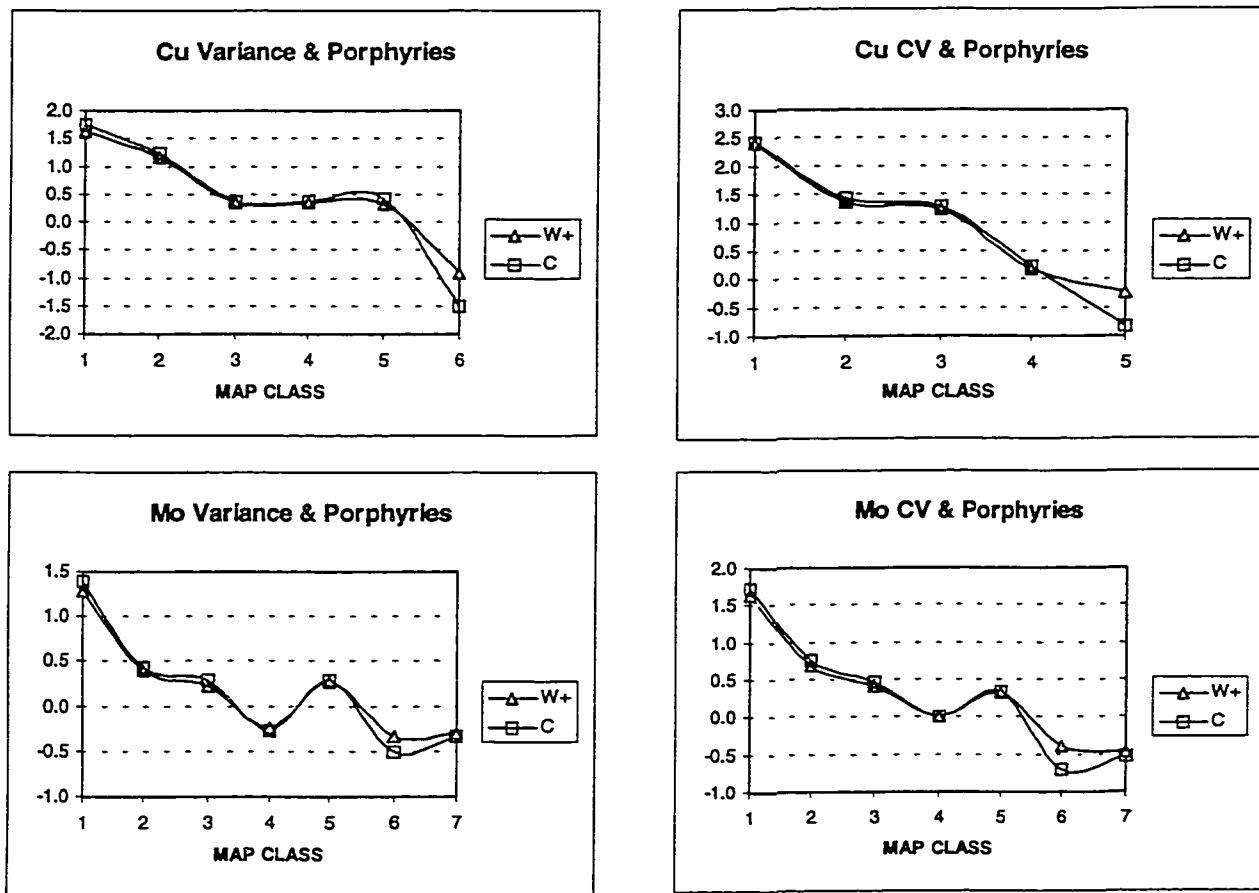


Figure 13. Decrease of W^+ and C (contrast) with lower values of variance and coefficient of variation (CV) of Cu and Mo, indicating association of known porphyry deposits with top classes (high values) of variance and coefficient of variation (CV) of Cu and Mo in stream sediment samples.

5.3 MULTIVARIATE ANALYSIS

5.3.1 INTRODUCTION

An interpretation of the systematic relationships of 20 elements is almost impossible without applying some form of dimension-reducing technique. Multivariate statistics helps to summarise data and reduce the number of variables necessary to describe them. These techniques look at the pattern of relationships between several variables simultaneously. The outcome of these dimension-reducing techniques usually provides significantly fewer, new variables, which describe variation and can be tied to specific geochemical/geological processes. Multivariate data analysis techniques applied to geochemical data, such as principal component analysis, and discriminant analysis, provide a numerical and graphical means through which the relationships of the elements and samples can be studied. These methods were used here to find new variables that can be used as geochemical indicators of regions with porphyry mineralization.

The use of robust estimates for the calculations assists significantly in assessing multielement relationships. Otherwise, the presence of outliers can distort the resulting linear relationships that are obtained in methods such as principal components analysis (Grunsky, 1991).

The mineralized geological units and in general geochemical provinces are usually associated with multielement geochemical signatures that are atypical relative to regional background variation through depleted or increased abundance of a particular suite of elements. Usually certain kinds of mineralization have a specific association of elements. These known associations may be used as an exploration tool. By considering the geological factors for selecting the data set or sampling, multivariate techniques have the ability to show the

existing association of elements (samples) related to a certain area. A brief explanation is presented for each of the multivariate analysis techniques used in this chapter.

5.3.2 PRINCIPAL COMPONENTS AND FACTOR ANALYSIS

If N different elements are analysed for geochemical samples, to plot the location of a sample with all the analytical results of N elements, a mathematically N dimensional space is needed. A simple example is a 3 dimensional space, assuming that we have only 3 elements for each sample. In such a case the x , y , and z co-ordinates of each sample can represent the amount of 3 different elements. For more than 3 dimensions, although geometrically not possible to plot, a mathematical N dimensional space can be defined. Principal component analysis (PCA), at its simplest, can be regarded simply as a technique for reducing multivariate data into fewer dimensions (Brower *et al.* 1979).

PCA transforms an original set of N variables into a new set of N principal components, which are orthogonal to each other (uncorrelated). The new co-ordinate system (principal components) is related to the original one through a series of linear transform equations. Although there are as many principal components as variables, the transformation is such that usually the first principal component is selected to maximise the explained variance, and succeeding principal components maximise the residual variance at each step. So the first few principal components invariably account for a large proportion of the total variance. PCA is perfectly general, it tests no hypotheses and has no underlying model. It is merely another form of data transformation (Rock, 1988).

PCA is performed by extracting eigenvectors and eigenvalues from correlation matrix between the original variables. The intention underlying the use of principal components in exploration geochemistry has generally been to separate the element associations inherent in

the structure of the correlation matrix into a number of groups of elements that together account for the greater part of the observed variability of the original data (Howarth, 1983).

In the PCA method, reduction of the number of variables necessary to describe the observed variations within a set of data is achieved by finding linear combinations of the variables (components) that best describe the distribution of the data (Grunsky, 1991). Ideally, each component can be interpreted as describing a geological process such as different effects of rock type, differentiation, alteration, mineralization,.....etc. By interpreting and identifying the geological meaning of the calculated factors, usually it is possible to calculate factor scores for each geochemical sample. If a certain factor represent the interested geological phenomenon, then creating a map for the calculated scores of that factor can be mapped to show its variation over the study area. Such maps can be very instructive in geochemical exploration.

The original principal components may be rotated while retaining their orthogonal relationships until the loadings for the elements are maximised in contrast. The intention is to make high loadings tend to +1 or -1 and low ones to 0.0, to facilitate interpretation with respect to the original variables (Howarth, 1983). In this study, extreme outliers for each element were removed, a logarithmic (base 10) transformation was applied, and variable correlation matrix was used in the factor analysis. The calculated principal components were rotated to facilitate the interpretation of the different subsets of data discussed here. Factor analysis was performed to group the minor element data into the principal elemental associations that best account for the variability of the data and to find out if it matched with certain mineralized and/or unmineralized areas.

5.3.3 DISCRIMINANT ANALYSIS

Discriminant analysis is also a multivariate statistical method, but the a linear combination is calculated to maximise the separating of groups of samples. Thus if we have two groups A , and B and based on this, two questions can be answered: (1) How efficiently can the groups be distinguished on available criteria, i.e. how different are they overall? and (2) assuming that A , and B are different, to which of these groups does another, 'unknown', single object X (sample) most likely belong? (Rock, 1988).

In discriminant analysis, a linear combination of the independent variables is formed and serves as the basis for assigning cases into A and B groups. Thus, information contained in multiple independent variables is summarised as a single index (Z). The weights are estimated so that they result in the best separation between the groups. The discriminant function is usually a linear combination of variables like:

$$Z = \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n$$

Coefficients $\beta_1, \beta_2, \dots$ are called *discriminant (canonical) coefficients* and are estimated from the data. The value of Z for an object (sample) is called *discriminant (canonical) score*. In this way each sample can be given a single Z score resulting from application of the above equation to the object (sample)'s X_i values. If a linear discriminant function is to distinguish samples related to group A from those related to B , the 2 groups must differ in their Z values.

Combining all the Z scores for each group yields a mean scores (centroid), $\bar{Z}_A$ and $\bar{Z}_B$ and a value halfway between these, Z_0 , is conventionally taken as the 'cut-off' criterion between the 2 groups (Rock, 1988). In a 100% efficient discriminant analysis, all Z values for group 1 are $> Z_0$, and for group 2 they are $< Z_0$. The efficiency of the analysis can thus be measured by the total proportion of objects, which satisfy these relationships. For example an efficiency of 90% means 1 object in 10 is misclassified.

5.3.4 APPLICATION OF MULTIVARIATE ANALYSIS TECHNIQUES ON GEOCHEMICAL DATA OF GEOLOGICAL UNITS OF THE STUDY AREA

5.3.4.1 FACTOR ANALYSIS ON GEOCHEMICAL DATA OF GUICHON PLUTONIC SUITE (EJgG) FOR SERIES OF (Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, pH, F in water, U in water)

Stream sediment and water samples located inside the Guichon plutonic suite (EJgG) were extracted from the main data file giving a total of 518 samples. Thirteen elements were used in the factor analysis, namely Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, from stream sediment data and pH, F in water (F-wat) and U in water (U-wat) from water samples. After removing extreme outliers 473 samples were entered into the analysis. The data were first $\log_{10}$ transformed except for the pH, which has a close to normal distribution, and then standardised z scores of these $\log_{10}$ values were used. Principal component analysis with correlation matrix was applied here for extracting the factors and equimax method was used for rotation. Table 8 shows the rotated factor solution for the first five factors. The element loadings on the factors vary from +1 through 0 to -1. The element loadings being a measure of the strength of element association in a particular factor (Armour-Brown *et al.*, 1970). Of thirteen existing factors (the number of variables) only the first five have eigenvalues greater than 1. This factor analysis showed that the following associations exist between elements:

Fe-Mn-Co, (F-wat)-(U-wat)-pH, Zn-Cu, U-Mo- (Ni, but in opposite direction), and Pb-Hg.

Table 8. Rotated factor loadings matrix.

	Factor1	Factor2	Factor3	Factor4	Factor5
Fe	0.84	-0.13	0.24	0.07	0.01
Mn	0.83	0.01	-0.01	0.08	0.13
Co	0.68	-0.08	0.42	-0.37	0.10
F-Wat	-0.06	0.83	-0.08	-0.05	0.04
U-Wat	-0.12	0.83	-0.05	0.17	0.03
pH	0.04	0.78	0.17	-0.25	-0.13
Zn	0.12	0.10	0.79	0.06	0.09
Cu	0.25	-0.08	0.74	0.02	0.06
U	0.02	-0.02	0.05	0.79	0.25
Mo	0.21	-0.13	0.43	0.59	-0.02
Ni	0.35	-0.06	0.36	-0.56	0.40
Hg	0.14	-0.05	-0.08	0.03	0.88
Pb	-0.12	0.08	0.49	0.25	0.62

The numbers in Table 8 are shown graphically in Figure 15 by bar charts for each of the factor loadings. Characteristics of all the 13 extracted factors are shown in Table 9. The proportion of the overall data variability contained in each factor is expressed by the magnitude of the eigenvalues (Armour-Brown *et al.*, 1970). In the factor analysis, the scree plot displays eigenvalues for different factors (Figure 14).

Table 9. Characteristics of 13 possible factors.

Factor	Eigenvalue	% of Var	Cum. %
1	3.29	25.3	25.3
2	2.05	15.7	41
3	1.76	13.5	54.5
4	1.13	8.7	63.2
5	1.01	7.8	71
6	0.77	5.9	77
7	0.71	5.5	82.4
8	0.51	4	86.4
9	0.45	3.4	89.8
10	0.43	3.3	93.2
11	0.35	2.7	95.9
12	0.32	2.4	98.3
13	0.22	1.7	100

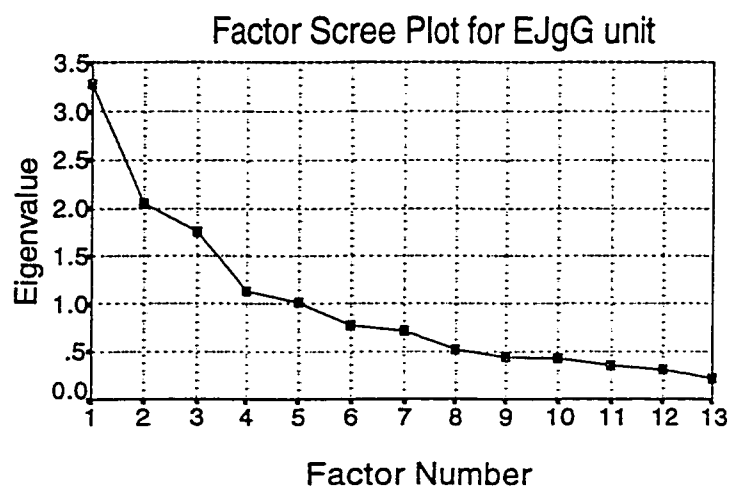


Figure 14. Scree plot for 13 possible factors.

The first five factors account for a total of 71% of the data variability and all the last 8 factors for the remaining percentage of total variability (29%). Association of Fe-Mn-Co in factor 1 reflects the association of Fe and Mn oxides and adsorption of metallic ions in the secondary

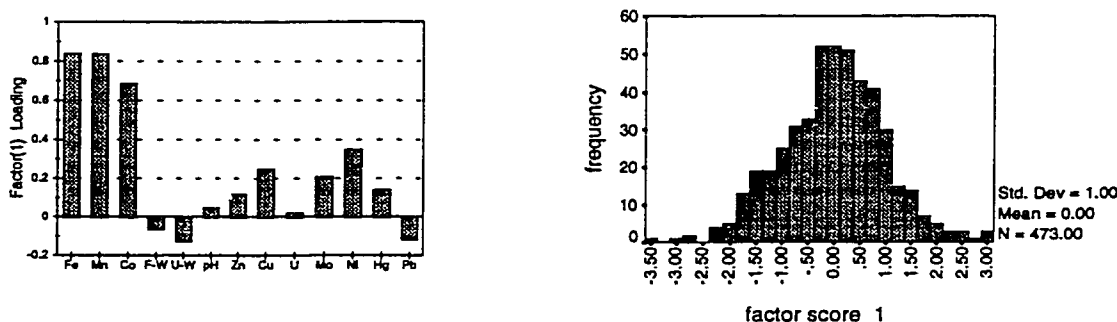


Figure 15. Factor loadings and histogram for scores of factor 1.

environments by oxides of Fe and Mn. Presence of Co in this group is due to its strong tendency of absorption and coprecipitation with Fe and Mn oxides (Levinson, 1980, Jenne, 1968). Nickel with 0.35 and Cu with 0.25 as their loadings also show some minor associations with factor 1. This is probably due to the adsorption by Fe and Mn oxides. Factor 1 accounts for 25.3% of total variability.

The second factor with 15.7% of total variability represents (F-wat)-(U-wat)-pH assemblage and can reflect changes in the pH of water and consequently variations of U and F in water (F-wat) that are both pH dependent. The natural solubility of U in alkaline waters increases because of formation of uranyl complexes (Cameron, 1980) therefore the amount of U in water (U-wat) is correlated to the pH values.

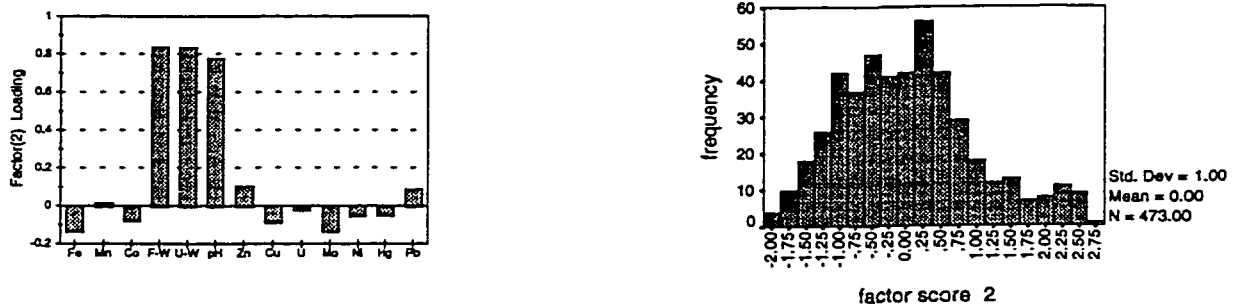


Figure 16. Factor loadings and histogram for scores of factor 2.

The third factor accounts for 13.5% of the total variation and represents Zn-Cu association. This factor together with the fourth factor (with 8.7% of the total variation) could be considered as indicators of mineralized areas inside Guichon plutonic suite (EJgG). Since Cu itself is an indicator element for porphyry mineralizations and increases near the mineralized areas, factor 3 that represent Cu-Zn association could also be used as an indicator.

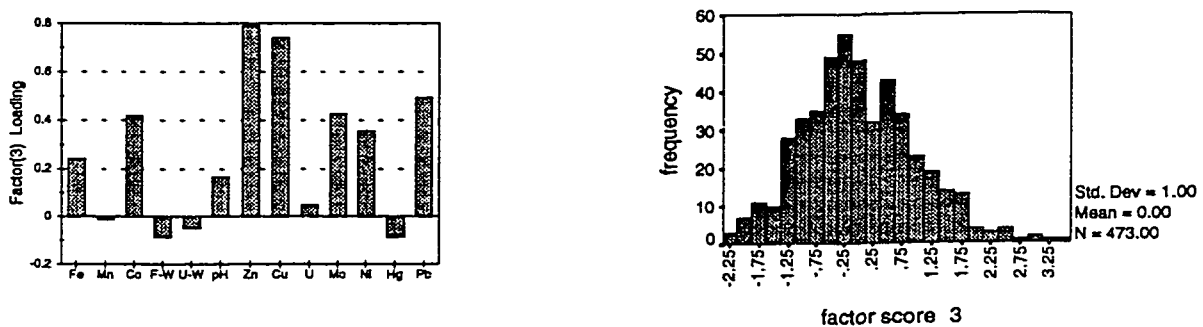


Figure 17. Factor loadings and histogram for scores of factor 3.

Copper is either medium or high mobile in oxidising and acid environments that usually exist near the mineralized zones. In the neutral to alkaline environments, Mo is more mobile

(Cameron, 1986, Levinson, 1980). This fact has a great practical significance in geochemical exploration for those porphyry deposits, which contain Mo. This mobility makes Mo a pathfinder element for such deposits (Levinson, 1980).

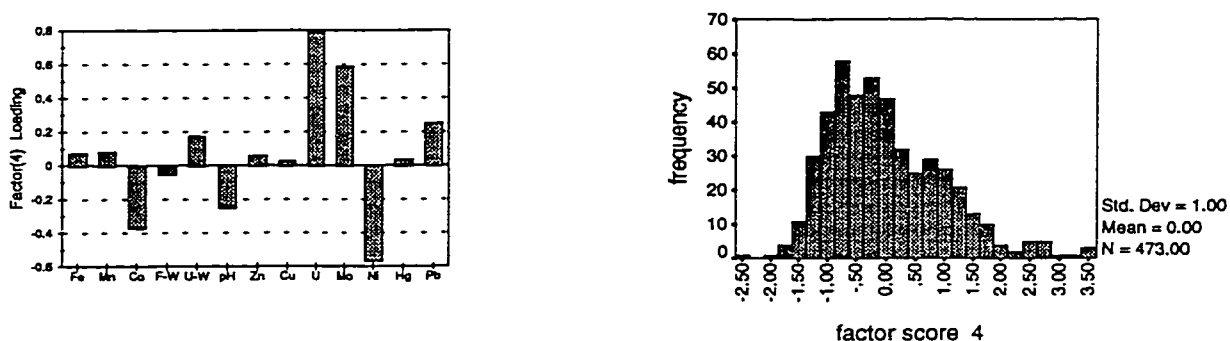


Figure 18. Factor loadings and histogram for scores of factor 4.

Factor 4 representing association of U-Mo in stream sediments could be used as an indicator of porphyry mineralizations. As Figure 18 shows, its factor scores have also a positively skewed distribution. The fifth factor represents Pb-Hg correlation, which most likely reflects the backgrounds for these elements.

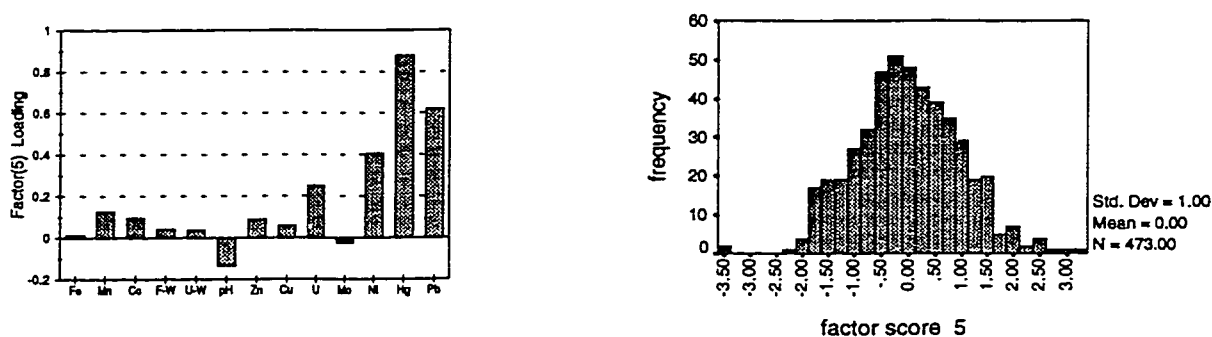


Figure 19. Factor loadings and histogram for scores of factor 5.

In addition, maps were created by a moving average method to see the distribution of scores of samples for factor 3 and 4 in the whole Guichon plutonic suite (EJgG), (Figure 21, Figure 22 and Figure 23). Fourteen km was selected for the radius of the moving cell with maximum 8 points for consideration and with decay rate of 0.05 for weighting function inside the moving cell.

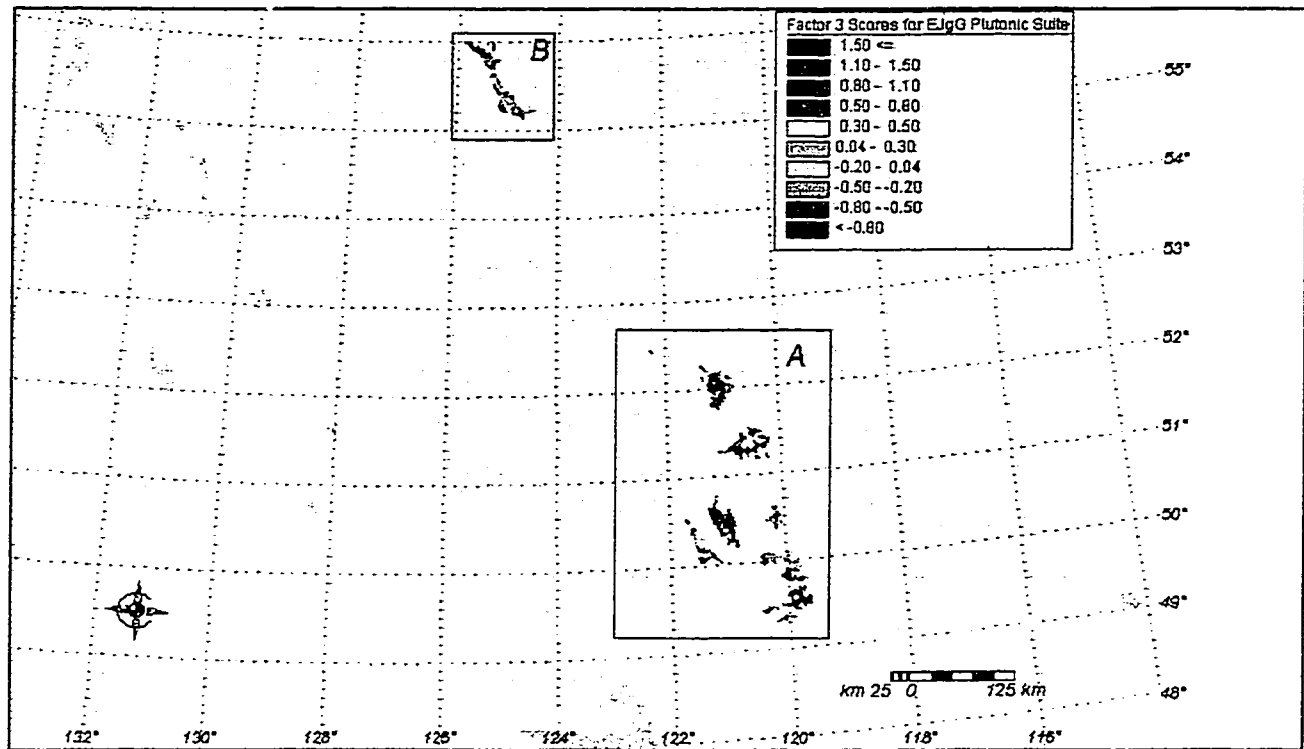


Figure 21. Factor 3 (Cu-Zn) scores calculated for the NGR samples located inside the Guichon plutonic suite (EJgG). Areas A and B are zoomed in the next figures for details.

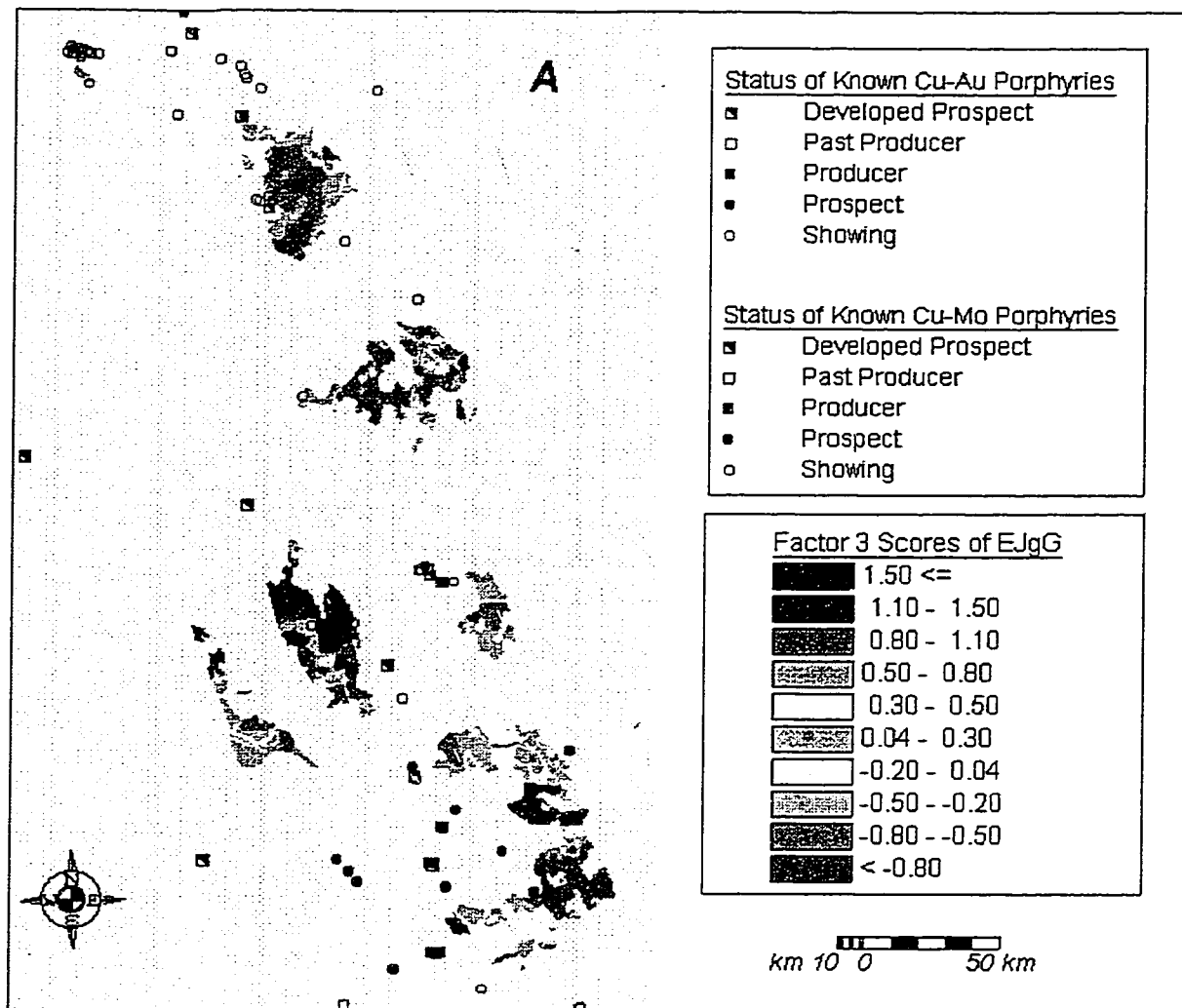
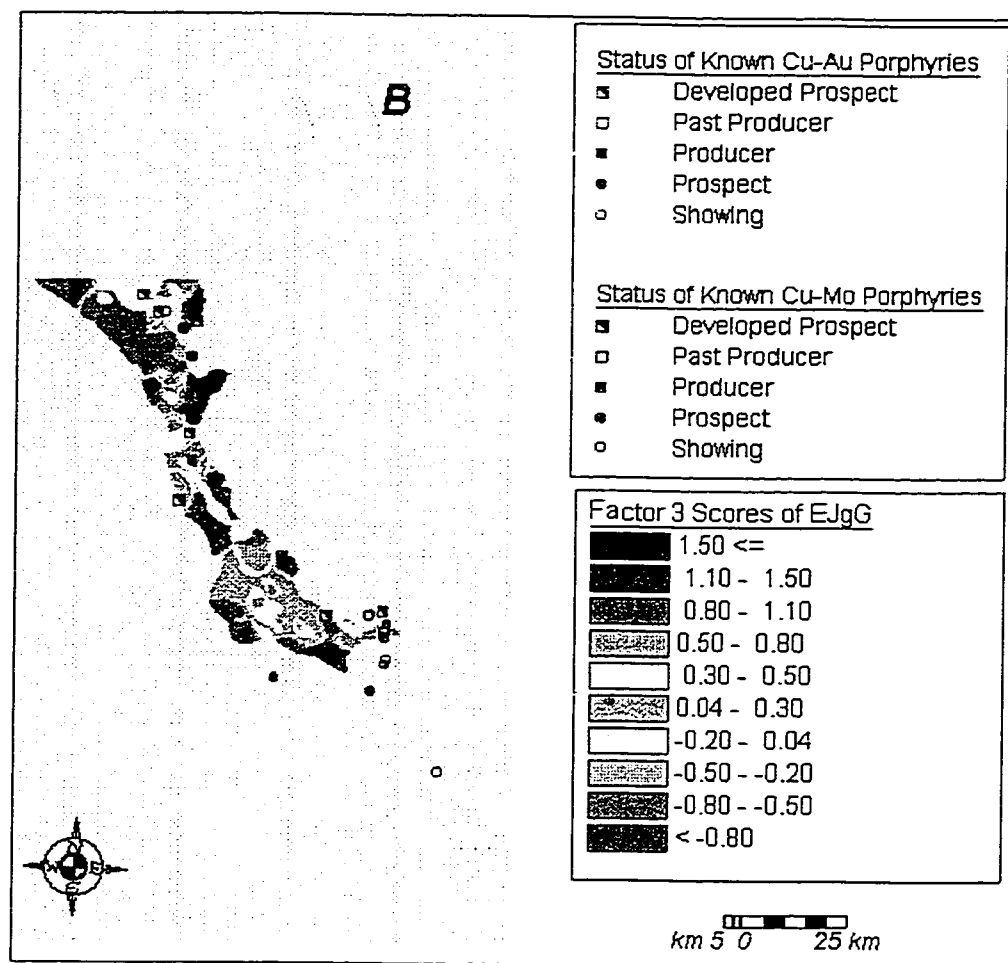


Figure 22. Factor 3 (Cu-Zn) scores in Guichon Plutonic Suite (EJgG) in areas A and B of Figure 21 with known porphyry

porphyries

porphyries

G



3 of Figure 21 with known porphyry Cu-Mo and Cu-Au deposits. 379 samples are located in part A and 94 samples in part B.

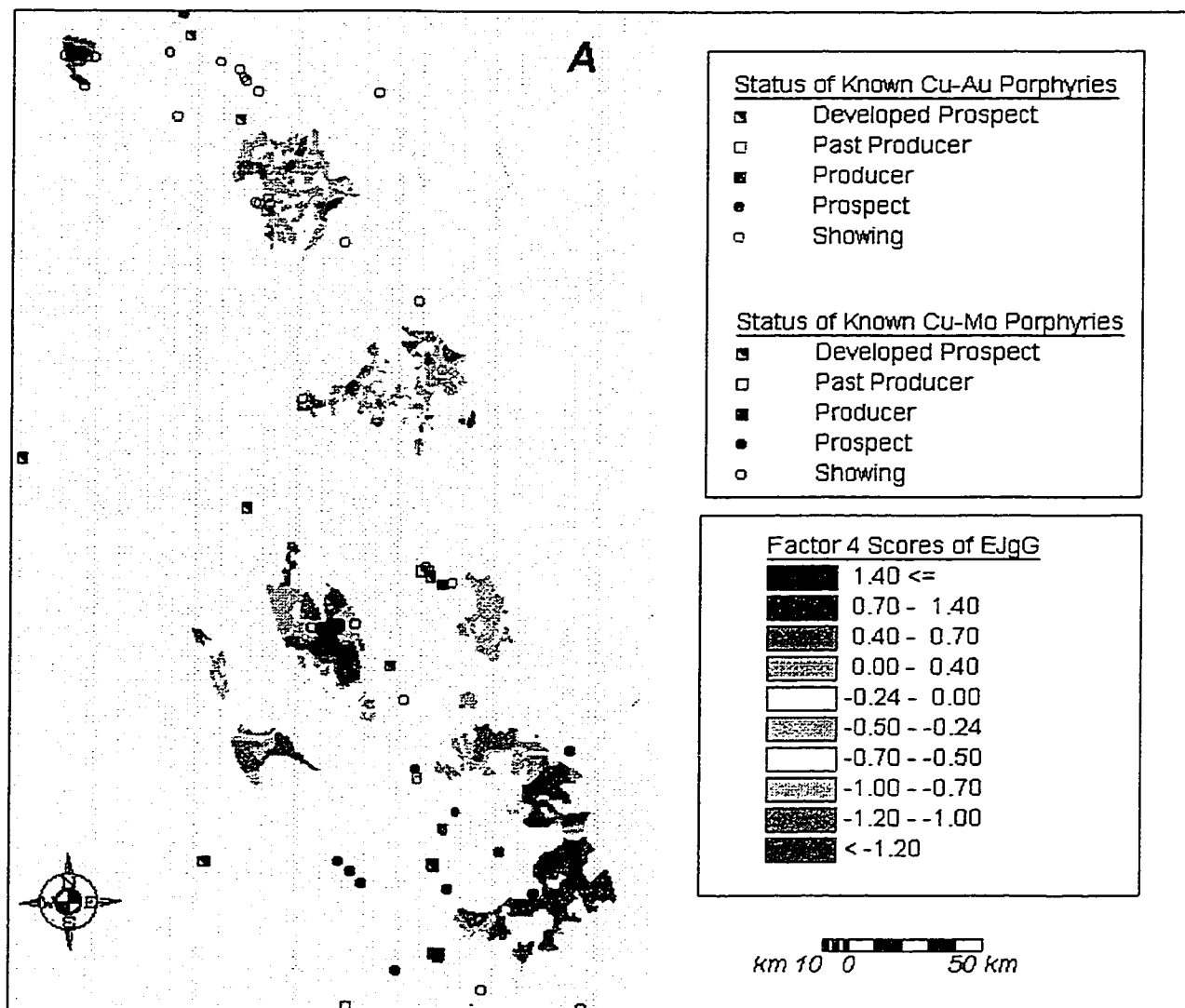
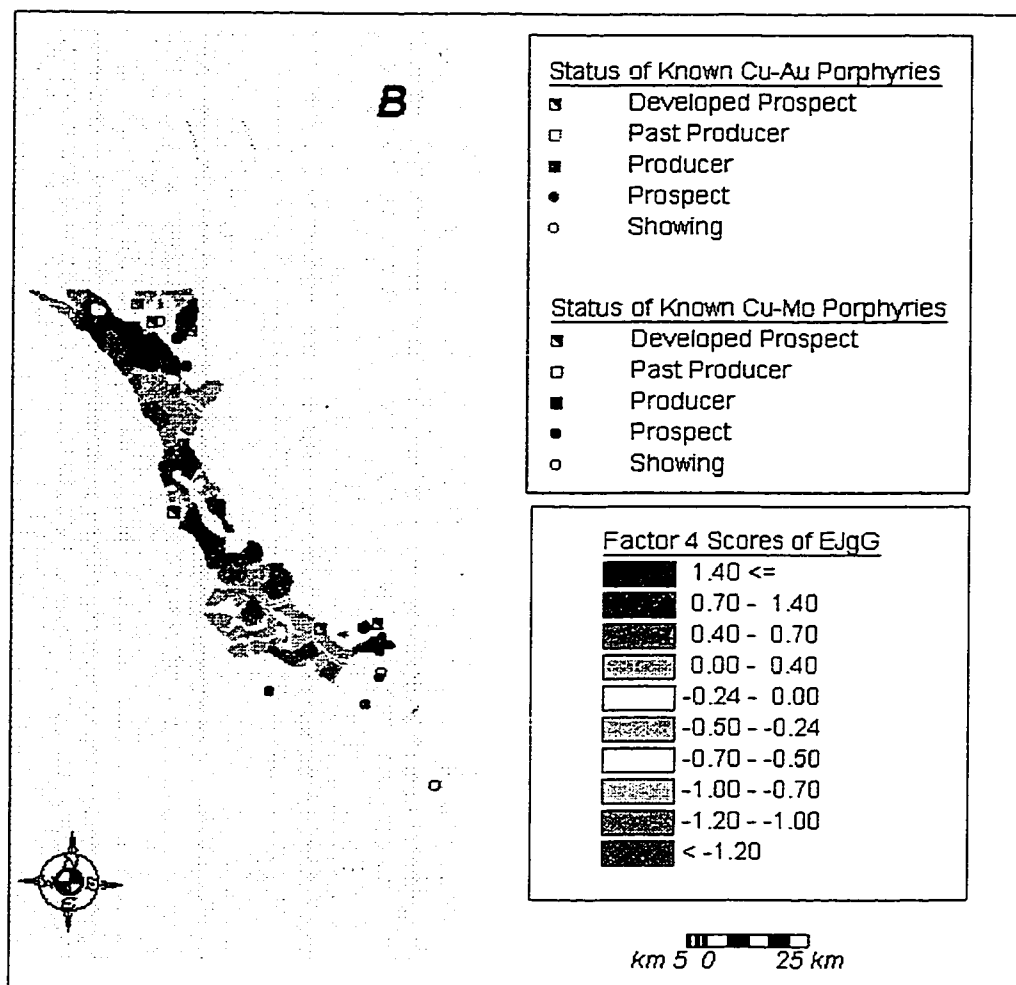


Figure 23. Factor 4 (U-Mo) scores in Guichon Plutonic Suite (EJgG) in areas A & B of Figure 21 with known porphyry

Porphyries
ect

Porphyries
ect

gG



f Figure 21 with known porphyry Cu-Mo and Cu-Au deposits. 379 samples are located in part A and 94 samples in part B.

As these maps show, in most cases, locations of the known porphyry deposits match with the high classes and values of scores of these factors. These factor scores are used in the final chapter as indicators of porphyry mineralizations inside the Guichon plutonic suite (EJgG).

5.3.4.2 SERIES OF (As, Au, Ba, Br, Ce, Cr, Cs, Hf, La, Lu, Na, Rb, Sc, Sm, Ta, Th, U, Yb, Zr)

For some NGR map sheets, some new analyses were done by the method of neutron activation on samples already collected for NGR by British Columbia Geological Survey (BCGS). The analyses include measurements of new elements such as As, Au, Ba, Br, Ce, Cr, Cs, Hf, La, Lu, Na, Rb, Sc, Sm, Ta, Th, U, Yb, Zr. Unfortunately, the analysis results of these elements were not available for all the map sheets covering the Guichon plutonic suite (EJgG). Of 518 samples inside the Guichon plutonic suite (EJgG), 256 samples have analyses for these elements. After separating extreme outliers, 231 samples were used for multivariate analyses. These elements were selected as the second series of elements for the multivariate analysis. Extreme outliers were also removed for these elements before starting the multivariate analysis. The data was then $\log_{10}$ transformed except for Ba, Na, and Rb, which have normal distributions (Appendix A-1). Principal component analysis of the correlation matrix was applied here for extracting the principal components and an oblique (non-orthogonal) method was used for rotation that gave a better result than initial orthogonal result. Table 10 shows rotated factor solution for the first four factors. Of nineteen existing factors (the number of variables) only the first four factors were considered significant having eigenvalues greater than 1. They account for 69.3% of the total variability of the data.

Table 10. Factor loadings matrix after oblique rotation.

	<i>Dimension 1</i>	<i>Dimension 2</i>	<i>Dimension 3</i>
Ba	0.34	1.47	1.32
As	-1.95	0.70	0.25
Au	-1.20	0.67	-0.88
Br	-2.06	-0.54	-1.31
Ce	1.16	-0.74	-0.10
Cr	-1.60	-0.62	1.61
Cs	-0.05	1.51	-0.57
Hf	1.04	-0.45	0.81
La	1.12	-0.61	-0.45
Mo	-0.92	1.09	-1.20
Sc	-1.37	-0.83	1.08
Sm	0.70	-0.92	-0.11
Ta	1.37	-0.60	-0.13
Th	1.07	-0.44	-0.49
U	0.34	-0.34	-1.48
Yb	-0.82	-1.39	0.32
Zr	0.97	-0.81	0.35
Rb	1.06	1.16	0.11
Na	0.80	1.68	0.86

Factor 1 represents the association of REE elements and elements such as Zr, Hf and U, Th. These are granophile elements (Strong, 1981). They generally do not enter into the structure of rock-forming silicates during crystallisation of magma and tend to be preferentially concentrated in the residual fluids high in water, volatiles and silica (Levinson, 1980). Therefore quartz-rich leucocratic granitoids are enriched in granophile elements (Strong, 1981). Factor 1 may represent quartz-rich phases of Guichon plutonic suite. As Table 11 shows, factor 1 alone accounts for 36.6% of the total variability of the data.

Factor 2 can represent major element associations. The element pairs K-Rb have similar ionic radii, electronegativities, and ionisation potential and therefore Rb is incorporated in K minerals (Plimer and Elliott, 1979). Referring to Table 10 for factor 2, Rb is in close association with Na and Ba. Unfortunately K was not analysed in the new analysis but by considering the genetically close association of Rb and K, factor 2 is interpreted as the more alkalic phases of EJgG plutonic suite. Factor 2 accounts for 13.4% of the total variability.

Factor 3, with 10.5% of the total variability, shows the association of As, Mo, Au and Cs. Molybdenum and Au are known as well known pathfinder elements for porphyry deposits (Rose, 1979, Levinson, 1980). Caesium is an element that could be concentrated in biotite in granitoid rocks (Beus and Grigorian, 1977). Its association with other elements of factor 3 can be related to the biotite of the mineralized plutonic bodies. Arsenic usually is a pathfinder for sulphides (Hg-Sb-Ag-Zn-Pb) and epithermal mineralizations (Rose, 1979, Levinson, 1980). It can be associated with porphyry deposits in the lower temperatures of mineralizations or higher levels of deposits (Beus and Grigorian, 1977, Jensen and Bateman, 1979). In consequence, factor 3 is considered here as an indicator of mineralization.

Factor 4, with 8.9% of the total variability, shows the association of Cr and Sc. This association is thought to represent background values of Cr and Sc in the plutonic rocks of Guichon plutonic suite (EJgG). The scree plot of Figure 24 shows the sudden decrease of loadings of the first four factors. Based on the eigenvalues, only the first fourth factors are considered here as significant.

Table 11. Characteristics of 13 possible factors.

	<i>Dimension 1</i>	<i>Dimension 2</i>	<i>Dimension 3</i>
<i>Ba</i>	0.34	1.47	1.32
<i>As</i>	-1.95	0.70	0.25
<i>Au</i>	-1.20	0.67	-0.88
<i>Br</i>	-2.06	-0.54	-1.31
<i>Ce</i>	1.16	-0.74	-0.10
<i>Cr</i>	-1.60	-0.62	1.61
<i>Cs</i>	-0.05	1.51	-0.57
<i>Hf</i>	1.04	-0.45	0.81
<i>La</i>	1.12	-0.61	-0.45
<i>Mo</i>	-0.92	1.09	-1.20
<i>Sc</i>	-1.37	-0.83	1.08
<i>Sm</i>	0.70	-0.92	-0.11
<i>Ta</i>	1.37	-0.60	-0.13
<i>Th</i>	1.07	-0.44	-0.49
<i>U</i>	0.34	-0.34	-1.48
<i>Yb</i>	-0.82	-1.39	0.32
<i>Zr</i>	0.97	-0.81	0.35
<i>Rb</i>	1.06	1.16	0.11
<i>Na</i>	0.80	1.68	0.86

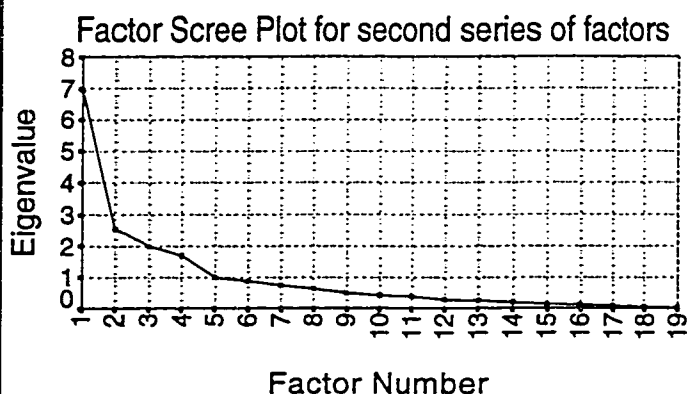


Figure 24. Scree plot for 13 possible factors.

The oblique method for rotation in some cases permits the variables to have high loadings for only certain factors. This makes it easier to identify the meaningful factors (SPSS, 1993). Since oblique rotation is used here, the relationships between the factors are not orthogonal and the factors are correlated with each other (SPSS, 1993). It is unlikely that influences in nature are uncorrelated (SPSS, 1993). Especially in geology, many phenomena can be correlated with each other. Thus oblique rotations have been found to yield substantively meaningful factors (SPSS, 1993).

Correlation matrix for the factors is shown in Table 12. Note that there are small correlations between these four factors. In the case of an orthogonal method for rotation, the factor correlation matrix is an identity matrix that is, there are 1's on the diagonal and 0's for correlation between different factors (SPSS, 1993).

Table 12. Factor correlation matrix for the first four factors (rotated by oblique method).

	Factor 1	Factor 2	Factor 3	Factor 4
Factor 1	1			
Factor 2	-0.21	1		
Factor 3	0.08	0.04	1	
Factor 4	-0.03	0.14	-0.07	1

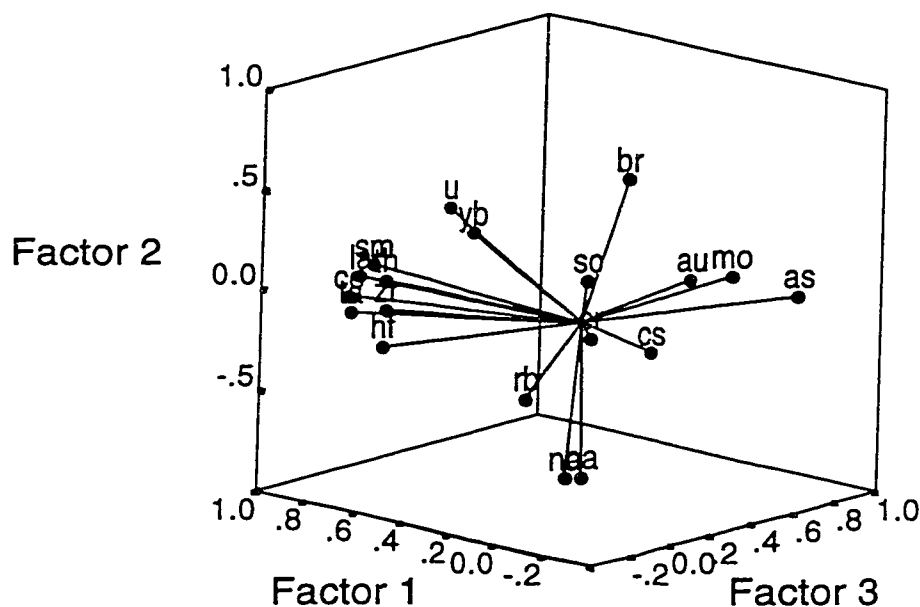


Figure 25. Factor plot in rotated factor space for the second series of elements. Two-dimensional plots for loadings of each pair of factors are shown in Appendix B-1.

As Table 12 shows, there is a small positive correlation between factor 2 (representing more alkalic units) and factor 4 (representing more mafic parts) and a small negative correlation between factor 1 (more felsic units) and factor 2 (more alkalic units). All other correlations are very close to 0.

Distributions of factor 1 and 3 scores are both positively skewed. These distributions can be considered as mixing of generally two very close to normal populations. Probability plot of factor 3 scores, which is the factor of interest, is shown in Figure 26. In this probability plot, it is easier to distinguish these two major populations with a breakpoint value of 1 that separates them from each other. Figure 27 show that only few samples have high to very high scores for factor 3. This is typical of anomalous populations.

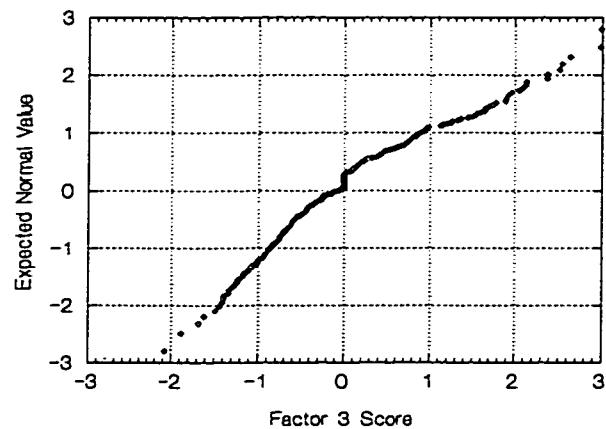


Figure 26. Probability plot for distribution of factor 3 scores.

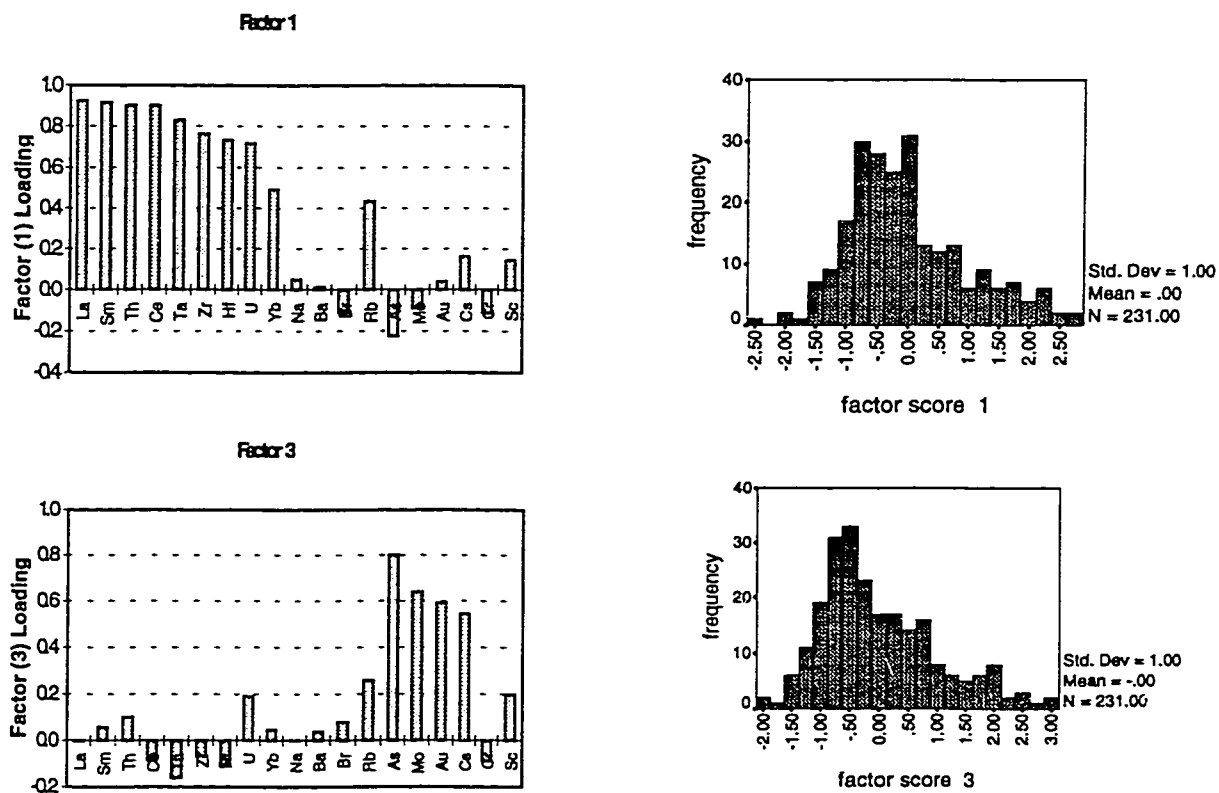


Figure 27. Factor loadings and histogram for scores of factor 1 and 3.

Scores of factor 2 have a normal distribution (Figure 28). Distribution of factor 4 on the contrary to the scores of factor 1 and 3, is negatively skewed which means most of the samples have scored high on this factor. Since most of the Guichon plutonic suite (EJgG) comprises granitoid rocks, this factor could not be related to the mafic units. It most likely represents the background values for Cr and Sc.

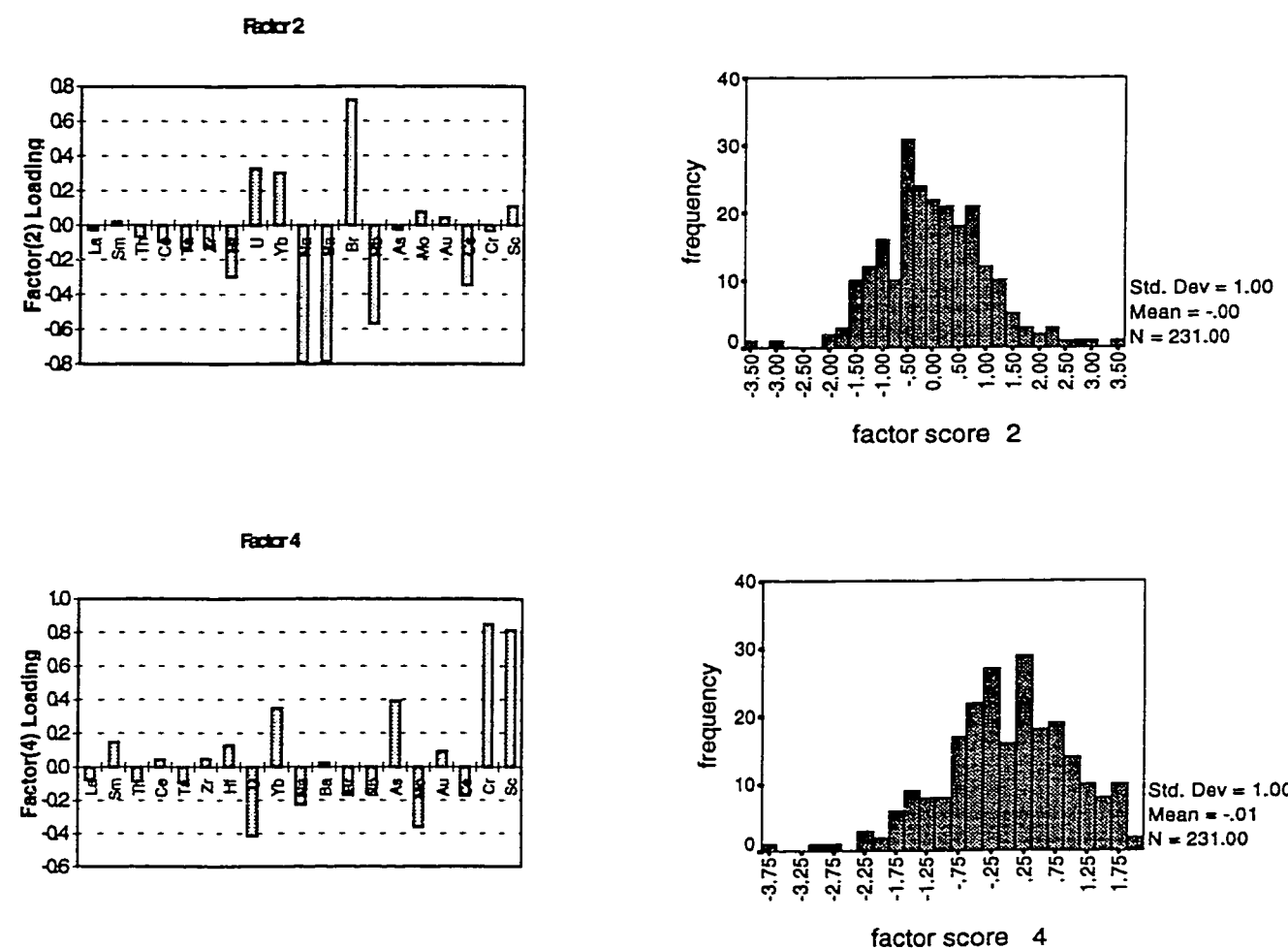


Figure 28. Factor loadings and histogram for scores of factor 2 and 4.

Scores for factor 3 are mapped for samples that have the analytical results for the new set of elements all along the Guichon plutonic suite (EJgG) in the study area. The moving average method was used for mapping with 14 km as the radius of the moving cell and 8 points for consideration, with decay rate of 0.05 for weighting function inside the moving cell. Locations of the known porphyry deposits are also shown on this map for comparison to the locations where factor 3 scores have high values. The result of factor 3 scores matches closely with the results of the previous factor 3 and 4 scores related to the first series of elements for the same area of Guichon plutonic suite (EJgG)(Figure 29). Unfortunately, the Guichon Creek and Wild Horse

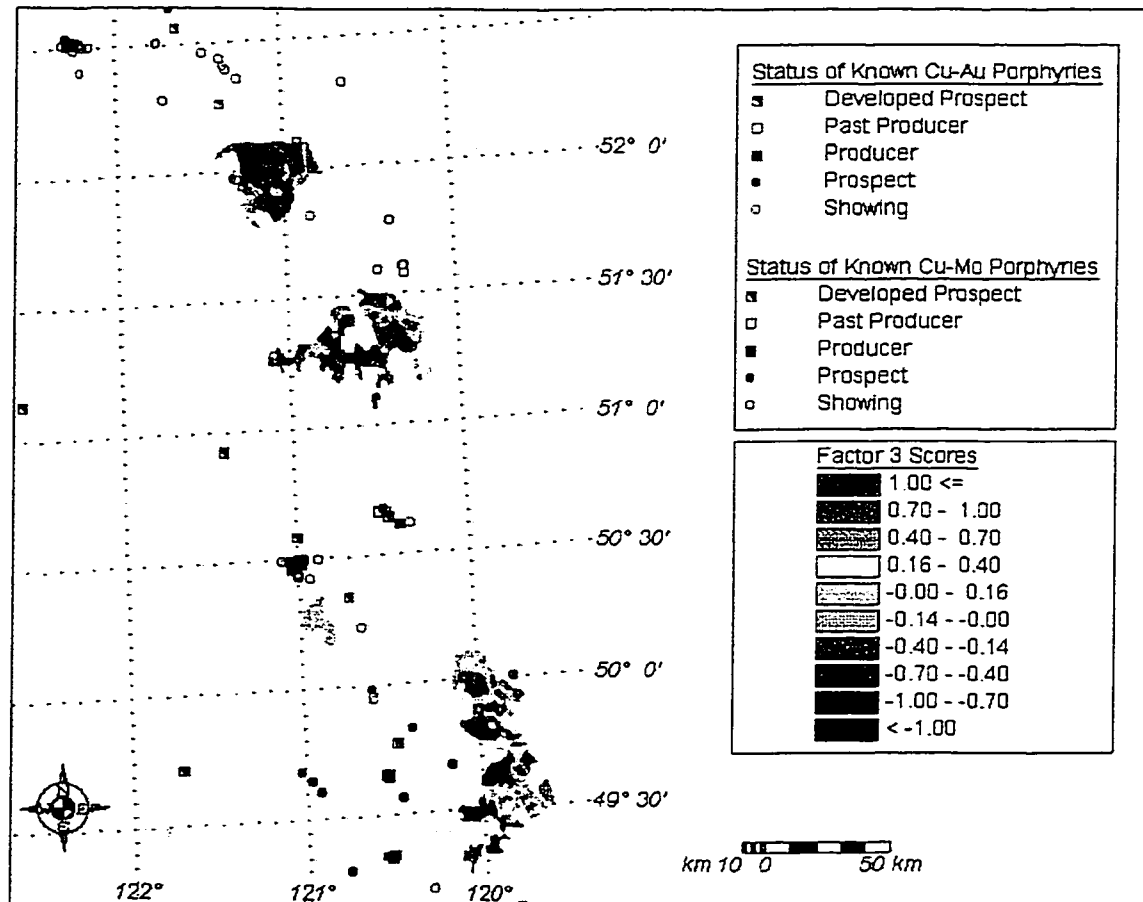
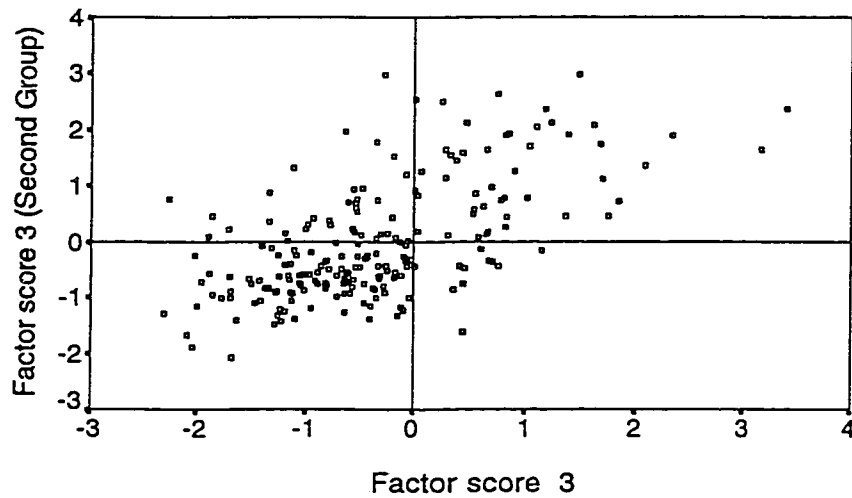
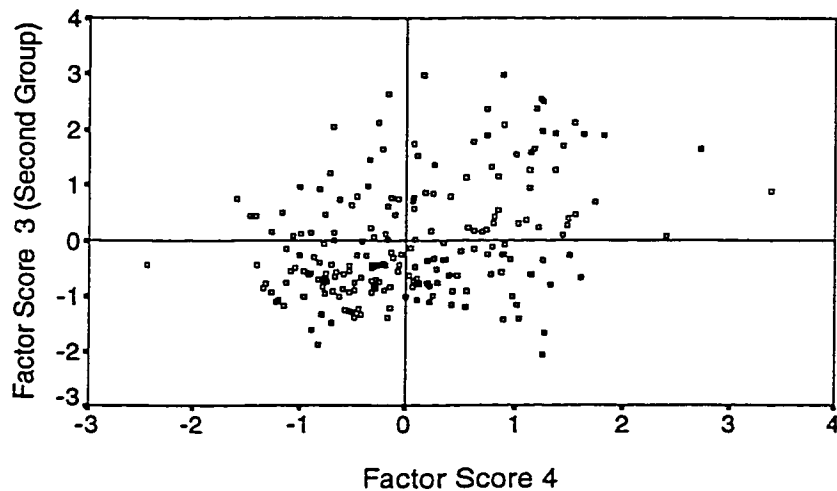


Figure 29. Distribution of factor 3 scores in Guichon plutonic suite (EJgG) wherever the analysis results for the second series of elements were available.

batholiths are located in the area where analyses of the second series of elements are not available. For the areas where the results of the second series of elements are available, the generated factor 3 scores of Figure 29 was compared with the factor 3 and factor 4 scores maps of the first series of elements (Figures 22 and 23). For this comparison, because of the measurement scale of these factor scores, scatter



(a)



(b)

Figure 30. Scatter plots for factor 3 and 4 scores and factor 3 scores of the second group of elements in Guichon plutonic suite (EJgG).

plots and Pearson correlation coefficient were used. As Figure 30 shows Factor 3 of the first group (representing Cu-Zn) and second group of elements (representing As, Mo, Au, Cs) show more correlation with each other than factor 4 (U, Mo) and factor 3 of the second group. The calculated Pearson correlation coefficient for variables of Figure 30a is 0.61 and for Figure 30b is 0.35.

5.3.4.3 DISCRIMINANT ANALYSIS FOR THE GEOCHEMICAL DATA OF GUICHON PLUTONIC SUITE (EJgG)

5.3.4.3.1 TRAINING OR CONTROL AREA

The training or control area is defined as the area in which quantitative relationships between the target pattern and the input data are established (Chung, 1995). In other words, in the control area(s) the rules that exist for the target pattern must be found. Selecting the appropriate control area is an important matter because the conditions found in the control area is going to be extended to a larger area. In selecting the control area, similarity of the geological conditions must be considered.

An example of a control or a training area is to select mineralized and an unmineralized geological polygon(s) of the same geological unit or rock type and to study their differences for geochemical, geophysical,....etc. characteristics. Defining such a control or training area is a necessity to start a discriminant analysis. Here two geological polygons of the Guichon plutonic suite (EJgG) were selected as the control or training area. Guichon Creek batholith (1090 km²) is a famous mineralized unit of Guichon plutonic suite (EJgG). Wild Horse batholith (336 km²) located about 60 km east of it, is a smaller batholith and can be considered as a most likely unmineralized unit of Guichon plutonic suite (EJgG) (McMillan, personal communication, 1996).

The unmineralized zones of Guichon plutonic suite (EJgG) could be another phase of intrusion of this plutonic suite (McMillan, personal communication, 1996).

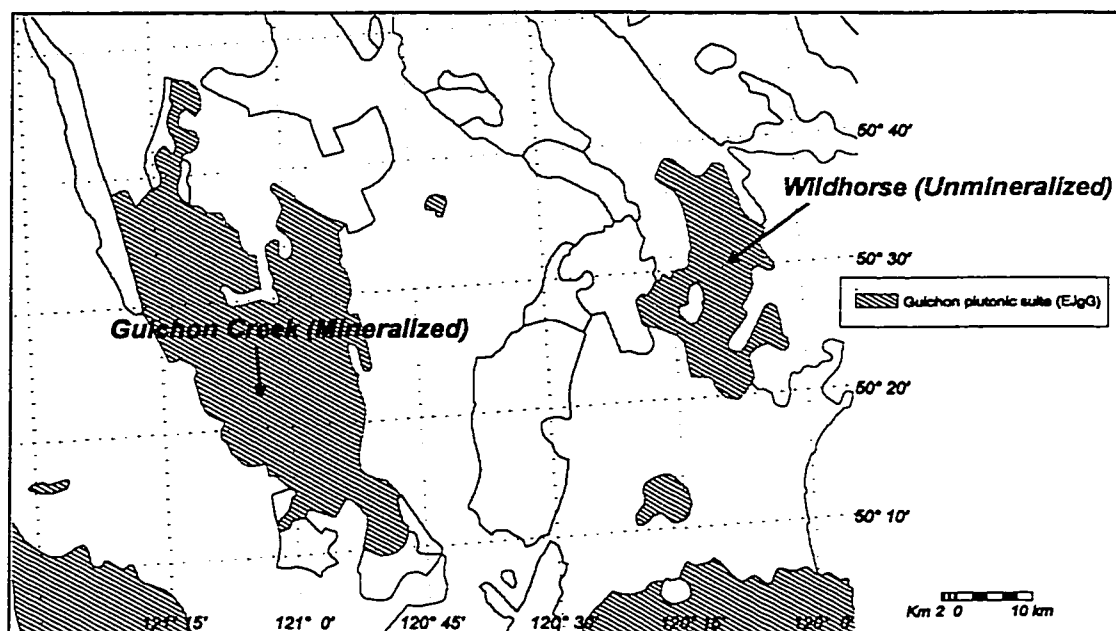


Figure 31. Control area for the discriminant analysis. Guichon Creek batholith is selected as the mineralized and Wild Horse batholith as the unmineralized unit.

The objective for doing the discriminant analysis was to differentiate geochemical samples related to mineralized group from those samples related to unmineralized group. In addition, to determine the probability of samples belonging to mineralized or unmineralized units all over the Guichon plutonic suite (EJgG) based on the information from the training area.

The discriminant equation was calculated utilising log transformed values of the elements Co, Cu, Fe, Mn, Mo, Ni, Pb, U, Zn from stream sediment, F in water (F-wat) and U in water (U-wat) from water samples. For pH, because of its distribution, which is close to normal, the original values were used without $\log_{10}$ transformation. After removal of extreme outliers, 474 samples were entered into the analysis. Univariate tests of significance help to identify some differences among the groups. A significance test is necessary as the first step in discriminant

analysis to select only the variables (elements) that help to differentiate two groups from each other. Therefore, ANOVA *F* values for different elements of two groups were calculated to test equality of group means at 95% confidence level. The numerical results of the *F* values and their significance and Wilks' lambda are shown in Table 13. When variables are considered individually, lambda is the ratio of the within-group sum of squares to the total sum of squares. A lambda of 1 occurs when two observed grouped means are equal. Values close to 0 occur when within-groups variability is small compared to the total variability - that is, when most of the total variability is attributable to differences between the means of the groups. Thus large values of lambda indicate that group means do not appear to be different, while small values indicate that group means appear to be different (SPSS, 1993).

As Table 13 shows, except for Mn, Pb, U and Zn, for all other elements and pH the calculated *F* value is larger than the significance value. Therefore, for Cu, Fe, F in water (F-wat), Mo, Ni, U in water (U-wat) and pH, at 95% confidence level it is possible to consider that the means of two populations of mineralized and unmineralized are different. In addition, among these, Cu has the highest difference for the mean between the two groups of mineralized and unmineralized samples.

Table 13. Wilks' Lambda and univariate F-ratio with 1 and 58 degrees of freedom for investigating difference between means of elements for mineralized and unmineralized units (N=474).

Variable	Wilks' Lambda	F	Significance
Co	0.98	0.98	0.326
Cu	0.50	59.12	0.000
Fe	0.93	4.08	0.048
F-WAT	0.96	2.70	0.106
Mn	1.00	0.05	0.821
Mo	0.92	5.05	0.028
Ni	0.89	7.13	0.010
Pb	1.00	0.05	0.819
U	1.00	0.00	0.975
U-WAT	0.91	5.51	0.022
Zn	0.99	0.47	0.497
pH	0.88	8.22	0.006

Also to examine the correlation between elements of two groups, the pooled within-groups correlation matrix is calculated for the predictor variables (Table 1 of Appendix C). A pooled within-group correlation matrix is obtained by averaging the separate correlation matrices for all groups and then computing the correlation matrix (SPSS, 1993).

Since Mn, Pb, U and Zn do not have significant difference for their means between group 1 and 2 (mineralized and unmineralized), they were not entered into the discriminant function calculation. For those variables with significant difference for their means (Co, Cu, Fe, F-wat, Mo, Ni, U-wat, pH) the discriminant function is calculated as:

$$Z = 0.85(\text{Co}) + 2.28(\text{Cu}) + 2.15(\text{Fe}) - 0.87(\text{F-wat}) - 0.07(\text{Mo}) - 2.16(\text{Ni}) - 0.37(\text{U-wat}) + 2.26(\text{pH}) - 19.12$$

This discriminant function classifies 94.6% of the group 1 and 95.8% of the group 2 samples in their own group (Table 14).

Table 14. Percentages of samples of group 1, 2 and all other samples classified by the calculated discriminant function into group 1 or 2.

	<i>No. of Cases</i>	<i>Predicted Group Membership</i>	
		<i>1</i>	<i>2</i>
Group 1	37	35 (94.6%)	2 (5.40%)
Group 2	24	1 (4.2%)	23 (95.8%)
Ungrouped cases (rest of the data)	413	91 (22.0%)	322 (78.0%)

Group 1= mineralized

Group 2= unmineralized

The percent of "grouped" cases correctly classified in their own group is 95.8% that represents the general efficiency of this discriminant function. Figure 32 shows the histogram of the calculated Z scores from the above equation. Figure 33 shows the probability plot for the calculated Z scores. Both Figure 32 and Figure 33 show the presence of two groups.

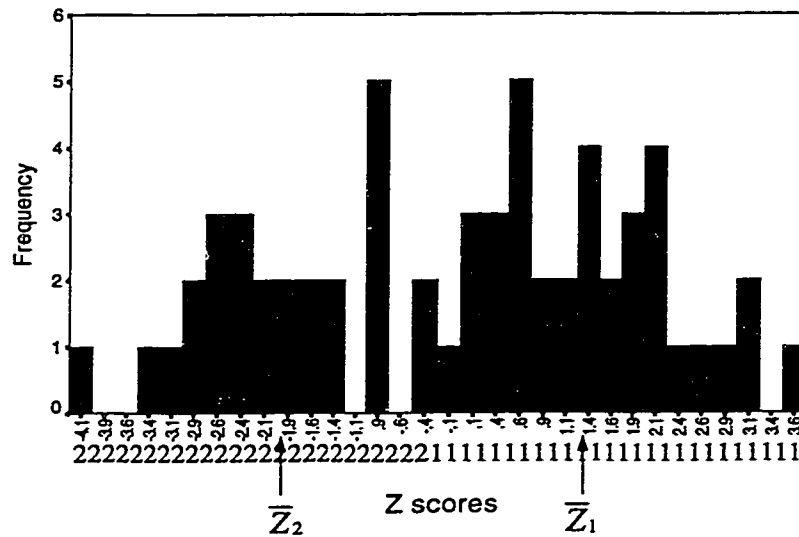


Figure 32. Histogram of calculated discriminant Z scores for group 1 and 2 and their centroids.

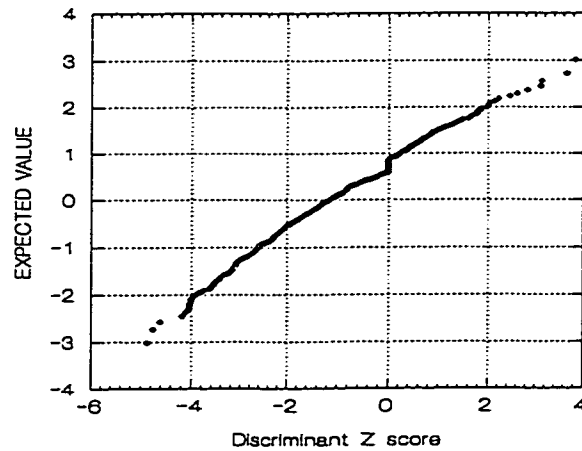


Figure 33. Probability plot for the calculated Z scores.

A method to assess the contribution of a variable to the discriminant function is to examine the correlations between the values of the function (calculated Z scores) and the values of the variables (SPSS, 1993). To do this, the Pearson correlation between the discriminant function Z scores and the original variables was calculated (SPSS, 1993). A pooled within-groups

correlation matrix was calculated in which separate correlation matrices were calculated for each group and the results were combined to obtain the overall pooled within-groups correlation matrix. In Table 15, correlations between discriminating variables and canonical discriminant functions for two cases are shown. First, elements with significant differences for their means (Co, Cu, Fe, F-wat, Mo, Ni, U-wat, and pH) are considered, and then these plus elements with insignificant difference for their means (Pb, Mn, U, and Zn) were also included in the calculations. The results for both cases are indicated in Table 15 (a) and (b).

Table 15. Pooled within-groups correlations between discriminating variables and canonical discriminant functions a) for elements with significant difference for their means, b) for all elements.

(a)

Cu	0.605
pH	0.225
Ni	-0.210
U-WAT	-0.185
Mo	0.177
Fe	0.159
F-WAT	-0.129
Co	0.078

(b)

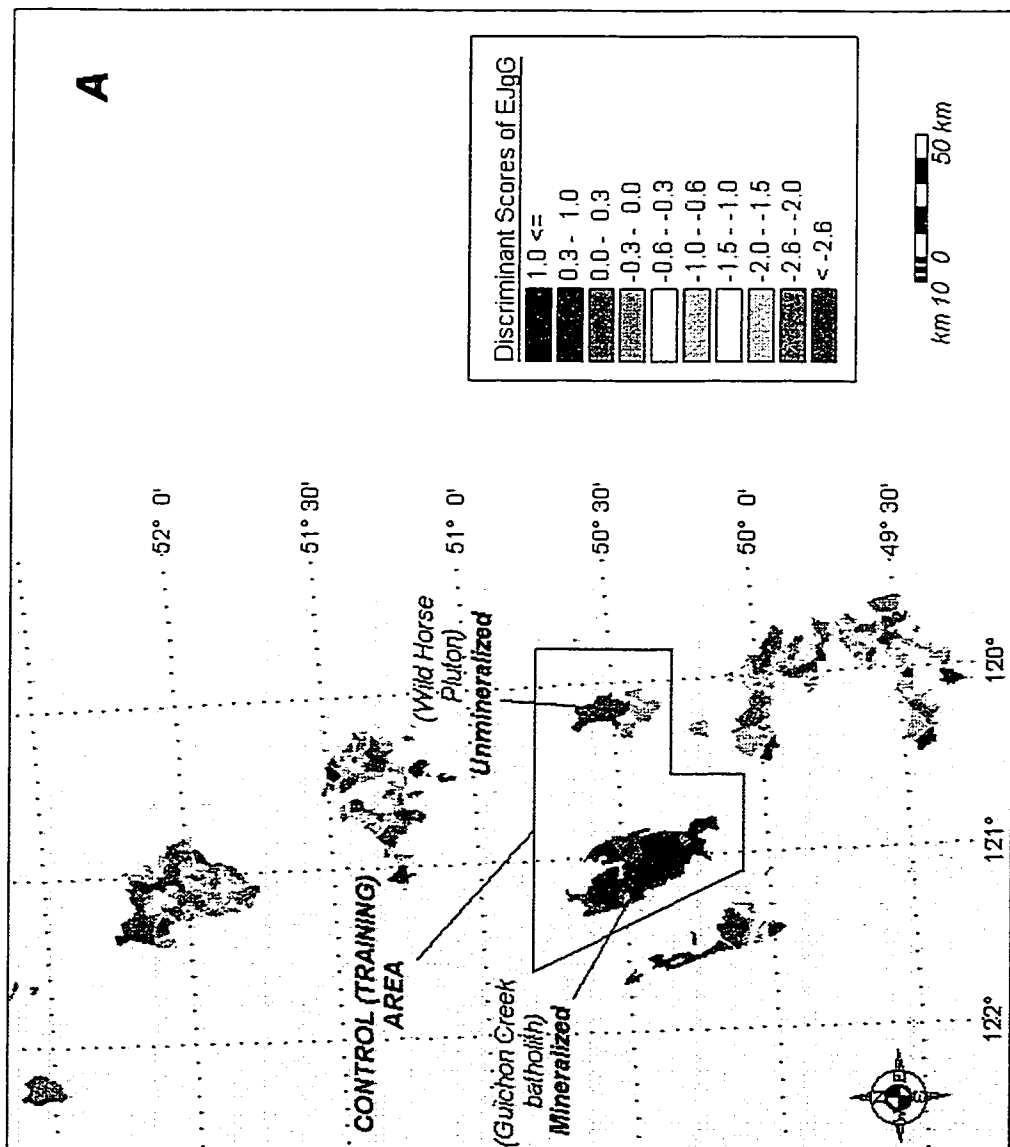
Cu	0.560
pH	0.209
Ni	-0.195
U-WAT	-0.171
Mo	0.164
Fe	0.147
F-WAT	-0.120
Co	0.072
Zn	-0.050
Pb	0.017
Mn	0.017
U	0.002

In these tables, variables are ordered by the magnitude of their correlation with the discriminant function. As Table 15 shows Cu has the dominant contribution to the discriminant function in both cases. It follows by pH and Mo. As Table 15b shows, variables with insignificant differences for their mean (Pb, Mn, U, Zn) have the smallest correlations with the discriminant function, so including these elements does not have major effect in the discriminant function.

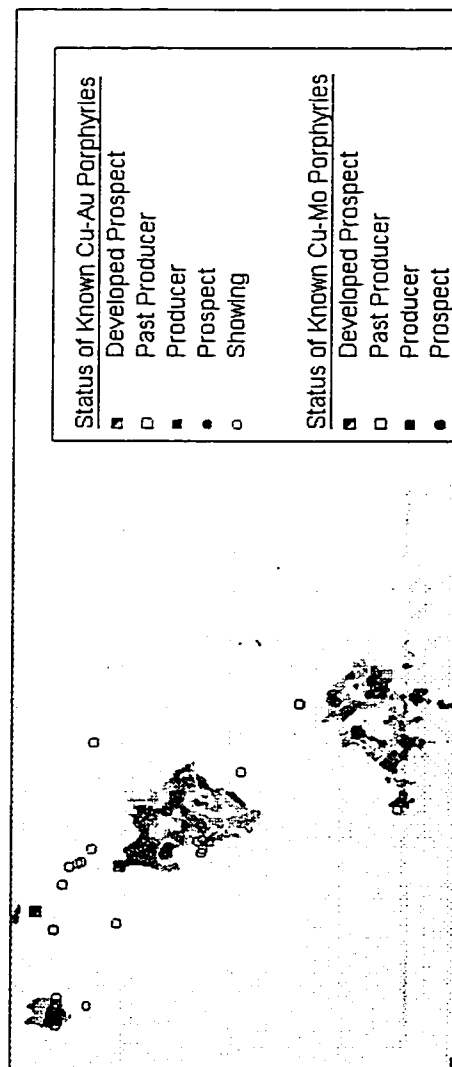
The value of canonical discriminant function evaluated at group means (centroids) are

$\bar{Z}_1 = 1.294$ for group 1 and $\bar{Z}_2 = -2.082$ for group 2. Therefore, Z_0 which is halfway between these is -0.394 . In this way based on the calculated discriminant score for each sample and using the cut-off value of $Z_0 = -0.394$, it is possible to assign different samples in group 1 or 2. Although each sample is classified in this way into either group 1 or group 2, it is possible to assign a posterior probability for each sample for belonging to each of these groups. The posterior probability is calculated based on the prior probability and conditional probability. Prior probability is based on the observed proportions of cases in each group. To calculate the conditional probability, each case is assumed to belong to a particular group, and the probability of the observed score given membership in the group is estimated (SPSS,1993). Posterior probability increases as the calculated Z score gets farther from the cut off value of Z_0 . This probability is calculated for different samples inside Guichon plutonic suite (EJgG).

The value of discriminant function score (Z) could be used to disaggregate samples related to mineralized parts of Guichon plutonic suite (EJgG) from others related to unmineralized parts. Mapping the calculated Z scores or probability of belonging to mineralized group (group 1), could be used as criteria for grading different parts of Guichon plutonic suite (EJgG). Maps of Figure 34 and Figure 35 show discriminant scores and probability for samples to belong to the mineralized group (group 1). Known porphyry deposits of different types are also indicated in these maps for comparison. These maps are made by a moving average method to reduce the noise and to reveal the general trends for these variables. Fourteen km was selected for the radius of the moving cell with maximum 8 points for consideration and with decay rate of 0.05 for weighting function inside the moving cell. In both Figure 34a and 34b a visual comparison shows that in many cases location of known porphyry deposits match with the high discriminant function score (Z) and high probability for samples to belong to the mineralized group.



(a1)



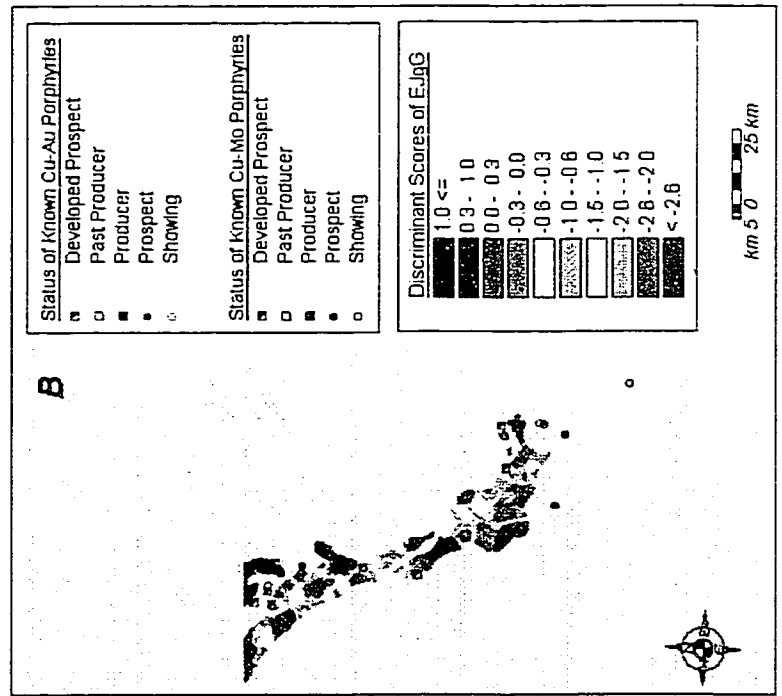
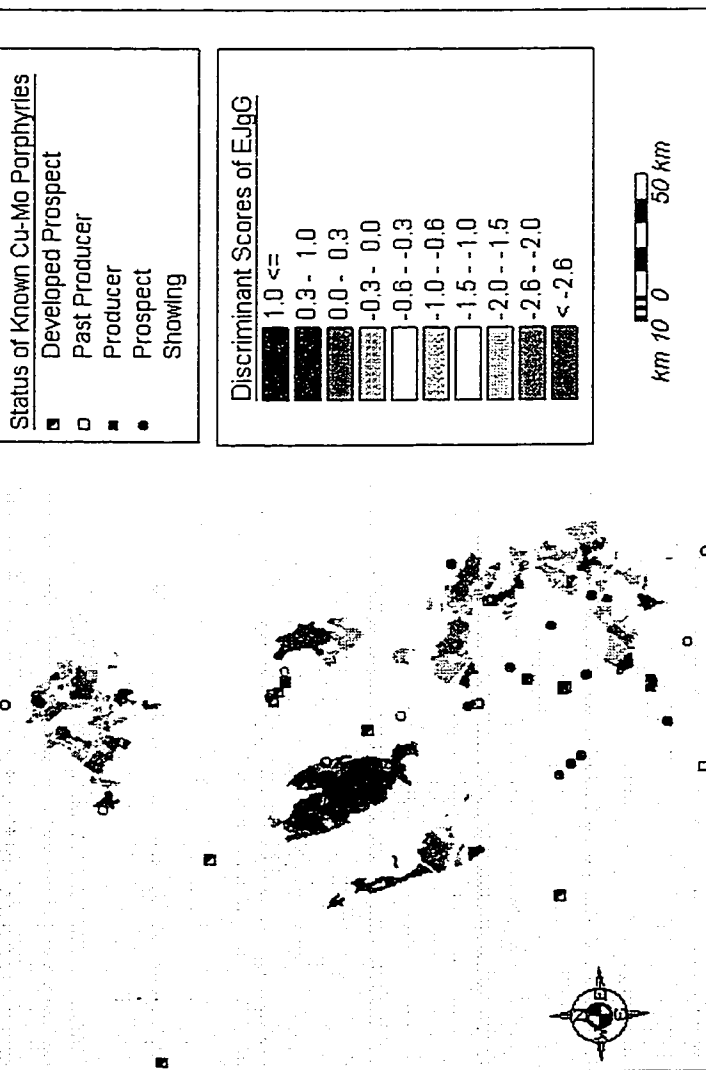


Figure 34. a1) Discriminant function scores(Z) in Guichon Plutonic Suite (EjgG) zoomed in area A and the control area. a2) Known porphyry Cu-Mo & Mo deposits shown on the same discriminant scores(Z) map. b) Discriminant function scores(Z) in area B with known porphyry Cu-Mo and Cu-Au deposits.

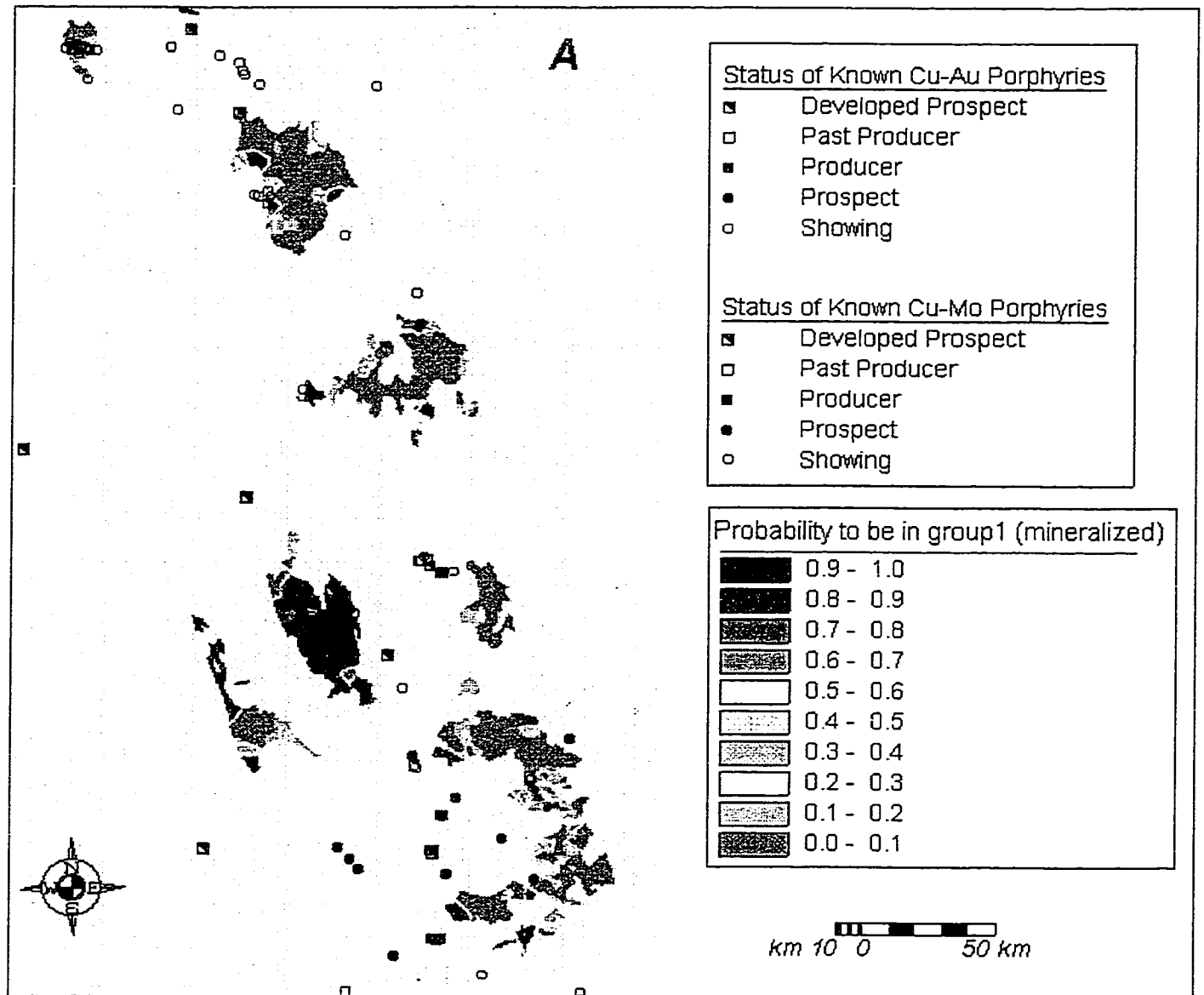
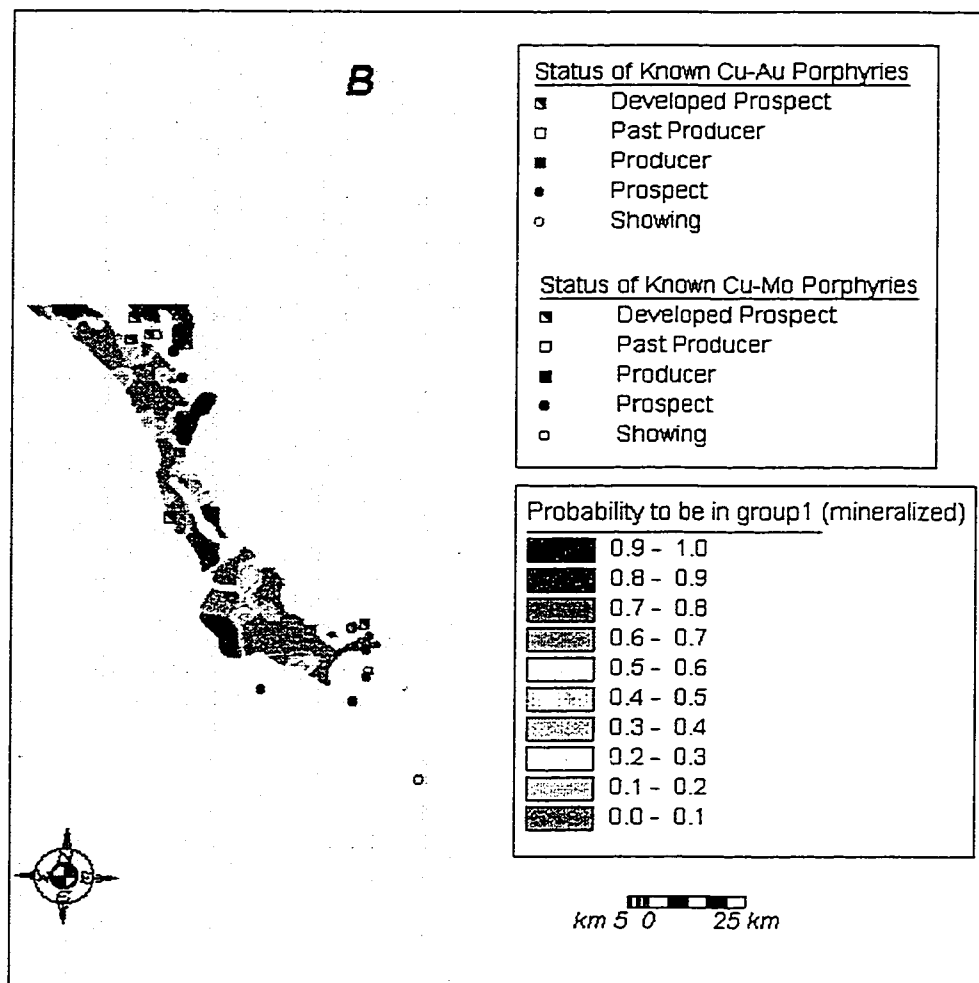
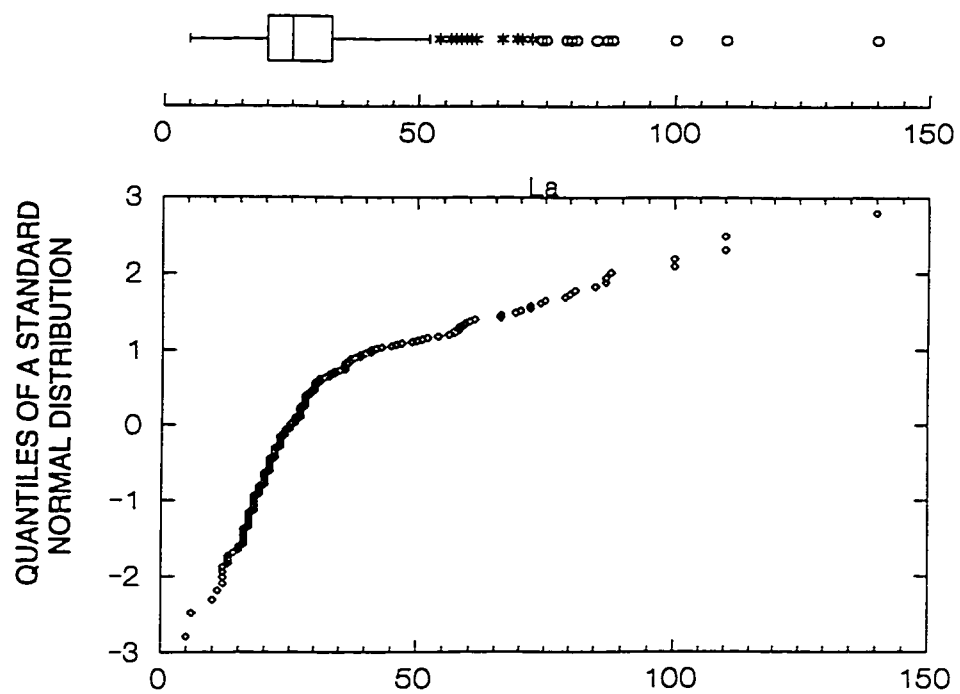
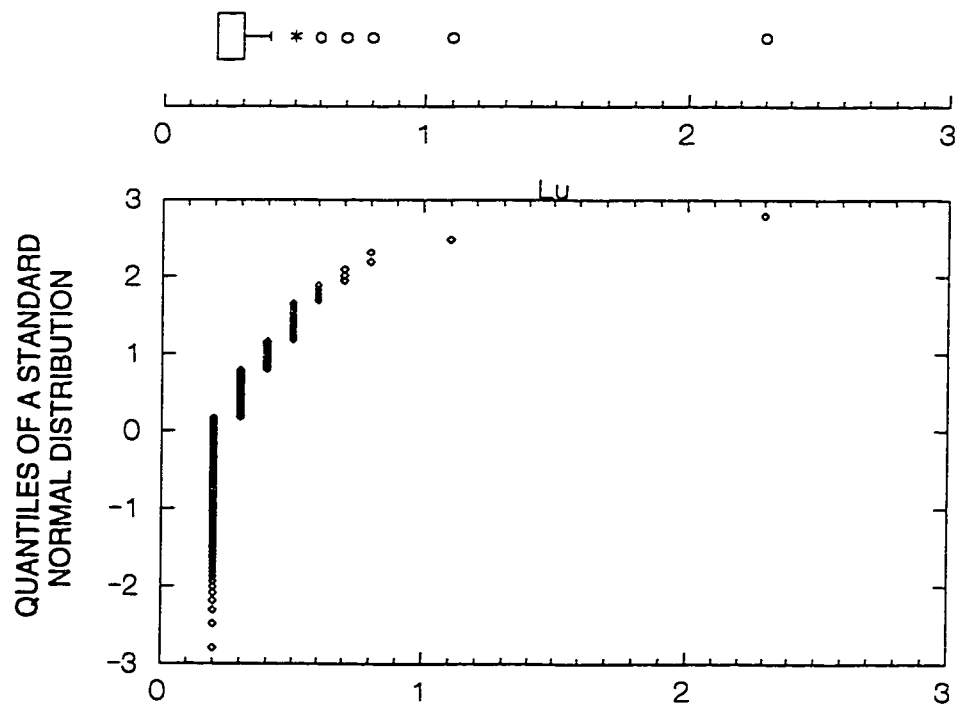


Figure 35. Probability of samples to be in group 1 (mineralized) of discriminant analysis of Guichon Plutonic Suite (EJ)

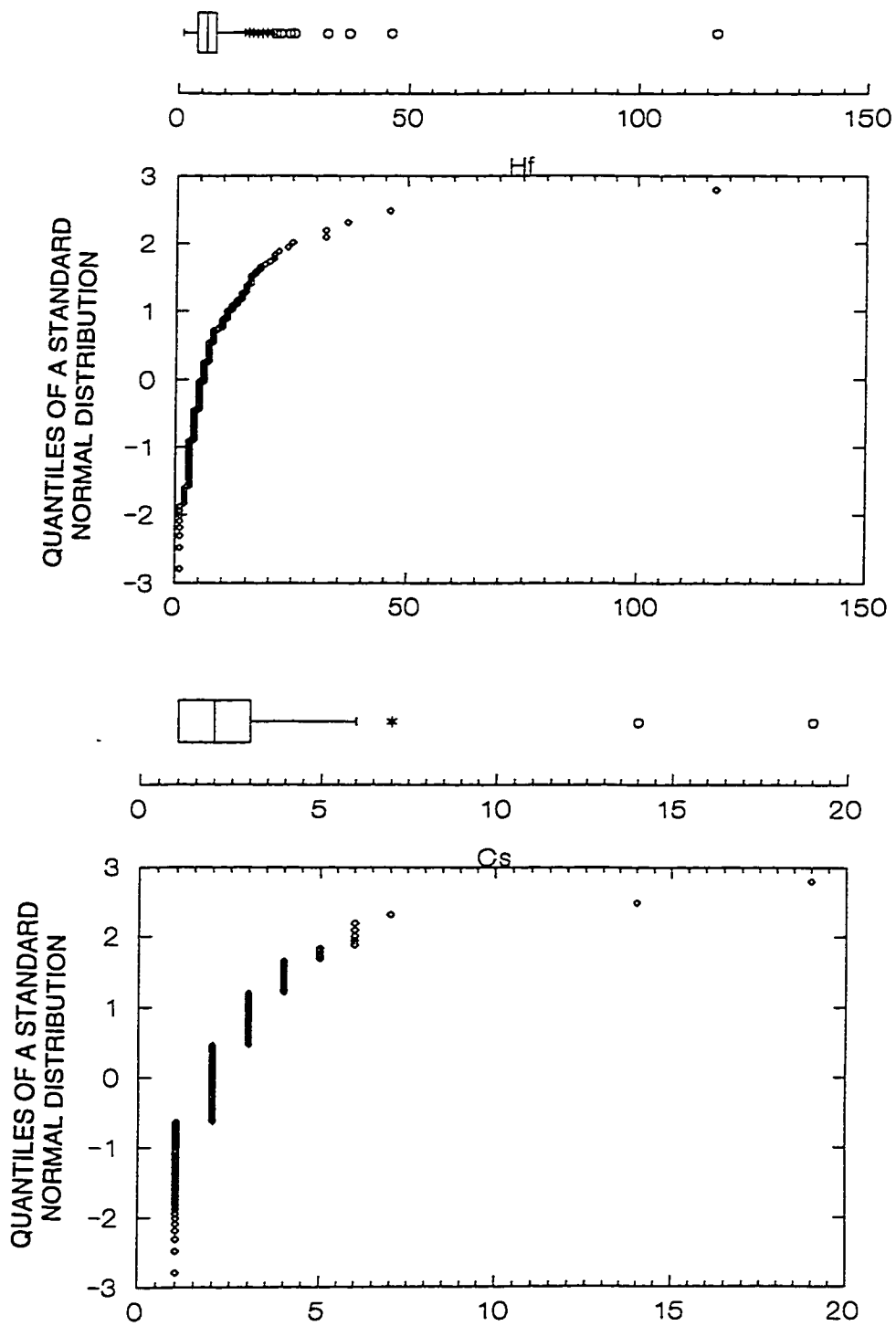
red)



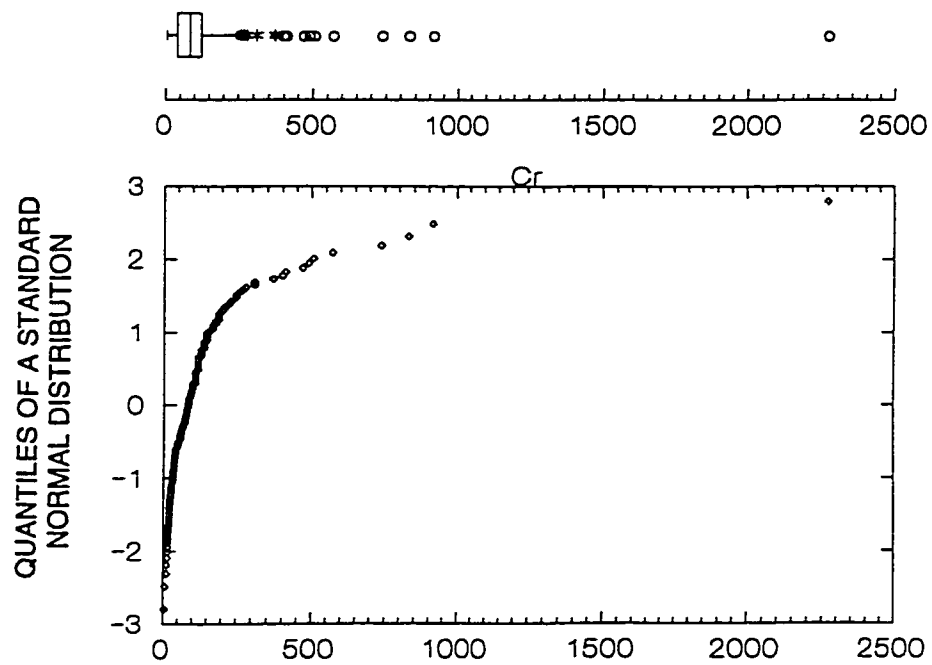
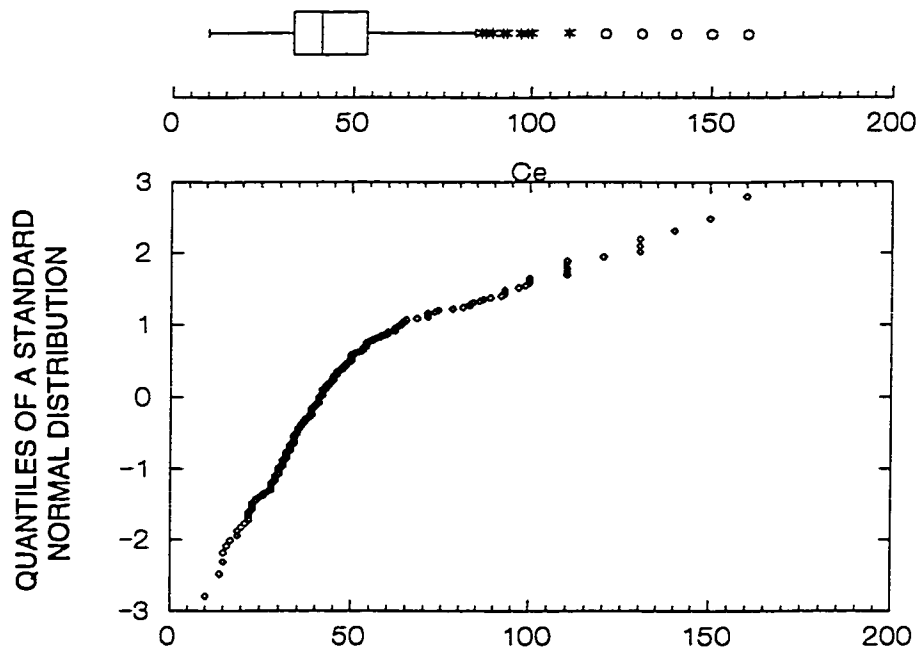
onic Suite (EJgG) in A and B areas..



