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Regional geochemical study of Cretaceous acidic rocks in the northern Canadian Cordillera as a tool for broad mineral exploration

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Synopsis

A constant problem in the interpretation of geochemical exploration data is the varying background levels encountered in different sample materials. This problem is most severe with certain trace elements present in the common rock-forming minerals, e.g. copper and zinc in hornblende and biotite, and lead in potash feldspar. Variations in rock type, and, hence, mineralogy, lead to wide variations in whole-rock trace-element content.

The Geological Survey of Canada has undertaken a rock geochemistry programme in east and central Yukon, and, as part of this study, an approach to the interpretation of base-metal trace-element data has been evolved. Principal-component analysis is used to orthogonalize the major- and minor-element data, which leads to a new set of variables that tend to be geological-process-orientated rather than chemical-response-orientated. The principal-component scores are computed and selectively used in a multiple-regression model with the trace-element data. Attention is thereby focussed on samples having abnormal contents of the trace elements in terms of the geological processes represented in the sample.

The resulting screened data are compared with the raw data, both sets being interpreted in the light of the distribution of known mineral occurrences. The interpretative procedure evolved delineates certain bodies of acid plutonic rocks as being of interest in terms of mineral potential, whereas an inspection of the raw data either failed to indicate the nearby mineral occurrences or, more importantly, was not considered selective enough. On the basis of these findings it is concluded that the interpretative technique is locally of value and may have broader application to other problems and other areas.

The use of rock geochemistry as an exploration tool has not been extensive outside the U.S.S.R. Until recently, studies in the west have been relatively few and have tended to be of an academic nature. The last five years have seen a resurgence of interest in the methods by western geochemists—for a variety of reasons. Many of the early attempts in the use of rock geochemistry had limited success due to an inadequate understanding of the problems of acquiring truly representative samples. Adequate analytical techniques are now available, in terms of precision and productivity, to handle the large number of samples derived from well-planned sampling programmes. Rock geochemistry also offers a detour around the problems of modification of trace-element patterns imposed by the secondary environment, and leads to data which may be used for more basic studies related to regional petrogenesis and the geochemical relationship of the rocks to associated mineral occurrences.

The Geological Survey of Canada commenced a study of the application of the sampling and analysis of granitoid rocks in the Yukon and adjoining areas of the Northwest Territories in 1969. The objectives of the programme are twofold: first, to investigate the use of bedrock geochemistry as a tool for broad mineral reconnaissance—that is, to design a geochemical filter that could be used at an early stage of a planned exploration effort to select those areas of increased mineral potential out of a much larger area of general interest; and, secondly, by means of the data, to establish correlations between discrete plutonic bodies and investigate both the regional petrogenesis of the area within the tectonic framework of the Northern Cordillera and the geochemical relationships of the plutonic rocks to the mineral occurrences associated with them.

Description of field area

The field area forms part of the Cordilleran system, which can be traced from Antarctica, through the Americas and into the northeastern U.S.S.R. The granitoids of the Selwyn Fold Belt extend arcuately on the northeastern side of the Tintina Trench for some 500 miles between Watson Lake and Dawson. The data presented in this paper relate to the northern half of this belt between 60° 20′ N and 64° 40′ N (Fig. 1). The acid intrusive rocks exhibit K–Ar ages in the range 74–110 m. y. (Middle to Upper Cretaceous), and it is considered that the deformation just prior to the intrusion of the granitoids took place during the Columbian orogeny.[5] A wide range of compositions is present, extremes being alaskite, granite, syenite and quartz-diorite; however, the vast majority of the rocks are granodiorites or quartz-monzonites. The granitoids are intruded into sedimentary and metamorphic rocks of Proterozoic to Cretaceous age. The oldest rocks are Helikian and are found in the northern parts of the study area: these were deformed by the Racklan orogeny, and a great thickness of Hadrynian impure clastic sediments was then deposited. No definite unconformity has been observed between the Hadrynian sediments and the overlying Lower Cambrian miogeosynclinal rocks. Both Middle and Upper Cambrian rocks were deposited, but are only observed in the eastern part of the field area. The Selwyn Basin is composed mainly of Silurian graptolitic shales, siltstones and cherts; some Ordovician rocks may be present, and this whole assembly lies unconformably on Hadrynian rocks and grades upwards into eugeosynclinal Devono–Mississippian shales and chert-pebble conglomerates. In the northwest of the field area, near Dawson, Triassic shales occur, but apart from some sandstones and shales north of Ross River, Triassic strata are not found. Both Jurassic and Cretaceous sediments are found only in the northwest and north of the field area, and some Lower Cretaceous basaltic flows occur northeast of Ross River.