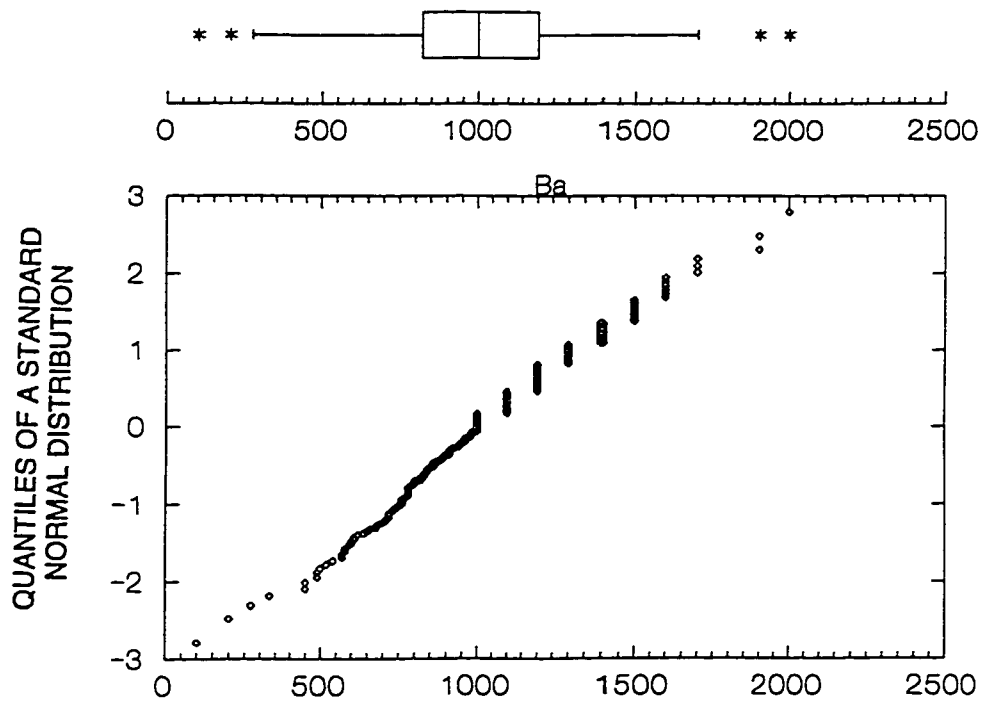
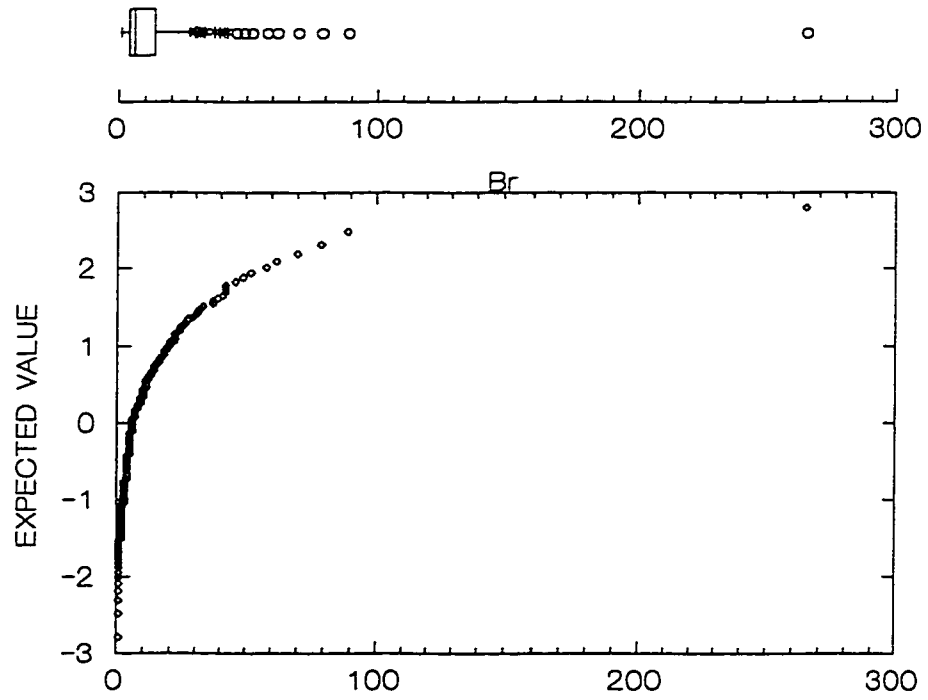
Guichon Plutonic Suite (EJqG)



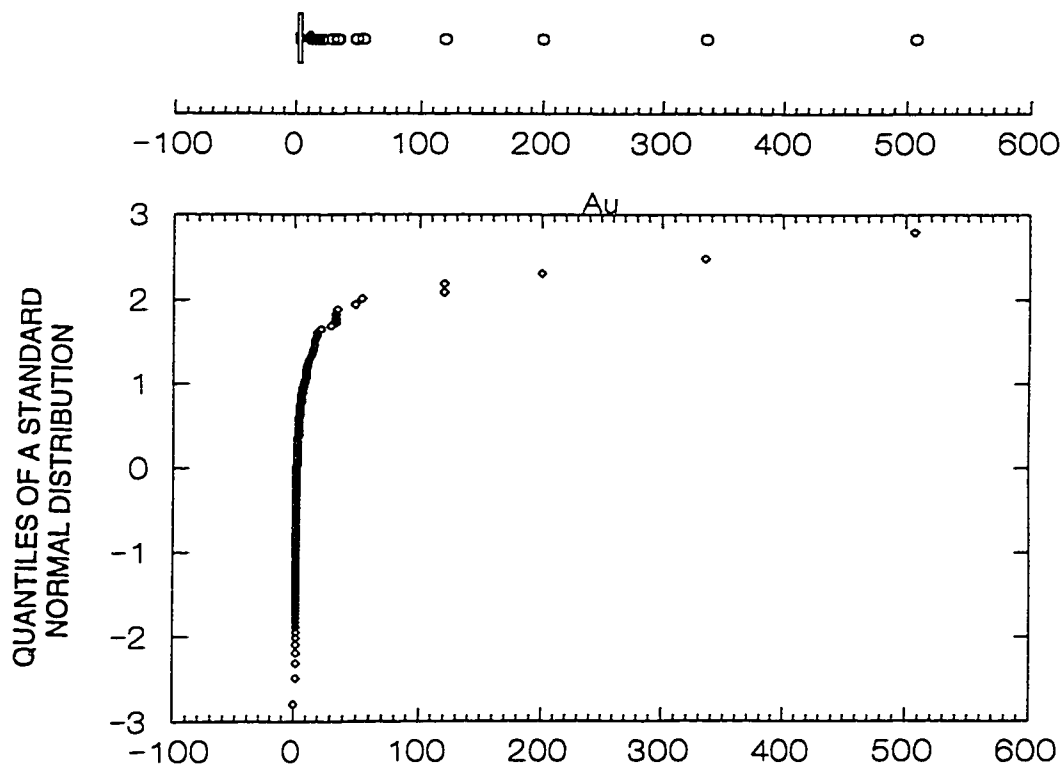
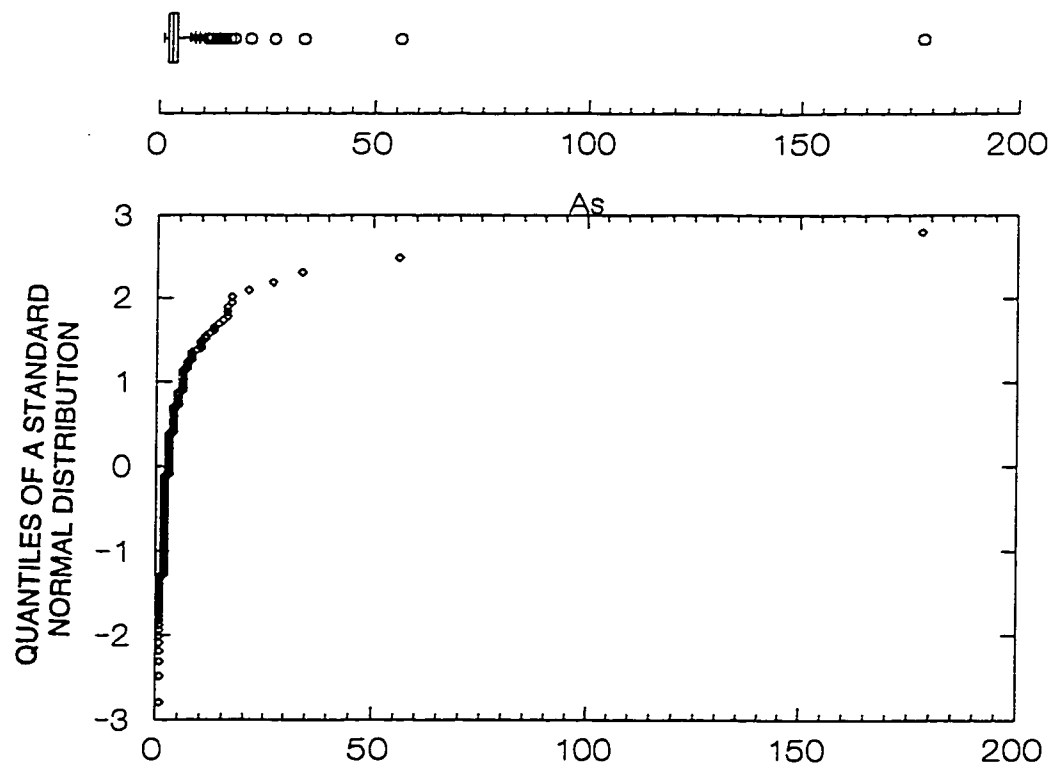
Guichon Plutonic Suite (EJgG)



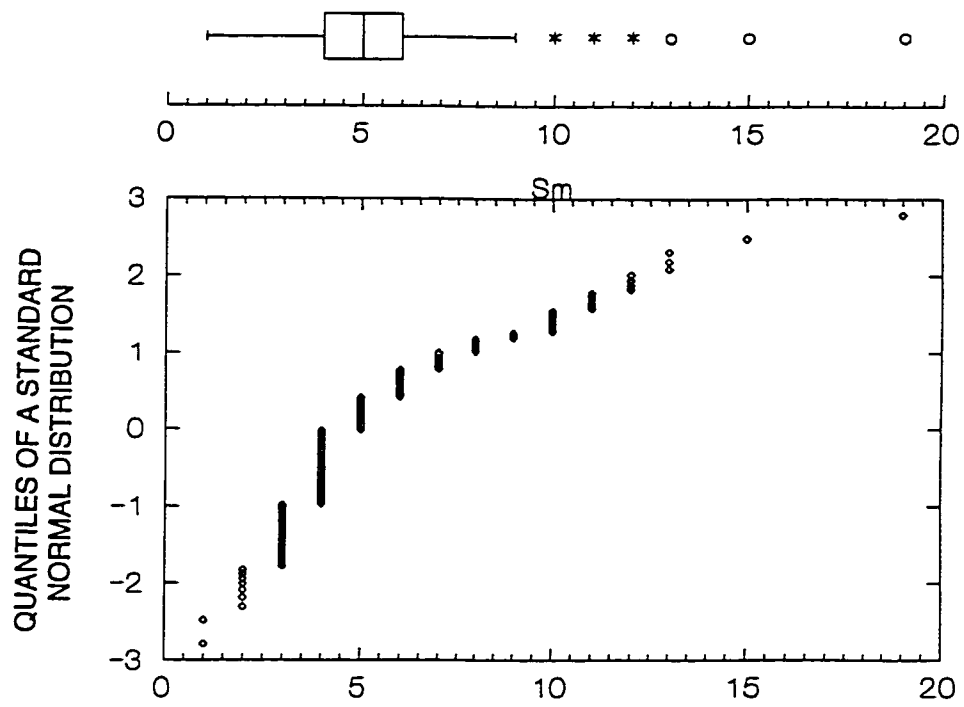
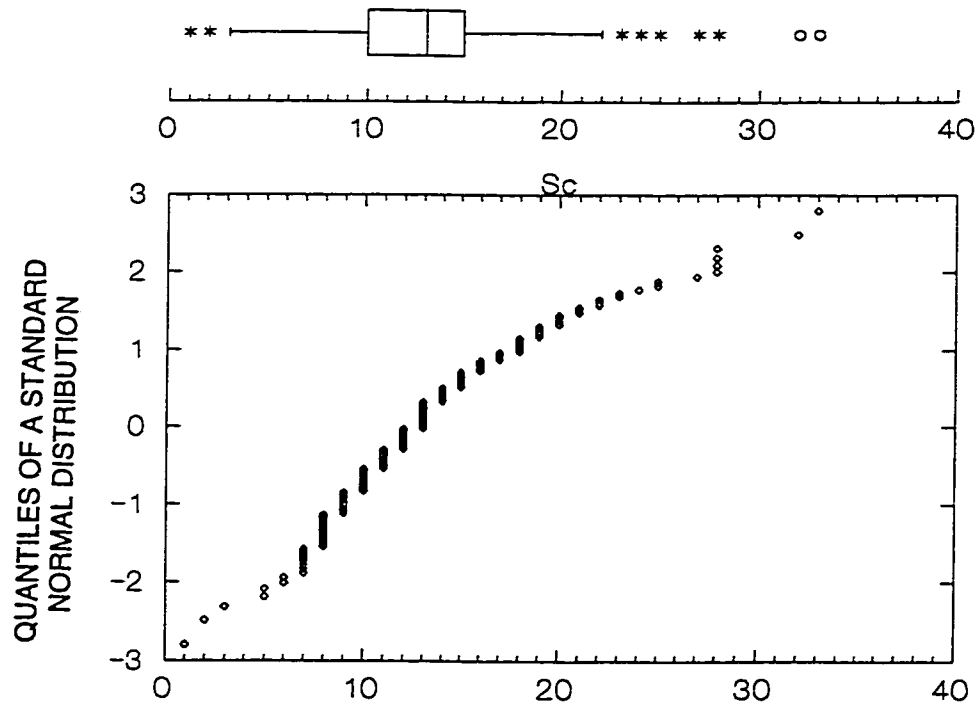
Guichon Plutonic Suite (EJgG)



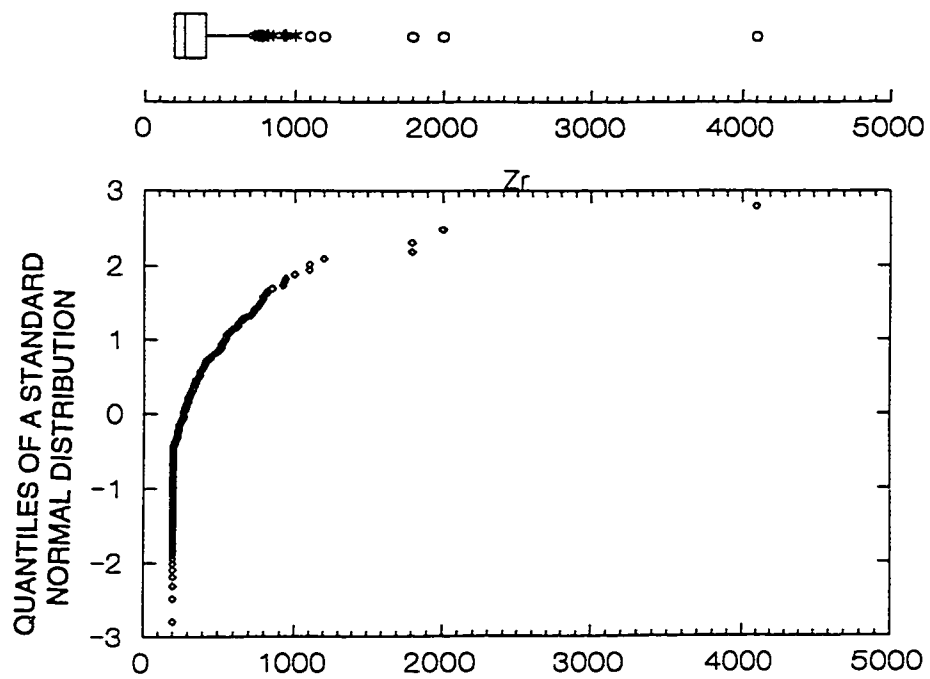
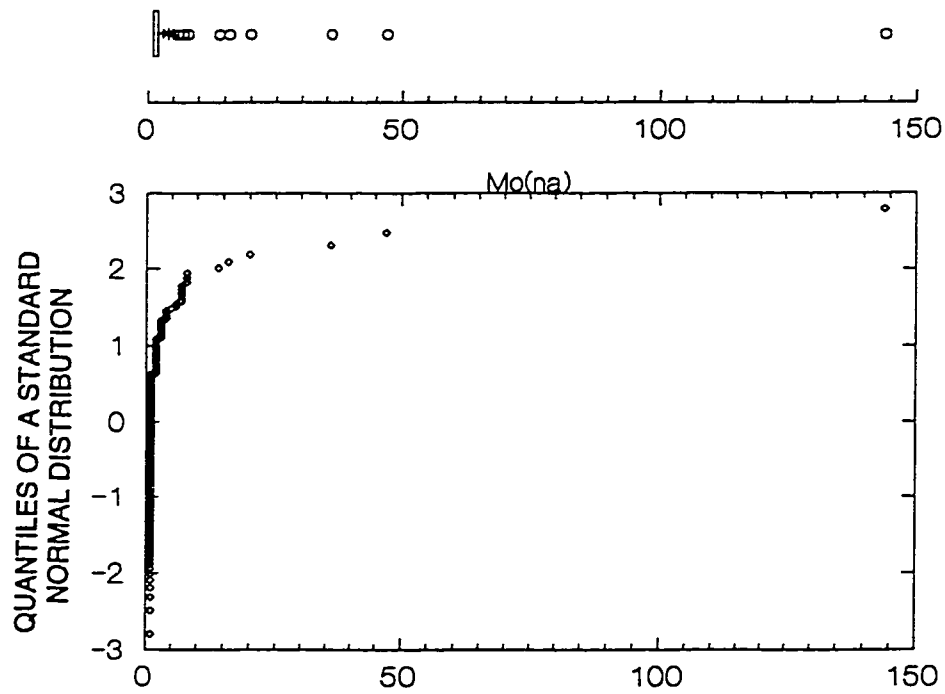
Guichon Plutonic Suite (EJgG)



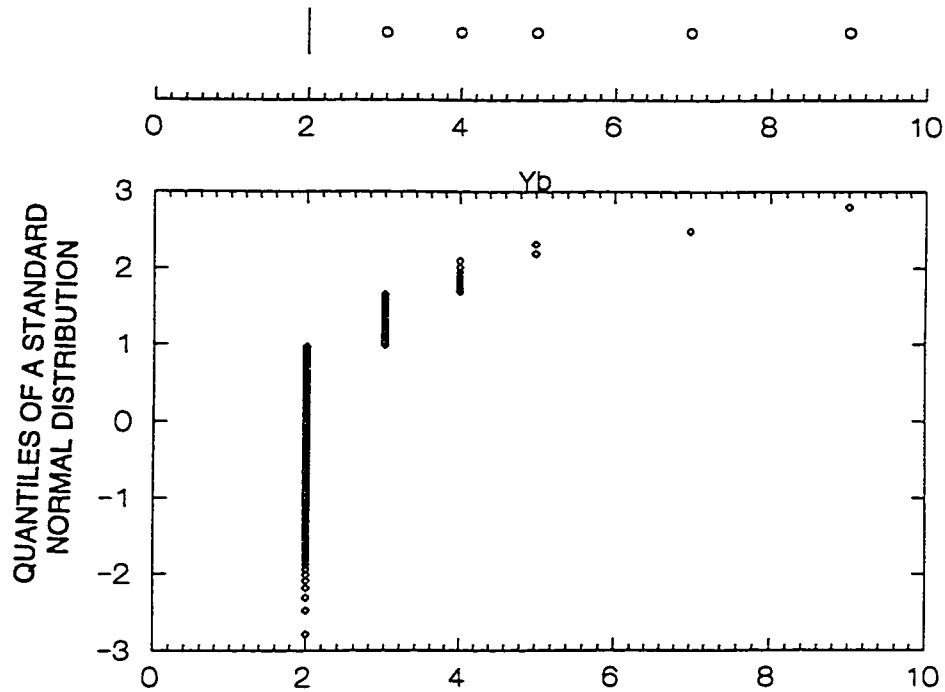
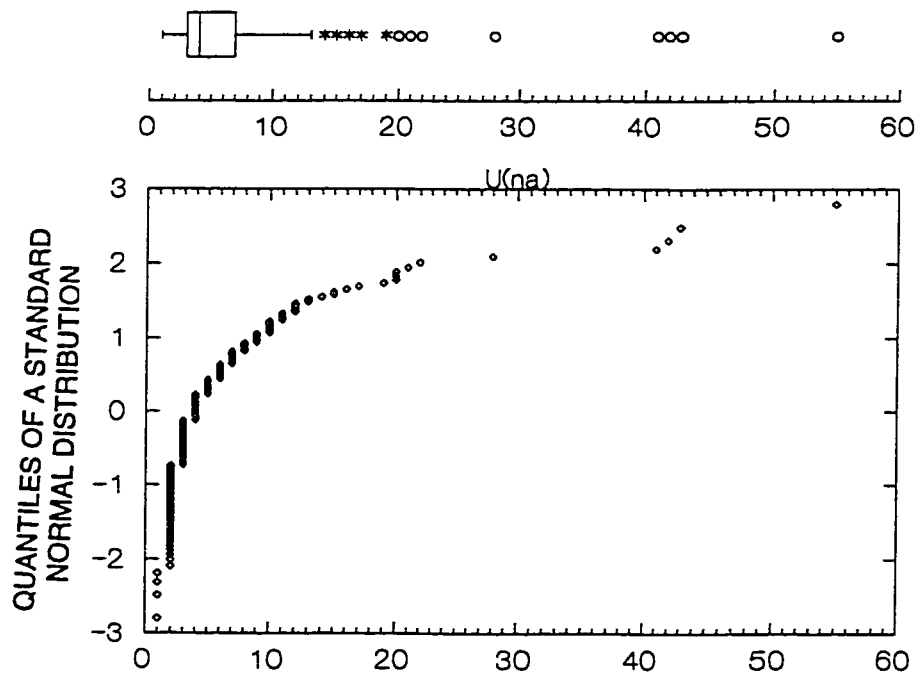
Guichon Plutonic Suite (EJqG)



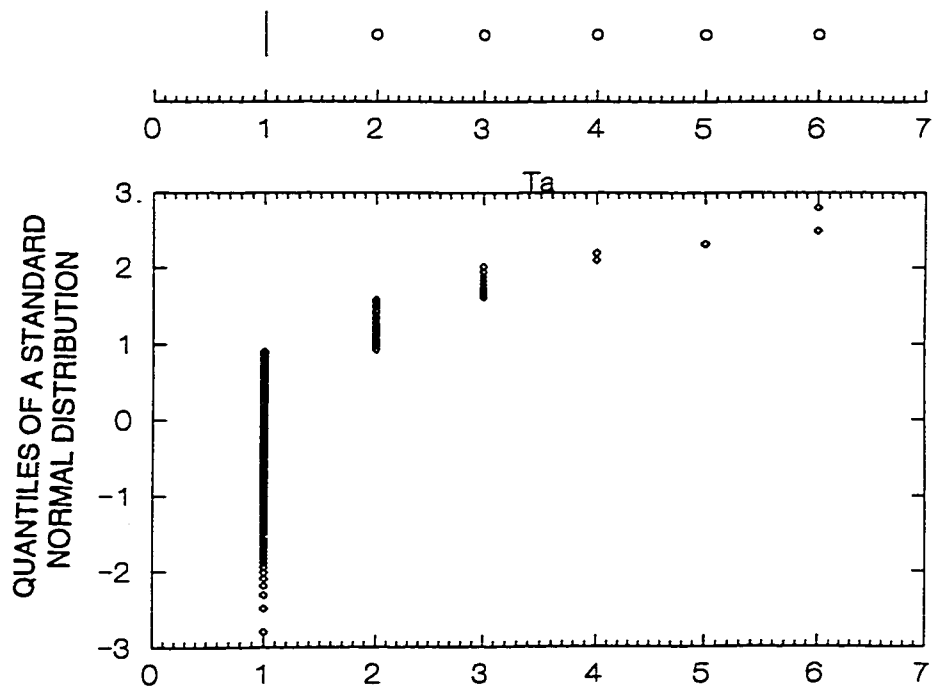
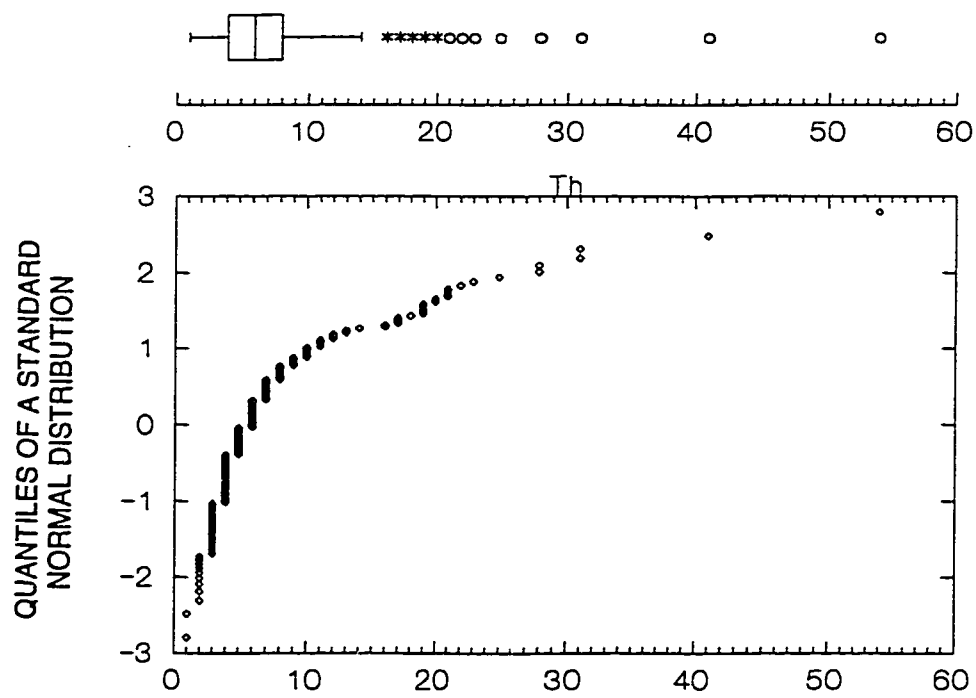
Guichon Plutonic Suite (EJgG)



Guichon Plutonic Suite (EJgG)

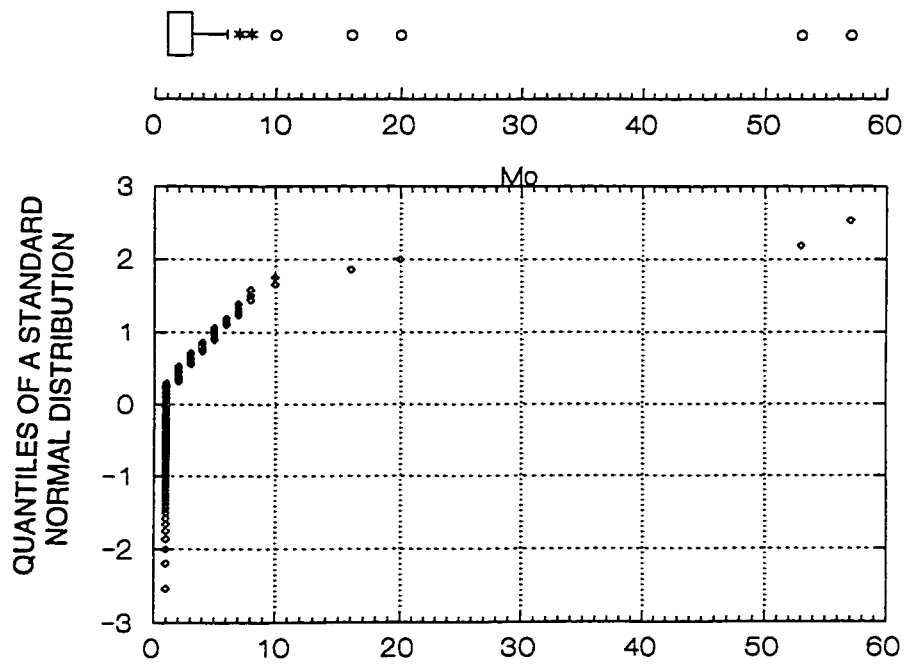
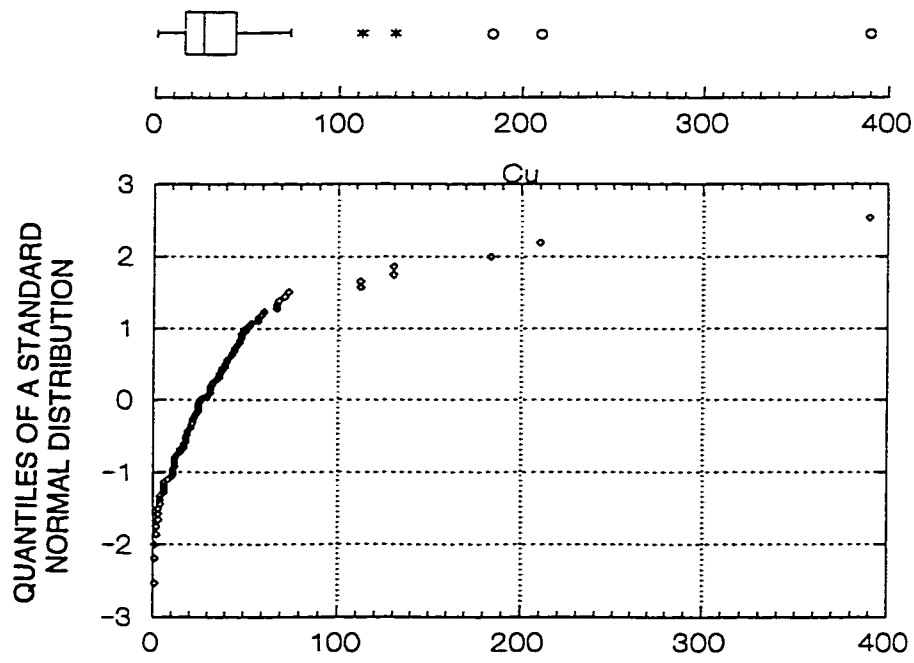


Guichon Plutonic Suite (EJqG)

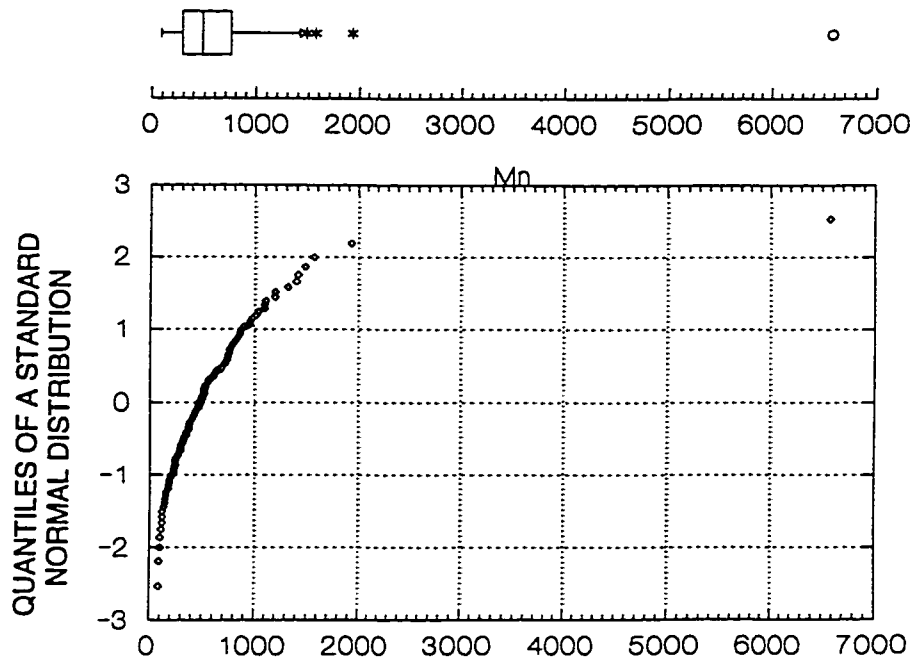
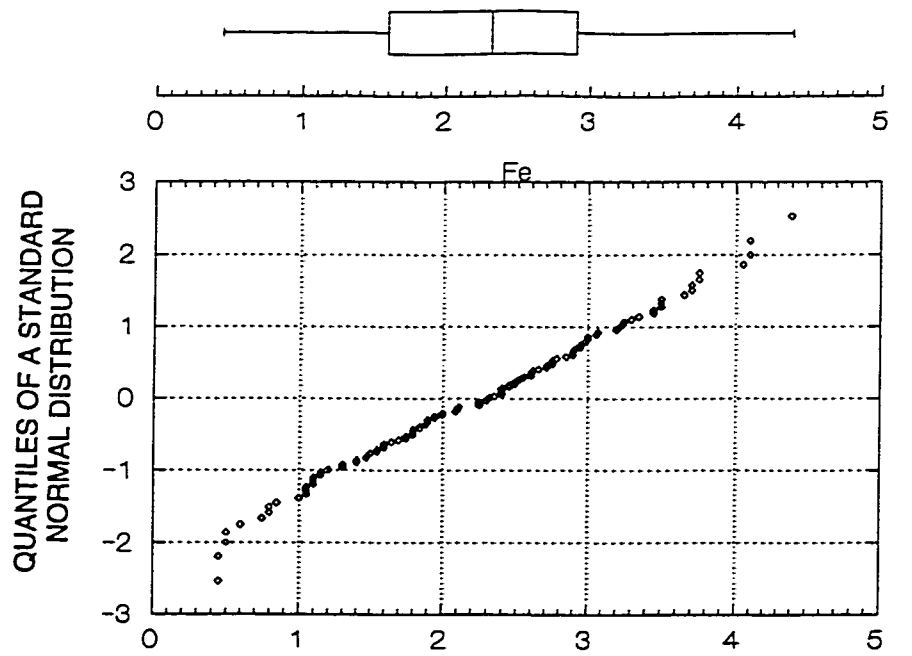


Guichon Plutonic Suite (EJgG)

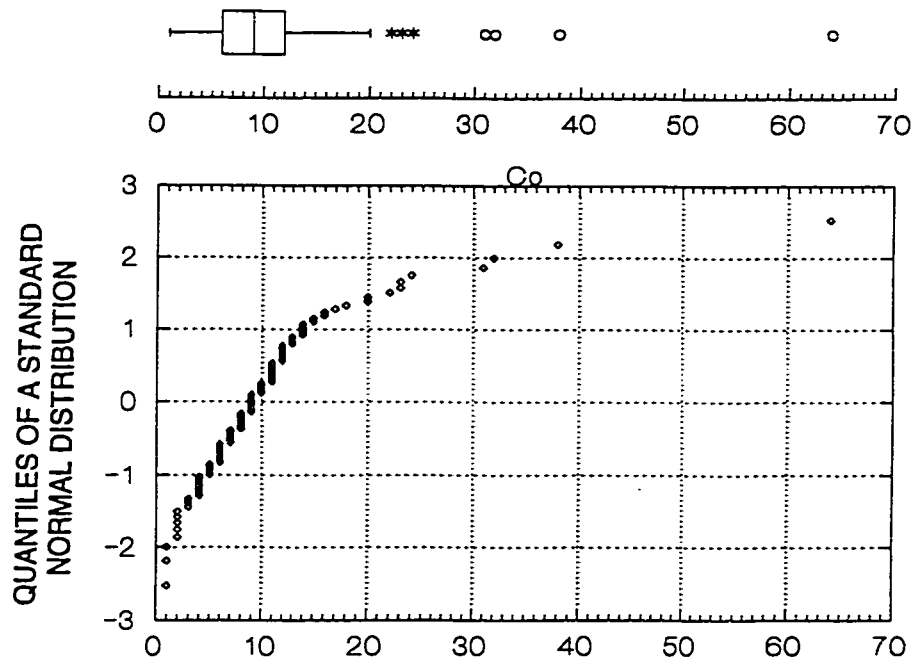
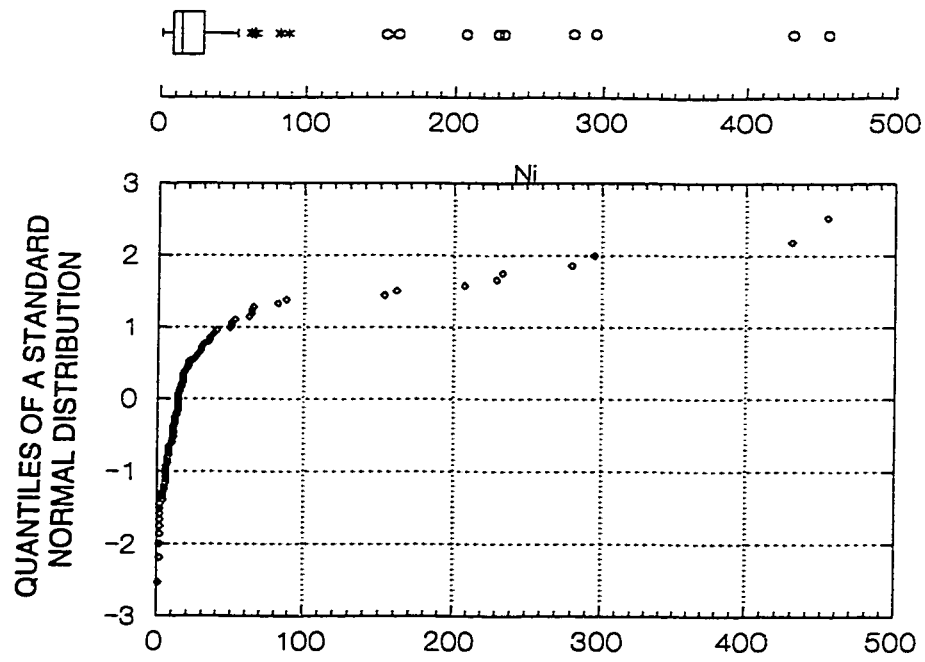
APPENDIX A-2



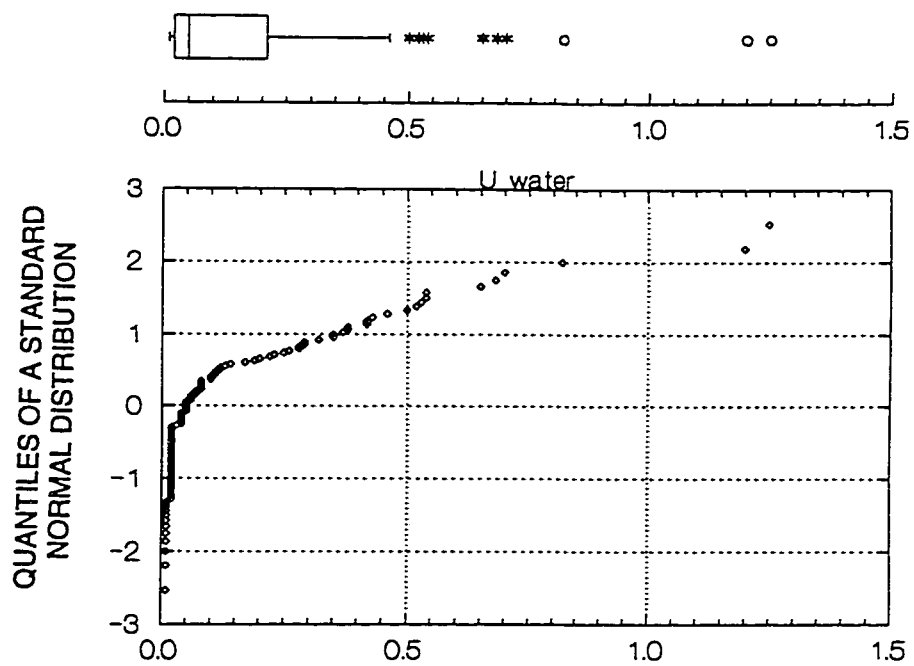
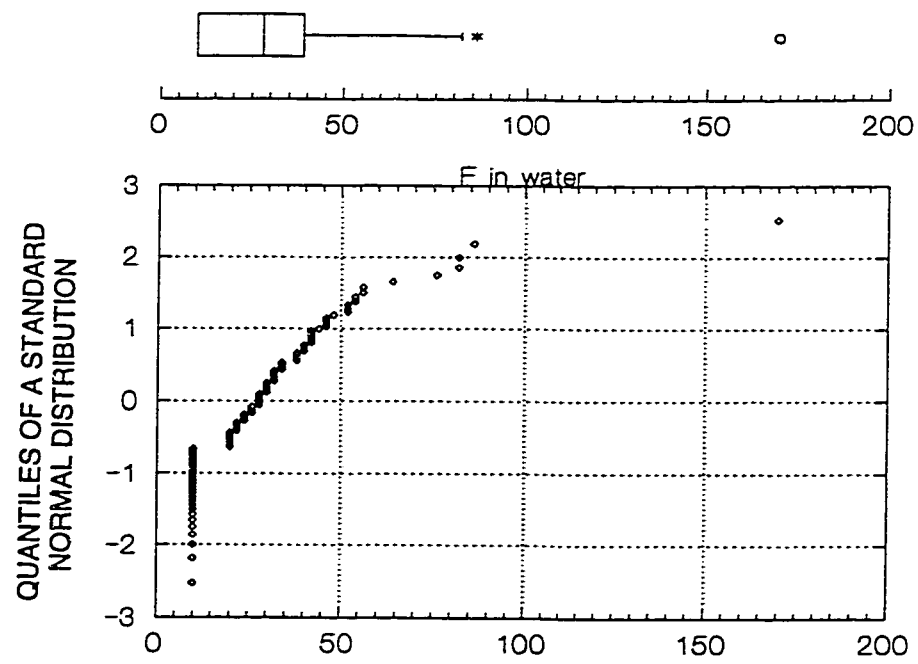
Bulkley (LKqB), Francois Lake (JKqF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites



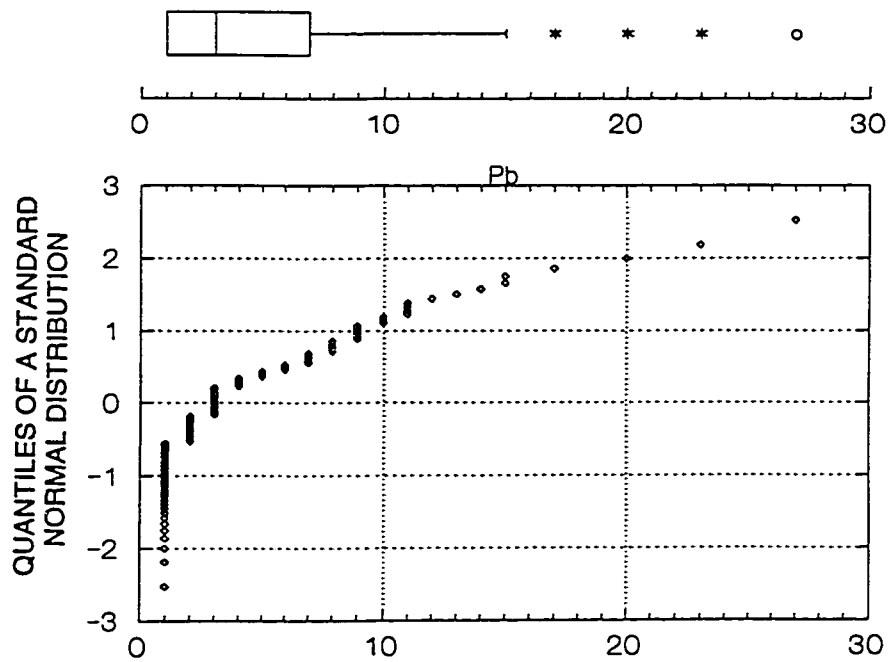
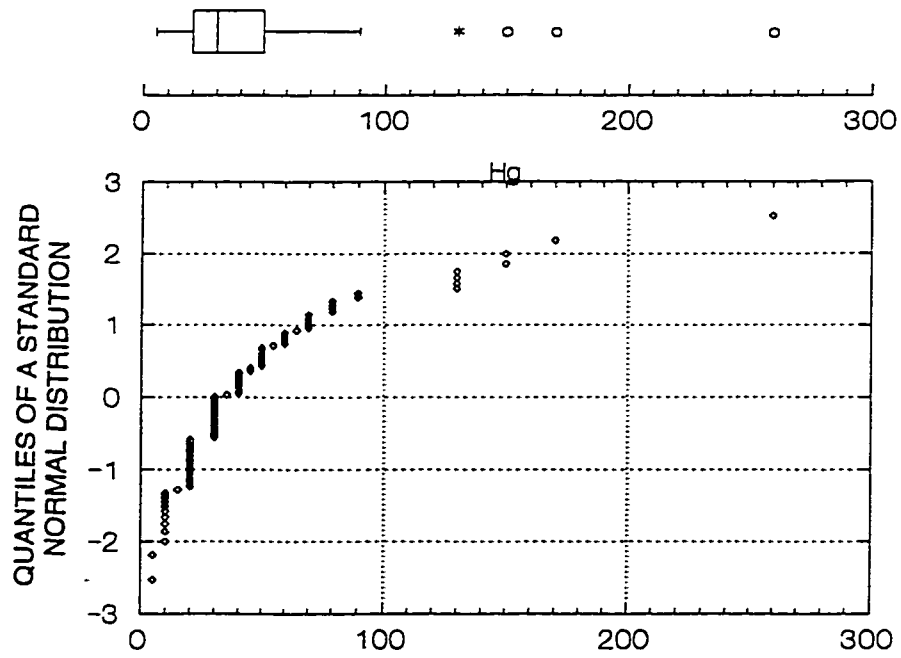
Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites



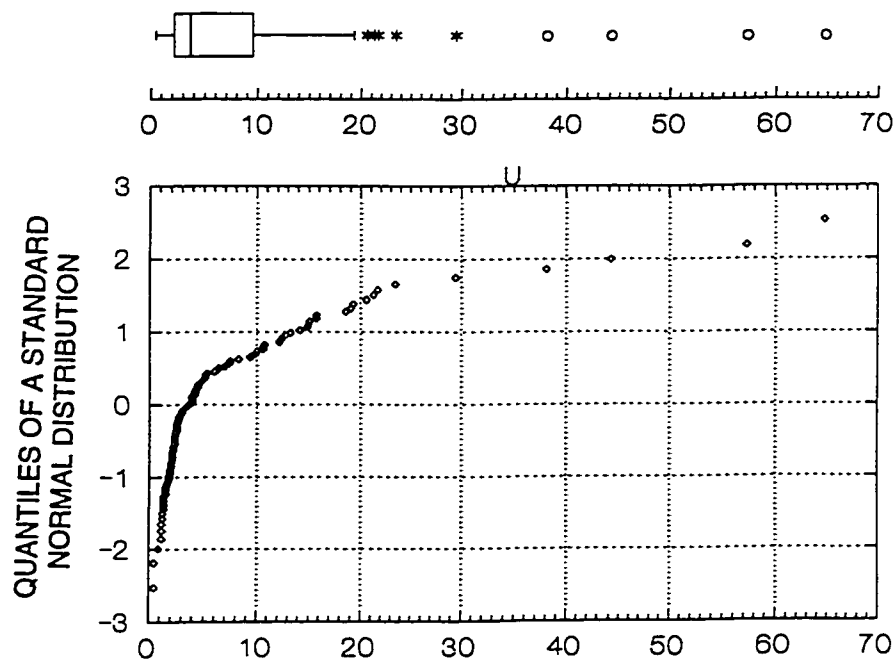
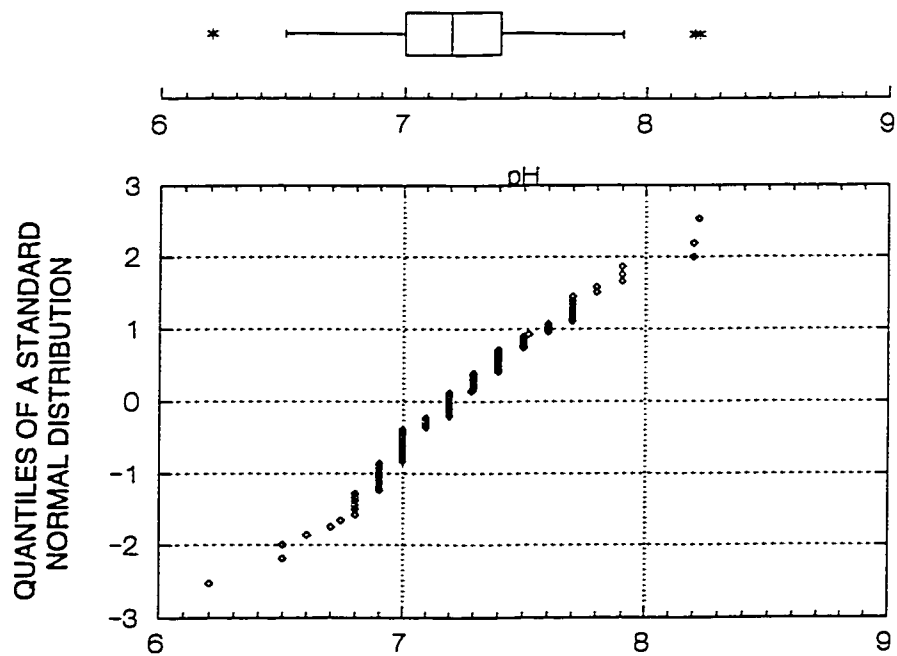
Bulkley (LKqB), Francois Lake (JKqF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites



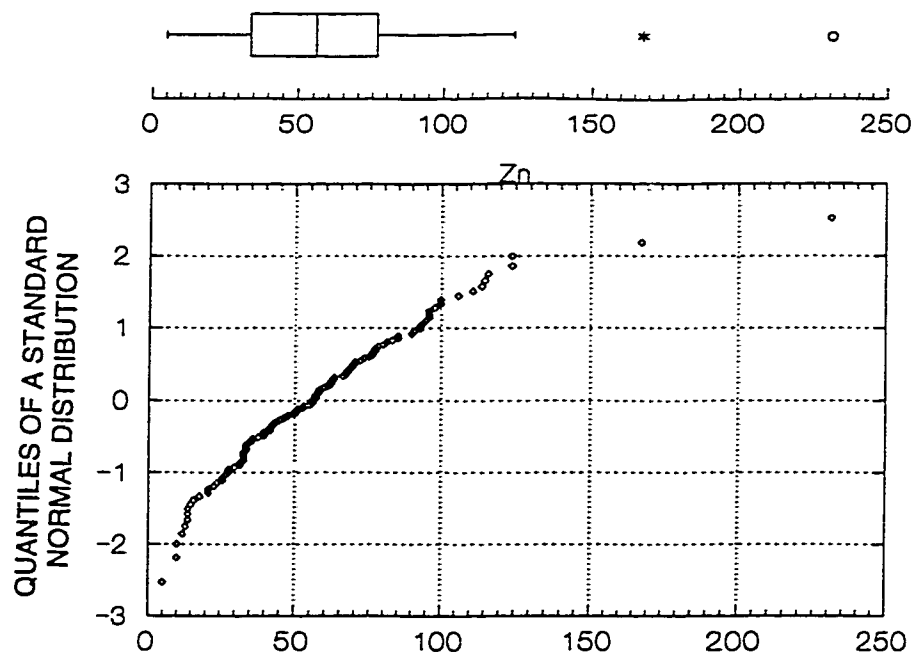
Bulkley (LKqB), Francois Lake (JKqF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites



Bulkley (LKqB), Francois Lake (JKqF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites

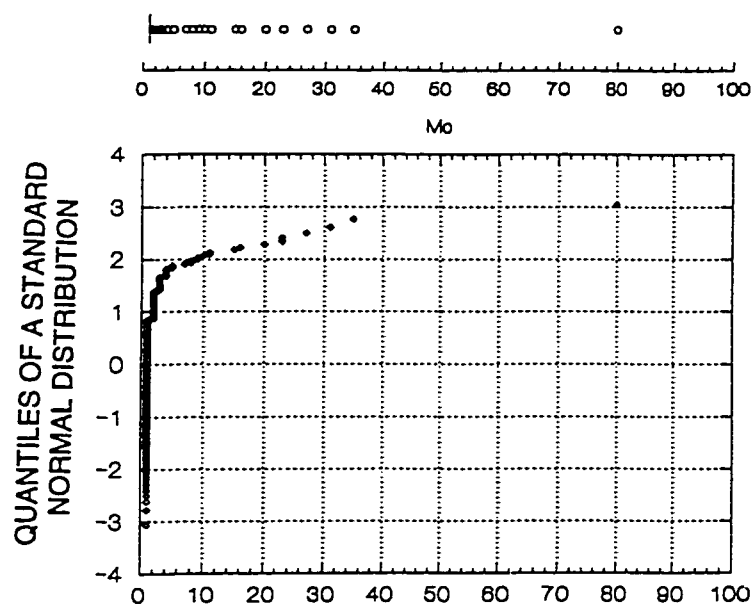
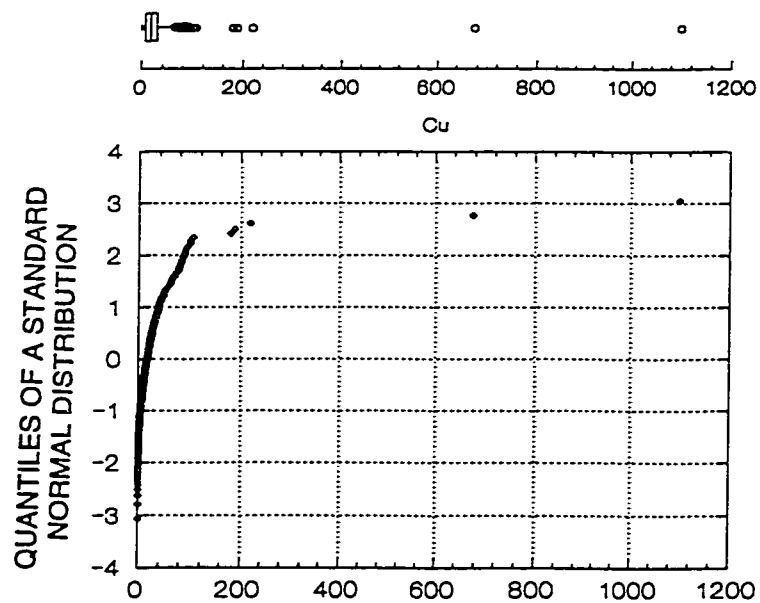


Bulkley (LKqB), Francois Lake (JKqF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites

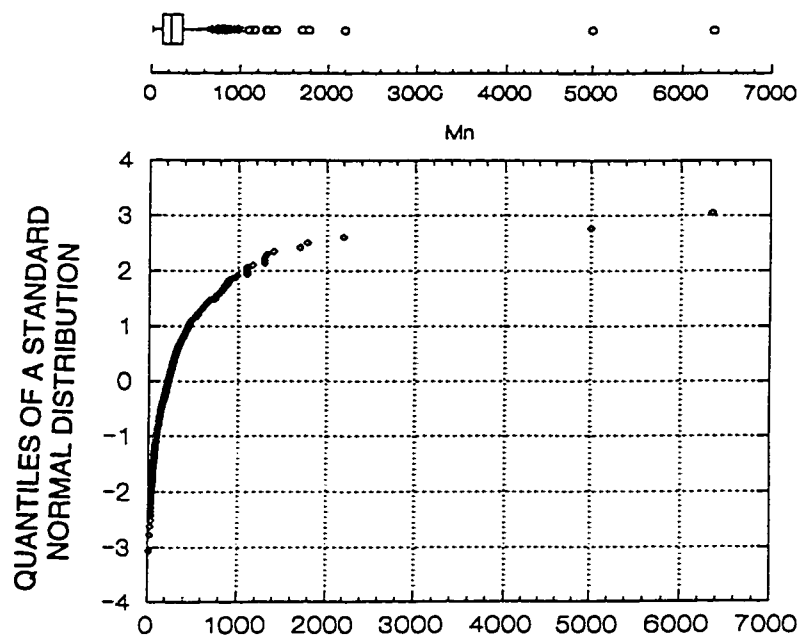
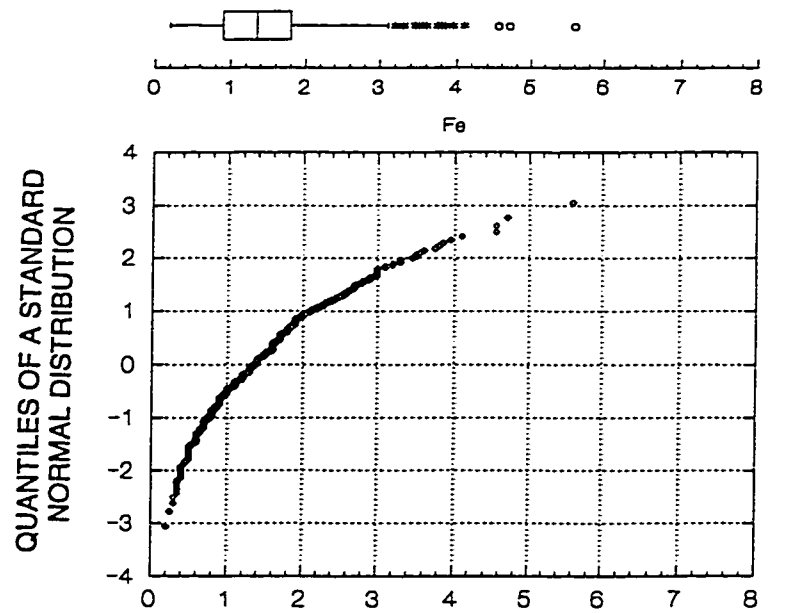


Bulkley (LKqB), Francois Lake (JKqF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites

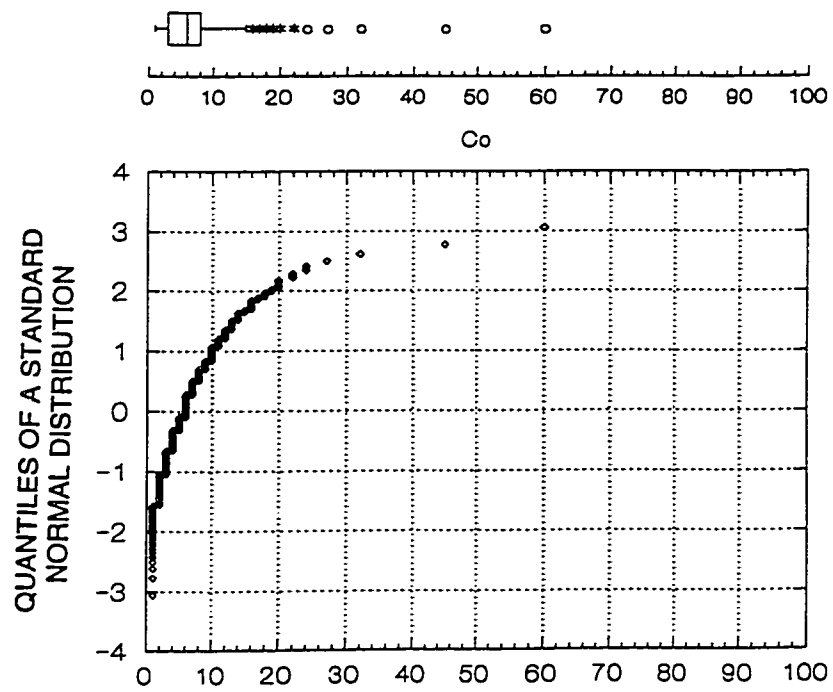
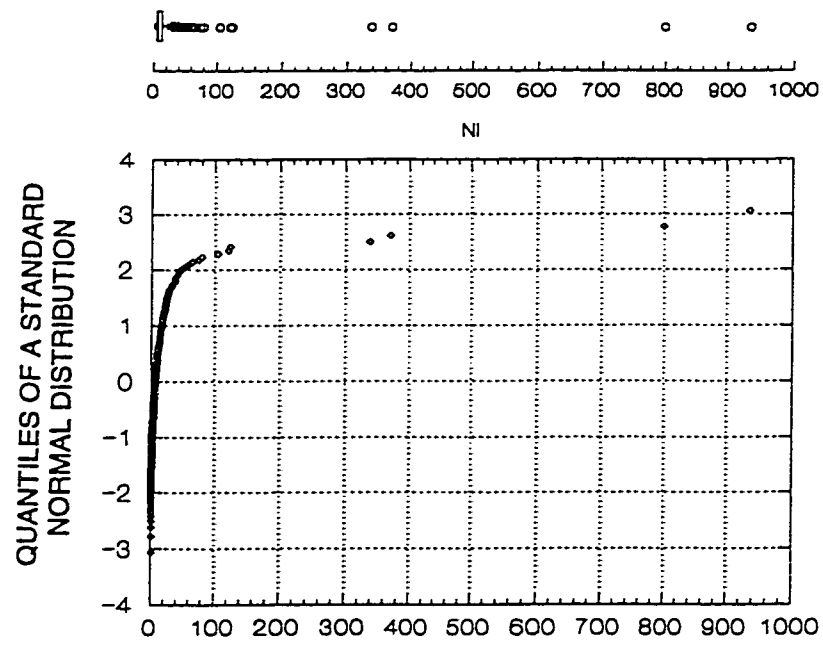
APPENDIX A-3



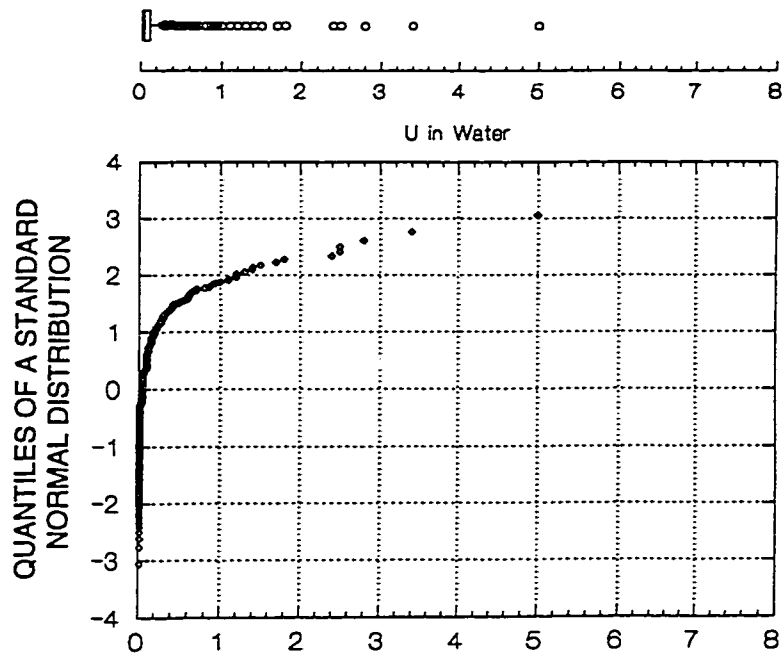
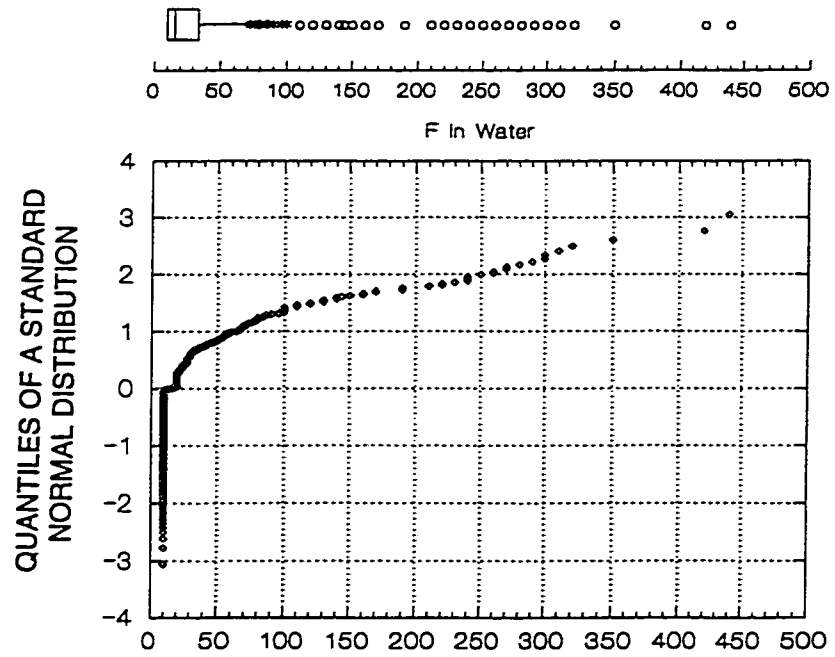
Late Cretaceous plutonic suites (LKq)



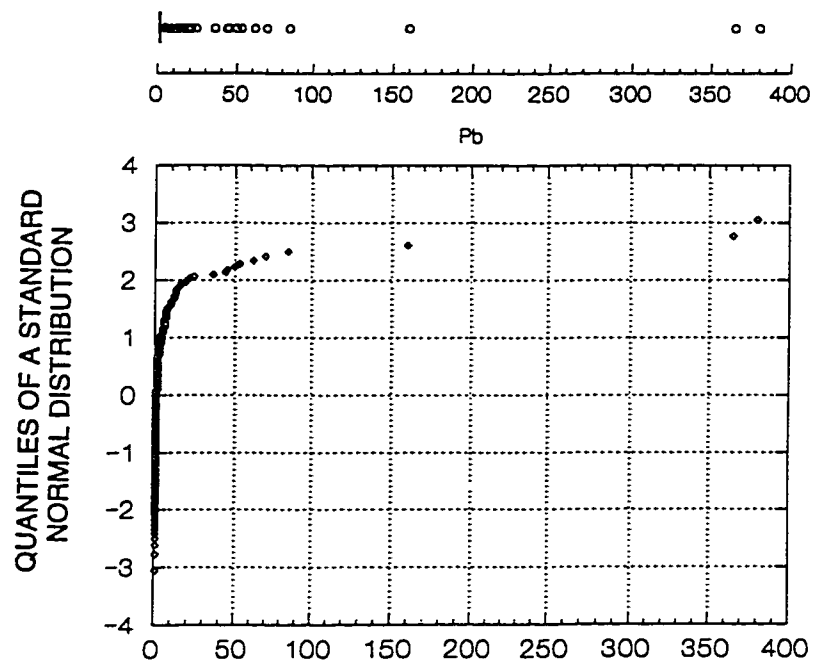
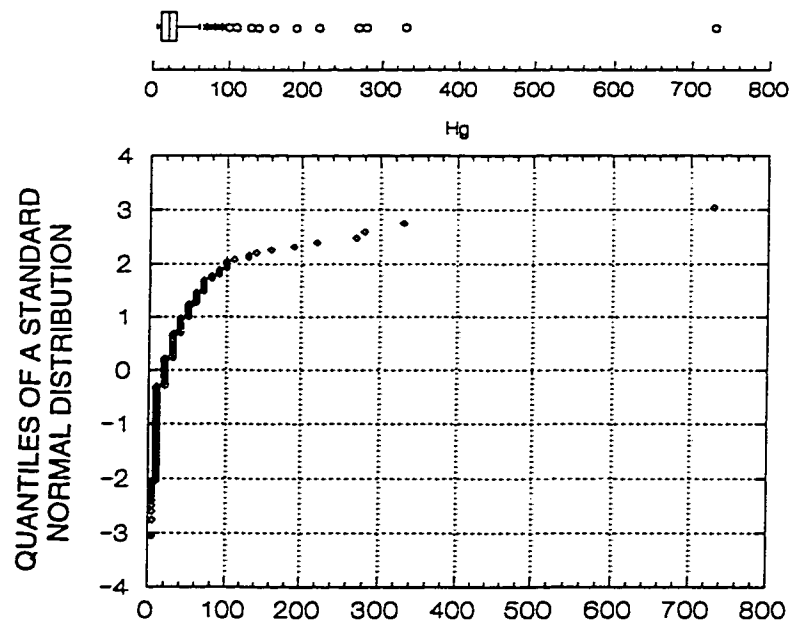
Late Cretaceous plutonic suites (LKq)



Late Cretaceous plutonic suites (LKg)

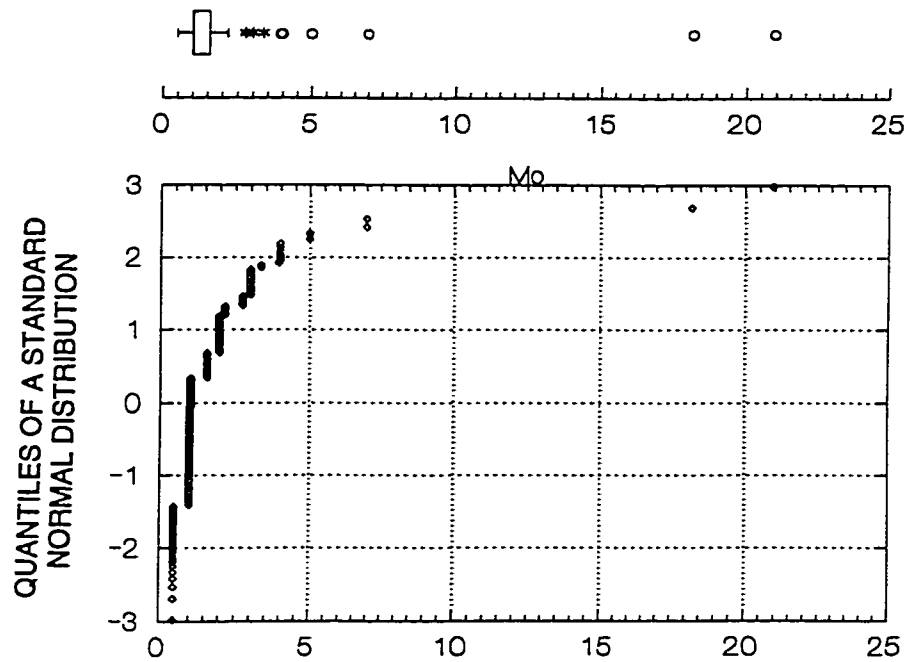
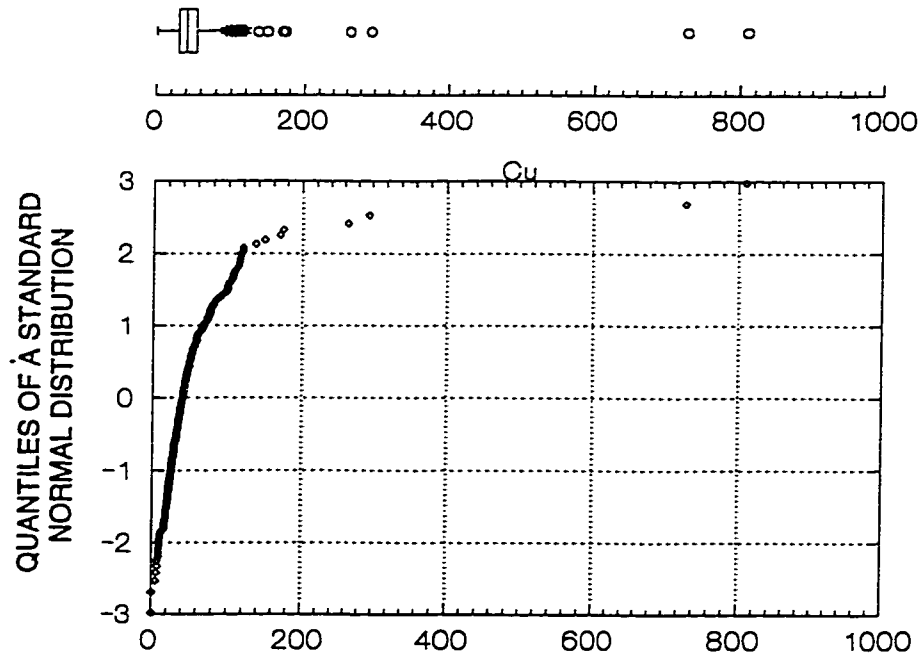


Late Cretaceous plutonic suites (LKq)

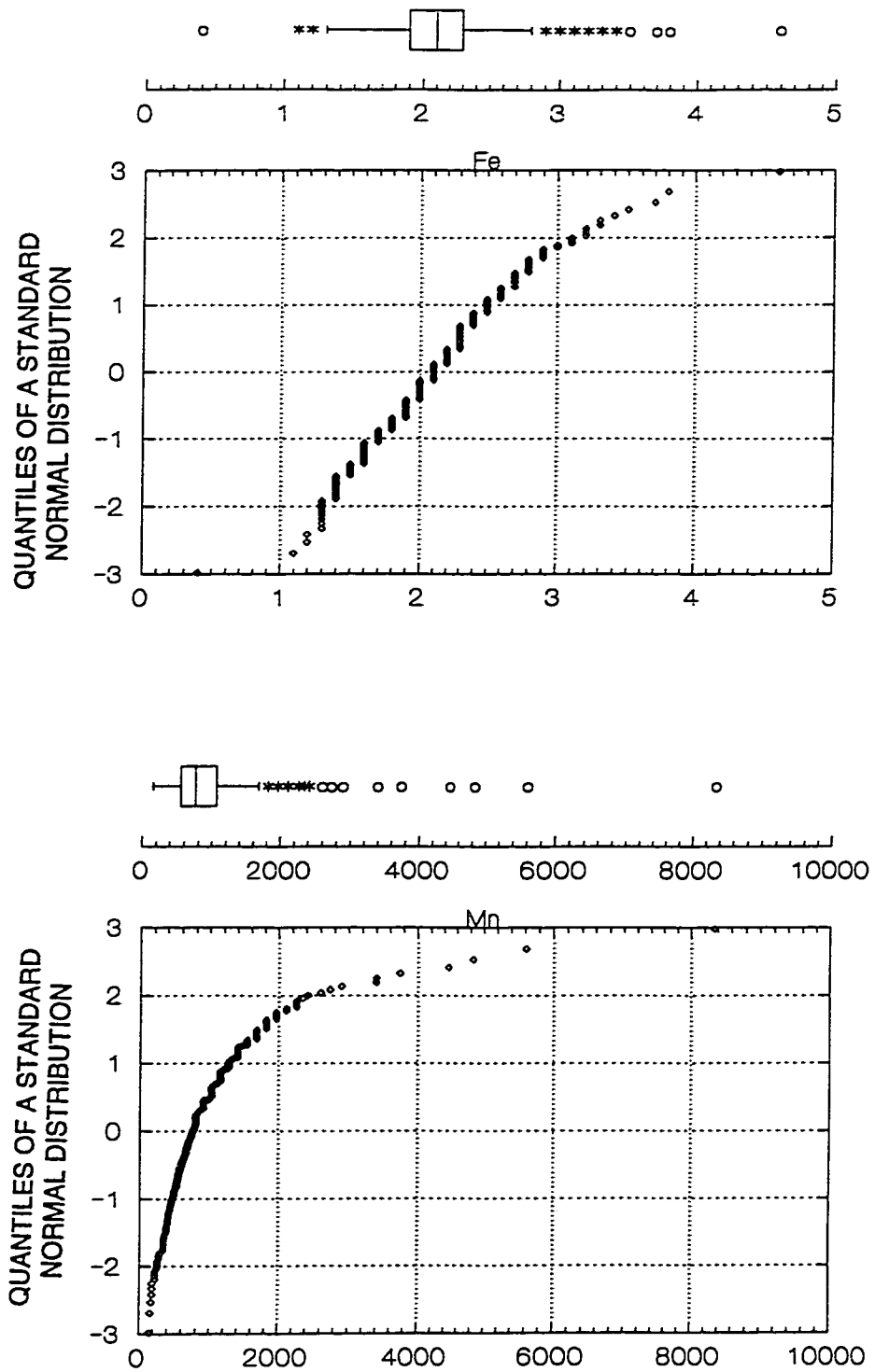


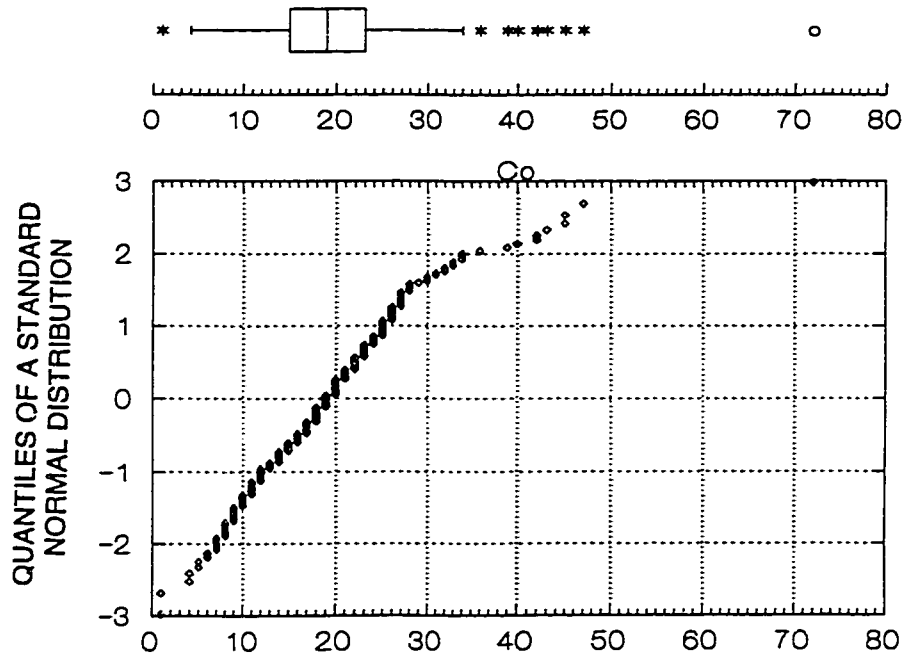
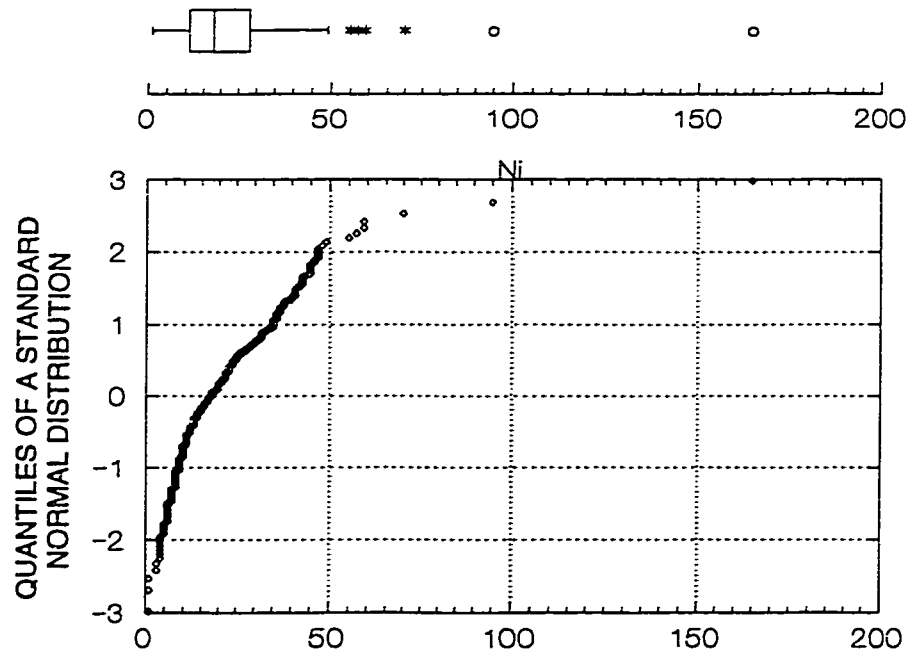
Late Cretaceous plutonic suites (LKg)

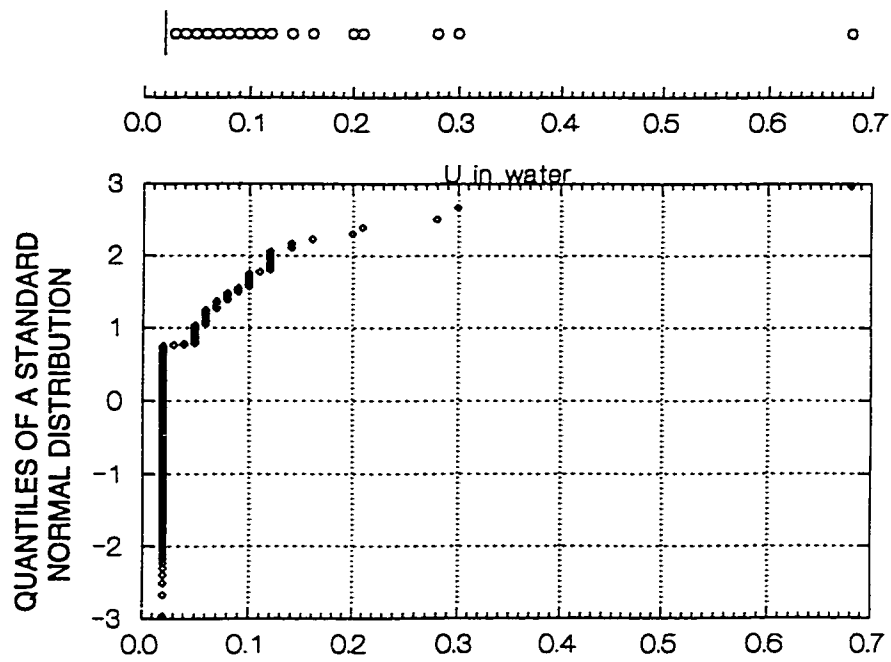
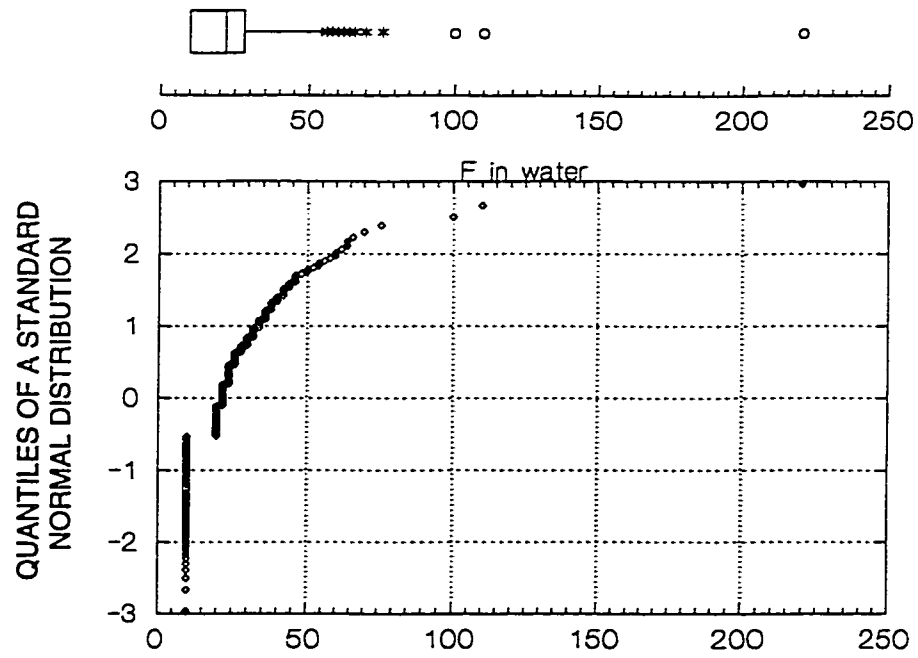
APPENDIX A-4

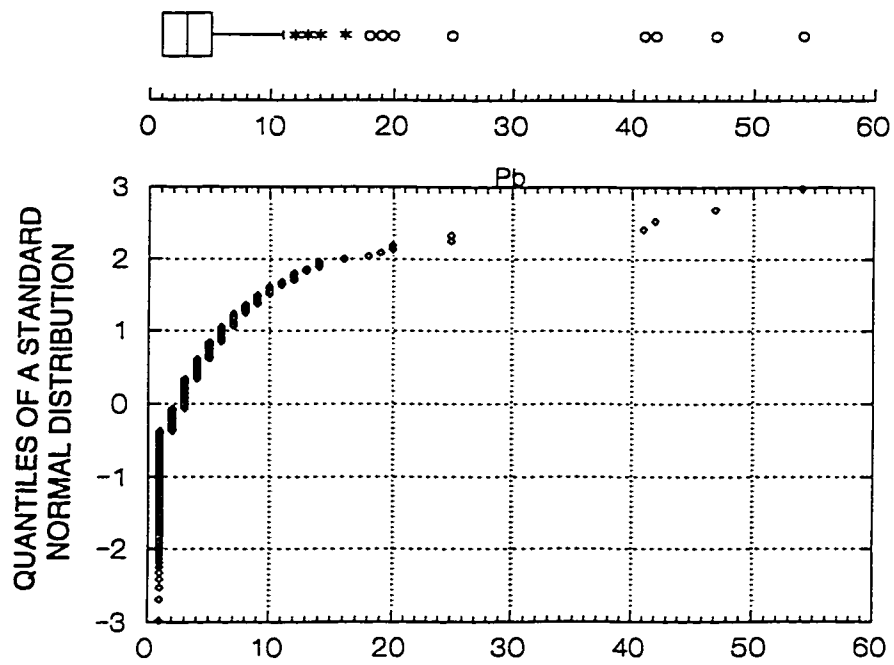
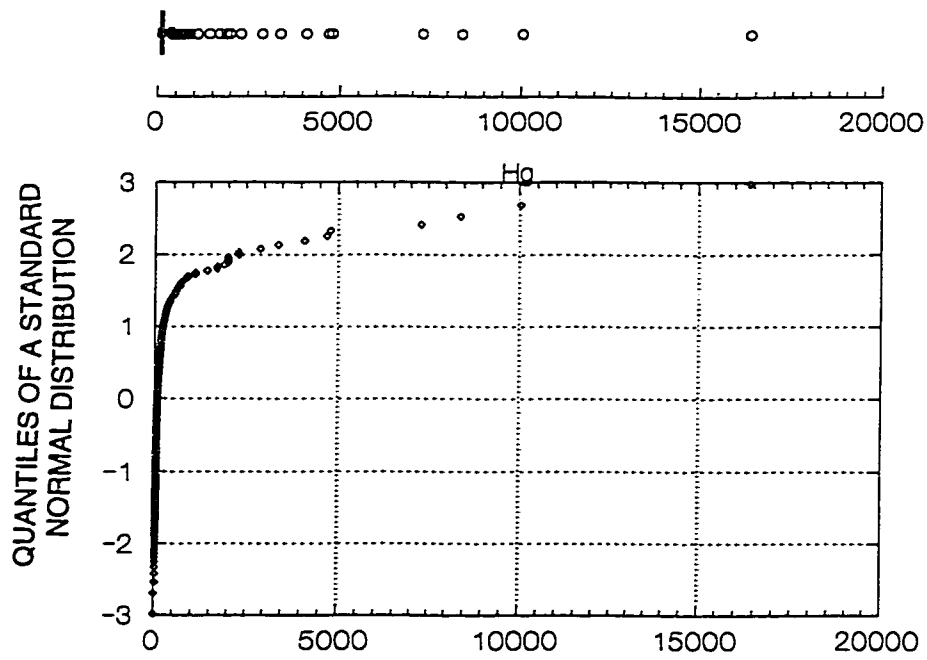


Bonanza Group (JB)

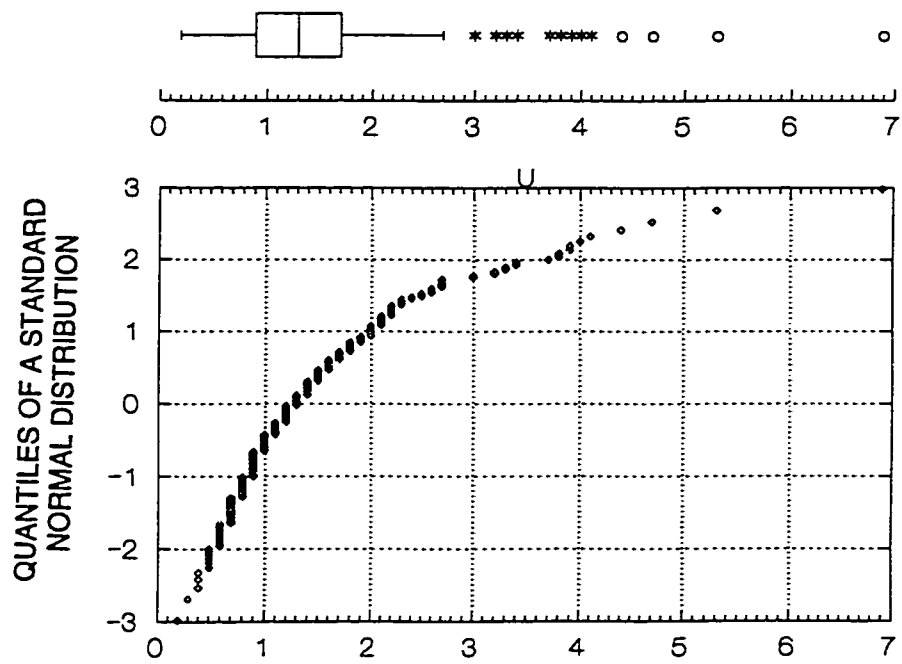
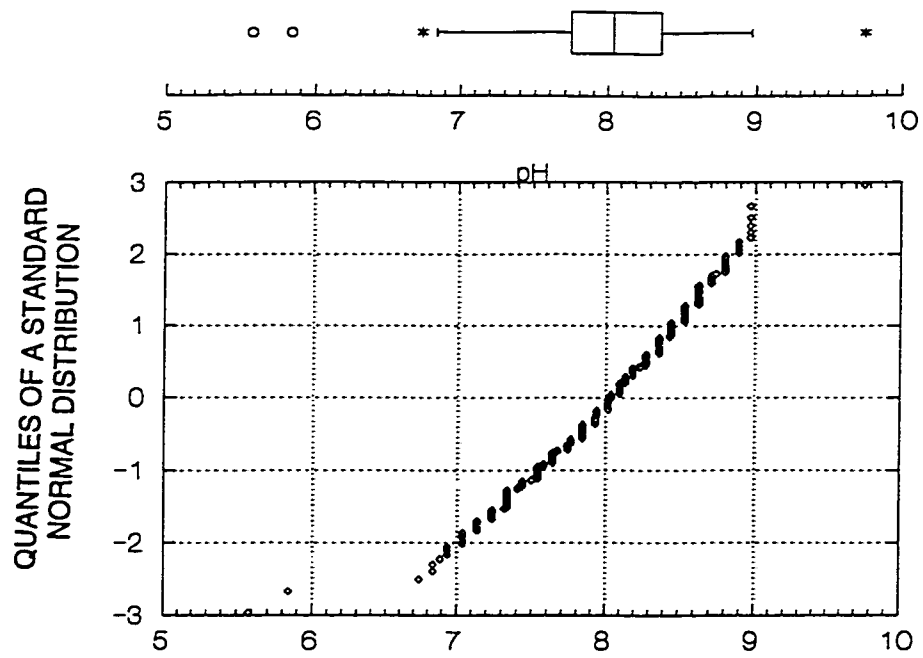


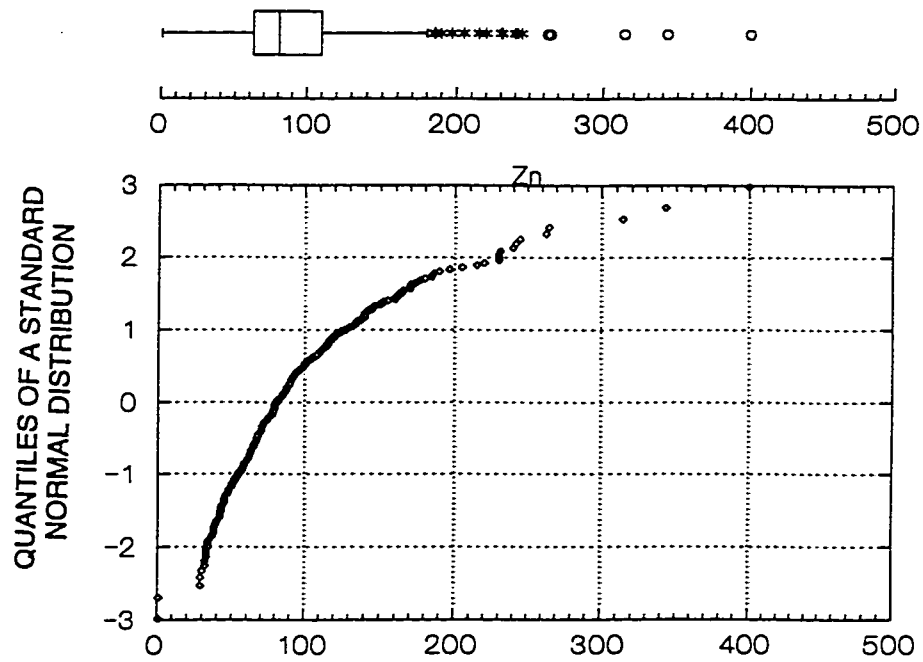
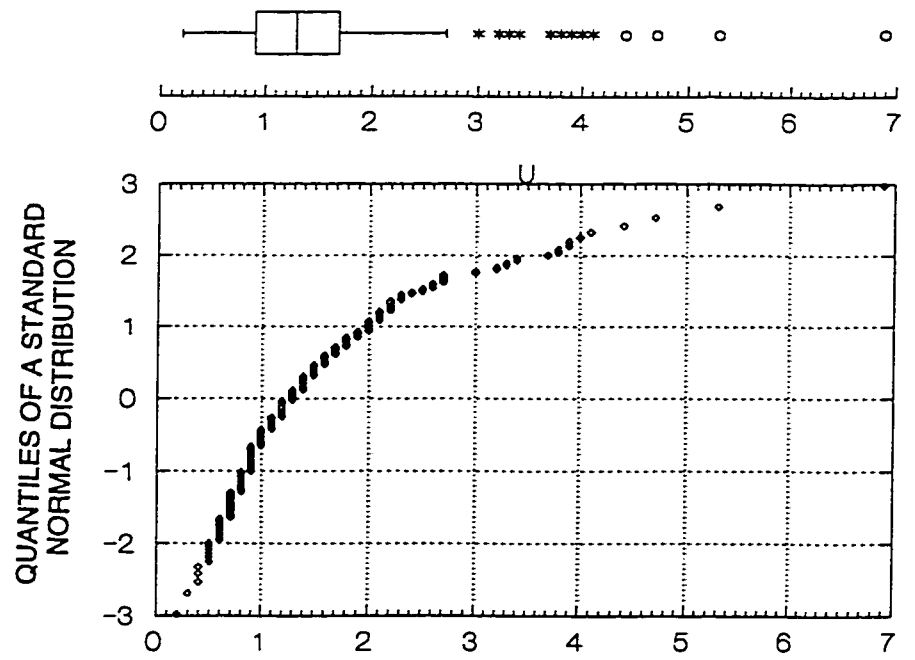




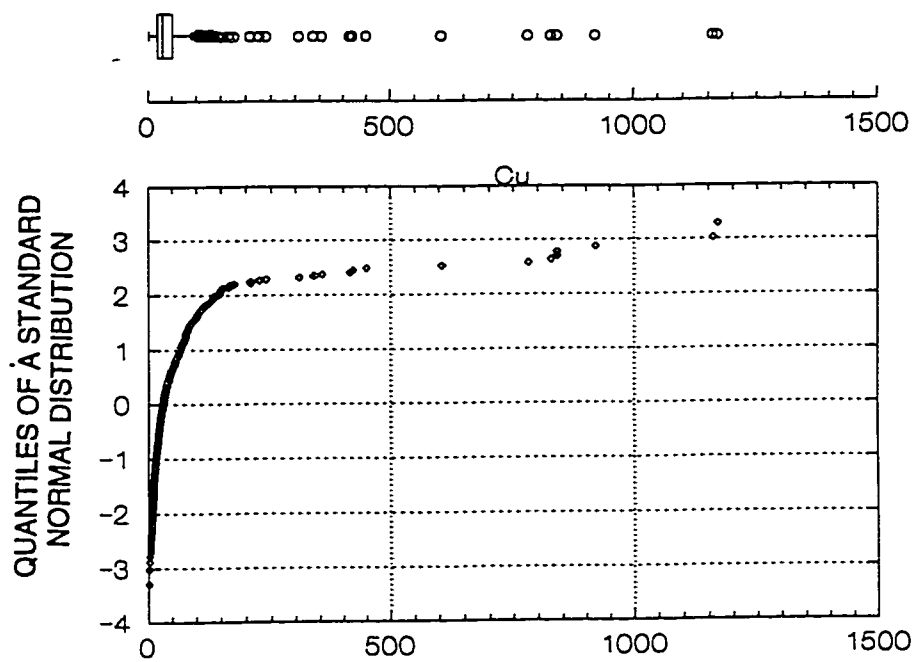
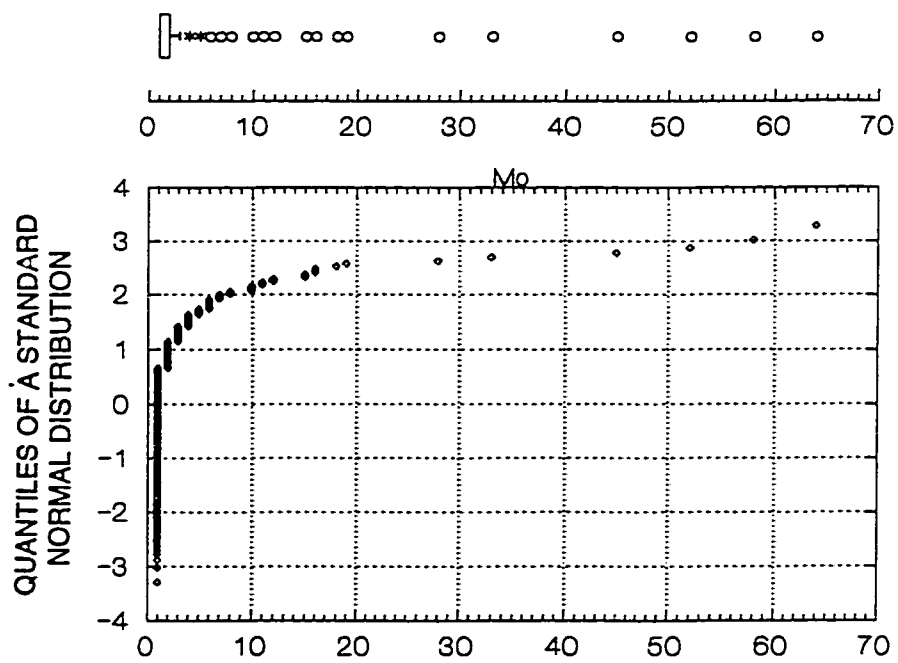


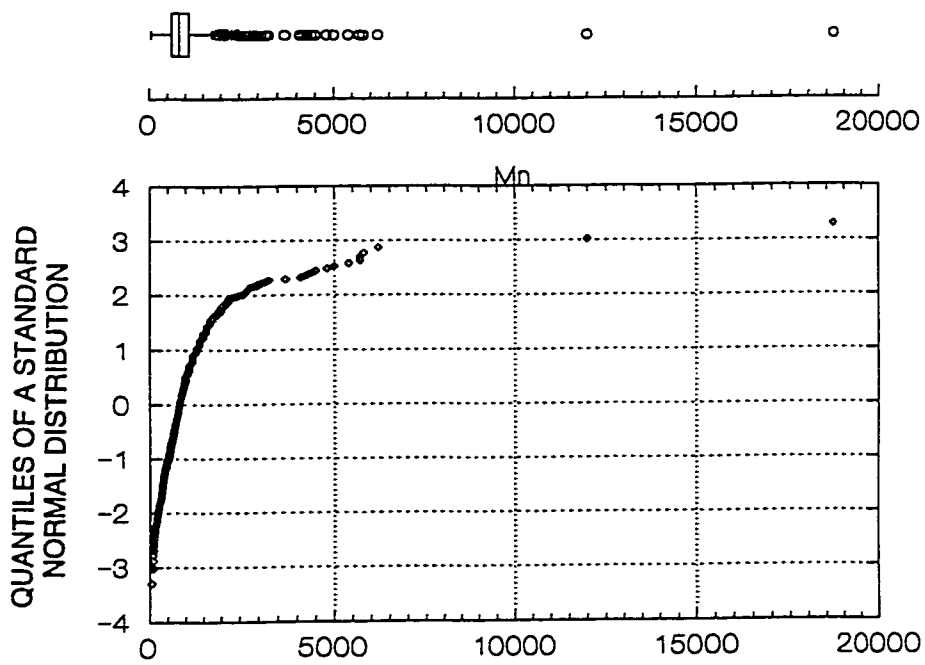
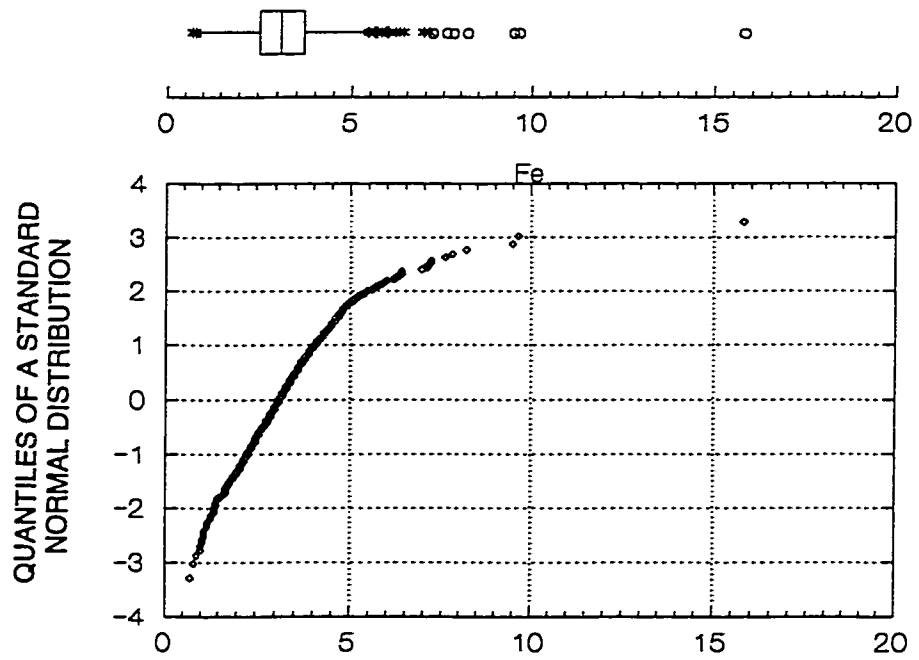
Bonanza Group (JB)



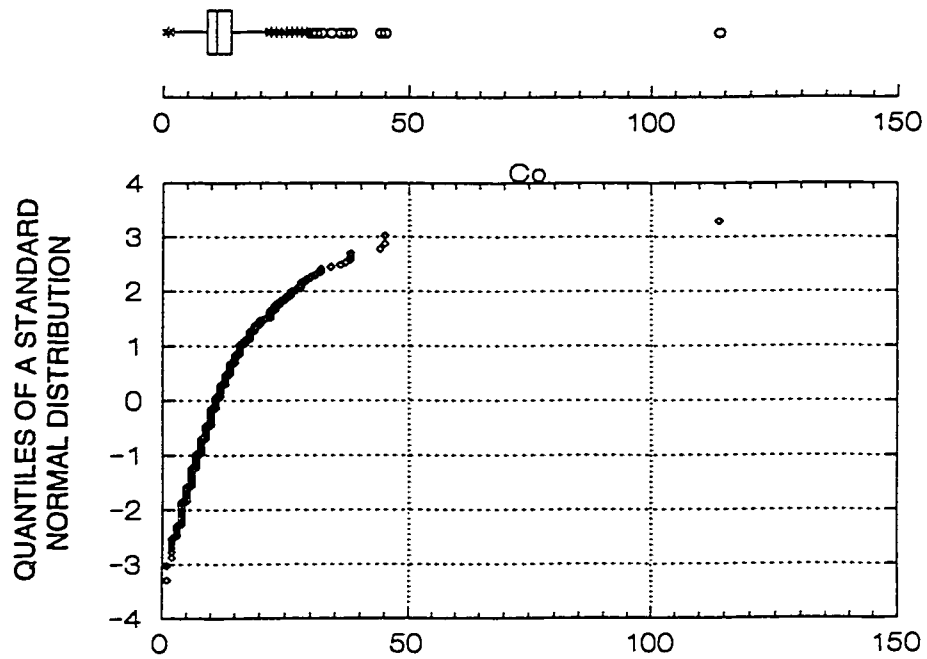
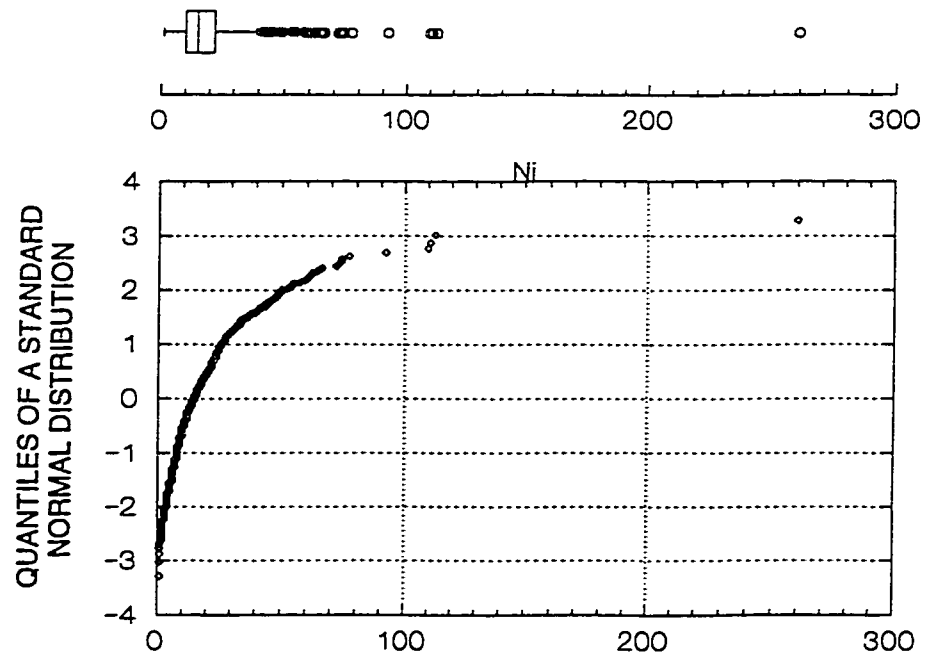


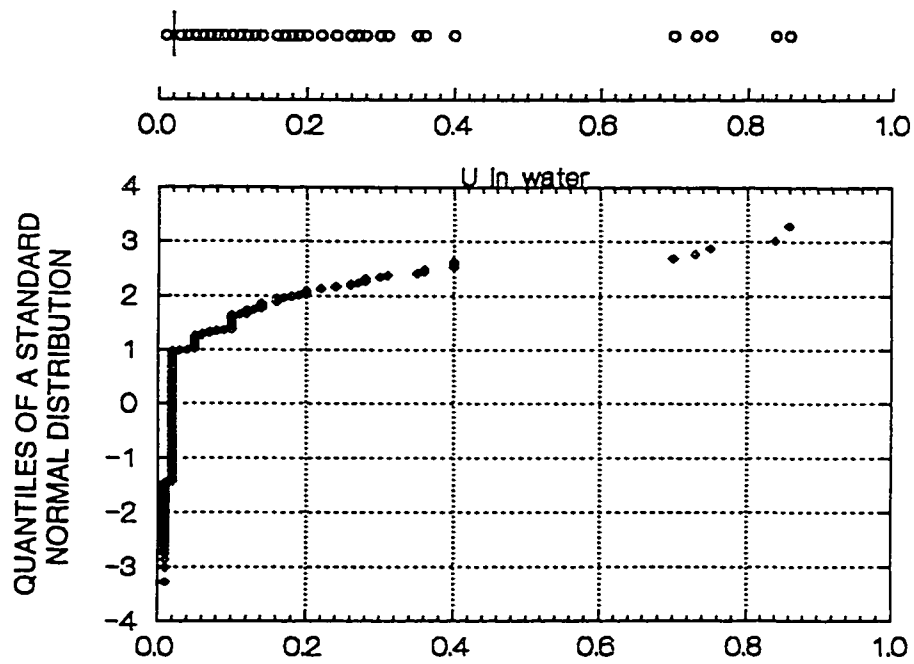
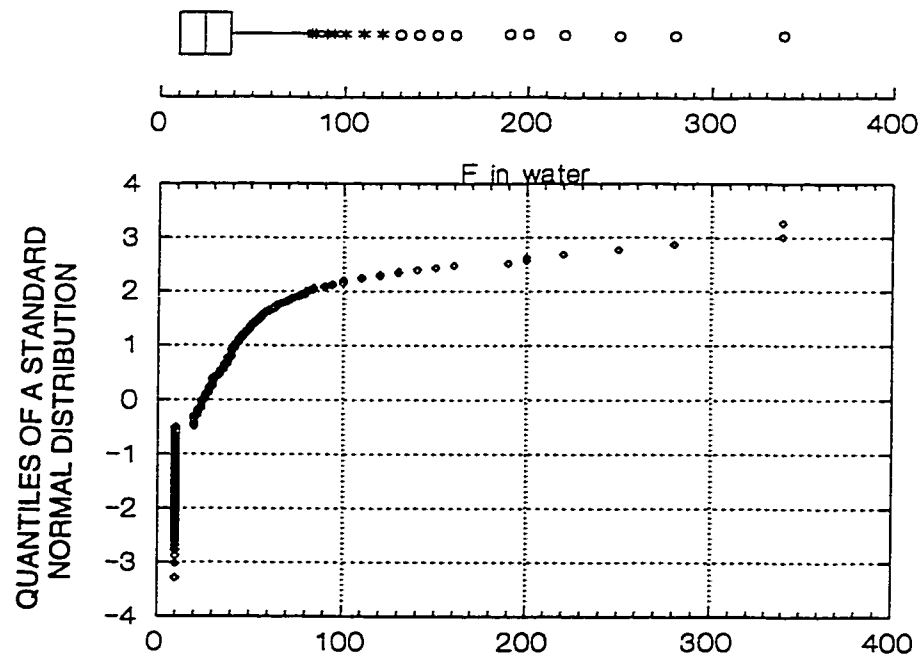
APPENDIX A-5

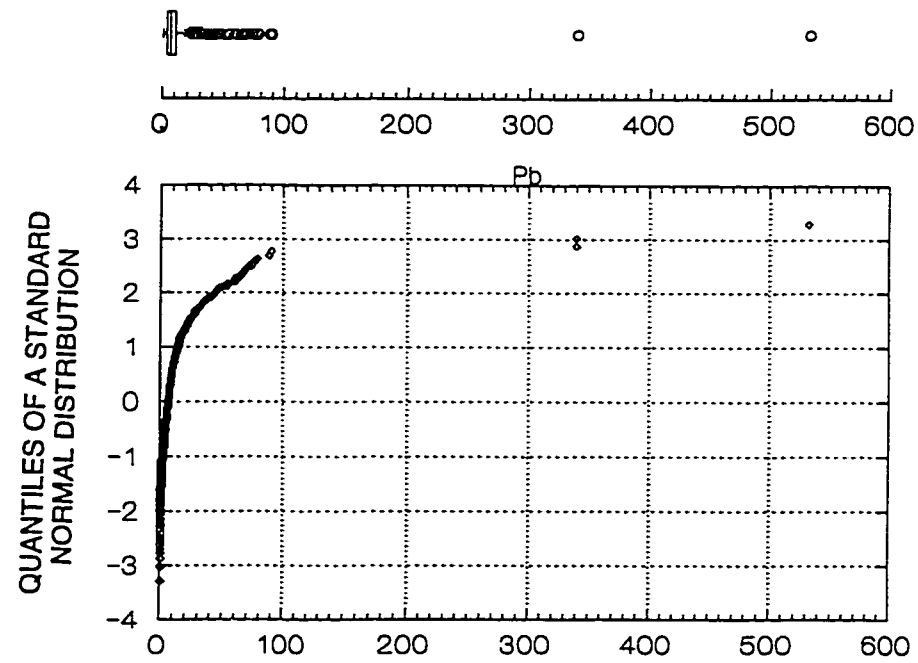
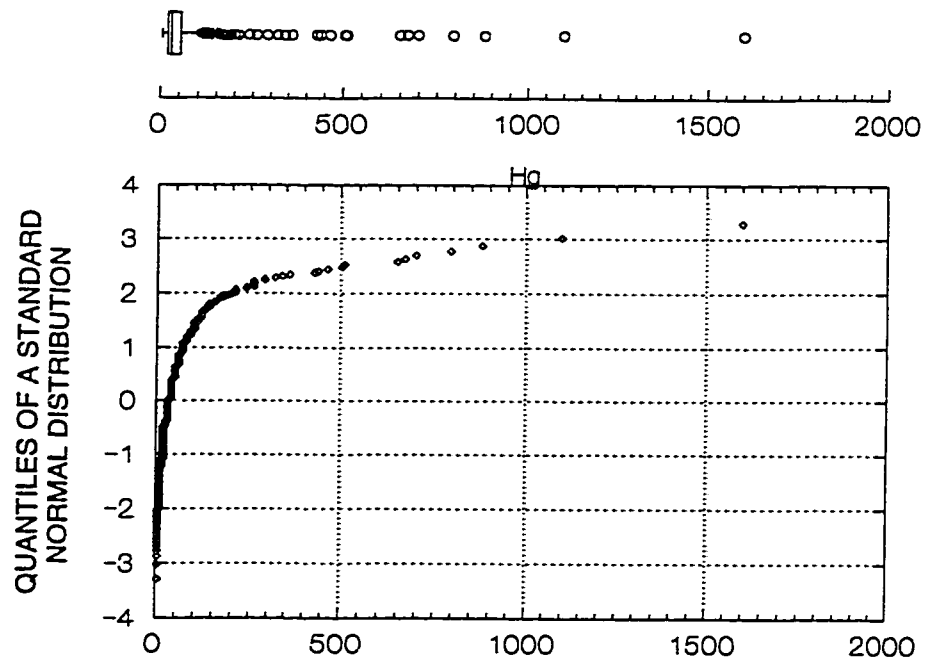




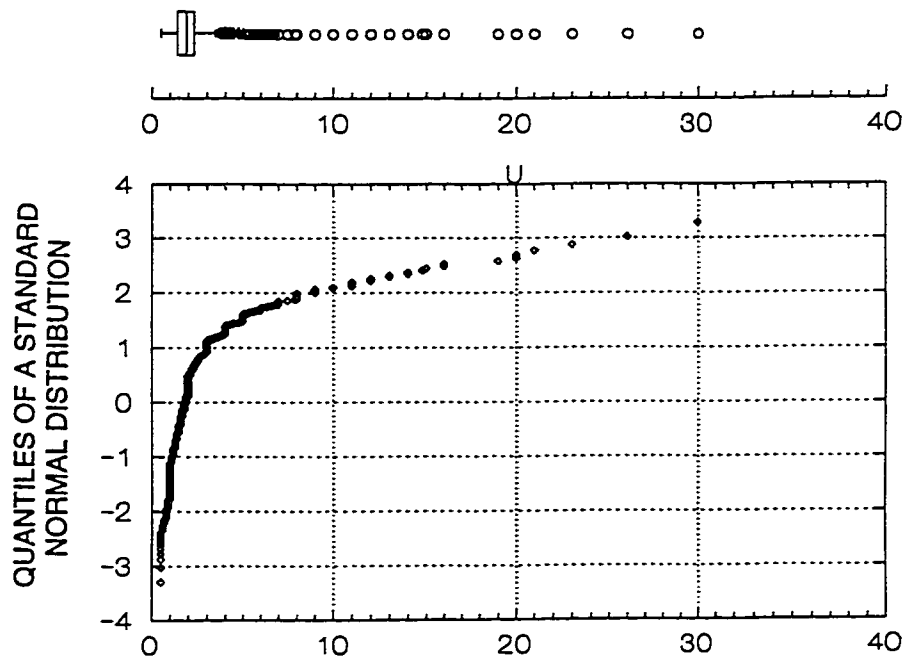
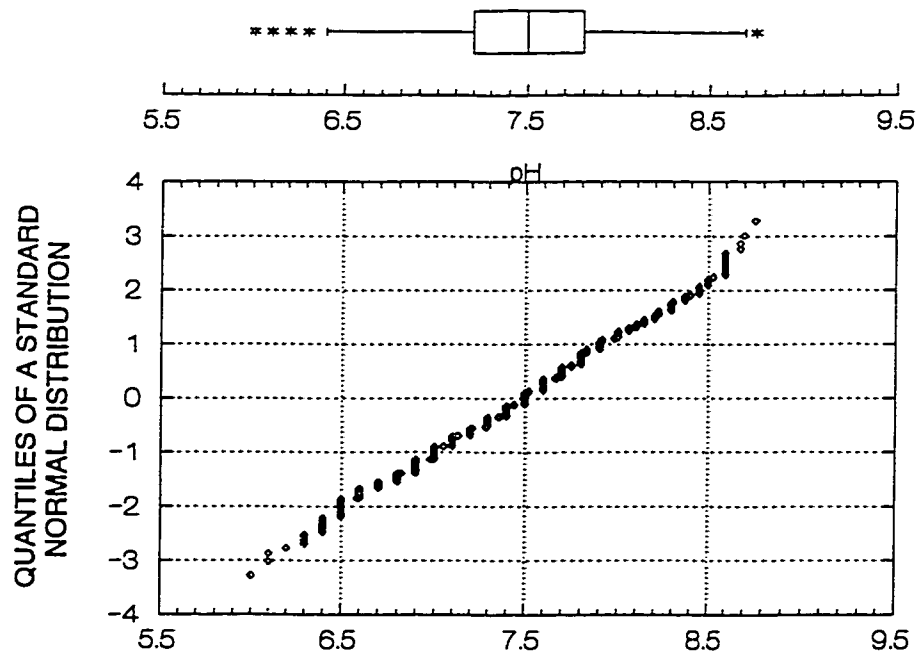
Hazelton (JH)

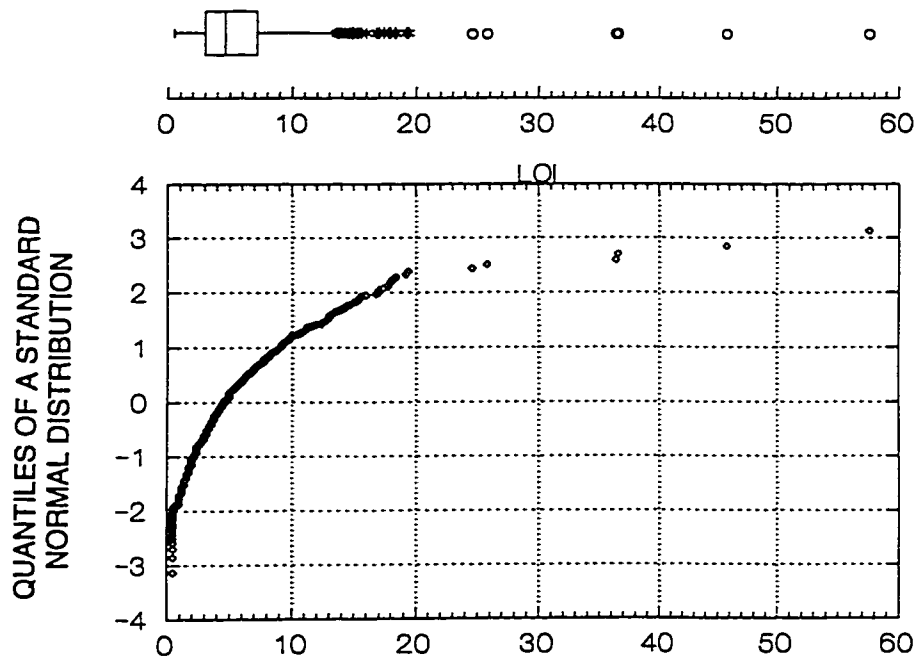
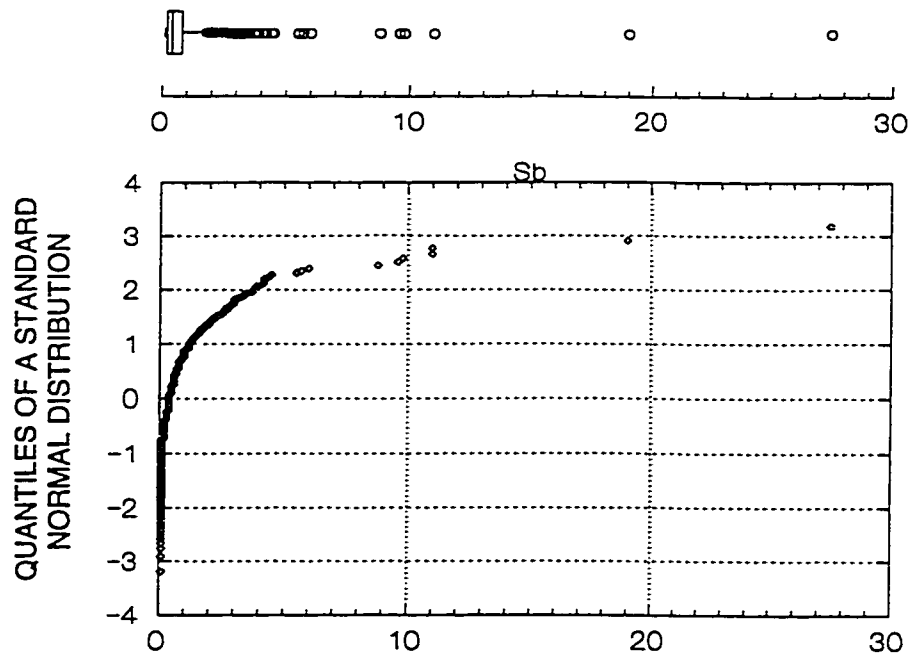




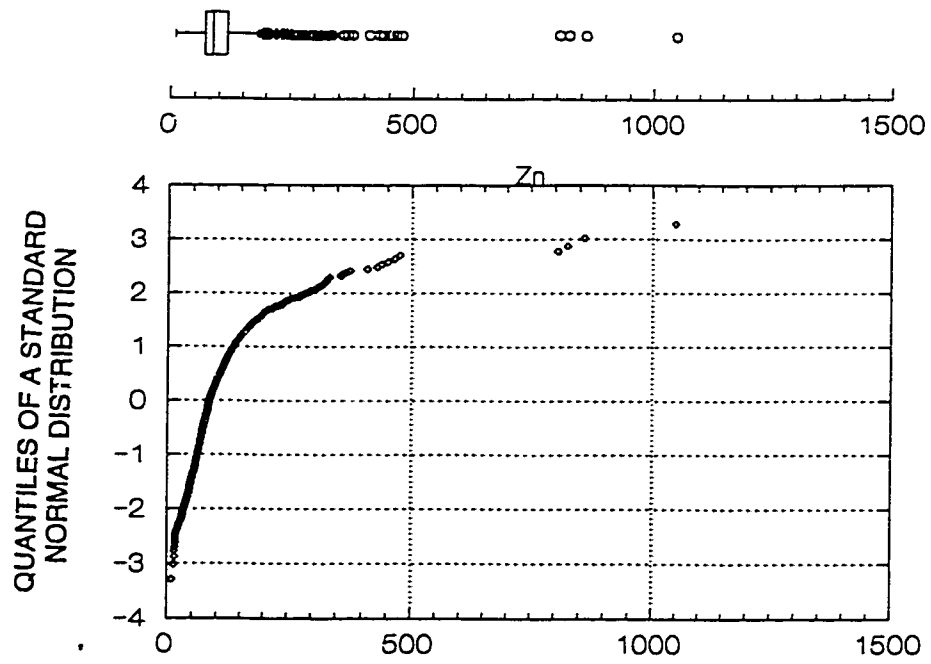


Hazelton (JH)

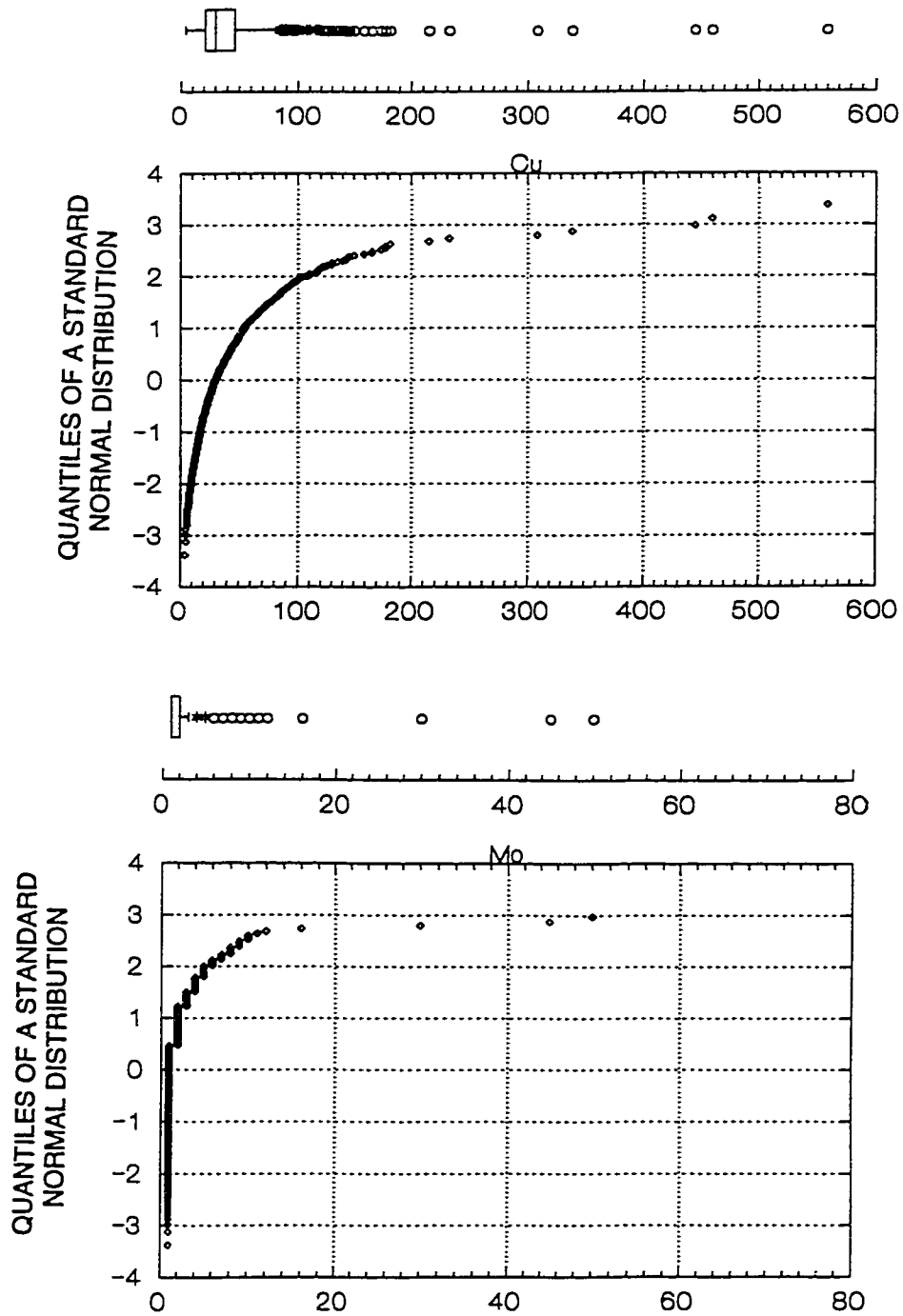


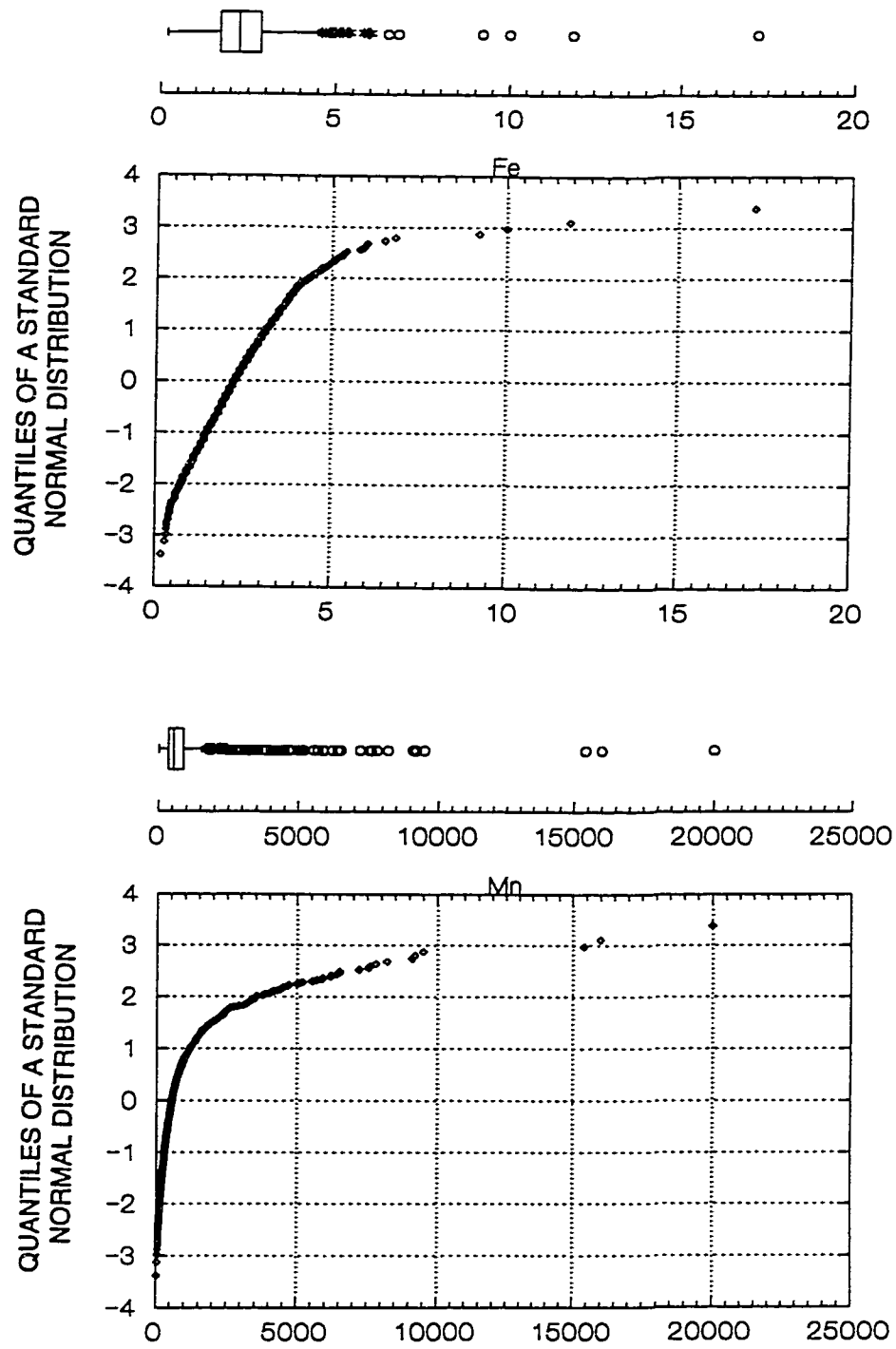


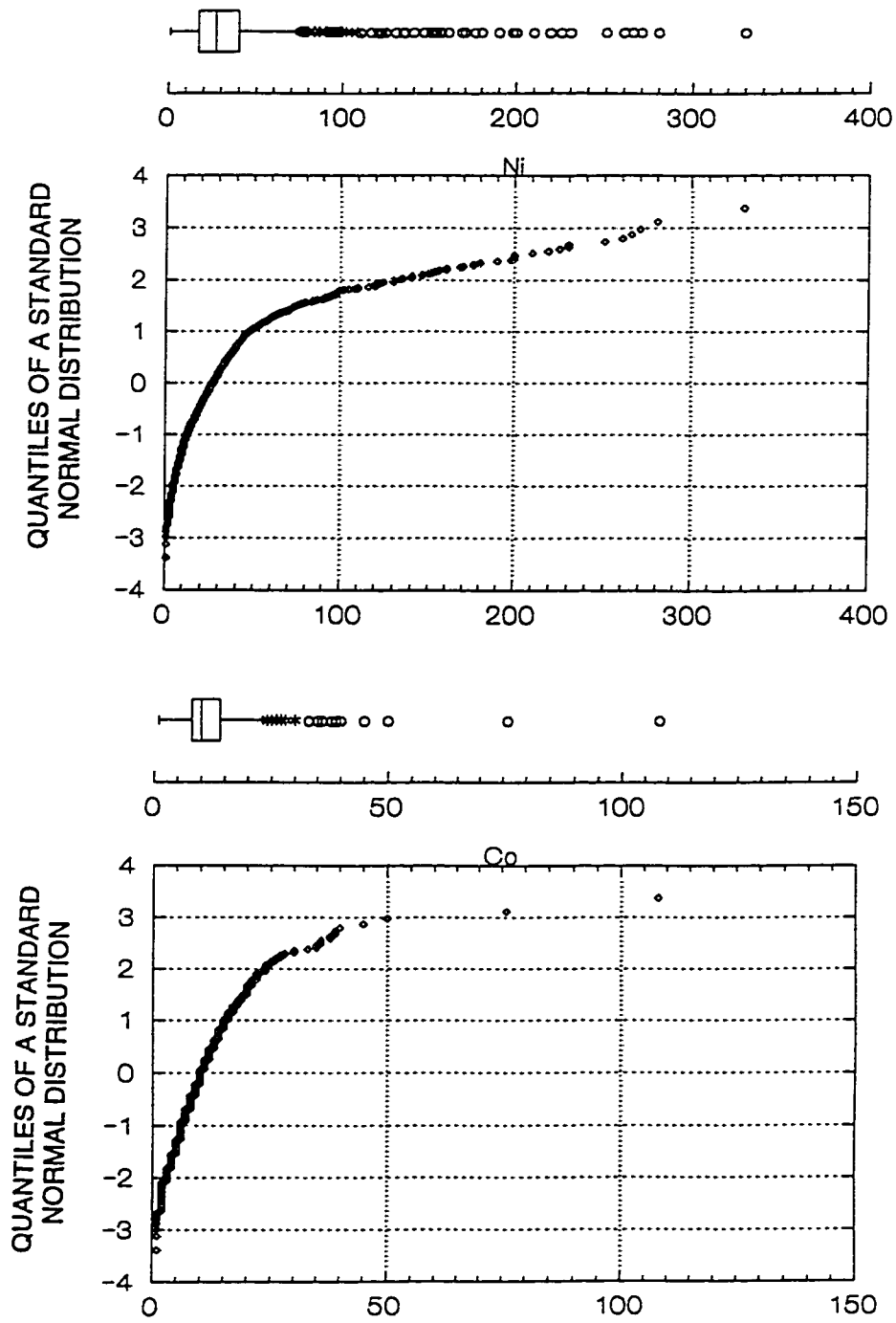
Hazelton (JH)

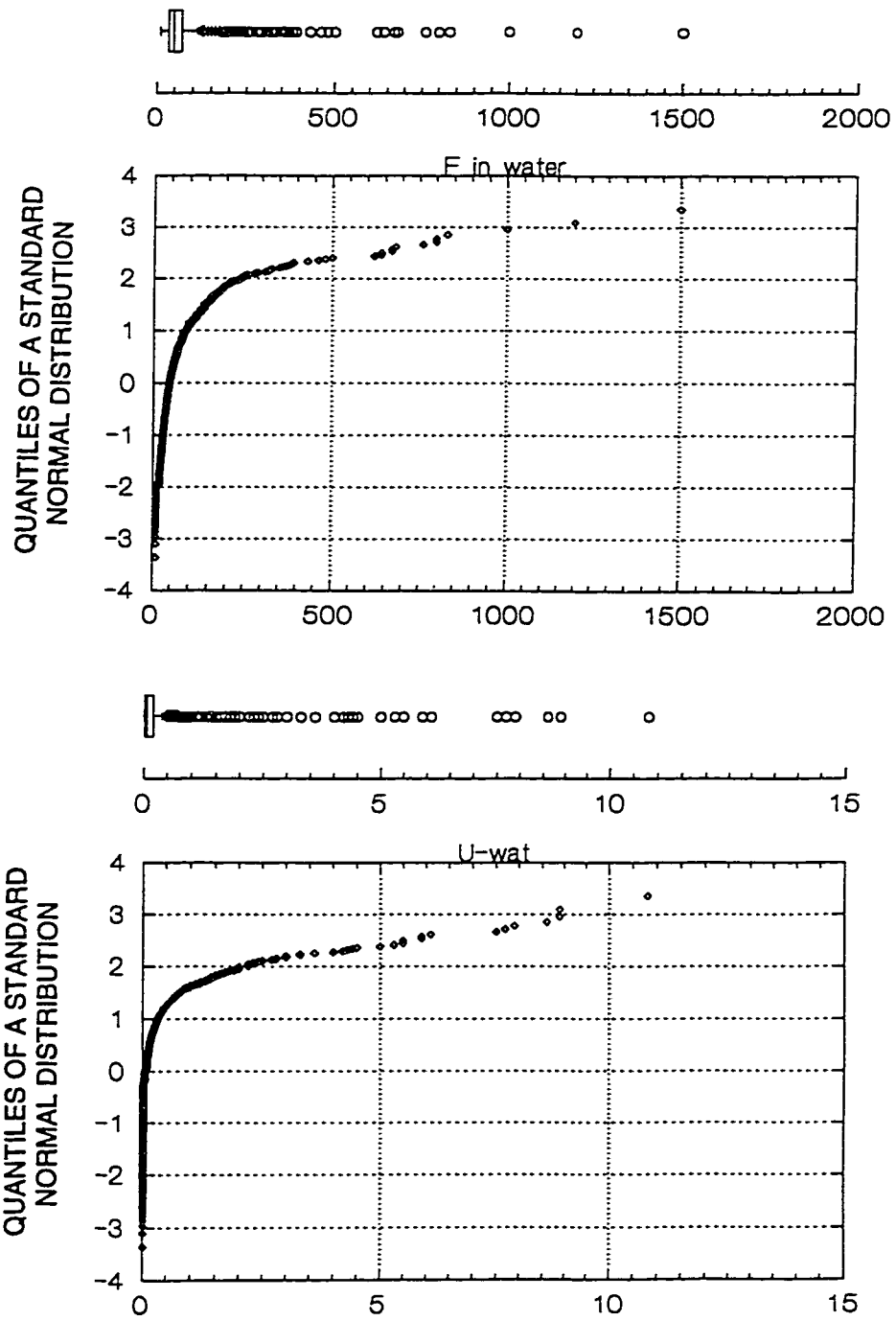


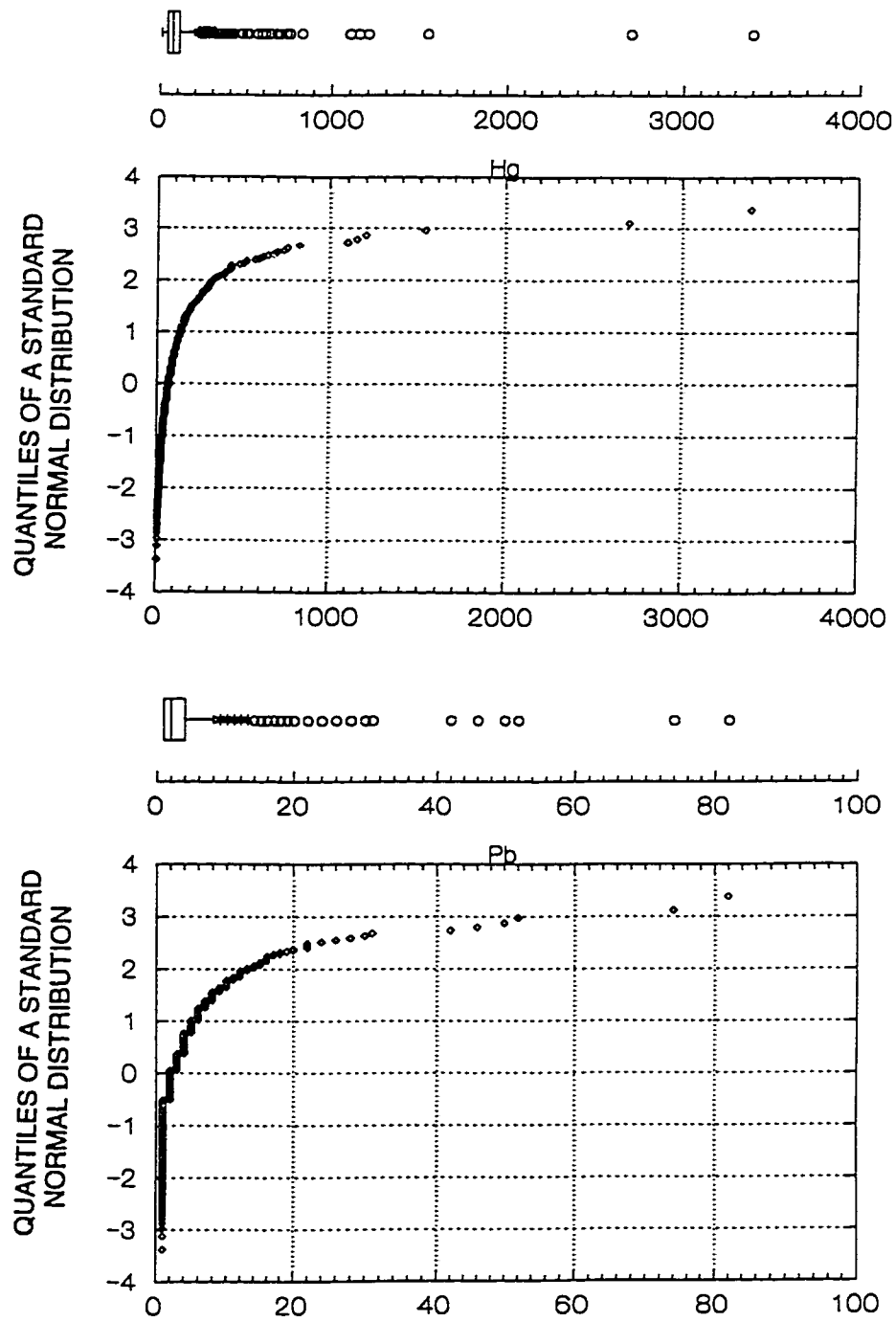
APPENDIX A-6

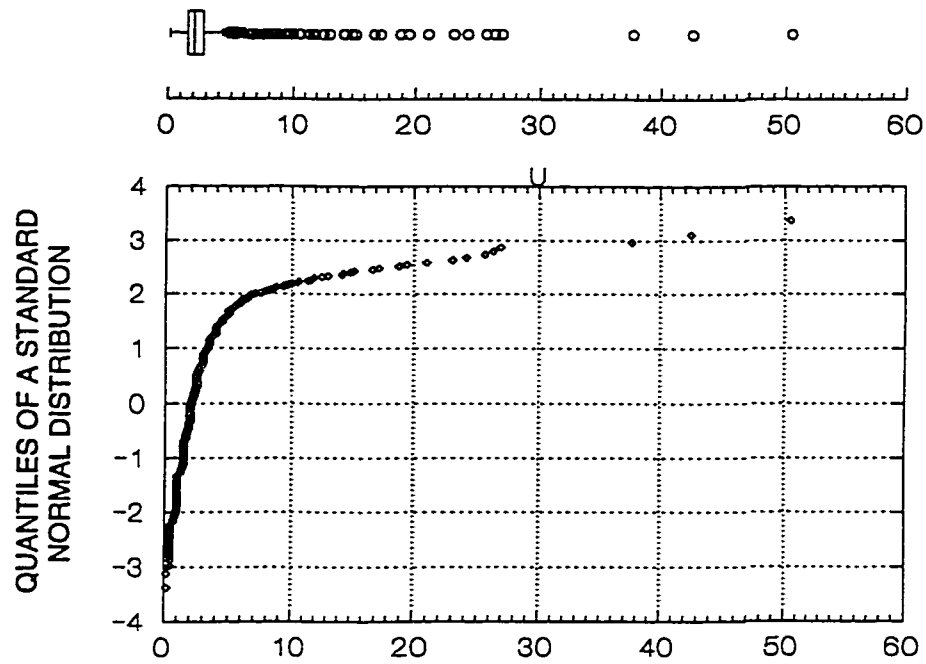
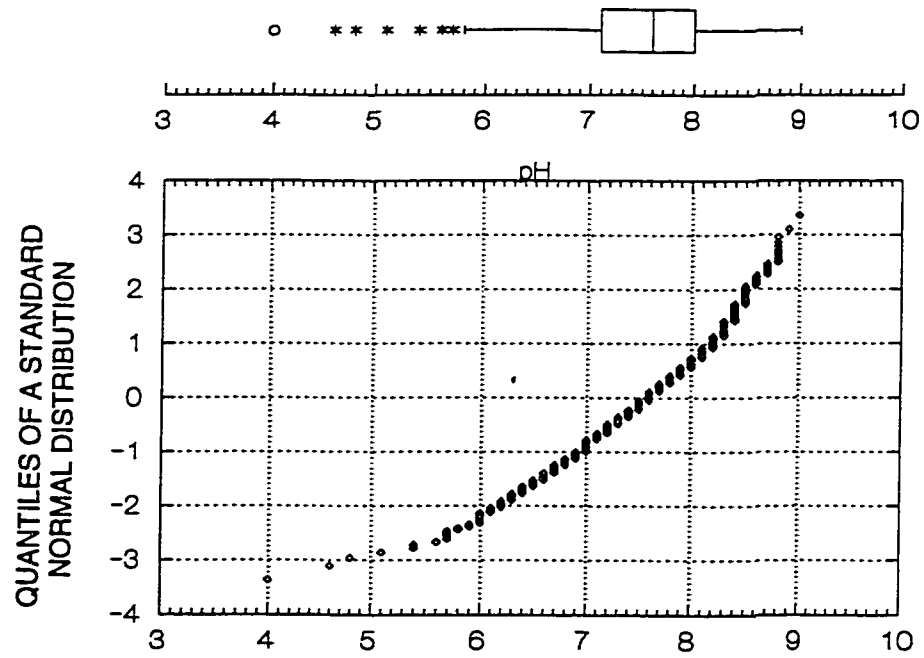






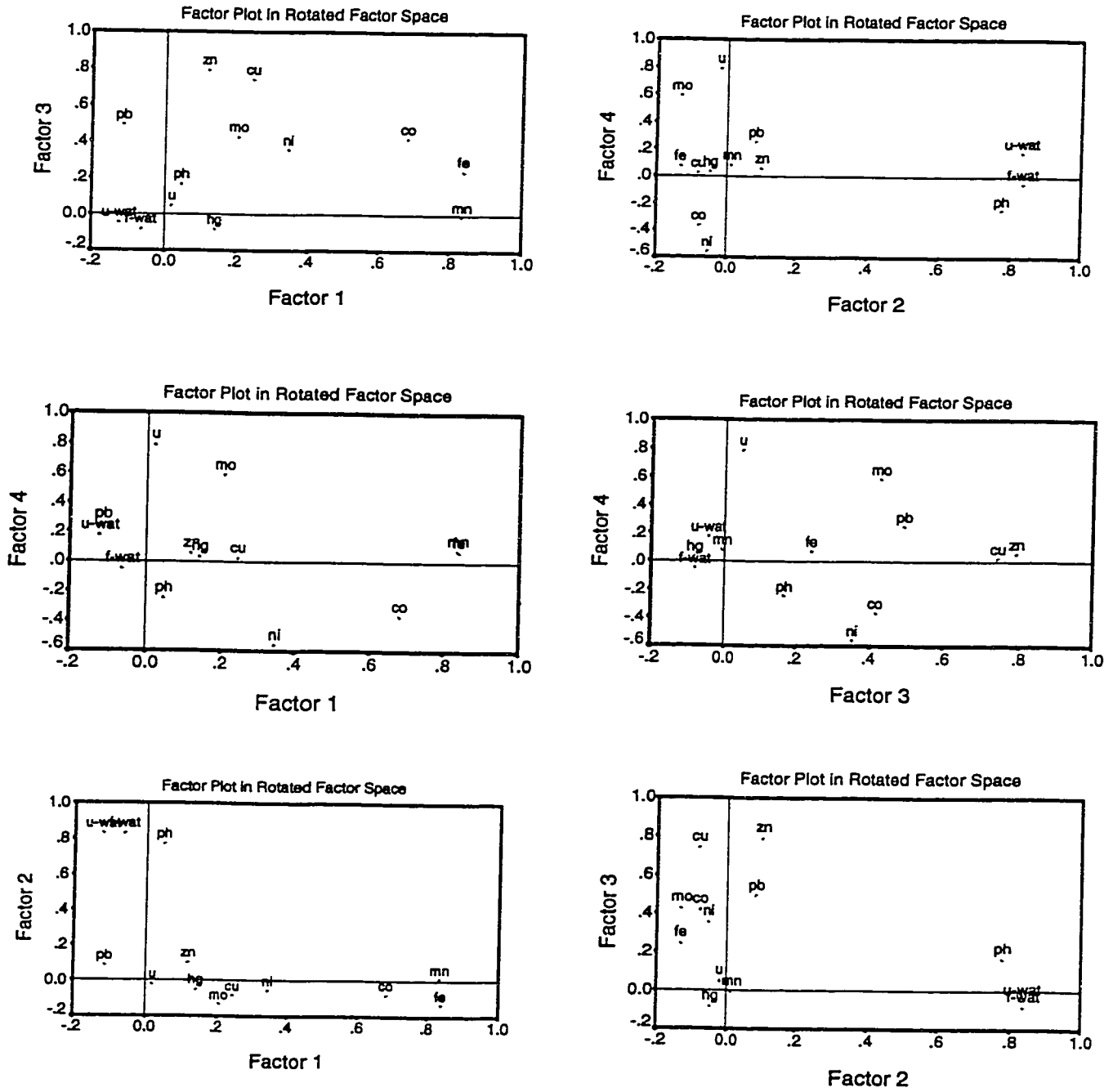




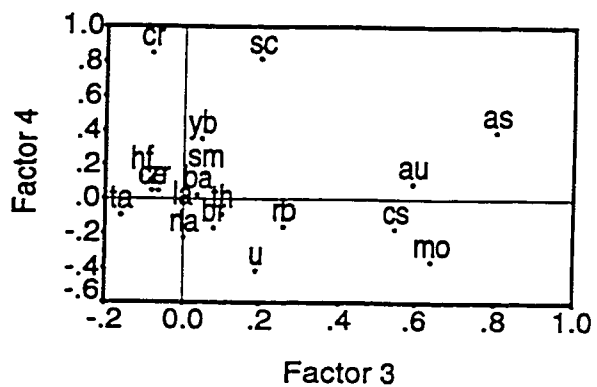
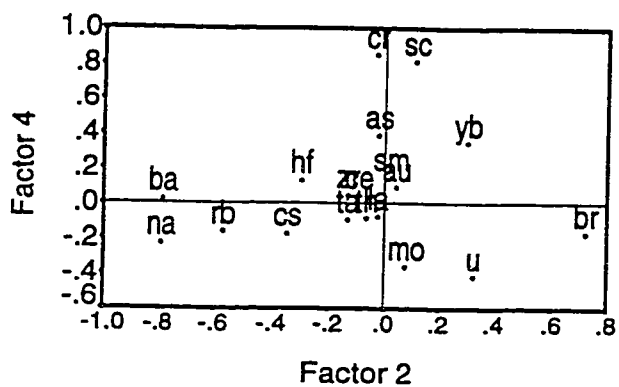
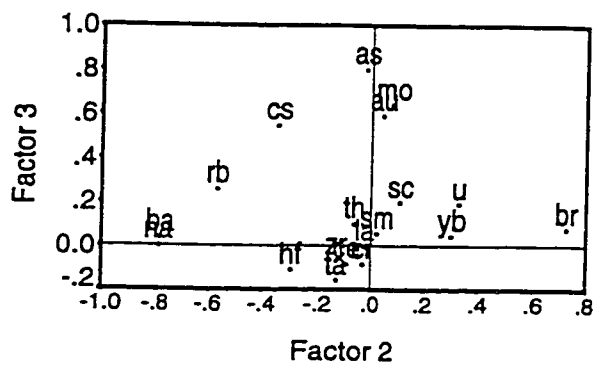
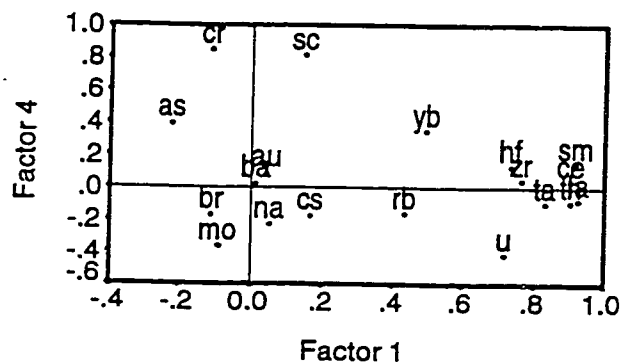
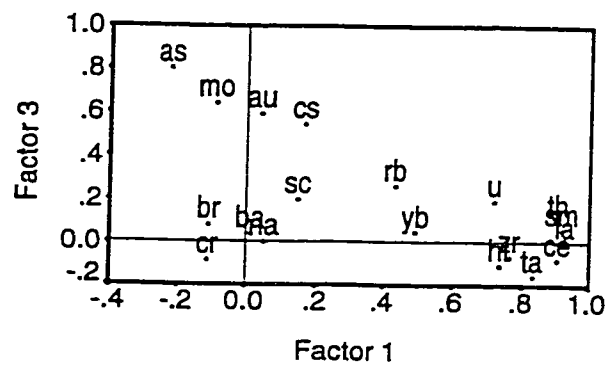
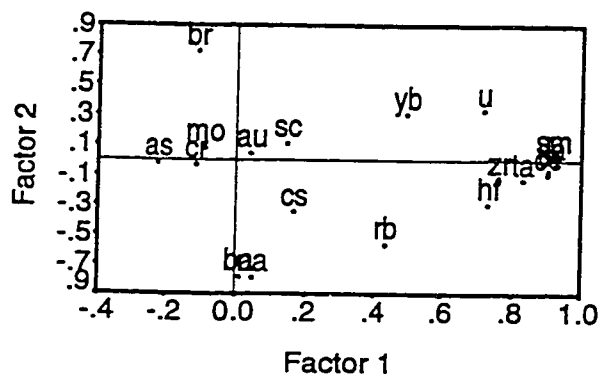


APPENDIX B-1

Relationships between different factor loadings in 2 dimensions for the first series and second series of elements for Guichon plutonic suite (EJgG).



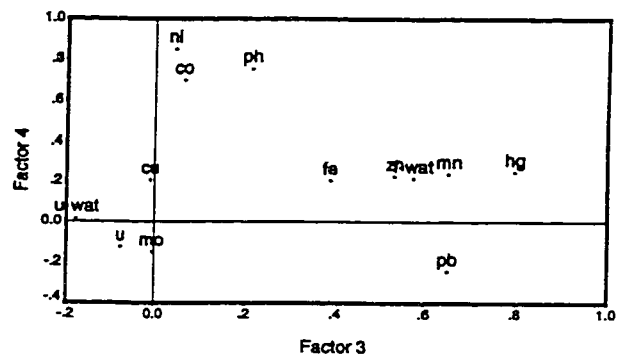
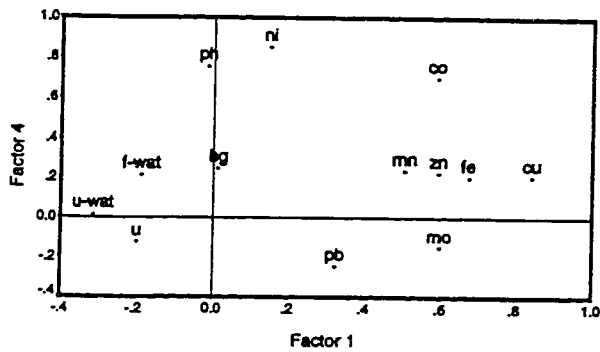
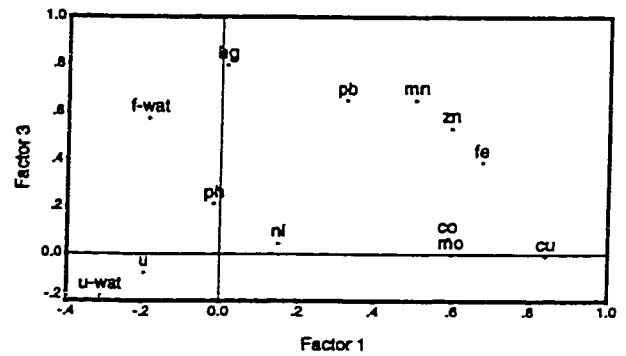
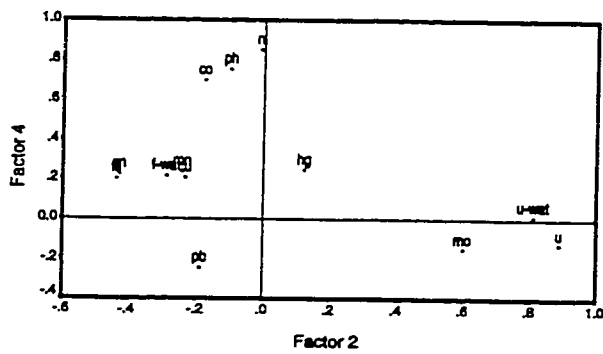
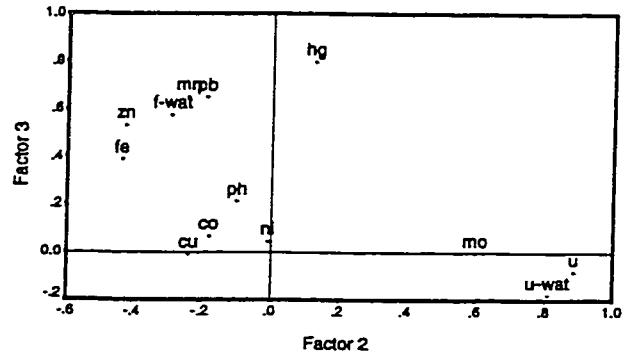
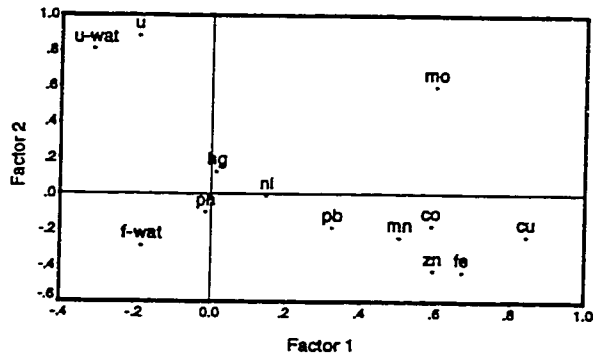
First series of elements



Second series of elements

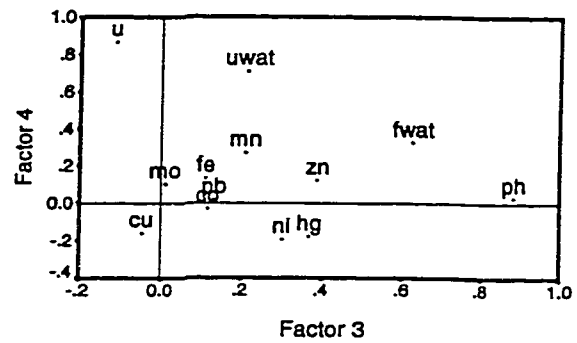
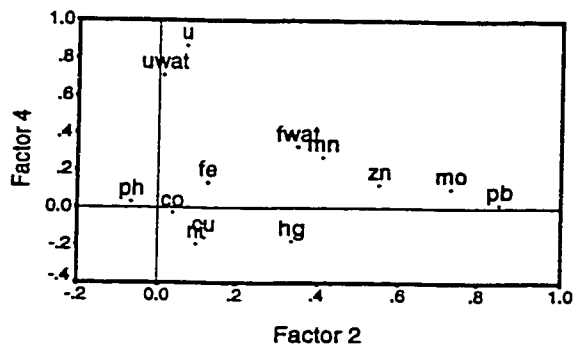
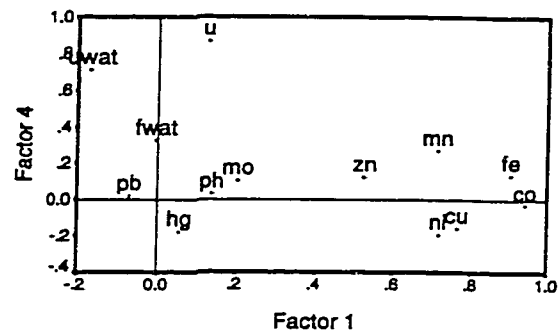
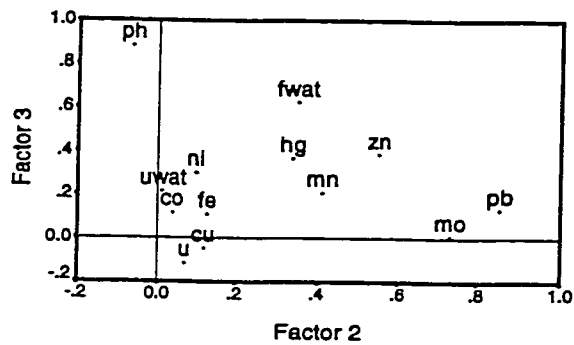
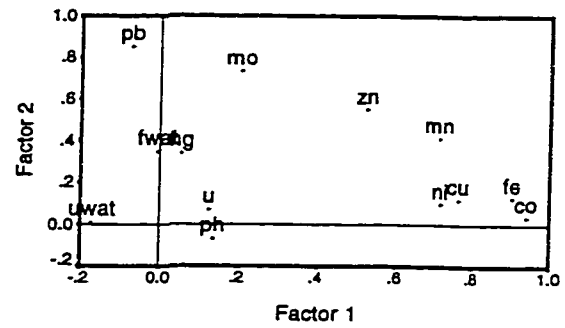
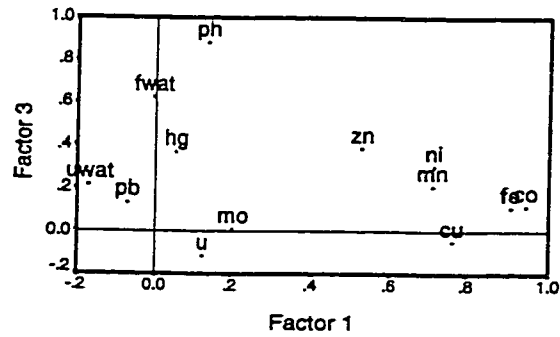
APPENDIX B-2

Relationships between different factor loadings in 2 dimensions for Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites.



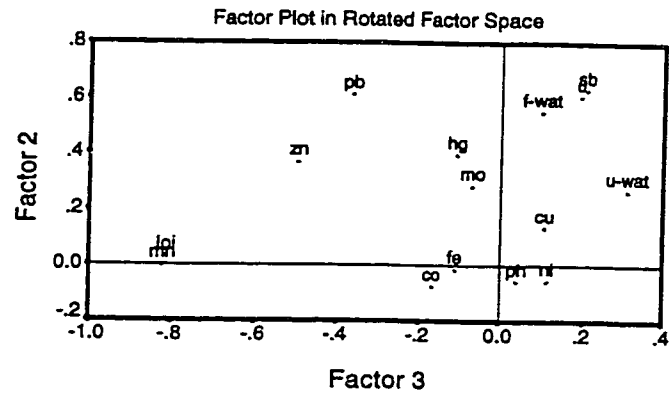
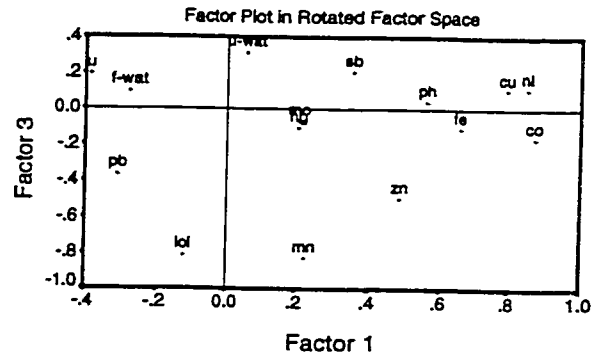
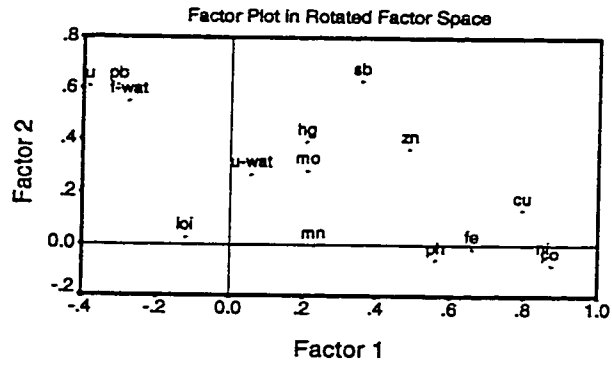
APPENDIX B-3

Relationships between different factor loadings in 2 dimensions for Late Cretaceous plutonic suites (Lkg).



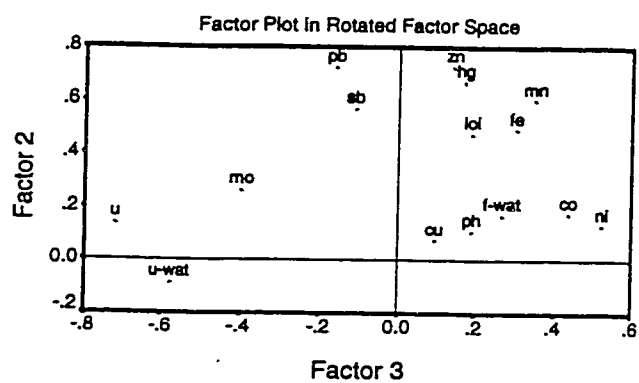
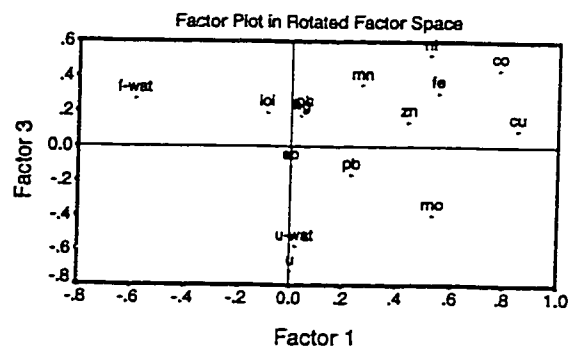
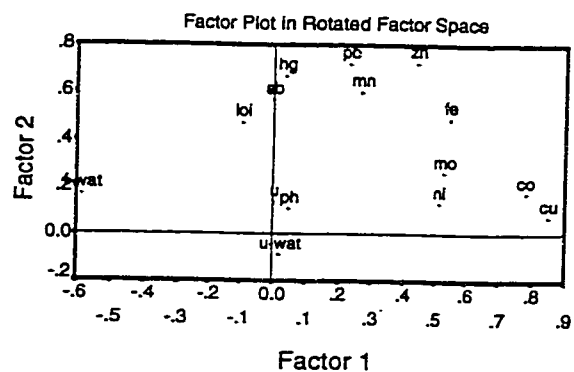
APPENDIX B-4

Relationships between different factor loadings in 2 dimensions for Bonanza arc volcanics (JB).



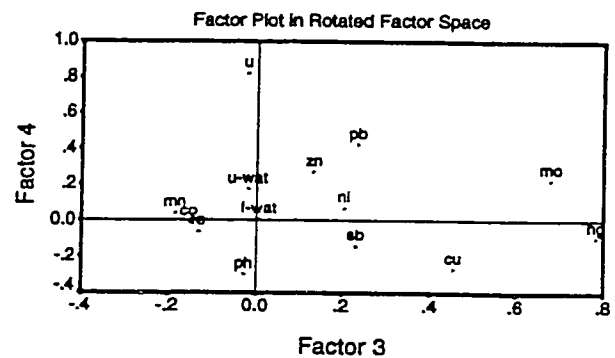
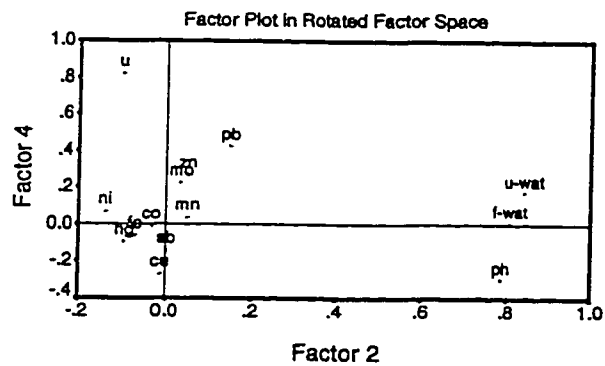
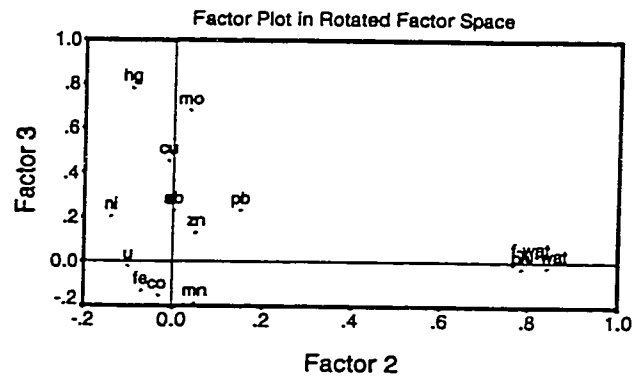
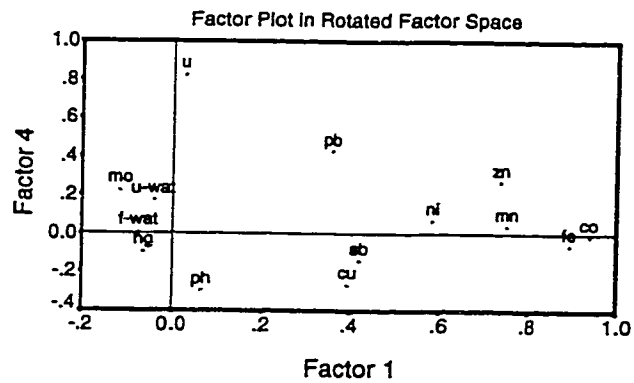
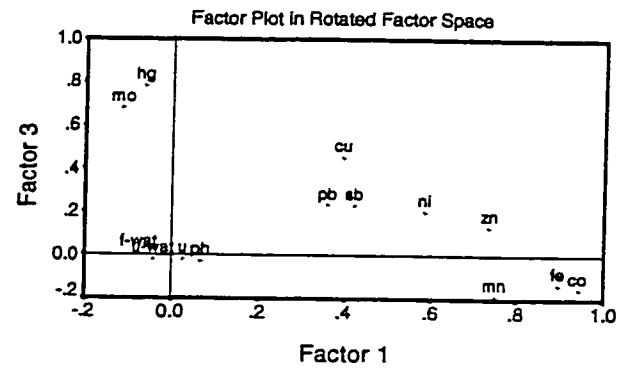
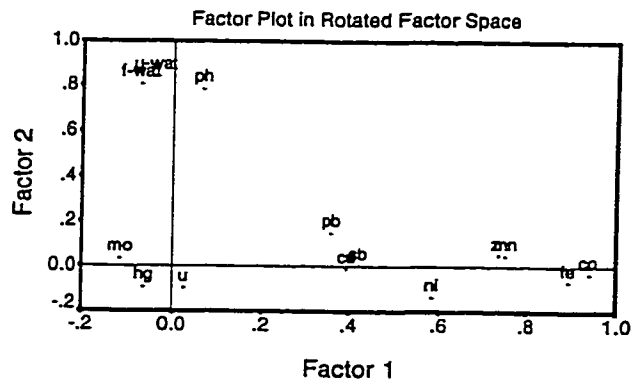
APPENDIX B-5

Relationships between different factor loadings in 2 dimensions for Hazelton arc volcanics (JH).



APPENDIX B-6

Relationships between different factor loadings in 2 dimensions for Takla and Nicola arc volcanics (TrJ, TrJN).



APPENDIX C

Table 1. Pooled within-groups correlation matrix for training groups of mineralized and unmineralized of Guichon plutonic suite (EJgG).

	Co	Cu	Fe	F-WAT	Mn	Mo	Ni	Pb	U	U-WAT	Zn	pH
Co	1											
Cu	0.15	1										
Fe	0.41	0.34	1									
F-WAT	0.20	-0.23	-0.28	1								
Mn	0.23	0.33	0.49	-0.10	1							
Mo	0.04	0.32	0.37	-0.49	0.33	1						
Ni	0.59	0.26	0.49	0.14	0.23	-0.07	1					
Pb	0.02	0.20	0.24	-0.23	0.08	0.12	0.42	1				
U	-0.08	0.42	0.35	-0.33	0.10	0.23	0.03	0.20	1			
U-WAT	0.11	-0.20	-0.21	0.69	-0.24	-0.40	0.08	-0.24	-0.17	1		
Zn	0.49	0.16	0.38	0.19	0.27	0.08	0.72	0.39	-0.13	0.11	1	
pH	0.09	-0.34	-0.39	0.72	-0.24	-0.52	-0.03	-0.19	-0.39	0.56	-0.04	1

Table 2. Wilks' Lambda (U-statistic) and univariate F-ratio with 1 and 58 degrees of freedom for variables of training groups of mineralized and unmineralized of EJgG unit.

Variable	Wilks' Lambda	F	Significance
Co	0.98	0.98	0.326
Cu	0.50	59.12	0.000
Fe	0.93	4.08	0.048
F-WAT	0.96	2.70	0.106
Mn	1.00	0.05	0.821
Mo	0.92	5.05	0.028
Ni	0.89	7.13	0.010
Pb	1.00	0.05	0.819
U	1.00	0.00	0.975
U-WAT	0.91	5.51	0.022
Zn	0.99	0.47	0.497
pH	0.88	8.22	0.006

Table 3. Unstandardized canonical discriminant function.

ELEMENT	Coefficients
Co	0.600
Cu	2.534
Fe	3.238
F-WAT	-0.827
Mn	-0.931
Mo	-0.288
Ni	-2.997
Pb	0.142
U	-1.009
U-WAT	-0.404
Zn	1.965
pH	2.050
(Constant)	-17.473

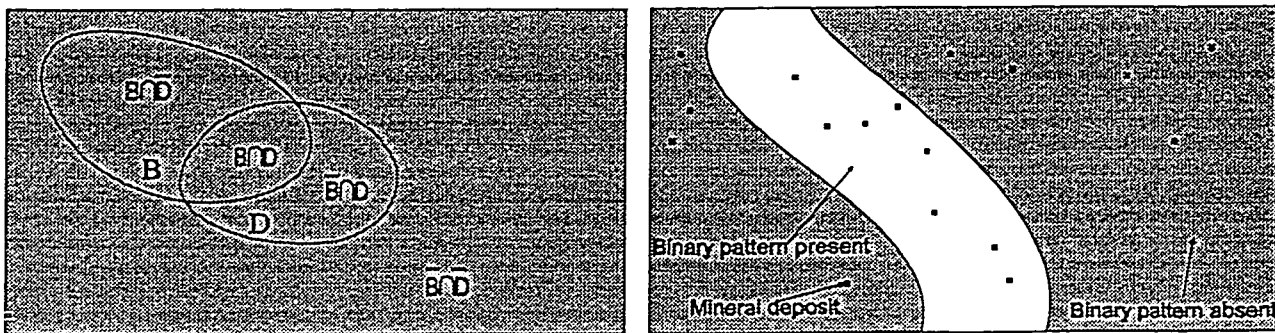
APPENDIX D-1

Weights of evidence & contrast (C)

Contrast is used for quantifying spatial association between binary map patterns and distribution of points. It can also be used for predictive modeling. The strength of association between the input map and the known mineral occurrence points is expressed as contrast:

$$C_i = W_i^+ - W_i^-$$

By calculating weight of evidence & contrast, the accompany of point data sets (here known mineral deposits) with different binary pattern (different geological units) could be quantitatively assessed. Weights are calculated using measurements of the area of binary pattern, the total study area, the number of mineral occurrences within the binary pattern, and the total number of occurrences in the study area (Bonham-Carter, 1994). By considering all the deposits as D set and binary patterns as B, different areas in the whole study area could be defined as it is shown in the Venn diagram of Figure 1.



B= set of binary pattern
D= set of all mineral deposit points

Figure 1. Set of mineral deposit points that mostly are located inside a certain binary pattern (i.e. a certain geological class) and its mathematical representation by Venn diagram.

The positive and negative weights of evidence associated with the presence and absence of the i th binary pattern are defined as:

$$W_i^+ = \ln \{ P(B_i|D) / P(B_i|\bar{D}) \}$$

and

$$W_i^- = \ln \{ P(\bar{B}_i|D) / P(\bar{B}_i|\bar{D}) \}$$

where $\ln$ represents natural logarithm and p is probability, also :

$$P(B_i|D) = N(B \cap D) / N(D) \quad \text{or :}$$

{(area) number of deposits (points) in the binary pattern / total (area) number of deposits (points)}

$$P(B_i|\bar{D}) = N(B \cap \bar{D}) / N(\bar{D}) \quad \text{or :}$$

{area of the binary pattern with no deposits (points) / area with no deposits (points)}

$$P(\bar{B}_i|D) = N(\bar{B} \cap D) / N(D) \quad \text{or :}$$

{(area) number of deposits (points) located outside the binary pattern / total (area) number of deposits (points)}

$$P(\bar{B}_i|\bar{D}) = N(\bar{B} \cap \bar{D}) / N(\bar{D}) \quad \text{or :}$$

{total area minus (area of the pattern and area of deposits (points)) / area with no deposit (points)}

Then contrast for the i th map with respect to the points is defined as: $C_i = W_i^+ - W_i^-$.

Contrast provides a convenient measure of the strength of correlation between spatial distribution of points (deposits) and binary maps (different geological units). The more distribution of a certain set of points is related to presence of certain polygons, the higher will be the calculated value for contrast (Bonham-Carter, 1994).

APPENDIX D-2

Contingency coefficient

The contingency coefficient (C) is estimated by:

$$C = \sqrt{\frac{\Phi^2}{\Phi^2 + 1}} = \sqrt{\frac{GFX^2}{GFX^2 + n}}$$

where Φ^2 is the goodness-of-fit chi-square GFX, and n is the sample size.

$$(\Phi^2 = \frac{GFX^2}{n})$$

Chi square coefficient is a measure of the degree of correlation, association or dependence of a sample. Contingency coefficient (C) lies between 0 and 1 (TYDAC, 1997).

Tschuprow's T

Tschuprow's T varies between 0 (for total independence) and 1. Tschuprow's T is calculated by:

$$T = \sqrt{\frac{\Phi^2}{\sqrt{(I-1)(J-1)}}} = \sqrt{\frac{GFX^2}{n\sqrt{(I-1)(J-1)}}}$$

where I and J are the number of classes in the first and second map (TYDAC, 1997).

Cramer's V

Cramer's V corrects for some of the deficiencies of C and T in that it achieves its maximum in asymmetrical number of classes of map pairs under (SPANS, 1993).

$$T = \sqrt{\frac{\Phi^2}{m}} = \sqrt{\frac{GFX^2}{nm}}$$

where m equals the smaller of (I-1) or (J-1). Cramer's V is always at least as large as the Tschuprow's T (TYDAC, 1997).

APPENDIX D-3

Odds ratio and Alpha

Odds ratio provides a measure of association between the two binary patterns (A and B). It is defined as:

$$O_r = \frac{O(B|A)}{O(B|\bar{A})} = \frac{N(A \cap B) \cdot N(\bar{A} \cap \bar{B})}{N(\bar{A} \cap B) \cdot N(A \cap \bar{B})}$$

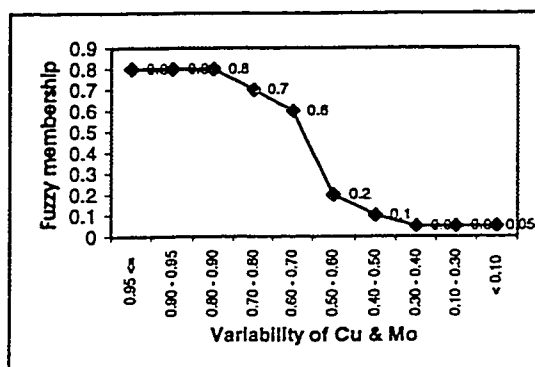
$O(B|A)$ and $O(B|\bar{A})$ are the odds that pattern B is present given the presence or absence of pattern A, respectively. The numerator is a measure of agreement between the patterns, and the denominator a measure of disagreement. The odds ratio is always positive, being greater than 1 for patterns that are positively associated, 1 if the two patterns are independent and less than 1 if they are negatively associated (Bonham-Carter, 1994).

The difference of the square root of the conditional odds, divided by the square root of their sum, provides another convenient measure, referred to as alpha:

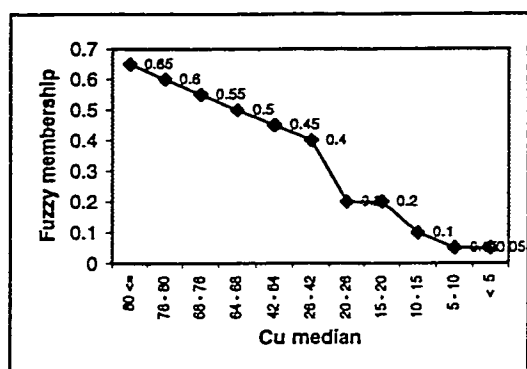
$$\alpha = \frac{\sqrt{O(B|A)} - \sqrt{O(B|\bar{A})}}{\sqrt{O(B|A)} + \sqrt{O(B|\bar{A})}} = \frac{\sqrt{N(A \cap B) / N(A \cap \bar{B})} - \sqrt{N(\bar{A} \cap B) / N(\bar{A} \cap \bar{B})}}{\sqrt{N(A \cap B) / N(A \cap \bar{B})} + \sqrt{N(\bar{A} \cap B) / N(\bar{A} \cap \bar{B})}}$$

Alpha ranges in value between -1 and +1 (negative and positive correlation, respectively), with 0 implying independence of the two patterns, i.e. no association (Bonham-Carter, 1994).

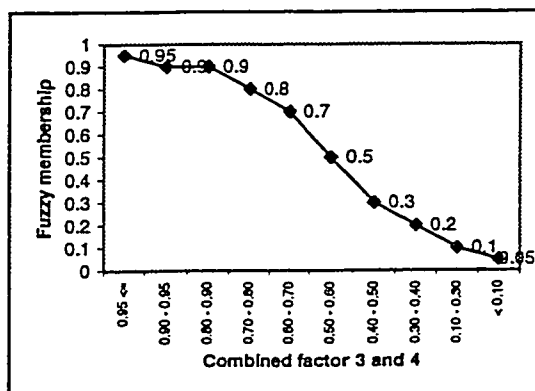
Variability of indicator and pathfinder elements



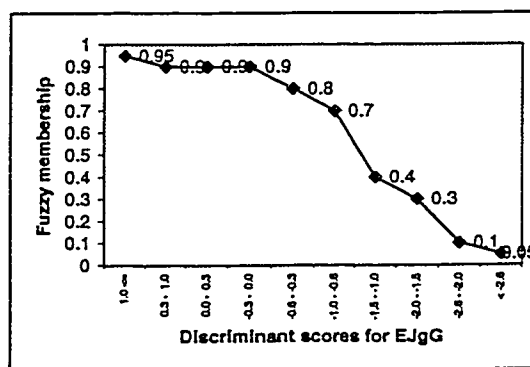
Median of Cu



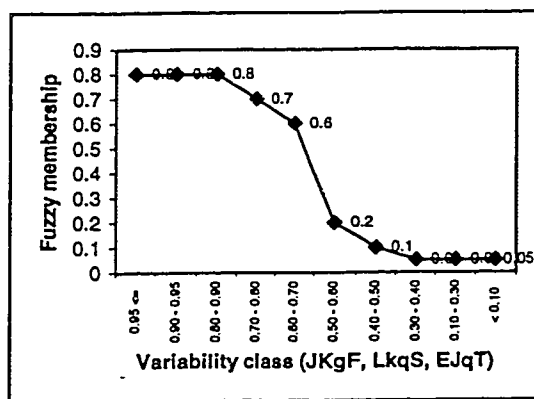
Combined factor 3 and 4 for Guichon plutonic suite (EJgG)



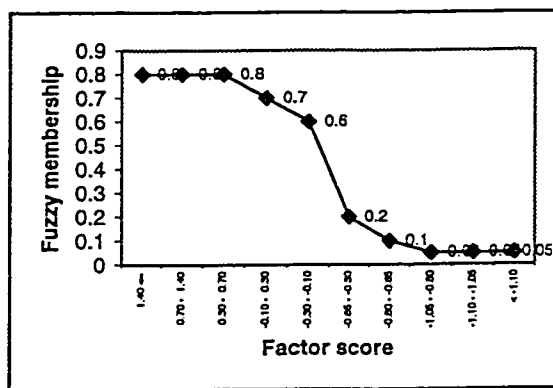
Discriminant analysis score for Guichon plutonic suite (EJgG)



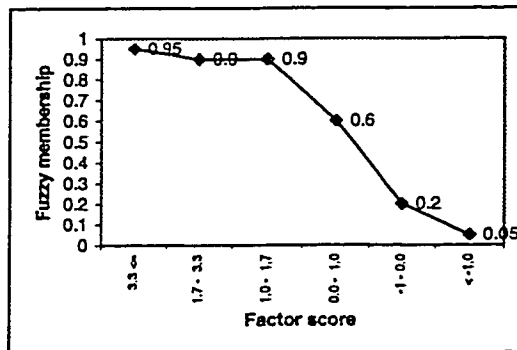
Francois Lake (JKgF), Surprise Lake (LkqS), Topley (EJqT)
Variability of indicator and pathfinder elements



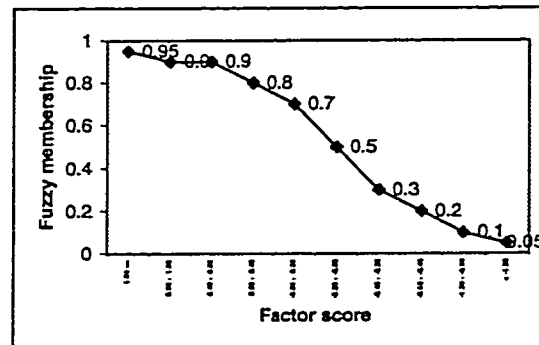
Factor indicating mineralization



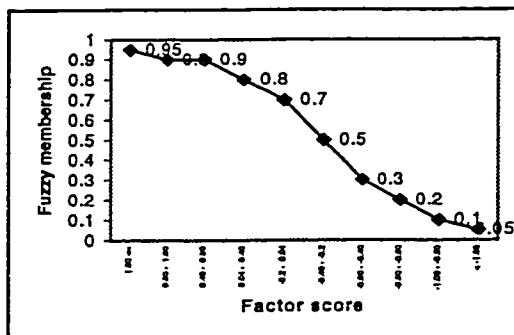
Factor indicating mineralization
in Late Cretaceous Plutonic Suites (Lkg)



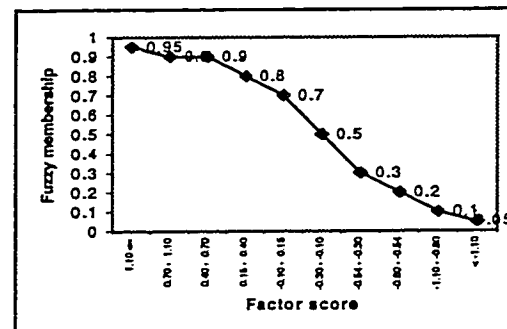
Factor indicating mineralization
in Bonanza group (JB)



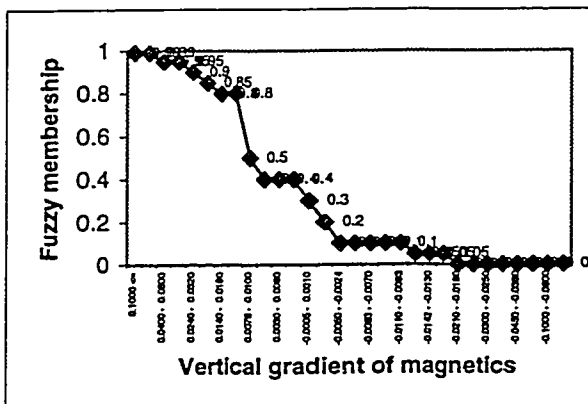
Factor indicating mineralization
in Hazelton (JH)



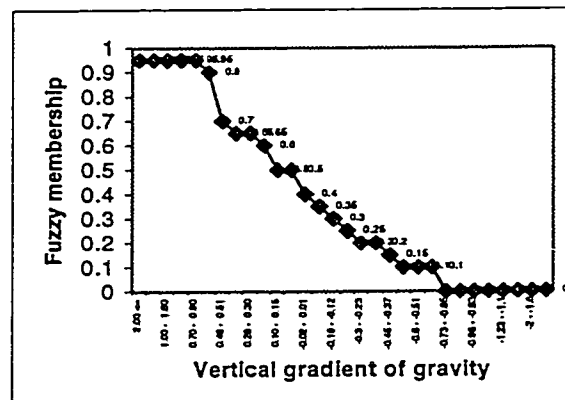
Factor indicating mineralization
in Takla and Nicola (TrJ, TrJN)



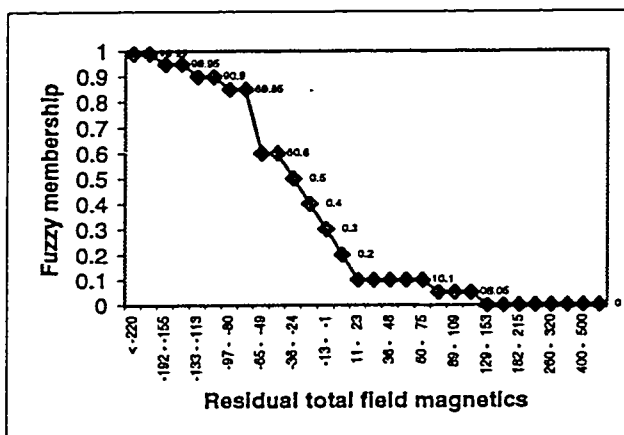
Vertical gradient of magnetics



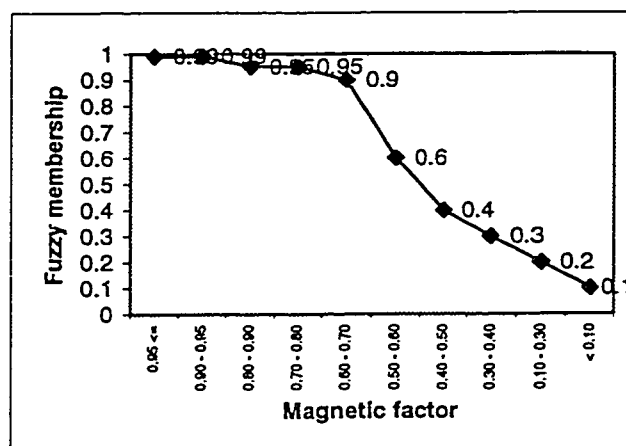
Vertical gradient of gravity
only for Takla and Nicola



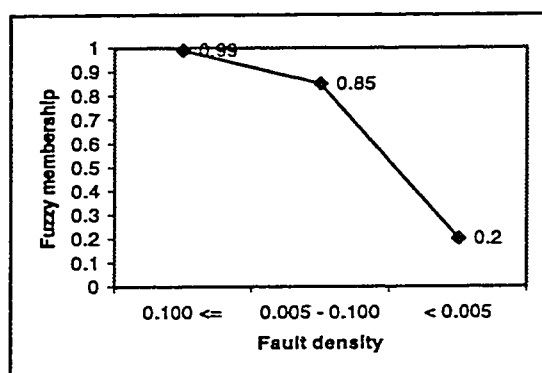
Residual total field magnetics



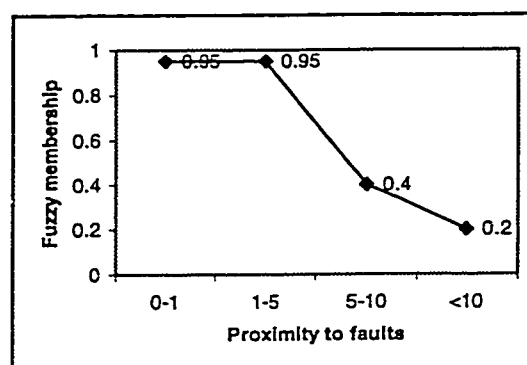
Magnetic factor



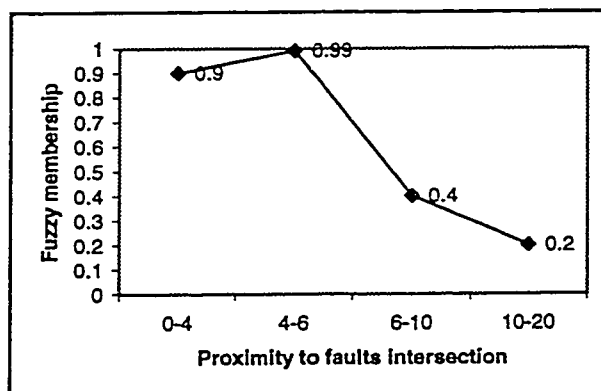
Faults density



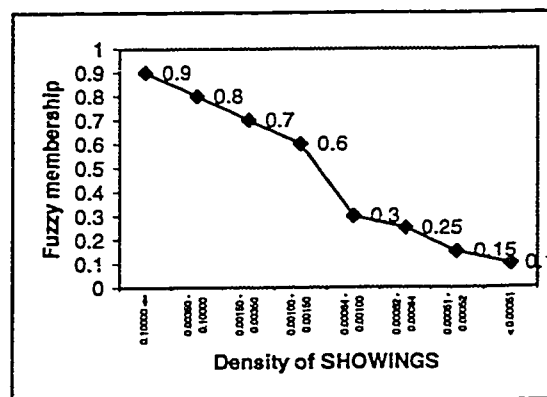
Proximity to faults



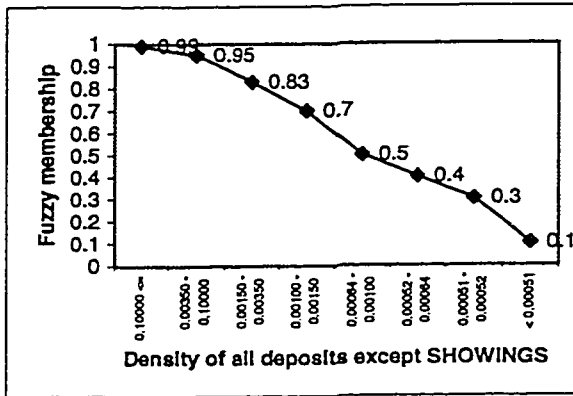
Proximity to intersection of faults



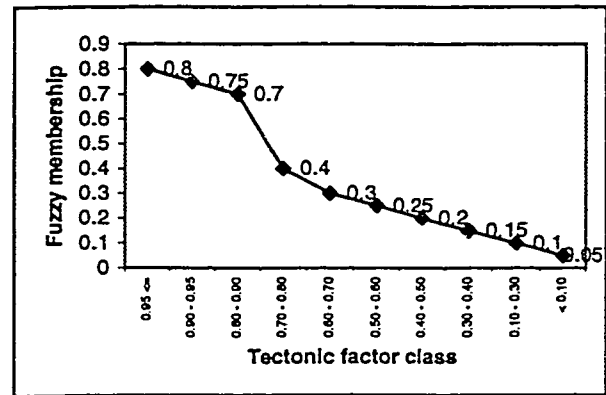
Density of SHOWINGS



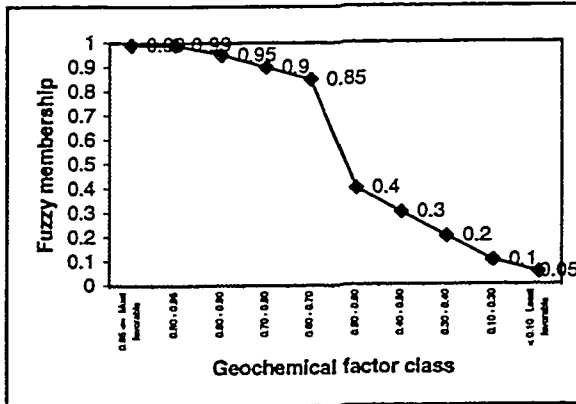
Density of *non-SHOWINGS*



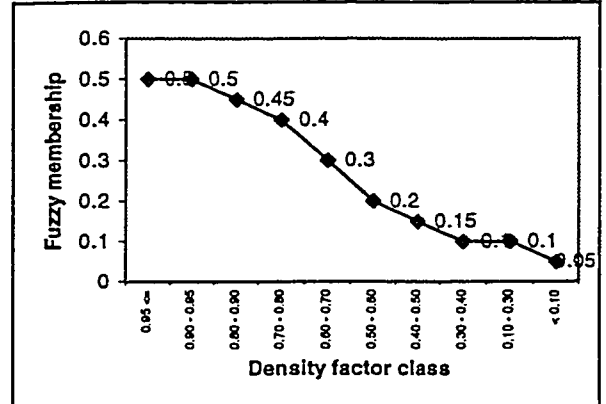
Tectonic factor



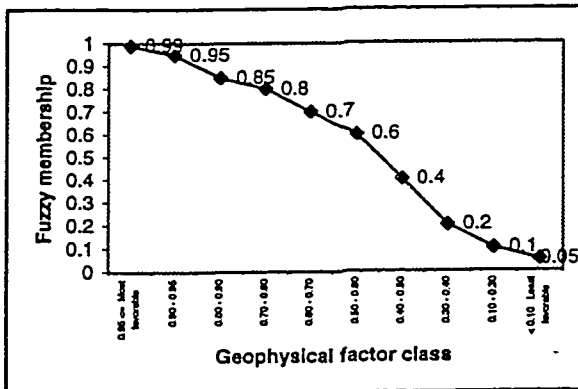
Geochemical factor



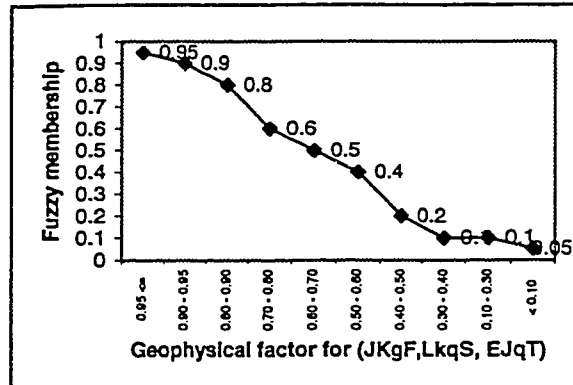
Density factor



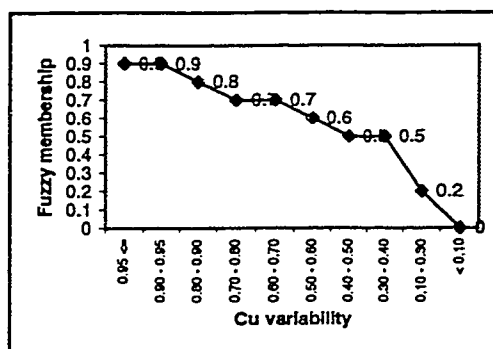
Geophysical factor



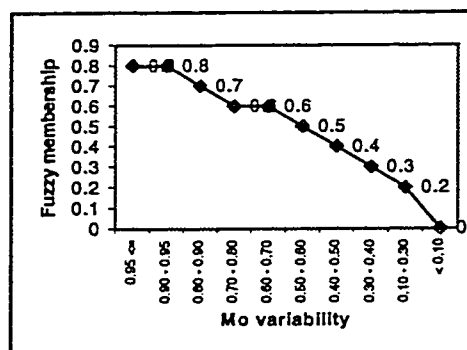
Geophysical factor for Francois Lake (JKgF),
Surprise Lake (LkqS) and Topley (EJqT)



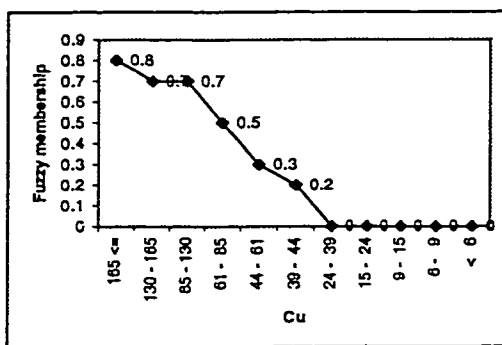
Cu variability



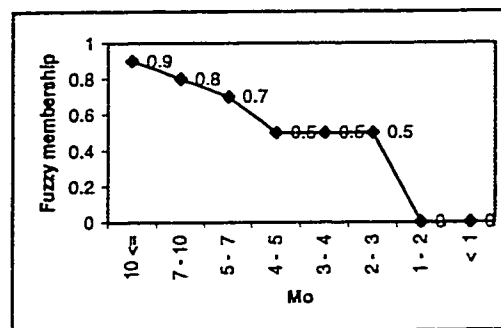
Mo variability



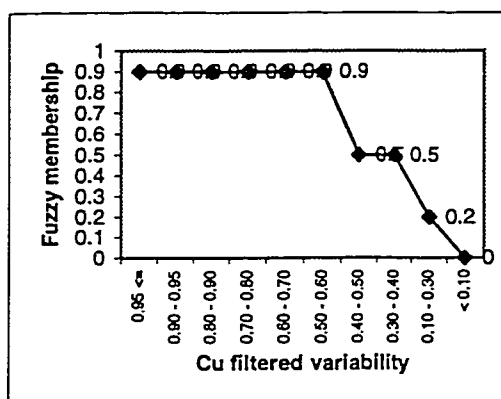
Cu



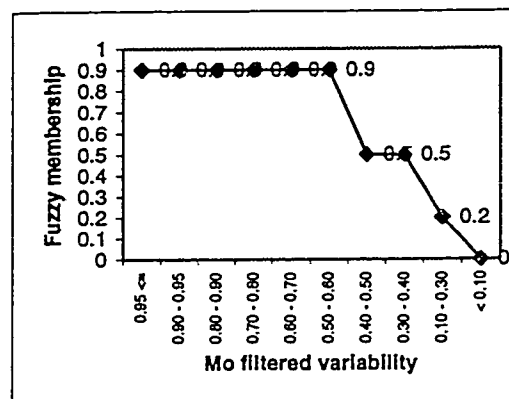
Mo



Cu filtered variability



Mo filtered variability

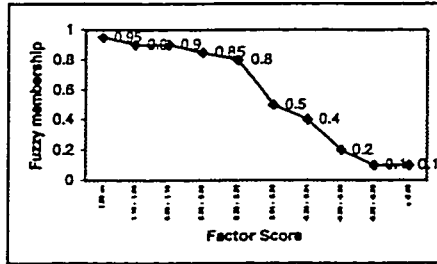


APPENDIX E

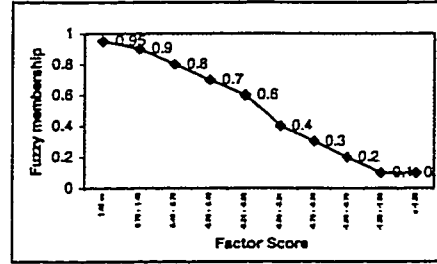
Fuzzy membership values assigned to different classes of maps used in different inference networks of the fuzzy logic modeling.