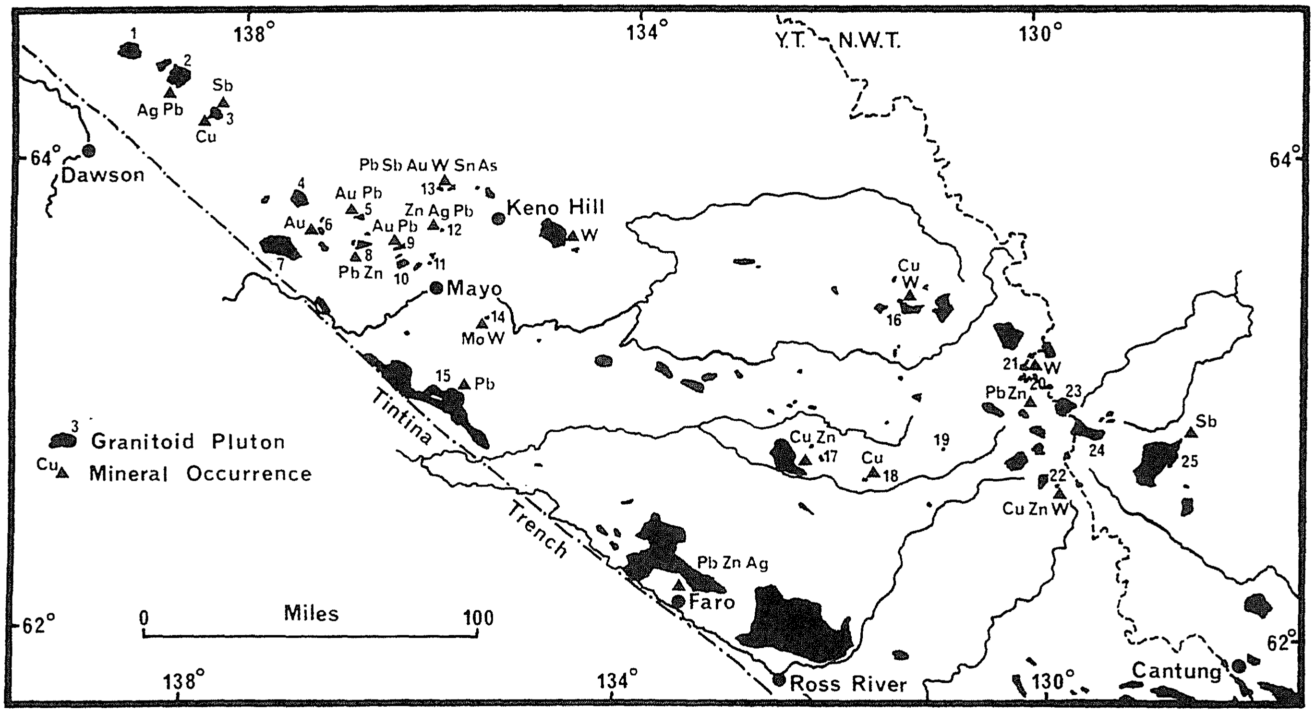

Fig. 1 Location of granitoids and major mineral occurrences

The intrusion of the Selwyn Belt granitoids was not accompanied by strong compressional activity, evidence for this being the lack of strong folding over much of the central part of the field area. Along the eastern margin and in the northwest of the field area folding was more intense, but the general tectonic situation in late Columbian times must have been one of platformal uplift.