Guichon plutonic suite (EJgG)

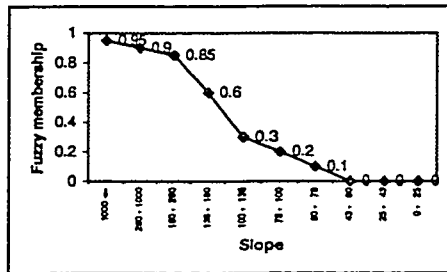
Factor 3



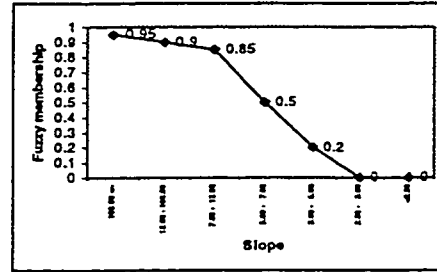
Factor 4



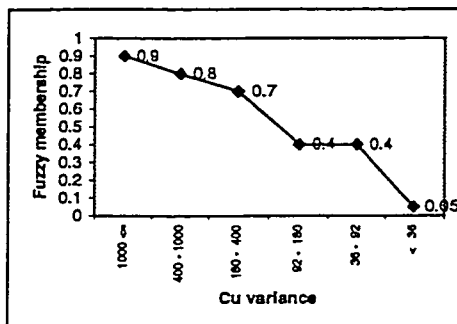
Cu slope



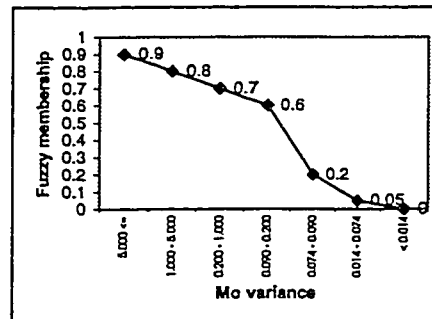
Mo slope



Cu variance



Mo variance



5.3.4.4 COMPARISON WITH THE GEOLOGY OF GUICHON PLUTONIC SUITE

Figure 36 shows Guichon plutonic suite in the southern British Columbia. The map of Figure 36 has the details of 1/50,000 scale maps published as a part of the mineral potential project of British Columbia. In the digital files of these geological maps, Guichon plutonic suite is named as series of TrJGg, (which is equivalent to EJGg for the same plutons which is referred to in the 1/1000,000 tectonic map of Canadian Cordillera). As Figure 36 shows, Guichon plutonic suite comprise of several plutonic phases. The central parts of the Guichon Creek batholith (TrJGqm1 in Figure 36) host most of the porphyry deposits of this pluton. This phase which is called Bethsaida is mainly quartz monzonite to granodiorite and slightly younger porphyry dikes and plugs. Rocks at the border of the Guichon Creek batholith are older and more mafic; successive phases moving inward toward the core are younger and more felsic (Casselman *et al.* , 1995).

In maps created in the previous sections for distribution of factor 3, factor 4 scores and also high scores for the discriminant function, high values for these parameters inside the Guichon Creek batholith is mainly located close to or within the Bethsaida phase. Wild Horse batholith is a part of another phase (TrJGgd) which is mainly Granodiorite, quartz diorite, quartz monzonite; lesser monzonite, diorite and gabbro. This phase in many locations matches with the low scores for factor 3, 4 and the discriminant function. In Figure 22, Figure 23, and Figure 34 areas with high scores for factor 3, 4 and the discriminant function may represent mineralized zones inside these plutonic intrusions related to other phases of mineralizations different than Bethsaida phase of Guichon Creek batholith.

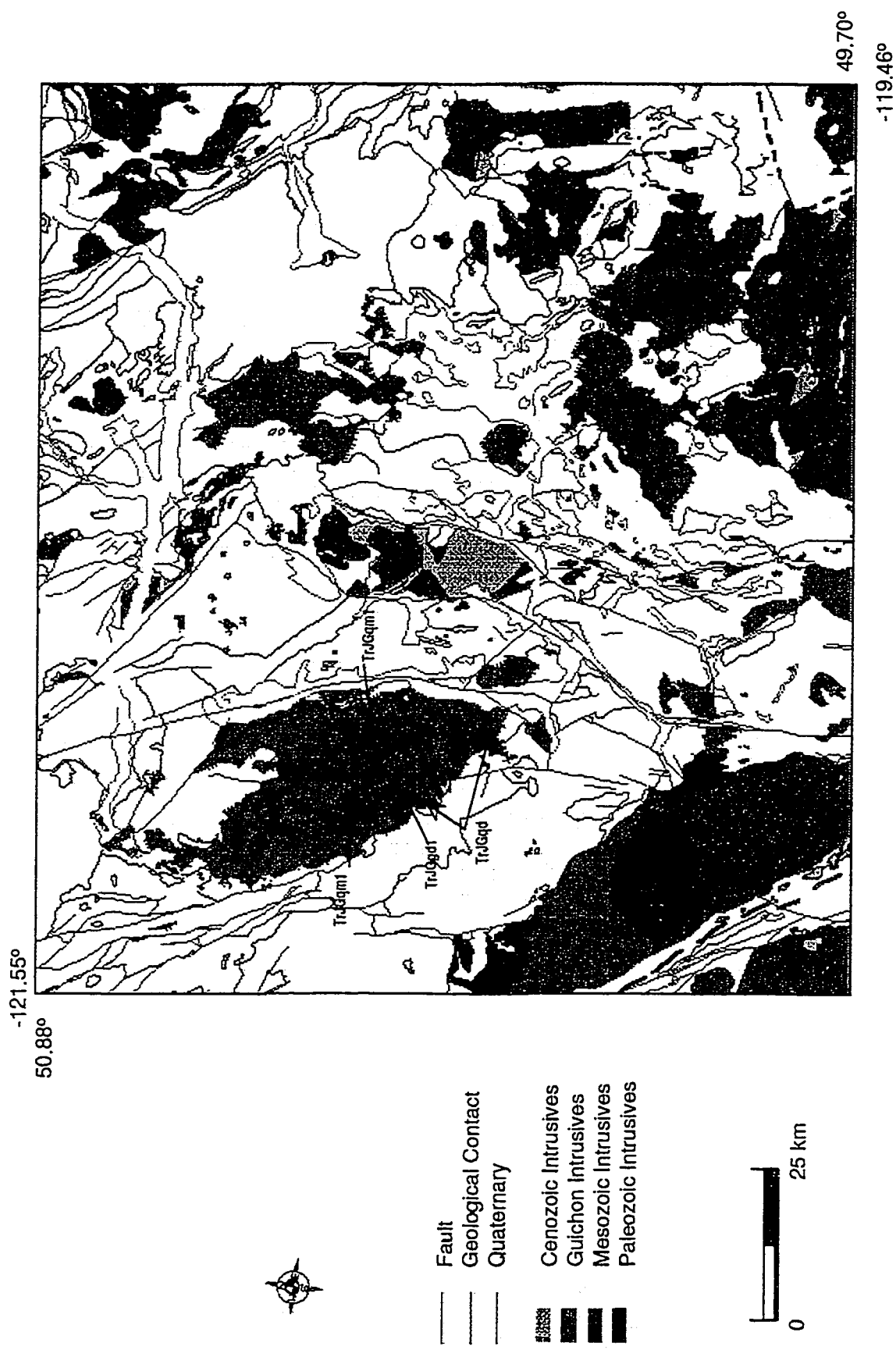


Figure 36. Different phases of Guichon plutonic suite and other plutonic intrusives near Guichon Creek batholith..

5.3.4.5 FACTOR ANALYSIS ON GEOCHEMICAL DATA OF BULKLEY (LKgB), FRANCOIS LAKE (JKgF), SURPRISE LAKE (Lkqs) AND TOPLEY (EJqT) PLUTONIC SUITES

Stream sediment and water samples located inside the Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites were extracted from the original data file. Of 116 extracted samples, the extreme outliers were removed and 108 samples were used for the multivariate analysis. Thirteen elements were used in the factor analysis, namely Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, from stream sediment data and pH, F in water (F-wat), and U in water (U-wat) from water samples. Since pH and Fe have very close to normal distributions, they were not $\log_{10}$ transformed and their original values were standardised. All other elements were first $\log_{10}$ transformed and then standardised z scores of them were calculated. Principal component analysis with the correlation matrix was used for extracting factors and equimax method was applied for rotating the original factor solution. Table 16 shows the rotated factor solution for the first four factors. These four factors account for 74.7% of the total variability and have eigenvalues greater than 1.

Table 16. Rotated factor loadings matrix for the first four factors.

	Factor 1	Factor 2	Factor 3	Factor 4
Cu	0.84	-0.23	-0.01	0.21
Fe	0.67	-0.43	0.39	0.20
Zn	0.59	-0.43	0.53	0.23
U	-0.19	0.89	-0.08	-0.12
U-wat	-0.31	0.81	-0.18	0.01
Mo	0.60	0.60	0.00	-0.15
Hg	0.01	0.12	0.80	0.25
Mn	0.50	-0.24	0.65	0.24
Pb	0.32	-0.19	0.65	-0.25
F-wat	-0.18	-0.29	0.57	0.21
Ni	0.15	-0.01	0.04	0.85
pH	-0.02	-0.10	0.21	0.75
Co	0.59	-0.18	0.07	0.70

Table 17. Eigenvalues and percent of variability related to factors.

Factor	Eigenvalue	% of Var	Cum %
1	5.23	40.2	40.2
2	1.64	12.6	52.8
3	1.49	11.5	64.3
4	1.35	10.4	74.7
5	0.98	7.5	82.2
6	0.68	5.2	87.4
7	0.50	3.8	91.2
8	0.34	2.6	93.8
9	0.22	1.7	95.5
10	0.20	1.5	97
11	0.15	1.2	98.2
12	0.14	1.1	99.3
13	0.09	0.7	100

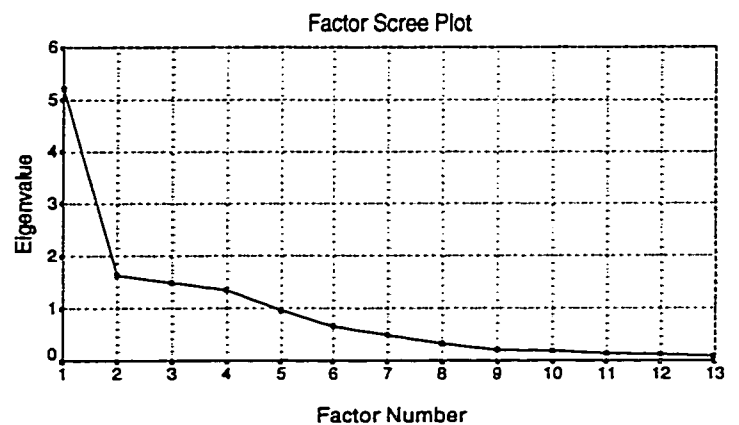


Figure 37. Scree plot for 13 possible factors.

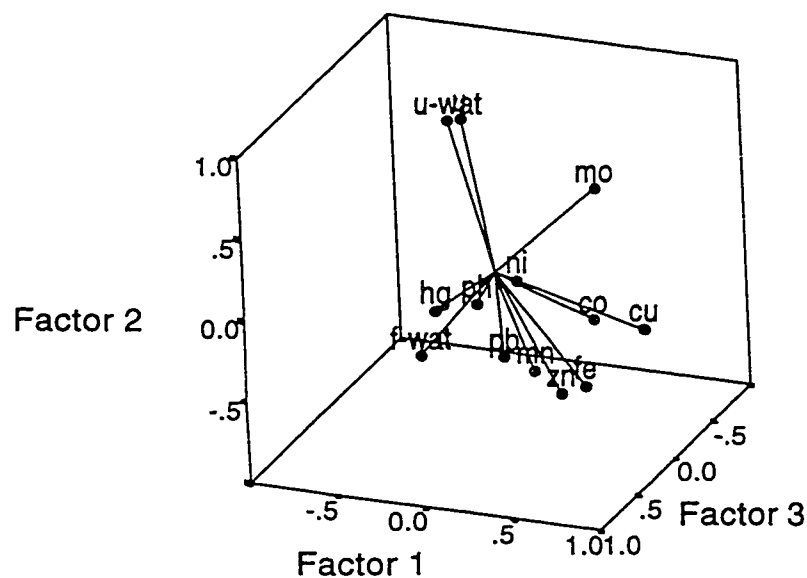


Figure 38. Configuration of factor loadings for the first three factors. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-2.

Factor 1 shows the association of Cu, Fe, Zn, Mo and Co. This factor alone accounts for 40.2% of the variability. The calculated scores for this factor for all samples inside these units show a distribution, which is very close to normal (Figure 39). This factor could be related to the background values of these major and trace elements in the plutonic rocks inside Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites. Molybdenum has equal loadings for factor 1 and 2. The ideal situation in any factor analysis is not to have high weights for an element in more than one factor. The situation for Mo may indicate the role of Mo in two geological phenomena. Almost similar situations exist for Co, Mn and Zn.

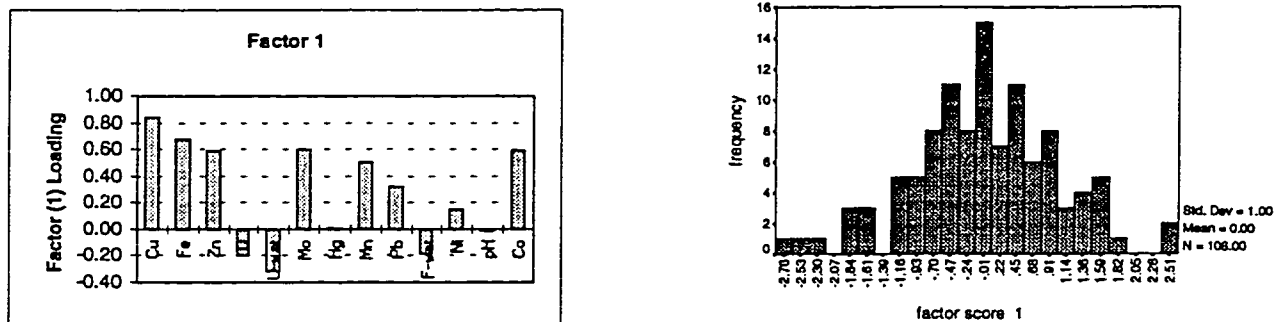


Figure 39. Factor loadings and histogram for factor 1 scores.

Considering that Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites are among the major hosts of porphyry Mo and Cu-Mo deposits in the study area, the association of U, U in water (U-wat) and Mo represented by factor 2 can be considered as an indicator of mineralization. Factor 2 scores show generally a positively skewed distribution which means most of the samples have low values for this score.

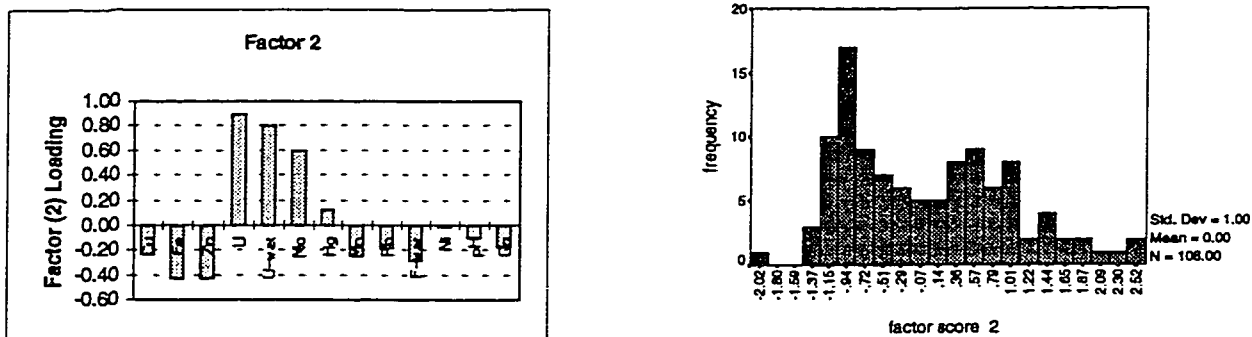


Figure 40. Factor loadings and histogram for scores of factor 2.

Careful study of factor 2 scores distribution shows that two major groups or populations exist here. Group 2 in Figure 41 most likely indicates samples located in mineralized or potentially mineralized areas. Factor 2 accounts for 12.6% of variation. One generalisation could be made that factor scores of a “common phenomenon” factor have a symmetric or negatively skewed distribution, while “rare” factor(s) have positively skewed distributions (Tripathi, 1979). To check

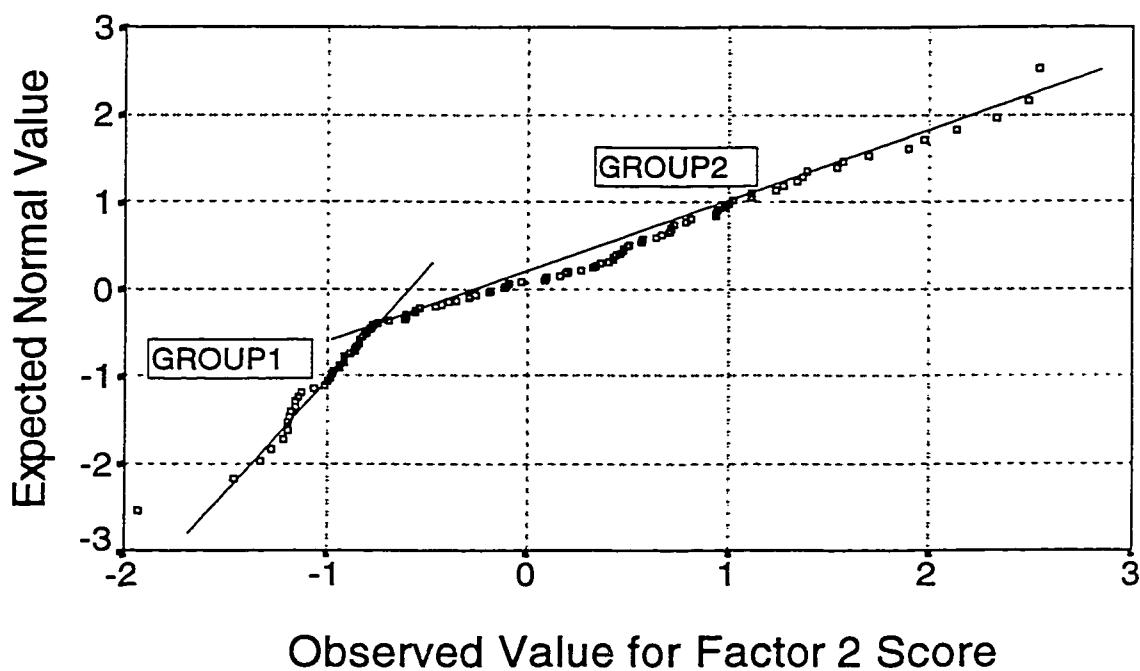


Figure 41. Probability plot for scores of factor 2.

this idea, factor 2 scores were mapped over the study area. Figure 45 show this map and the location of known porphyry deposits.

Factor 3 accounts for 11.5% of the variations. As Figure 42 shows, this factor represents association of Mn, Fe and trace elements such as Hg, Zn, Pb and F in water (F-wat). This factor is considered here as indicating the effect of scavenging metallic ions by oxides of Fe and Mn. Factor 3 shows almost a negatively skewed distribution (Figure 42).

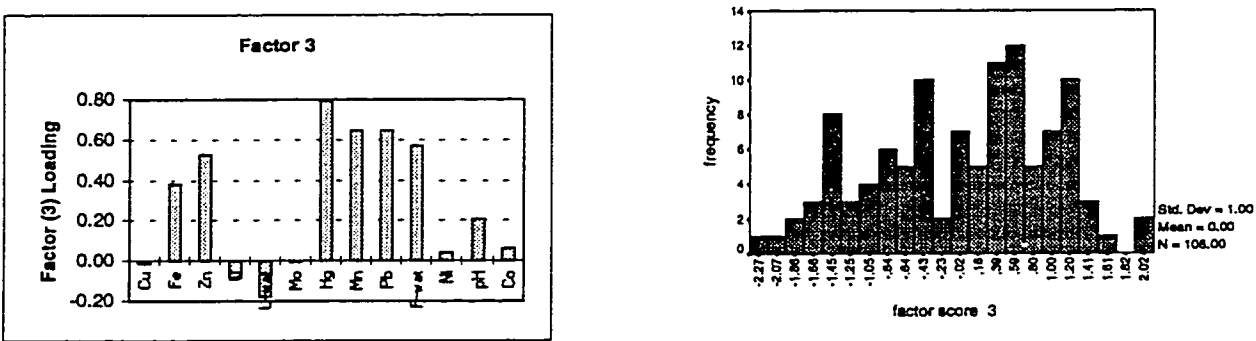


Figure 42. Factor loadings and histogram for scores of factor 3.

Factor 4 with the association of Ni, Co, and pH can indicate background values of Ni and Co. Histogram for the scores of this factor shows an approximately normal distribution.

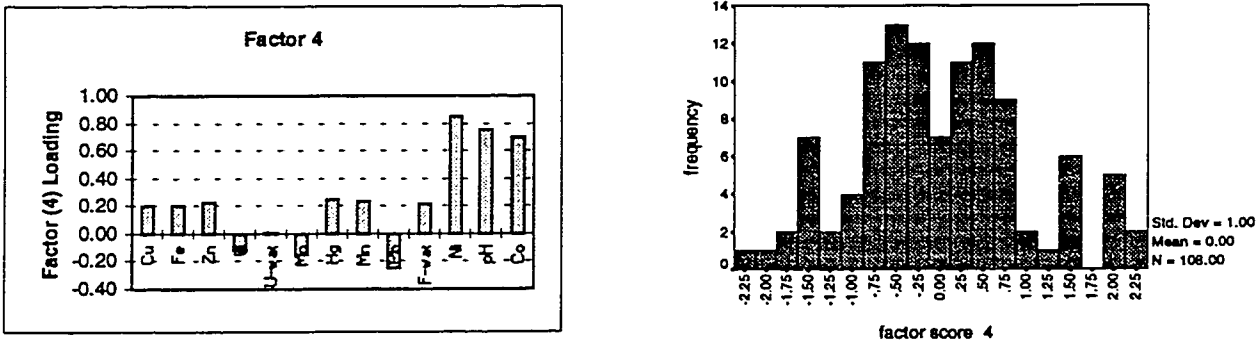


Figure 43. Factor loadings and histogram for scores of factor 4.

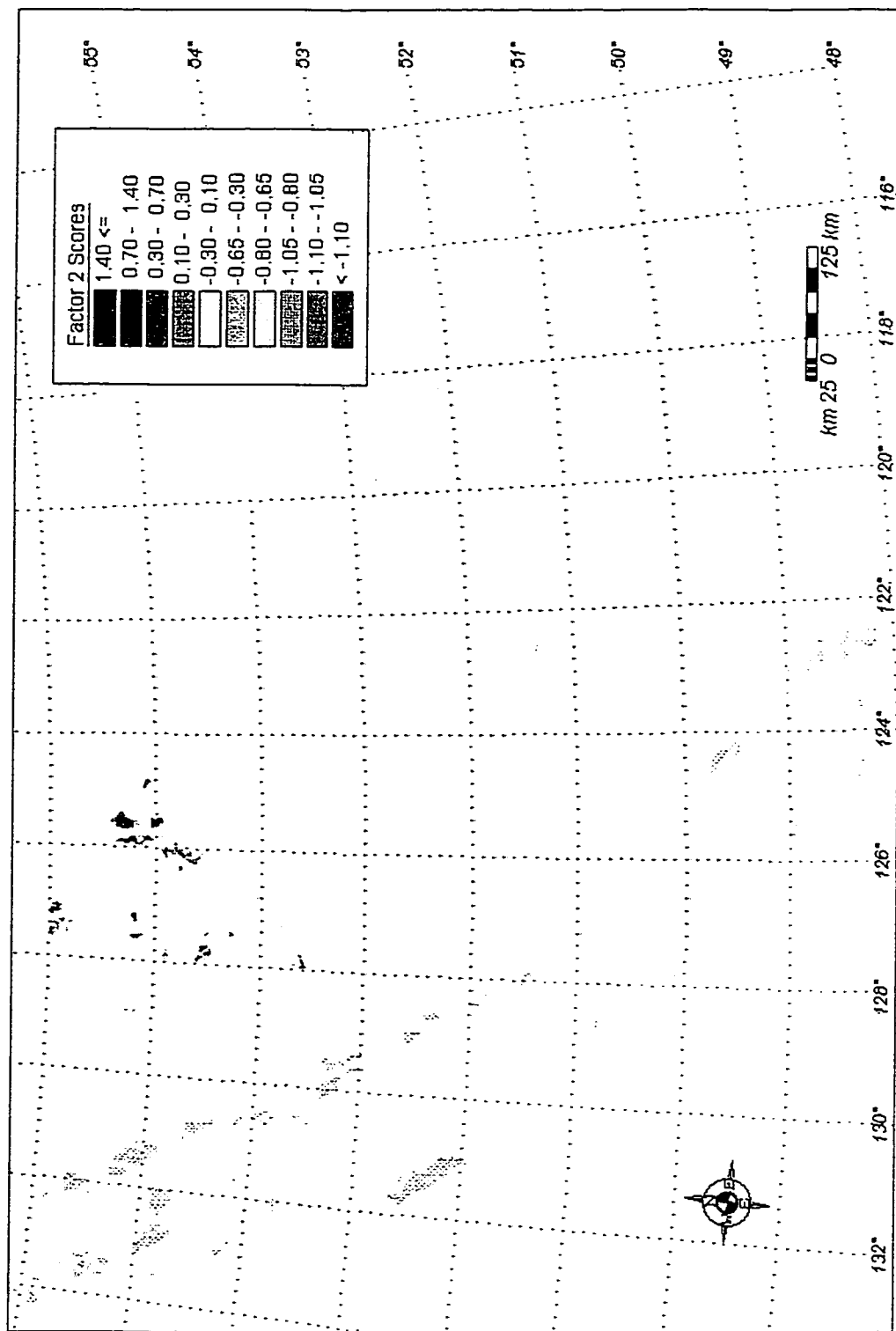


Figure 44. Distribution of factor 2 scores in Bulkely (LKgB), Francois Lake (JKgF), Surprise Lake (LKqs) and Topley (EJqT) plutonic suites.

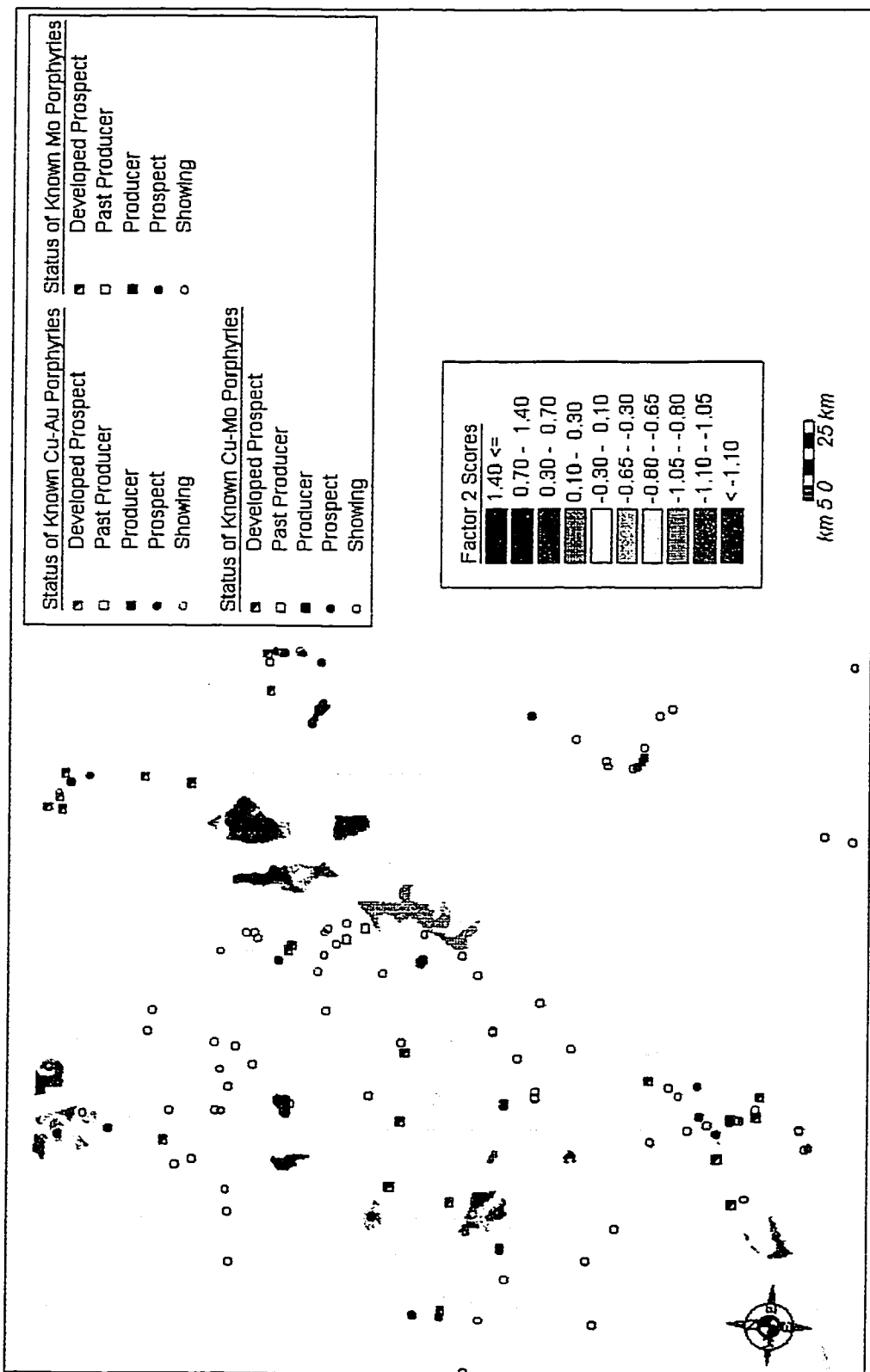


Figure 45. Factor 2 scores and known porphyry deposits inside Bulkely (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites.

5.3.4.6 FACTOR ANALYSIS ON GEOCHEMICAL DATA OF LATE CRETACEOUS PLUTONIC SUITE (LKg)

A total of 598 stream sediment and 591 water samples are located inside the Late Cretaceous plutonic suite (LKg). After removal of extreme outliers, 547 samples were entered into the multivariate analysis. Multivariate analysis was performed on Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, and Zn from stream sediment data and pH, F in water (F-wat) and U in water (U-wat) from water samples. Also here pH has a close to normal distribution, it was not log₁₀ transformed and the original values were standardised. All other elements were log₁₀ transformed and then standardised z scores of them were calculated. Principal component method with the correlation matrix was used for extracting factors and equimax method was applied for rotating the original factor solution. Table 18 shows the rotated factor solution for the first four factors. These four factors account for 69% of the total variability and have eigenvalues greater than 1.

Table 18. Rotated factor loadings matrix for the first four factors.

	Factor 1	Factor 2	Factor 3	Factor 4
Co	0.94	0.04	0.12	-0.03
Fe	0.90	0.13	0.11	0.13
Cu	0.76	0.12	-0.05	-0.16
Ni	0.71	0.10	0.30	-0.19
Mn	0.71	0.41	0.21	0.27
Pb	-0.07	0.85	0.13	0.02
Mo	0.20	0.73	0.01	0.10
Zn	0.52	0.55	0.39	0.12
pH	0.14	-0.07	0.88	0.03
F-WAT	-0.01	0.35	0.62	0.33
Hg	0.05	0.34	0.37	-0.18
U	0.12	0.07	-0.12	0.87
U-WAT	-0.17	0.01	0.21	0.71

Table 19. Eigenvalues and percent of variability related to factors.

Factor	Eigenvalue	% of Var	Cum %
1	4.58	35.2	35.2
2	2.00	15.4	50.6
3	1.29	9.9	60.5
4	1.10	8.5	69
5	0.94	7.2	76.2
6	0.81	6.2	82.5
7	0.57	4.4	86.9
8	0.46	3.6	90.4
9	0.41	3.2	93.6
10	0.40	3.1	96.7
11	0.18	1.4	98.1
12	0.14	1.1	99.2
13	0.10	0.8	100

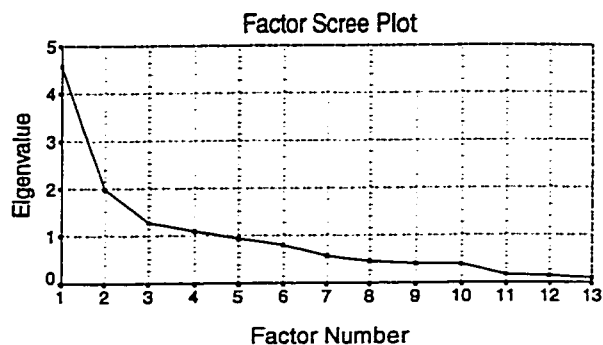


Figure 46. Scree plot for 13 possible factors.

Factor 1 shows the association of Co, Fe, Cu, Ni, and Mn. This factor which alone accounts for 35.2% of the variability can be related to the background values of these elements in the Late Cretaceous plutonic suite (Lkg). It may also indicate the adsorption of metallic ions to Fe and Mn oxides. Scores of this factor have a close to normal distribution (Figure 47).

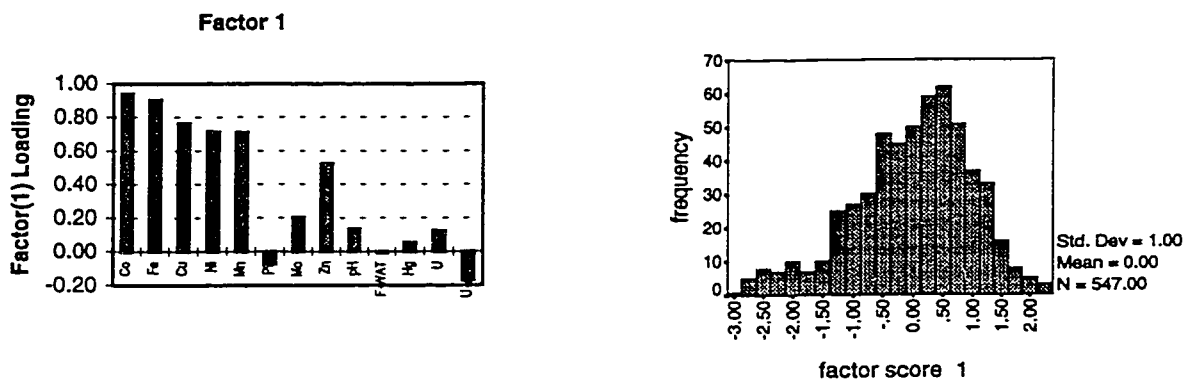


Figure 47. Factor loadings and histogram for scores of factor 1.

Factor 2 has high loadings for Pb, Mo, Zn and smaller ones for Mn, F in water (F-wat) and Hg. Factor 2 which accounts for 15.4% of variability of the data, can represent mineralizations inside the Late Cretaceous plutonic suite (Lkg). The histogram of its scores shows a positively skewed distribution (Figure 48).

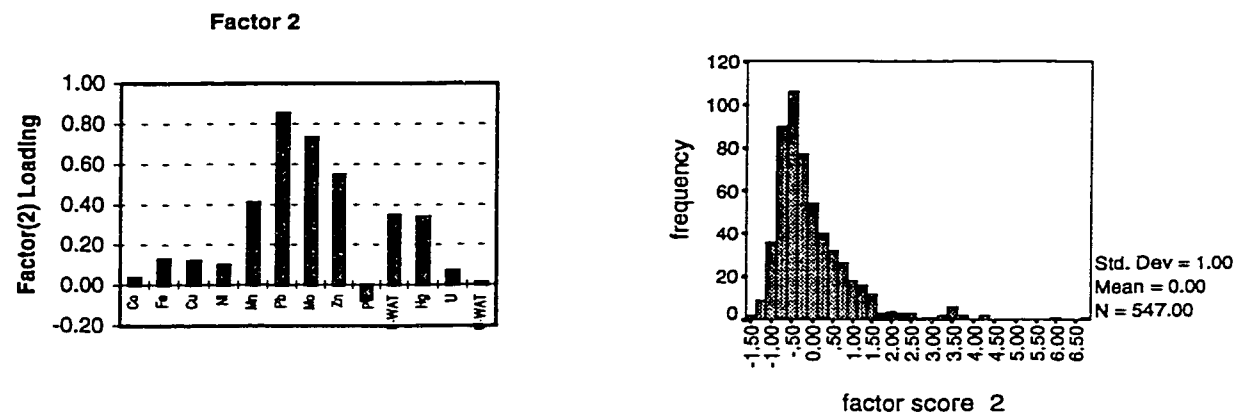


Figure 48. Factor loadings and histogram for scores of factor 2.

Factor 3 accounting for 9.9% of the variability, represents the association of pH and F in water (F-wat). Mercury and Zn have also smaller contribution into this factor. The histogram of factor 3 scores shows a normal distribution (Figure 49).

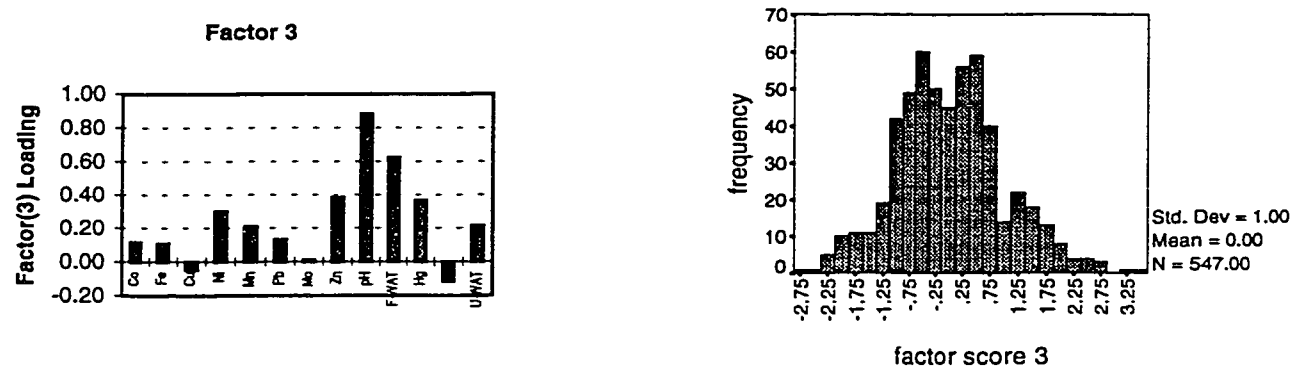


Figure 49. Factor loadings and histogram for scores of factor 3.

Factor 4 shows the association of U in stream sediments and U in water (U-wat). Cameron (1980) has shown that in neutral to acidic conditions, U in stream sediments and U in water (U-wat) have a positive correlation with each other but in alkaline conditions U in water (U-wat) increases while U in stream sediments decreases. The Late Cretaceous plutonic suite (Lkg) comprise mainly felsic plutonic intrusions. Therefore, it is possible to expect not to have high alkaline pH values in this plutonic unit. Variations of pH inside this plutonic suite confirm this.

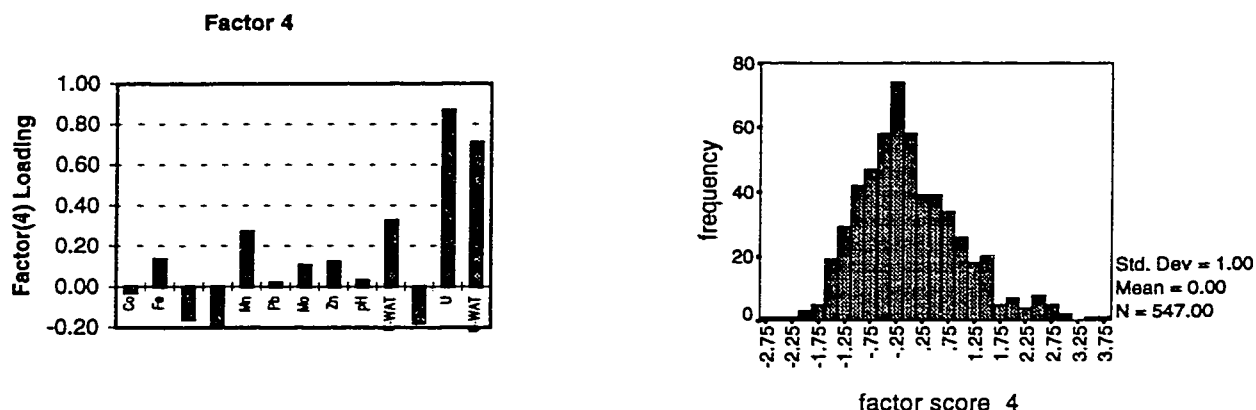


Figure 50. Factor loadings and histogram for scores of factor 4.

Location of different elements based on loadings of factors 1 to 3 is plotted in Figure 51. Factor 2 was mapped in the Late Cretaceous plutonic suite (Lkg) by a moving average method (Figure 52, Figure 53). Fourteen km was selected for the radius of the moving cell with maximum 8 points for consideration and with decay rate of 0.05 for weighting function inside the moving cell. For comparison, locations of known porphyry deposits are also shown on this map.

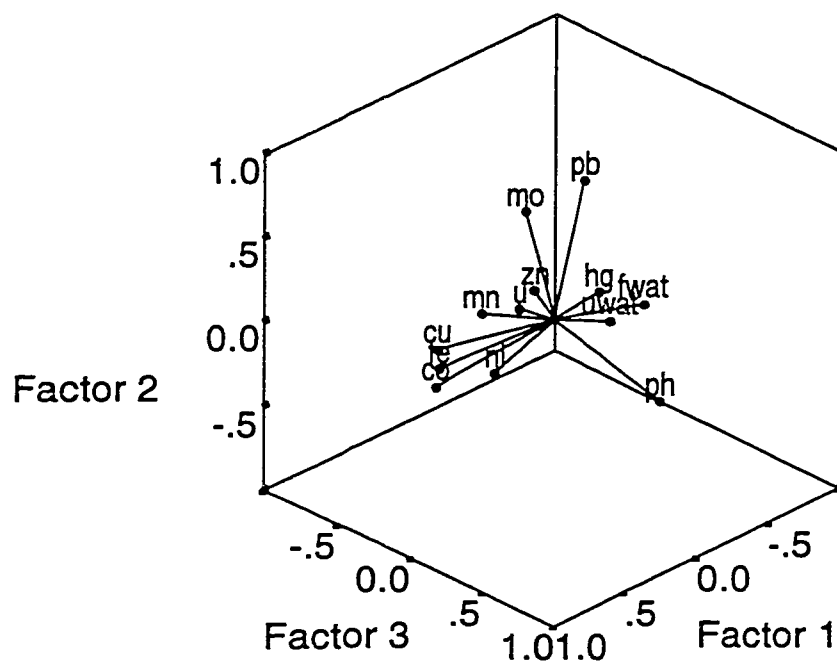


Figure 51. Configuration of factor loadings of the first three factors. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-3.

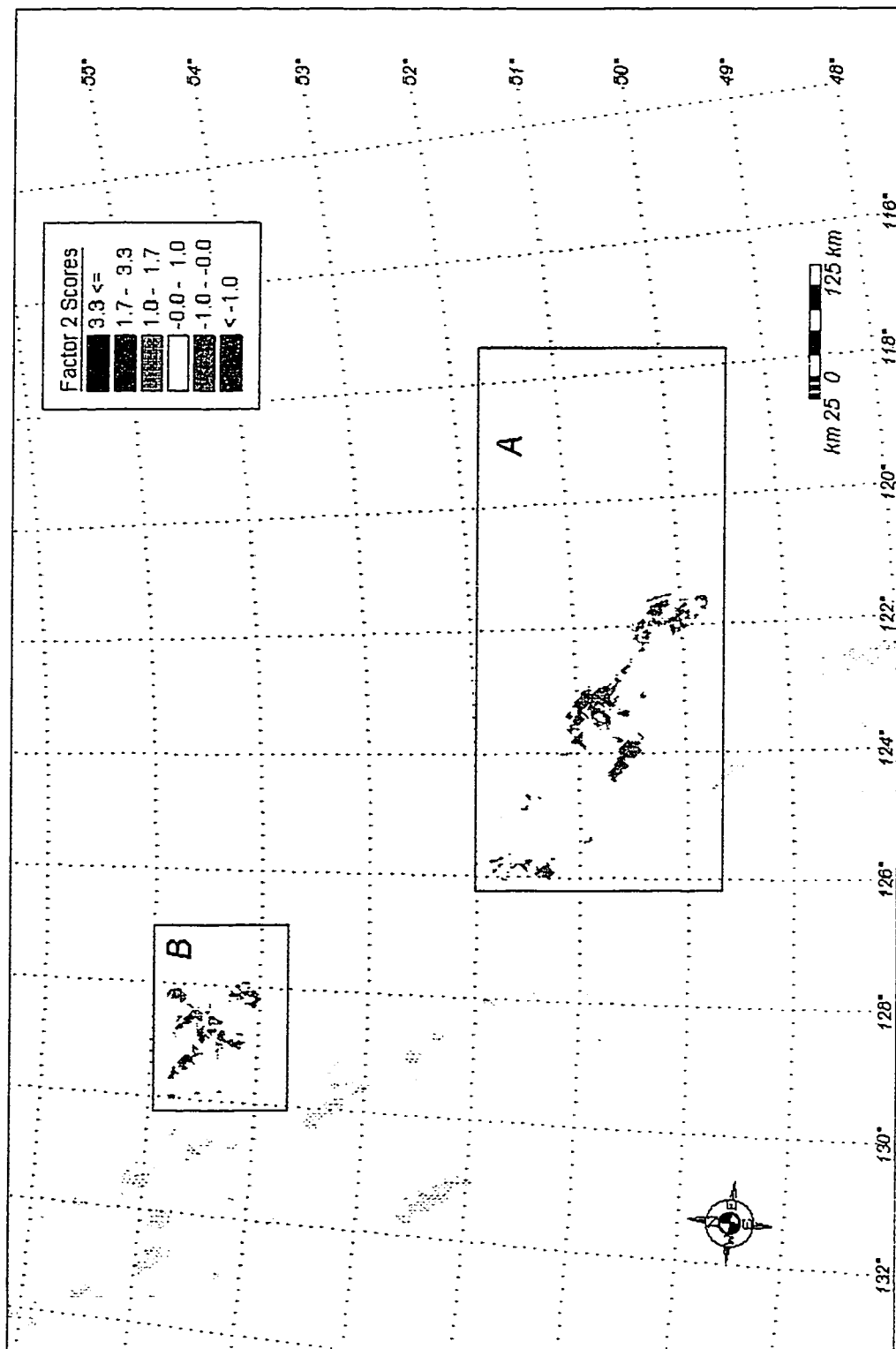
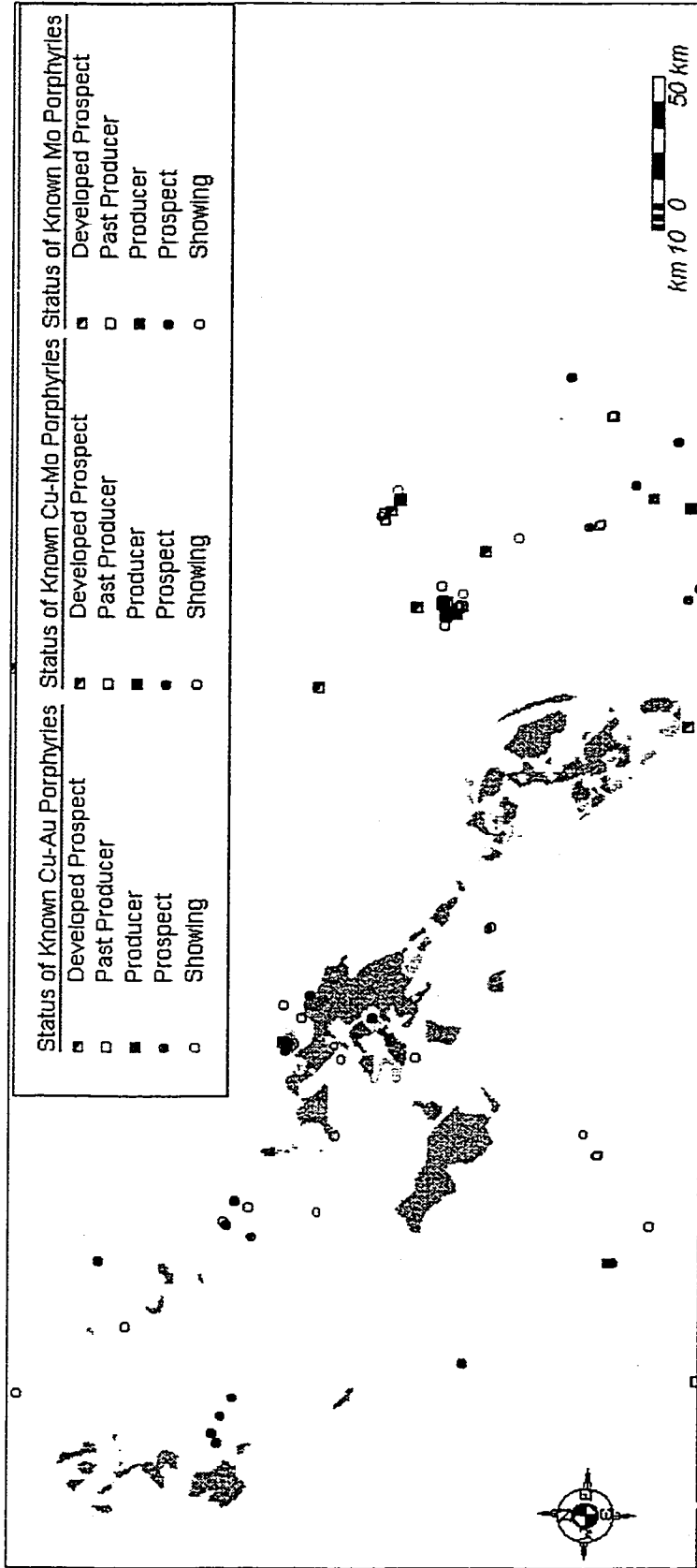
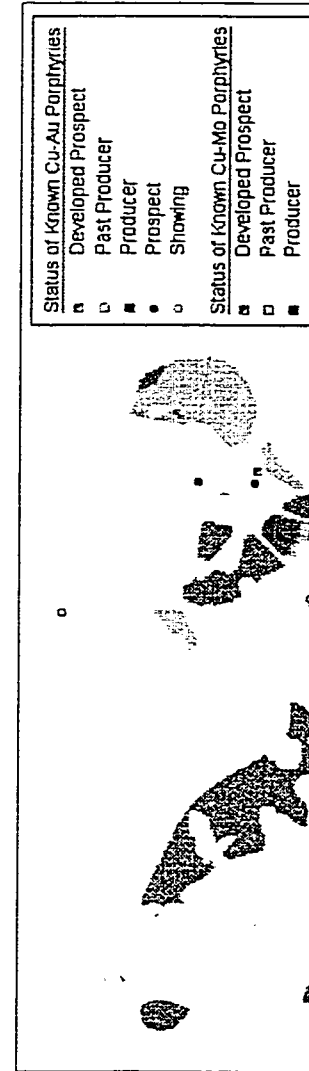
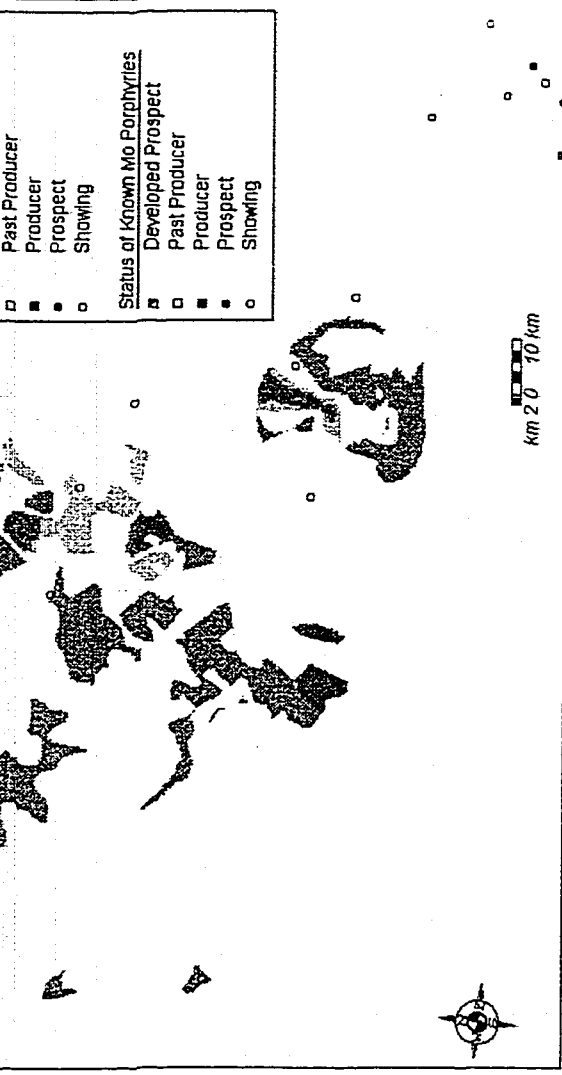


Figure 52. Factor 2 scores in Late Cretaceous plutonic suite (LKG).



(A)





(B)

Figure 53. Factor 2 scores in Late Cretaceous Plutonic Suite (LKG) zoomed in A & B areas with known porphyry Cu-Mo and Cu-Au and Mo deposits.

5.3.4.7 FACTOR ANALYSIS ON GEOCHEMICAL DATA OF BONANZA ARC VOLCANICS (JB)

A total of 466 stream sediment and water samples located inside the Bonanza arc volcanic group (JB), were extracted from the NGR data files. As in previous cases, all the samples classified as extreme outliers were excluded from the multivariate analyses which leaves 416 samples for the multivariate analysis. The elements that were used in the factor analysis, were Co, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U, Zn, and LOI from stream sediment data and pH, F in water (F-wat) and U in water (U-wat) from water samples. Also here pH and Fe had very close to normal distributions so original values were standardised and used in the analysis. For all other elements the standardised z scores of the $\log_{10}$ transformed values were calculated and used in the analyses. Principal component method with correlation matrix was applied for calculating the factors. Here for rotation the oblique method (direct oblmin) was used. Table 20a shows the rotated factor solution for the first 3 factors. To generalise groups of elements, here three factors were calculated by principal component analysis although factor 4 and 5 have also eigenvalues of greater than 1. These first 3 factors account for 51.2% of total variation.

Table 20 a) Factor loadings for the rotated solution, b) Eigenvalues for all the possible factors, c) Correlation matrix between calculated factors.

(a)

	<i>Factor 1</i>	<i>Factor 2</i>	<i>Factor 3</i>
<i>Co</i>	0.87	-0.08	-0.17
<i>Ni</i>	0.85	-0.06	0.11
<i>Cu</i>	0.79	0.13	0.11
<i>Fe</i>	0.66	-0.02	-0.11
<i>pH</i>	0.56	-0.06	0.04
<i>Sb</i>	0.35	0.63	0.21
<i>Pb</i>	-0.31	0.61	-0.37
<i>U</i>	-0.38	0.61	0.19
<i>F-wat</i>	-0.28	0.55	0.10
<i>Hg</i>	0.21	0.39	-0.11
<i>Mo</i>	0.21	0.28	-0.07
<i>Mn</i>	0.23	0.00	-0.82
<i>LOI</i>	-0.12	0.03	-0.81
<i>Zn</i>	0.48	0.37	-0.50
<i>U-wat</i>	0.06	0.27	0.31

(b)

<i>Factor</i>	<i>Eigenvalue</i>	<i>% of Var</i>	<i>Cum %</i>
1	3,96	26,4	26,4
2	1,93	12,9	39,3
3	1,79	11,9	51,2
4	1,27	8,4	59,6
5	1,02	6,8	66,4
6	0,92	6,1	72,6
7	0,79	5,3	77,9
8	0,72	4,8	82,6
9	0,63	4,2	86,9
10	0,56	3,7	90,6
11	0,50	3,3	93,9
12	0,33	2,2	96,1
13	0,25	1,6	97,7
14	0,20	1,4	99,1
15	0,14	0,9	100

(c)

	<i>Factor 1</i>	<i>Factor 2</i>	<i>Factor 3</i>
<i>Factor 1</i>	1		
<i>Factor 2</i>	0,05	1	
<i>Factor 3</i>	-0,13	0,00	1

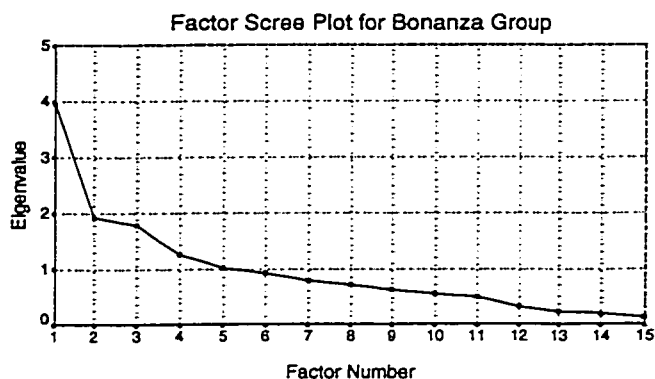


Figure 54. Scree plot for all the 15 possible factors.

Since oblique method (direct oblimin) was used here, the calculated factors can have correlations with each other (Table 20c). Except for factor 1 and factor 3 that have a very small negative correlation (-0.13), the other correlation coefficients are very close to 0. Therefore, this oblique solution is not very far from an orthogonal solution.

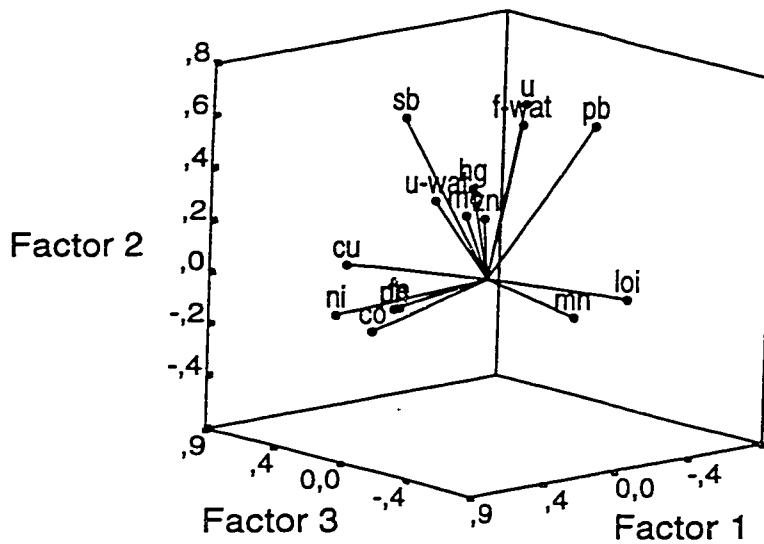


Figure 55. Configuration of factor loadings of the first three factors. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-4.

As factor loadings in Table 20a and Figure 56 show, factor 1 indicates the association of Co, Cu, Ni, Cr, Fe, pH, and possibly Zn. In Figure 56 the histogram of the calculated scores for this factor shows a distribution with a negative skewness. Hence, for most of the samples the score for this factor is high. Here factor 1 is considered as indicating background values for the elements associated with this factor. This factor accounts for 26.4% of variability of the data.

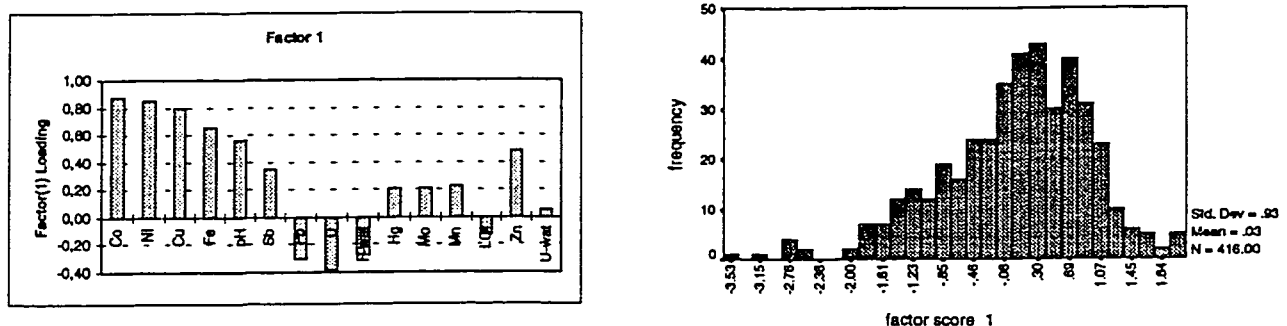


Figure 56. Factor loadings and histogram for the scores of factor 1.

Factor 2 accounting for 12.9% of the variability, shows the association of Sb, Pb, U, F in water (F-wat), Hg, and Mo. Compared to factor 1, the scores of this factor show a distribution with a slight positive skewness (Figure 57). By considering the association of elements represented by this factor and statistical and spatial distribution of its scores over Bonanza Group (JB) as indicated in Figure 58 and 59, this factor could represent mineralizations within the Bonanza group.

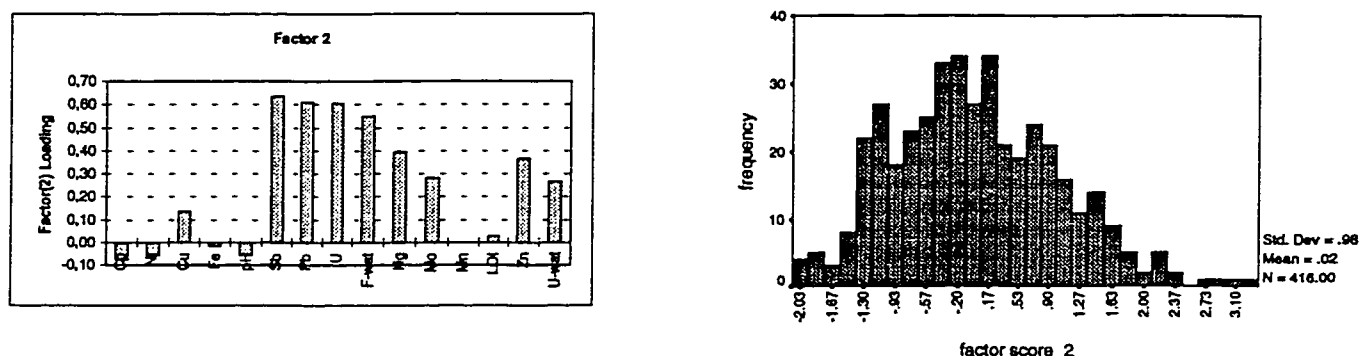


Figure 57. Factor loadings and histogram for the scores of factor 2.

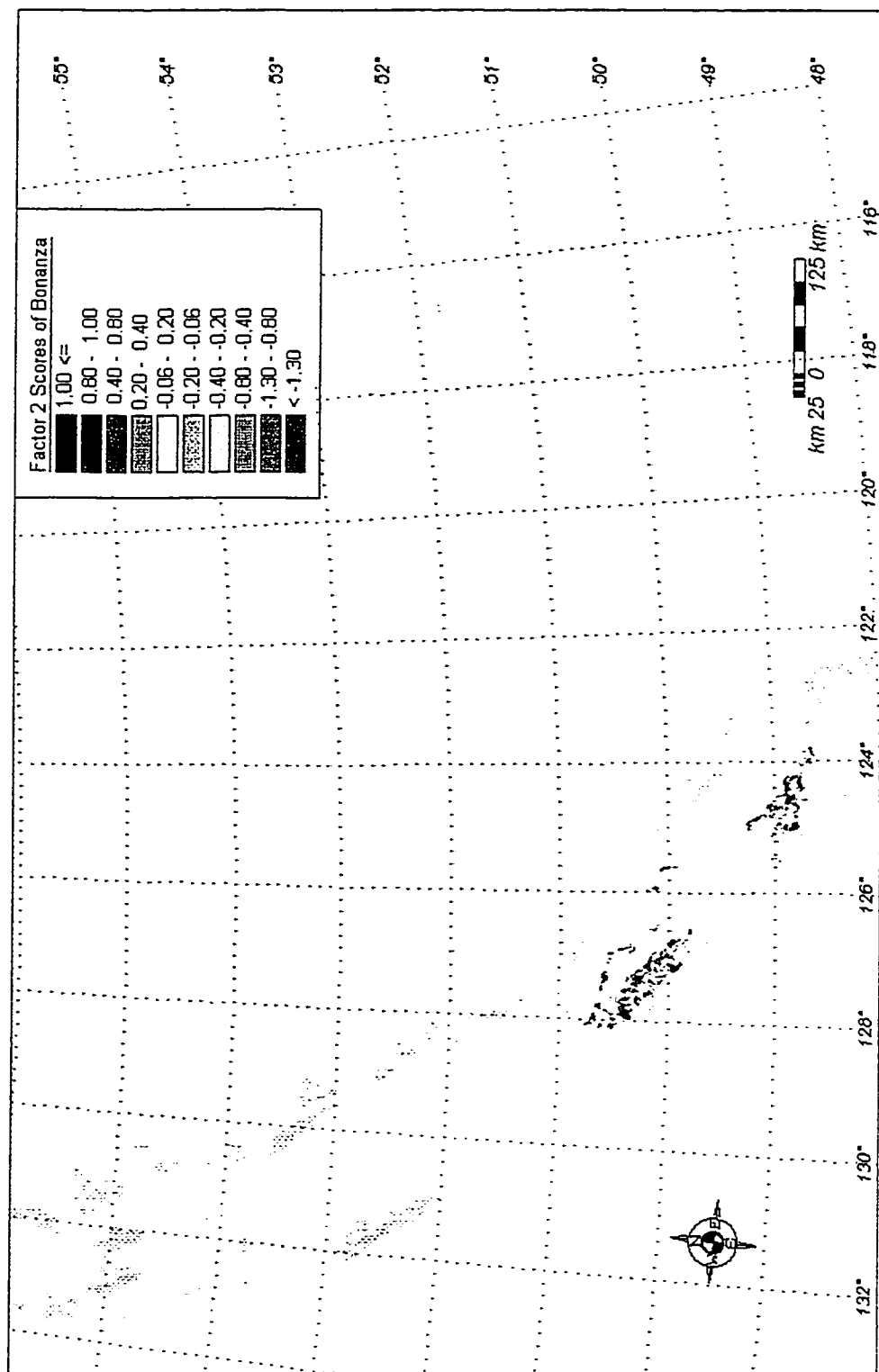


Figure 58. Location of the calculated factor 2 scores for Bonanza (JB) Group.

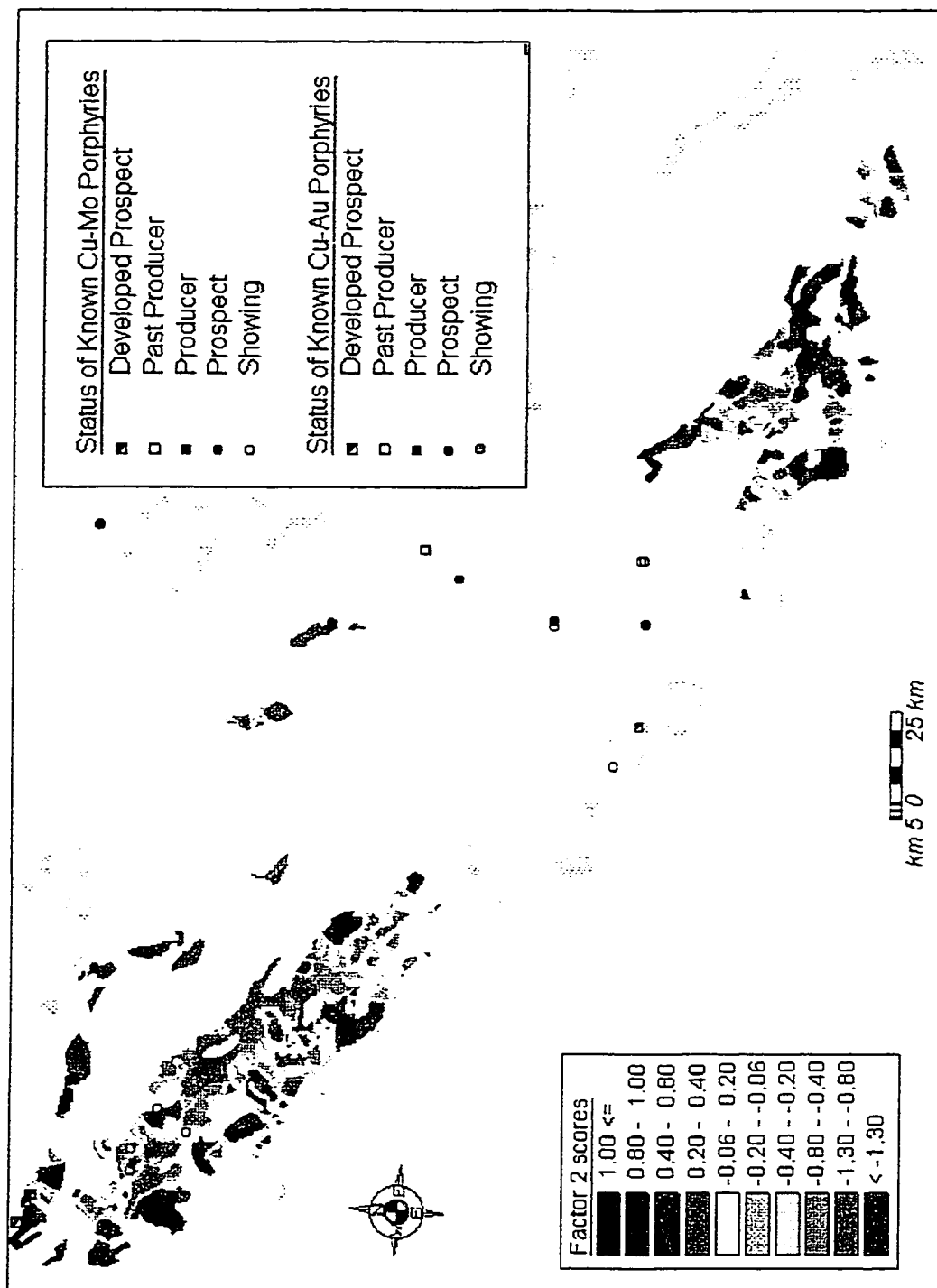


Figure 59. Factor 2 scores in Bonanza Group (JB) with known porphyry Cu-Mo & Mo deposits.

The association of Mn, LOI, Zn and U in water (U-wat) is represented by factor 3. Only U in water (U-wat) has an opposite sign relative to the others. This factor could be considered as an indicator of adsorption of metallic ions to Mn oxides and organic material. Scores of this factor are normally distributed (Figure 60).

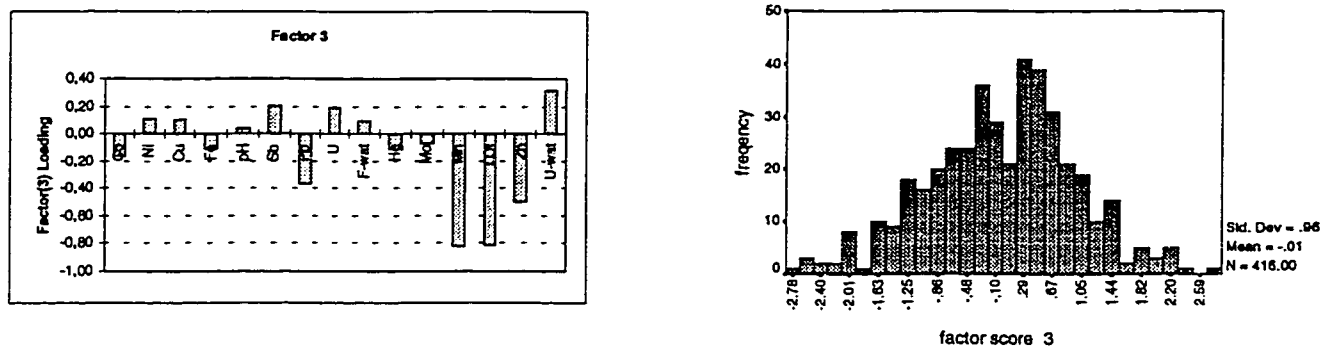


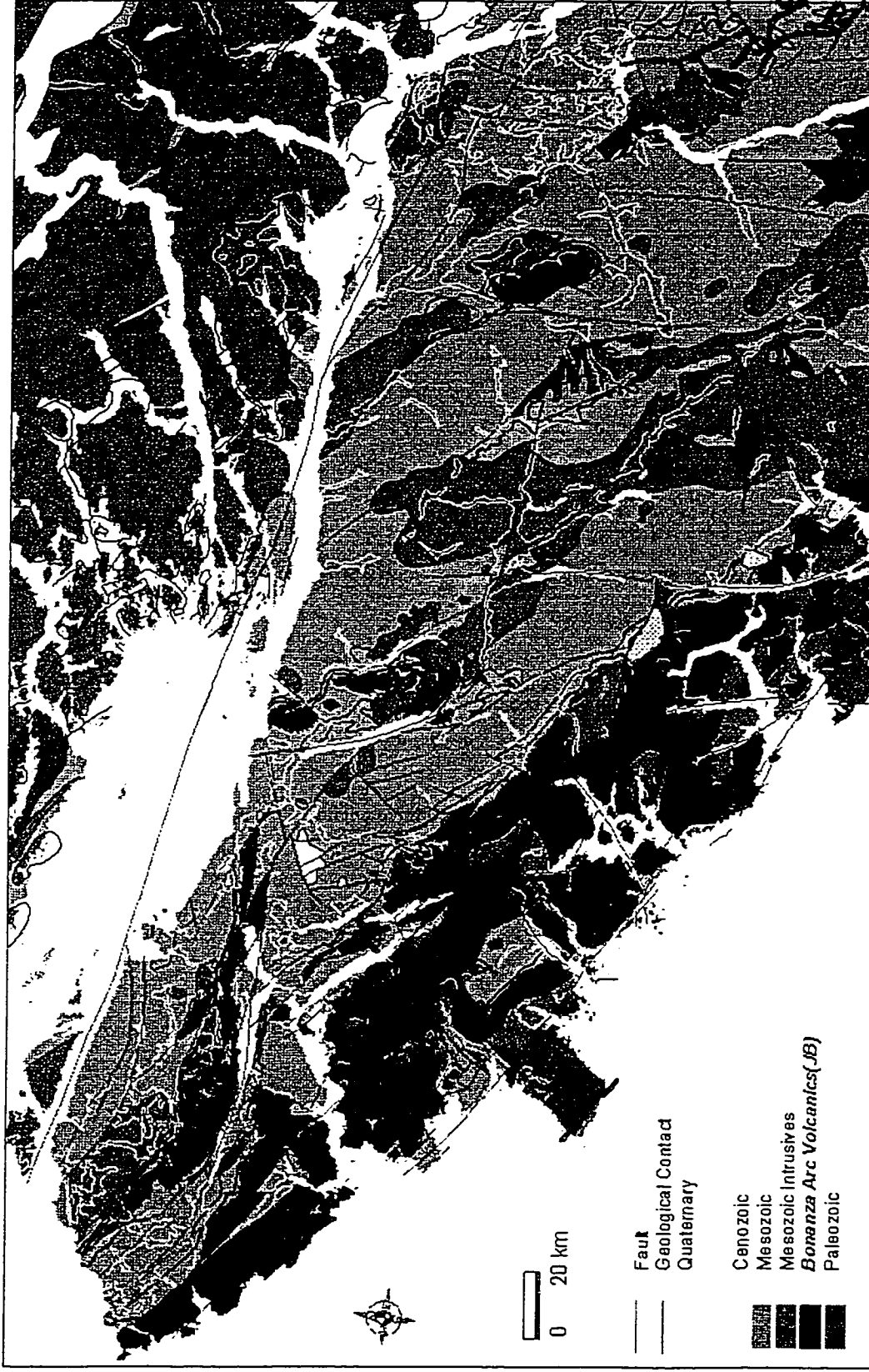
Figure 60. Loadings for factor 3 and histogram of its scores.

5.3.4.8 COMPARISON WITH THE GEOLOGY OF BONANZA ARC VOLCANICS

Figure 61 shows distribution of Bonanza arc volcanics (JB) in the northern Vancouver Island with details of 1/50,000 scale. Bonanza Group which is Lower Jurassic in age, mainly comprises of massive pillowed basalt to andesite flows, dacite to rhyolite massive or laminated lava, green and maroon tuff, feldspar crystal tuff, breccia, tuffaceous sandstone, argillite, pebble conglomerate and minor limestone (Sinemurian to Pliensbachian). In some locations, rocks of Bonanza are intruded by early to middle Jurassic Island plutonic suites (JI). This plutonic suite is mainly granodiorite, quartz diorite, quartz monzonite, diorite, agmatite, feldspar porphyry, minor gabbro and aplite with the age of 170-185 Ma. In many locations intrusive bodies of this plutonic suite are responsible for porphyry mineralization inside Bonanza. In many cases high scores for factor 2 in Bonanza (Figure 59) match with locations where Island plutonic suite intrusions are in contact with Bonanza arc volcanics or close to these intrusions (Figure 61).

50.95

-128.45



-125.25

49.68

Figure 61. Distribution of Bonanza arc volcanics (JB) in northern Vancouver Island.

5.3.4.9 FACTOR ANALYSIS ON GEOCHEMICAL DATA OF HAZELTON ARC VOLCANICS GROUP (JH)

Cobalt, Cu, Fe, Hg, Pb, Mn, Mo, Ni, U and Zn from stream sediment data and pH, F in water (F-wat), U in water (U-wat) from water samples were entered into the factor analysis for Hazleton Group (JH). There are 1332 samples inside Hazleton Group (JH). Here pH has a normal distribution so the original values are directly standardised. For elements, $\log_{10}$ transformed values were standardised and used for the factor analysis. After calculating the factors, an orthogonal method (Equimax) was used here to rotate the factors.

As Table 21 shows, the first four factors have eigenvalues greater than 1. Table 22 shows the loadings for the rotated factor solution. The first four factors account for 65.5% of the total variability.

Table 21. Eigenvalues and for all the possible factors.

Factor	Eigenvalue	% of Var	Cum %
1	4.13	31.7	31.7
2	1.67	12.9	44.6
3	1.50	11.5	56.1
4	1.22	9.4	65.5
5	0.91	7.0	72.5
6	0.68	5.3	77.8
7	0.65	5.0	82.8
8	0.59	4.5	87.3
9	0.48	3.7	91
10	0.43	3.3	94.3
11	0.35	2.7	97.1
12	0.22	1.7	98.8
13	0.16	1.2	100

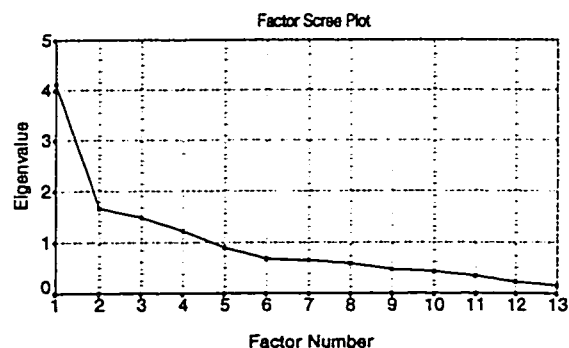


Figure 62. Scree plot for all the 13 possible factors.

Table 22. Factor loadings for the rotated solution.

	Factor 1	Factor 2	Factor 3	Factor 4
Co	0.90	0.22	-0.09	0.05
Cu	0.81	0.15	0.18	-0.14
Ni	0.70	0.16	-0.23	0.12
Pb	-0.02	0.84	0.13	-0.21
Zn	0.35	0.82	0.00	-0.03
Mn	0.33	0.63	-0.13	0.25
Hg	0.07	0.60	0.00	0.32
Fe	0.55	0.59	-0.09	0.09
U	-0.25	0.05	0.72	-0.07
U-wat	-0.06	-0.25	0.68	0.18
Mo	0.28	0.27	0.64	-0.05
pH	0.17	0.01	0.22	0.81
F-wat	-0.42	0.05	-0.30	0.59

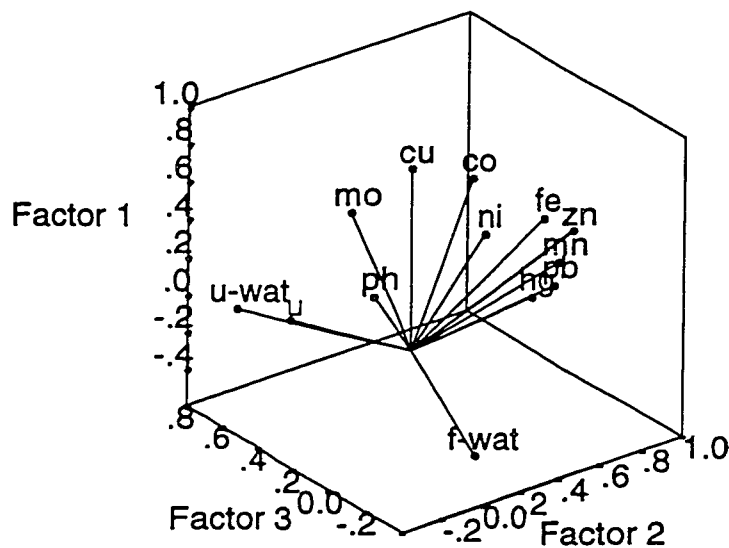


Figure 63. Factor loadings for factor 1, 2 and 3. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-5.

Calculated scores of factor 1 show generally a distribution similar to normal (Figure 64). Factor 2 with association of Pb, Zn, Mn, Hg, and Fe may represent absorption and coprecipitation of Pb, Zn and Hg to oxides of Mn and Fe in the oxidising and secondary geochemical environments. The scores for this factor also show a normal distribution. Almost universal association of Mo with porphyry Cu deposits makes it a useful guide to that type of

deposit in both residual soil and in stream water and sediment (Rose et al., 1979). By considering the association of elements related to factor 3 (Mo, U, and U-wat), this factor is considered as an indicator of mineralizations in Hazleton Group (JH). 11.5% of the total variability can be explained by this factor.

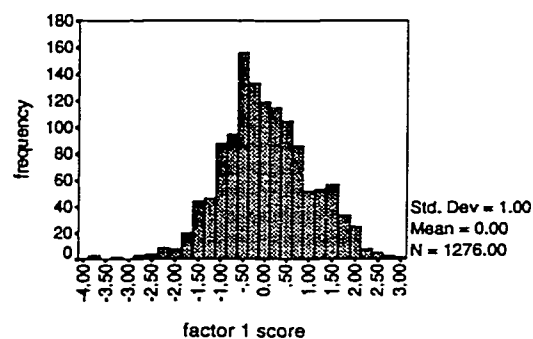
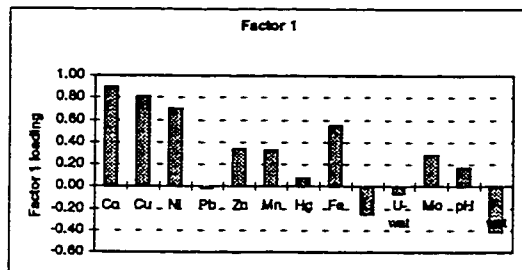


Figure 64. Factor loadings and histogram for scores of factor 1.

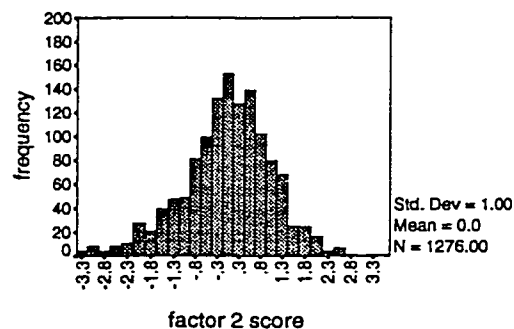
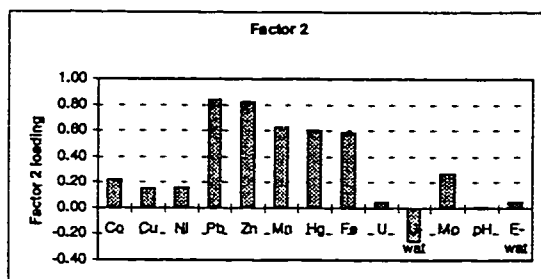


Figure 65. Factor loadings and histogram for scores of factor 2.

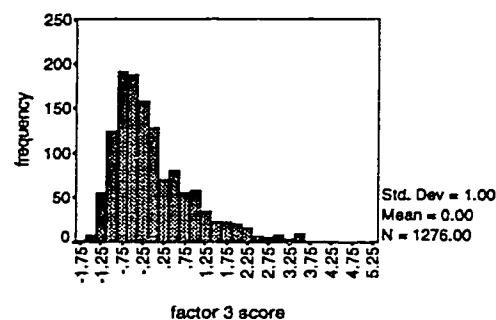
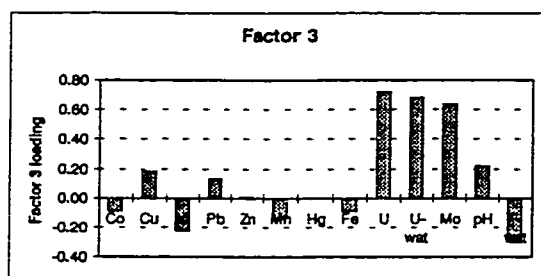


Figure 66. Factor loadings and histogram for scores of factor 3.

As Figure 66 shows, calculated scores for factor 3, show a positively skewed distribution. Scores of factor 3 are mapped by a moving average method to see its variations over the study area in Hazleton Group (JH) (Figure 68, 69). Fourteen km was selected for the radius of the moving cell with maximum 8 points for consideration and with decay rate of 0.05 for weighting function inside the moving cell. Locations of the known porphyry deposits of different types are also indicated in this map. In general areas with high scores for factor 3 match with the location of known porphyry mineralized areas (Figure 69).

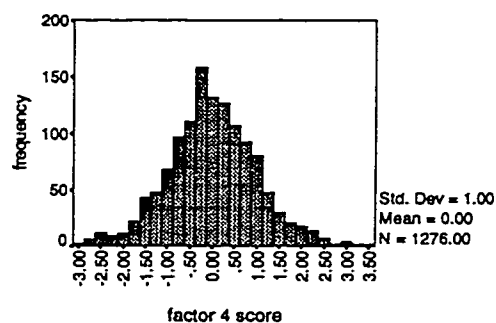
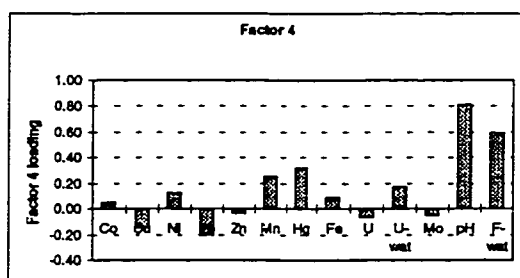


Figure 67. Factor loadings and histogram for scores of factor 4.

Factor 4 with association of pH and F in water reflects the dependability of F in water with pH. Since this is not a rare geological phenomenon its scores show a normal distribution.

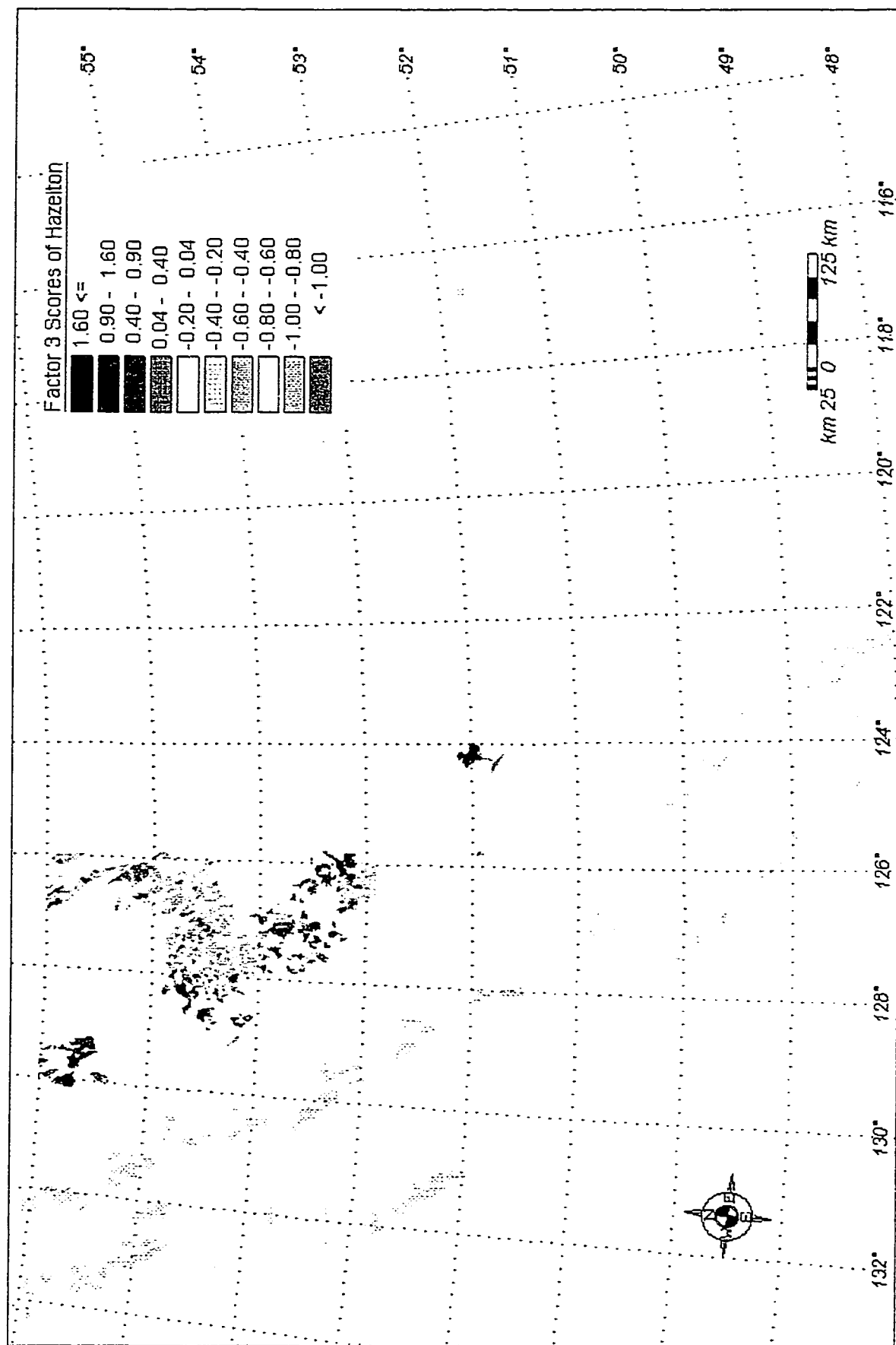


Figure 68. Location and distribution of factor 3 scores in Hazelton arc volcanics (JH).

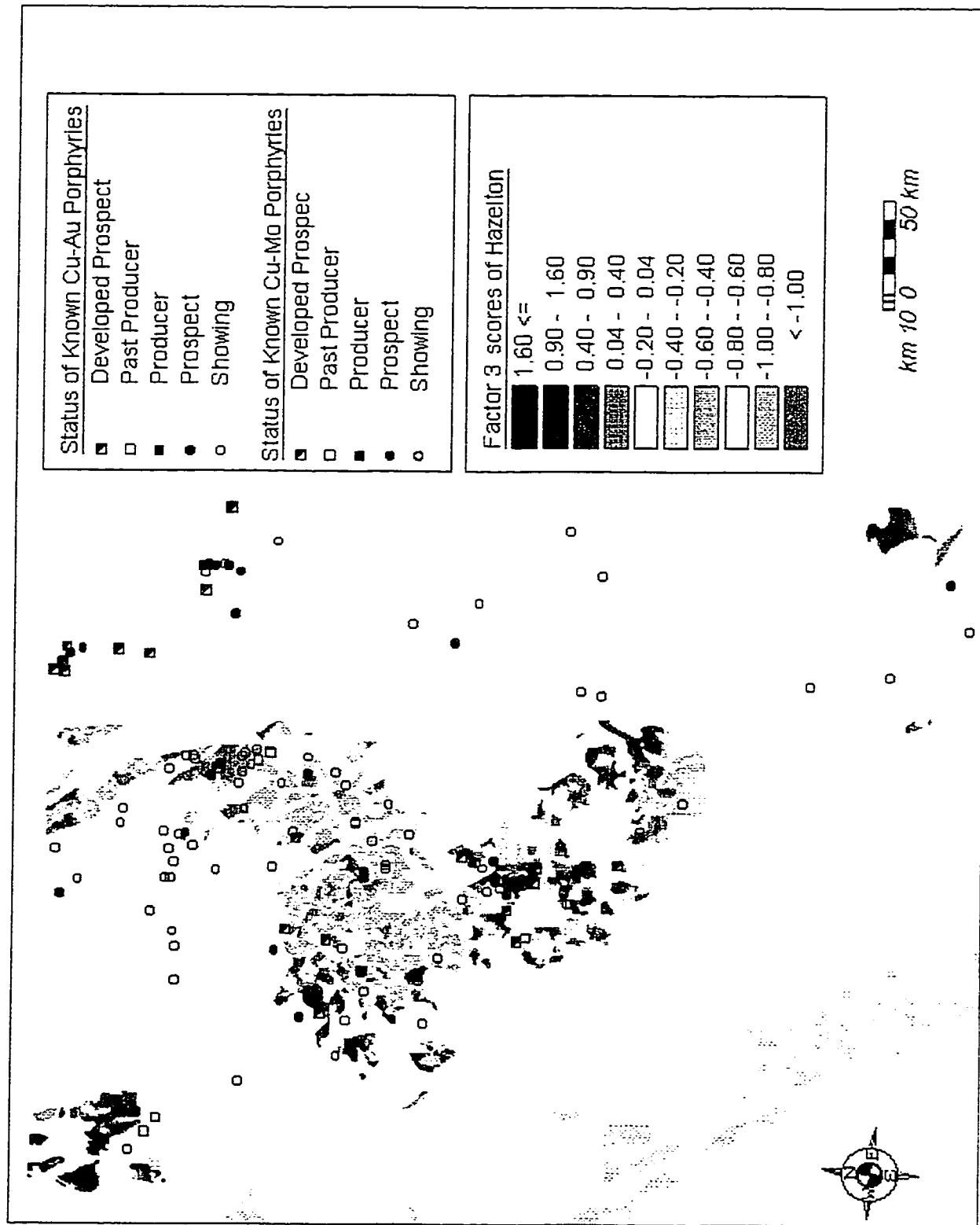


Figure 69. Distribution of factor 3 scores in Hazelton arc volcanics (JH) and known porphyry deposits.

5.3.4.10 FACTOR ANALYSIS ON GEOCHEMICAL DATA OF TAKLA & NICOLA (TrJ, TrJN) ARC VOLCANICS

1841 samples are located within the boundaries of Takla and Nicola arc volcanics (TrJ, TrJN). Of these samples, 1793 were entered into the multivariate analysis. Cobalt, Cu, Fe, Hg, Pb, Mn, Mo, Ni, Sb, U and Zn from stream sediment samples and pH, F in water (F-wat) and U in water from water samples were used for multivariate. Samples inside Takla and Nicola (TrJ, TrJN) did not have enough data for other elements and LOI so these variables were not considered for the multivariate analyses. As the scree plot in Figure 70 and Table 23b show, the first four factors have significant eigenvalues. The eigenvalue has a rapid decrease from factor 1 to 4. Here these first four factors were extracted and used.

Table 23 a) Factor loadings for the rotated solution, b) Eigenvalues for all the possible factors, c) Correlation matrix between calculated factors.

(a)

	Factor 1	Factor 2	Factor 3	Factor 4
Co	0.94	-0.03	-0.15	-0.01
Fe	0.90	-0.07	-0.13	-0.06
Mn	0.75	0.05	-0.19	0.04
Zn	0.73	0.05	0.13	0.27
Ni	0.58	-0.14	0.20	0.07
Sb	0.42	0.00	0.23	-0.14
U-wat	-0.04	0.84	-0.02	0.17
F-wat	-0.07	0.81	0.01	0.01
pH	0.06	0.79	-0.03	-0.30
Hg	-0.06	-0.09	0.78	-0.10
Mo	-0.11	0.03	0.68	0.23
Cu	0.39	-0.01	0.45	-0.27
U	0.03	-0.10	-0.02	0.82
Pb	0.36	0.15	0.23	0.42

(b)

Factor	Eigenvalue	% of Var	Cum %
1	3.89	27.8	27.8
2	2.05	14.7	42.4
3	1.39	10	52.4
4	1.13	8.1	60.4
5	0.97	6.9	67.4
6	0.88	6.3	73.7
7	0.75	5.4	79
8	0.72	5.1	84.2
9	0.63	4.5	88.6
10	0.44	3.1	91.8
11	0.37	2.6	94.4
12	0.34	2.4	96.8
13	0.28	2	98.8
14	0.16	1.2	100

(c)

	Factor 1	Factor 2	Factor 3	Factor 4
Factor 1	1			
Factor 2	-0.04	1		
Factor 3	0.24	-0.08	1	
Factor 4	0.04	0.01	0.08	1

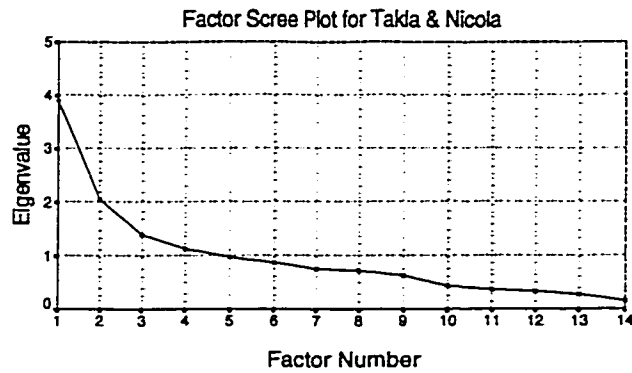


Figure 70. Scree plot for all the 14 possible factors.

After calculating factors, an oblique method (direct oblimin) was used for rotation therefore a correlation matrix was calculated for them (Table 23c). Except for factor 1 and 3 with a correlation coefficient of 0.24, all other correlation coefficients are very close to 0.

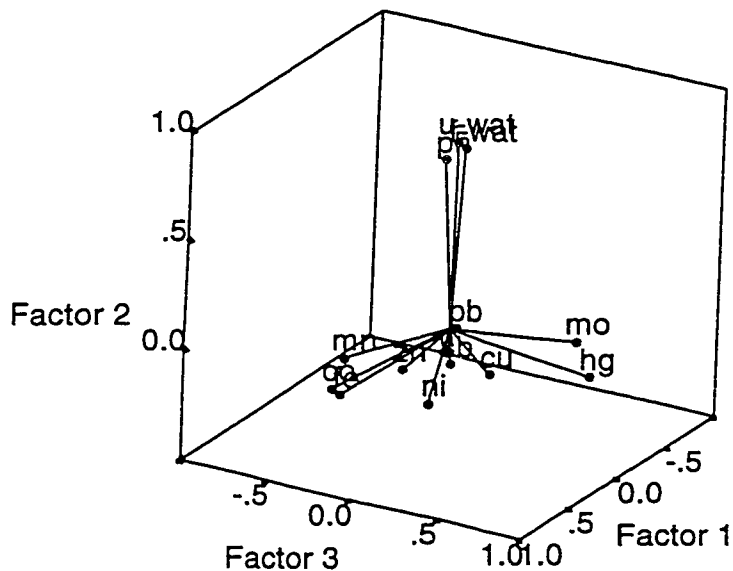


Figure 71. Loadings of factor 1, 2 and 3. Two dimensional plots for loadings of each pair of factors are shown in Appendix B-6.

First factor, which accounts for 27.8% of the total variance, can be related to manganese oxide coatings. Scores for this factor shows a distribution very close to normal (Figure 72). In

addition to Mn, Fe and some trace metals (Co, Zn, and Ni) have high loadings on factor 1. This suggests that much of the variation of these metals is a direct result of the variation in the amount of manganese oxide coatings. The three trace elements that have the highest loadings on this factor (Co, Zn, and Ni) are those, which Nowlan (1976) has found to be strongly scavenged by Mn oxides. Among these, Co and Zn are those which are known to substitute readily in some manganese oxide structures (Loganathan and Burau, 1973; Burns, 1976). As loadings of factor 1 shows, a small part of the variation of Cu can be also because of the absorption to Mn and Fe oxides.

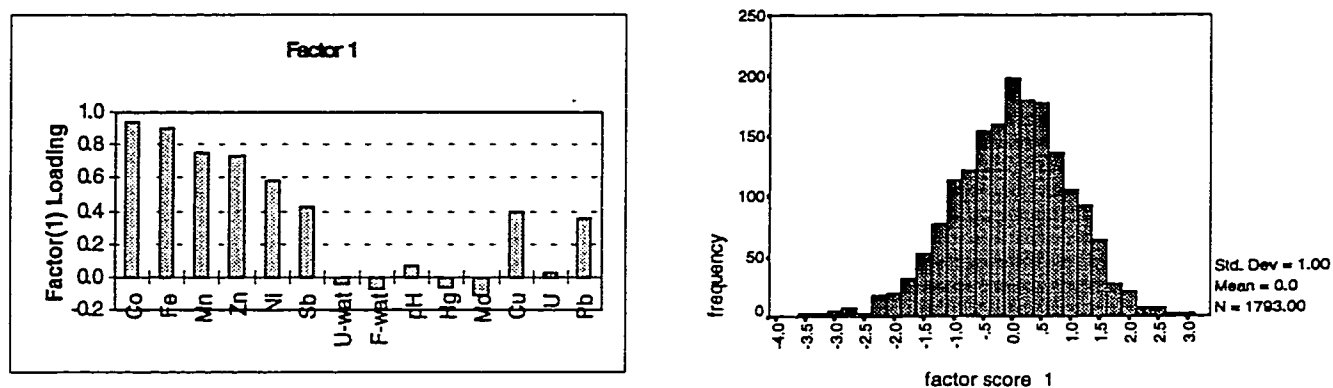


Figure 72. Factor loadings and histogram for scores of factor 1.

Factor 2 accounts for 14.7% of the total variance and has strong loadings for U in water (U-wat), F in water (F-wat), and pH and very close to 0 for other elements. Like most of the previous cases, this could be due to the natural association of U complexes with pH and its high dependence on the mobility of F and U in water (U-wat) to pH (Cameron, 1980). Distribution of the scores of this factor has a positive skewness (Figure 73). Samples with high score for factor 2 might be representative of areas with U and Mo mineralization.

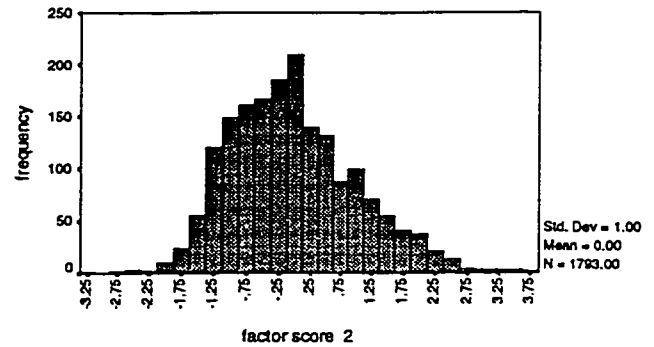
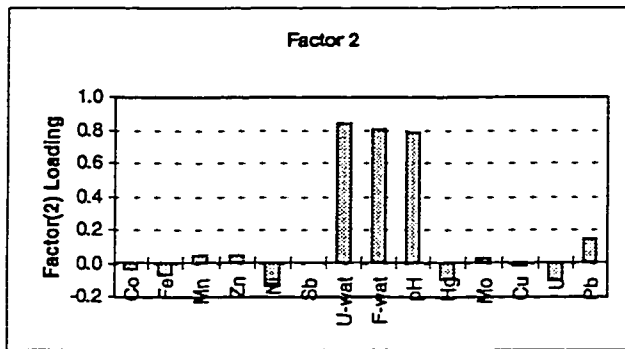


Figure 73. Factor loadings and histogram for the scores of factor 2.

Factor 3 accounting for 10% of the total variability of the data, can represent porphyry mineralizations inside Takla & Nicola (TrJ, TrJN). It has high loadings for Hg, Mo and Cu as Figure 74 shows. Mercury is associated especially with epithermal sulphide deposits and could be used as a pathfinder for this kind of deposits (Levinson, 1980, Rose et. al. 1979). In a complete porphyry system, it is possible to have gradual change in temperature and thereby a change of mineralization from porphyry to epithermal deposits (Titley and Beane, 1981). So at least for some cases the association of Hg could be considered as indirectly related to the porphyry mineralizations.

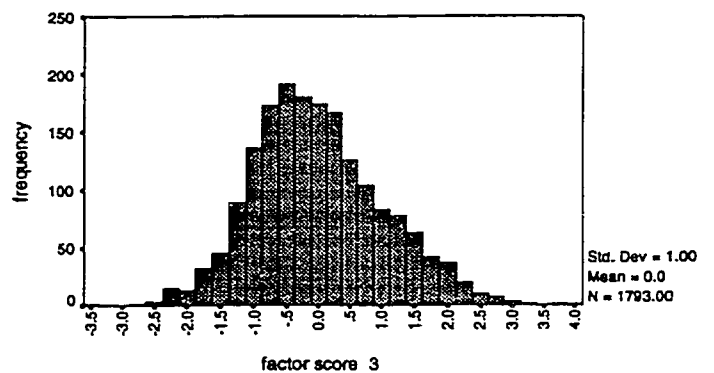
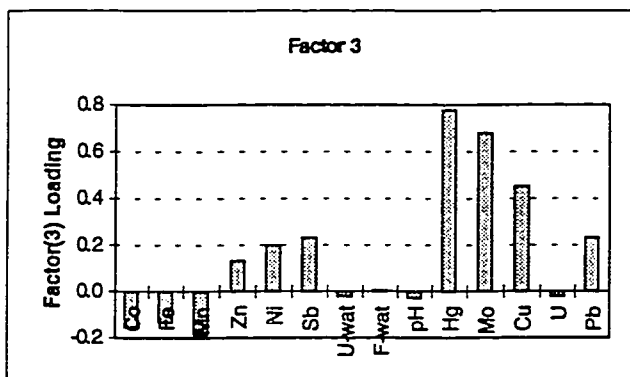


Figure 74. Factor loadings and histogram for the scores of factor 3.

The scores of factor 3 show slightly positive skewness (Figure 74). To see the variations of factor 3 scores with location of the known porphyry deposits, map of Figure 75 and 76 are generated by a moving average method with the same parameters for the moving cell as previous cases.

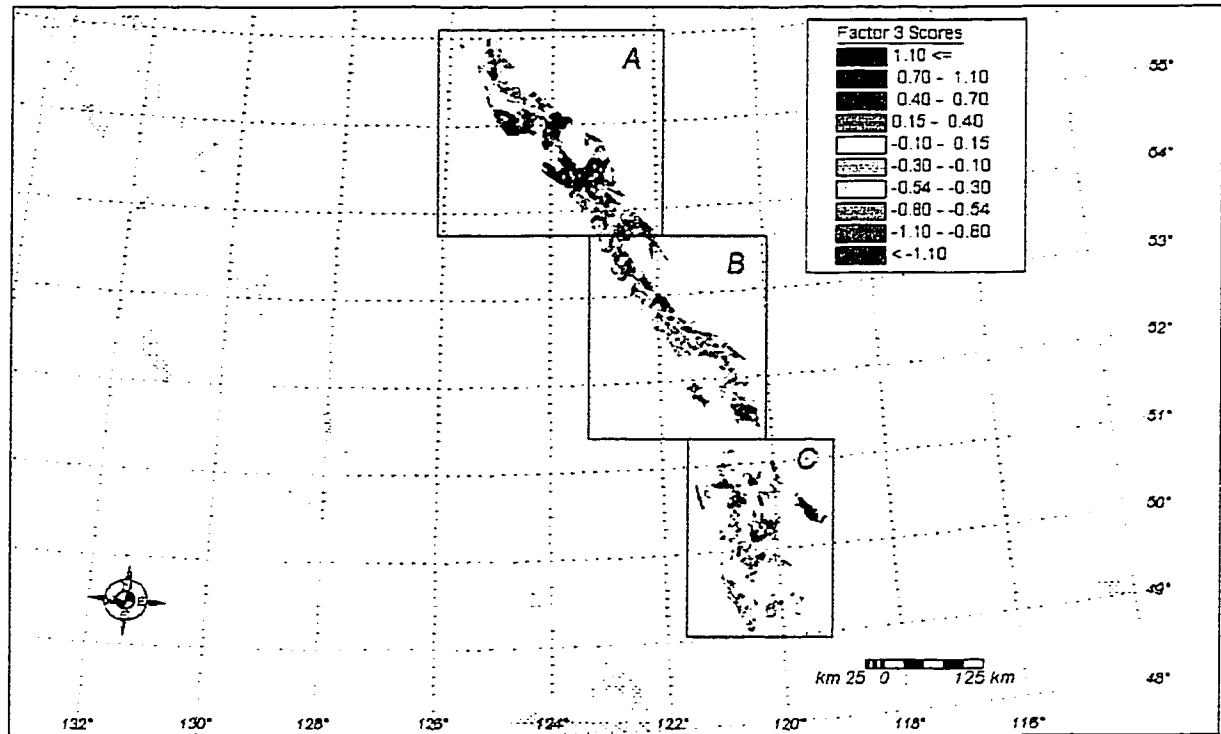
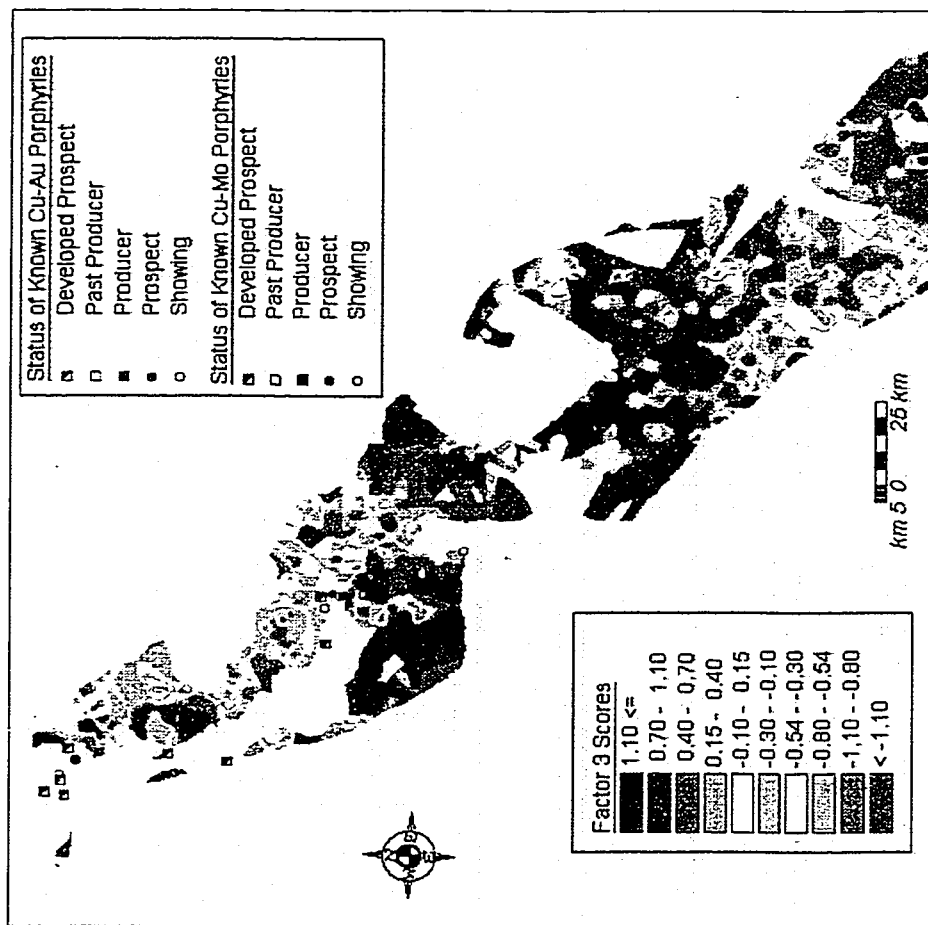


Figure 75. Factor 3 scores in Takla and Nicola (TrJ, TrJN). Three areas of A, B and C are plotted in more details in Figure 76.



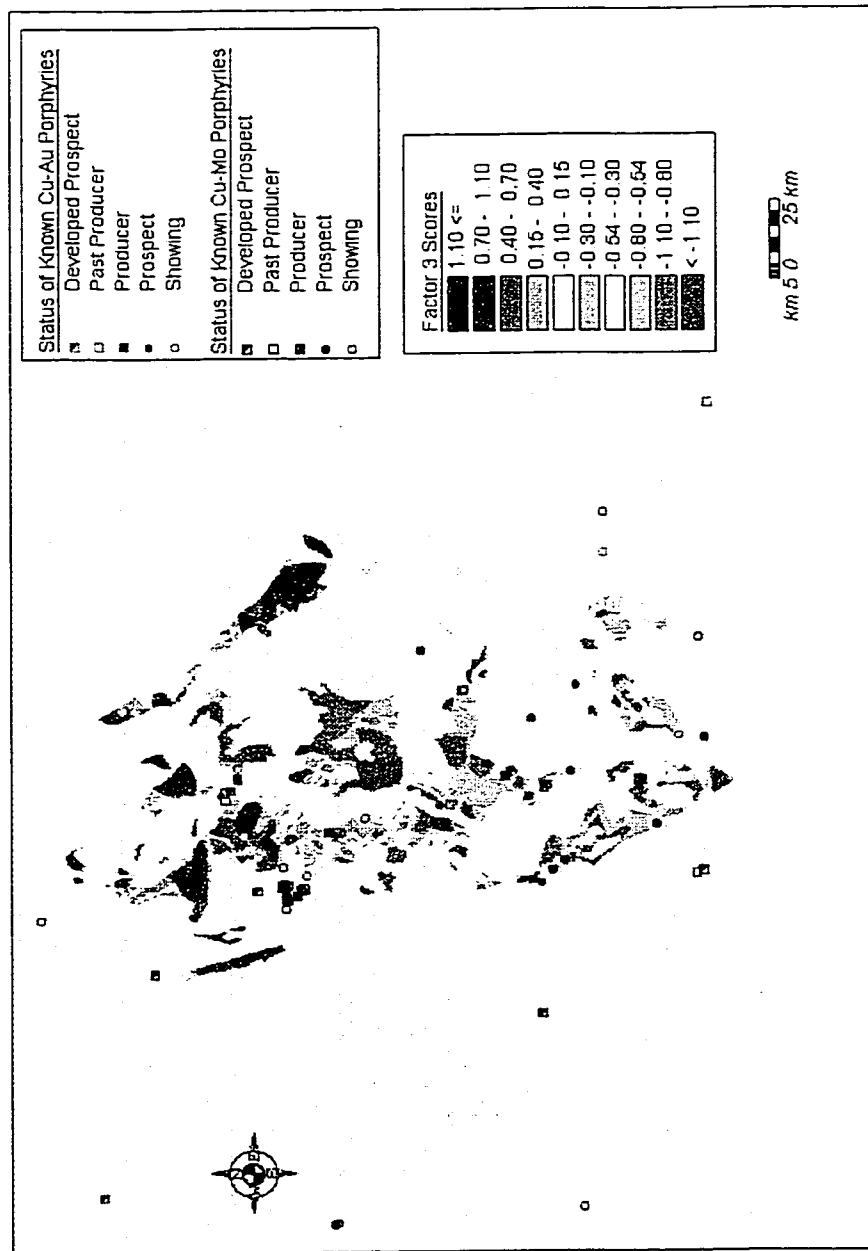
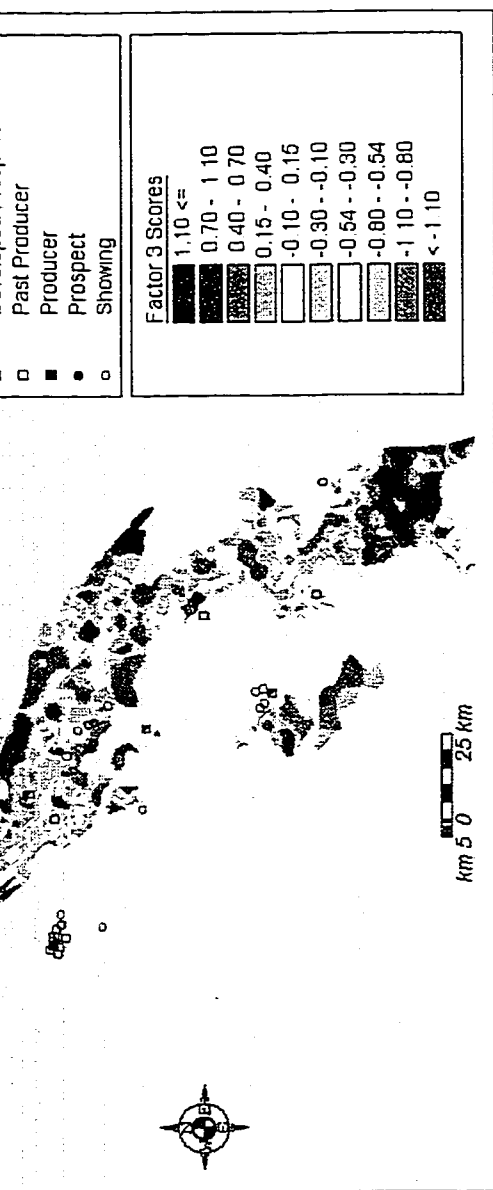


Figure 76. Factor 3 scores for Takla and Nicola (TrJ, TrJN) on areas of A, B, and C.

Factor 4 accounts for 8.1% of the total variance. It has high loadings for U (in stream sediments) and Pb. For factor 4, the loading for pH is very small but it is in the opposite direction of the loading for U (in stream sediments). This might be due to the nature of mobility of U in stream sediments with pH. Factor loadings and distribution of scores of this factor are shown in (Figure 77). Factor 4 scores have a normal distribution.

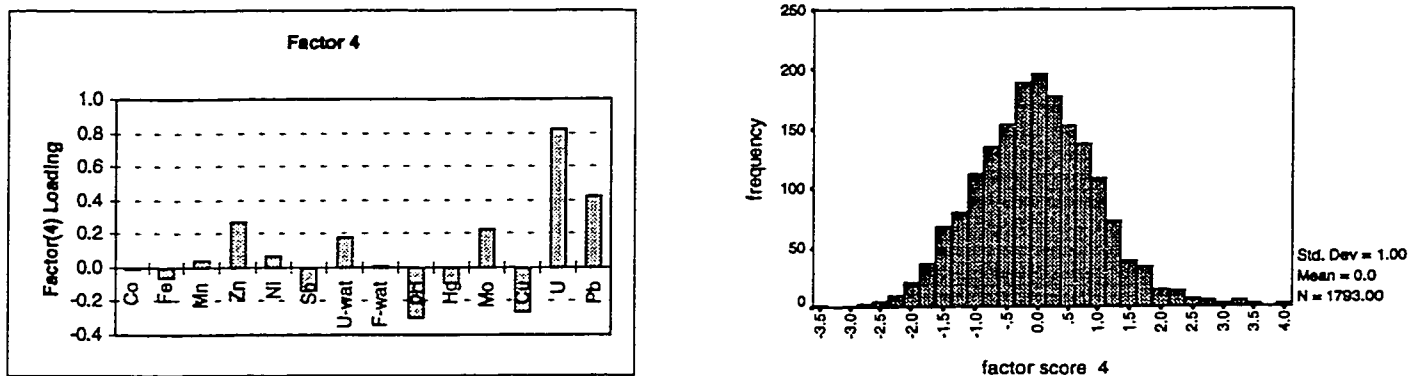


Figure 77. Factor loadings and histogram for the scores of factor 4.

CHAPTER 6

GEOPHYSICAL CHARACTERISTICS OF PORPHYRY MINERALIZED AREAS AND ANALYSIS

6.1 INTRODUCTION

In many mineral potential mapping studies, geophysical data have been used as an important element for analysis (An *et al.* 1991, Agterberg *et al.* 1993, Bonham-Carter, 1994, Bonham-Carter *et al.* 1990, Wright and Bonham-Carter, 1996) especially if there is a known or possible relationship between a geophysical signature and a certain type of mineralization.

At the regional and local scales, airborne magnetic surveys, which are rapid and economical, have been a part of porphyry deposits explorations. Both intrusions and related alteration systems may have characteristic magnetic signature, which in the ideal case, form distinctive anomalies in regional surveys (Thompson, 1995). These patterns may reflect the increased concentration of secondary magnetite in potassic alteration zones, or magnetite destruction in other peripheral styles of alteration (Thompson,

1995), or high magnetite in the original intrusive plutons responsible for mineralizations (Lueck and Russell, 1993). In British Columbia, most of the known mineralized zones and porphyry deposits show an association with magnetic highs. In this chapter magnetic and gravity data of the study area are used as another indicator of potentially mineralized areas. Based on the data and their analysis, geophysical maps are generated and are entered into the final integration of layers by GIS modelling.

6.2 ANALYSIS OF AEROMAGNETIC DATA

6.2.1 INTRODUCTION

Magnetic susceptibility of rocks is the significant variable in magnetics. It plays the role as density does in gravity interpretation (Telford *et al.*, 1990). Most common rock-forming minerals exhibit a very low magnetic susceptibility and rocks owe their magnetic character to the generally small proportion of magnetic minerals that they contain. There are mainly two geochemical groups, which provide such minerals. The iron-titanium-oxygen group possesses a solid solution series of magnetic minerals from magnetite (Fe_2O_3) to ulvospinel (Fe_2TiO_4). The iron-sulphur group provides the magnetic mineral pyrrhotite (FeS_{1+x} , $0 < x < 0.15$) whose magnetic susceptibility is dependent upon the actual composition (Kearey & Brooks, 1984). By far the most common magnetic mineral is magnetite. Although the size, shape and dispersion of the magnetite grains within a rock affect its magnetic character, it is reasonable to classify the magnetic behaviour of rocks according to their overall magnetite content. The magnetite content and, hence, the susceptibility of rocks is extremely variable and there can be considerable overlap between different lithologies. It is not usually possible to identify with certainty the causative lithology of any anomaly from magnetic information alone (Kearey & Brooks, 1984). Basic igneous rocks are usually highly magnetic due to their relatively high

magnetite content, which reflect their high total Fe content. The proportion of magnetite in igneous rocks tends to decrease with increasing acidity so that acid igneous rocks, although variable in their magnetic behaviour, are usually less magnetic than basic rocks. Metamorphic rocks are also variable in their magnetic character (Kearey & Brooks, 1984). Sedimentary rocks are effectively non-magnetic unless they contain a significant amount of magnetite in the heavy mineral fraction. Where magnetic anomalies are observed over sediment-covered areas the anomalies are generally caused by an underlying igneous or metamorphic basement, or by intrusions into the sediments (Kearey & Brooks, 1984).

Common causes of magnetic anomalies include dykes, faults, folded or truncated sills and lava flows, massive basic to intermediate intrusions, metamorphic basement rocks and certain ore bodies. Magnetic anomalies range in amplitude from a few tens of nanotesla (nT) over deep metamorphic basement to several hundred nT over basic intrusions and may reach amplitude of several thousand nT over magnetite ores (Kearey & Brooks, 1984).

In certain ore-forming environments magnetic contrasts are useful as pathfinders to mineral deposits (Grant, 1984; McIntyre, 1980; Clark, 1983; Wright, 1981). Conversion of pre-existing nonmagnetic phases or growth from ore-related fluids, can develop such magnetic contrasts (Reynolds *et al.*, 1990).

6.2.2 PORPHYRY DEPOSITS AND MAGNETIC SUSCEPTIBILITY

The association of magnetite with many porphyry Cu deposits makes these deposits attractive targets for magnetic exploration. Associated peripheral skarns may also cause magnetic anomalies beside the igneous intrusion and alteration (Reynolds *et al.*, 1990). Jerome (1966) presented a model of porphyry Cu deposit that portrays secondary

magnetite in a skarn zone at the margins of a mineralized intrusion as the cause of ground magnetic and aeromagnetic highs that might define an annular anomaly around an orebody. Grant (1984) discussed porphyries and concluded that recognition of favourable environments for porphyry Cu deposits may be on the magnetic identification of felsic-intermediate plutons of appropriate size (about 1-10 km in diameter) and on the possible existence of a “magmatic halo” within the pluton.

A parameter responsible for magnetic halos of porphyry mineralizations is the magnetisation associated with the alteration in the K-feldspar alteration zone. In such environments, magnetite appears as a result of hydrothermal alteration of ferromagnesian minerals mainly in the zone of secondary biotite (Guilbert and Park, 1985). In some cases, the original intrusion or the volcanics that host the porphyry mineralization has high amounts of magnetite. Most likely, this is the reason to have high magnetic susceptibility even at the regional scale over such plutonic suites or volcanics.

Volcanic rocks exhibit many characteristics of their intrusive equivalents. However, combinations of exsolution and high-temperature oxidation commonly cause enormous variations in the magnetic properties of volcanic rocks, even within individual flows (Wilson *et al.*, 1968; Haggerty, 1976).

Airborne magnetic surveys have been done on many known porphyry mineralized areas of British Columbia. In most cases, the mineralized areas have coincidence with high magnetite values. Such surveys sometimes have led to discovery of new mineralized zones and porphyry deposits. Two examples of porphyry deposits discovered by the airborne magnetic method are: Sat property in the Babine Lake area in west-central British Columbia (Carter *et al.*, 1995) and Hushamu deposit in Bonanza Group volcanic rocks in Northern Vancouver Island (Dasler *et al.*, 1995). The Hashamu

deposit is located in a belt of magnetite-rich Bonanza Group volcanic rocks, with numerous magnetic highs, trending northwest from the Island Copper porphyry mine. Airborne magnetic survey has recorded an intense, positive magnetic anomaly within the mineralized zones which is in the contact of granodiorite intrusions and the Nicola Group of Whipsaw porphyry system in Similkameen district in south western British Columbia (Richardson, 1995).

In the Morrison-Hearne Hill of Babine region in west-central British Columbia magnetic surveys were used for defining the limits of the host intrusions, zones of secondary biotite alteration and associated mineralization (Woolverton, 1964; Fountain, 1969; Carson and Jambor, 1976). In Taurus porphyry Cu-Mo deposit in east-central Alaska, total magnetic field from airborne surveys is used for determining the limits of a mineralized Cretaceous granodiorite which has a high primary magnetite content (Leriche, 1995). Also in the Sulphurets porphyry Au mineralized zones in northern British Columbia, airborne magnetic survey is used beside other geophysical methods for geological interpretations and identifying the limits of interested geological units and potassium alteration associated with porphyry mineralization in the district (Fowler and Wells, 1995). In Galore Creek porphyry Cu-Au deposit in north-western British Columbia a number of important features that relate to lithologies, alteration and structure are recognised from the airborne geophysical data. In this area, patterns of magmatic highs correspond with syenite intrusions while volcanic rocks have relatively low magnetic susceptivities (Enns *et al.*, 1995). Copper Canyon porphyry Cu-Au deposit in the Galore Creek area is another example for association of positive magnetic anomalies with the intrusive syenite responsible for mineralization (Bottomer and Leary, 1995).

In Mount Milligan area, the airborne magnetic surveys confirmed the presence of a large regional magnetic high centred over Mount Milligan, which was previously documented on the Geological Survey of Canada Regional Aeromagnetic Map 1584G-Wittsichica Lake. This magnetic high is related to the Mount Miligan intrusive complex and indicates that the complex is more extensive than its area of exposure (Sketchley *et al.*, 1995).

Airborne magnetometer results for Katie porphyry Cu-Au deposit in south-eastern British Columbia show anomalies over the Bonnington pluton in the north and the Wallack Creek pluton in the south. In these plutons, all of the area covered by the arcuate magnetic anomaly is underlain by Elise Formation volcanic rocks (Naciuk and Hawkins, 1995).

In many cases in British Columbia airborne or ground magnetic surveys have outlined the strong magnetite hornfels and zone of potassic alteration related to the mineralized intrusion which has provided a guide for subsequent exploration on the properties. Some examples are the Huckleberry porphyry deposit of Tahtsa Lake district in west-central British Columbia (Jackson and Illerbrun, 1995), Casino porphyry deposit in west central Yukon (Bower *et al.*, 1995), and Taseko porphyry Cu-Au-Mo deposit in central British Columbia (Osborne and Allen, 1995).

Association of magnetic highs with porphyry mineralizations is especially important for porphyry deposits related to the alkalic suites in the British Columbia. Mount Polley, which is an alkalic porphyry Cu-Au deposit in south-central British Columbia, is an example. The aeromagnetic anomaly over Mount Polley was noted and subsequent prospecting led to the discovery of Cu mineralizations in this area (Fraser *et al.*, 1995).

Within the framework of Cordilleran alkaline intrusions, there is a unique group of plutons characterised by pyroxenite and syenite (Lueck *et al.*, 1993). Some members of

this plutonic suite host porphyry Cu-Au mineralization and mineralized plutons show distinct petrological differences from barren plutons (Lueck and Russell, 1993). The presence of both hornblende and magnetite in these plutons is an important criteria for the differentiation of mineralized from barren intrusions plutons (Lueck and Russell, 1993).

Lueck and Russell (1993), have considered 12 pluton in British Columbia which are in the group of alkaline intrusions. Table 1 shows their results for the differences between the mineralized and barren plutons.

Table 1*- Silica-undersaturated plutons and the relationship between mineralogy and Cu-Au porphyry mineralization.

Pluton	Dominant Mafic Mineral	Abundant Magnetite	Terrane
<i>Mineralized (Cu-Au)</i>			
Galore Creek	Hornblende	Yes	Stikinia
Averill	Hornblende	Yes	Quesnellia
Duckling Creek	Hornblende	Yes	Quesnellia
Mt. Polley	Hornblende	Yes	Quesnellia
Rayfield River	Hornblende	Yes	Quesnellia
<i>No Known porphyry deposit</i>			
Rugged Mountain	Augite	No	Stikinia
Zippa Mountain	Augite	No	Stikinia
Ten Mile Creek	Augite	No	Stikinia
Whiterocks Mountain	Augite	No	Stikinia
Kruger Mountain	Augite	No	Quesnellia
Kamloops Syenite	Augite	No	Quesnellia

*(Lueck and Russell, 1993)

All of these plutons intrude Palaeozoic to Triassic assemblages. They are latest Triassic to Early Jurassic in age and are formed from arc-related magmas related to Stikinia and Quesnellia terranes.

6.2.3 RESIDUAL TOTAL FIELD MAGNETICS

In airborne magnetic surveys the earth's magnetic field is measured. When a ferrous material is placed within a magnetic field such as the earth's, it develops an induced magnetic field. The induced field is superimposed on the earth's field at that location creating a magnetic anomaly. Magnetic surveys have the advantage to show the geology and structures beneath the earth's surface. Often, deep ore bodies are visible in airborne magnetic data (Parasnis, 1996). Residuals are the difference between an observed value of the response variable and the value predicted by the model (Moore and McCabe, 1993). By separating the residual from the regional earth's magnetic field, it is possible to highlight the areas with high or low magnetics. The residual is particularly effective with magnetic data where inflection points mark the edges of magnetic features (MacLeod and Dobush, 1990).

Here it is shown that the residual total field magnetics can serve as a good indicator of mineralized zones of certain types of porphyry deposits. The aeromagnetic data, which is used here, is from the airborne data of Geophysical Centre, Geological Survey of Canada. This data is in a grid format with a resolution of 2 km. Residual total field magnetics was mapped with a moving average method to see its relationship with the distribution of known porphyry deposits of different types (Figure 1). The advantage of moving average method is that it can reduce the existing noise in the data and reveals the general trends.

Figure 1 shows also the boundaries of the study area. Visual comparison between the location of residual total field magnetics highs and points representing porphyry deposits shows that in most cases there is a positive association. In addition, it is obvious from Figure 2 that certain geological units have higher backgrounds than others.

The known porphyry deposits related to Cu-Au alkalic group and Cu-Mo group show higher association than porphyry Mo deposits with the residual total field magnetic highs (Figure 1). A comparison between the magnetic map of Figure 1 and the geology map of the study area shows that the contact of different rock types with very different backgrounds for magnetic susceptibilities in some cases is reflected in the magnetic map. Also in some areas trace of the regional faults is indicated in the magnetic map.

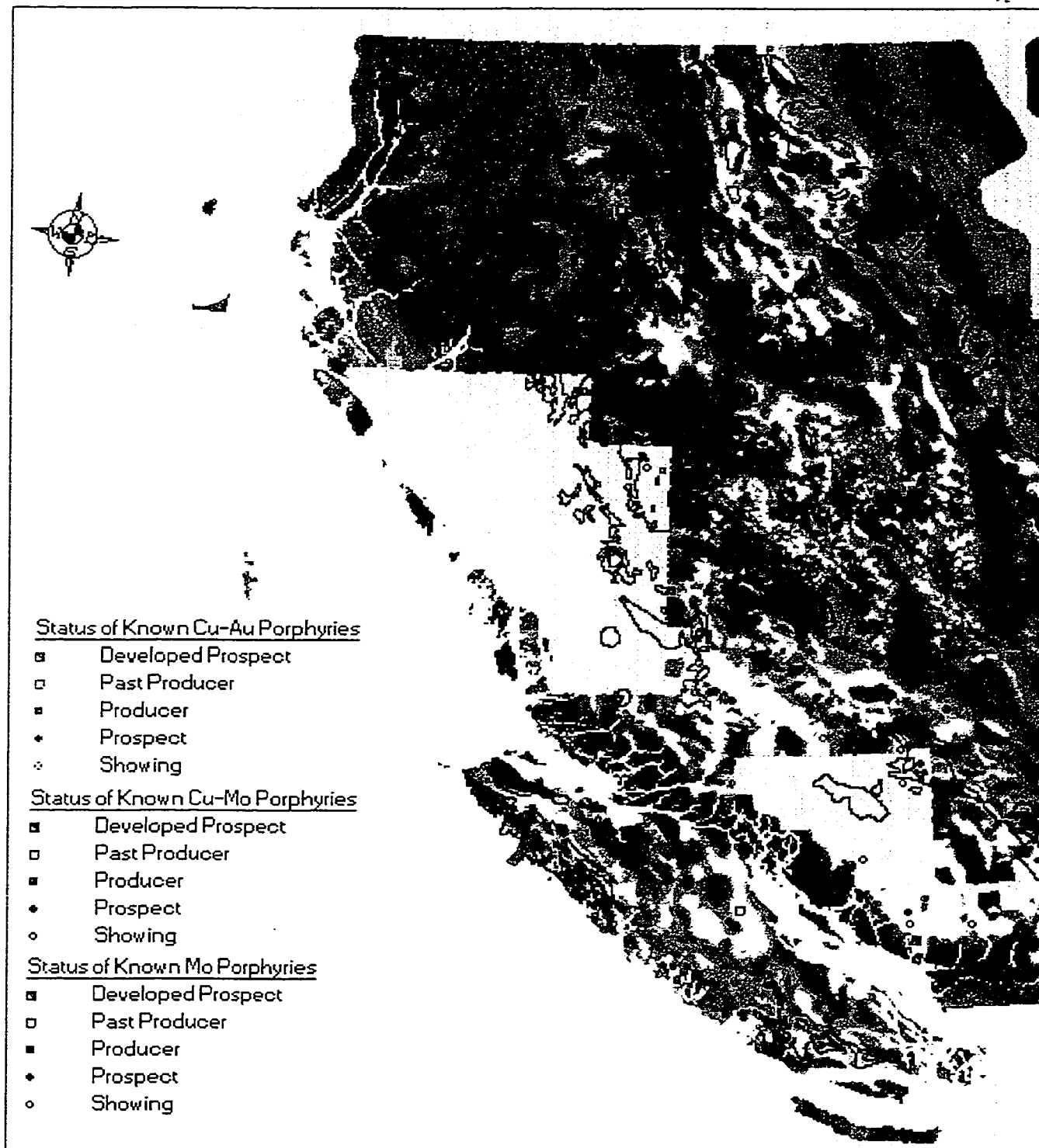
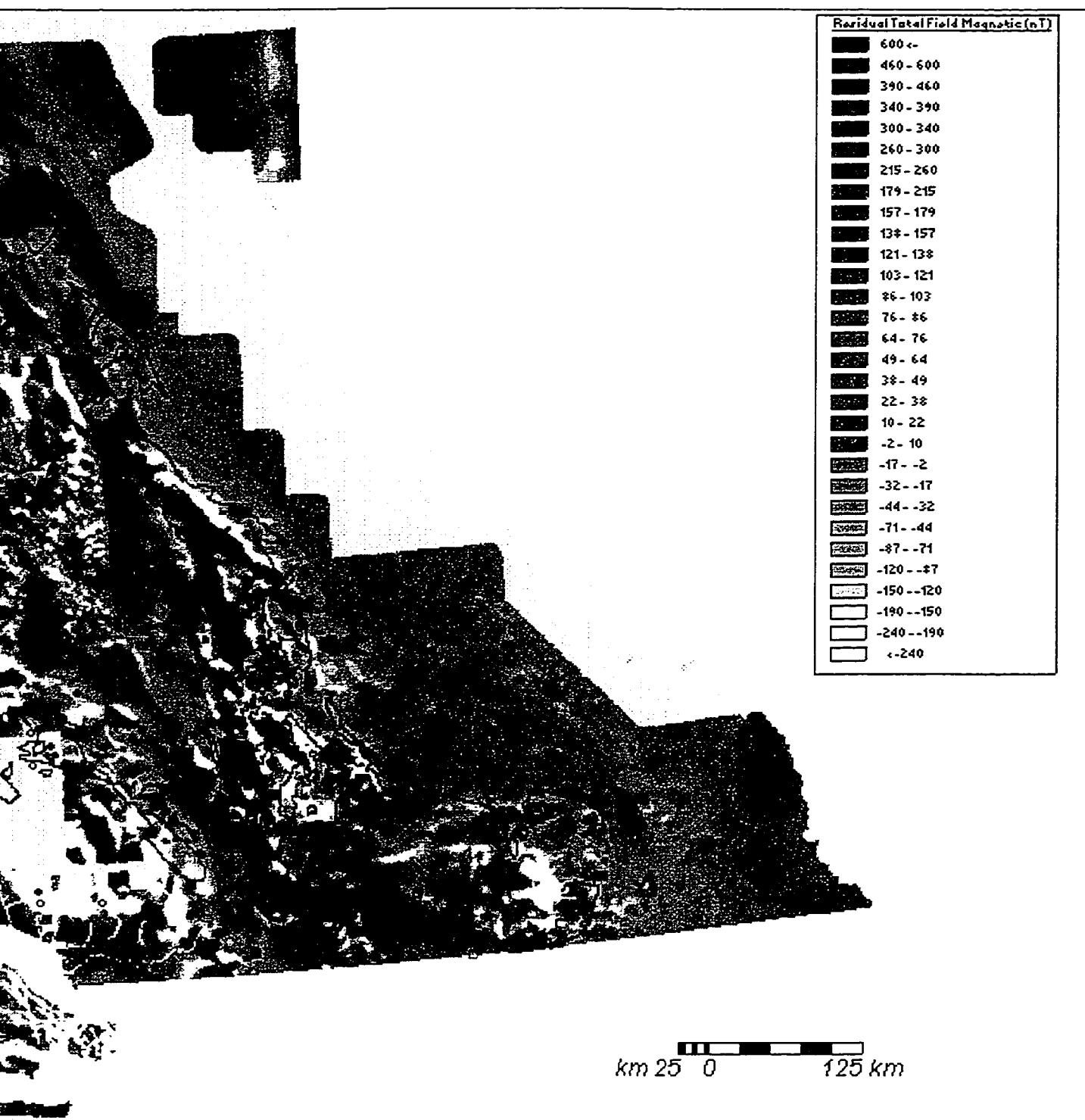


Figure 1. Residual total field magnetics with boundaries of the study area and porphyry deposits.



deposits.

At the regional scale, a component of the total variability of magnetic susceptibility is due to different background levels related to diversity of geological units. The box plot of Figure 2 shows the distribution of residual total field magnetics in different plutonic units of the study area. Only those plutonic units that contain more than 10 aeromagnetic measurements were included in Figure 2.

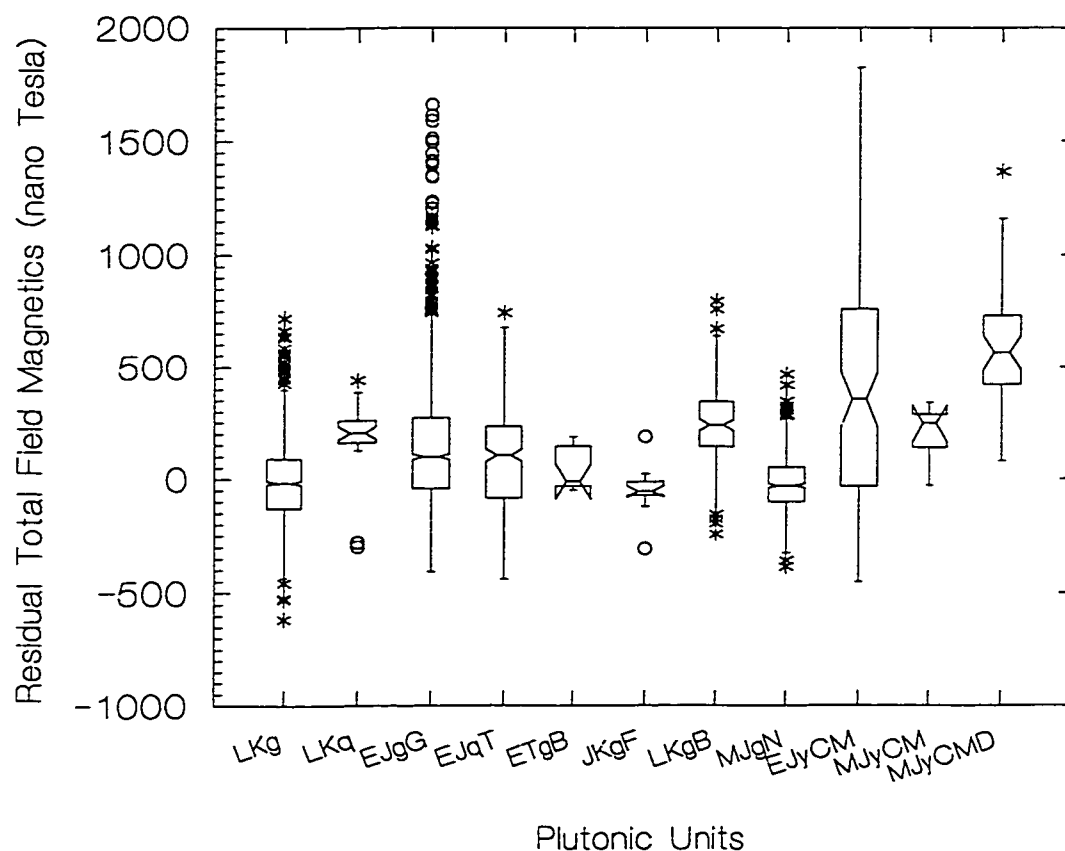


Figure 2. Box plot for the residual total field magnetics in different geological units that contain more than 10 measurements.(for 95% confidence level)

The boxes of Figure 2 are notched at the median and return to full width at the lower and upper confidence interval values. Geological units that are known as major hosts of porphyry Cu-Au deposits group such as Copper Mountain Intrusions (EJyCM, MJyCM,

and MJyCMD) have higher residual total field magnetics (Figure 2) than the geological units related to Mo type of porphyry deposits such as Francois Lake intrusions (JKgF). This indirectly may reflect the presence of magnetite in more alkaline plutons associated with the Copper Mountain Intrusions (EJyCM, MJyCMD) (Table 1).

To quantify and check the spatial association of each group of porphyry Cu-Au, Cu-Mo and Mo deposits with different classes of residual total field magnetics map, a weight of evidence analysis was performed. In this case combining all different types of porphyry deposits together for the weight of evidence analysis leads to confusing results, therefore different groups were analysed separately. Figure 3 shows variations of contrast ($C = W^+ - W^-$) and number of known porphyry deposits of Cu-Au type with different classes of residual total field magnetics map. Class 1 indicates the highest and class 29 the lowest levels of residual total field magnetics. Although there is some noise in the graphs of Figure 3, they still show a general decrease of contrast as classes of residual total field magnetics move towards the lower levels. This means porphyry Cu-Au deposits have higher spatial association with the high levels of residual total field magnetics.

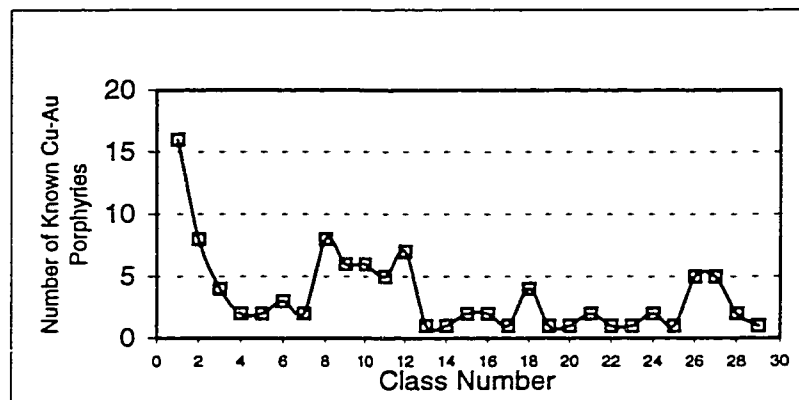
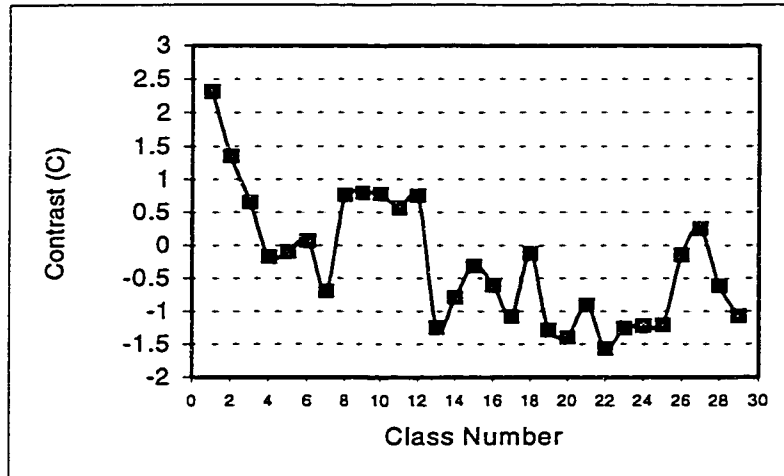


Figure 3. Decrease of contrast and number of known porphyry Cu-Au deposits from class 1 to 29 of the residual total field magnetics map. Class 1 is the highest and class 29 represents the lowest level of the residual total field magnetics.

Porphyry Cu-Mo deposits have also a decreasing trend for both contrast (C) and number of known porphyry Cu-Mo deposits with the high levels of residual total field magnetics (Figure 4). The decreasing trends for this group have more fluctuations and noise than the Cu-Au group.

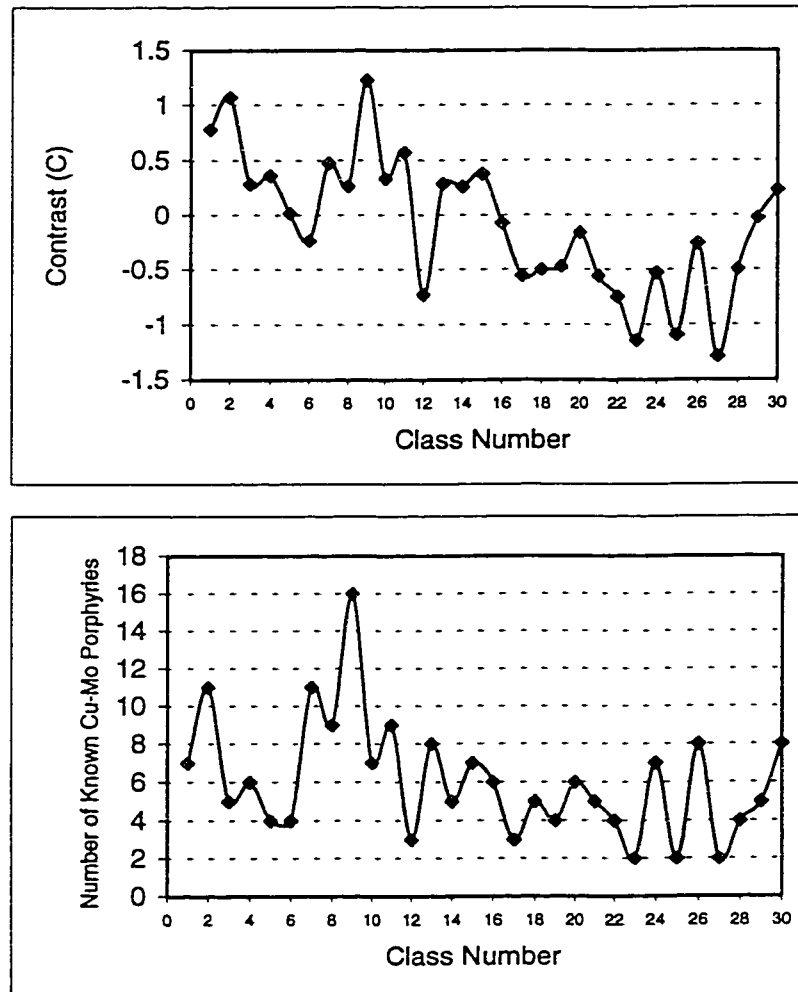


Figure 4. Decrease of contrast and number of known porphyry Cu-Mo deposits with higher classes of the residual total field magnetics map. Class 1 is the highest and class 29 represents the lowest level of the residual total field magnetics.

The group of porphyry Mo deposits does not show the obvious decreasing trends shown in graphs of Figure 3 and 4. In other words, this group of porphyry deposits does

not show a strong affinity to high levels of residual total field magnetics. This can be due to lower amounts of magnetic minerals and magnetic susceptibility in the host rocks and plutonic rocks related to porphyry Mo deposits.

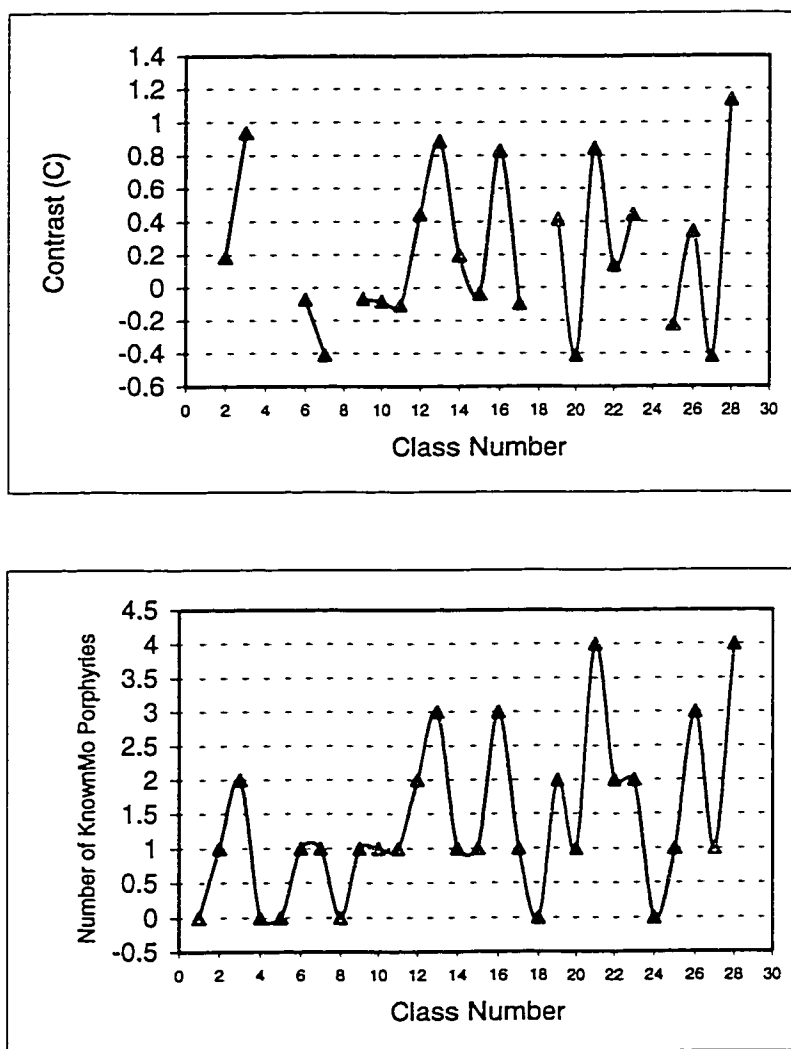


Figure 5. Variations of contrast and number of known porphyry Mo deposits with higher classes of the residual total field magnetics map. Class 1 is the highest residual total field magnetics and class 29 represents the lowest level of residual total field magnetics.

As no known porphyry Mo deposit is located inside some classes of residual total field magnetics map, it is not possible to assign any contrast (C) values for such classes

therefore there are gaps in the curve for variations of contrast (C) (Figure 5). Based on the results of Figure 3, 4, and 5 and distribution of known porphyry deposits shown in Figures 1, fuzzy membership values are assigned to different classes of the residual total field magnetics map. Such fuzzy membership values are needed for combining all the input maps in the final chapter.

6.2.4 VERTICAL DERIVATIVE (GRADIENT) OF MAGNETICS

The difference in magnetic intensity between two vertically separated points divided by the distance between them is the vertical gradient. It can also be considered as the rate of change of the magnetic field in the vertical direction or the first derivative. First derivatives express the slope of the field in a direction. This technique reduces interference from solar magnetic storms and regional magnetic changes.

It is shown here that the vertical derivative (gradient) of magnetics can be used with certain limitations as an indirect indicator of some mineralized zones at the regional scale. Figure 6 shows the vertical derivative (gradient) of magnetics with the location of different types of known porphyry deposits and boundaries of the study area. In many cases porphyry deposits are located in areas with high gradient of magnetics. This is more obvious inside the arc volcanic units such as Takla (TrJ), which hosts many porphyry Cu-Au deposits (Figure 6). Intrusion of plutonic bodies inside the arc volcanic units might be a reason to have such high gradients of magnetics. In British Columbia, porphyry-mineralising intrusions usually have widely different magnetic characteristics. In many locations, such plutonic intrusions may not have outcrops but they still may have their effect on the local magnetic susceptibility and gradient.

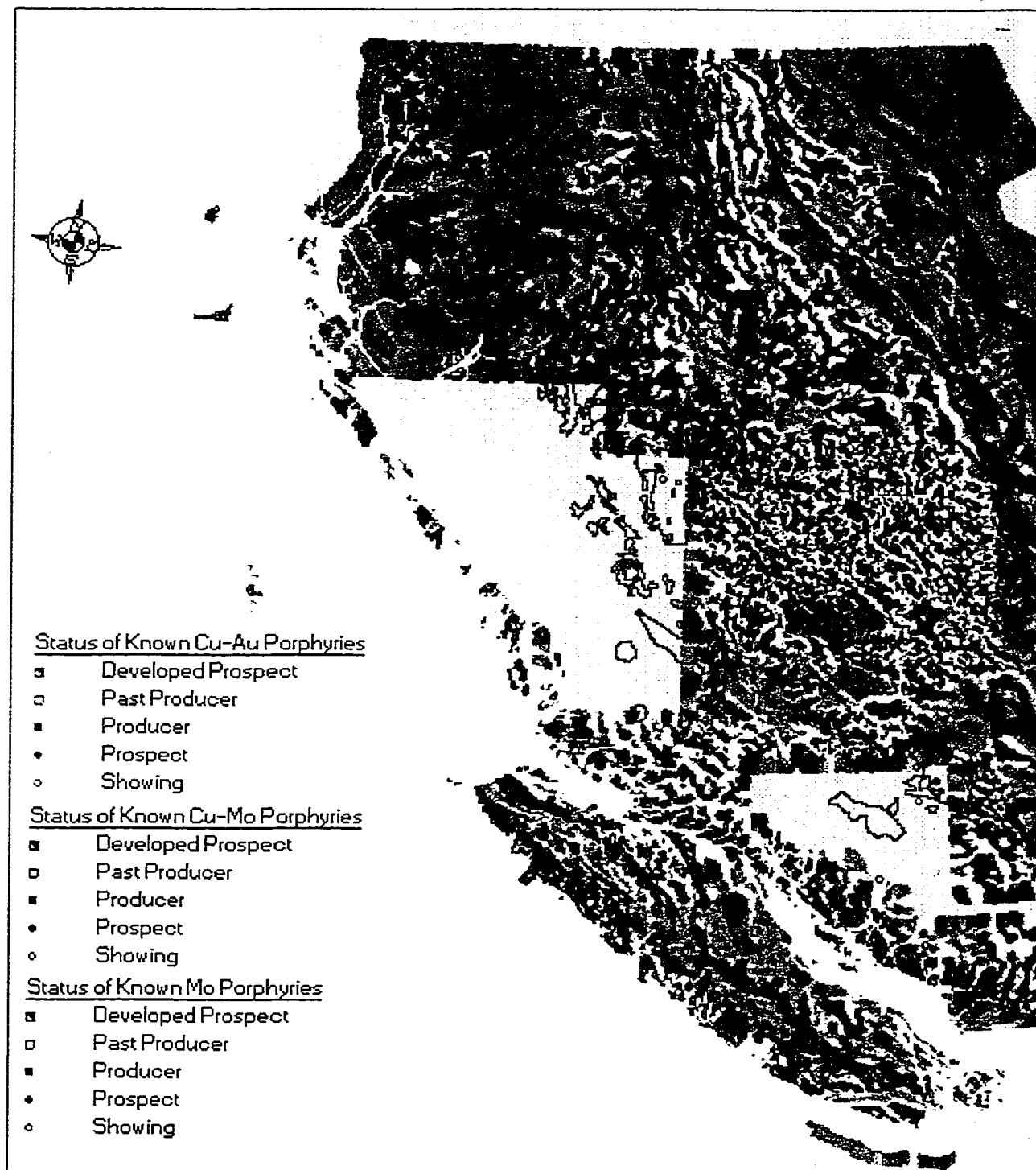
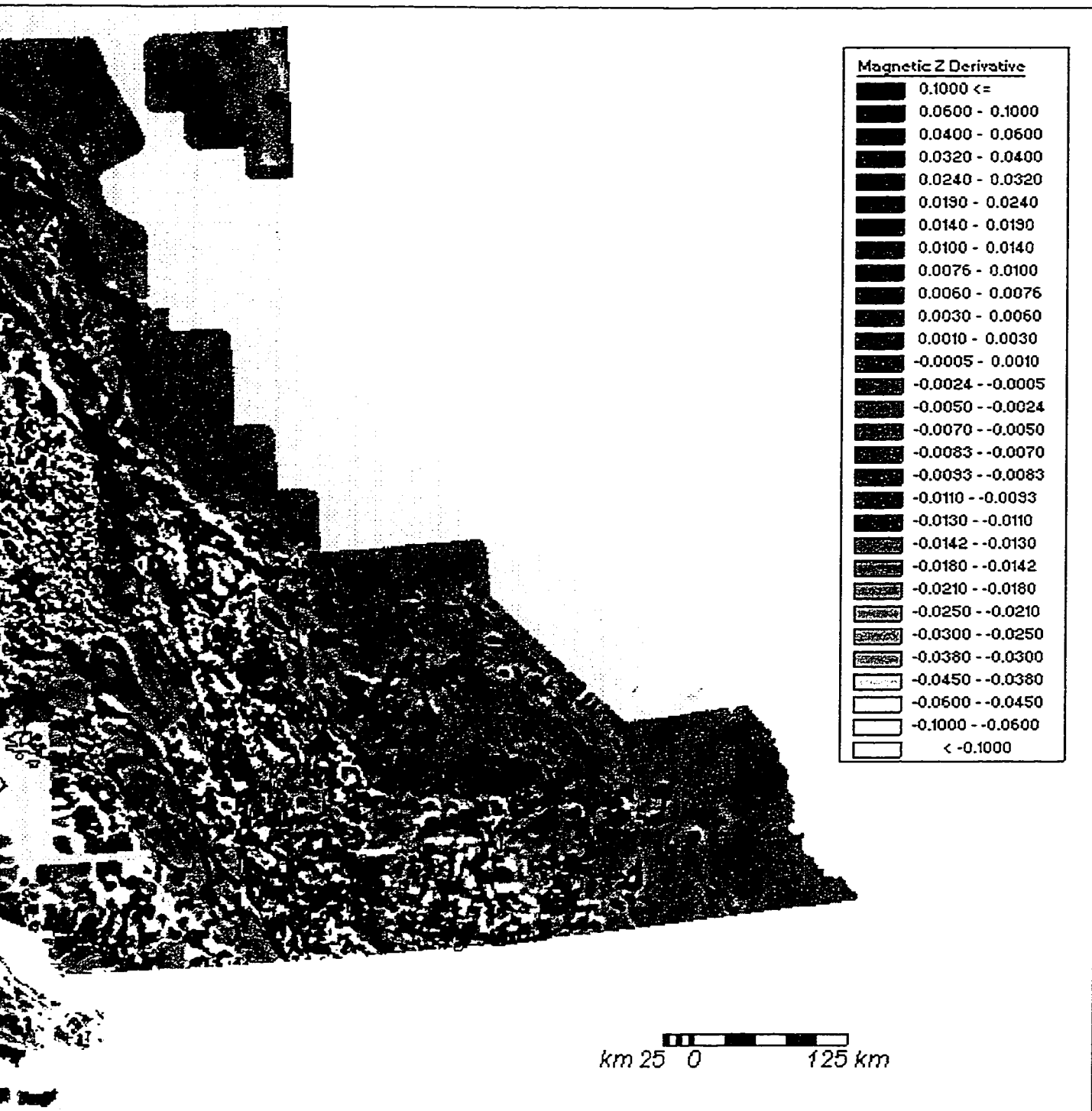


Figure 6. Vertical derivative (gradient) of magnetics with boundaries of the study area and porphyry dep



porphyry deposits.

Weight of evidence analysis was done to check spatial association of each group of porphyry Cu-Au, Cu-Mo and Mo deposits with different classes of the vertical derivative (gradient) of magnetics map.

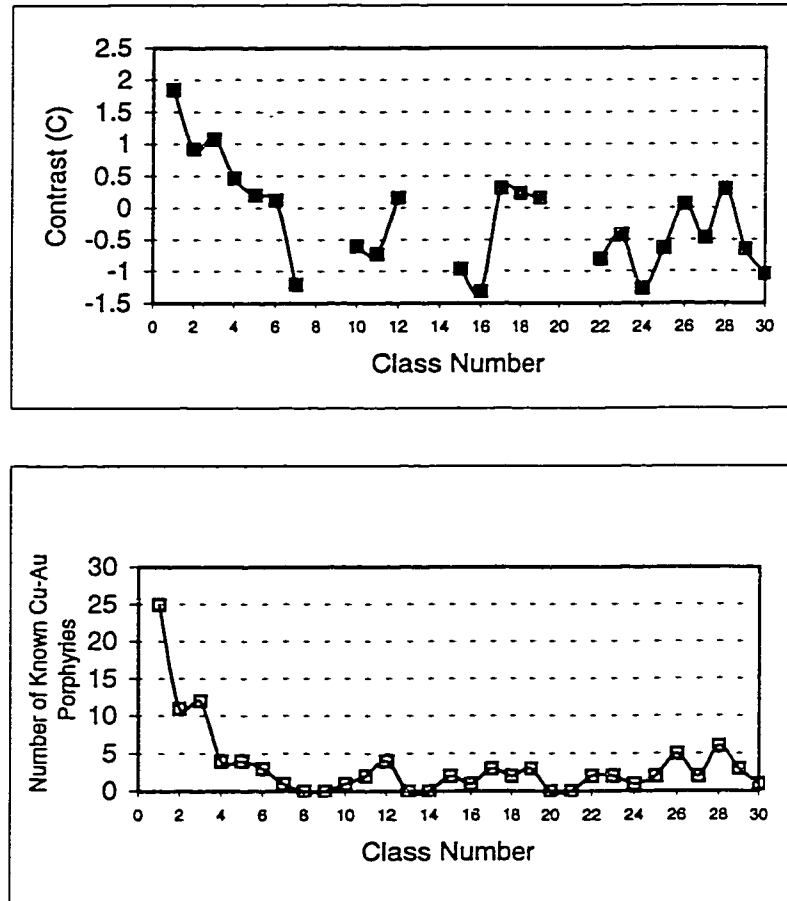


Figure 7. Decrease of contrast and number of known porphyry Cu-Au deposits with higher classes of the vertical derivative (gradient) of magnetics map. Class 1 represents the highest level and class 30 represents the lowest level of the vertical derivative (gradient) of magnetics.

The area occupied by class 1, 2, 3, and 4 of vertical derivative (gradient) of magnetics map is 78974 km², which is 16.27% of the total area of this map. These classes contain more than 50% of known porphyry Cu-Au deposits (Figure 7). This is reflected also in the calculated contrast (C) values of this map. A similar situation exists

for the group of porphyry Cu-Mo deposits and classes of the vertical derivative (gradient) of magnetics map.

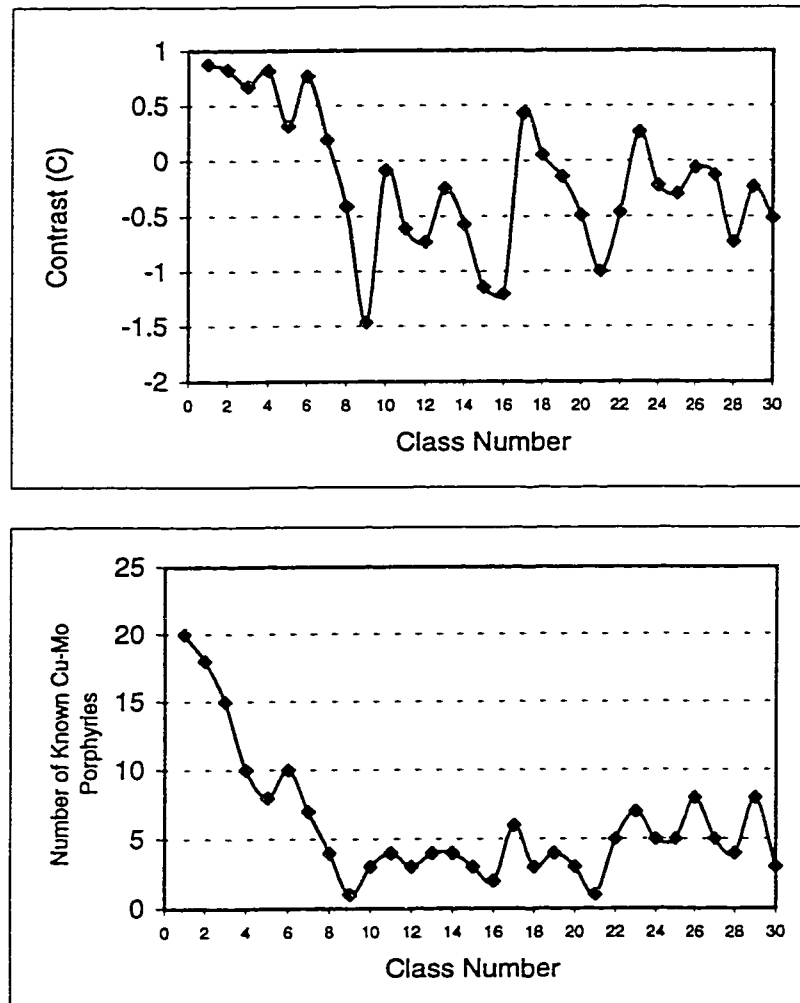


Figure 8. Decrease of contrast and number of known porphyry Cu-Mo deposits with higher classes of the vertical derivative (gradient) of residual total field magnetics map. Class 1 represents the highest level and class 30 represents the lowest level of the vertical derivative (gradient) of magnetics.

As Figure 7 and 8 show, many known porphyry Cu-Mo deposits have a high spatial association with high values of the vertical derivative (gradient) of magnetics. For porphyry Mo deposits, this association is not as strong as Cu-Au and Cu-Mo group (Figure 9).

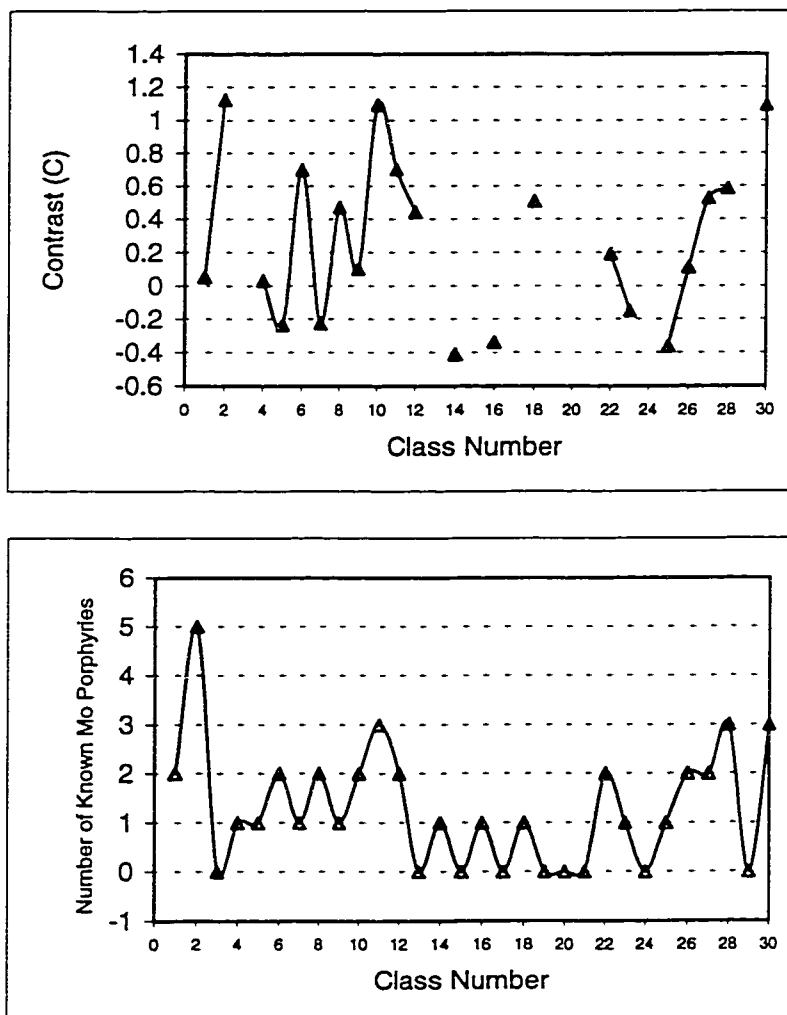


Figure 9. Variations of contrast and number of known porphyry Mo deposits with classes of the vertical derivative (gradient) of residual total field magnetics map. Class 1 represents the highest level and class 30 represents the lowest level of the vertical derivative (gradient) of magnetics.

6.3 ANALYSIS OF GRAVITY DATA

6.3.1 INTRODUCTION

In gravity surveys the gravitational field at a series of different locations over an area of interest is measured. The objective in exploration work is to associate variations with differences in the distribution of densities and hence rock types. Gravity measurements can be used beside other geophysical methods to map the subsurface geology. The relative variation in rock density is quite small, and there is considerable overlap in the measured densities of different rock types (the highest densities typically observed are about 3.0 gm/cm^3 while the lowest densities are about 1.0 gm/cm^3). The fundamental parameter controlling the magnetic field variations of interest to us, magnetic susceptibility, on the other hand, can vary greatly up to several hundred times. For example, the magnetic susceptibility of limestones is in the range of $0\text{--}3 \times 10^3$ while for peridotite it can be up to $90\text{--}200 \times 10^3$ (SI) (Griffiths and King, 1981). This is one of the significant differences between gravity and magnetic surveys.

6.3.2 RELATIONSHIP BETWEEN GRAVITY DATA AND PORPHYRY DEPOSITS

Gravity anomalies are perturbations of the normal gravity field of the Earth, generated by geological bodies, which have a density different from that of the surrounding rocks. Rock density depends on the lithology of the rocks. As the proportion of SiO_2 decreases, the proportion of the denser iron Fe and magnesium Mg increases so the overall rock density increases. Therefore, basic igneous rocks (such as gabbro) and dense metamorphosed basement rocks (such as gneisses) have a high density but acid igneous rocks (such as granite intrusions) and sedimentary basins containing young porous sediments have a low density.

Depending on the type of intrusion and nature of the host rock, intrusive bodies can cause high or low gravity anomalies. Since plutonic intrusions are associated with porphyry deposits, in some cases, it might be possible to use gravity anomalies as an indicator of such plutonic intrusions.

The gravity data used here are from the Geophysical Centre, Geological Survey of Canada. It is in a grid with the resolution of 5 km.

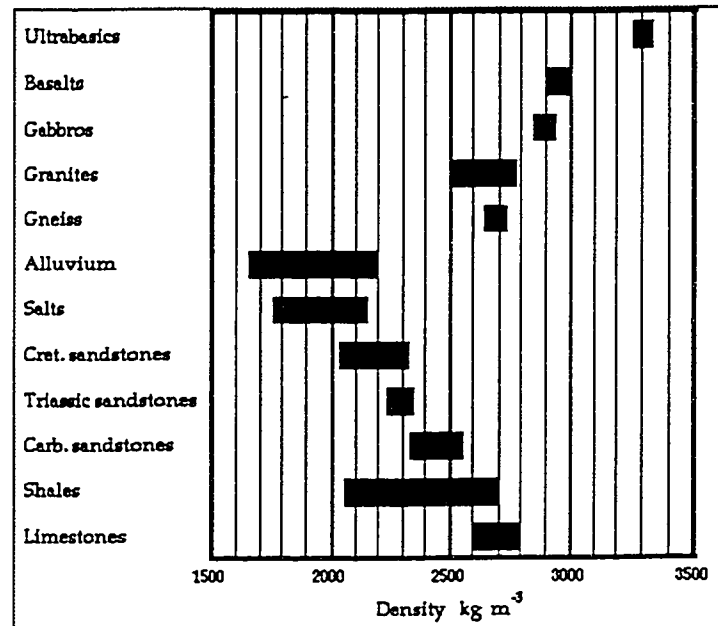


Figure 10. Density ranges of common rock types (Telford *et al.* 1990).

6.3.3 VERTICAL DERIVATIVE (GRADIENT) OF BOUGUER GRAVITY ANOMALIES

Very high or low classes of vertical derivative (gradient) of Bouguer gravity anomalies can represent a sudden change in density of rocks due to different rock types in contact with each other. Such contacts may be due to intrusions, faulting, fracturing, shearing, and/or the effect of subtle alteration along these zones (Turner *et al.*, 1982). Using this

geophysical parameter was more appropriate than the Bouguer gravity anomalies because in some areas it could show some associations with the locations of some of the known porphyry deposits.

Figure 11 shows the map for distribution of vertical derivative (gradient) of Bouguer anomalies. As these figures show, inside the plutonic units such as Late Cretaceous plutonic intrusions (Lkg) or Guichon plutonic suites (EJgG) the gradient of Bouguer gravity anomalies is less than that of the arc volcanic units such as Takla and Nicola (TrJ, TrJN) or Hazelton (JH) or Bonanza (JB). This is probably due to smaller differences in density of different phases of intrusions inside the plutonic units. Figure 12 shows the area of different classes of vertical derivative (gradient) of Bouguer gravity anomalies map, inside the study area. As Figure 12 shows, top classes of the vertical derivative (gradient) of Bouguer gravity anomalies map are mainly located inside the arc volcanic units such as Takla and Nicola (TrJ, TrJN).

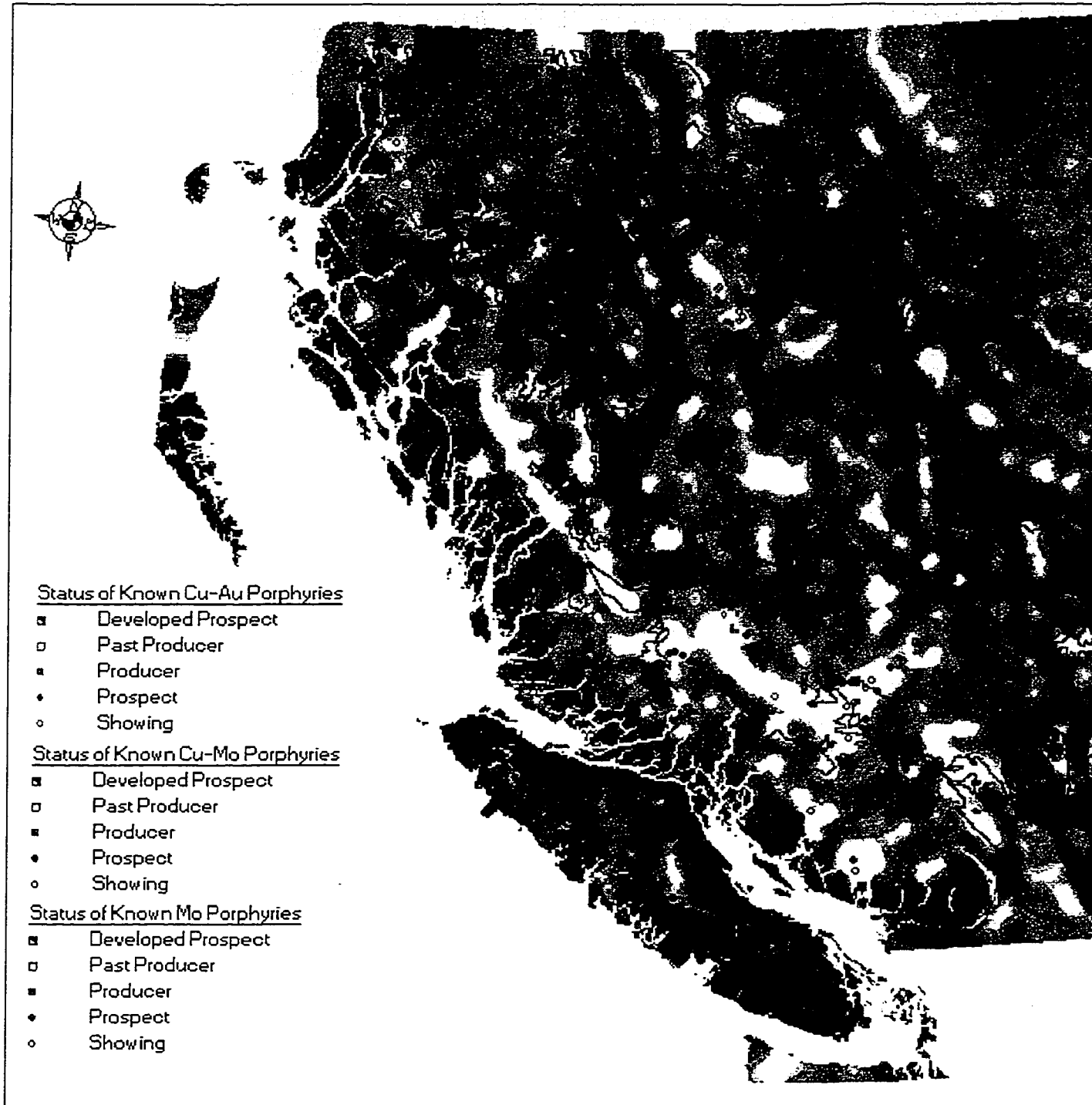
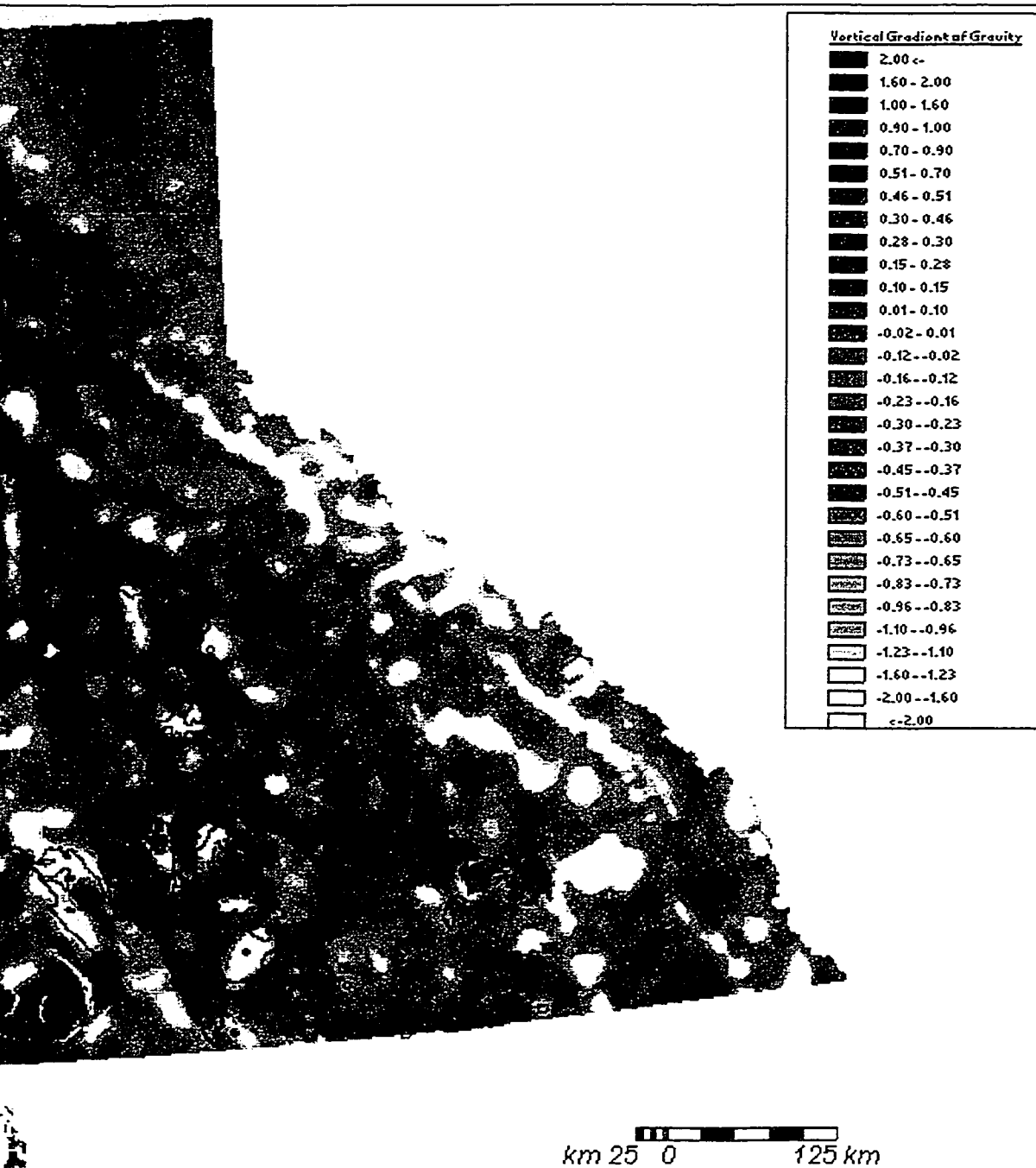


Figure 11. Vertical derivative (gradient) of Bouguer gravity anomalies with boundaries of the study area and porphyries.



study area and porphyry deposits.

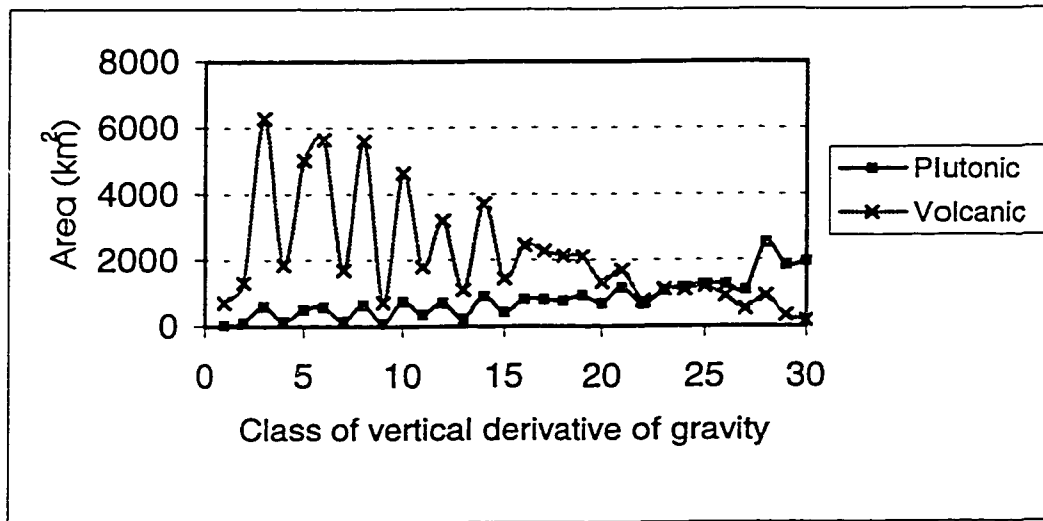


Figure 12. Area of each class of gradient of Bouguer gravity anomalies map inside the plutonic and volcanic units of the study area.

In many cases, the location of high values for gradient of Bouguer gravity anomalies corresponds with location of plutonic intrusions inside the arc volcanic units or areas close to such intrusions. This can be one of the reasons to have high gradient of Bouguer gravity anomalies inside the arc volcanic units. Here different phases of a certain plutonic unit do not show a gradient as strong as a plutonic intrusion inside an arc volcanic unit.

Figure 13 show the box plot for distribution of vertical derivative (gradient) of Bouguer gravity anomalies in different geological units of the study area. For preparing this diagram, geological units with less than 10 samples were omitted.

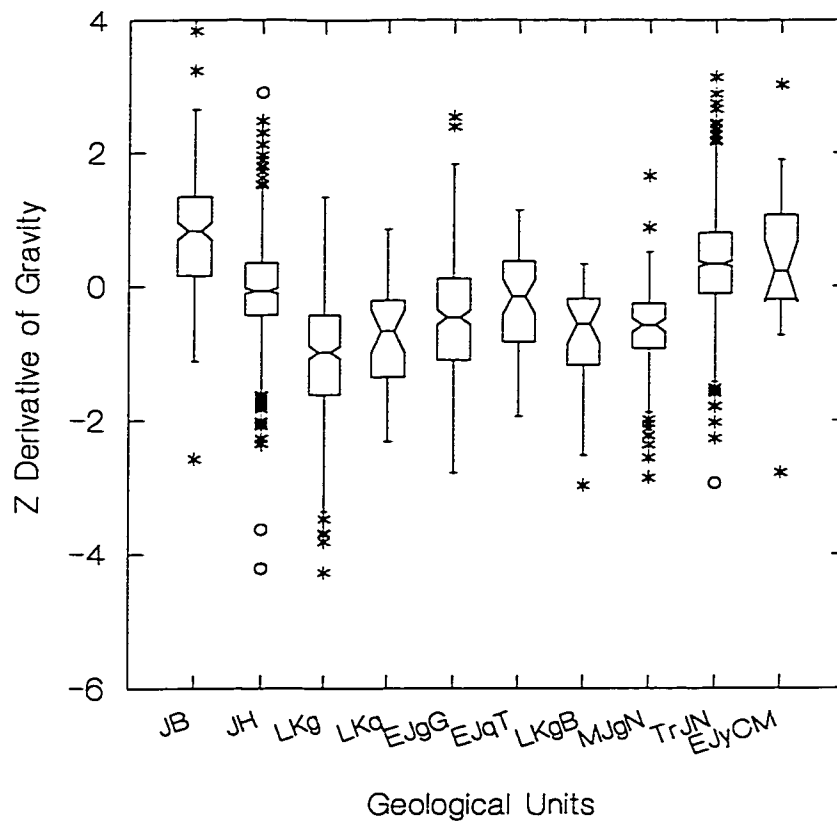


Figure 13. Box plot for distribution of vertical derivative (gradient) of Bouguer gravity anomalies in different geological units of the study area.

The box plot of Figure 13 also shows the significantly higher median (at 95% confidence level) for this geophysical characteristic inside Bonanza (JB), Hazelton (JH), and Takla and Nicola (TrJ, TrJN) which are all arc volcanics. The number of outliers is also higher in these units than the other plutonic units of the study area.

As Figure 11 shows, a lot of the known porphyry Cu-Au deposits that are inside the arc volcanic units such as Takla and Nicola (TrJ, TrJN) are located in areas with high vertical derivative (gradient) of Bouguer gravity anomalies. In the Takla and Nicola (TrJ, TrJN), this geophysical characteristic could probably be useful and used as an indicator of areas with high potential for mineralizations. Other types of porphyry deposits inside

the arc volcanic units of Hazelton (JH) and Bonanza (JB) do not show such a strong association with high gradients of Bouguer gravity anomalies. To quantify these spatial associations, weight of evidence analysis was done. Because plutonic and arc volcanic units show different characteristics for their vertical derivative (gradient) of Bouguer gravity anomalies, map of this geophysical parameter was cut by the boundaries of the arc volcanic units of the study area and weight of evidence analysis was done between different groups of porphyry deposits and this new map. Similarly weight of evidence analysis was also performed between different groups of porphyry deposits and only those parts of the vertical derivative (gradient) of Bouguer gravity anomalies map located inside the plutonic units of the study area.

The weight of evidence analysis showed that only porphyry Cu-Au deposits located inside the volcanic units of the study area show high spatial association with the high levels of vertical derivative (gradient) of Bouguer gravity anomalies (Figure 14). High level intrusions associated with porphyry Cu-Au deposits can be the reason for this obvious association. This association is not very clear for those porphyry Cu-Au deposits located inside the plutonic units of the study area (Figure 15).

Other groups of porphyry deposits do not show such an association with high levels of vertical derivative (gradient) of Bouguer gravity anomalies neither in volcanic units nor in plutonic units of the study area (Figure 16, 17, 18).

The porphyry Mo deposits do not show a clear association with classes of vertical derivative (gradient) of Bouguer gravity anomalies inside the volcanic units of the study area (Figure 18). There is only 1 porphyry Mo deposit inside the plutonic units of the study area, therefore contrast (C) was not calculated. In addition, there is only 1 porphyry Mo deposit in the class 11 of vertical derivative (gradient) of Bouguer gravity anomalies map. The results of this chapter are used in the final chapter to decide on the

maps that must be used to generate the geophysical factor map and also to select the fuzzy membership values needed to create the final favorability maps.

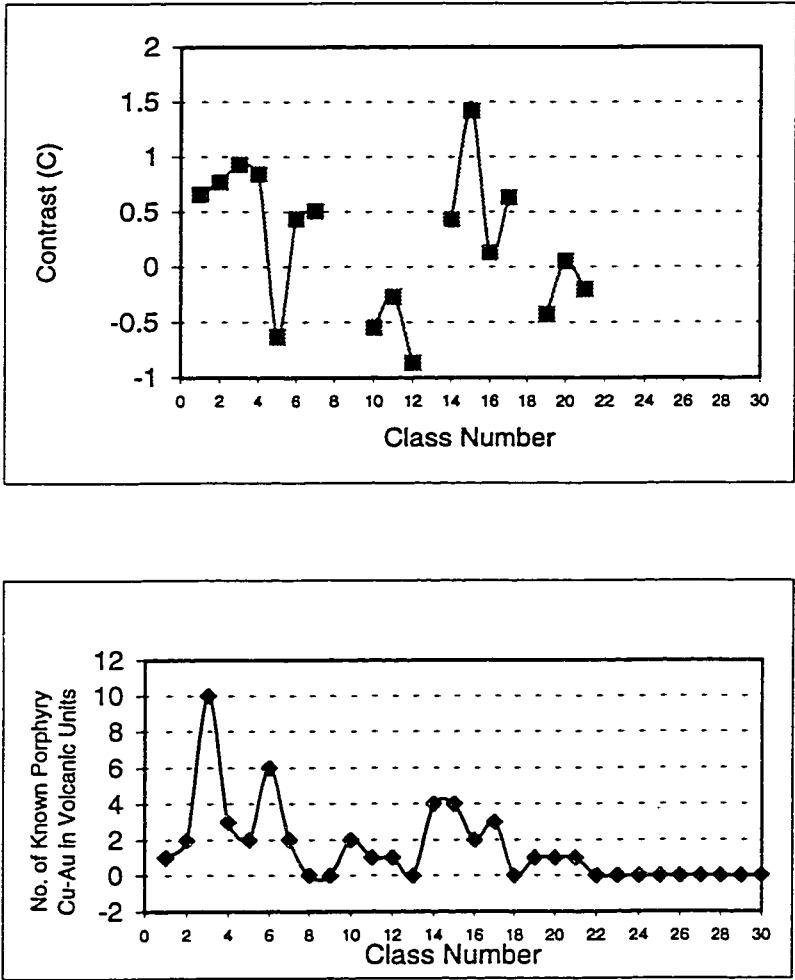


Figure 14. Variations of contrast and number of known porphyry Cu-Au deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the volcanic units of the study area.

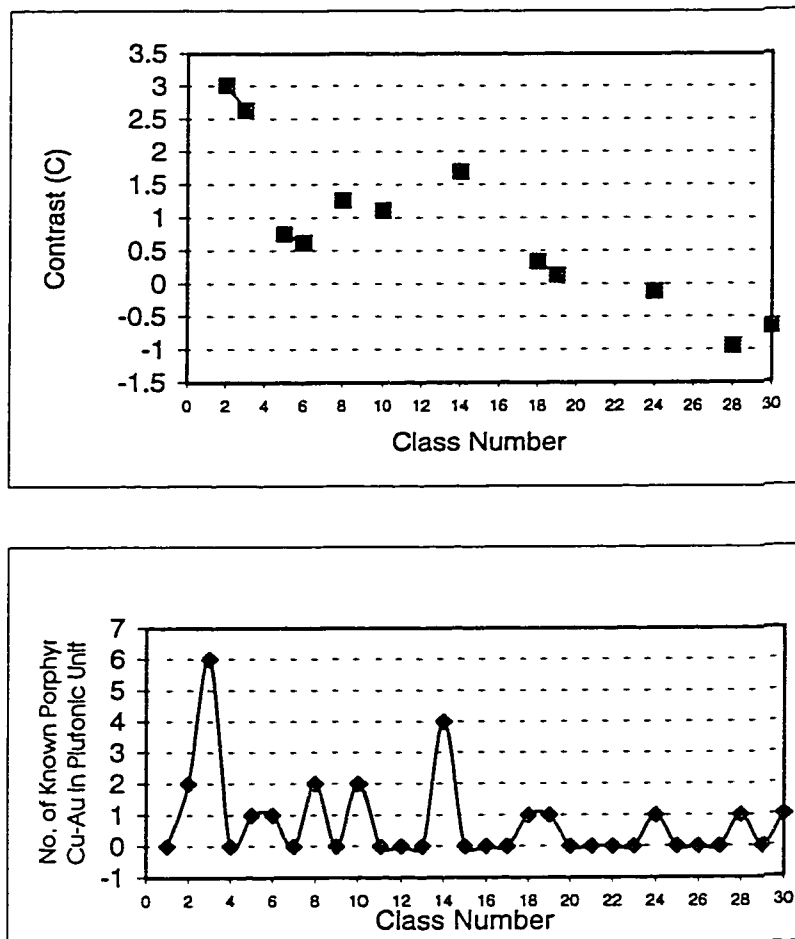


Figure 15. Variations of contrast and number of known porphyry Cu-Au deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the plutonic units of the study area.

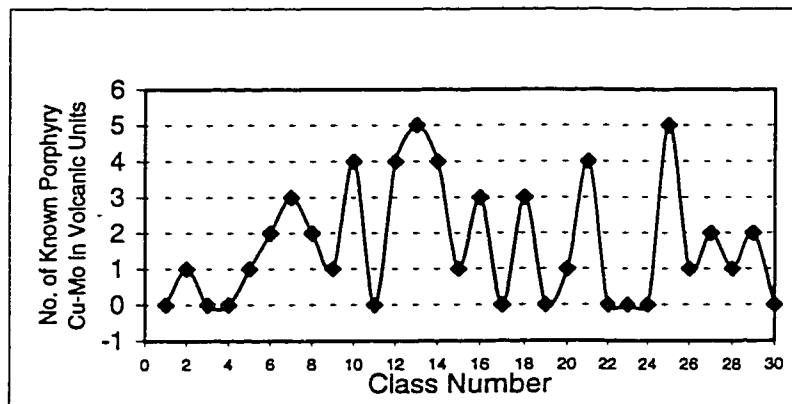
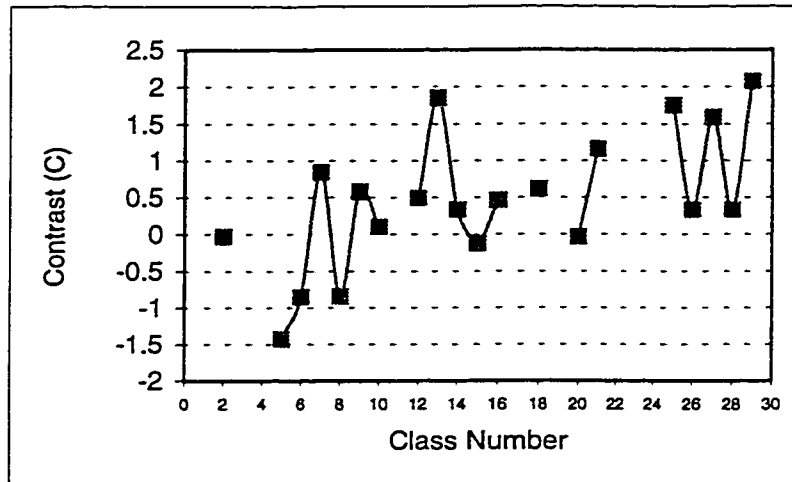


Figure 16. Variations of contrast and number of known porphyry Cu-Mo deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the volcanic units of the study area.

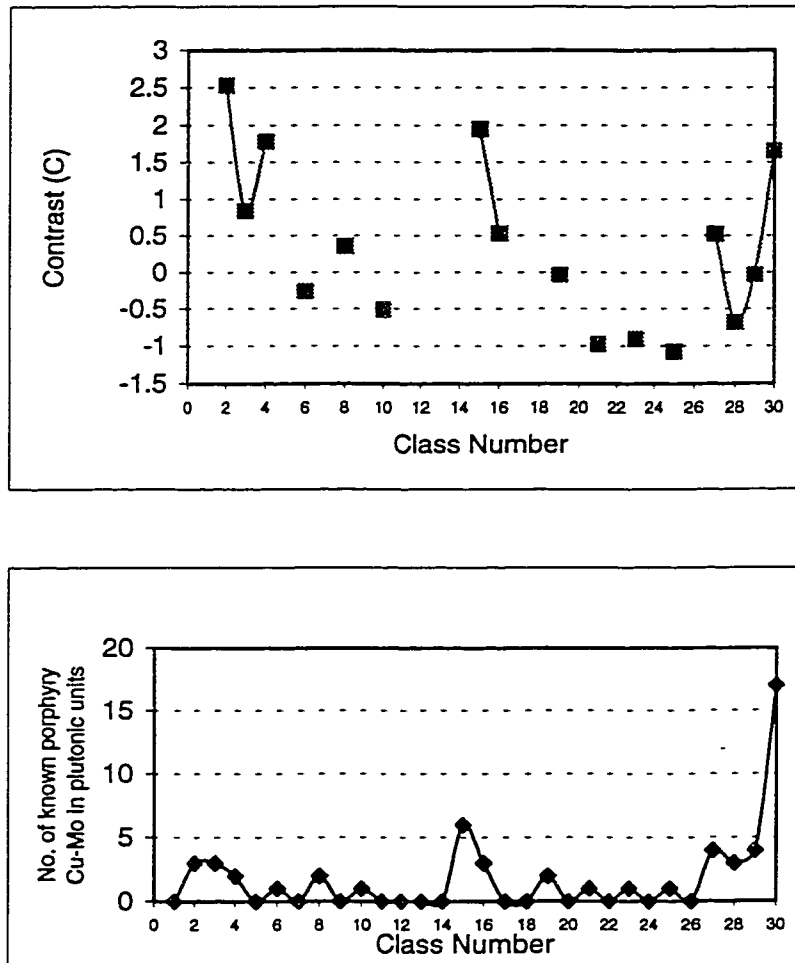


Figure 17. Variations of contrast and number of known porphyry Cu-Mo deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the plutonic units of the study area.

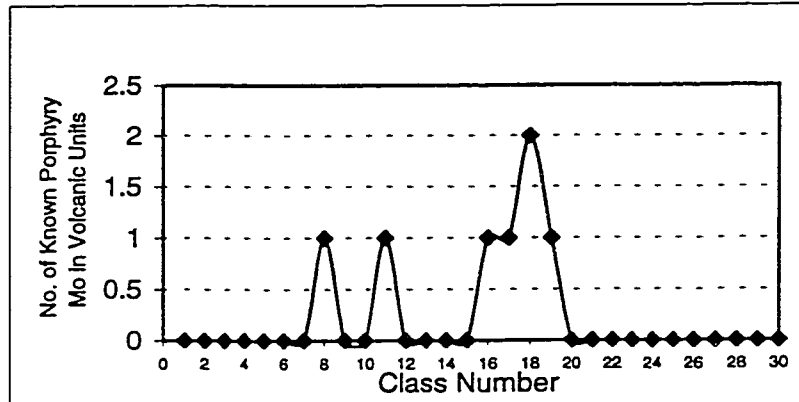
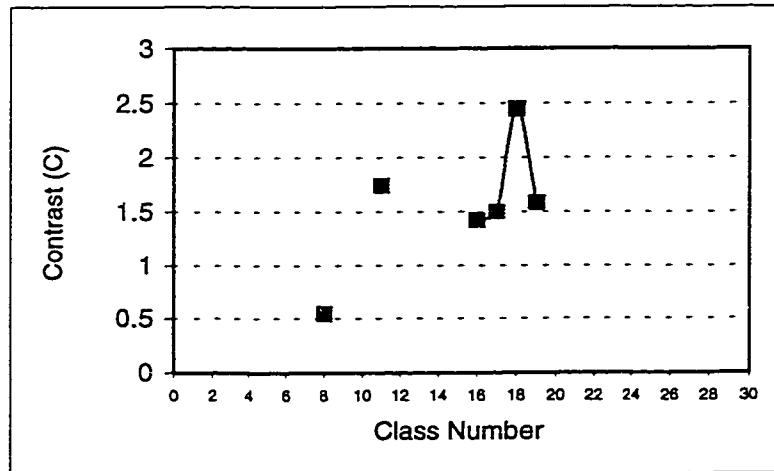


Figure 18. Variations of contrast and number of known porphyry Mo deposits with classes of vertical derivative (gradient) of Bouguer gravity anomalies map that are located only inside the volcanic units of the study area.

CHAPTER 7

TECTONIC CONTROL

7.1 INTRODUCTION

Strong structural control is indicated for many deposits of the Canadian Cordillera (Seraphim & Hollister, 1976). Both the main intrusions and the alkalic porphyries tend to lie along well-defined tectonic features (McMillan, 1994, Preto, 1996, personal communication). All six of the largest known porphyry deposits in south-western British Columbia are located within a few miles of, and north-east of, major north-west-trending fault zones (Seraphim & Hollister, 1976).

In this chapter relationship of faults with distribution of known porphyry deposits inside the study area is investigated. The faults that are utilised here are extracted from geological digital files with the scale of 1/250,000. These files were obtained from British Columbia Mineral Potential Project. Known porphyry deposits are extracted from MINFILE (1996). Three types of maps were created and tested to see the relationship of faults with distribution of known porphyry deposits. These maps are:

1. Density of faults (length of faults per km²).
2. Smoothed map of buffer zones around the faults.
3. Smoothed map of buffer zones around the points of fault intersection

The method of weight of evidence (Bonham-Carter, 1994) was utilised to study the association of known porphyry deposits and classes of the above maps. This comparison showed a very strong spatial correlation at the regional scale, between the areas with high density of faults, regions close to faults, or fault intersection and the known porphyry deposits. This reflects the favourable tectonic environments for the formation of these deposits. In addition, these maps are compared with each other to check their own spatial associations and similarities. Here it was shown that, the smoothed maps of buffer zones around faults, and the smoothed map of buffer zones around points of fault intersection, are very similar to the fault density map. Therefore, in cases of existing a limitation in a GIS system for generating a fault density map, it is possible to substitute it with either of these maps; the smoothed buffers around faults or; the smoothed buffers around fault intersection.

7.2 RELATIONSHIP BETWEEN FAULTS AND PORPHYRY DEPOSITS IN BRITISH COLUMBIA

Porphyry deposits in the Canadian Cordillera have, in some instances, an apparent close spatial relation to major faults. For example, the Iron Mask batholith lies lengthwise in a major cross structure of the Quesnellia (Carr and Reed, 1976). Preto (1979) and Nelson (1991) stress the importance of thinking of reactivated, older, porphyry-related structures when evaluating structures controlling Tertiary basins in the Intermontane Belt. Afton, Copper Mountain and

Mount Milligan all have younger structurally controlled basins adjacent to them (Seraphim & Hollister 1976).

Other groups of deposits appear to be related to separate north- and north-east-trending zones, which are perhaps zones of rifting. A group of Cu-Mo deposits in the Stikinia are located on small porphyry intrusions proximate to the Hickman pluton, and on or near north-trending faults and lineaments postulated to be rifts (Seraphim & Hollister 1976).

A group of Mo deposits on the east flank of the Coast Range plutonic complex in Alice Arm district are in a terrane which has two different structural styles, one with north-trending folds and faults and the other with north-easterly lineaments and zones of structural weakness. Porphyry Cu-Mo deposits in the Babine district have a close spatial relation to strong fault zones and lineaments trending north-westerly, where as those in the Tahtsa district are located in a terrane which has a north-easterly structural style. The deposits related to the Iron Mask intrusion near Kamloops are on the flanks of the intrusion, and trend north-westerly. Those in Highland Valley are, on the other hand, near the core of the intrusion and have a well-defined relation to two fault systems, one striking north-north-east and the other east-southeast (McMillan, 1996, personal communication). The deposits in the Copper Mountain district are in a setting similar to that at Kamloops; the intersection of minor easterly and north-easterly breaks with the strong north-west-trending.

Fractures, faults and breccias control the emplacement of porphyry mineralizations. Seraphim & Hollister (1976) have discussed this relationship and control within 3 orders of scale: (1) regional, i.e., Canadian Cordillera as a whole; (2) districts, containing abundant porphyry mineral deposits; and (3) individual deposits, that have different district structural controls.

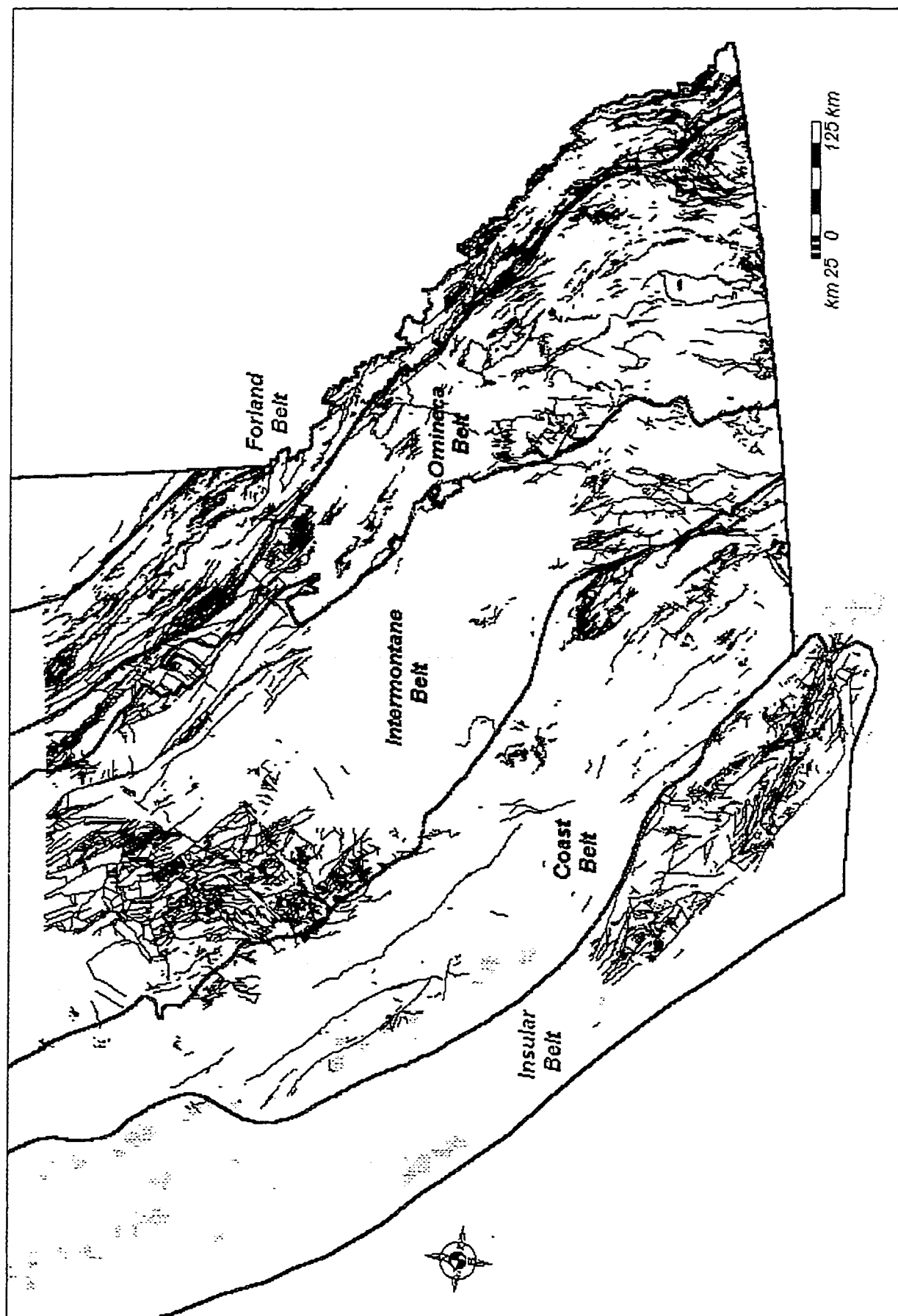


Figure 1. Distribution of faults inside southern and middle British Columbia

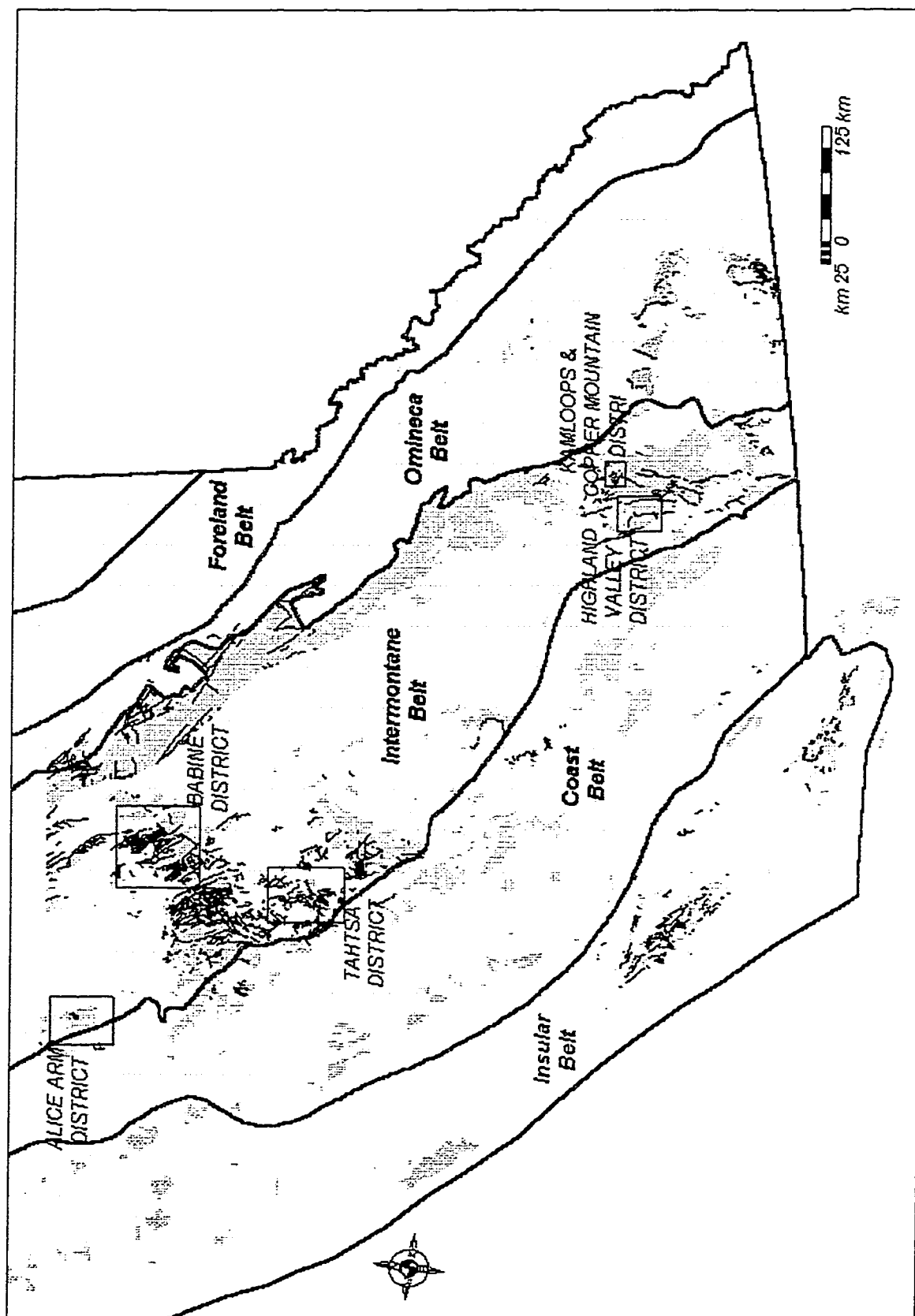


Figure 2. Faults inside geological units of the study area and the location of districts discussed in the text.

7.3 REGIONAL SETTING

In the Canadian Cordillera most of the major, more continuous faults and lineaments are in a set which trends north-west (N 35° to 40° W), (Gabrielse *et al.*, 1991, Seraphim & Hollister, 1976).

At the regional scale 3 major fault systems are dominant.

- The Rocky Mountain Trench, although not mapped as a continuous fault (Little, 1961), is a major lineament along which some displacement appears to have occurred locally. It is located between latitudes 54° and 55°N.
- The north-westerly transcurrent fault systems, appear to be suture zones which bound major crustal blocks. Serpentine bodies and zones of penetrative dynamic metamorphism are present along these faults. Some faults of this system may have been obliterated by some of the Late Cretaceous Early Tertiary intrusions of the complex (Seraphim & Hollister, 1976). The inclination of some members of the set differs from that of other members. Eisbacher (1972) and Wheeler (1970) show some faults, such as the Nahlin and King Salmon, as north-east-dipping thrusts and others, such as the Cold Fish and some strands north of the Yalakom, as south-west-dipping thrust. They show yet others, such as the Yalakom, Teslin and Queen Charlotte, to be vertical, right-lateral strikeslip faults (Seraphim & Hollister, 1976).
- Northerly and north-easterly striking fault systems, on the other hand, appear to be of tensional origin, and many porphyry deposits, in the Tahtsa region, for example, appear to be emplaced along these fractures, such as the Mess Creek (Stikinia district), Takla (Babine district) and Summers Creek (Copper Mountain - Highland Valley district) are shown as either vertical or inclined (Eisbacher, 1972) or with non-determined dips. They are suspected to be normal faults (Seraphim & Hollister, 1976).

Metasomatism and plutonism along and near the northerly and north-easterly striking systems differ from that along the north-westerly striking systems (Seraphim & Hollister, 1976). Major north-westerly striking faults tend to be broad shear zones containing fissile minerals such as muscovite, biotite, chlorite (or other hydrothermal alteration products), blue schist metamorphic mineral assemblages and serpentinites (Seraphim & Hollister, 1976).

Northerly and north-easterly striking fault systems, on the other hand, appear to be shallower seated. They are characterised by belts of granitoid or syenitic intrusions and andesitic volcanics. Examples are: (1) the Mess Creek fault system and parallel lineaments in the Stikinia district, accompanied by syenite porphyries (Barr, 1972), by Triassic andesites and by the Tertiary volcanic complex of Mt. Edziza (Souther and Simons, 1972); (2) the north-easterly trending fracture systems in the Tahtsa district and the Takla fault in the Babine, accompanied by Triassic and Jurassic andesitic volcanics and felsic intrusions (Carter, 1974); (3) the Summers Creek and other northerly striking fractures in the Copper Mountain-Highland Valley-Kamloops belt, accompanied by Triassic, Jurassic and Tertiary andesitic volcanics and felsic intrusions (Rice, 1974). These are briefly described in the following section on "District Settings".

Major faults, fractures, breccias and porphyry mineral deposits are rare or unknown in three regions:

- *Coast Plutonic Belt*: is occupied by the Coast Range Plutonic Complex. Abundant granitic intrusions and granitized and strongly foliated metamorphic rocks in the complex apparently form an unfavourable environment for the development of porphyry plutons and mineralization.

- *Capping of intercontinental sedimentary basins:* The north and central parts of the Bowser Basin are likewise almost empty of porphyry mineral deposits. These areas are underlain almost entirely by subaerial siltstones and greywackes, with local carbonaceous strata and coal seams. Volcanic rocks, intrusions and porphyry deposits all diminish in abundance inward from the margins of the basin (Seraphim & Hollister, 1976).

- *Capping of Cenozoic volcanics:* Most of the Chilcotin plateau, also devoid of known deposits of porphyry mineralization, is underlain by Cenozoic volcanic rocks. Many of these volcanic rocks are faulted, but known porphyritic intrusions are barren or very low grade (Seraphim & Hollister, 1976).

- *Rocky Mountain Thrust Belt:* Porphyry deposits are only rarely associated with thrust faults (Hollister, 1978). Rocky Mountain thrust belt is almost empty of known porphyry deposits.

A single fault may have been re-activated under a different regime. The existence of two regimes may serve to explain why porphyry deposits near the north-westerly trending fault set have a different structural setting than those near the north- and north-easterly trending set (Seraphim & Hollister, 1976).

Six important porphyry deposits that are located the farthest south-west in British Columbia (Fish Lake, Poison Mountain, Salal, O.K., Island Copper and Catface) all lie within a few miles of and north-east of major members of the north-west set. A number of other individual porphyry deposits are emplaced on or near minor faults which are close to and probably subsidiary to, but not necessarily north-east of, major north-west fault systems (e.g. Casino, Mt. Nansen Gibraltar, Cariboo Bell and Boss Mountain) (Seraphim & Hollister, 1976).

Porphyry deposits may occur also along the northerly and north-easterly striking fault systems, and in this setting they tend to occur in groups. The northerly and north-easterly striking fault systems, such as the Mess Creek in the Stikinia, and the Summers Creek and Highland Valley faults in the Copper Mountain and Highland Valley districts, appear to be rifts, i.e., tension systems (Souther and Symons 1972, Preto, 1974, Hollister *et al.*, 1975).

7.4 DISTRICT SETTINGS

Individual intrusions and shapes of deposits commonly appear to be controlled by a major fault or shear direction. North-easterly striking faults in British Columbia appear to be of tensional origin, and many porphyry deposits, in the Tahtsa region, for example, appear to be emplaced along these fractures. Nielsen (1976) believes that structural features described for the Highland Valley, Babine and Tahtsa districts generally are consistent with an origin by shallow compressional tectonic stresses and north to north-west faults at Highland Valley, Granisle and Morrison have right-lateral displacement and may be strike-slip faults with movement in response to lateral compression. North to north-east fractures appear to be tensional features along which dikes and hypabyssal stocks are intruded (e.g., at Granisle and Bethlehem). The structural pattern is consistent with a regional near-horizontal principal stress directed north to north-easterly (as recognised at Highland Valley by McMillan, 1971, Casselman *et al.*, 1995), a model which appears consistent with regional tectonic patterns that evolved between Upper Triassic and Oligocene time (Monger, 1972 and Monger *et al.*, 1982).

Inside the following discussed districts, there are many examples that emphasise the importance of faulted areas and fault intersection and their close relationship with the distribution of porphyry deposits and plutonic intrusions related to mineralizations. Location of these districts is shown on the map of Figure 2.

7.4.1 STIKINIA DISTRICT

Hickman complex which is a series of Triassic calc-alkalic and alkalic intrusions is located in northern British Columbia (57° N, 131° to $131^{\circ} 30'W$). These intrusions are associated with porphyry deposits. All of these deposits are located on faults or lineaments, which probably are generated by faults (Seraphim & Hollister, 1976). The Hickman complex is centred on the Sphaler-Scud fault and two parallel lineaments. Two intrusions near the Hickman pluton that contain porphyry deposits (Schaft Creek and Sphaler Creek) are emplaced at the intersection of the north-east- and north-west-trending fault zones.

Alternative hypotheses exist with regard to the origin of the Hickman pluton. Either the faults controlled the emplacement of the pluton and neighbouring intrusions or the intrusions caused the faulting. In many cases different workers (Seraphim & Hollister, 1976) would favour the first alternative, because the breaks are regional rather than being localised near the intrusions, and because at least two of the regional breaks are accompanied by linear belts containing numerous lithologically similar syenite porphyries.

7.4.2 ALICE ARM DISTRICT

The group of porphyries near Alice Arm ($55^{\circ} 15'N$, $129^{\circ} 30'W$) show no close spatial relation to major faults and fractures as mapped. However, most of the lineaments, which do exist in this locality, strike northerly and north-easterly, and are believed to reflect regional tensional conditions. Sketches of the small individual intrusions shown by Woodcock and Carter (1976) show that the 4 porphyry Mo deposits, without exception, are characterised by north-east-trending fractures. The Bell Moly intrusion is elongated north-easterly. Several Cenozoic lava flows, aligned north-easterly between and near the B.C. Moly and Bell Moly deposits, also may be related to a north-easterly striking fault that is not exposed (Seraphim & Hollister,

1976). The Ajax deposit has higher fracture density and better grade of mineralization near the north-easterly and northerly trending fracture zones (Seraphim & Hollister, 1976).

7.4.3 BABINE DISTRICT

Lineaments in the Babine district trend predominantly north-westerly and are grouped to the west of the major northerly striking Takla fault. Individual fault zones are difficult to trace, because thick till covers much of the area, but trenching and drilling on many deposits, and mining on the Granisle and Bell (Newman), have exposed some of the faults. Numerous small, mineralized intrusions are situated adjacent to major north-north-westerly trending fault system (Seraphim & Hollister, 1976) and are spatially related to them (Carter *et al.*, 1995, Preto, 1996, personal communication). The deep-seated faults and related zones provided conduits for calc-alkaline magmas. Product of these magmatic episodes includes plutons of the Late Cretaceous Bulkley intrusions (Carter, 1976, 1981) and the Eocene Babine igneous suite .

It may be more than coincidental that both Granisle and Bell are situated at intersections of north-east-striking faults with the north-west-striking faults and both contain intrusion breccia pipes (Kirkham, 1971). The Caves deposit at Trail Peak also occurs at a fault intersection similar to those described above. Recognition of the importance of intersections has led to prospecting of intersections elsewhere in this district (Seraphim & Hollister, 1976).

The north-west-trending Bulkley Valley fault forms the transition between the dominantly north-west-trending terrane in the Babine district and the dominantly north-east-trending terrane in the Tahtsa district (Seraphim & Hollister, 1976).

7.4.4 TAHTSA DISTRICT

The trend of most of the lineaments and folds in the Tahtsa district, even more so than in Babine, is obvious from the trend of the district's system of lakes and broad valleys. Many of the lakes along this part of the east flank of the Coast Range, such as Morice, Nanika, Kidprice, Tahtsa, Coles and Whitesail, are elongated north-easterly. These lakes and the broad valleys are believed to be surface expressions of zones of north-easterly trending faults and fractures (Seraphim & Hollister, 1976).

Porphyry mineralization, as in the Alice Arm and Babine districts, is associated with calc-alkalic stocks less than 1 km in diameter. The Huckleberry deposit is suggested by Carr (1965) to be localised by two north-east faults, which bound it, closely on the north and south. The stock is elongated north-easterly. Northeast and north-west lineaments disclosed by aerial photographs are common in the Huckleberry Mountain area, and some of these lineaments probably represent faults. The major fracture directions in the intruded volcanic rocks and the porphyry plugs also trend north-east and north-west (Carter, 1970).

The Berg deposit in this district, as mapped by Ney (1972) does not include strong fault zones. A possible post-mineral dike system of quartz latite porphyry near the core of the intrusive complex, however, is shown to strike north-easterly, and to be cut by one or more minor north-west faults. Although a north-east-trending mineralized fracture set exists at this deposit, most mineralized veinlets appear to be related to an annular set, which is peripheral to the quartz monzonite phase of this pluton.

Seraphim & Hollister, (1976) believe that the numerous north-easterly striking faults and lineaments in the Tahisa district form a tension system developed between the through-going north-westerly shear zones, and that the porphyries were emplaced in the areas of tension.

7.4.5 HIGHLAND VALLEY DISTRICT

Highland Valley is the best described and most thoroughly investigated of porphyry Cu-Mo districts in British Columbia. The Guichon Creek batholith is elongated north-south, approximately bisected by many north-southstriking broad fault systems, which is included under the name of the Lornex fault. A second broad system of faults, which includes the Highland Valley fault, strikes north-westerly through the batholith. The zone of intersection of these two systems is coincident with the core of the batholith and with the main group of porphyry mineral deposits (Casselman *et al.*, 1995).

Hollister *et al.* (1975) postulated that continued simultaneous and alternate displacements along the two fault systems, caused by regional forces, permitted repeated injections of a continually differentiating magma and its associated hydrothermal fluids. The batholith formed as a dilatant centre, with the dilatation providing tectonic openings. Igneous rock and mineralization filled the openings developed, most of which were strands or conjugate to strands of either the Highland Valley or the Lornex fault zones (Seraphim & Hollister, 1976).

The Highmont system of porphyry dikes, breccia pipes and mineralization occupies a zone considered to be part of the Highland Valley fault system. The mineralized bodies occur on the flanks of a composite porphyry dike and related breccias, the emplacement of which may be controlled by a strand of that fault. The individual mineralized veins and veinlets are in sets, which appear to be conjugate to the controlling major strand (Bergey *et al.*, 1971).

The Bethlehem group of porphyry orebodies shows a close relation to a north-trending fault system. There are many mineralized north-trending faults and breccias passing through the area containing the Bethlehem orebodies (Coveney, 1963).

The fault system inferred by McMillan *et al.*, (1995) within the mineralized zone of J.A. district, very closely parallels the Highland Valley and Lornex fault systems, and the ore zone itself is elongated north-westerly, parallel to the former.

The Lornex-Valley mineralization is postulated to have been the last to be emplaced. Ninety per cent of the 14,000 fractures recorded in the Valley orebody are shown to belong predominantly to two sets, one parallel to the Lornex (N-S) and the other to the Highland Valley fault (NW) (McMillan, 1971, 1996, personal communications, 1995). Right-lateral movement on the Lornex fault, offsetting Lornex and Valley Copper ore zones, was postulated with the discovery of the Valley Copper deposit.

A series of Tertiary extrusions and sedimentary rocks, aligned in a general north-south direction coincident with the Lornex fault and also west-north-west parallel to the Highland Valley fault, indicate that tensional tectonic activity continued or was reactivated long after the emplacement of the mineralization (McMillan, 1996, personal communication, 1995). McMillan (1995) suggests that rifting occurred or was reactivated during Tertiary time in at least two periods, Eocene and Oligocene.

Thus, all of the orebodies in the Highland Valley are interpreted to have a very close relationship to strands of the two major fault systems in the district. The long dimensions of the Highmont group, Lornex Valley (prior to the offset of the segments) and J.A. are all north-westerly, parallel to the Highland Valley fault. The long dimension of the East Jersey orebody is parallel to the Lornex fault. The individual fractures that are mineralized within the orebodies are predominantly either parallel or conjugate to the major faults (Seraphim & Hollister, 1976).

7.4.6 KAMLOOPS AND COPPER MOUNTAIN DISTRICTS

Two other districts which should be discussed, because of a variation of their settings from any of the above, are those at Kamloops (Iron Mask intrusion, with the Afton, Galaxy, Kimberley Copper, Ajax-Monte Carlo, Leemac and other deposits) and at Copper Mountain (Copper Mountain and Ingerbelle groups of orebodies). The mineralized bodies in these camps are associated with faults, fault intersections and breccia zones at or very close to the periphery of irregular intrusions which have minimum lateral dimensions of several km² (Carr and Reed, 1976, Stanley *et al*, 1995). This setting contrasts sharply with that at Highland Valley, where the groups of mineral deposits are near the core of the intrusion.

The intrusive histories of these plutons and the Guichon Creek intrusion at Highland Valley are similar in that they are formed by a series of pulses of related intrusions, with the better mineralization being related to the late (and more felsic?) phases (Seraphim & Hollister, 1976). The structural setting, however, differs in that the latest phases at Iron Mask are near the perimeter of the intrusive complex (Northcote, 1974), whereas the Guichon Creek batholith formed by differentiation proceeding inwards, with the latest phases emplaced near the core (Northcote, 1969, McMillan, 1976, 1995). The difference might be attributed to the location of the faults and fracture systems that were open enough to act as conduits at the time of the late intrusions (Seraphim & Hollister, 1976).

The Copper Mountain stock is similar to the Guichon Creek batholith in that the more felsic phases of the Copper Mountain stock are near the core (Montgomery, 1967), but the orebodies are grouped on the north flank along a major north-west break, the Main fault, and localised by minor north and north-east breaks such as the Red Butte and Tremblay faults (Fahrni *et al*, 1976a; Preto, 1972, Stanley *et al.*, 1995). However, Fahrni *et al.* (1976a) suggest that the porphyry orebodies are genetically related to the Lost Horse intrusions, which occur only on the north flank of the Copper Mountain stock, rather than to the stock itself. In either case, the

orebodies are directly related, both in general and in particular, to fault zones (Preto, 1996, personal communication). Some of the north-east-trending fault zones also carry Tertiary dikes, indicating that tensional conditions continued into Tertiary time (Seraphim & Hollister, 1976).

Within a general compressional stress field local tensional features, may develop. Tensional openings may result along or adjacent to a major strike-slip fault owing to horizontal displacement along the fault where a change in attitude of the fault surface exists (Figure 3). Thus, there will be the preferred location for veins, dikes and passive intrusions so commonly associated with porphyry mineralizations (Stringham, 1966, Nielson, 1976, McMillan, 1996, personal communication). The location and shape of intrusions, dikes and sulphide systems for many years have been considered to be related to pre-existing bedrock structure. The concept that ancient faults within the crust are the location of repeated and renewed movement by repeated deformation and are the channels along which magmas and solutions rise, was first emphasised by Billingsley and Locke (1941), (McMillan, 1996, personal communication).

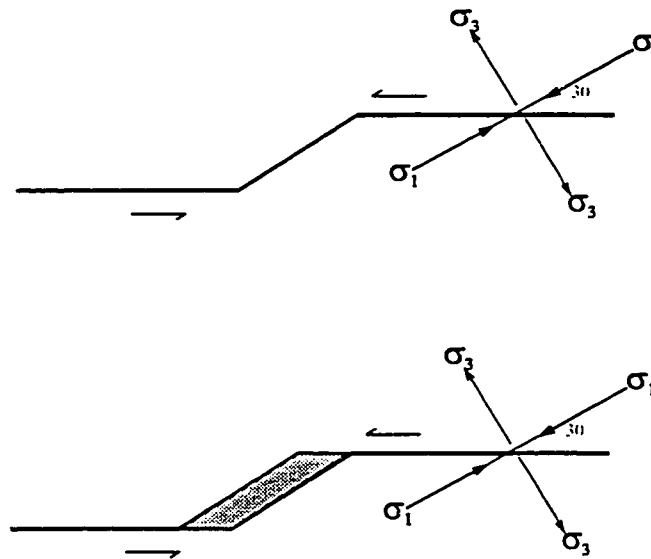


Figure 3. A tensional opening formed at flexure in a fault surface.

7.5 SPATIAL ANALYSIS FOR DISTRIBUTION OF FAULTS AND KNOWN PORPHYRY DEPOSITS

To investigate the spatial association of known porphyry deposits and faults inside the study area, three kinds of maps were generated:

1. Density of faults (length of faults per km²).
2. Smoothed map of buffer zones around faults.
3. Smoothed map of buffer zones around points of fault intersection.

7.5.1 SPATIAL DENSITY OF FAULTS

Spatial density of linear features represents length of lineaments within a grid cell of preselected size, per unit area of the grid. Density can be calculated at the location of nodes of a grid put over the study area. To do that, a certain distance is selected around each grid node. The total length of the faults located inside such a cell, with the node in its centre, must be calculated. This total length value can be applied, to calculate the density of faults inside that cell. This calculated density is assigned to the node of the grid. By contouring these density values, a map can be generated to show the density of faults inside a study area. Hence, areas with complex intersections of linear features or highly fractured, will receive high scores. These areas as mentioned above are important in prospecting for porphyry deposits. 2.5 km was selected for the size of the grid for calculating density of faults.

Raines (1978) and Turner et al. (1982) have studied structural controls in an area of porphyry mineralization in the south-western United States and Northern Mexico. The studied zones were interpreted to be structurally defined zones that are a primary regional control of mineralization in the porphyry Cu province of northern Sonora in Northern Mexico (Turner et al., 1982, Raines 1978). In this area they have studied the coincidence of the areas with high

concentration and density of linear features, areas of limonite concentration on flanks of the lineament zones, subtle deflections on the regional gravity field, anomalous geochemical trends and the presence of known porphyry Cu deposits.

Density of faults was calculated inside the geological units of the study area (introduced in chapter 3) where faults at the scale of 1/250,000 exist. The result was compared with the distribution of known porphyry deposits of different types and categories. Since porphyry deposits are only rarely associated with thrust faults (Hollister, 1978), for generating the maps of Figure 4 and 5, thrust faults were excluded prior to density calculations.

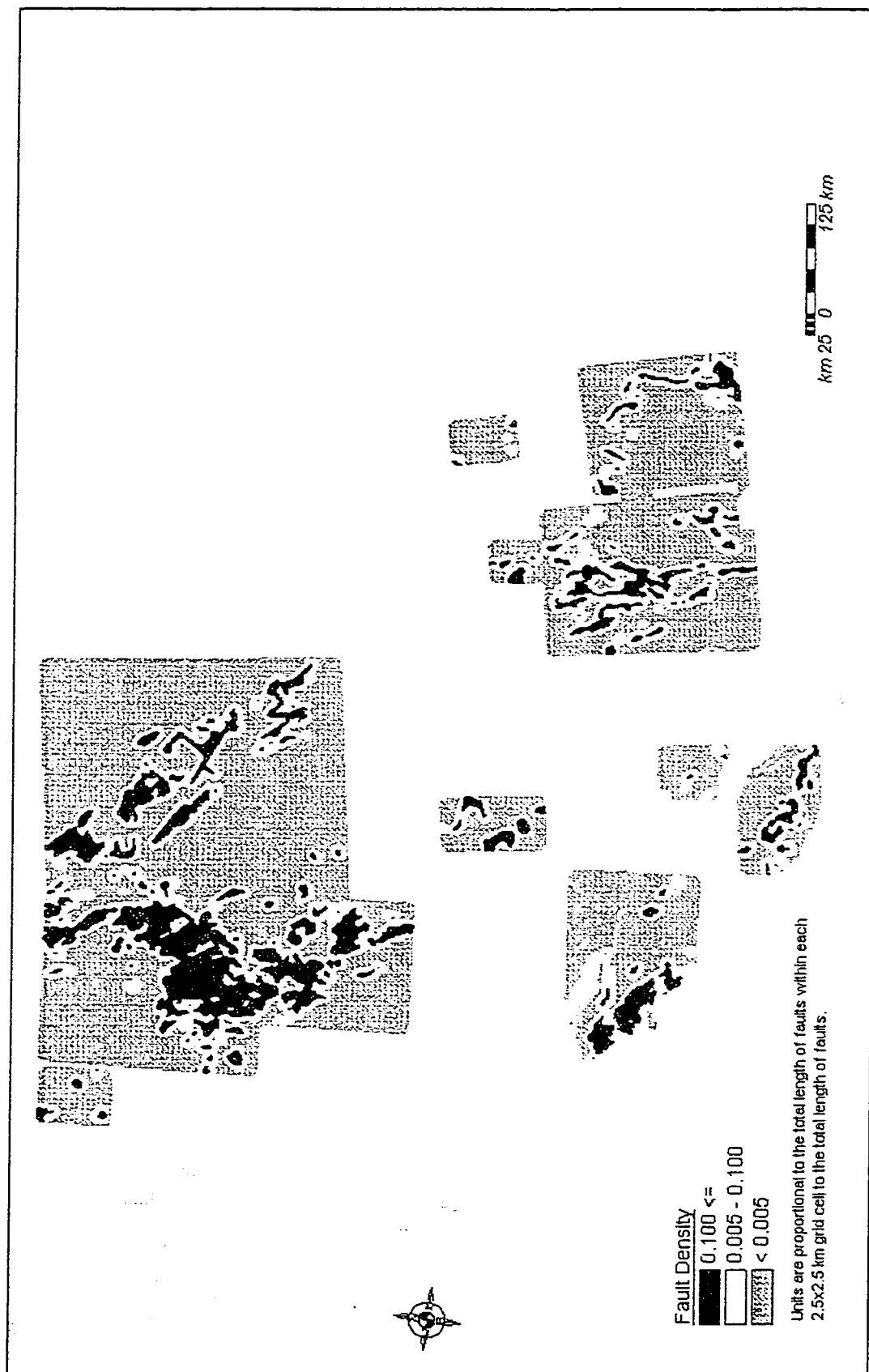


Figure 4. Density of faults inside rectangular grids covering different parts of the geological units of the study area, where faults at the scale of 1/250,000 exist.

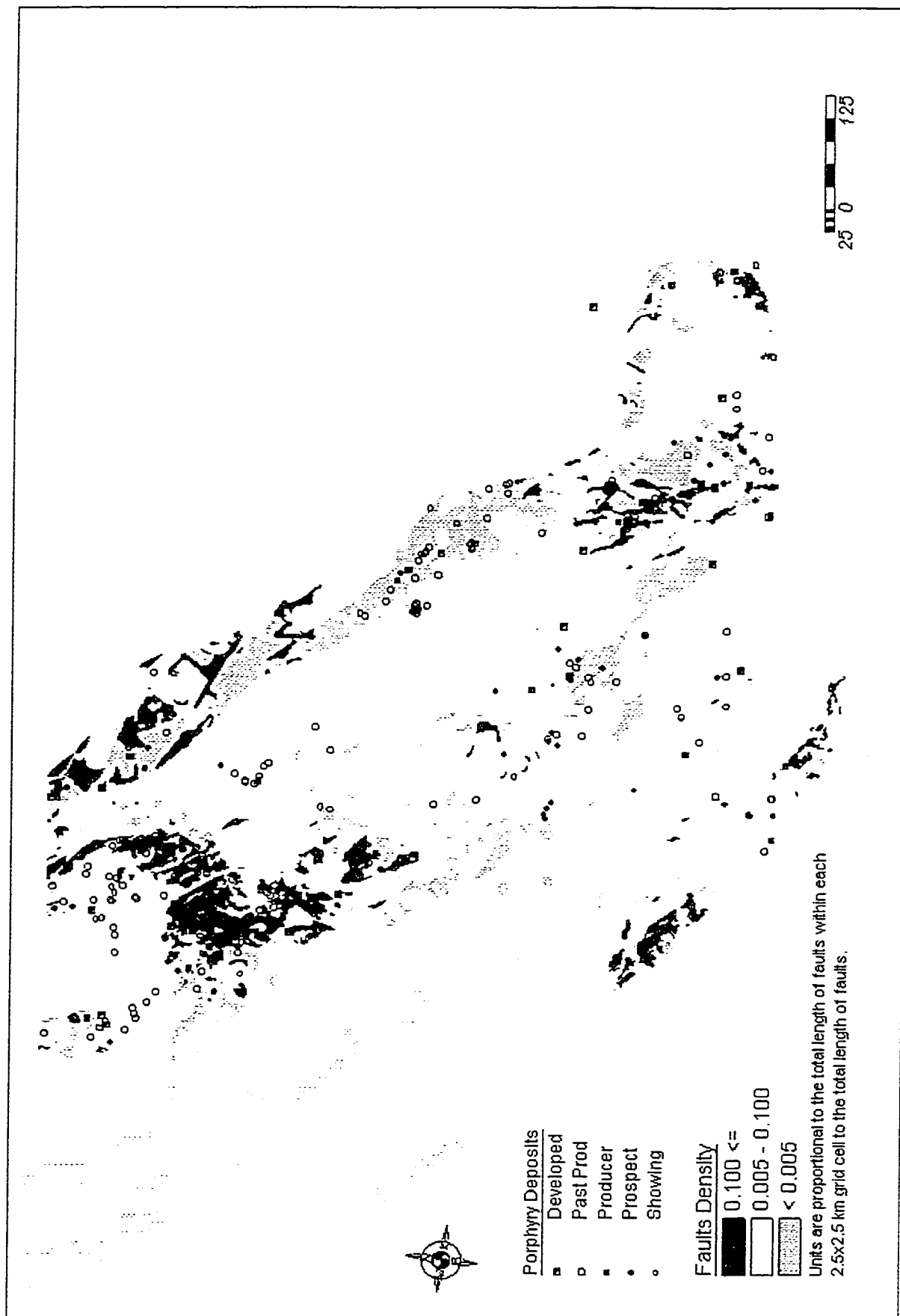


Figure 5. Density of faults cut by the boundaries of geological units of the study area.

7.5.2 BUFFER ZONES AROUND FAULTS

This is perhaps the simplest method to create a map to show the proximity to faults. Corridor maps are most often used in proximity analysis, where distance from a linear feature is important. In the geographical information systems, these corridor maps are named buffer maps. In Figure 6, the width of the buffers around faults was selected as 0.5, 1, 2, 5, and 10 km. After generating this buffer map, it was smoothed by passing a median filter with the size of 17x17 cells (Figure 7). Such a smoothing removes noise and reveals the general proximity to faults. This smoothed buffer map is then cut by the boundaries of the geological units of the study area.

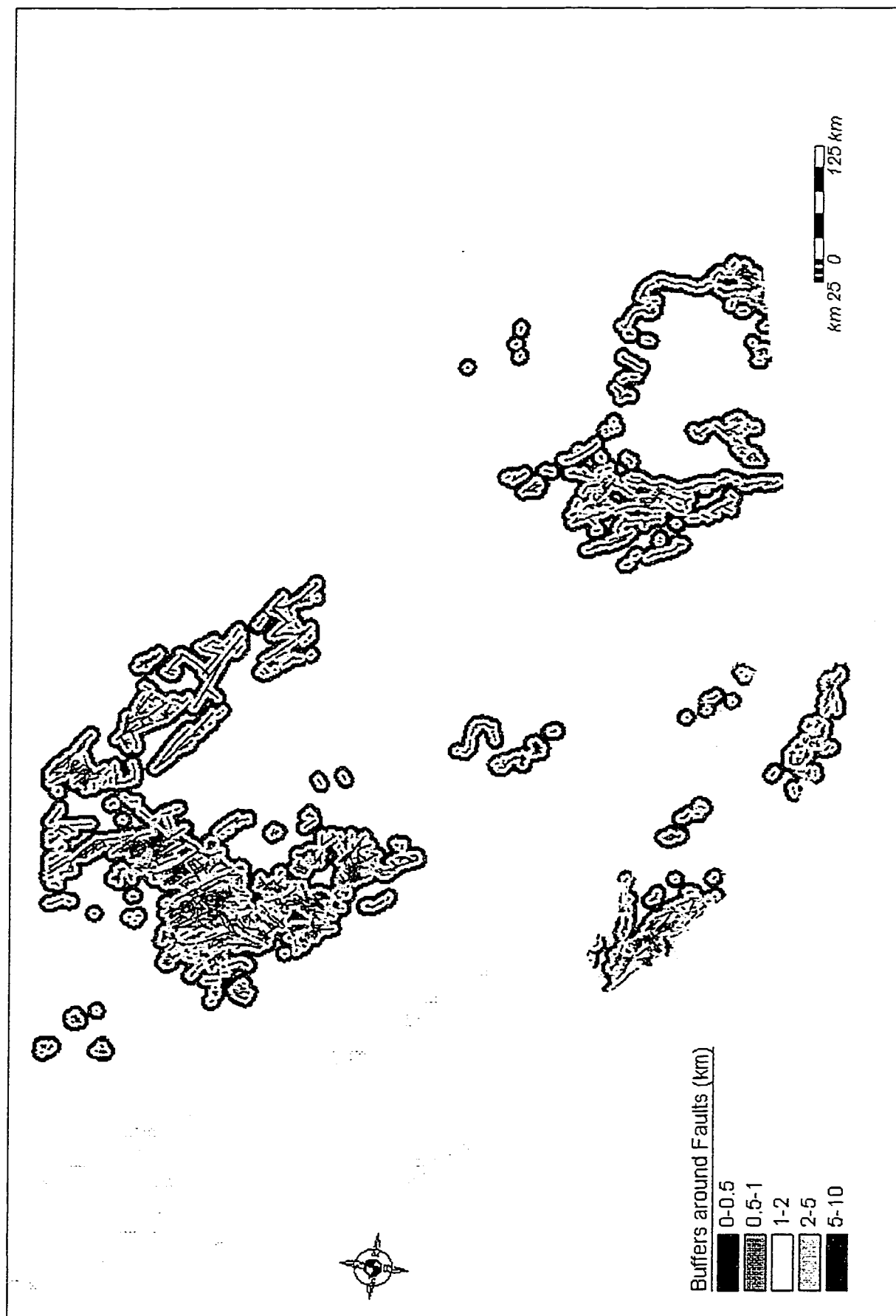


Figure 6. Buffer zones around faults inside geological units of the study area.

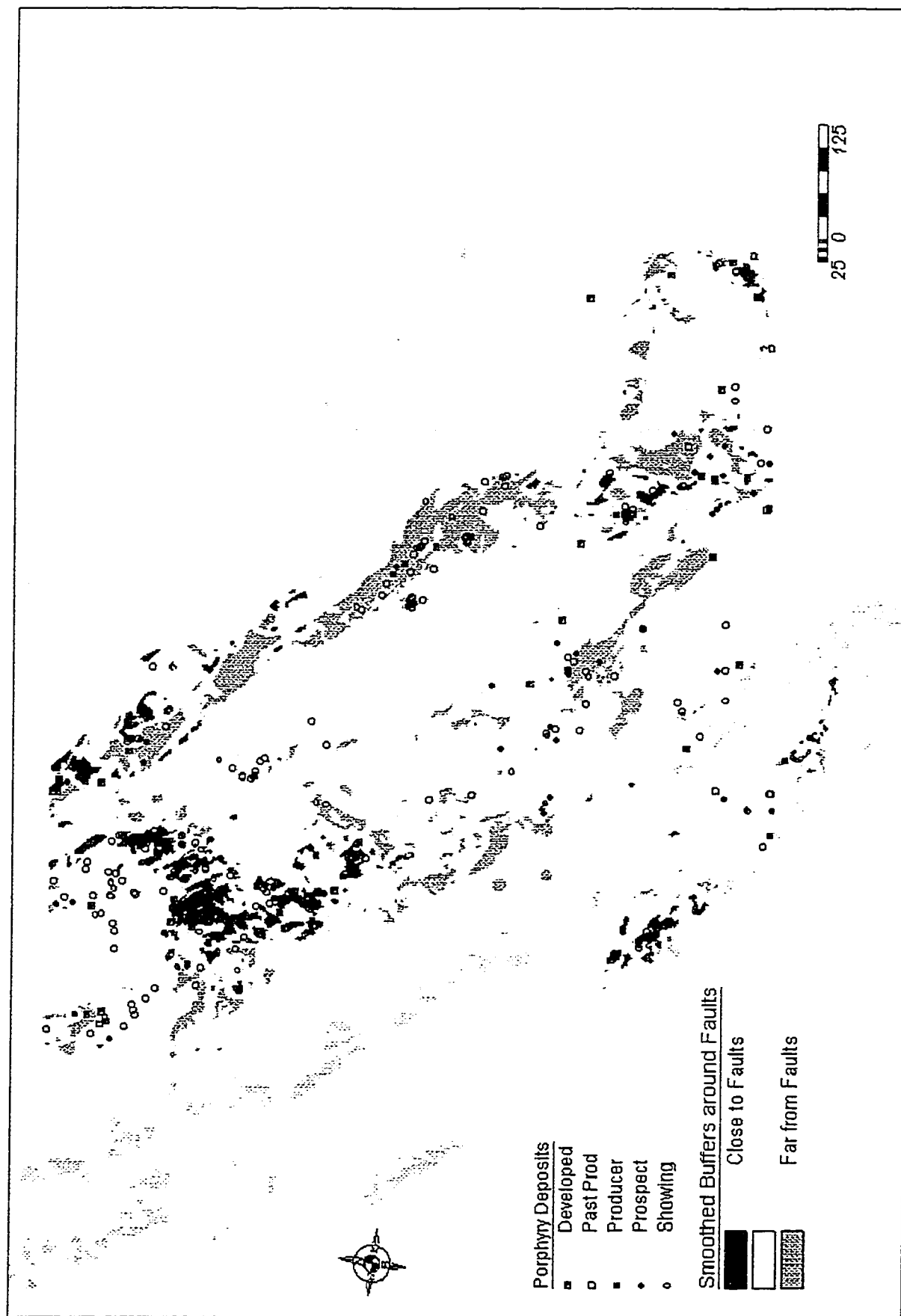


Figure 7. Smoothed map of buffer zones around faults cut by the boundaries of the study area.

7.5.3 BUFFER ZONES AROUND POINTS OF FAULTS INTERSECTION

Points of fault intersection are potentially important because they provide the fracturing that control the emplacement of plutonic intrusions and mineralization. Many examples of porphyry mineralizations are known in British Columbia that are located near the fault intersection. Several examples were discussed earlier in this chapter. Considering the importance of highly faulted areas and intersections of faults, a point was assigned wherever a fault intersected with another inside the geological units of the study area. Circular buffers are frequently used in proximity analysis, where distance from a point such as fault intersection, is important. Here, for these points, buffer zones were created as 2, 4, 6, 10 and 20 km corridors. This map was then filtered by passing a median filter with the size of 19x19 cells over the study area to reduce the noise. In this way, general proximity to fault intersection was revealed (Figure 9).

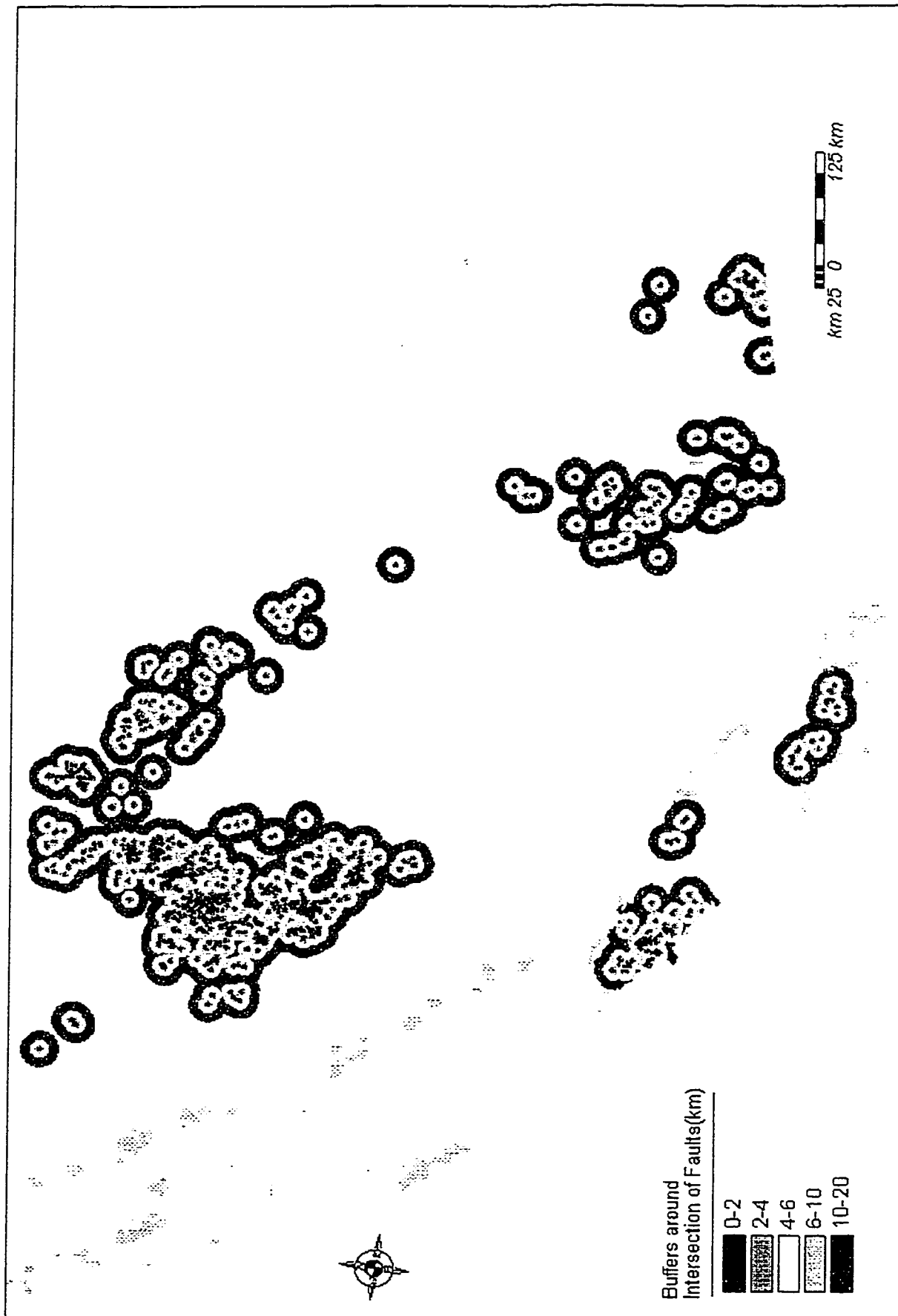


Figure 8. Buffer zones around points of fault intersection.

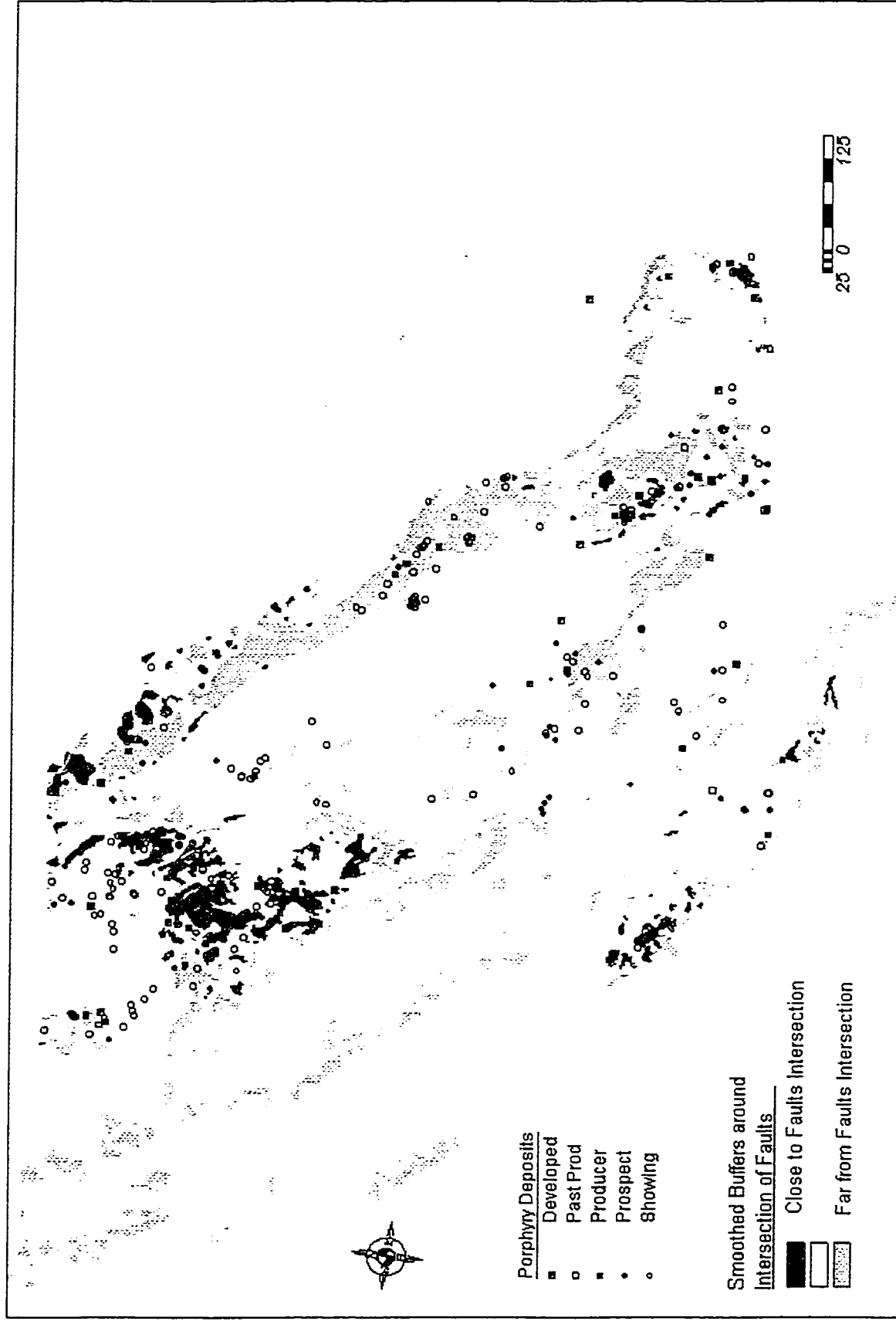
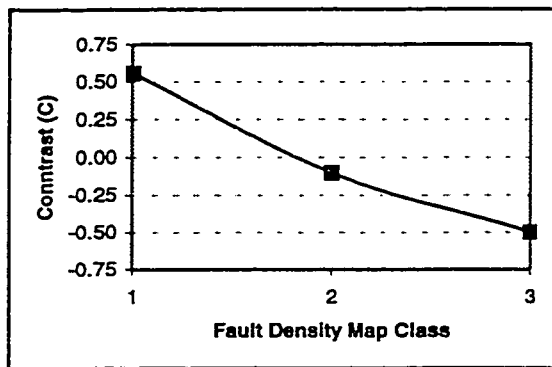


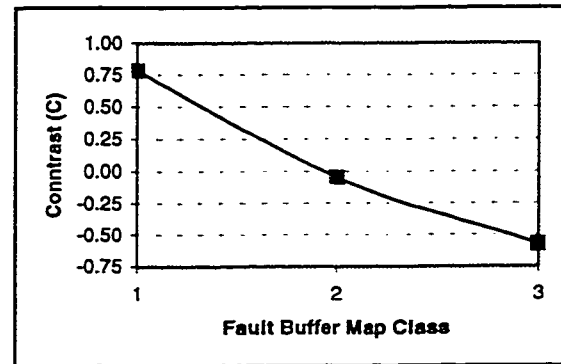
Figure 9. Smoothed map of buffer zones around points of fault intersection inside the study area.

7.6 DISCUSSION

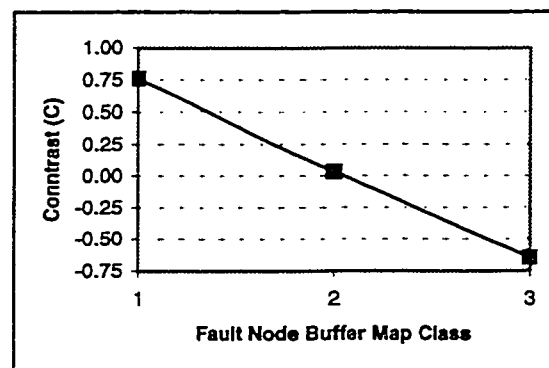
As Figure 5, 7, and 9 show, most of the known porphyry deposits appear inside the top classes of fault density map and in close proximity to faults, or fault intersection. Therefore, these maps could be useful in showing the areas of high potential for prospecting porphyry deposits. To quantify this association, a weight of evidence analysis was done between the known porphyry deposits that locate inside the geological units of the study area and maps of Figure 5, 7, and 9. Figure 10 shows results of this analysis. For simplicity, the point of fault intersection is referred here also as fault node.



(a)



(b)



(c)

Figure 10. Variation of contrast (C), a) Between porphyry deposits & fault density map. b) Between porphyry deposits & smoothed fault buffer map. c) Between porphyry deposits & smoothed fault node buffer map.

Class 1 and 2 of fault density map represent areas with high densities of faults. Although these 2 classes cover about 57% of the study area, most of the known porphyry deposits (68%) are located within these classes. This spatial association is reflected also in the W^+ and contrast (C) that rapidly decrease from class 1 to 3 (Figure 10-a).

The other two maps (smoothed fault buffer and smoothed fault node buffer maps) also show the same trend for variations of W^+ and contrast (C). For fault buffer map, about 68% of the known porphyry deposits are located inside class 1 and 2 and the area of these two classes is 54% of the total area of fault buffer map. Similarly, class 1 and 2 of fault node buffer map contains most of the known porphyry deposits (59%), that represent the spatial association of deposits with regions close to faults and faults intersections.

Beside the above mentioned spatial associations, the 3 maps of fault density, fault buffer, and fault node buffer are very similar to each other. Similar classes of these maps, in many locations, have matching coverages. Several spatial statistical parameters were calculated here to show their correlation (Table 1).

Table 1. Contingency Coefficient, Tschuprow's T and Cramer's V for the three maps.

BETWEEN MAPS	Contingency Coefficient	Tschuprow's T	Cramer's V
A & B	0.73	0.75	0.75
A & C	0.64	0.59	0.59
B & C	0.66	0.61	0.61

A: Density of faults

B: Smoothed buffers around faults

C: Smoothed buffers around faults intersections

A contingency coefficient of close to 1 means the two compared maps are very similar to each other. Tschuprow's T and Cramer's V lay between 0 and 1. As the spatial association of two maps increases, these parameters get closer to 1. Total independence of two maps results

in 0 for these parameters. Formulas to calculate contingency coefficient Tschuprow's T and Cramer's V are given in Appendix D.

As Table 1 shows, the maps of density of faults, smoothed buffers around faults and smoothed buffers around faults intersections have high correlation with each other. Among these, maps of density of faults and smoothed buffers around faults are the most similar pairs of maps. This suggest that if in any GIS project, because of the limitation of the GIS software, it is not possible to generate a density map for linear features such as faults, the map of smoothed buffers around faults can be a reasonable substitute for the required fault density map.

To see how different individual classes of these maps are correlated with each other, odds ratio and alpha values are calculated between pairs of these 3 maps for all combinations of classes. The method for calculating odds ratio and alpha values is discussed in Appendix D. Odds ratio is the simpler measure to check the association between classes of two maps than alpha. The odds ratio is always positive, being greater than 1 for classes that are positively associated, 1 if the two classes of two maps are independent and less than 1 if they are negatively associated. Alpha ranges in value between -1 and +1 like a correlation coefficient, with 0 implying independence of the two classes (Bonham-Carter, 1994). As Table 2 shows, the odds ratios are highest for class 1 of all map pairs that are compared with each other. It decreases for higher classes. This reflects high spatial association of class 1 of these maps with each other. Among these 3 maps, density of faults and smoothed map of buffer zones around faults have the highest association for their class 1 with odds ratio of ~5446 and alpha of 0.97.

Table 2. Odds ratios and alpha values for classes of 3 maps compared as pairs with each other.

<i>Between fault density & fault buffer maps</i>					
ODDS RATIOS					
<i>Classes of fault density map</i>					
		1	2	3	
<i>Classes of fault buffer map</i>	1	5446	29.23	0.02	
	2	0.24	286	2.16	
	3	0.00	0.26	8332	
ALPHA					
<i>Classes of fault density map</i>					
		1	2	3	
<i>Classes of fault buffer map</i>	1	0.97	0.69	-0.75	
	2	-0.34	0.89	0.19	
	3	-1.00	-0.33	0.98	

<i>Between fault density & fault node buffer maps</i>					
ODDS RATIOS					
<i>Classes of fault node buffer map</i>					
		1	2	3	
<i>Classes of fault density map</i>	1	785	1.92	0.02	
	2	19.55	53	1.87	
	3	1.98	13.32	588	
ALPHA					
<i>Classes of fault node buffer map</i>					
		1	2	3	
<i>Classes of fault density map</i>	1	0.93	0.16	-0.74	
	2	0.63	0.76	0.16	
	3	0.17	0.57	0.92	

<i>Between fault buffer & fault node buffer maps</i>					
ODDS RATIOS					
<i>Classes of fault node buffer map</i>					
		1	2	3	
<i>Classes of fault buffer map</i>	1	448	10.00	0.02	
	2	6.61	90	2.70	
	3	0.39	9.25	565	
ALPHA					
<i>Classes of fault node buffer map</i>					
		1	2	3	
<i>Classes of fault buffer map</i>	1	0.91	0.52	-0.75	
	2	0.44	0.81	0.24	
	3	-0.23	0.51	0.92	

CHAPTER 8

MODELING AND INTEGRATION OF DATA

8.1 INTRODUCTION

Integration of data from diverse sources is the ultimate purpose of most GIS projects in order to describe and analyse interactions, to make predictions with models, and to provide support for decision-makers (Bonham-Carter, 1994). Using a GIS for site selection whether the site is for exploration of mineral deposits, a landfill, a nuclear or toxic waste, a dam, residential development, involves finding locations or zones that satisfy a set of criteria. If the criteria are defined as a set of deterministic rules, the model consists of applying Boolean operators (logical “AND”, “OR”, NOT,...) to a set of input maps, and the output is a binary map (Bonham-Carter, 1994). In a binary map only two situations are possible, each location is either satisfactory or not. Alternatively, each location may be evaluated according to weighted criteria, resulting in a ranking on a suitability scale. The subsequent selection process then benefits from the ability to assess suitability rankings, rather than simply presence/absence (Bonham-Carter, 1994). GIS modelling of mineral potential also involves calculating a suitability, or mineral favourability, from geoscientific maps. The potential is calculated by weighting

and combining multiple sources of evidence. The assignment of weights to maps is carried out either by analysing the importance of evidence relative to known mineral deposits, or by using the subjective judgement of mineral deposits by geologists (Bonham-Carter, 1994). Models used for the site selection process are usually “prescriptive” (Bonham-Carter, 1994). In geosciences, they involve the application of a set of criteria that are set out as favourable. Such criteria may result from a blend of geochemical, geophysical, tectonic, stratigraphy factors. On the other hand, mineral potential mapping involves the use of “predictive” models, because the ultimate purpose of determining mineral potential is to discover new deposits (Bonham-Carter, 1994).

Favourability maps for prospecting porphyry deposits were generated in this chapter by combining several input maps that were created in the previous chapters. For this integration, the fuzzy logic method was utilised.

8.2 TYPES OF MODELS

Modelling in geosciences is classified into three types: Theoretical, Empirical and Hybrid. The difference between these types based on the kinds of relationships that the models represent is shown in Table 1. This section is mainly derived from (Bonham-Carter, 1994).

Table 1* - A Classification of models used in geology. These are symbolic models as opposed to physical scale models.

Class	Type of Relationship	Example	
		Field of Application	Model
Theoretical	Physical/Chemical principle	Groundwater flow	Equations of flow
Hybrid	Semi-empirical	Sediment transport	Transport equation
Empirical	Heuristic or statistical	Mineral Deposit prediction	Statistical regression

* Graeme Bonham-Carter (1994)

In a very general sense, a GIS model can be thought of as the process of combining a set of input maps with a function, to produce an output map.

$$\text{Output map} = f(\text{two or more input maps})$$

The function, f , takes many different forms, but the relationships expressed by the function are either based on a theoretical understanding of physical and chemical principles, or they are empirical, based on observations of data, or some blend of theory and empiricism. Models for predicting mineral potential, based on statistical relationships or on heuristic relationships, are examples of empirical models. The physical and chemical principles governing the formation of mineral deposits are for the most part too complex for direct prediction from mathematically-expressed theory. The prediction of mineral deposits must rely mostly on empirical relationships, with the aid of descriptive "deposit models".

Study of mineral deposits has led to the recognition of a large number of classes of deposit, or deposit types. Each deposit type consists of a number of actual deposits, regarded as being sufficiently similar in terms of their characteristics, to be treated as a descriptive "model" that guides the search for new deposits of the same type. The description of a deposit model does include, as far as possible, an evaluation of the chemical and physical processes that control deposit formation, but the model can not be expressed in purely mathematical terms. In applying GIS to the mapping of mineral potential, deposit models play a role both in the selection and derivation of maps that are likely to be good predictors of the deposit-type under consideration, and for the assignment of weights to the various predictor maps. In the function which is used to combine maps together, weights must be assigned to different input maps and their classes. Assignment of these weights can either be carried out by using characteristics

of the data itself like using an actual study region to estimate the spatial relationships between predictor maps and the response map based on the known mineral deposits; or the weights can be estimated on the basis of expert opinion. These two types are sometimes called "data-driven" and "knowledge-driven" models.

8.3 FUZZY LOGIC METHOD

Fuzzy logic is a "knowledge-driven" method of modelling. It is used in this chapter to combine different input maps. Fuzzy logic was introduced by Lotfi Zadeh of University of California at Berkeley in 1965 as a means to model the uncertainty of natural language. It is a superset of conventional Boolean logic. In Boolean logic, each fact or proposition, such as 'it will rain tomorrow,' must be either true or false. However fuzzy logic handles the concept of partial truth -- truth values between "completely true" and "completely false". Much of the information that people use about the world involves some degree of uncertainty. Like probability theory, fuzzy logic attaches numeric values between 0 and 1 to each proposition in order to represent uncertainty. Whereas probability theory measures how likely the proposition is to be correct, fuzzy logic measures the degree to which the proposition is correct. For example, the proposition 'person A is tall' may have a degree of correctness of 0.8. In fuzzy logic the degree to which an object matches a certain category is considered and can be measured. Set theory is used to manipulate such information mathematically and by computers. In set theory, the membership of an object or element can be defined as "true=1", or "false=0". In other words, an object belongs to a certain set or it does not. However, the membership of a fuzzy set can be expressed on a continuous scale from 1 (full membership) to 0 (full non-membership) (Zadeh, 1965, Zimmermann, 1991, Li and Yen, 1995). In this way in the fuzzy logic

method, it is possible to have gradations for the membership to a certain set (Klir and Yuan, 1995, Bonham-Carter, 1994). For instance, membership of geochemical samples to the set of anomaly samples can be defined by a fuzzy membership. Very high values of a certain element can be anomalous, with a fuzzy membership of 1; and very low values at or below background have a fuzzy membership of 0. Between these two extremes, a range of possible membership values exists.

In some cases, an analytical function might be expressed for fuzzy membership values for different ranges of the variable (x). For example, for a certain case, it can be defined as:

$$\mu(x) = \begin{cases} 0 & \text{if } x < 50 \\ (x-50)/250 & \text{if } 50 < x < 250 \\ 1 & \text{if } x > 250 \end{cases}$$

Here x can be the concentration value of an element and $\mu(x)$ is the fuzzy membership of geochemical samples that introduces the relationship of samples to the set of anomaly samples. The shape of the function need not be linear as the above example. It can take on any analytical or arbitrary shape appropriate to the problem at hand (Bonham-Carter, 1994). In many cases in geosciences, it may not be possible to find such a mathematical function to introduce the memberships. Instead, fuzzy membership functions can be expressed as lists of tables of numbers. Such a table includes the fuzzy membership value for each class of a map. In this case, instead of a continuous function, a discrete function is used to represent the fuzzy membership values. For example, a table of fuzzy membership values for classes of a geochemical map can be

as shown in Table 2. In Table 2, to each class representing a certain level of an element, a fuzzy membership value is assigned.

Table 2. An example of fuzzy membership values for classes of a geochemical map.

MAP CLASS (x)	ELEMENT CONCENTRATION (ppm)	FUZZY MEMBERSHIP $\mu(x)$
1	>320	1
2	320-280	0.85
3	280-200	0.5
4	200-85	0.3
5	85-20	0
6	<20	0

In the fuzzy logic method, the level of measurement of the mapped variable can be nominal, ordinal or interval. There are no practical constraints on the choice of fuzzy membership values (Bonham-Carter, 1994). Values must be chosen to reflect the degree of membership to a certain set. It can be based on subjective judgement. The fuzzy membership values reflect the relative importance of each map, as well as the relative importance of each class of a single map (Bonham-Carter, 1994).

8.3.1 COMBINING FUZZY MEMBERSHIP VALUES

Different operators can be employed to combine the fuzzy membership values of several maps together. Bonham-Carter (1994) and An *et al.* (1991) have discussed 5 operators that were found to be useful for combining exploration datasets, namely fuzzy “AND”, fuzzy “OR”, fuzzy algebraic product, fuzzy algebraic sum and fuzzy gamma operators.

8.3.1.1 FUZZY “AND”

Fuzzy “AND” is equivalent to a Boolean “AND” (logical intersection) operation. It is defined as:

$$\mu_{\text{combination}} = \text{Min} (\mu_A, \mu_B, \mu_C, \dots)$$

where at a particular location on the input maps, μ_A is the membership value for map A, μ_B is this values for map B and so on.

For example for a certain location, if the membership value for map A is 0.80 and for map B is 0.4, then the membership value for the combination by fuzzy “AND” is 0.4 which is the minimum of these numbers. Applying fuzzy “AND” results in a conservative estimate of set membership, with a tendency to produce small values.

8.3.1.2 FUZZY “OR”

Fuzzy “OR” is like the Boolean “OR” (logical union). In fuzzy “OR”, the output membership values are controlled by the maximum values of any of the input maps for any particular location; therefore, it is an “optimistic” operator. It is defined as:

$$\mu_{\text{combination}} = \text{Max} (\mu_A, \mu_B, \mu_C, \dots)$$

8.3.1.3 FUZZY ALGEBRAIC PRODUCT

Fuzzy algebraic product is defined as the product of all the membership values at a certain location:

$$\mu_{\text{combination}} = \prod_{i=1}^n \mu_i$$

where μ_i is the fuzzy membership value for the i-th map. The combined fuzzy membership value by this operator tends to be very small, due to multiplying several numbers that are less than 1. The output is always smaller than, or equal to, the smallest membership value. For a certain location, with the membership value of 0.8 for map A and 0.4 for map B, the fuzzy algebraic product is $0.8 \times 0.4 = 0.32$ which is smaller than both.

8.3.1.4 FUZZY ALGEBRAIC SUM

Although the fuzzy algebraic product is simply an algebraic product, the fuzzy algebraic sum is not an algebraic sum. This operator is defined as:

$$\mu_{\text{combination}} = 1 - \prod_{i=1}^n (1 - \mu_i)$$

Here the $\mu_{\text{combination}}$ is always larger, or equal to, the largest contributing fuzzy membership value. Here two pieces of evidence that both favour a hypothesis reinforce one another and the combined evidence is more supportive than either piece of evidence taken individually (Bonham-Carter, 1994). For example for two maps, if at a certain location the membership value of map A is 0.8 and for map B it is 0.4, then the fuzzy algebraic sum will be: $1 - (1-0.8) \times (1-0.4) = 0.88$ which is larger than both.

8.3.1.5 GAMMA OPERATION

In many situations, a combined fuzzy membership that is between the two “decreasing” and “increasing” cases is needed. The fuzzy gamma operator allows the degree of “AND” and “OR” to be parameterised and is among many fuzzy compensating operators that return results greater than the intersection and less than union operators (Zimmermann, 1991). The advantage of the gamma operator is that when one or more data sets indicating strong possibilities and others very weak possibilities, the resulting aggregation can produce possibilities somewhere between the extremes, with the degree of compensation controlled by the magnitude of the gamma parameter (Wright and Bonham-Carter, 1996).

Gamma operator is a combination of fuzzy algebraic product and fuzzy algebraic sum. This operator is defined as:

$$\mu_{\text{combination}} = (\text{fuzzy algebraic sum})^{\gamma} \cdot (\text{fuzzy algebraic product})^{(1-\gamma)}$$

where γ is a parameter chosen in the range of (0,1). With $\gamma = 1$, the combination is the same as fuzzy algebraic sum and with $\gamma = 0$, it is equal to fuzzy algebraic product. Judicious choice of γ produces output values that ensure a flexible compromise between the “increasing” tendencies of the fuzzy algebraic sum and the “decreasing” effects of the fuzzy algebraic product (Bonham-Carter, 1994). For example, if $\gamma = 0.7$, then the combination of 0.8 and 0.4 as the membership values of map A and B at a certain location, will be $0.88^{0.7} \times 0.32^{(1-0.7)} = 0.65$ which is between 0.8 and 0.4. Figure 1 shows the effect of variations in $\mu_{\text{combination}}$ for different values of γ . The “increasing” effects of large γ values has been best seemed to reflect the subjective decision-makings in the typical exploration projects (Bonham-Carter, 1994).

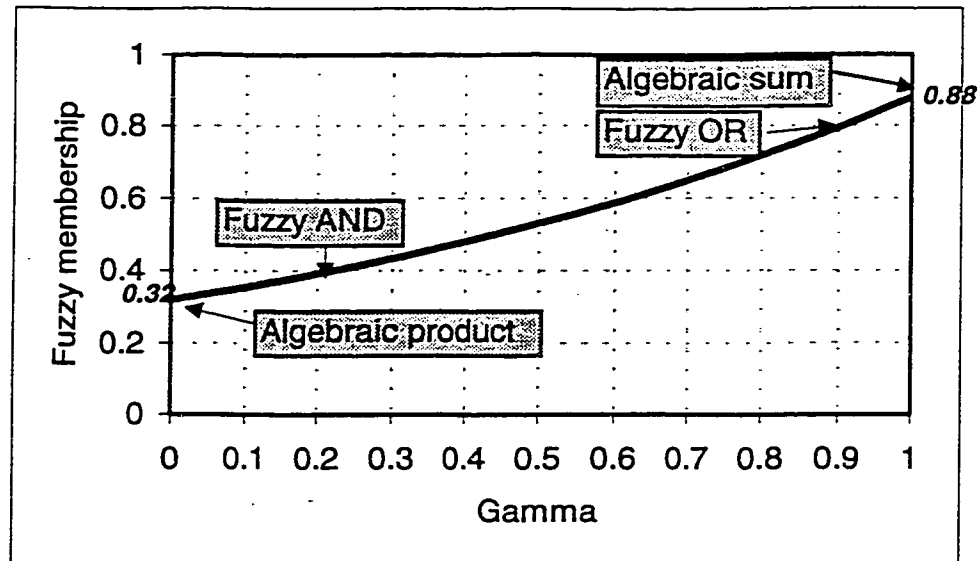


Figure 1. Variations of the combined fuzzy membership values ($\mu_{\text{combination}}$) for different values of γ for the discussed example of $\mu_A = 0.8$ and $\mu_B = 0.4$.

8.4 INTEGRATION OF MAPS

Different scenarios can be prepared for integration of a certain number of “evidence” maps. Instead of combining all the maps in one step and by one operation, it is sometimes more appropriate to link together some maps to support an intermediate hypothesis (Bonham-Carter, 1994). The result of intermediate steps can be then combined with other “evidence” maps or the result of other intermediate steps to make the final favourability map. The inference network that summarises the combination of all “evidence” maps is shown in Figure 2. Each of the factor maps indicated in Figure 2 was created by combining several other maps as explained below. The final favourability maps were generated separately for different groups of geological units discussed in chapter 3 and 5.

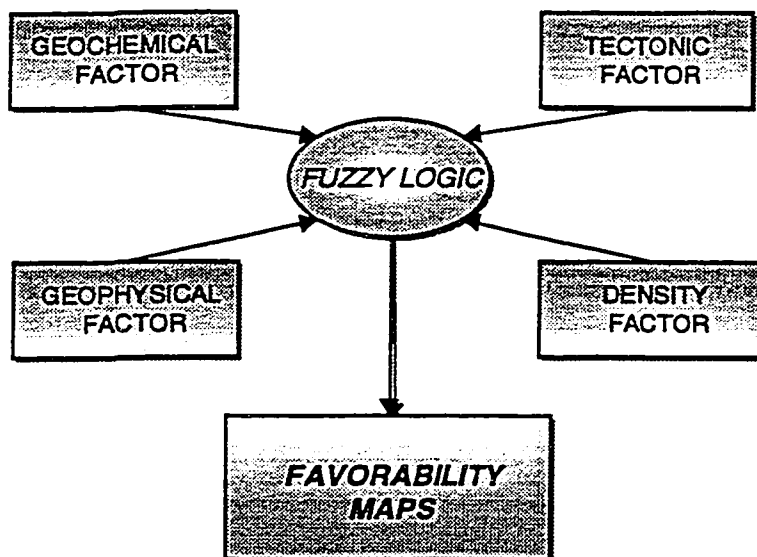


Figure 2. Generalised inference network to create favourability maps.

Unfortunately the fuzzy logic method of modelling does not have a formal method for calculating variance or other measures of error. A form of considering uncertainty in fuzzy logic can be by the membership values. Areas with fuzzy membership values close to 1 and close 0 can be considered as the most certain and those with fuzzy membership values near 0.5 can have the most uncertainty to be assigned into the two sets of potentially mineralized and unmineralized zones.

8.4.1 GEOCHEMICAL FACTOR

Figure 3 shows the geochemical factor of the generalised inference network shown in Figure 2. To create the geochemical factor, the highest fuzzy memberships were assigned to the factor map indicating the mineralization. For Guichon plutonic suite (EJgG), the map of discriminant analysis scores was also used to create the

geochemical factor map (Figure 3). In addition, the factor 3 and 4 were combined by fuzzy “OR”, only for Guichon plutonic suite (EJgG). For other geological units, the single identified factor indicating mineralization was used (Figure 3).

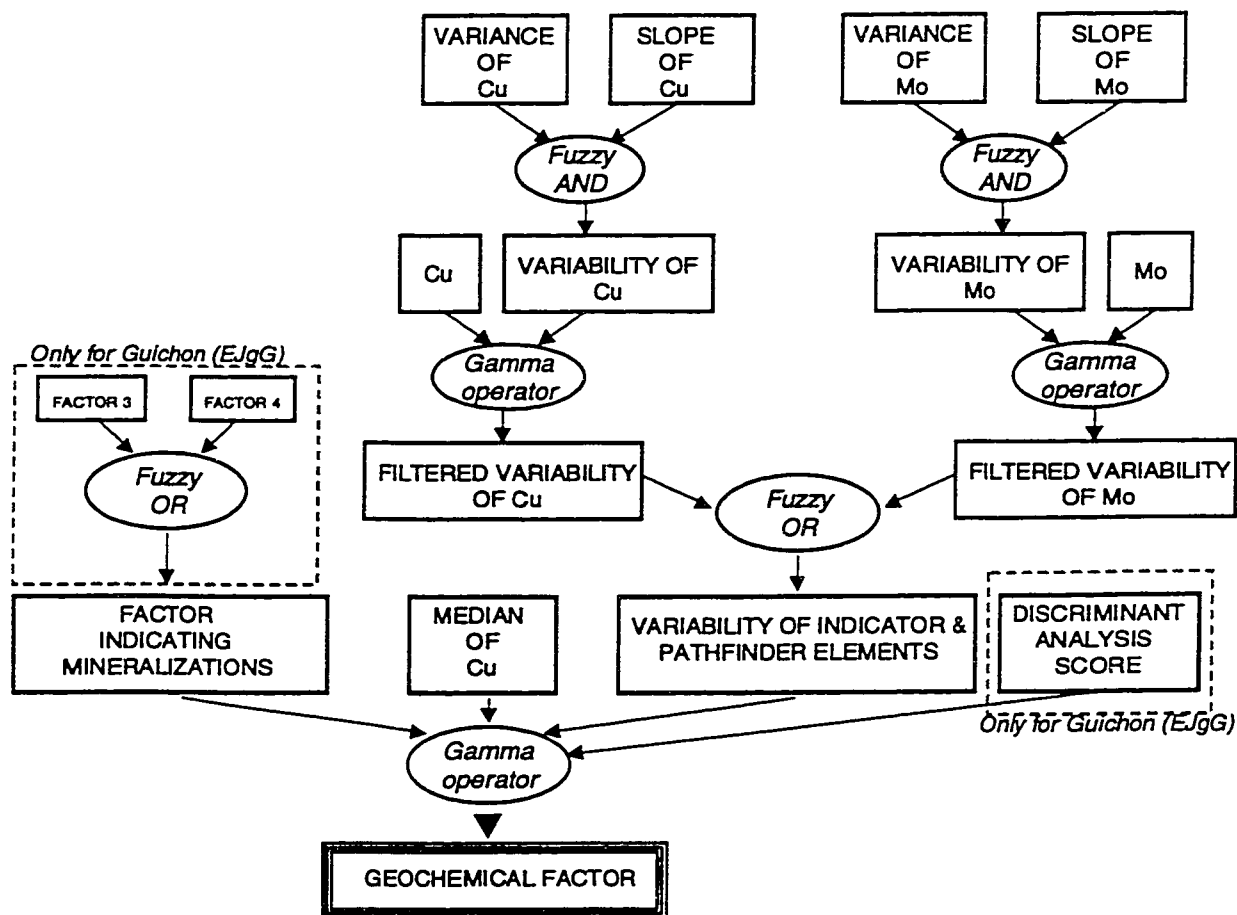
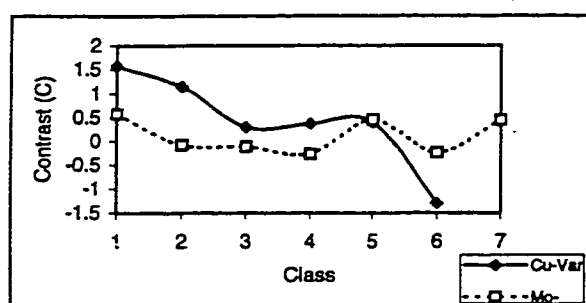


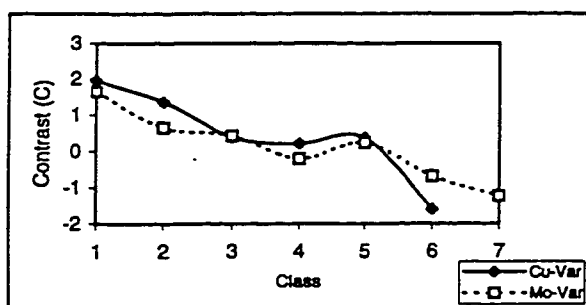
Figure 3. The inference network to generate the geochemical factor map.

In assigning fuzzy membership values to classes of the maps, used to generate the variability maps indicated in the inference network of Figure 3, different degrees of associations of porphyry Cu-Au, Cu-Mo and Mo with these maps were considered. To quantify these associations, weights of evidence and contrast (C) were calculated (Figure 4). Porphyry Cu-Au deposits show a high association with Cu and its variability

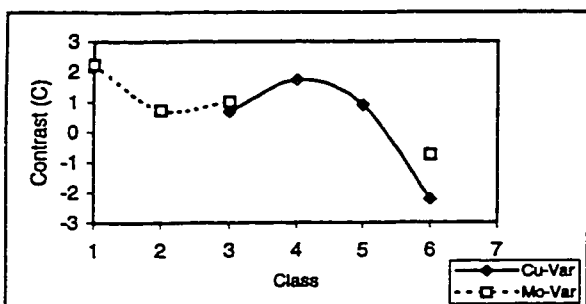
but not with Mo. It is vice versa for porphyry Mo deposits. Porphyry Cu-Mo deposits have high association with both Cu and Mo and their variabilities (Figure 4). Hence for Francois Lake (JKgF), Surprise Lake (LkqS), Topley (EJqT) and Bulkley Intrusions (LKgB), which host many porphyry Mo and/or Cu-Mo deposits, higher fuzzy membership values were assigned to classes of Mo and its variability maps than Cu. The slope and variance maps were combined by fuzzy “AND” to indicate the variability of Cu and Mo. To filter areas with high variability and high levels of Cu or Mo, the maps of these elements were combined by a fuzzy gamma operator ($\gamma = 0.9$) with high membership values only for high levels of Cu and Mo (Figure 3).



(a)



(b)



(c)

Figure 4. Variation of contrast (C) for different classes of Cu and Mo variance maps with a) porphyry Cu-Au deposits, b) porphyry Cu-Mo deposits, c) porphyry Mo deposits.

Finally, by combining the filtered variability maps of Cu and Mo by fuzzy “OR”, a map was created to represent the variability of both Cu and Mo as indicator and pathfinder elements. Such a map was generated separately for groups of geological units introduced in chapter 3. This was due to the slightly different fuzzy membership values used for Mo and its variability maps for the group of geological units indicated above. Variability of Cu and Mo maps created for different geological units were then combined to have one map for all the study area (Figure 5).

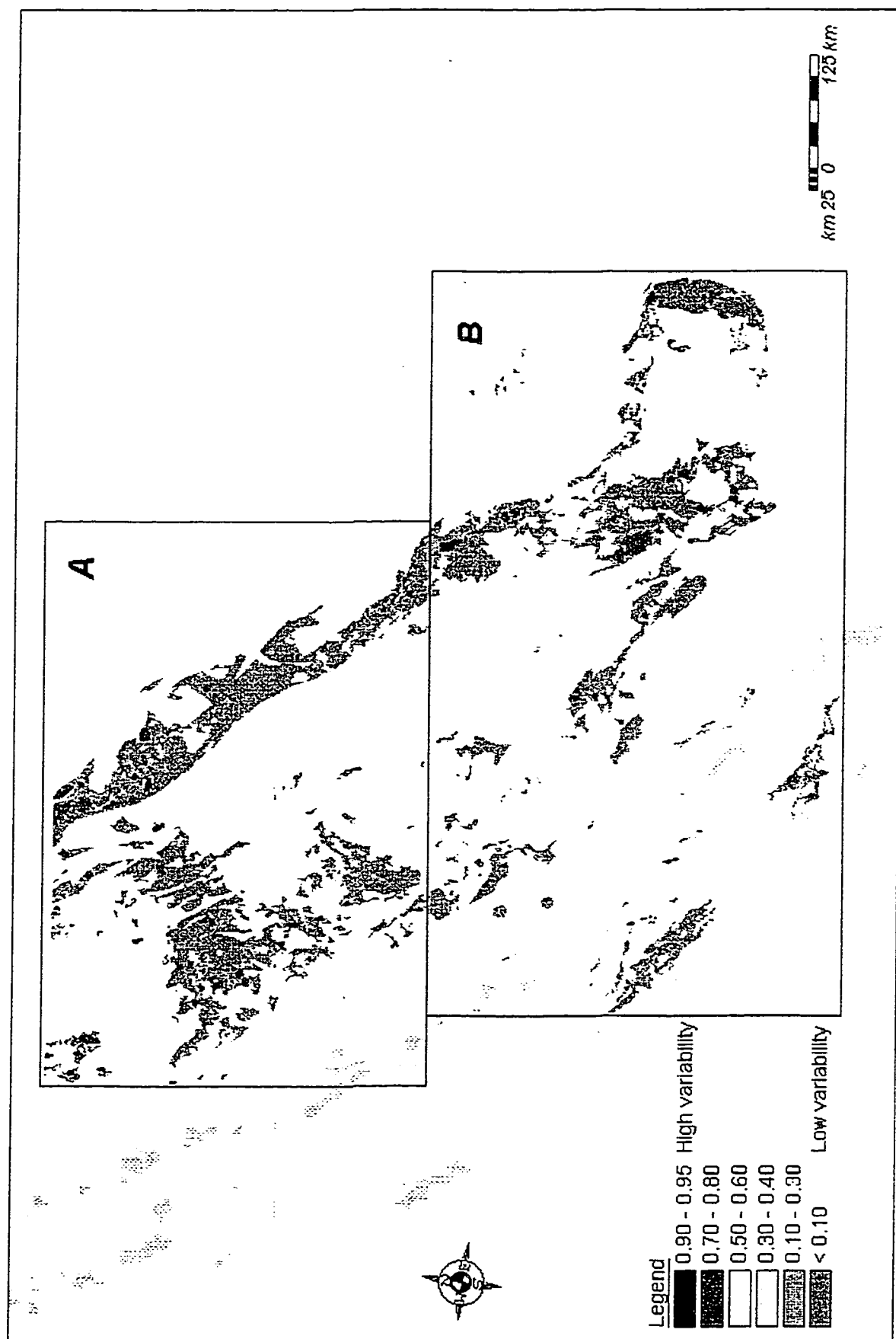


Figure 5. Combined variability of Cu and Mo in the geological units of the study area

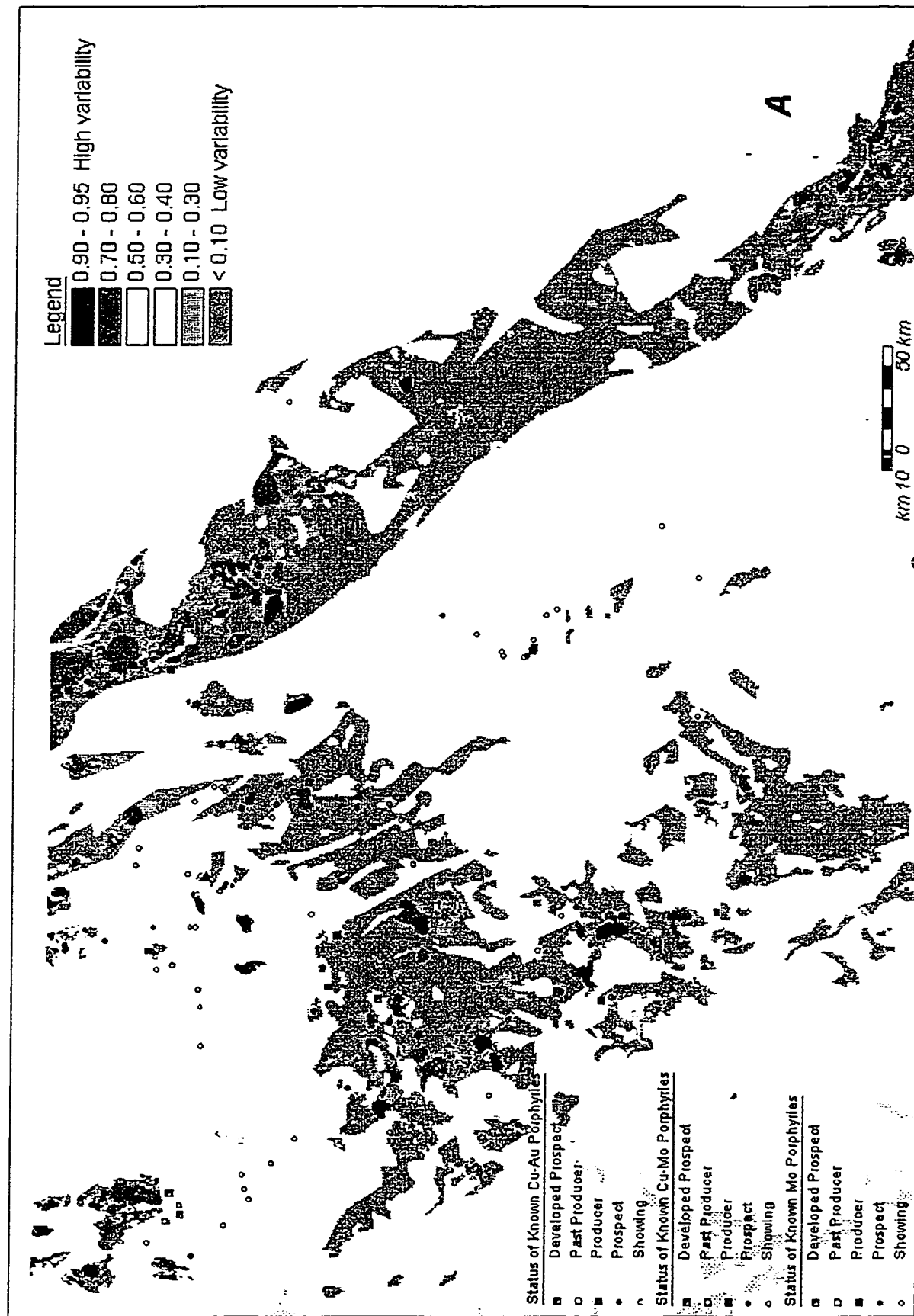


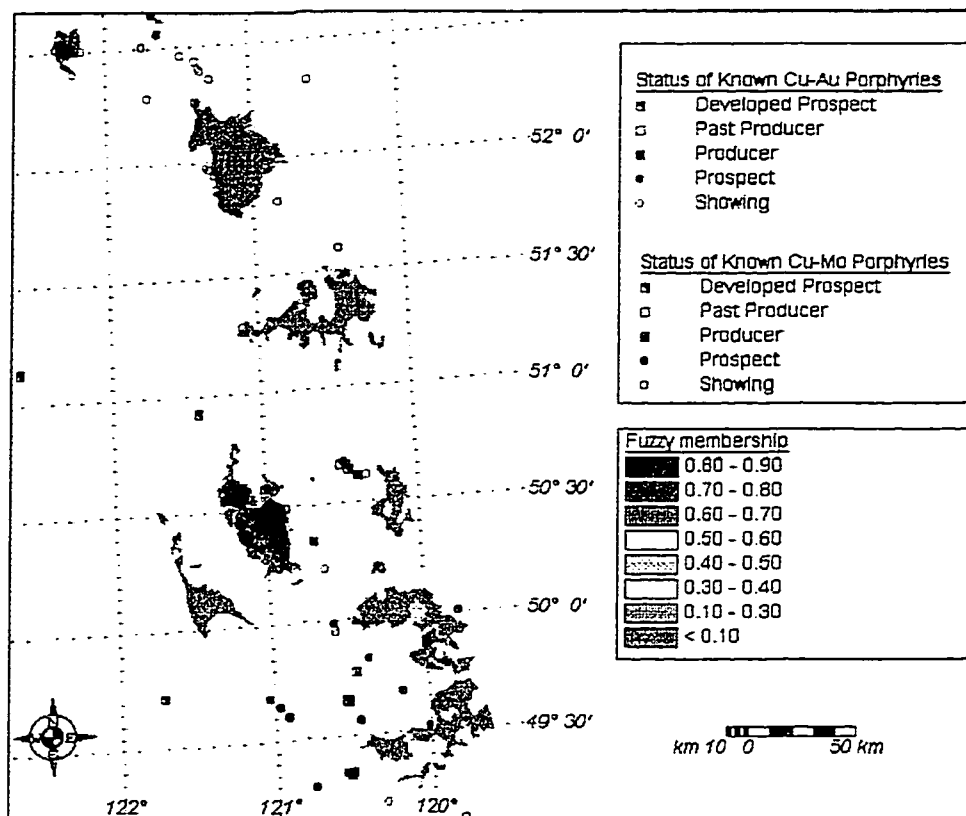
Figure 6. Combined variability of Cu and Mo zoomed in area A.



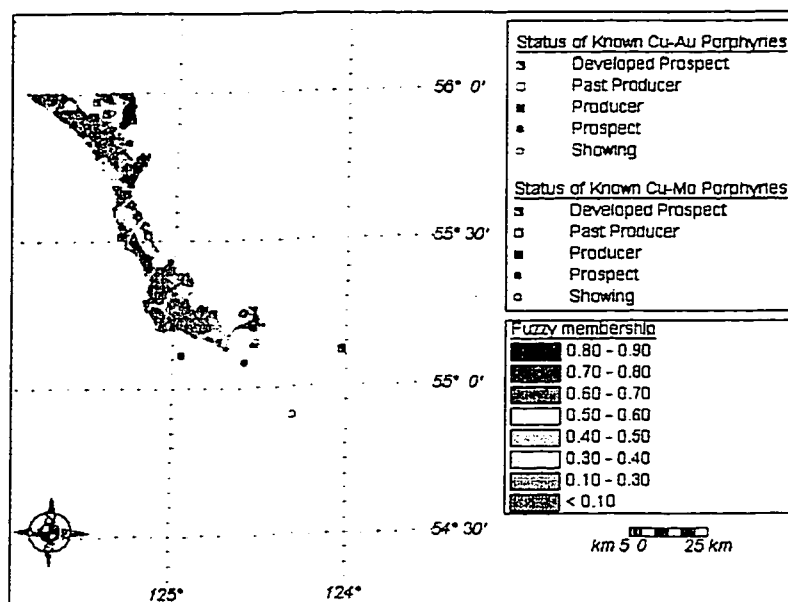
Figure 7. Zoomed variability of Cu and Mo zoomed in area B of Figure 5.

8.4.1.1 *GUICHON PLUTONIC SUITES (EJgG)*

In Guichon plutonic suite (EJgG), both factor 3 and 4 show mineralization. Therefore, these maps were combined by fuzzy “OR”. The result was used, as well as the other “evidence” maps indicated in the inference network of Figure 3, to generate the geochemical factor map Figure 8.



(a)



(b)

Figure 8. Geochemical factor for a) lower part and b) upper part of Guichon plutonic suite (EJgG).

8.4.1.2 BULKLEY (LKgB), FRANCOIS LAKE (JKgF), SURPRISE LAKE (Lkqs), TOPLEY (EJqT) PLUTONIC SUITES

The “evidence” maps used here to generate the geochemical factor for these geological units are factor 2 scores, median of Cu, and variability of Cu and Mo. These geological units host mainly porphyry Mo and Cu-Mo deposits in the study area. In combining them, higher fuzzy membership values were assigned to factor 2 scores map than other maps indicated in Figure 3. The generated geochemical factor for these geological units by using fuzzy gamma operator ($\gamma = 0.9$) is shown in Figure 9.

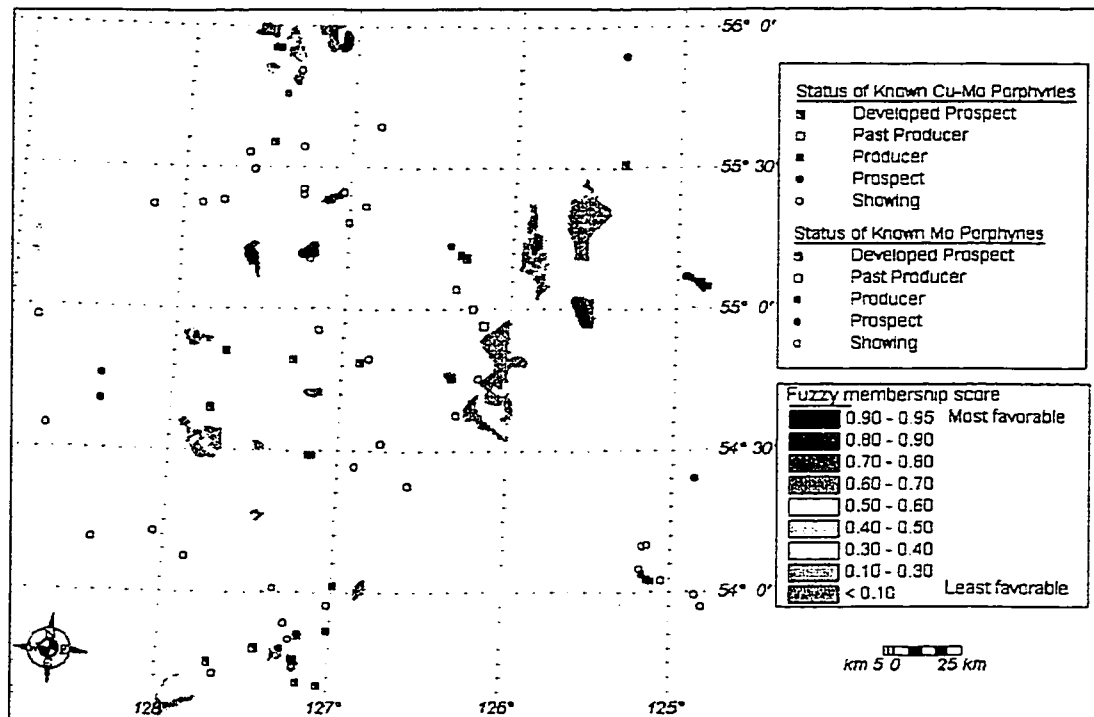
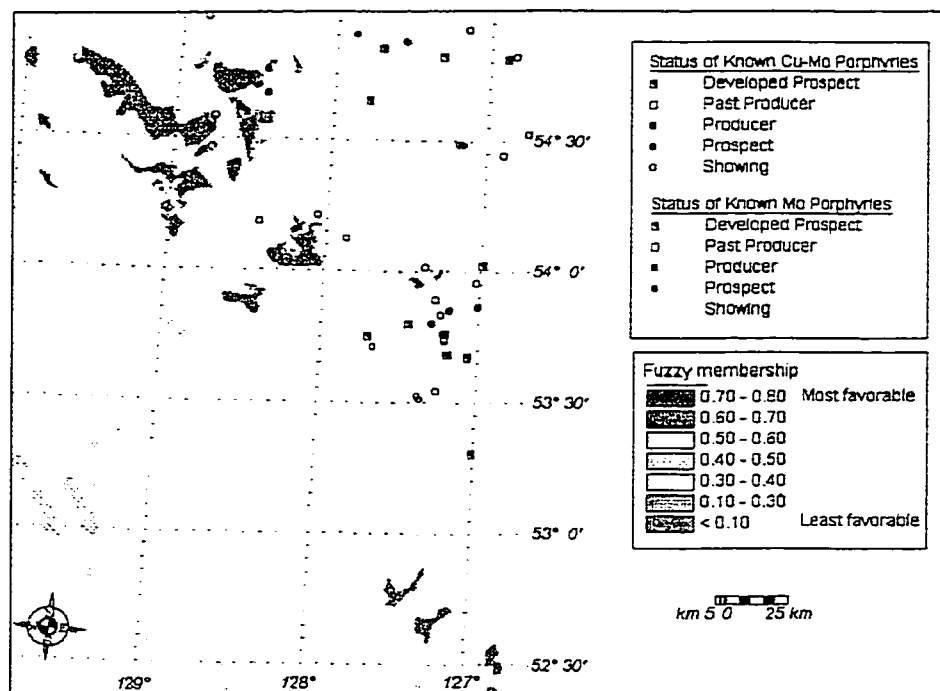


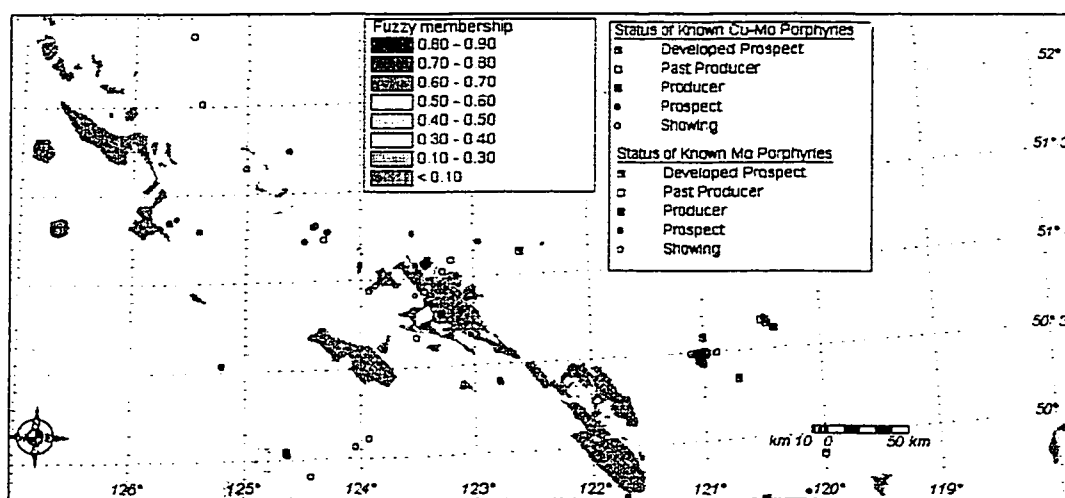
Figure 9. Geochemical factor for Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs), Topley (EJqT) plutonic suites.

8.4.1.3 LATE CRETACEOUS PLUTONIC SUITES (Lkg)

For Late Cretaceous plutonic suites (Lkg), the map of factor 2 scores was used to generate the geochemical factor as indicated in the Inference network of Figure 3.



(a)



(b)

Figure 10. Geochemical factor for a) upper part and b) lower part of Late Cretaceous plutonic suites (Lkg).

8.4.1.4 BONANZA ARC VOLCANICS (JB)

The geochemical factor map (Figure 11) was generated using factor 2 scores, median of Cu and the combined variability of Cu and Mo. In the area near the Island Copper mining camp, geochemical factor map has received a low level of favourability. This might be due to the lack of geochemical samples near this mining camp to indicate this mineralized area in the maps, which were used for creating the geochemical factor.

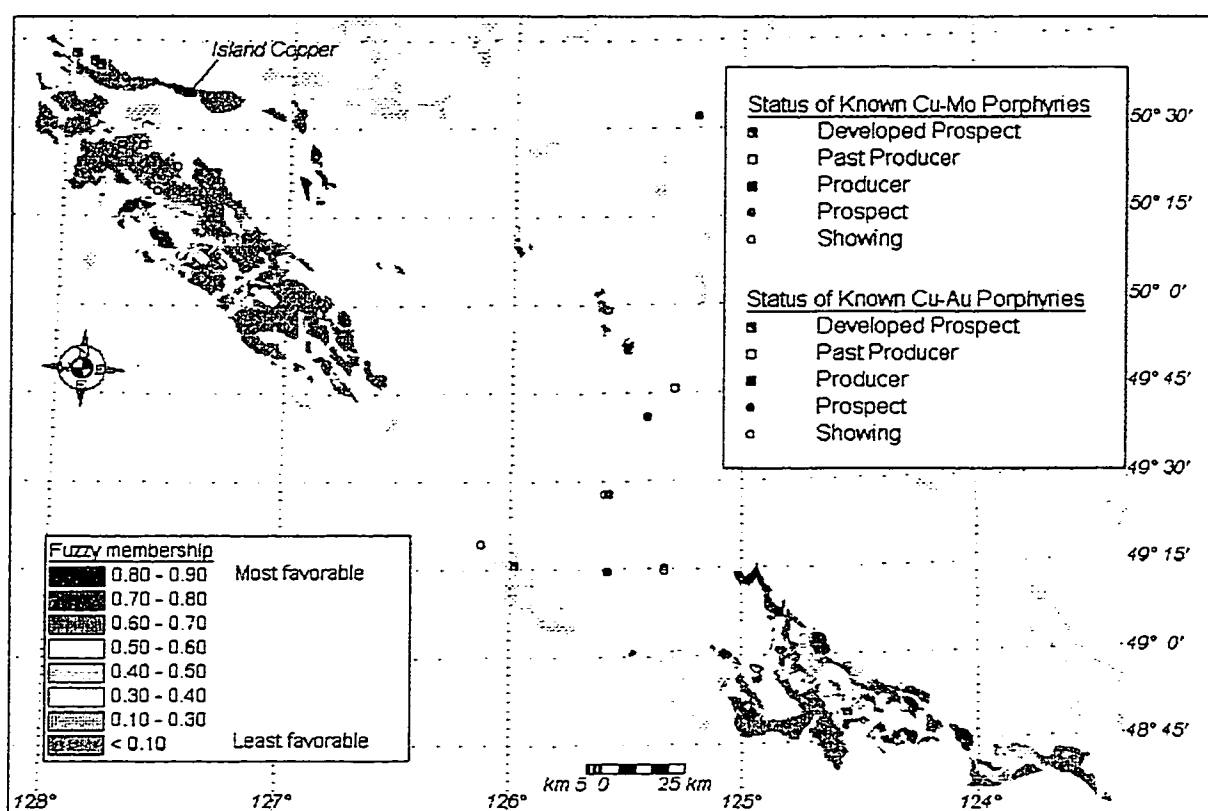


Figure 11. Geochemical factor for Bonanza (JB).

8.4.1.5 HAZELTON ARC VOLCANICS (JH)

For Hazelton (JH), the map of factor 3 was used to generate the map of geochemical factor as indicated in the inference network of Figure 3. The resulting geochemical factor map is shown in Figure 12.

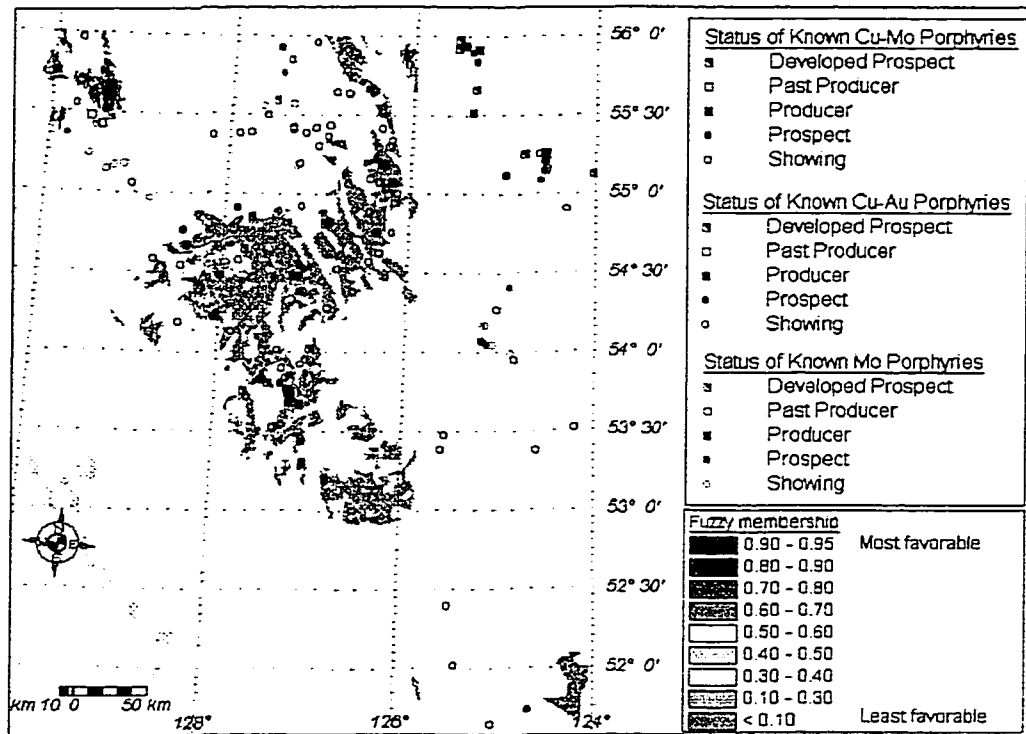


Figure 12. Geochemical factor for Hazelton arc volcanics (JH).

8.4.1.6 TAKLA & NICOLA ARC VOLCANICS (TrJ, TrJN)

For Takla and Nicola arc volcanics (TrJ, TrJN) the map of factor 3 could indicate the mineralizations. Therefore, this map was used with the other maps indicated in the inference network of Figure 3 to create the geochemical factor. As Figure 13 shows, in most cases, the known porphyry deposits are located inside the top classes of the created geochemical factor map.

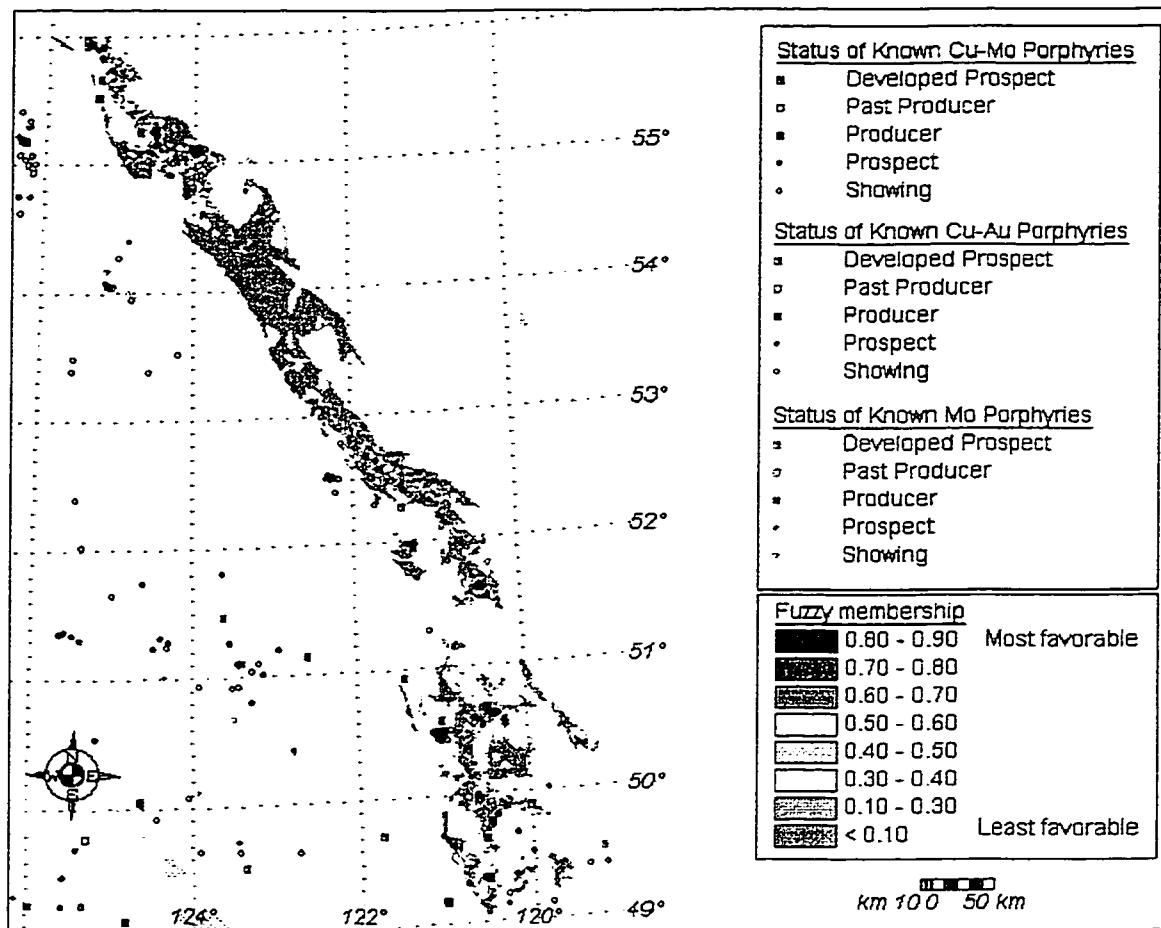


Figure 13. Geochemical factor for Takla and Nicola (TrJ, TrJN).

8.4.2 GEOPHYSICAL FACTOR

Figure 14 shows the inference network, which was used to combine the geophysical “evidence” maps. Two maps of residual total field magnetics and vertical gradient of magnetics were combined using fuzzy “AND”. Therefore, for the resulting map, fuzzy memberships are high wherever both residual total field magnetics and vertical gradient of magnetics are high. The resulting map was used as the geophysical factor map for all geological units of the study area except Takla and Nicola (TrJ, TrJN). In Takla, high

classes of vertical gradient of gravity have associations with the location of many porphyry Cu-Au deposits. This was also used as another “evidence” map beside the magnetics map for Takla and Nicola (TrJ, TrJN). As Figure 14 shows, vertical gradient of gravity map was combined by gamma operator with the resulting map from combination of magnetics maps. This map was used as the geophysical factor map for Takla and Nicola (TrJ, TrJN). Figure 15 shows the final geophysical factor map. It was created by joining the geophysical factor map, which was separately generated for Takla and Nicola (TrJ, TrJN), with the geophysical factor map of all other geological units.

As Figure 15, and 16 show, a few small parts of the geological units, mainly located in Coast Belt, are not covered by the geophysical maps. Consequently, for these parts no geophysical factor was entered into the final integration of all factor maps shown in Figure 2.

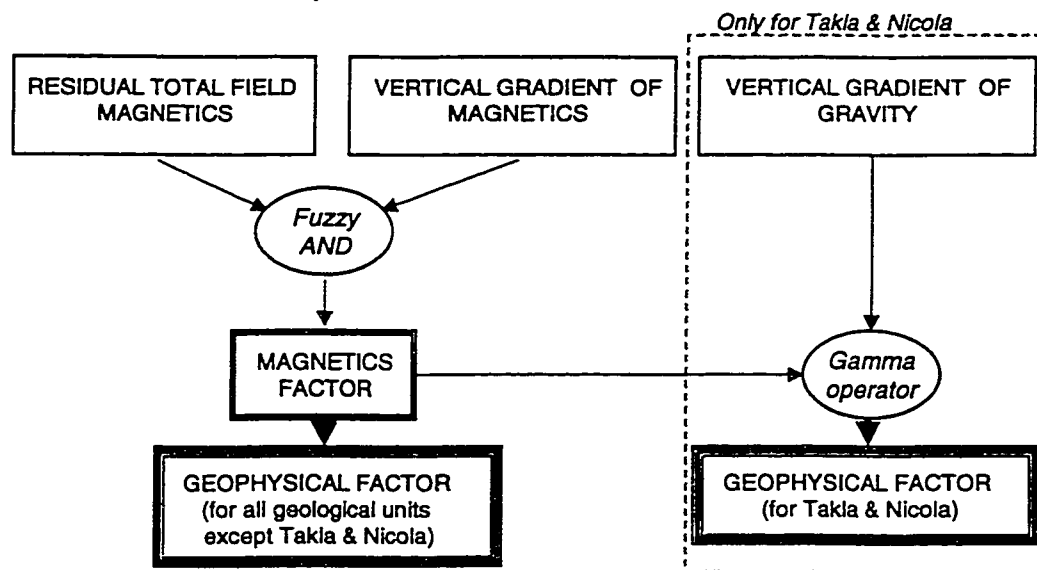


Figure 14. Inference network to create the geophysical factor map.

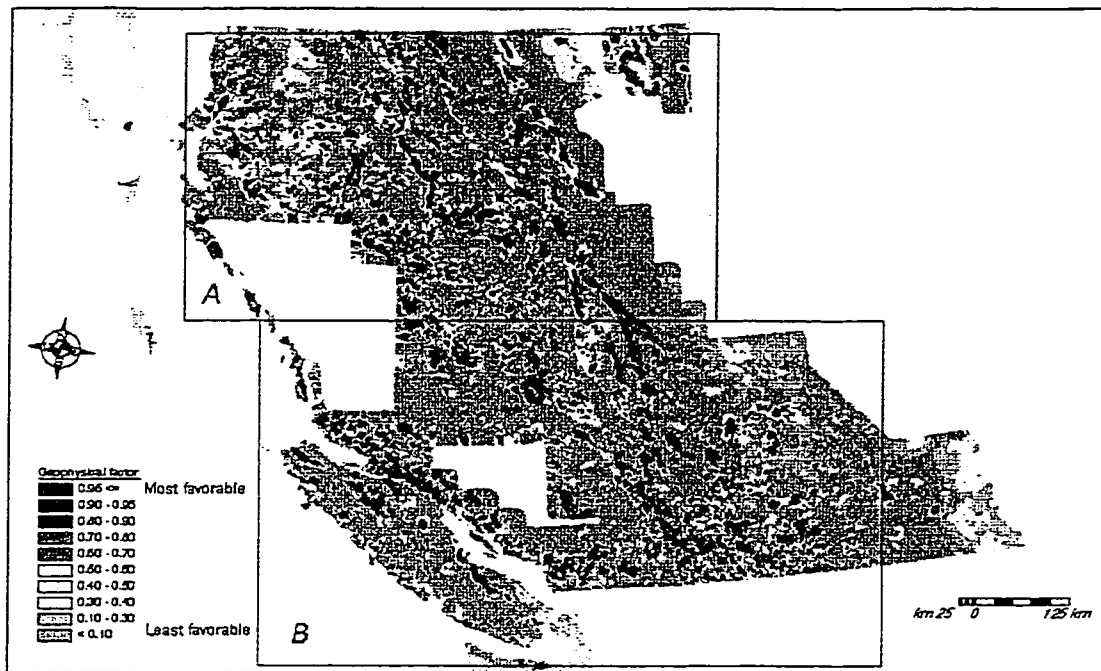


Figure 15. Geophysical factor map generated as explained in Figure 14.

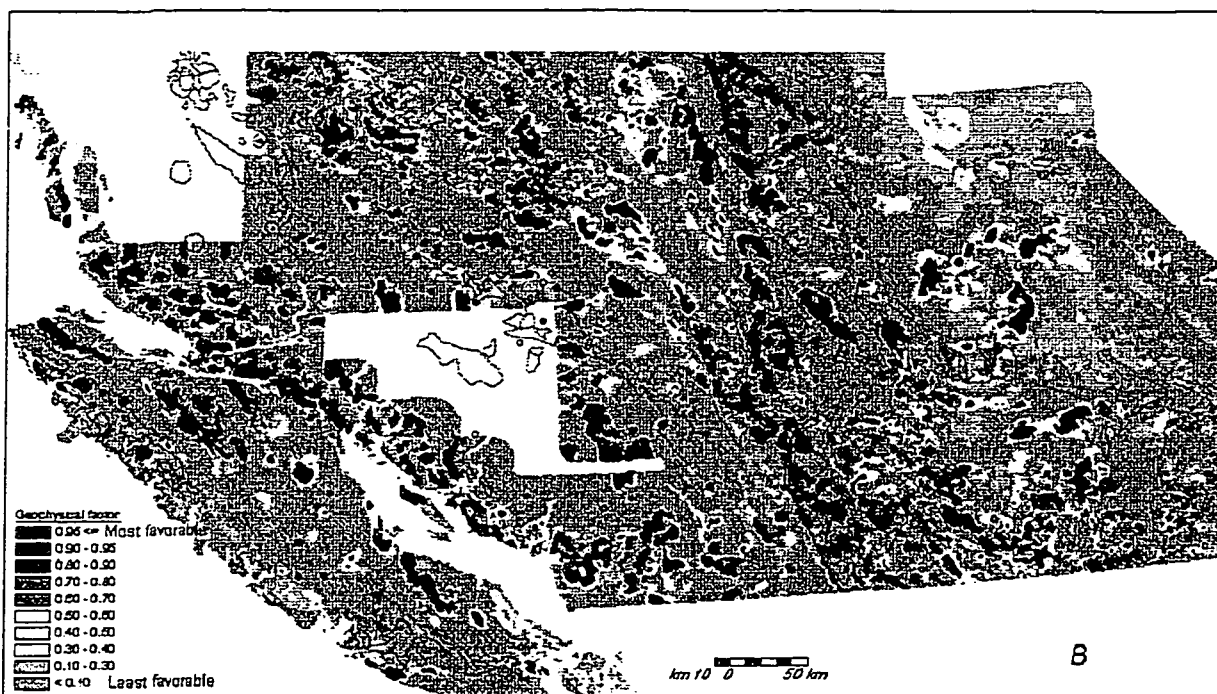
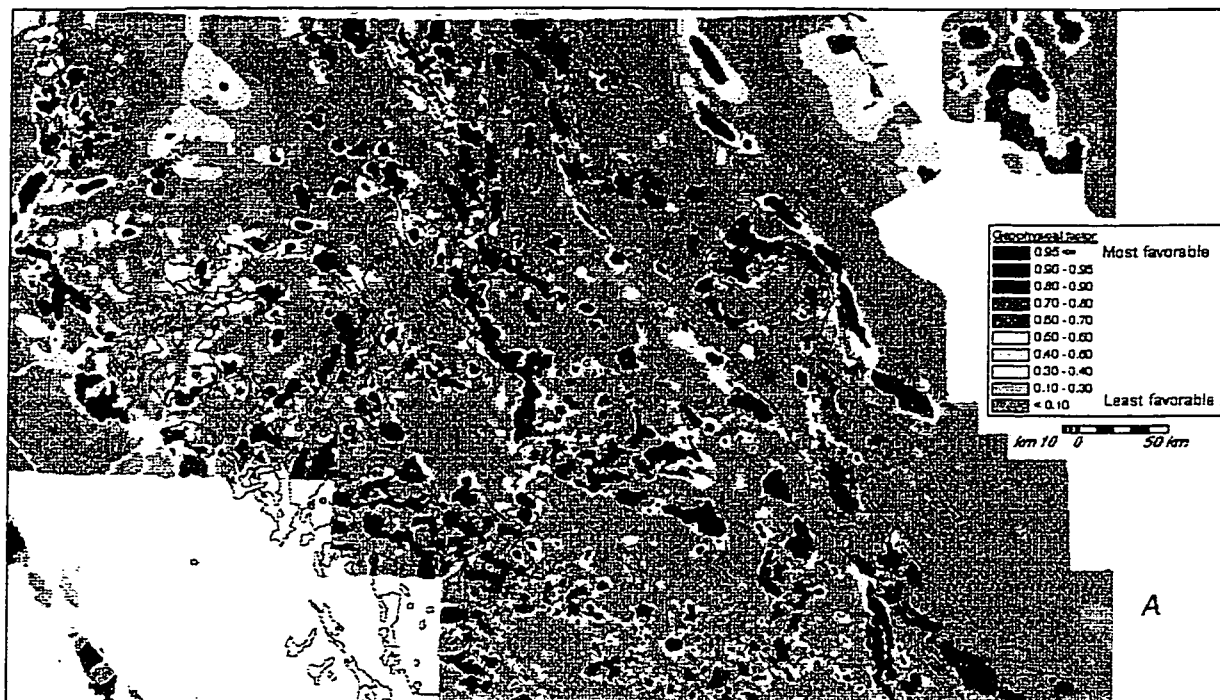


Figure16. Final geophysical factor map zoomed in A and B areas of Figure15.

8.4.3 ***TECTONIC FACTOR***

As discussed in chapter 7, 3 maps of proximity to faults, density of faults and proximity to intersection of faults are similar to each other and each can be considered as an “evidence” map. To create the tectonic factor map, these three maps were combined by fuzzy “OR”. Fuzzy “OR” assigns high memberships, wherever high classes of these three maps exist. The resulting tectonic factor map is shown in Figure 18 and 19. As Figure 19 shows, top classes of the tectonic factor map contains most of the known porphyry deposits with different status.

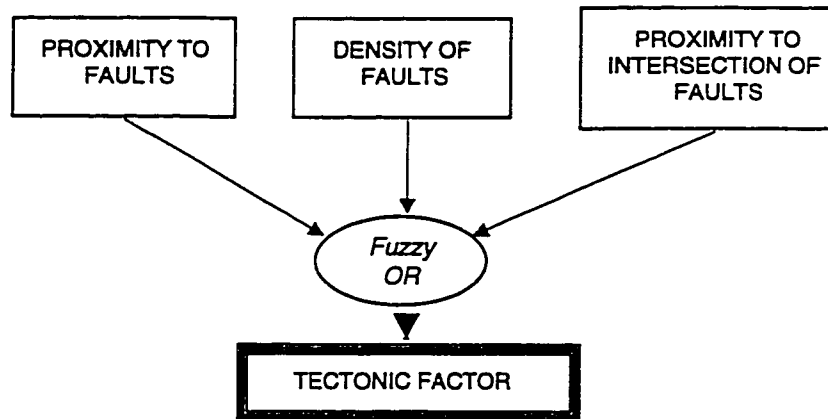


Figure 17. Inference network to create the tectonic factor.

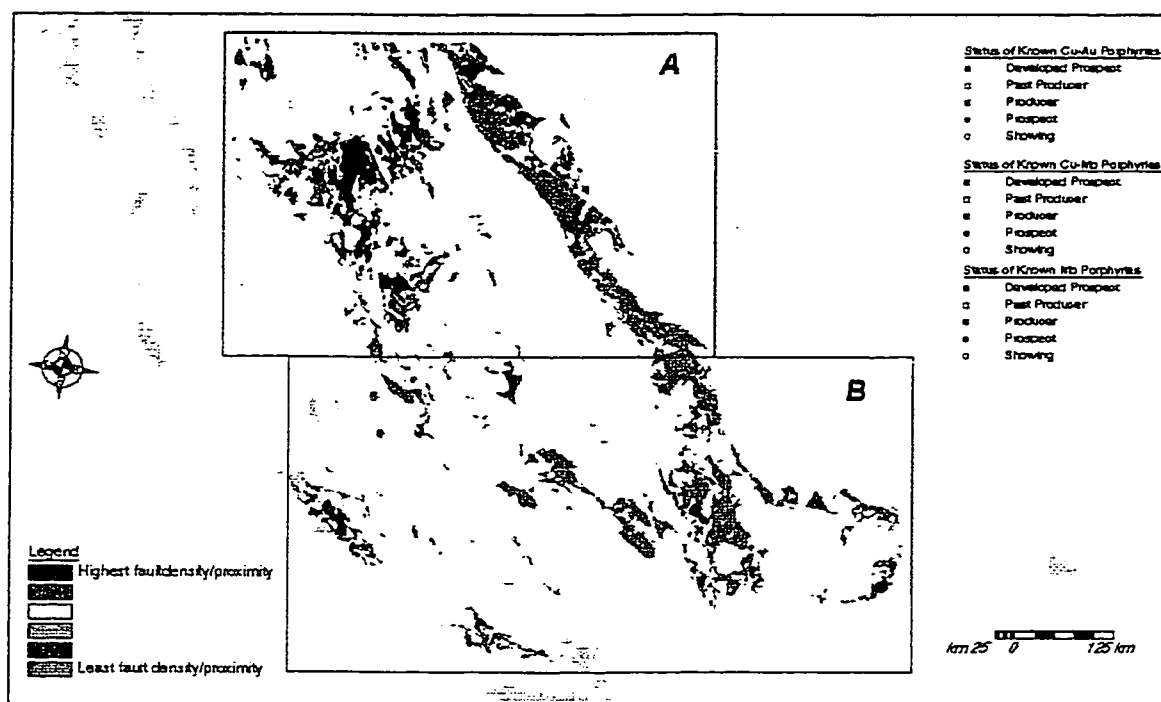


Figure 18. Tectonic factor map generated by combining three "evidence" maps by fuzzy OR.

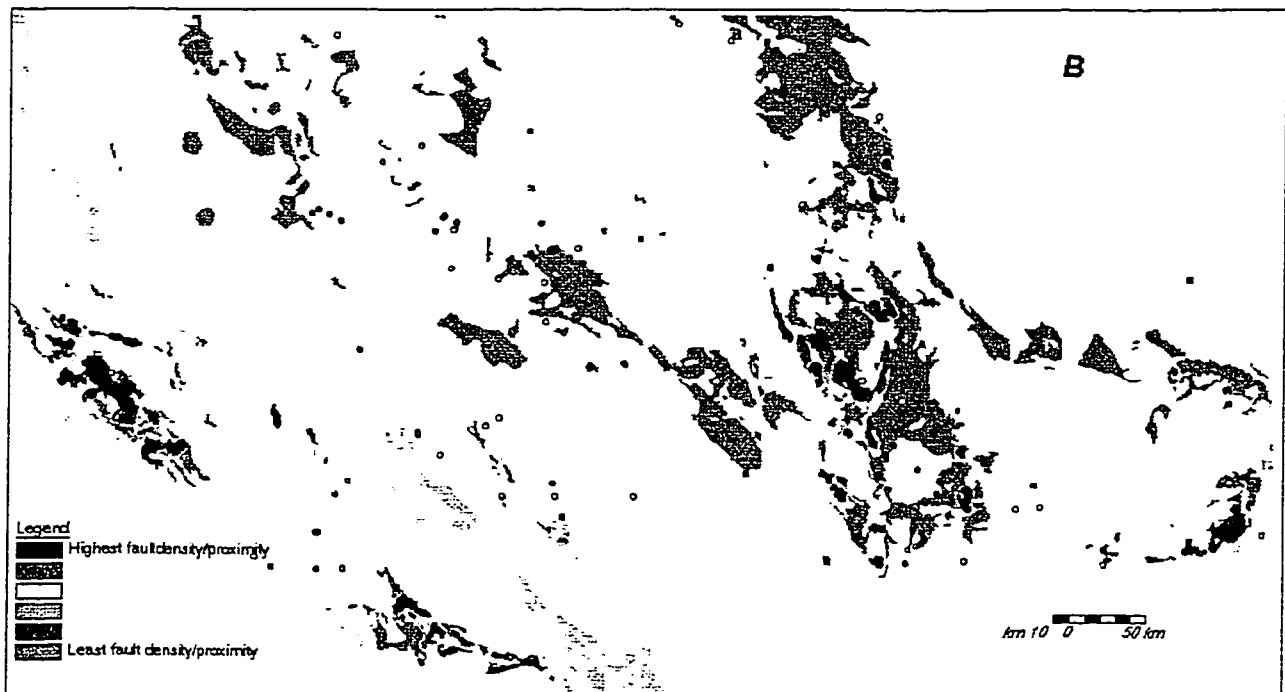
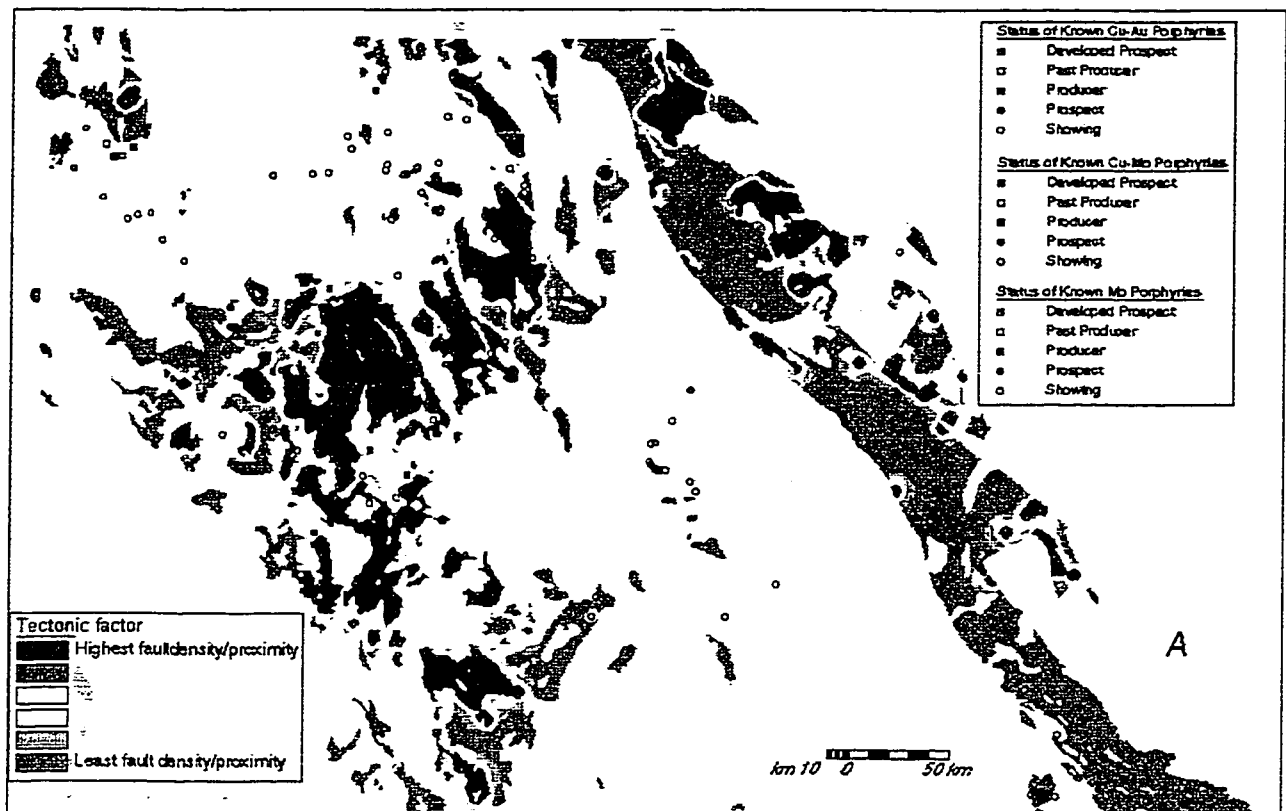


Figure 19. Tectonic factor map zoomed in the northern and southern part of the study area (A and B areas of Figure 18).

8.4.4 DISTRIBUTION OF KNOWN PORPHYRY DEPOSITS FACTOR (DENSITY FACTOR)

As discussed earlier in chapter 3, areas with high density for known porphyry deposits should receive high score in combining maps. To assign less weight where SHOWINGS are located, all known porphyry deposits with this status were separated and a density map was created only for SHOWINGS. Similarly, another density map was generated only for all known porphyry deposits with the status of PRODUCER, PAST PRODUCER, DEVELOPED PROSPECT and PROSPECT. Then these two density maps were combined by fuzzy "OR" to create the density factor (Figure 20). In the combination of Figure 20, smaller membership values were assigned to classes of SHOWINGS density map than the classes of the similar map but for PRODUCERS, PAST PRODUCERS, DEVELOPED PROSPECTS and PROSPECTS. The resulting map, which is used as the density factor, is shown in Figure 21. The distribution factor map received the least fuzzy membership values in combining all different factors for the final favourability maps.

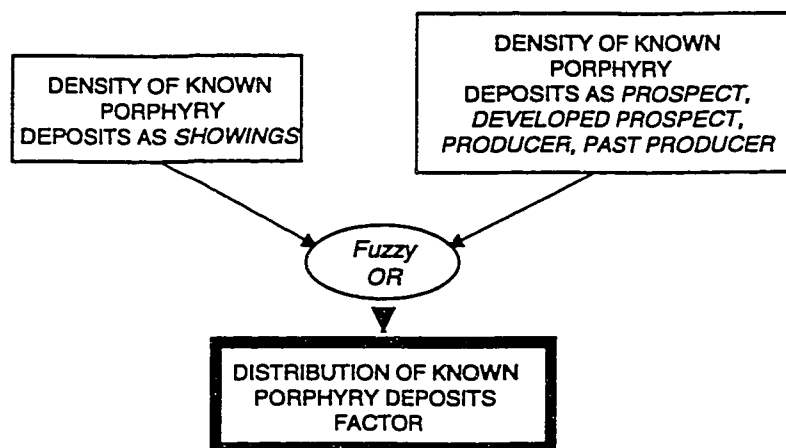


Figure 20. Inference network to create the distribution factor.

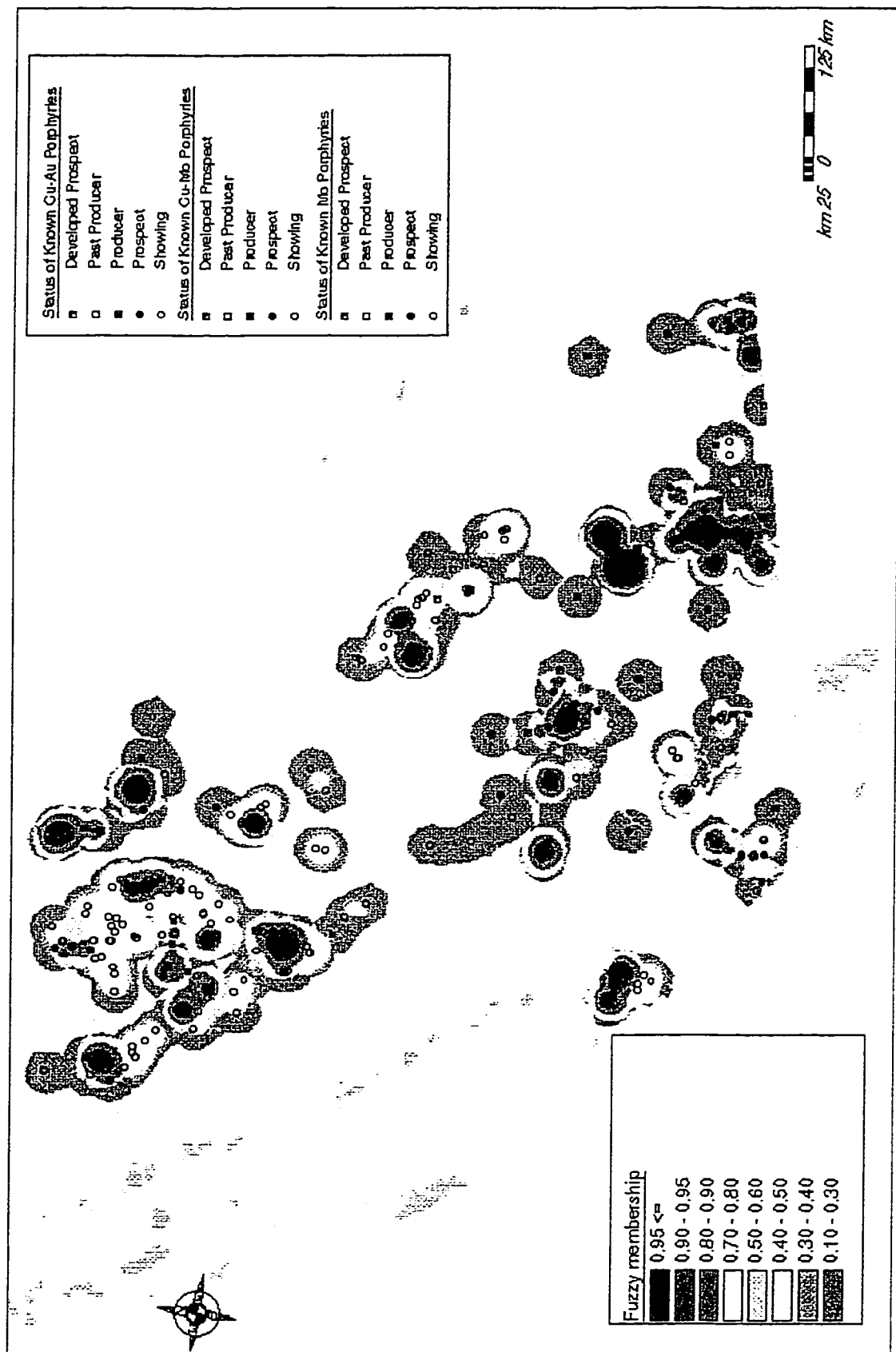


Figure 21. Density factor created by combining density of SHOWINGS and density of all other status types except SHOWINGS (with less fuzzy membership values for classes of SHOWINGS map).

8.4.5 INTEGRATION OF ALL FACTOR MAPS

The last step for creating the favourability maps for each geological units or groups of geological units of the study area was to combine all the generated factor maps by the gamma operator (Figure 22). In all cases in these combinations, the highest fuzzy membership values were assigned to top classes of geochemical factor and the least to density factor map (Appendix E).

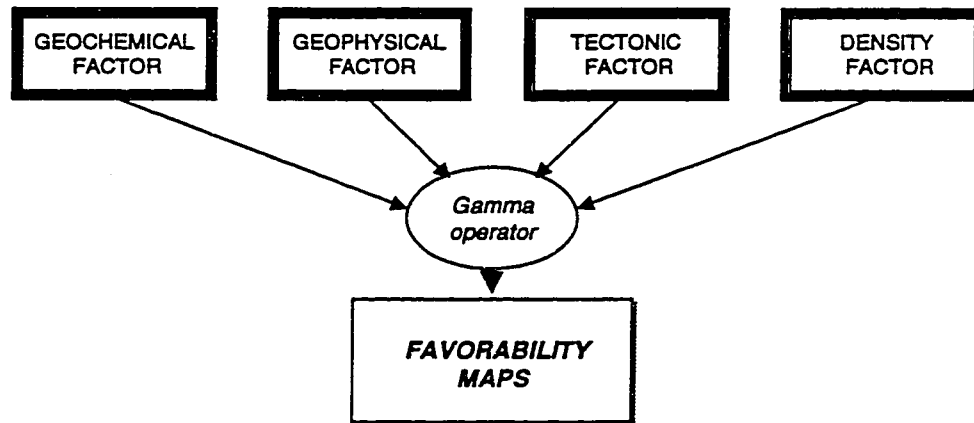


Figure 22. Inference network to create the favourability maps.

Slightly smaller fuzzy membership values were used for the classes of the geophysical factor map for the group of Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites (Appendix E). This was done because, they do not show very strong spatial association with magnetic maps for the porphyry Mo mineralized areas. In this step, for all combinations, a gamma of 0.95 was selected. Fuzzy membership tables used for different factor maps are shown in Appendix E. Figure 23 to 28 show the generated favourability maps for different geological units or groups of geological units of the study area. In most cases, known porphyry deposits of different status that are located inside the geological units of the study area are also located inside the promising areas predicted by favourability maps.

8.4.5.1 GUICHON PLUTONIC SUITE (EJgG)

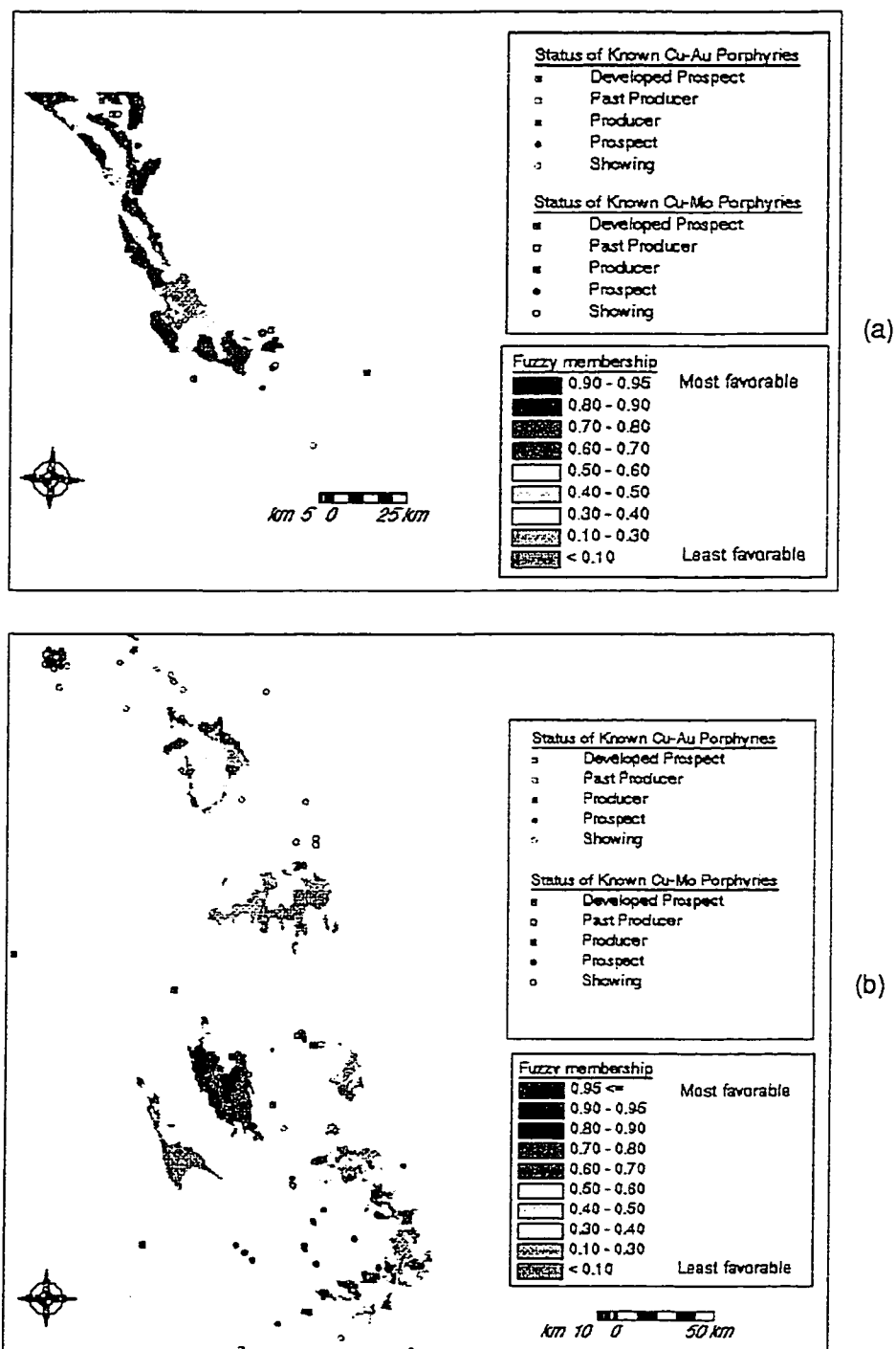


Figure 23. Favourability maps for a) northern and b) southern parts of Guichon plutonic suite (EJgG) created by combining all factors by gamma operator ($\gamma = 0.95$).

8.4.5.2 BULKLEY (LKgB), FRANCOIS LAKE (JKgF), SURPRISE LAKE (Lkqs), TOPLEY (EJqT) PLUTONIC SUITES

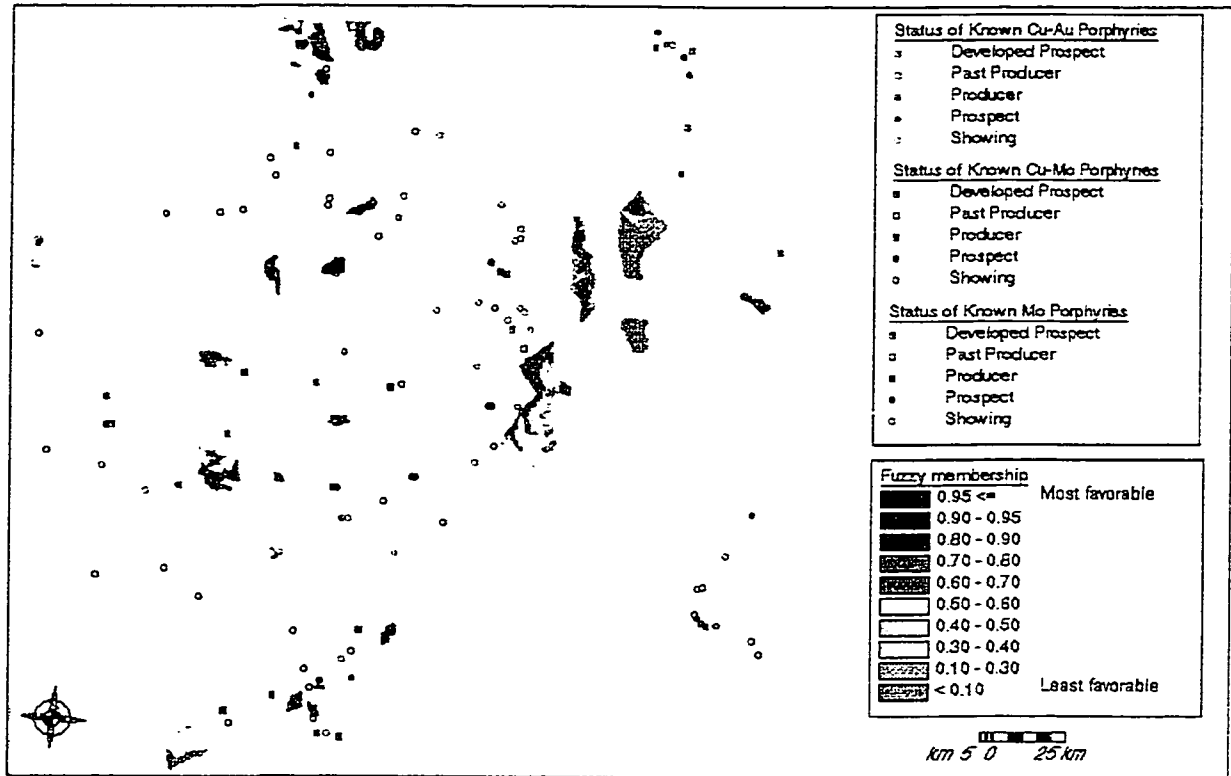
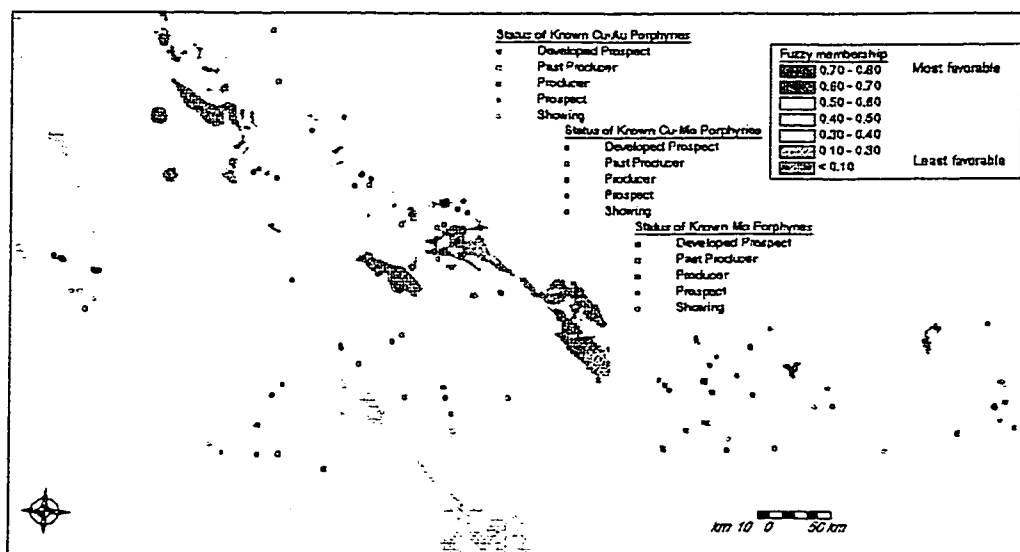
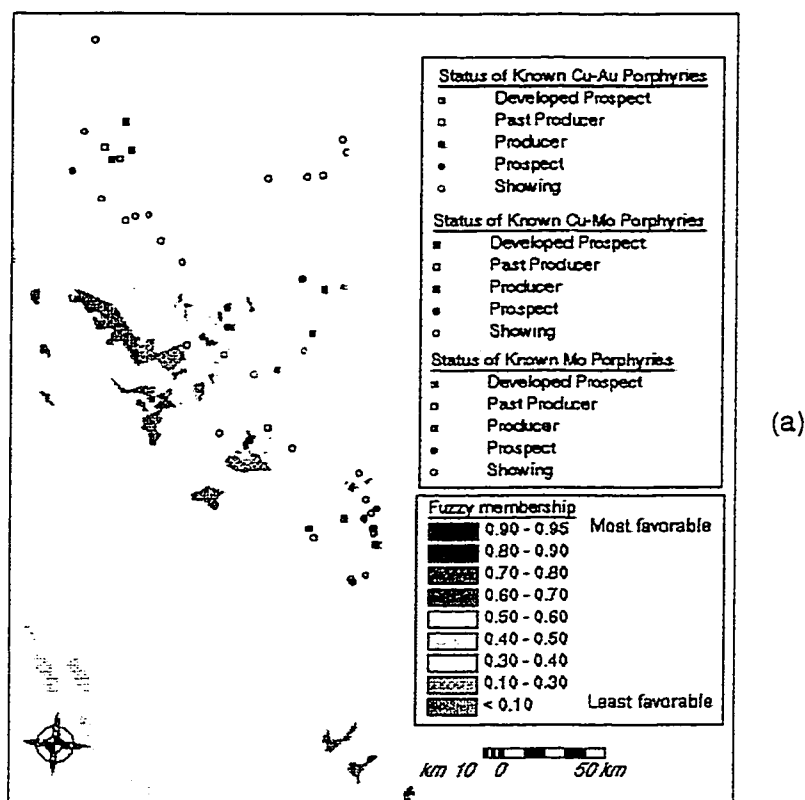


Figure 24. Favourability map for Bulkley (LKgB), Francois Lake (JKgF), Surprise Lake (Lkqs) and Topley (EJqT) plutonic suites created by combining all factors by gamma operator ($\gamma = 0.95$).

8.4.5.3 LATE CRETACEOUS PLUTONIC SUITE (Lkg)



(b)

Figure 25. Favourability maps of Late Cretaceous plutonic suite (Lkg) created by combining all factors by gamma operator ($\gamma = 0.95$) in a) northern and b) southern part of study area.

8.4.5.4 BONANZA ARC VOLCANICS (JB)

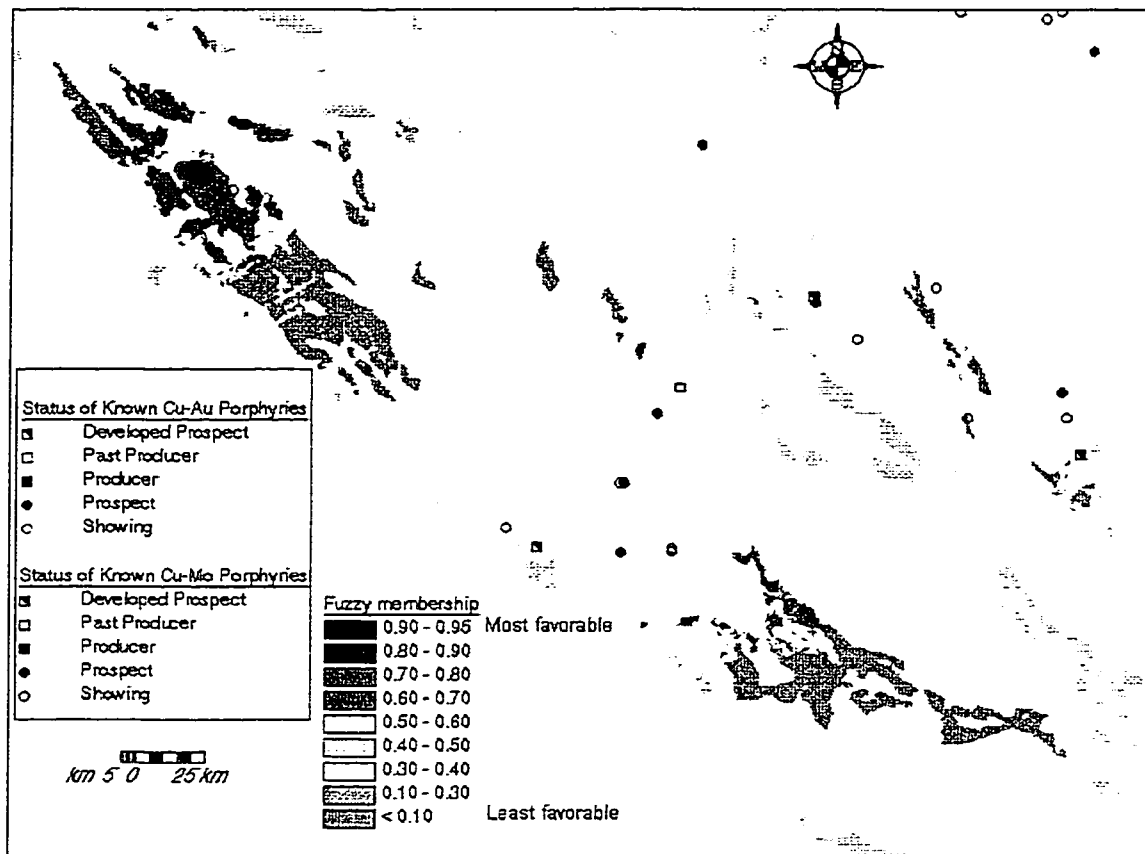


Figure 26. Favourability map of Bonanza (JB) created by combining all factors by gamma operator ($\gamma = 0.95$).

8.4.5.5 HAZELTON ARC VOLCANICS (JH)

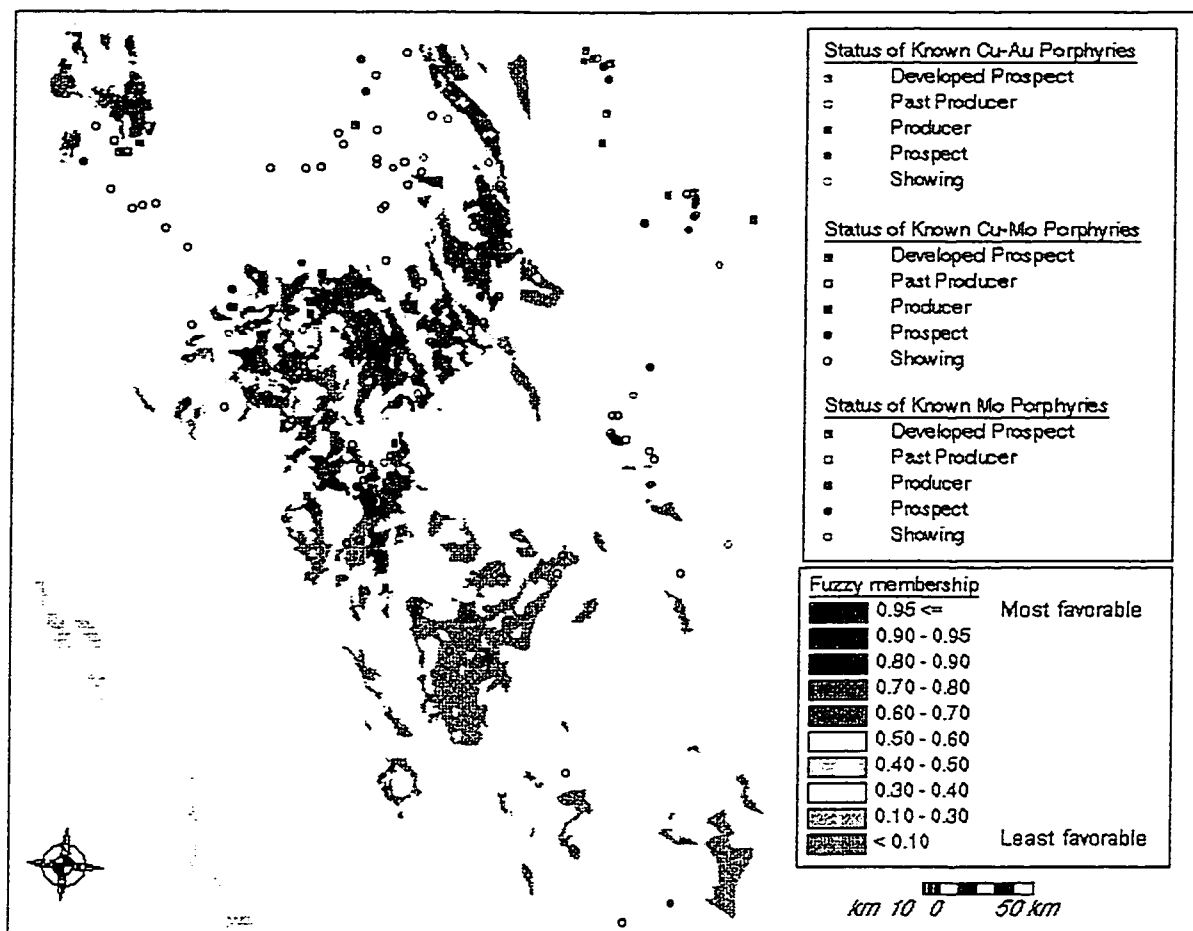


Figure 27. Favourability map of Hazelton (JH) created by combining all factors by gamma operator ($\gamma = 0.95$).

8.4.5.6 TAKLA & NICOLA ARC VOLCANICS (TrJ, TrJN)

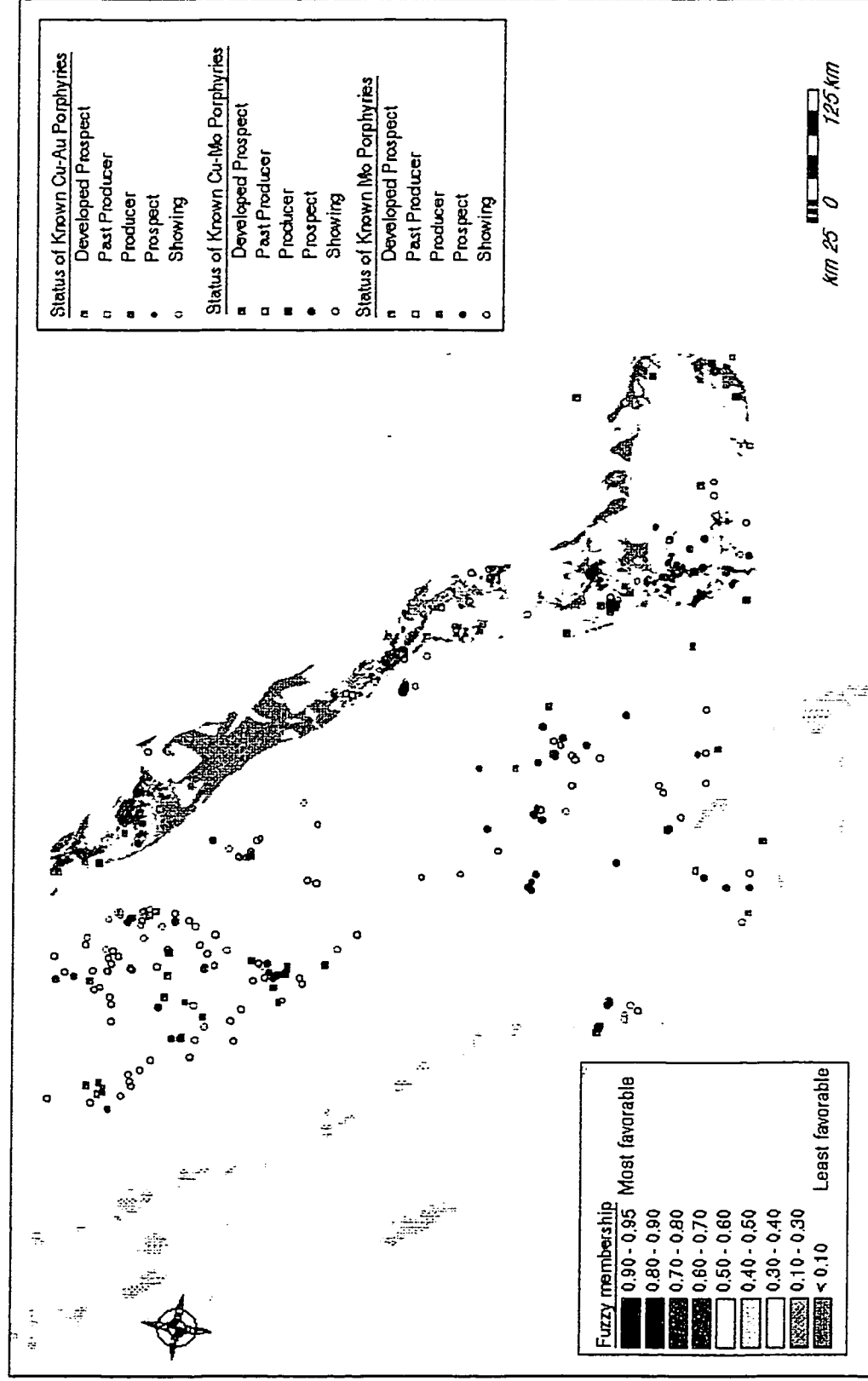


Figure 28. Favourability map of Takla and Nicola arc volcanics (TrJ, TrJN) created by combining all factors by gamma operator ($\gamma = 0.95$).

8.4.6 MOST FAVOURABLE AREAS FOR PROSPECTING PORPHYRY DEPOSITS INSIDE THE STUDY AREA

Joining all the generated favourability maps for different geological units or groups of geological units of the study area results in a map, shown in Figure 29. About 90% (68 of 76) of all porphyry deposits with the status of PRODUCER, PAST PRODUCER, DEVELOPED PROSPECT and PROSPECT, and 66% (53 of 80) of all SHOWINGS are located inside the top 5 classes of the favourability map of Figure 29 with fuzzy memberships of greater than 0.6. Weights of evidence (W^+ , W^-) and contrast (C) were calculated for all porphyry deposits with the status of PRODUCER, PAST PRODUCER, DEVELOPED PROSPECT and PROSPECT that are located inside the geological units of the study and classes of the favourability map. Similar calculations were done for all

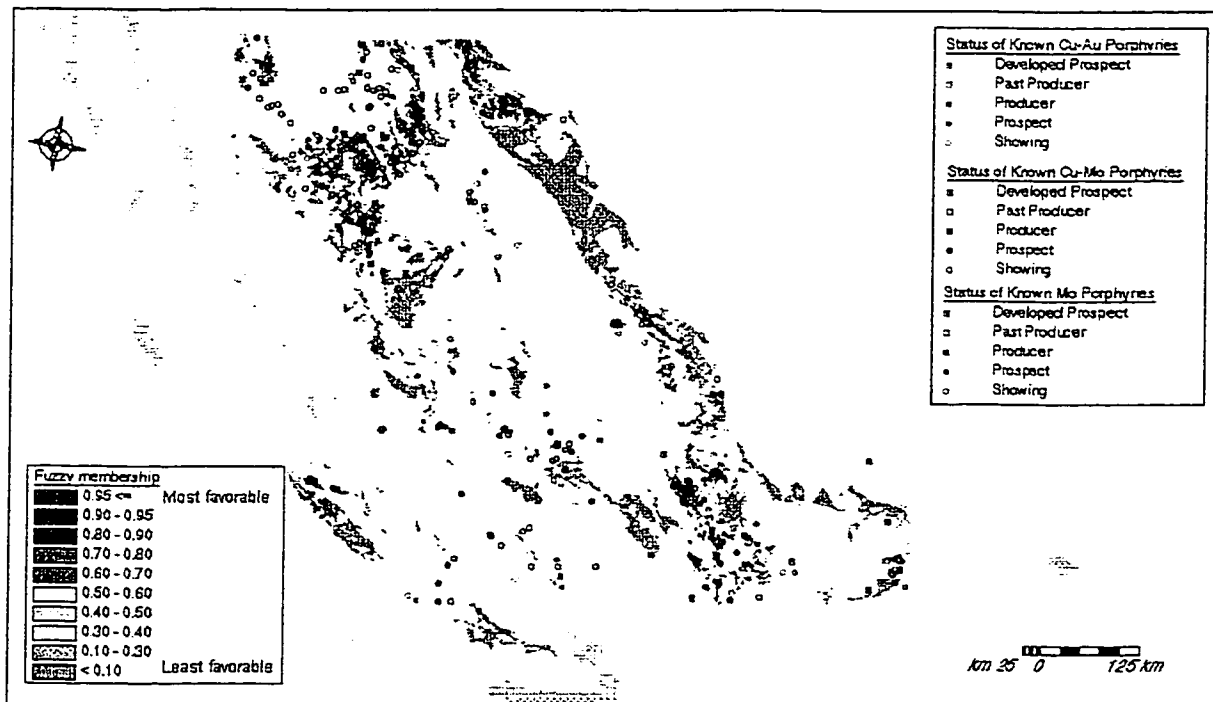


Figure 29. Favourability map for the whole study area, created by combining all factors by gamma operator ($\gamma = 0.95$).

SHOWINGS. Figure 30 showing a decreasing trend for contrast (C) with decreasing the fuzzy memberships emphasises the spatial association of porphyry deposits with the top classes of the favourability map. This association is especially strong for the top three

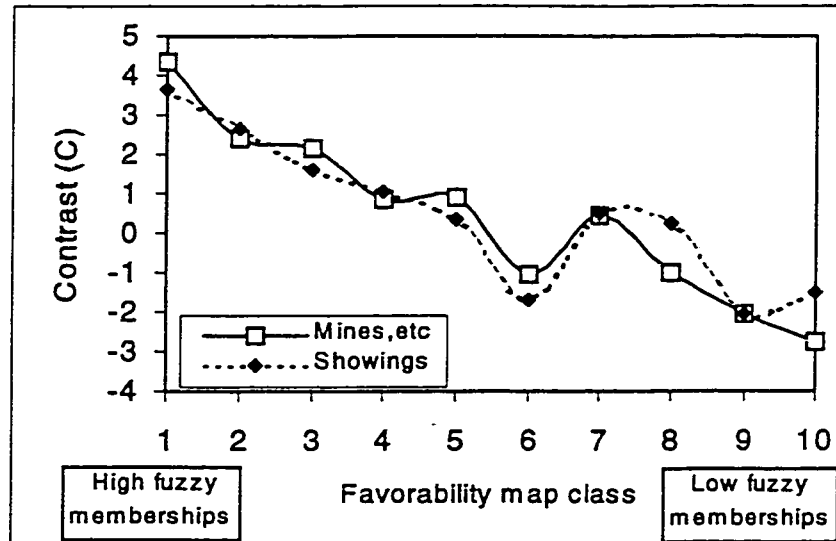


Figure 30. Variations of contrast (C) with different classes of favourability map.

classes of the favourability map. Here it is supposed that there are no more undiscovered porphyry deposits inside the area of mining camps. Therefore, mining camp zones were subtracted from the generated favourability maps. To do this subtraction, a buffer zone with the radius of 2.5 km was assigned around all the PRODUCERS, PAST PRODUCERS, DEVELOPED PROSPECTS and PROSPECTS to represent the mining camps. Similarly, a buffer zone with the radius of 1.5 km was assigned around all SHOWINGS. Then these two maps of buffer zones were merged together to have one map representing mining zones around the known porphyry deposits. Figure 31 and 32 show the map of buffer zones overlaid on the favourability map.

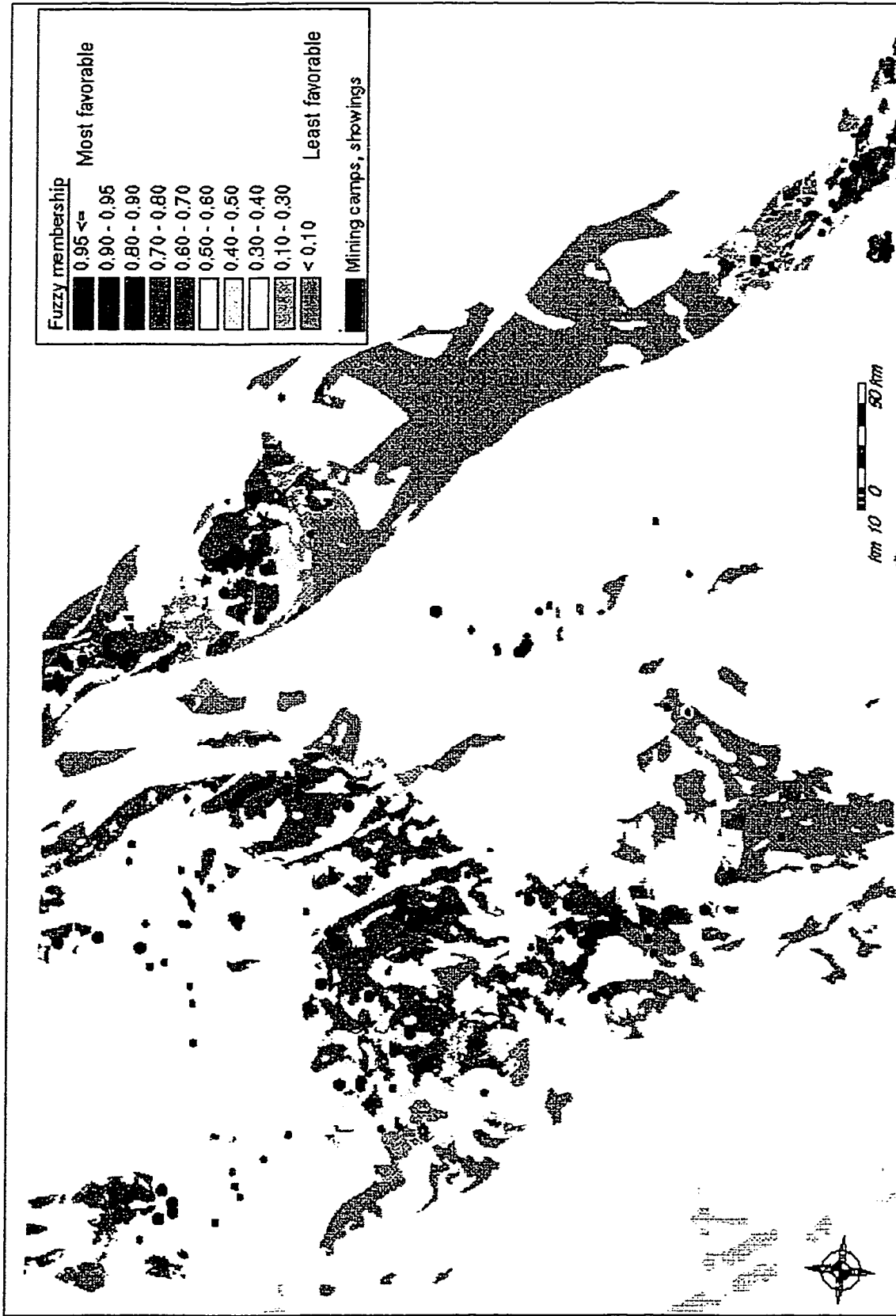


Figure 31. Favourability map with buffer zones around mining camps and SHOWINGS in the northern part of the study area.

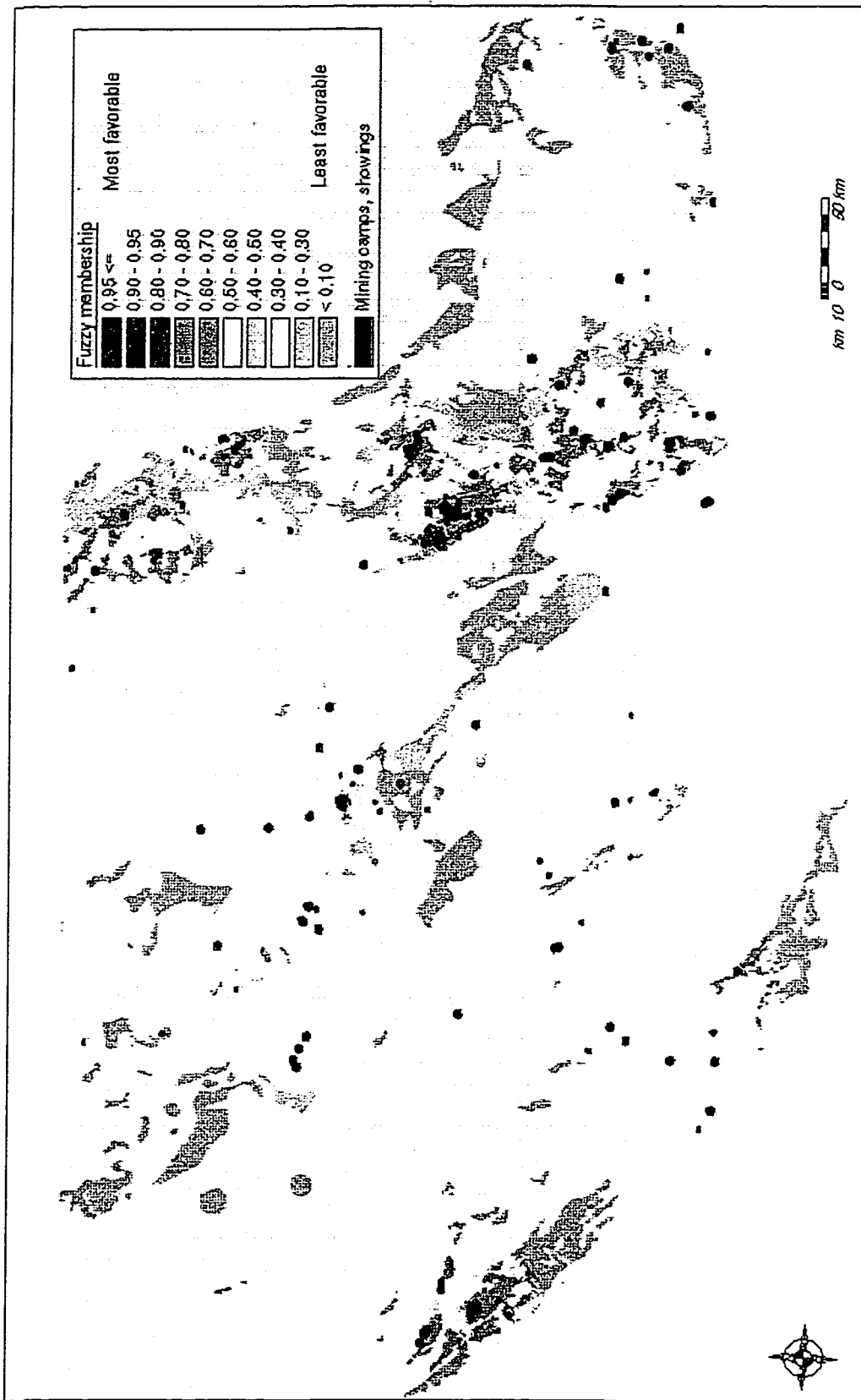


Figure 32. Favourability map with buffer zones around mining camps and SHOWINGS in the southern part of the study area.

To select the most favourable areas for prospecting porphyry deposits, parts of the favourability map with very high favourability but outside mining camps were selected. To do this, all areas of the favourability map located inside the discussed buffer zones of mining camps and SHOWINGS and all classes greater than 4 were eliminated from further consideration. The resulting map shows the most suitable locations in the study area for prospecting porphyry deposits and detailed studies (Figure 33, 34 and 35).

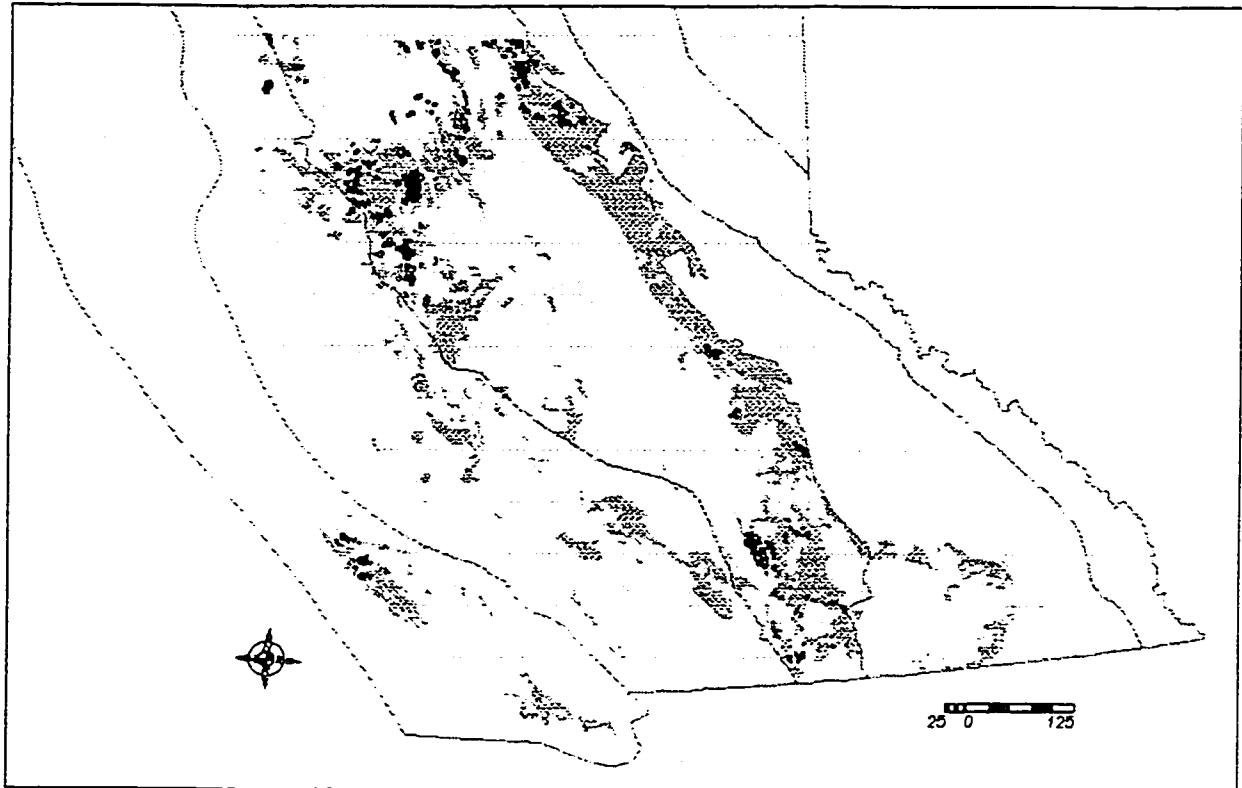


Figure 33. Distribution of the most favourable areas for prospecting porphyry deposits and detailed studies in the study area.

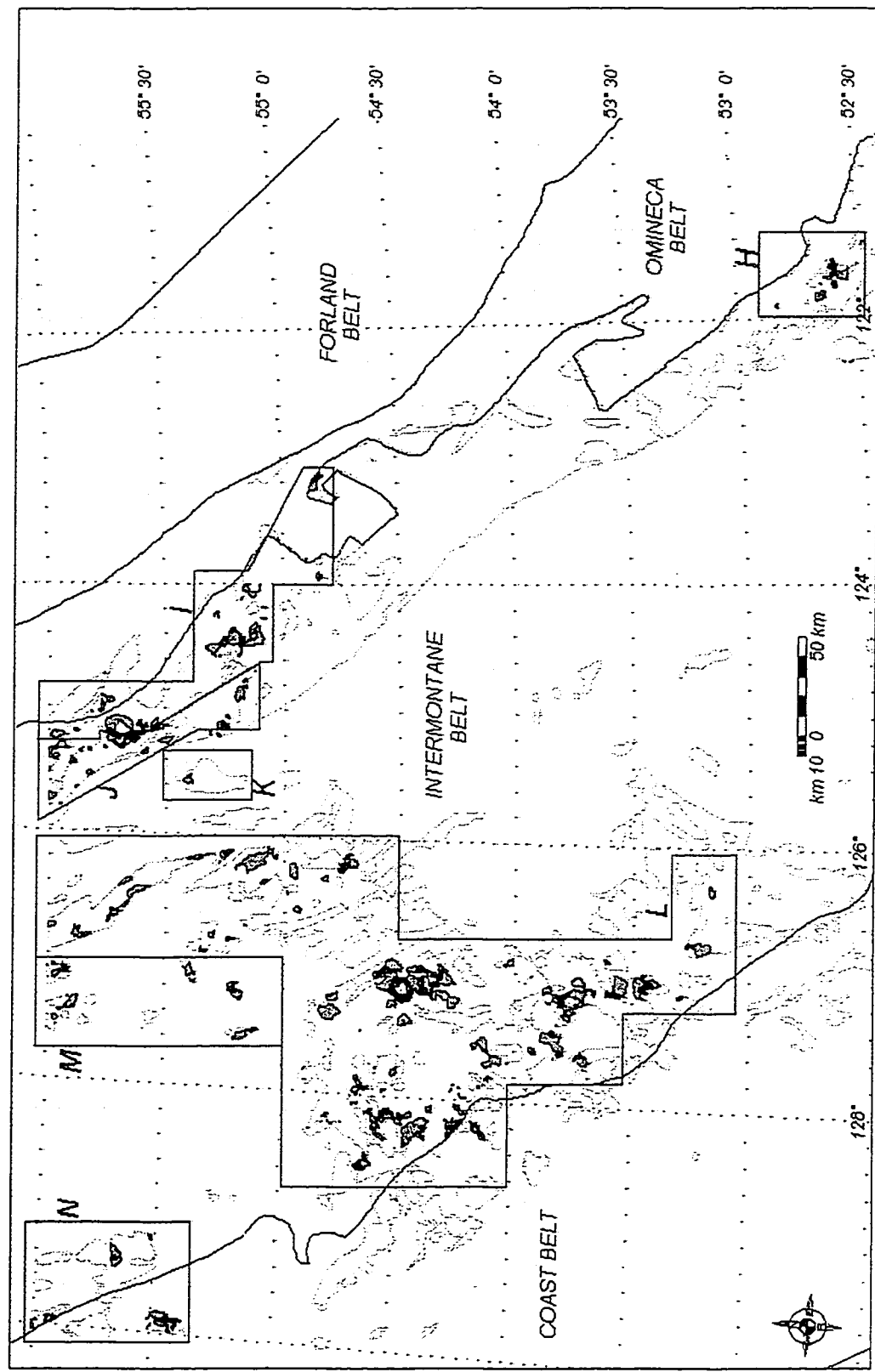


Figure 34. Distribution of the most favourable areas for prospecting porphyry deposits and detailed studies in northern part of the study area.

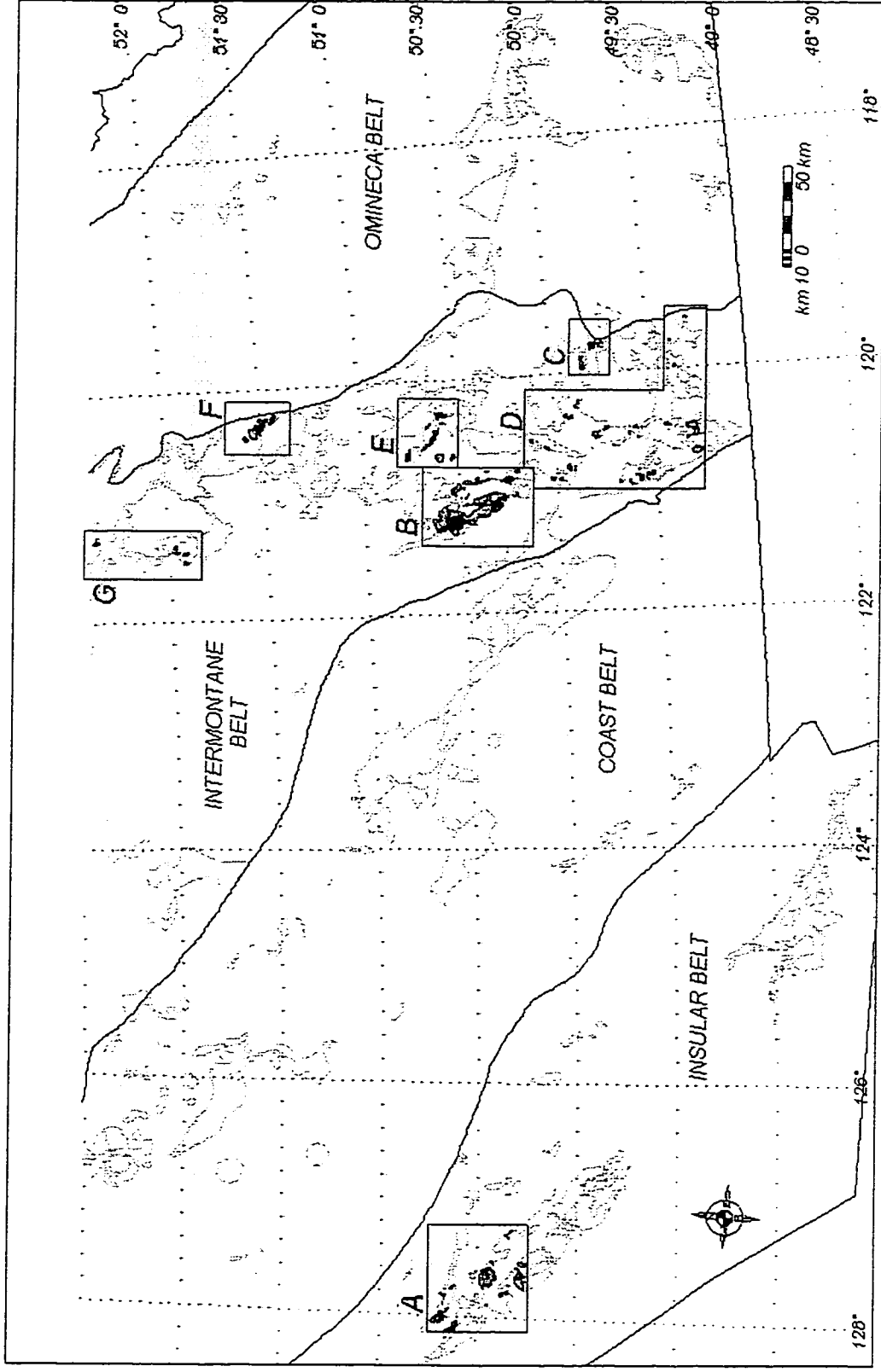


Figure 35. Distribution of the most favourable areas for prospecting porphyry deposits and detailed studies in southern part of the study area.

Map of Figure 33 is shown in detail in Figure 34 and 35 for the northern and southern part of the study area. The most favourable areas as shown in Figure 34 and 35 are:

Area A: This area is located in Vancouver Island in Wrangellia terrane. It is mainly underlain by northwest trending Lower Jurassic Bonanza Group volcanics and sediments (JB). Locally, bedded tuff, massive tuff, lapilli tuff and tuff breccia of the Bonanza Group are intruded by diorite, quartz diorite and quartz feldspar porphyry or quartz monzonite of the Island plutonic suite (Carson, 1968). Several porphyry deposits have been found in Bonanza Group.

Area B: Favourable areas in this location, lie in Quesnellia terrane within the Early Jurassic-Late Triassic Guichon Creek batholith (EJgG). This batholith is known as one of the most mineralized batholiths in Intermontane Belt for porphyry deposits (McMillan, personal communications, 1996). Guichon Creek batholith is a semiconcordant granitoid pluton ranging in composition from diorite at the outer margins to quartz monzonite at the core (Olade & Fletcher, 1976). Some of the most famous porphyry deposits of British Columbia such as Highland Valley (Lornex, Valley Copper, Bethlehem and Highmont) are located in this batholith.

Area C: This area covers the Pennask Mountain area which is in Quesnellia terrane and is mainly underlain by a roof pendant comprising westerly younging, Upper Triassic sedimentary and volcanoclastic rocks of the Nicola Group. These are intruded and enclosed to the north, east and south by plutonic rocks of the Early Jurassic Pennask batholith and Middle Jurassic Osprey Lake batholith. Brenda which is a porphyry Cu-Mo

deposit is located in area C. It is within the "Brenda stock", a composite quartz diorite/granodiorite body which forms part of the Pennask batholith.

Area D, F, G, H, I: These areas are located in Takla and Nicola arc volcanics (TrJ, TrJN). Upper Triassic to Lower Jurassic Takla and Nicola Group in Quesnellia comprise sedimentary and volcanic rocks of porphyritic pyroclastics and flows, and associated alkaline intrusions and volcanic clastics. The intrusions vary from diorite to monzonite in composition and are thought to be comagmatic with the Takla and Nicola Group, ranging in age from Late Triassic to Early Jurassic. Much of the copper mineralization and associated alteration of the Takla and Nicola can be attributed to the emplacement of such intrusions.

Area J: This area is located in Quesnellia represented by Middle Triassic to Lower Jurassic Takla Group volcanic and sedimentary rocks of island-arc affinity and related intrusions. It contains the Late Triassic-Early Cretaceous Hogem Intrusive Complex. Middle Jurassic Duckling Creek Syenite Complex is another group of plutonic intrusions associated with porphyry mineralization in this area, which is one phase of the Late Triassic to Early Cretaceous Hogem Intrusive Complex. These plutonic suites have been emplaced into volcanic rocks of the Takla Group. Porphyry deposits such as Lorraine, Ato and Dorothy are located in this area.

Area K: Topley intrusive suite (EJqT) of the Early Jurassic in area K of Figure 34, is a part of post-accretion intrusion terranes. This plutonic suite is mainly granodiorite, diorite and quartz diorite. Topley felsic plutons in some locations intrude both Lower and Middle Jurassic Hazleton strata.

Area L, N: Lower to Middle Jurassic volcanic and sedimentary rocks of the Hazleton Group in area L and N are located in Stikinia in the south of Bowser Basin. It comprises mainly andesites-dacite pyroclastics and clastic volcanics and low alkali calc-alkaline subaerial basalt to rhyolite.

Area M: In this area Bulkley intrusions of Late Cretaceous (LKgB) are associated with many porphyry Mo mineralization. Bulkley intrusions are high-level mainly calc-alkaline, granodiorite to quartz monzonite in many locations in the form of stocks. Fog is a porphyry Mo deposit in this area.

8.5 EVALUATION OF RESULTS

To evaluate results of the final potential maps indicating the most favourable areas within the geological units of the study area are compared here to the map that is published by the mineral potential project of British Columbia Geological Survey Branch.

8.5.1 MINERAL POTENTIAL PROJECT OF BRITISH COLUMBIA

Mineral potential project of British Columbia Geological Survey has applied the following method to generate a potential map for all types of metallic deposits and another one for the industrial minerals of all kinds. All the explanation for the mineral potential project indicated below is derived from (Kilby, 1995).

The mineral potential program has completed regional scale mineral resource assessments for British Columbia. It was initiated in 1992 to meet the need for current regional mineral potential information in regional and sub-regional land-use planning. To provide readily useable mineral resource information to this process, the land within

each region is ranked with respect to its mineral potential using quantitative analysis. The assessment of mineral potential in this project takes two forms, a phase 1 and phase 2 analysis. In phase 1 historical information is used to rank the land base with respect to its mineral potential. The phase 2 analysis uses a combination of historical and subjective probability estimates by industry experts to achieve a ranking of the land base. Upon completion of the geological compilation, the region is divided into mineral assessment tracts. These tracts are units in which the geology can be considered to be similar at a scale of 1:250, 000. Tract boundaries are geological features such as faults or major contacts. Tract definitions reflect significant differences in lithology, structure and geological history, particularly where these are important to metallogeny. Once defined, these tracts become the base unit areas in which the assessments in phase 1 and phase 2 are performed.

Phase 1 analysis is the prediction of the relative future value of the land base by analysis of historical information. Four parameters were used in this analysis; value of past exploration, value of known resources, value of past production and number of discovered mineral occurrences. Within each tract, the value of each of the four parameters was calculated. These parameter values were normalized by dividing them by the areas of the tracts. Tracts were then ranked by each normalized parameter and given an ordinal value related to the ranking. The ordinal values for each parameter range from 1, for the lowest ranking tract, to n, the number of tracts in the region, for the highest ranking tract. Each tract then had four ranking values, one for each of the parameters. These rankings were then multiplied by a weighting factor proportional to their perceived importance in predicting future value, and summed for a final ranking value. The final ranking was used to order all tracts within a region from most to least potential. This type of analysis makes some very large assumptions and must be used

with these assumptions in mind. To a large extent it assumes that new resources will be discovered near previously discovered resources. This assumption neglects the possibility that new types of deposits, completely unrelated to known deposits, may exist or that the importance (value) of commodities may change over time. The rankings are based on the market value of commodities.

Phase 2 analysis evaluates both known resources and predicted future resources. The value of known resources is compiled from the literature and, as described above, was added to the MINFILE database. The amount of resources to be discovered in the future was obtained by soliciting probabilistic estimates from individuals with expertise in the area to be assessed or in the deposit types believed to exist in the area. The methodology used for these predictions is similar to the three-part methodology of the United States Geological Survey (Singer, 1993).

To make a probabilistic estimate for a particular deposit type in a tract, the estimator actually makes several estimates at different probability levels. The value reported for each of these estimates is the probability of at least a specified number of deposits being discovered or proved in the future. The first question estimators ask themselves when making an estimate is: "What is the chance of at least one more deposit of this type being discovered or proved in this tract?". This value is then recorded on a linear scale from 1 to 100% probability, with a "1" indicating at least one deposit. Estimators then ask the same question with respect to increasing numbers of deposits until they reach a number beyond which they feel there is no chance of that number of deposits being found in that tract in the future. Each of the estimates are then run through the Mark 3 Monte Carlo Simulator to determine the amount of mineral commodity predicted by the estimate. Simply, the simulator combines the probability distribution of deposit discoveries provided by the estimators with the grade and tonnage probability

distributions compiled from known deposits. The output from the simulator is the probability distribution of volume of the commodities associated with the deposit type.

Figure 36 shows the final potential map, which is created by the British Columbia Geological Survey as explained above. In this map the most favourable tracts have red and purple colour. A visual comparison between the potential maps created in this thesis (Figure 29 to Figure 35) shows that generally areas of high favourability of these two different potential maps have similarity in their spatial distribution. In Figure 37, the outlines of the most favourable areas of Figure 34 and Figure 35 is overlaid on the mineral potential map of the British Columbia Geological Survey. As Figure 37 shows almost in all locations, the most favourable areas introduced in this thesis are located inside the top 3 classes of the mineral potential map of the British Columbia Geological Survey.

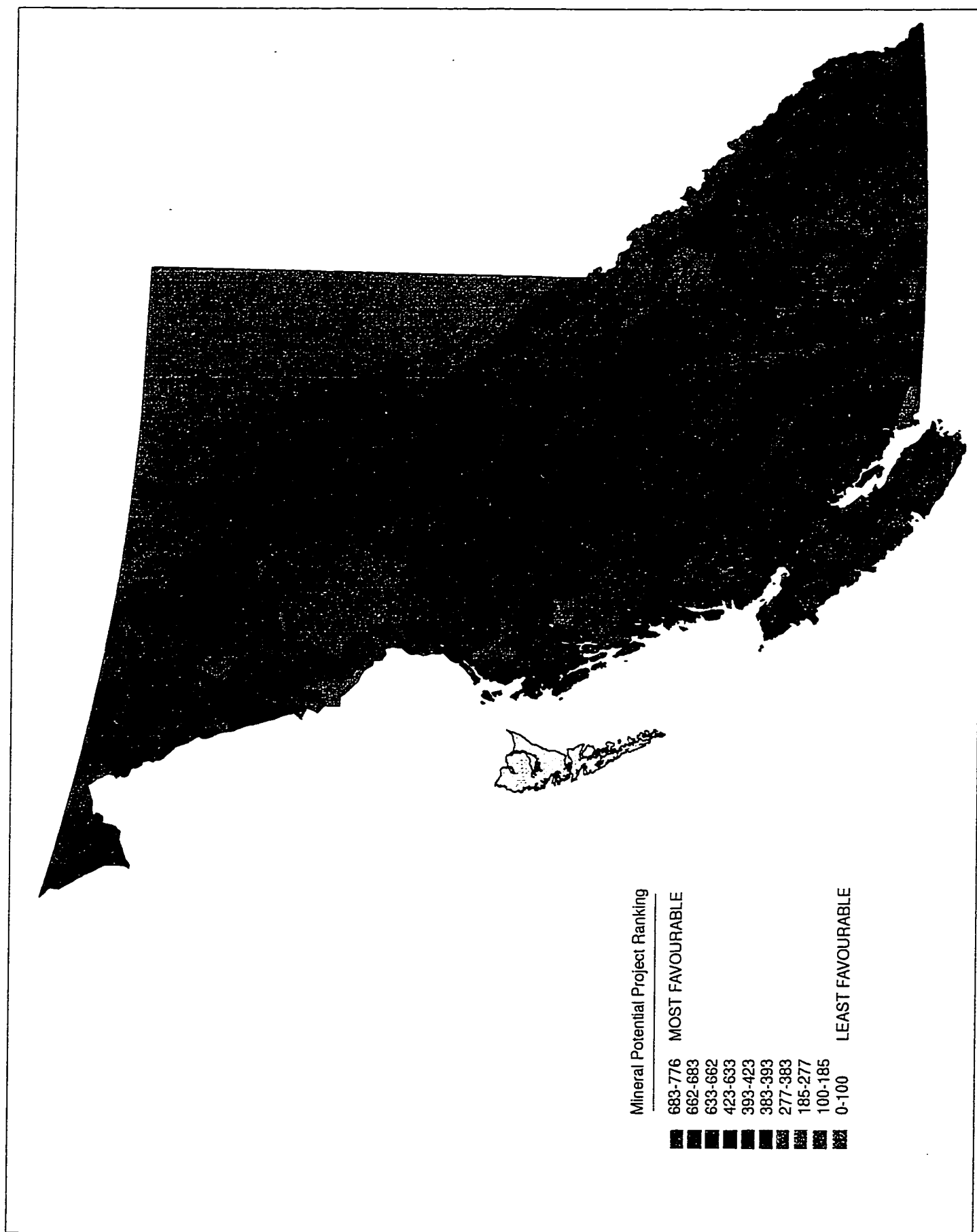
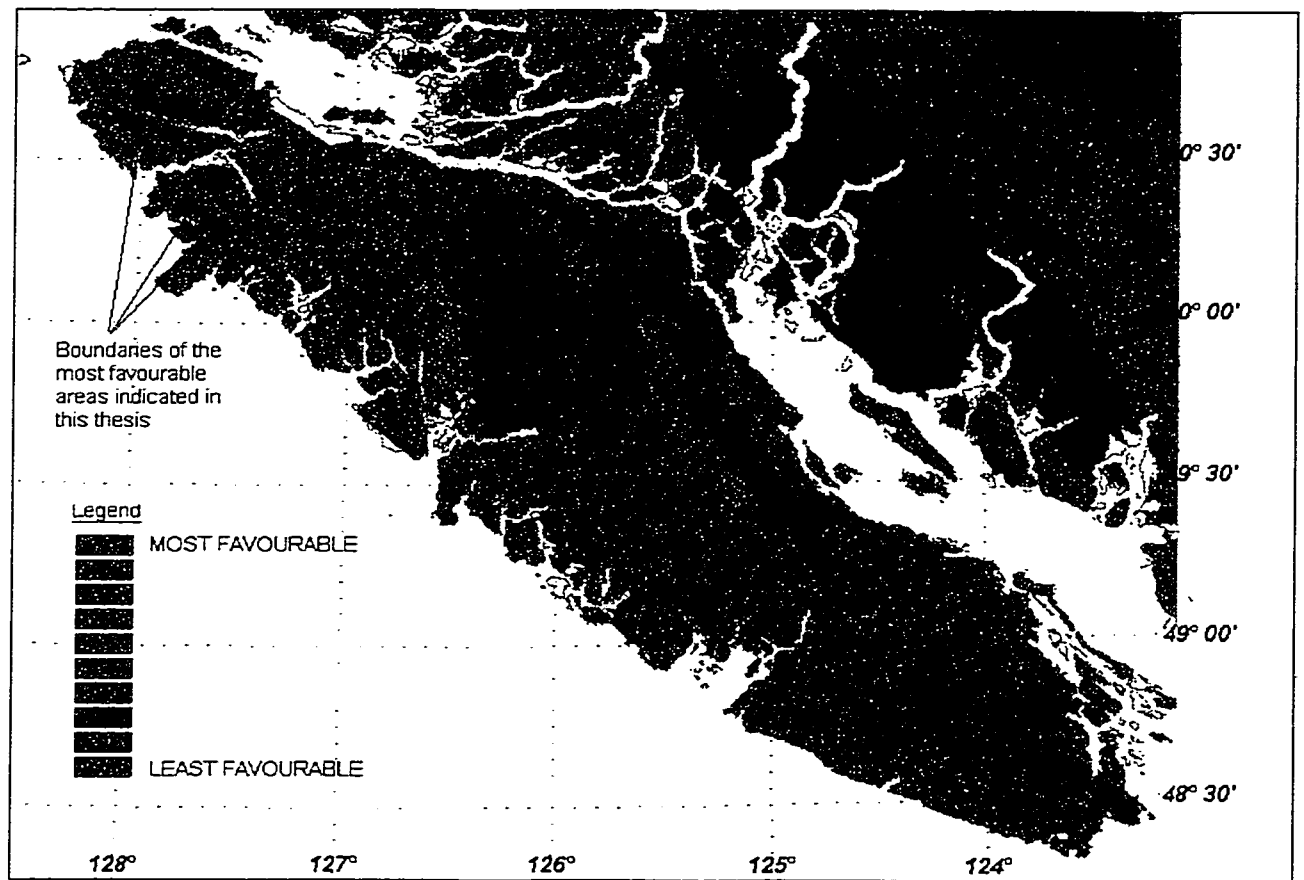
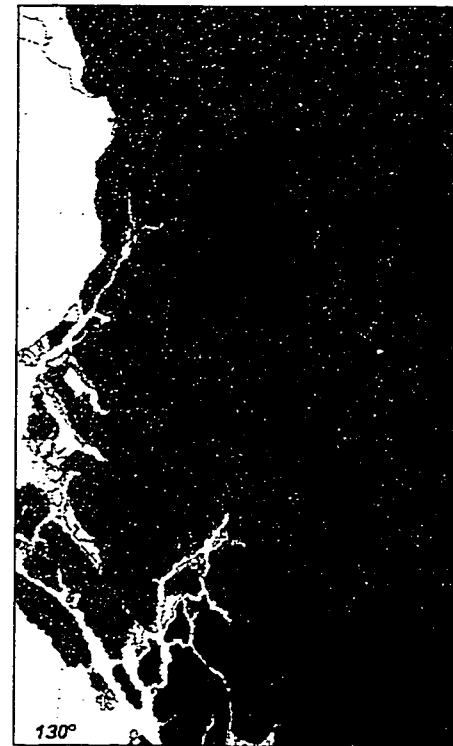
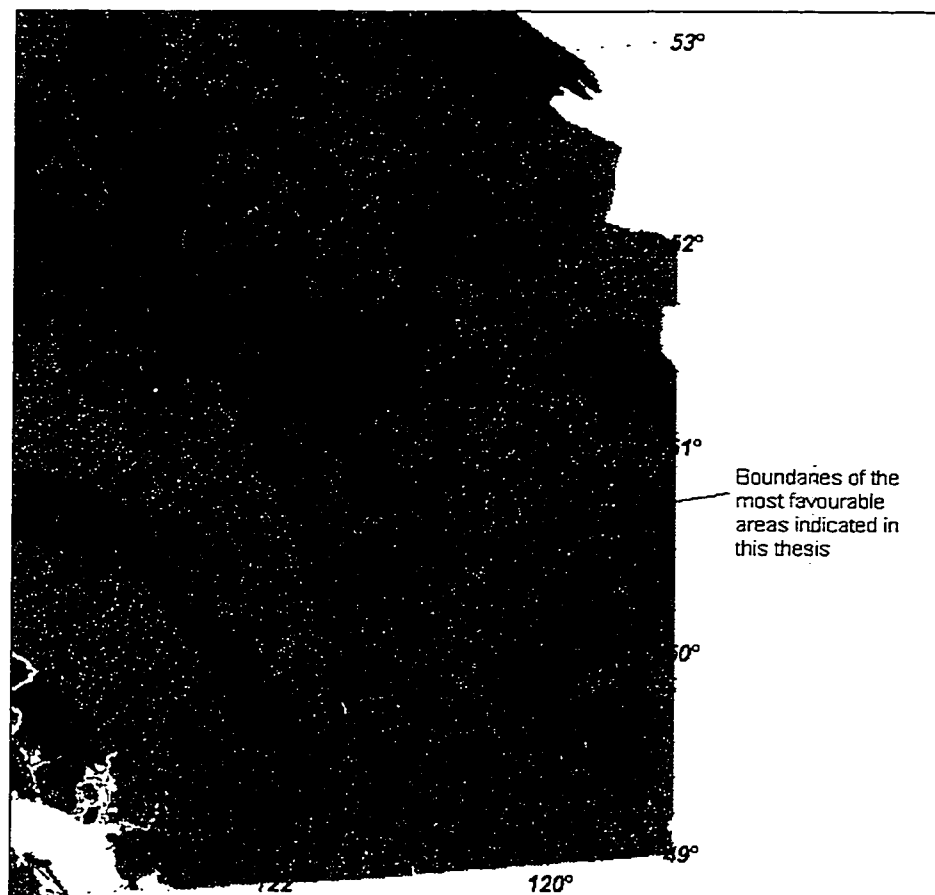
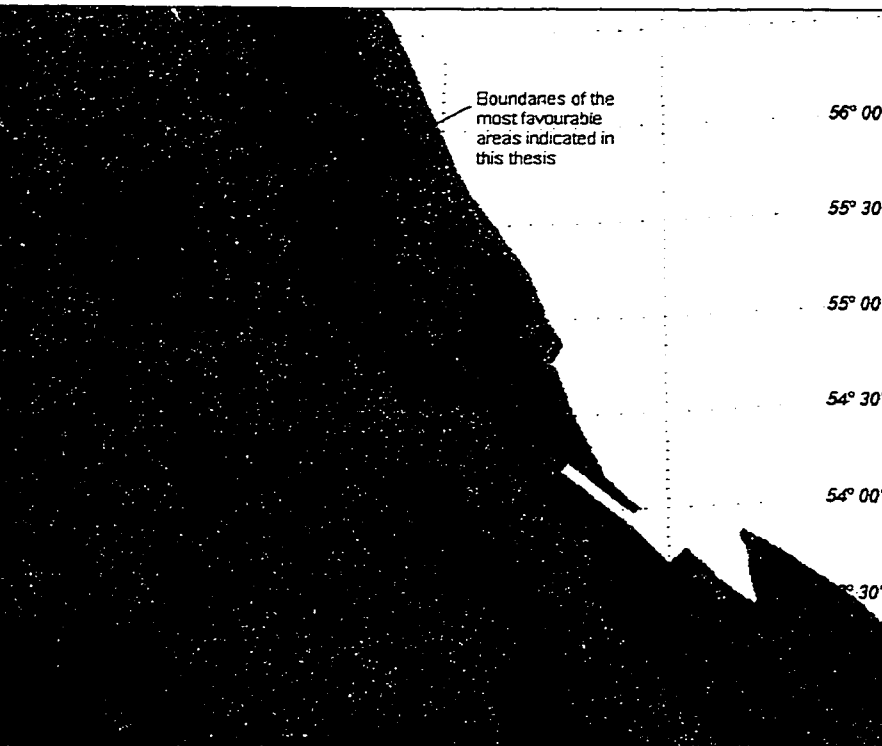


Figure 36. Mineral potential map from the mineral potential project of British Columbia.

Figure 37. Overlay of the boundaries of the most favourable areas created in this thesis on the mineral potential map for metallic deposits of the British Columbia Geological Survey.





8.6 CONCLUSIONS

GIS is able to play a prominent role in decision making in prospecting and exploration projects. Modelling in GIS enables geologists to combine several “evidence” maps, each directly or indirectly related to mineralization. GIS can be used to emphasise the spatial relationships among different maps and entities. In the past the usual methods which have been used by geologists for proposing the best locations for prospecting porphyry deposits included mainly visual comparison of different maps either by simple comparison or with the help of a light table. In many cases such work is time-consuming, since a considerable amount of data must be considered visually specially for large study areas. In this thesis it was shown that even at the regional scale it is possible to use modelling with GIS to deduce the most favourable areas for prospecting porphyry deposits.

In summary in this thesis it was noticed that:

- GIS makes it possible to link, or integrate, information that is difficult to associate through any other means. Thus, GIS can use combinations of mapped variables to build and analyse new variables. Such new variables can be used as a factor (such as geochemical, geophysical,...) that, even individually, can be an indicator of areas with high potential for porphyry mineralization. The modelling which is possible to be performed by GIS is beyond the capability of manual methods.
- For some map sheets geochemical data show a boundary shift between adjacent surveys. By the method introduced in Chapter 4, it is possible to remove this boundary shift and level the data and then perform further data analysis.

- In most cases, the median of Cu in stream sediments is higher inside the mineralized polygons of the geological units known as the main hosts of porphyry deposits than other polygons of the same geological unit.
- Parameters measuring the spatial variability (local variance, coefficient of variation and slope) of Cu and Mo in stream sediments can be predictive of the areas with porphyry mineralization within selected geological units.
- Disaggregating the geochemical data by the geological unit, is necessary before applying statistical analysis at the regional scale.
- Applying discriminant analysis to geochemical samples in plutonic units subdivided into mineralized and barren groups, and are large enough to have enough number of samples, is useful to predict and map the mineralized zones in the plutonic suite.
- Factor analysis can be a useful tool at the regional scale if performed on the data of a certain geological unit or groups of geological units similar to each other that host porphyry deposits. Factor scores can be mapped to represent areas with high potential for porphyry mineralization. The scores of such factor(s) usually have a positively skewed distribution, despite logtransforming the spatial variables.
- At the regional scale, areas with porphyry Cu-Au and Cu-Mo mineralization show a strong association with top (most magnetic) classes of the magnetic maps. This association is not distinct for porphyry Mo deposits. Therefore a map created by combining residual total field magnetics and vertical derivative (gradient) of magnetics can be a useful geophysical factor, as an indicator of plutonic intrusions with an elevated potential for porphyry mineralization.

- Inside Takla and Nicola (TrJ, TrJN) as a major arc volcanic unit, vertical derivative (gradient) of Bouguer gravity anomalies can also be used as another geophysical indicator of areas with high potential for porphyry mineralization.
- The smoothed maps of buffer zones around faults, and the smoothed map of buffer zones around points of intersection of faults, are similar to the fault density map. Therefore, if a limitation exist in a GIS system for generating a fault density map, it is possible to substitute it with either of the other maps. These maps can be used as the tectonic factor indicating the potentially favourable areas for plutonic intrusions. Future data for faults at the regional or district scale with more detailed studies, can enhance the maps representing the tectonic features.
- Calculating and mapping fuzzy membership values over the study area even at the regional scale can be useful in proposing areas with high potential for porphyry mineralization.
- Weights of evidence (a “data driven” method) can be used in addition to fuzzy logic (a “knowledge driven” method), to help in deciding the fuzzy memberships values for individual classes of maps used as evidence.

References

- Agterberg, F.P., Bonham-Carter G.F., Cheng, Q., Wright, D.F., 1993. Weights of evidence modelling and weighted logistic regression for mineral potential mapping. In J.C. Davis and U.C. Hertzfeld (Editors), *Computers in Geology: 25 years of progress*, Oxford University Press, New York, 298 pp.
- Allen, J.M., Richardson, J. 1970. The geological setting of the Valley Copper orebody. CIM Annual General Meeting, Toronto preprint.
- Allen, D.G., Panteleyev, A. and Armstrong, A.T., 1976. Galore Creek. In A. Sutherland Brown (Editors), *Porphyry deposits of the Canadian Cordillera*, Canadian Institute of Mining and Metallurgy, Special volume 15: 402-416.
- Amson, S.D., McClelland, W.C., Patchett, P.J., Gehrels, G.E., Anderson, R.G., 1989. Nd isotopes and phanerozoic crustal genesis in the Canadian Cordillera. *Nature*, 337: 705-709.
- Amson, S.D., Patchett, P.J., Gehrels, G.E., Anderson, R.G., 1990. Nd and Sr isotopic characterisation of the Wrangellia terrain and implications for crustal growth of the Canadian Cordillera. *Journal of Geology*, 98: 749-762.
- An, P., Moon, W.M. and Renz, A. 1991. Application of fuzzy set theory to integrated mineral exploration, *Canadian Journal of Exploration Geophysics*, 27: No. 1:1-11.
- Anderson, R.G., Thorkelson, D.J., 1990. Mesozoic stratigraphy and setting for some mineral deposits in Iskut River map area, north-western British Columbia. *Current Research, Part E, Geological Survey of Canada 90-1E*: 131-140.
- Armstrong, R.L., 1988. Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera. *Geological Society of America, Special paper 218*: 55-91.
- Armour-Brown, A., Nichol, I., 1970. Regional geochemical reconnaissance and the location of metallogenic provinces. *Economic Geology*, 65: 312-330.
- Atwater, T., 1970. Implication of plate tectonics for the Cenozoic tectonic evolution of western North America, *Geological Society of America, Bulletin 31*: 3513-3536.
- Barr, D.A. 1972. Relation of structure to the syenite porphyries of the Stikine River district. *Geological Association of Canada, Cordillera Section Symposium, Vancouver, B.C. abstract*, 7 pp.
- Barr, D.A., 1966. The Galore Creek copper deposits. *CIM Bulletin*, 59: 841-853.
- Barr, D.A., Fox, P.E., Preto, V. A., 1976. The alkaline suite porphyry deposits_ a summary. In A. Sutherland Brown (Editor), *Porphyry deposits of Canadian Cordillera*. Canadian Institute of Mining and Metallurgy Special Volume 15 :359-367.

- Bergey, W. R., Carr, J. M., and Reed, A. J. 1971. The Highmont copper-molybdenum deposits, Highland Valley, British Columbia. CIM Bulletin, 64:No. 716: 68-76.
- Beus A.A. , Grigorian S.V. , 1977. Geochemical exploration methods for mineral deposits. Applied Publishing Ltd., Chicago.
- Billingsley, P., Locke A., 1941. Structure of ore districts in the continental framework. AIME Trans. 144: 9-64.
- Bonham-Carter, G.F., 1994. Geographic information systems for geoscientists: modelling with GIS. Pergamon Press, Oxford, 1994, 398 pp.
- Bonham-Carter, G.F., Agterberg, F.P. and Wright, D.F., 1990. Weights of evidence modelling: a new approach to mapping mineral potential in statistical applications in the earth sciences. In Agterberg, F.P. and Bonham-Carter, G.F. (Editors), Geological Survey of Canada, paper 89-9: 171-183.
- Bottomer, L.R., Leary, G.M., 1995. Copper Canyon porphyry copper-gold deposit, Galore Creek area, north-western British Columbia . In Schroeter, T.G (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 645-649.
- Bower, B., Payne, J., DeLong, C. and Rebagliati C.M., 1995. The oxide-gold, supergene and hypogene zones at the Casino gold-copper-molybdenum deposit, west central Yukon. In Schroeter, T.G (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 352-366.
- Brown, D.A., Logan, J.M., Orchard, M.H. and Bamber, W.E., 1991. Stratigraphic evolution of the Palaeozoic Stikinia assemblage in the Stikinia and Iskut River area, north-western British Columbia, Canadian Journal of Earth Sciences, 28, 958-972.
- Burns, R.G., 1976. The uptake of cobalt into ferromanganese nodules, soils, and synthetic manganese IV oxides, Geochimica et Cosmochimica Acta, 40: 95-102.
- Cameron, E.M., 1980. Geochemical exploration for uranium in northern lakes. Journal of Geochemical Exploration, 13: 221-250.
- Cameron, E.M., 1986. Regional geochemical reconnaissance; an introduction to the interpretation of data from central Baffin Island. Geological Survey of Canada, paper 86-10.
- Cant, D.J., Stockmal, G., 1989. The Alberta Foreland basin: relationship between stratigraphy and Cordilleran terrane accretion events: Canadian Journal of Earth Sciences Volume 26: 1264-1275.
- Cargill, D.G. 1975. Geology of the Island Copper mine. unpublished Ph.D. thesis, UBC.
- Carr, J.M. 1960. Porphyries, breccias and copper mineralization in Highland Valley, B.C., Canadian Mining Journal, 81: No. 11: 71-73.

- Carr, J.M. 1965. B.C. Department of Mines and Petroleum Resources Preliminary Geological Map, Highland Valley Area.
- Carr, J.M., Reed, A.J., 1976. Afton: A supergene copper deposit. In A. Sutherland Brown (Editor), Porphyry deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 376 -387.
- Carson D.J.T. & Jambor, J.L. 1974. Mineralogy, zonal relationships and economic significance of hydrothermal alteration at porphyry copper deposits, Babine Lake Area, British Columbia. Canadian Institute of Mining and Metallurgy, Bulletin 76: 110-133.
- Carson, D., 1973. The plutonic rocks of Vancouver Island. Geological Survey of Canada, Paper 72-44.
- Carson, D.J.T., 1968. Metallogenic study of Vancouver Island with emphasis on the relationship of plutonic rocks to mineral deposits. Ph.D. Thesis, Carleton University, Ottawa.
- Carson, D.J.T., Jambor, J.L., 1976. Morrison: Geology and evolution of a bisected annular porphyry Cu deposit. In A. Sutherland Brown (Editor), Porphyry deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 264-273.
- Carson, D.J.T., Jambor, J.L., Ogryzlo, P. and Richards, T.A., 1976. Bell Copper: Geology, geochemistry and genesis of a supergene-enriched, biotitized porphyry copper deposit with a superimposed phyllic zone, In A. Sutherland Brown (Editor), Porphyry deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 245 -263.
- Carten, R.B., White, W.H. and Stein, H.J., 1993. High grade granite-related Mo systems: Classification and origin. In R.V. Kirkham, W.D. Sinclair, R.I. Thorpe and J.M. Duke (Editors), High Deposit Modeling. Geological Association of Canada, Special Paper 40: 521-554.
- Carter, E. S., Orchard, M.J., Ross, C.A., Ross, J.R.P., Smith, P.L. and Tipper H.W., 1991. Part B. Paleotectonological signatures of terrains. In H. Gabrielse and C.J. Yorath (Editors), Chapter 2 of Geology of the Cordilleran Orogen, Canada, Geological Survey of Canada, pp. 28-38.
- Carter, N.C., Grove, E.W., 1971. Geological compilation map of the Stewart, Anyox, Alice Arm and Terrace areas, B.C. Department. of Mines and Petroleum Resources, Preliminary Map No. 8.
- Carter N.C., Dirom, G.E., Ogryzlo, P.L., 1995. Porphyry copper-gold deposits, Babine Lake area, west-central British Columbia. In T.G. Schroeter (Editor) Porphyry Deposits of the Northwestern Cordillera of North America. Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 247-255.

- Carter, N.C., 1970. CAVZ, B.C. Dept. of Mines and Petroleum Resources, Geology, Exploration & Mining, 1969: 110-112.
- Carter, N.C., 1971. Huckleberry. B.C. Department. of Mines and Petroleum Resources, Geology, Exploration & Mining, 1970: 104-107.
- Carter, N.C., 1974. Geology and geochronology of porphyry copper and molybdenum deposits in west-central British Columbia. Ph.D. thesis, University of British Columbia.
- Carter, N.C., 1976. Regional setting of porphyry deposits in west-central British Columbia. In A. Sutherland Brown (Editor), Porphyry deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 227-238.
- Carter, N.C., 1981. Porphyry copper and molybdenum deposits, west-central British Columbia. British Columbia Ministry of Energy Mines and Petroleum Resources, Bulletin 64, 150 pp.
- Casselman, M.J., McMillan, W.J. and Newman, K.M., 1995. Highland Valley porphyry copper deposits near Kamloops, British Columbia: A review and update with emphasis on the Valley deposit. In T.G. Schroeter (Editor) Porphyry Deposits of the Northwestern Cordillera of North America. Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 161-191.
- Christopher, P.A., Carter, N.C., 1976. Metallogeny and metallogenic epochs for porphyry mineral deposits in the Canadian Cordillera. In A. Sutherland Brown (Editor), Porphyry Deposits of Canadian Cordillera, Canadian Institute of Mining and Metallurgy special Volumes 15: 64-71.
- Chung, C.F., 1995. Notes of the workshop on concepts and techniques in modelling for GIS. in the 7th International Conference on Geomatics, Ottawa.
- Chung, C.F., Fabbri, A.G., 1993. The representation of geoscience information for data integration. Nonrenewable Resources: 2: No.2: 122-139.
- Chureh, N.B., 1971. Lexington, B.C. Department of Mines and Petroleum Resources, Geology, Exploration and Mining, 1970: 413-425.
- Clark, D.A., 1983. Comments on magnetic petrophysics. Bulletin of Australian Society of Exploration Geophysicists, 14: 49-62.
- Coney, P.J., 1989. Structural aspects of suspect terranes and accretionary tectonics in western North America. Journal of Structural Geology, 11: 117-125.
- Coveney, C.J., 1963. Bethlehem Copper Corp., geology. Western Miner, 36: No. 1: 27-55.
- Coveney, C.J., Stevens, D.C. and Ewanchuk, H. 1965. Grade control at Bethlehem copper. CIM Bulletin, 58: No. 64: 823-826.

- Cox, D.P. & Singer, D.A., 1988. Distribution of gold in porphyry copper deposits. United States Geological Survey, Open File Report 8846, 23 pp.
- Currie L., Parrish R.R., 1993. Jurassic accretion of Nisling terrain along the western margin of Stikinia, Coast Mountains, north-western British Columbia. *Geology*, 21: 235-238.
- Darnley, A.G., Bjorkund, A., Bolviken, B., Gustavsson, N., Koval, P.V., Plant, J.A., Steenfelt, A., Tauchid, M., Xuejing, Xie, Garrett, R.G. and Hall, G.E.M., 1995. A global geochemical database for environmental and resource management, Chapter 8: Data Management, Publication 19, Unesco publishing, Paris.
- Dasler, P.G., Young, M.J., Giroux, G. and Perello, J.A., 1995. The Hushamu porphyry copper-gold deposit, northern Vancouver Island, British Columbia. In Schroeter, T.G (Editor), *Porphyry deposits of the north-western Cordillera of North America*, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 367-376.
- Dixon, W.J., Massey, F.J., 1969. Introduction to statistical analysis. McGraw-Hill Book Company, New York.
- Economic Geology, 67: 184-97.
- Eisbacher, G.H., 1972. Major faults of Canadian Cordillera and S.E. Alaska. Geological Association of Canada, Cordilleran Section, Vancouver, B.C. abstract, 1314 pp.
- Engelbreton, D.C., 1983. Hotspots trace plate movements. *GEOS*, Volume 12, Spring.
- Engelbreton, D.C., Cox, A. and Gordon, R.G., 1985. Relative motions between oceanic and continental plates in the pacific basin; Geological Society of America, Special Paper 206: 59 pp.
- Enns, S.G., Thompson, J.F.H., Stanley, C.R. and Yarrow, E.W., 1995. The Galore Creek porphyry copper-gold deposits, north-western British Columbia. In Schroeter, T.G (Editor), *Porphyry deposits of the north-western Cordillera of North America*, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 630-644.
- Fahrni, K.C. 1951. Geology of Copper Mountain. *CIM Bulletin*, 44: No. 469: 317-324.
- Fahrni, K.C., Kim, H., Klein, G.H. and Carter, N.C., 1976. Granisle. In A. Sutherland Brown (Editor), *Porphyry deposits of the Canadian Cordillera*, Canadian Institute of Mining and Metallurgy, Special Volume 15: 239-244.
- Fahrni, K.C., Macauley, T.N. and Preto, V.A.G., 1976a. Copper Mountain and Ingerbelle. In A. Sutherland Brown (Editor), *Porphyry deposits of the Canadian Cordillera*, Canadian Institute of Mining and Metallurgy, Special Volume 15: 368-375.
- Fountain, D.K., 1969. The application of geophysics to disseminated sulphide deposits in British Columbia. McPhar Geophysics Limited, 39th Society of Exploration Geophysicists Annual International Meeting, Calgary, Alberta.

- Fowler, B.P., Wells, R.C., 1995. The Sulphurets Gold zone, north-western British Columbia. In Schroeter, T.G (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 484-498.
- Fox, P. 1989. Alkaline copper-gold porphyries: schizophrenic cousins of real porphyry coppers. Mineral Deposits Division, Geological Association of Canada, Copper Gold Porphyry Workshop, Vancouver, April, 1989.
- Fox, P.E., Grove, E.W., Seraphim, R.H. and Sutherland Brown, A., 1976. Schaft Creek, In A. Sutherland Brown (Editor), Porphyry deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 219 -226.
- Fraser, T.M., Stanly, C.R., Nikic, Z.T. and Pesalj, D.G., 1995. The Mount Polley alkalic porphyry copper-gold deposit, south-central British Columbia. In Schroeter, T.G (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 609-622.
- Friedman, R.M., Armstrong, R.L., 1992. Jurassic and Cretaceous geochronology of the southern Coast Belt, B.C., 490-510 N., unpublished paper submitted to Canadian Journal of Earth Sciences.
- Friedman, R.M., Cui, Y., 1993. Juvenile crust in the southern Coast Belt of British Columbia: Evidence from a regional Nd-Sr isotopic study of the southern Coast plutonic complex batholith. unpublished paper submitted to Canadian Journal of Earth Sciences.
- Friske, P.W.B., Hornbrook, E.H.W., 1991. Canada's national geochemical reconnaissance programme. Transactions of the Institution of Mining and Metallurgy, section B, Applied Earth Sciences, Vol. 100: B47-B56.
- Fyles, J.T., Harakal, J.E. and White, W.H., 1973. The age of sulphide mineralization at Rossland, British Columbia. Economic Geology, 68: 23-33.
- Gabrielse, H., Monger, J.W.H., Wheeler, J.O. and Yorath, C.J., 1991. Tectonic framework. In H. Gabrielse and C.J. Yorath (Editors), Chapter 2 of Geology of the Cordilleran Orogen, Canada, Geological Survey of Canada, pp. 15-59.
- Gabrielse, H., Reesor, J. E. 1974. The nature and settings of granitic plutons in the central and eastern parts of the Canadian Cordillera, Pacific Geology 8, Tokyo University Press, Tokyo, Japan, 109-138 pp.
- Gabrielse, H., Yorath, C.J., 1989. DNAG#4. The Cordilleran Orogen in Canada. Geoscience Canada, 16: 67-84.
- Gardner, M.C., Bergman, S.C., Cushing, G.W., MacKevett, E.M., Plafker, G., Campbell, R.B., DoUds, C.J., McClelland, W.C. and Mueller, P.A., 1988. Pennsylvanian pluton stitching of Wrangellia and the Alexander terrane, Wrangell Mountains, Alaska. Geology, 16: 967-971.

- Garrett, R.G., 1989, Another Cry from the heart. technical notes, Explore, No. 81: 9-13.
- Garrett, R.G., 1989. The role of computers in exploration geochemistry. In G.D. Garland (Editor), Proceedings of Exploration '87, Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater, Ontario geological Survey, Special Volume 3.
- Garrett, R.G., 1991. The management, analysis and display of exploration geochemical data. Paper #9, Mineral Resources Division, Geological Survey of Canada.
- Goodwill, C. 1975. Geology of Casino porphyry copper molybdenum deposit, Damson Range, Y.T., unpublished Ph.D. thesis, UBC.
- Grant F.S. , 1984. Aeromagnetics, geology, and ore environments II , magnetite and ore environments. Geoexploration, 23: 335-362.
- Griffiths, D.H., King, R.F., 1981. Applied geophysics for geologists and engineers. (2nd ed.), Pergamon Press. London.
- Grunsky, E., 1991. Strategies and methodologies for the interpretation of geochemical data. CSIRO, Division of Exploration Geoscience.
- Guilbert, J.M., Lowell, J.D., 1974. Variations in zoning patterns in porphyry ore deposits. Canadian Institute of Mining and Metallurgy, Bulletin 67: No.742: 99-109.
- Guilbert, J.M., Park, Jr. C. F, 1985. The geology of ore deposits, W.H. Freeman and Company, New York, 985 pp.
- Haggerty, S.E., 1976. Oxidation of opaque mineral oxides in basalts. In D. Rumble, (Editor), Oxide minerals, Mineralogical Society of America Short Course Notes, 3, Chapter 4: Hg-1-Hg-100.
- Hansen, V.L., Mortensen, J.K. and Armstrong, R.L., 1989. U-Pb, Rb-Sr and K-Ar isotopic constraints for ductile deformation and related metamorphism in the Teslin suture zone, south central Yukon. Canadian Journal of Earth Sciences, 26: 2224-2235.
- Harris, M.W. 1991. The Mt. Milligan porphyry system: a structural and genetic approach. Abstract, Canadian Institute of Mining and Metallurgy, 93rd Annual general Meeting, Vancouver, April 1991, 58 pp.
- Hollister, F.V., 1978. Geology of the porphyry copper deposits of the western hemisphere. New York, Society of Mining Engineers, 219 pp.
- Hollister, V.F., Allen, J.M., Anzalone, S.A., and Seraphim, R.H. 1975. Structural evolution of the Highland Valley, Canadian Journal of Earth Sciences, 12: 807-820. In A. Sutherland Brown (Editor) Porphyry deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 44-51.

- Howarth, R.J., 1983, Statistical and data analysis in geochemical prospecting, Elsevier, New York, 437 pp.
- Irving E., Monger, J.W.H. and Yole, R.W., 1980. New paleomagnetic evidence for displaced terranes in British Columbia; In D.W. Strangway (Editor), The continental crust and its mineral deposits, Geological Association of Canada, Special Paper 20: 441-456.
- Irving, E, Wynne, P.J., 1991. Paleomagnetism: Review and tectonic implications In H. Gabrielse and C.J. Yorathed (Editors), Chapter 3 of Geology of the Cordilleran Orogen, Canada, Geological Survey of Canada, pp. 61-86.
- Irving, E. ,Thorkelson,D.J., 1990. On determining paleohorizontal and latitudinal shifts: Paleomagnetism of Spences Bridge Group, British Columbia, Journal of Geophysics, 95: 19,327-19,348.
- Jackson, A., Illerbrun, K., 1995. Huckleberry porphyry copper deposit, Tahtsa Lake district, west-central British Columbia. In Schroeter, T.G (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 313-321.
- Jenne, E.A., 1968. Control on Mn, Fe, Co, Ni, Cu, Zn, concentrations in soils and water: the significant role of hydrous Mn and Fe oxides. American. Chemical Society, Adv. Chem., 73: 337-387.
- Jensen, M. L., Bateman, A. M., 1979. Economic mineral deposits, John Wiley & Sons, New York, 593 pp.
- Jones, D.L., Silberling, N.J. and Hillhouse, J., 1977. Wrangellia - a displaced terrain in north-western North America. Canadian Journal of Earth Sciences, 14: 2565-2577.
- Jurdy, D.M., 1984. The subduction of the Farallon plate beneath North America as derived from relative plate motions. Tectonics, 3: 107-113.
- Kearey, P., Brooks, M., 1984. An introduction to geophysical exploration. Blackwell Scientific Publications, Oxford.
- Keith, S.B., Swan, M.M., 1987. Oxidation state of magma series in the southwestern U.S.: Implications for base, precious and lithophile metal metallogeny. Abstract, Geological Society of America, Abstracts with programs, 19: 723-724.
- Keith, S.B., 1983. Distribution of fossil metallogenic systems and magma geochemical belts within the Great Basin and vicinity from 145 million years ago to present. Abstract, Geothermal Resources Council, Special Report 13: 285-286.
- Kesler, S.E, 1973. Copper, molybdenum and gold abundances in porphyry copper deposits. Economic Geology, 68: 106-112.

- Kilby, W. E., 1995. Mineral Potential Project - Overview; in Geological Fieldwork 1994, Grant, B. and Newell, J.M., Editors, B.C. Ministry of Energy, Mines and Petroleum Resources, Paper 1995-1.
- Kirkham, R.V., 1969. A mineralogical and geochemical study of the zonal distribution of ores in Hudson Bay Mountain, British Columbia. unpublished Ph.D. thesis, University of Wisconsin.
- Kirkham, R.V., 1971. Intermineral intrusions and their bearing on the origin of porphyry copper and molybdenum deposits. *Economic Geology*, 66: 1244-1249.
- Kirkham, R.V., 1972. Porphyry deposits. in Report of Activities, part B: November 1971 to March 1972, Geological Survey of Canada, Paper 72-1, part B: 62-64.
- Kirkham, R.V., Sinclair, W.D. 1996. Porphyry copper, gold, molybdenum, tungsten, tin, silver; in O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe (Editors), *Geology of Canadian Mineral Deposit Types*, Geological Survey of Canada, *Geology of Canada*, No. 8: 421-446, also Geological Society of America, *The Geology of North America*, v. P-1.
- Klir, G.J., Yuan, B., 1995. *Fuzzy sets and fuzzy logic theory and applications*. Prentice Hall, Upper addle River, 574 pp.
- Krumbein, W.C., Graybill, F.G., 1965. An Introduction to statistical models in geology. Chap. 8 and Table A.2 in Appendix, McGraw-Hill Book Company, New York.
- Lang, J.R., Stanly, C.R. and Thompson, J.F.H., 1994. Porphyry copper-gold deposits related to alkalic igneous rocks in the Triassic-Jurassic arc terranes of British Columbia. In F.W. Pierce and J.C. Bohn (Editors), *Bootprints along the Cordillera Symposium Volume*, Arizona Geological Society Digest, 20: 219-236.
- Leriche, P.D., 1995. Taurus copper-molybdenum porphyry deposit, east-central Alaska. In Schroeter, T.G (Editor), *Porphyry deposits of the north-western Cordillera of North America*, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 451-457.
- Leveille, R.A., Newberry, R.J. and Bull, K.F., 1988. An alkalinity-oxidation state diagram for discriminating some gold-favorable plutons. Abstract, Geological Society of America, Abstracts with Programs, Volume 20: 142.
- Levinson, A.A., 1980. Introduction to exploration geochemistry. (2nd ed.), Applied Publishing Ltd., Chicago.
- Li, H., Yen, V., 1995. *Fuzzy sets and fuzzy decision-making*. CRC Press, New York.
- Little, H.W., 1961. Geological map of British Columbia. Geological Survey of Canada, Map 932A.
- Loganathan, P., Burau, R.G., 1973. Sorption of heavy metal ions by a hydrous manganese oxide. *Geochimica et Cosmochimica Acta.*, 37: 1277-1294.

- Loggan, J.M., Panteleyev, A., 1991. Late Triassic early Jurassic alkaline magmatism and Cu-Au mineralization, Galore Creek, northwest British Columbia. Abstract, Canadian Institute of Mining and Metallurgy, 93rd Annual general Meeting, Vancouver, April 1991, 59 pp.
- Lowell, J.D. & Guilbert, J.M., 1970. Lateral and vertical alteration-mineralization zoning in porphyry ore deposits. *Economic Geology*, Vol.65: 373-408.
- Lueck, B.A., Neil, I. and Russell, J.K., 1993. The Rugged Mountain pluton: an example of the melanite bearing pyroxenite-syenite association. *Geological Association of Canada/Mineralogical Association of Canada, programs with Abstracts, Volume 18: A61.*
- Lueck, B.A., Russell, J.K., 1993. Silica-undersaturated, zoned, alkaline intrusions within the British Columbia Cordillera. *Geological Fieldwork 1993, Paper 1994-1: 311-315.*
- Lynch, J.J., 1992. Requests for proposals of analysis of water and stream sediment samples, National Geochemical Reconnaissance (NGR) Surveys Geological Survey of Canada and BC Regional Geochemical Survey.
- McClelland, W.C., Gehrels, G.E., Saleeby, J.B., 1992. Upper Jurassic-Lower Cretaceous basinal strata along the Cordilleran margin: Implications for the accretionary history of the Alexander-Wrangellia-Peninsular terrane. *Tectonics*, 11: No. 4: 823-835.
- MacLeod, I.N., Dobush, T.M., 1990. Geophysics: More than numbers processing and presentation of geophysical data. reprinted from the fourth national outdoor action conference on aquifer restoration, ground water monitoring and geophysical methods, May 14 - 17, Las Vegas, Nevada.
- Mardsen, H., Thorkelson, D.J., 1992. Geology of the Hazleton volcanic belt in British Columbia: implications for the Early to Middle Jurassic evolution of Stikinia. *Tectonics*, 11: 1266-1287.
- McIntyre, J.I., 1980. Geological significance of magnetic patterns related to magnetite in sediments and metasediments- A review. *Bulletin of Australian Society of Exploration Geophysicists*, 11: 19-33.
- McMillan, W.J., 1971. Valley Copper, B.C. Department. of Mines and Petroleum Resources, *Geology, Exploration & Mining*, 1970: 354-369.
- McMillan, W.J., 1973. J.A., B.C. Department. of Mines and Petroleum Resources, *Geology, Exploration & Mining*, 1972: 171-179.
- McMillan, W.J., 1976, Geology and genesis of the Highland Valley ore deposits and the Guichon Creek batholith. In A. Sutherland Brown (Editor), *Porphyry deposits of the Canadian Cordillera*, Canadian Institute of Mining and Metallurgy, Special Volume 15: 85-104.

- McMillan, W.J., Panteleyev, A., 1988. Porphyry copper deposits; in ore deposit models. Roberts, R.G. and Sheahan, P.A., (Editors), Geoscience Canada Reprint Series 3, Geological Association of Canada, 45-58; also in Geoscience Canada, Volume 7, No. 2: 52-63.
- McMillan, W.J., 1991. Porphyry deposits in the Canadian Cordillera. In ore deposits, tectonics and metallogeny in the Canadian Cordillera. British Columbia Ministry of Energy, Mines and Petroleum Resources, Paper 1991: 253-276.
- McMillan, W.J., 1994. Overview of the tectonic evolution and setting of mineral deposits. in the Canadian Cordillera in Ore deposits, tectonics and metallogeny in the Canadian Cordillera, Paper 1991-4, McMillan W.J., Hoy, T. , MacIntyre D.G., Nelson, J.L., Nixon, G.T., Hammac, J.L., Panteleyev, A., Ray, G.E., Webster, I.C.L., British Columbia Ministry of Energy, Mines and Petroleum Resources, pp. 276.
- McMillan, W.J., Thompson, J.F.H., Hart, C.J.R. and Johnston, S.T., 1995. Regional geological and tectonic setting of porphyry deposits in British Columbia and Yukon Territory. In T.G. Schroeter (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining and Metallurgy special Volumes 46: 40-57.
- Mihalynuk, M.G., Nelson, J. and Diakow, L.J., 1994. Cache Creek terrain entrapment: oroclinal paradox within the Canadian Cordillera. Tectonics, 13: No.2: 575-595.
- Mills, J.W., 1972. Origin of copper-bearing breccia pipes, Economic Geology, 67: 533-535.
- Monger, J.W.H. Wheeler, J.O., Tipper, H.W., Gabrielse, H., Harms, T., Struik, L.C., Campbell, R.B., Dodds, R.B., Gehrels, G.E. and O'Brien, J., 1991. part B. Cordilleran terrains, upper Devonian to Middle Jurassic assemblages. In H. Gabrielse and C.J. Yorath (Editors), Chapter 8 of Geology of the Cordilleran Orogen, Canada, Geological Survey of Canada, pp 281-327.
- Monger, J.W.H., 1972. Oceanic crust in the Canadian Cordillera; Contribution #4: in the ancient oceanic lithosphere, Canadian Contributions Numbers 1-11 to the Geodynamics Project. Earth Physics Branch, Energy, Mines and Resources, Canada, 42: No.3: 59-64.
- Monger, J.W.H., 1989. Overview of Cordilleran geology; in B. Ricketts (Editor), Western Canada sedimentary basin: A case history. Canadian Society of Petroleum Geologists, Chapter 2.
- Monger, J.W.H., 1991. Terrane concepts: Southern British Columbia. Abstract, Kamloops Exploration Group, April 1991.
- Monger, J.W.H., Price, R.A. and Tempelman-Kluit, D.J., 1982. Tectonic accretion and the origin of the two major metamorphic and plutonic belts in the Canadian Cordillera. Geology, 10: 70-75.

- Monger, J.W.H., Ross, C.A., 1971. Distribution of fusulinaceans in the western Canadian Cordillera. *Canadian Journal of Earth Sciences*, 8: 259- 278.
- Montgomery, J.H., 1967. Petrology, structure and origin of the Copper Mountain intrusions near Princeton, British Columbia. unpublished Ph.D. thesis, UBC.
- Moore, D., G. McCabe, 1993. Introduction to the practice of statistics. W.H. Freeman and Company, New York, 854 pp.
- Moore, W.J., Ianphere, M.A. and Obraddovich, J.D., 1968. Chronology of intrusion, volcanism and ore deposition at Bingham, Utah. *Economic Geology*, 63: 612-621.
- Mutschler, F.E., Mooney, T.C., and Johnson, D.C., 1990. Precious metal deposits related to alkaline igneous rocks- A space-time trip through the Cordillera. In *Proceedings of the Fourth Western Regional Conference on Precious metals and Environment, Society for Mining, Metallurgy, and Exploration SME-AIME*, 43-59.
- Mutschler, F.E., Wright, E.G., Ludington, S. and Abbott, J.T., 1981. Granite molybdenum systems. *Economic Geology*, 76: 874-897.
- Naciuk, T.M., Hawkins, T.G., 1995. The Katie copper-gold porphyry deposit, south-eastern British Columbia. In Schroeter, T.G (Editor), *Porphyry deposits of the north-western Cordillera of North America*, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 666-673.
- Nelson, J.L., 1991. The tectonic setting of alkaline porphyry suite copper-gold deposits in the Canadian Cordillera. 93rd Annual General Meeting, Abstract. Canadian Institute of Mining, Metallurgy and Petroleum, Vancouver, British Columbia, April 1991, 57 pp.
- Nelson, J.L., 1993. The Sylvester Allochthon: upper Palaeozoic marginal-basin and island-arc terrains in northern British Columbia. *Canadian Journal of Earth Sciences*, 30: 631-643.
- Nelson, J.L., MacIntyre, D., 1989. Metallogeny of north-eastern British Columbia. *Geoscience Canada*, 15: 113-116.
- Ney, C.S., 1972. Berg prospect. 24th Int. Geol. Congress, Field Excursion A09-C09, Copper and molybdenum deposits of the Western Cordillera, Guidebook, 25-27.
- Ney, C.S., 1976. Distribution and genesis of copper deposits in British Columbia. *CIM Special Volume*, 8, Tectonic history and mineral deposits of the western Cordillera, 295-303.
- Nielsen, R.L., 1976. Recent developments in the study of porphyry copper geology: A review. In A. Sutherland Brown (Editor), *Porphyry deposits of the Canadian Cordillera*, Canadian Institute of Mining and Metallurgy, Special Volume 15: 487-500.
- Northcote, K.E., 1969. Geology and geochronology of the Guichon Creek batholith, B.C. Department of Mines and Petroleum Resources, Bulletin No. 56.

- Northcote, K.E., 1973. Island Copper, B.C. Department of Mines and Petroleum Resources, Geology, Exploration & Mining, 1972: 293-303.
- Northcote, K.E., 1974. Geology of northwest half of Iron Mask batholith, B.C. Department of Mines and Petroleum Resources; Geological Fieldwork, 1974, 22 pp.
- Norton, D.L., and Cathles, L. M. 1973. Breccia pipes —Products of exsolved vapor from magmas, *Economic Geology*, 68: 540-546.
- Nowlan, G.A., 1976. Concretionary manganese-iron oxides in streams and their usefulness as a sample medium for geochemical prospecting. *Journal of Geochemical Exploration*, 6: 193-210.
- Olade, M.A., Fletcher, W.K., 1976. Trace element geochemistry of the Highland Valley and Guichon Creek batholith in relation to porphyry copper mineralization. *Economic Geology*, 71: 733-748.
- Open files of map sheets 2038, 2039, 2040, 2182, 2183, 2184, 867,865 of National Geochemical Reconnaissance Survey NGR, Geological Survey of Canada.
- Osborne, W.W., Allen D.G., 1995. The Taseko copper-gold-molybdenum deposit in central British Columbia. In Schroeter, T.G (Editor), *Porphyry deposits of the north-western Cordillera of North America*, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 441-450.
- Panteleyev, A., 1973. GC, HAB, BUY Stikine Copper B.C. Department of Mines and Petroleum Resources, Geology, Exploration & Mining, 1972: 520-526.
- Panteleyev, A., 1995a. Porphyry Cu-Au: Alkalic, in *Selected British Columbia Mineral Deposit Profiles, Volume 1 - Metallics and Coal*, Lefebure, D.V. and Ray, G.E., Editors, British Columbia Ministry of Energy of Employment and Investment, Open File 1995-20, pages 83-86.
- Panteleyev, A., 1995b. Porphyry Cu+/-Mo+/-Au, in *Selected British Columbia Mineral Deposit Profiles, Volume 1 - Metallics and Coal*, Lefebure, D.V. and Ray, G.E., Editors, British Columbia Ministry of Energy of Employment and Investment, Open File 1995-20, pages 87-92.
- Parasnis, D.S., 1996. *Principles of applied geophysics*. (4th ed.), Chapman-Hall, London.
- Parrish, R.R., 1983. Cenozoic thermal evolution and tectonics of the Coast Range of British Columbia: Fission track dating, apparent uplift rates, and patterns of uplift. *Tectonics*, 2: 601-631.
- Percival, J.A., Card, K.D., 1983. Archean crust as revealed in the Kapuskasing uplift, Superior Province, Canada. *Geology*, 11: 323-326.

- Perry, V.D., 1961. The significance of mineralized breccia pipes, Mining Engineering, 13: 367-377. petrology, and tectonogenesis. Economic Geology, 75th Anniversary Volume: 214-235.
- Plimer, I.R., Elliott, S.M., 1979. The use of Rb/Sr ratio as a guide to mineralization. Journal of Geochemical Exploration, 12: 21-34.
- Preto, V A., 1974. Geology of Aspen Grove area notes B.C. Department. of Mines and Petroleum Resources, Preliminary Map No. 15.
- Preto, V.A., 1972: Geology of Copper Mountain, B.C. Department of Mines and Petroleum Resources, Bulletin No. 59.
- Preto, V.A., 1977. Report on Afton, pothook; geology, exploration and mining in British Columbia. British Columbia Ministry of Energy, Mines and Petroleum Resources, 1972: 209-220.
- Preto, V.A., 1979, Geology of the Nicola group between Merritt and Princeton. British Columbia Ministry of Energy Mines and Petroleum Resources, 69: 90 pp.
- Price, R.A., Carmichale, D.M., 1986. Geometric test for Late Cretaceous-Paleogene intracontinental transform faulting in the Canadian Cordillera. Geology, 14: 468-471.
- Raines, G.L., 1978. Porphyry copper exploration model for northern Sonora, Mexico. Journal of Research , U.S. Geological Survey, 6: No. 1: 51-58.
- Rebagliati, M., Copeland D., 1989. Mount Milligan: an alkalic intrusive related gold-copper deposit. Mineral Deposits Division, Geological Association of Canada, Copper Gold Porphyry Workshop, Vancouver, and April, 1989.
- Reynolds, L.R., Rosenbaum J.G., Hudson, M.R. and Fishman, N.S., 1990. Rock magnetism, the distribution of magnetic minerals in the earth's crust, and aeromagnetic anomalies. In Geologic Applications of Modern Aeromagnetic Surveys, Proceedings of the U.S. geological Survey workshop on Geological Applications of Modern Aeromagnetic Surveys held January 6-8, 1987, in lakewood, Colorado, U.S. Geological Survey Bulletin No.1924: 24-45.
- Rice, H.M.A., 1974. Geology and mineral deposits of Princeton map area. Geological Survey of Canada, Mem. 243.
- Richardson, P.W., 1995. The Whipsaw porphyry system, Similkameen district, British Columbia. In Schroeter, T.G (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 530-533.
- Rock, N.M.S., 1988. Numerical Geology. Springer-Verlag, Berlin.
- Rose, A.W., Hawkes, H.E. and Webb J.S., 1979. Geochemistry in mineral exploration. (2nd ed.), Academic Press, London.

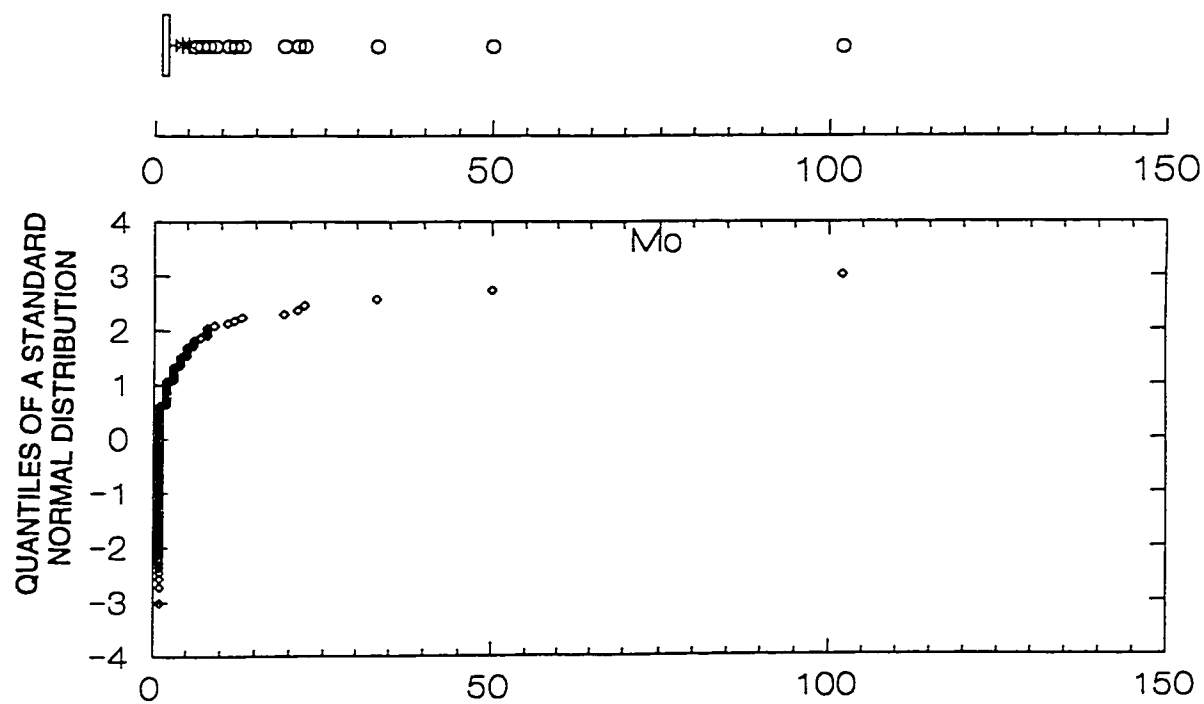
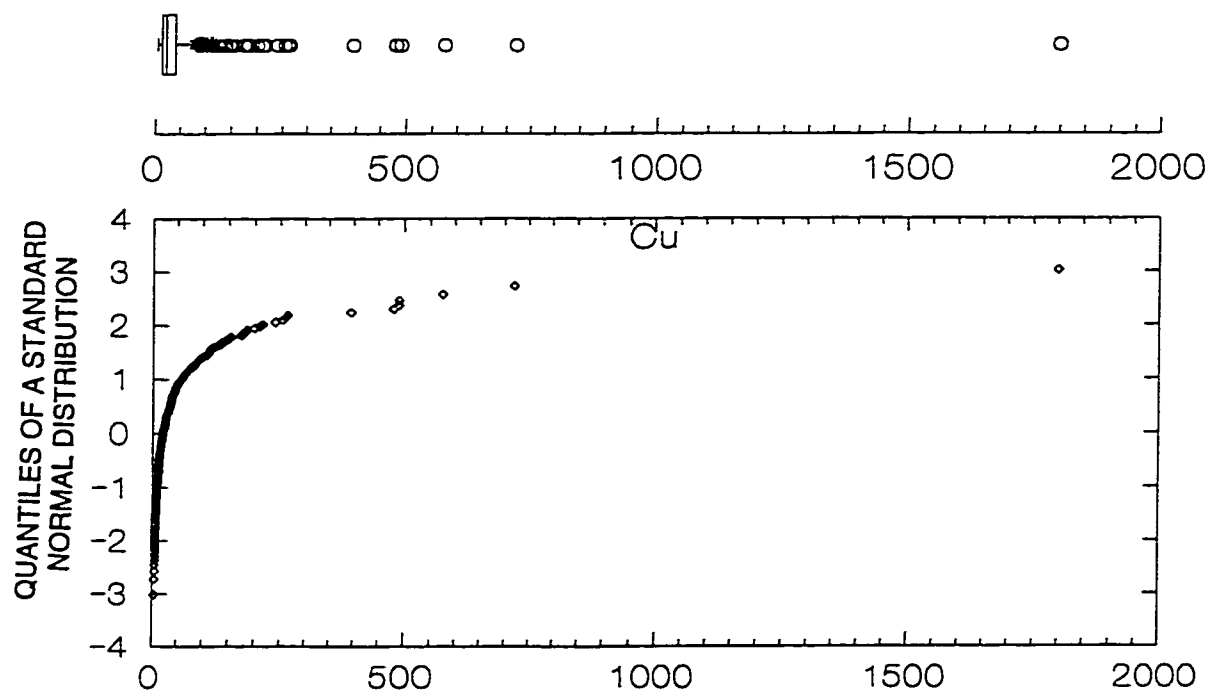
- Schroeter, T.G., 1997. British Columbia mineral exploration review-1996. B.C. Ministry of Employment and Investment.
- Seraphim, R.H., Hollister, V.F., 1976. Structural settings. In A. Sutherland Brown (Editor), Porphyry deposits of Canadian Cordillera. Canadian Institute of Mining and Metallurgy Special Volume 15 : 30-43.
- Sillitoe, R.H., 1972. A plate tectonic model for the origin of porphyry copper deposits. *Economic Geology*,
- Sillitoe, R.H., 1979. Some thoughts on gold-rich porphyry copper deposits. *Mineralium Deposita*, 14: 161-174.
- Sillitoe, R.H., 1987. Copper, gold and subduction: A trans-Pacific perspective; Pacific Rim Congress, Gold Coast, Australia.
- Sillitoe, R.H., 1989, Gold and silver deposits in porphyry systems. In Schafer, R.W., Cooper, J.J. and Vikre, P.G., (Editors), Bulk mineral precious metal deposits of the western United States, Symposium Proceedings, Geological Society of Nevada, 233-257.
- Sillitoe, R.H., 1991. Gold-rich porphyry copper deposits: Occurrence, model and exploration implications; in Mineral Deposit Modelling Session, International Association for the Genesis of Ore Deposits IAGOD, 8th Symposium, Ottawa, Ontario, August, 1990.
- Sillitoe, R.H., 1993. Gold-rich porphyry copper deposits: Geological model and exploration implications. In R.V. Kirkham, W.D. Sinclair, R.I. Thorpe and J.M. Duke (Editors), Mineral Deposit Modelling, Geological Association of Canada Special Paper 40: 465-478.
- Sinclair, W.D., 1995. Porphyry Mo (Low-F-type), in Selected British Columbia Mineral Deposit Profiles, Volume 1 - Metallics and Coal, Lefebvre, D.V. and Ray, G.E., Editors, British Columbia Ministry of Energy of Employment and Investment, Open File 1995-20, pages 93-96.
- Singer, D.A. 1993. Basic Concepts in Three-part Quantitative Assessments of Undiscovered Mineral Resources; Nonrenewable Resources, Volume 2, No. 2, pages 69-81.
- Sketchley, D.A., Rebagliati, C.M. and DeLong, C., 1995. Geology, alteration and zoning patterns of the Mount Milligan copper-gold deposits. In T.G. Schroeter, (Editor), Porphyry deposits of the north-western Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 650-665.
- Soregaroli, A.E., 1975. Geology of porphyry copper and molybdenum deposits. Geological Survey of Canada, Paper 75-1, 244 pp.

- Souther, J.G., Simons, R.T.A., 1972. Stratigraphy and paleomagnetism of Mount Edziza volcanic complex, northwestern British Columbia. Geological Survey of Canada, Paper 73-32.
- TYDAC, 1997. SPANS 7.0 Explorer manual, Nepean, TYDAC Research Inc.
- SPSS, 1993. Advanced Statistics, Release 6.0., SPSS Inc., Chicago, IL., 578 pp.
- Stanley, C.R., Holbek, P.M., Huyck, H.L.O., Lang, J.R., Preto, V.A.G., Blower, S.J. and Bottaro, J.C., 1995. Geology of the Copper Mountain alkalic copper-gold porphyry deposits, Princeton, British Columbia. In T.G. Schroeter (Editor) Porphyry Deposits of the Northwestern Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 537-564.
- Stringham, B., 1966. Igneous rock types and host rocks associated with porphyry copper deposits. In S.R., Titley and C.L. Hicks (Editors), Geology of porphyry copper deposits, southwestern North America. University of Arizona Press, 35-40 pp.
- Strong, D.F., 1981. A model for granophile mineral deposits. In ore deposit models, Geoscience Canada Reprint Series 3: 155-161.
- Sutherland Brown, A., 1971. Metallogeny of the Canadian Cordillera. Transactions, Canadian Institute of Mining and Metallurgy, 74: 1-25.
- Sutherland Brown, A., Cathro, R.J., 1976. A perspective of porphyry deposits. In A. Sutherland Brown (Editor) Porphyry Deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 7-16.
- Symons, D.T.A., Wellings, M.R., 1989. Paleomagnetism of the Eocene Kamloops Group and the cratonization of terranes of the Canadian Cordillera. Canadian Journal of Earth Sciences, 26: 821-828.
- SYSTAT, 1992. Statistics, Version 5. (2nd ed.), SYSTAT Inc., Evanston, IL., 724 pp.
- Telford, M.W., Geldart, L.P., Sheriff, R.E. and Keys, D.A., 1990. Applied geophysics. (2nd ed.), Cambridge University Press.
- Theodore, T.G., Menzie, W.D., 1984. Fluorine-deficient porphyry molybdenum deposits in the western North American Cordillera. In T.V. Janelidze and A.G. Tvalchrelidze (Editors), Proceedings of the Sixth Quadrennial Symposium, International Association on the Genesis of Ore Deposits, 463-470.
- Thompson, J.F.H., 1995. Exploration and research related to porphyry deposits. In T.G. Schroeter (Editor) Porphyry Deposits of the Northwestern Cordillera of North America, Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 46: 857-870.
- Thorkelson, D.J., 1992. Volcanic and tectonic evolution of the Hazelton Group in Spatsizi River 104H map-area, north-central British Columbia, Ph.D. thesis, 1-281, Carleton University, Ottawa, Ontario.

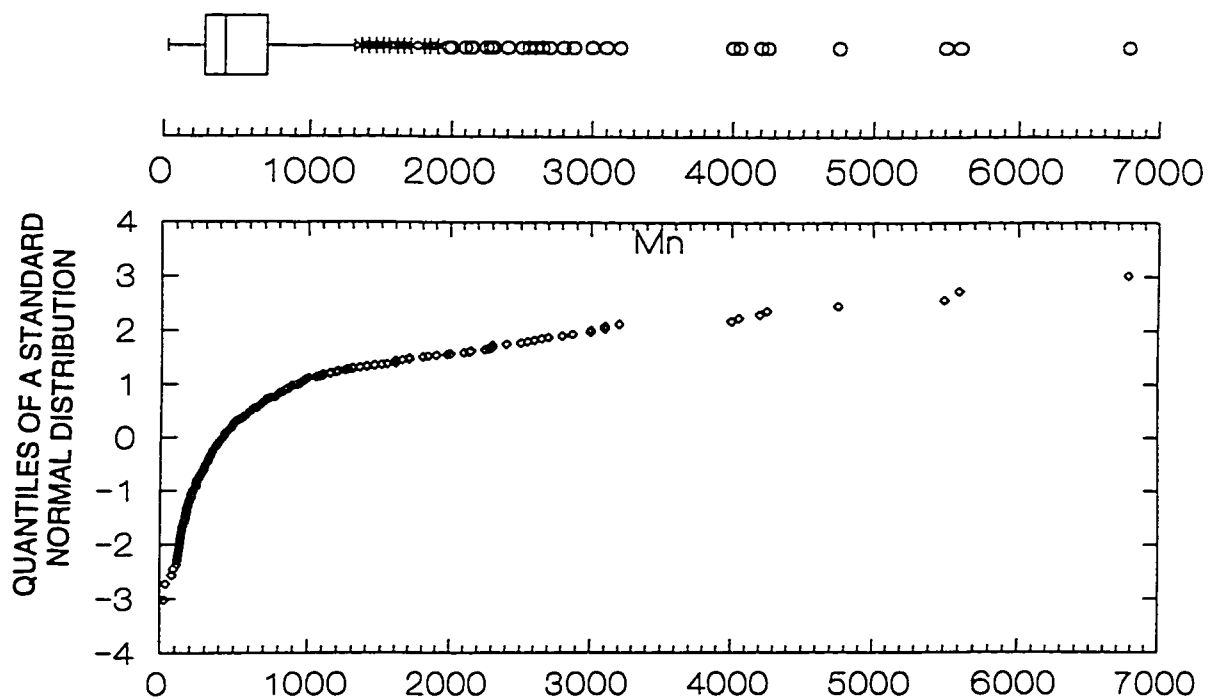
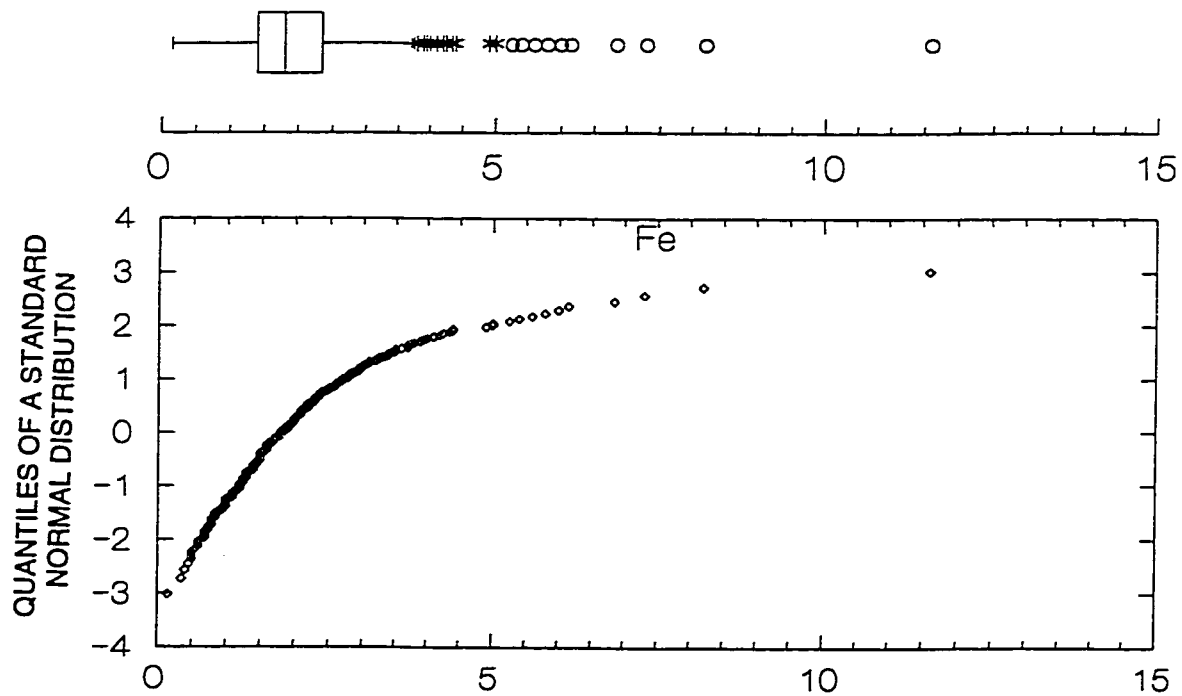
- Tipper, H.W., 1984. The Allochthonous Jurassic Lower Cretaceous terranes of the Canadian Cordillera and their relation to correlative strata of the North American craton; in Jurassic-Cretaceous Paleogeography of North America. In G.E.G. Westerman, (Editor), Geological Association of Canada, Special Paper 27: 113-120.
- Titley, S.R., Beane R.E., 1981. Porphyry copper deposits, part I and II, Economic Geology, 75th Anniversary vol.: 214-269.
- Titley, S.R.. Beane, R.E., 1981. Porphyry copper deposits. Part 1. Geological settings,
- Tripathi, V.S., 1979. Factor analysis in geochemical exploration, Journal of Geochemical Exploration, 11: 263-275.
- Turner, R.L., Raines, G.L., Kleinkopf, D. and Lee-Moreno, J.L. 1982. Regional northeast-trending structural control of mineralization northern Sonora, Mexico. Economic Geology, 77: 25-37.
- Van der Heyden P., 1992. A Middle Jurassic to Early tertiary Andean-Sierran arc model for the Coast Belt of British Columbia. Tectonics, 11: No. 1: 82-97.
- Vandall, T.A., Palmer, H.C., 1990. Upper limit of Docking time for Stikinia Terrane: Paleomagnetic evidence from the Eocene Ootsa Lake Group, British Columbia. Canadian Journal of Earth Sciences, 27: 212-218.
- Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V., Roest, W.R., 1997. Geological Map of Canada on CD-ROM, Geological Survey of Canada.
- Wernicke, B., Klepacki, D.W., 1988. Escape hypothesis for the Stikinia block. Geology, 16: 461-464.
- Westra, G., Keith, S.B., 1981. Classification and genesis of stockwork molybdenum deposits. Economic Geology, 76: 844-873.
- Wheeler, J.A., 1970. Structure of the southern Canadian Cordillera. Geological Association of Canada, Special Paper, 6.
- White, W.H., Bookstrom, A.A., Kamilli, R.J., Ganster, M.W., Smith, R.P., Ranta, D.E. and Steininger, R.C., 1981. Character and origin of Climax-type molybdenum deposits. Economic Geology, 75th Anniversary Volume: 270-316.
- White, W.H., Harakal, J.E. and Carter, N.C., 1968. Potassium-Argon ages of some ore deposits in British Columbia. CIM bulletin, 61: 1326- 1334.
- Wilks, S.S., 1962. Mathematical statistics. Wiley, New York, 644 pp.
- Wilson, R.L., Haggerty, S.E. and Watkins, N.D., 1968. Variation of paleomagnetic stability and other parameters in a vertical traverse of a single Icelandic lava. Geological Journal of Royal Astronomical Society, 16: 79-96.

- Woodcock, J.R., Carter, N.C., 1976. Geology and geochemistry of Alice Arm molybdenum deposits. In A. Sutherland Brown (Editor), Porphyry deposits of the Canadian Cordillera, Canadian Institute of Mining and Metallurgy, Special Volume 15: 462-475.
- Woodsworth, G.J., Anderson, R.G. and Armstrong, R.L., 1991. Plutonic regimes. In H. Gabrielse and C.J. Yorathed (Editors), Chapter 15 of Geology of the Cordilleran Orogen, Canada, Geological Survey of Canada, pp. 493-531.
- Woolverton, R., 1964. Report on the Morrison property, Morrison Lake Smithers British Columbia. Omineca Mining Division. Noranda Exploration Company, Limited Norpex Division.
- Wright, D.F., Bonham-Carter, G.F., 1996. VHMS favorability mapping with GIS-based integration models, Chisel Lake-Anderson Lake area in EXTECH I : A multidisciplinary approach to massive sulphide research in the rusty Lake-Snow Lake Greenstone Belts, Manitoba. In G.F. Bonham-Carter, A.G. Galley, and G.E.M. Hall (Editors), Geological Survey of Canada, Bulletin 426: 339-376, 387-401.
- Wright, P.M., 1981. Gravity and magnetic methods in mineral exploration. Economic Geology, 75th Anniversary Volume: 829-839.
- Zadeh, L.A., 1965. Fuzzy sets. Information and Control, 8: 338-353.
- Zadeh, L.A., 1986. Is probability theory sufficient for dealing with uncertainty: A Negative View, Elsevier Science Publishers B.V., 103-113.
- Zimmermann, H.J., 1991. Fuzzy set theory - and its applications. (2nd ed.), Kluwer-Nijhoff Publishing. Boston.

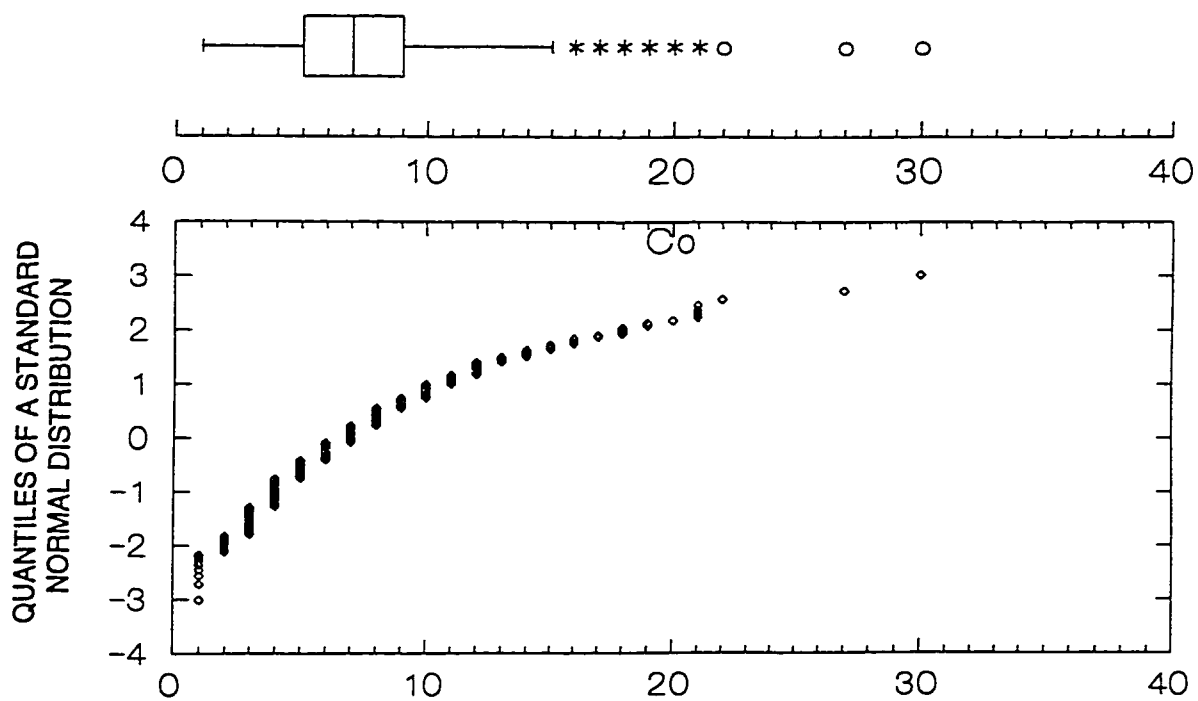
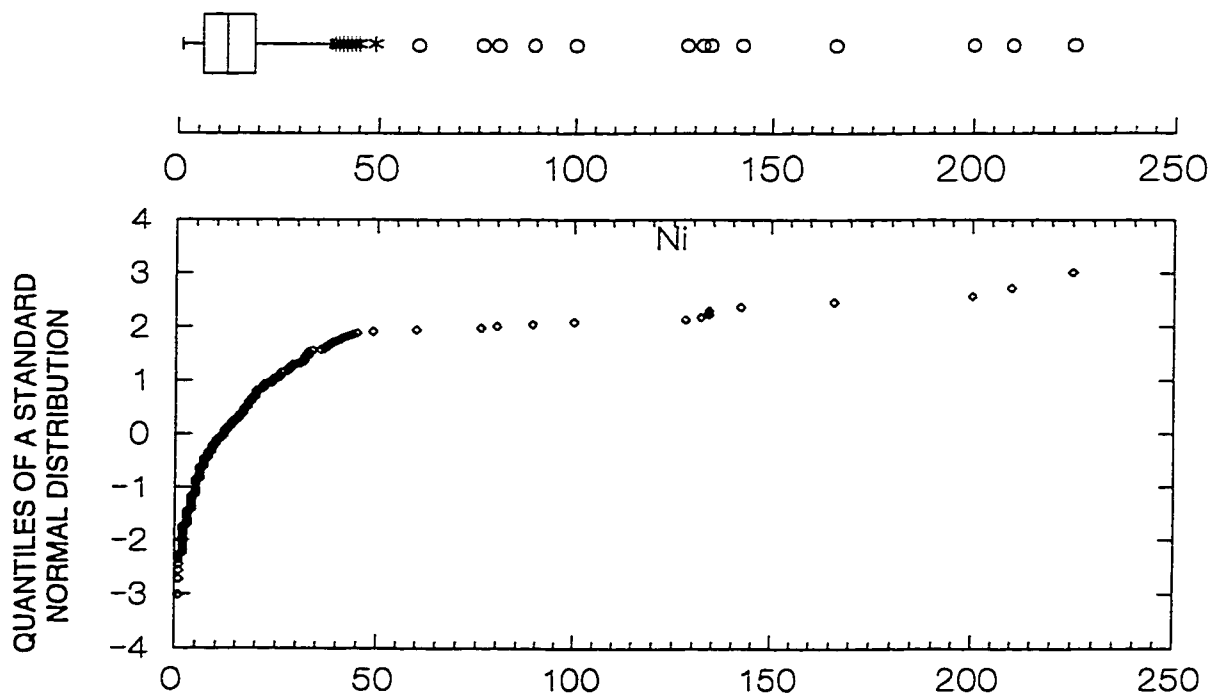
APPENDIX A-1



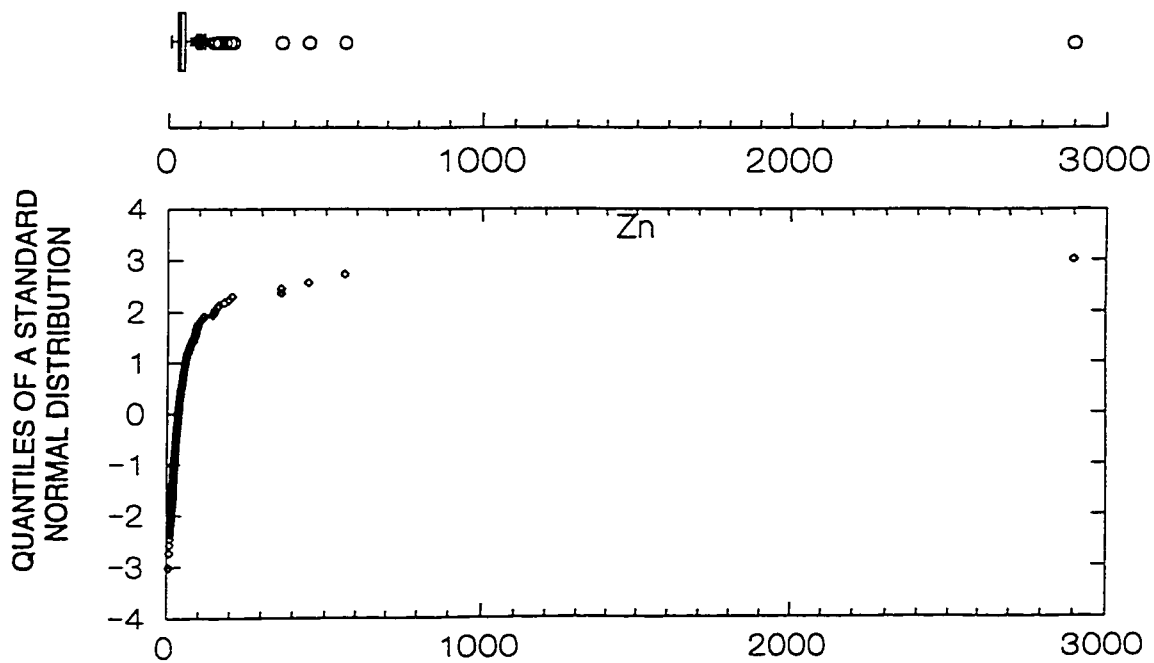
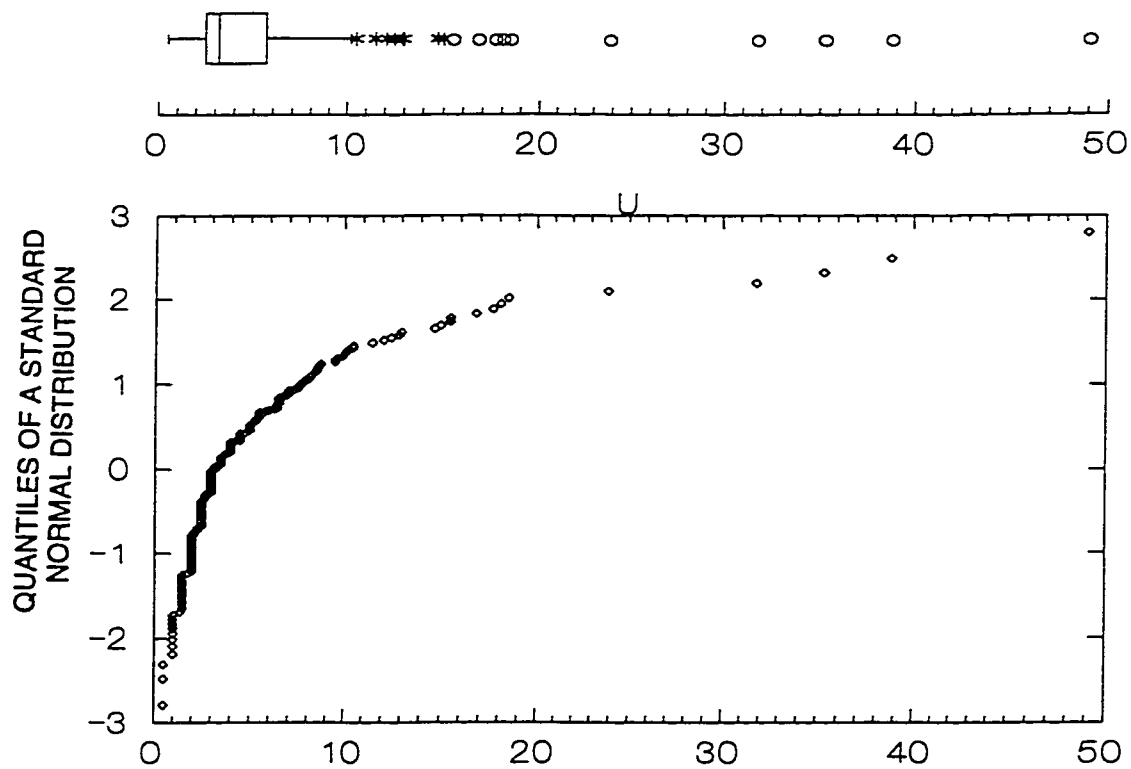
Guichon Plutonic Suite (EJqG)



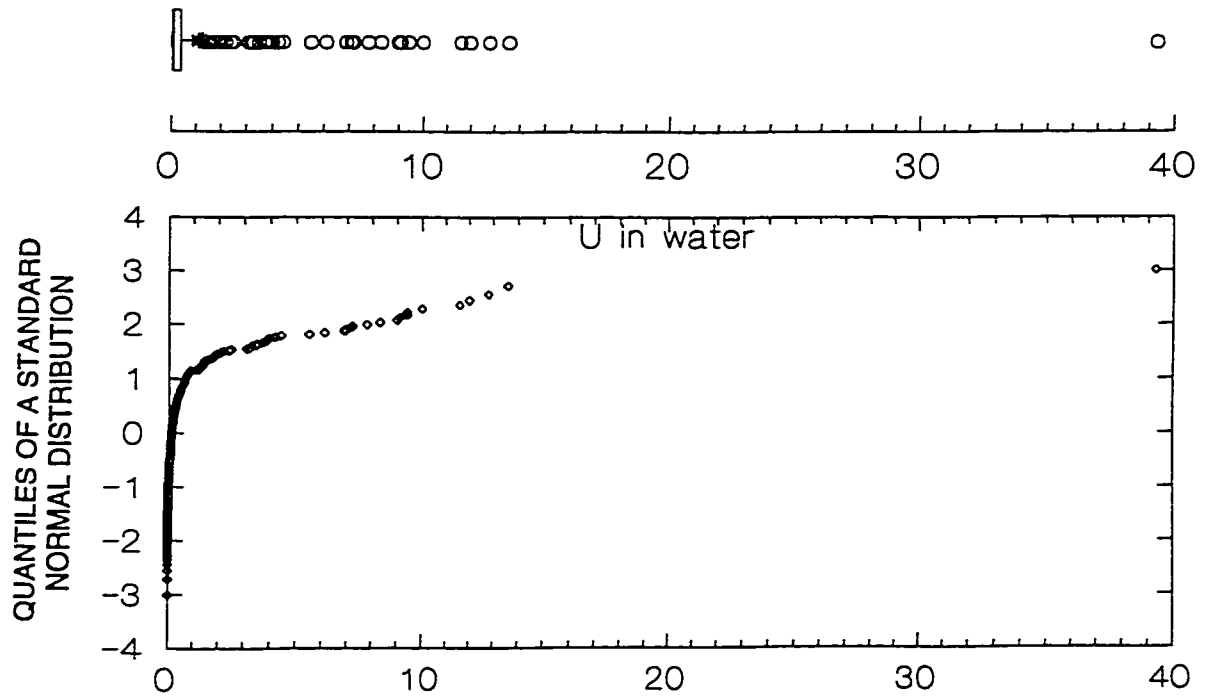
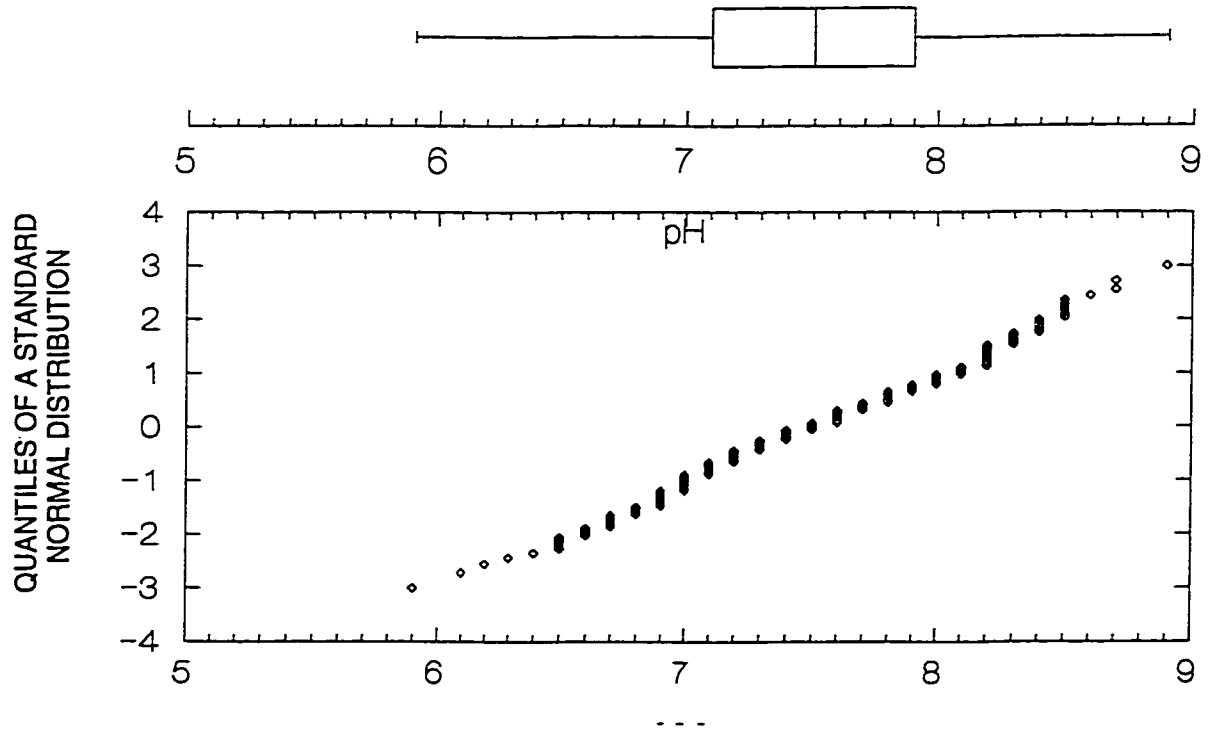
Guichon Plutonic Suite (EJgG)



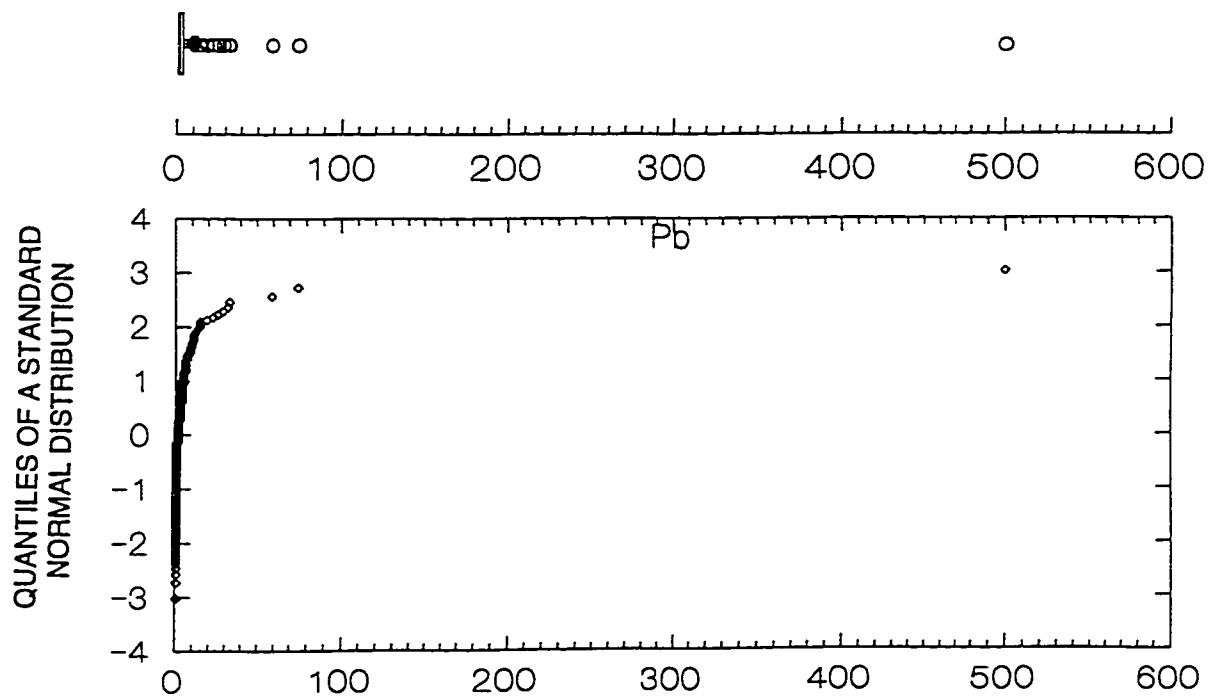
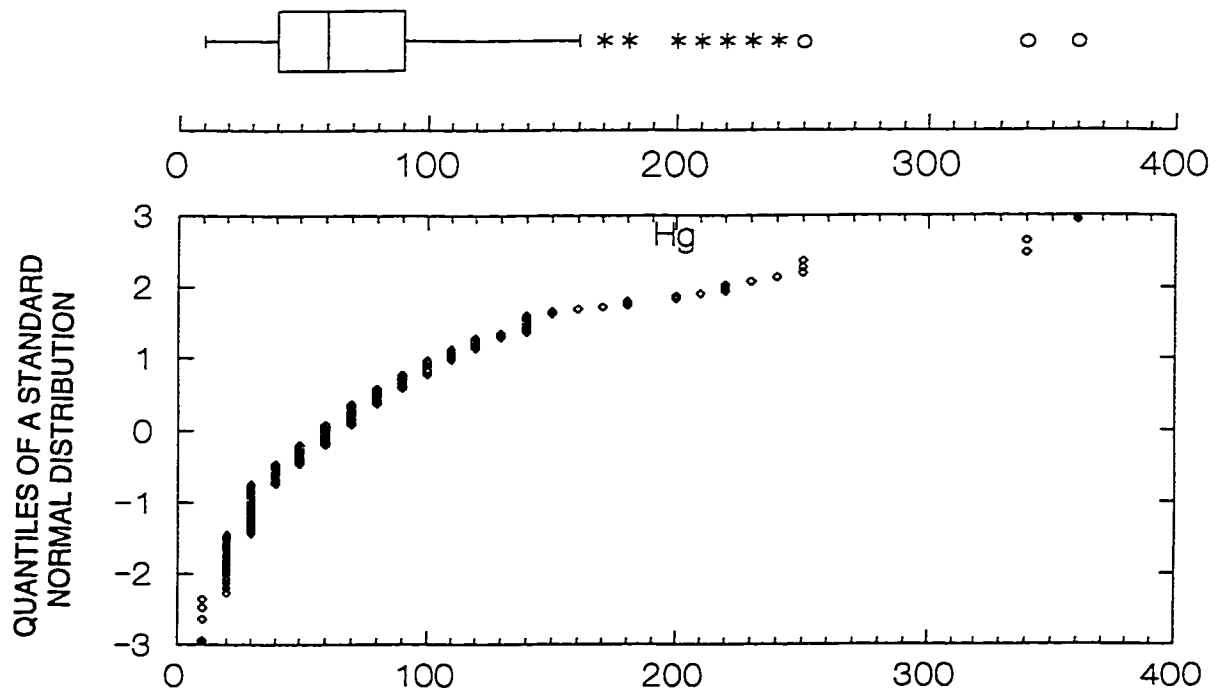
Guichon Plutonic Suite (EJgG)



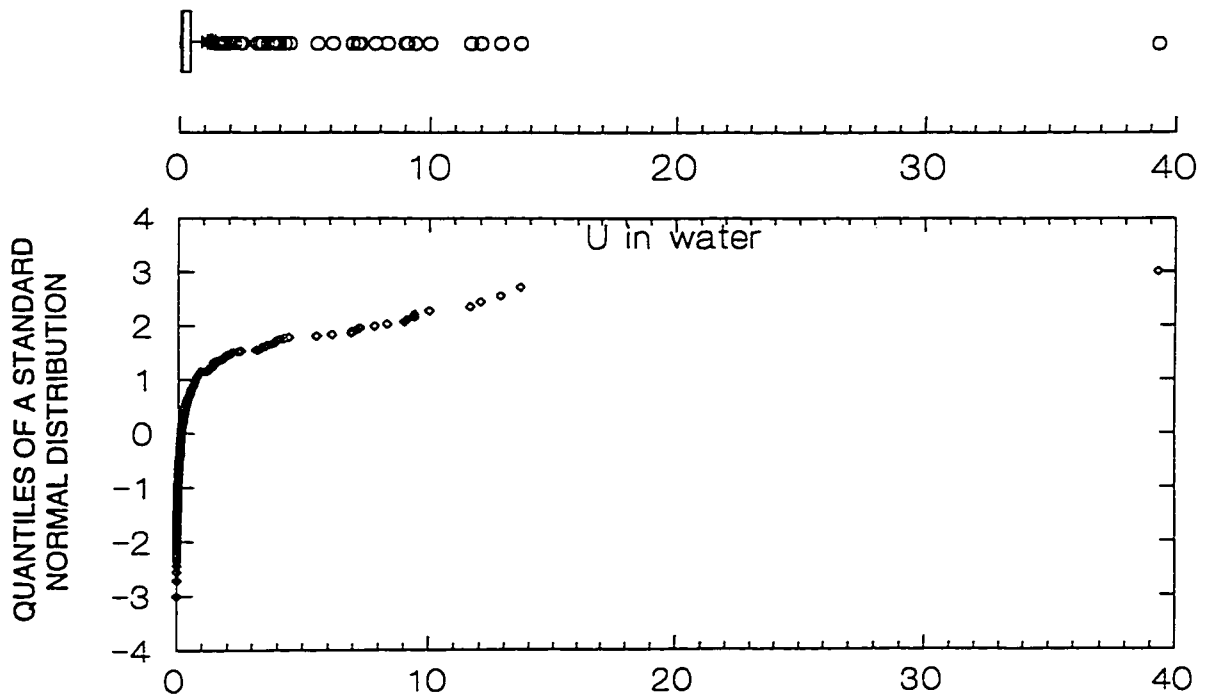
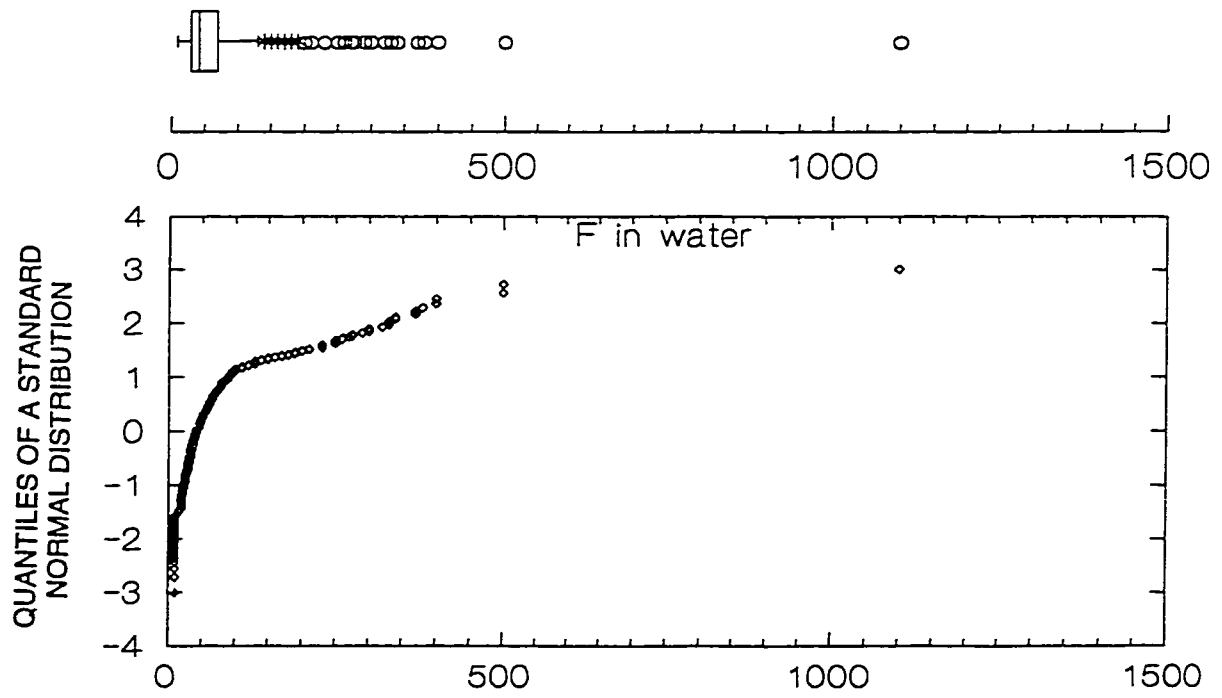
Guichon Plutonic Suite (EJqG)

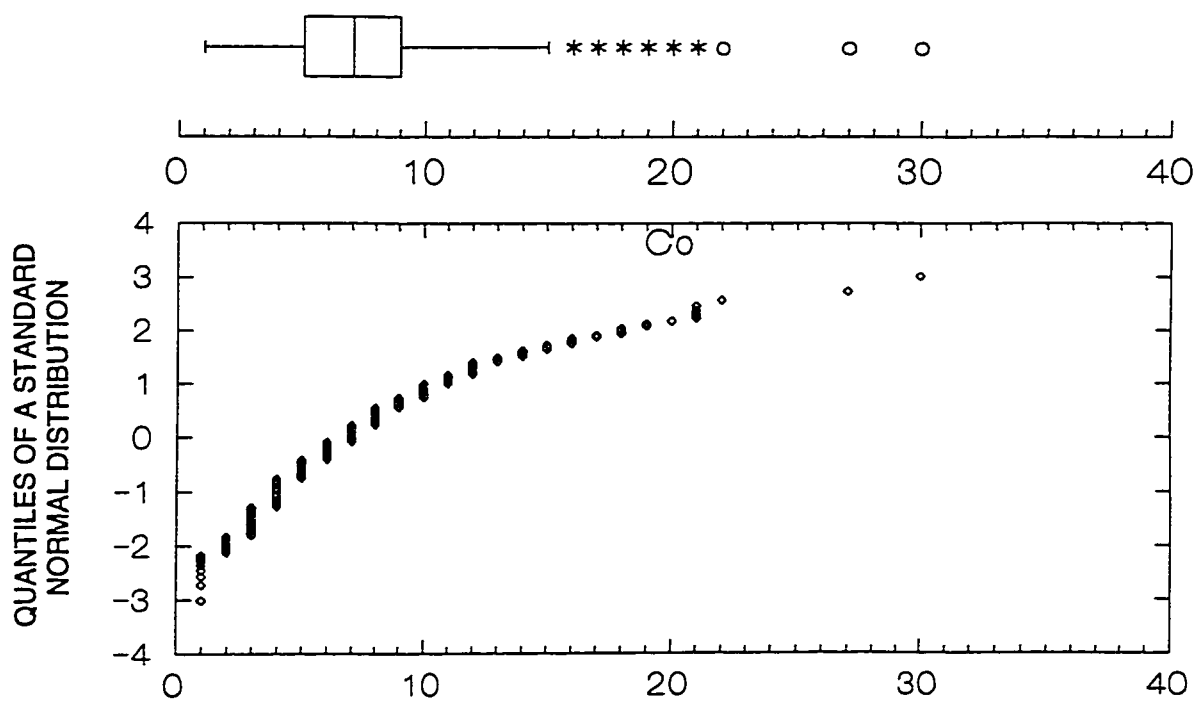
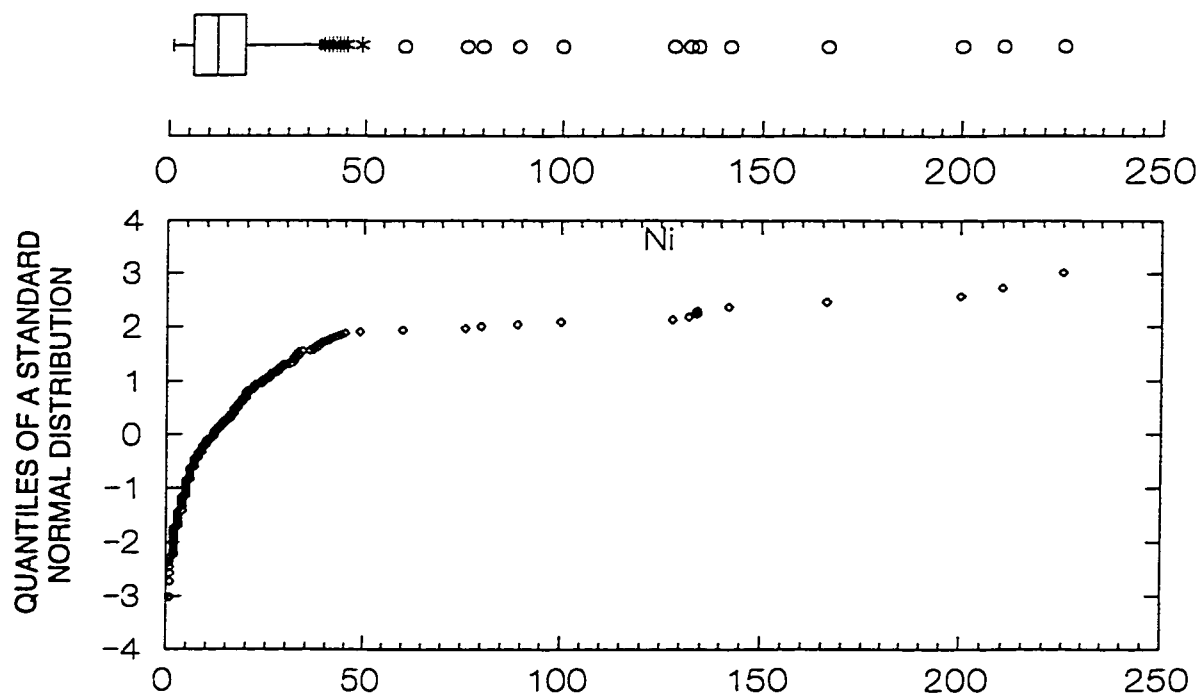


Guichon Plutonic Suite (EJqG)

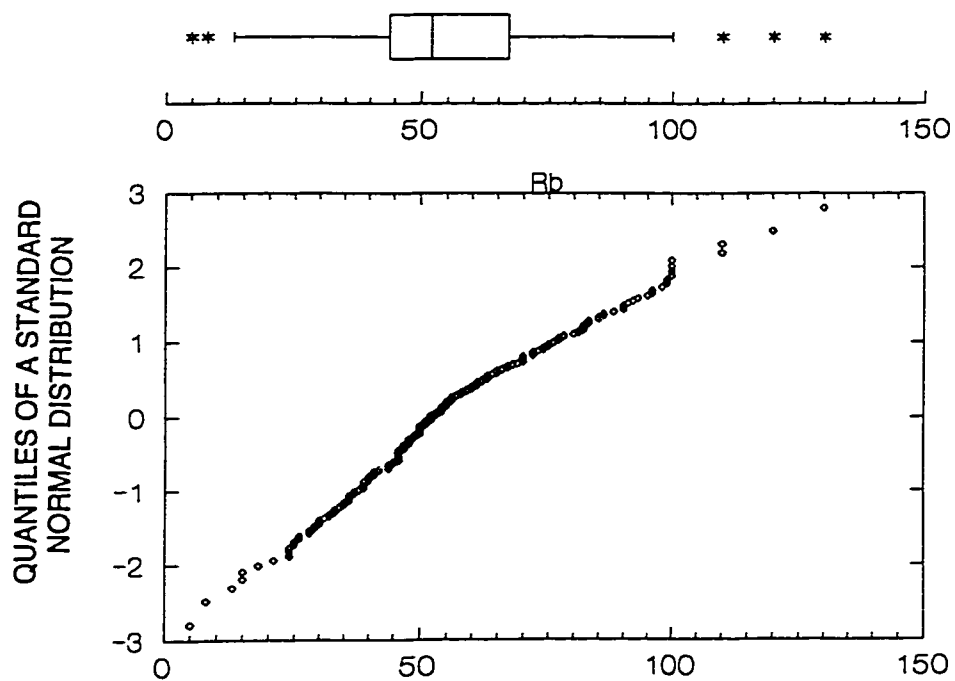
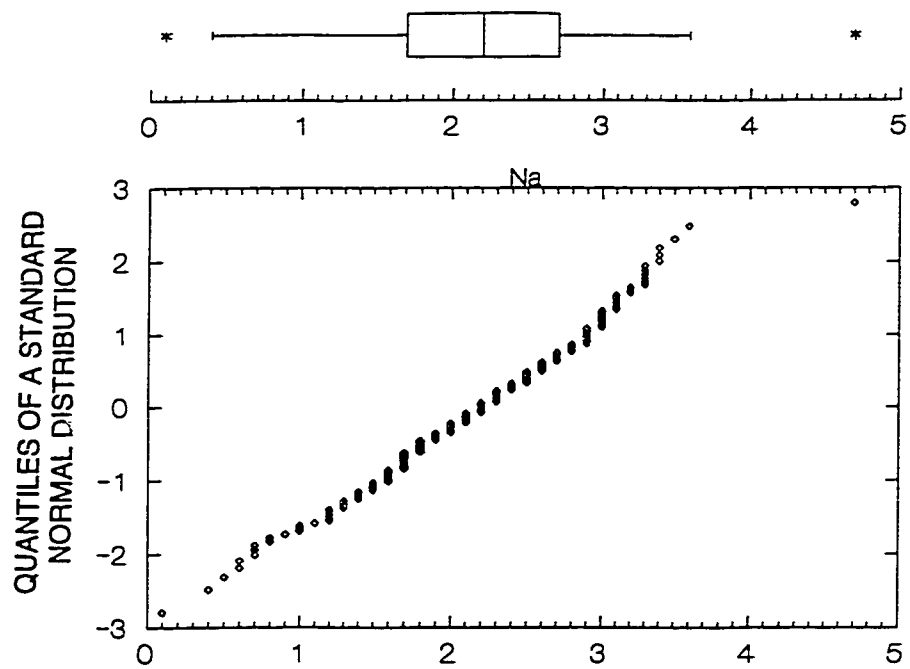


Guichon Plutonic Suite (EJqG)



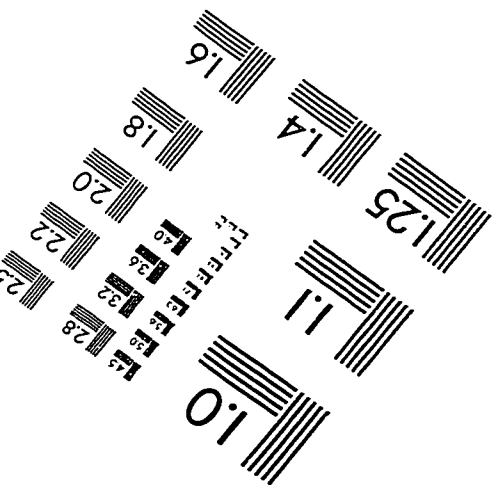
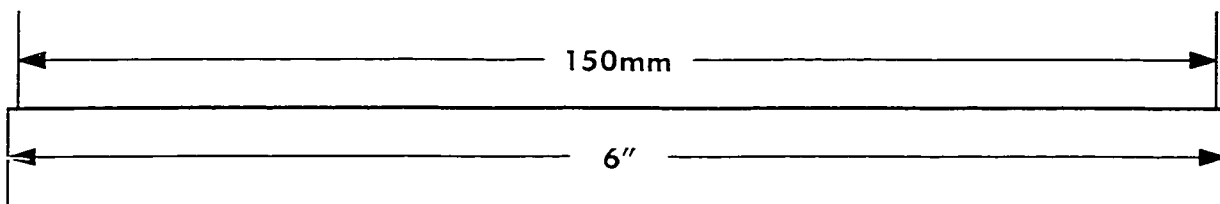
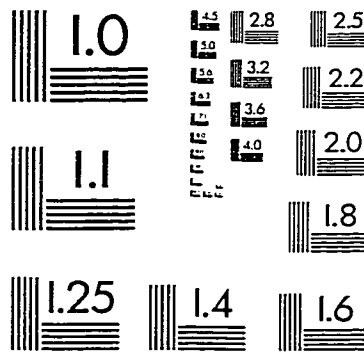
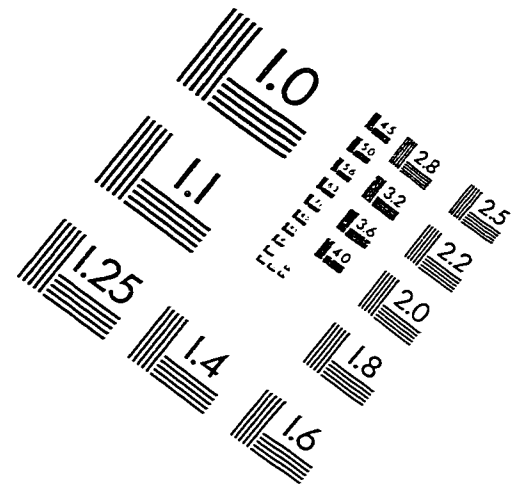
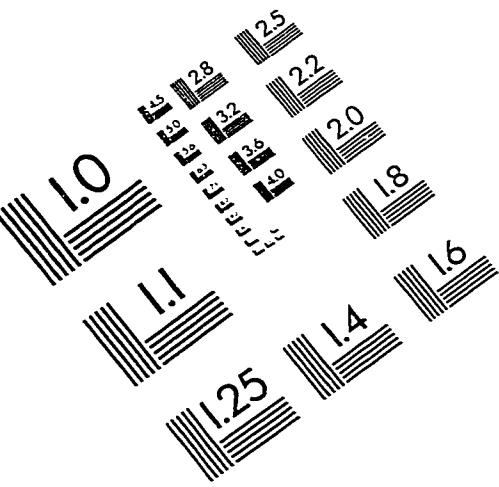


Guichon Plutonic Suite (EJgG)



Guichon Plutonic Suite (EJgG)

IMAGE EVALUATION TEST TARGET (QA-3)



APPLIED IMAGE, Inc.
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989

© 1993, Applied Image, Inc., All Rights Reserved