Only to the south of the area discussed in this paper do the granitoids seem to have been involved in post-intrusion folding. One possible explanation could be that those intrusives were emplaced early and were competent before the close of the Columbian tectonic event.

The Selwyn Fold Belt hosts a number of mineral deposits, those of greatest economic importance being the lead–zinc deposits and silver–lead–zinc deposits. The massive strata-bound lead–zinc deposits at Faro and Macmillan Pass (20, see Fig. 1) are probably totally unrelated to the acid intrusive rocks. The silver–lead–zinc deposits of Keno Hill are vein-type and their origin is still open to conjecture; however, the only probable link with the granitoid intrusives is that they may have provided a heat source to stimulate a plumbing system that mobilized the ore elements from the surrounding country rock and transported them to depositional sites in the veins. There are two distinct areas of tungsten mineralization, both of which have a direct relationship to the granitoid intrusives. The first, known as the Selwyn Belt, lies in the Selwyn Mountains and consists of scheelite skarns with associated chalcopyrite developed in the country rock at or close to the contacts of the intrusives. The two most important occurrences are at Cantung and Mount Allan (21) near Macmillan Pass. The second, named the McQuesten Belt, consists of gold–tungsten mineralization with associated lead and antimony minerals in some instances. The tungsten occurs both in skarns as scheelite and also in quartz veins as scheelite and wolframite, and the gold occurs in arsenopyrite veins forming part of the same mineralization sequence. Important occurrences of this type occur at Potato Hills (13) and Scheelite Dome (9), north and west of Mayo. Throughout the Selwyn Fold Belt there are many scattered base-metal showings of varying significance, some of which also contain silver and antimony in important amounts.

Sampling and analytical methods

The granitoids were sampled by use of duplicates collected at an ideal minimum of 15 sites per pluton. This minimum number of sites yields sufficient data for the statistics computed on each pluton to be meaningful. The same general approach and number of samples collected is adopted in the U.S.S.R. in exploration programmes aimed at defining granitoids associated with tantalum and beryllium mineralization.[21] The duplicate sampling allows the use of analysis of variance to ascertain if any single pluton is internally zoned and to assess the overall significance of observed patterns in the data.[7] In fact, the number of sample sites per pluton varies considerably. In large intrusions many more than 15 sites are sampled so that zoning may be defined at any predetermined scale—usually one site per 1–2 square miles; and in small rugged intrusions it is often impracticable to sample more than six sites owing to the constraints of time set in a large regional sampling programme.

The samples weigh between 2 and 3 lb each and are comprised of fresh chips collected over a small area, the second sample collected at a site usually being removed from the first by some 20 ft. Care was taken at all times to ensure that unaltered rocks were sampled for the purposes of the statistical analysis of the data. In certain instances disseminated sulphides were observed in the rocks and, where these were widespread and not a feature of secondary alteration, those rocks were sampled. Separate samples were collected of altered rocks and vein mineralization, and these have not been included in the data under discussion. The problems of obtaining a random unbiased sample for geochemical programmes have been discussed by Miesch.[13] All but a hand specimen and material for thin-section work are reduced to −60 mesh, and a split of this material is ground to −100 mesh. The analyses for the major and minor elements were carried out after a lithium tetraborate fusion; Si, Al, Mg, Ca, Ti and Mn were determined by optical spectroscopy[4] and Na, K and Fe were determined by atomic absorption spectrophotometry after dissolution of the fusion product with dilute nitric acid. The trace-element determinations were carried out by atomic absorption spectrophotometry after a HF–$HClO_4$ attack; for Pb a deuterium arc lamp was used to correct for background variations in Ca and Mg.

Investigation of sampling and analytical variability: precision and accuracy

The analytical variances and precisions were determined by both replicate analysis of a bulk sample and a large number of repeat analyses of randomly chosen samples. These data, together with the overall sampling variability data derived from the duplicate sampling, were used in an analysis of variance (Table 1). All the elements exhibit a regional variability that is significantly higher, at the 99% level, than the local variability, the critical value for F being approximately 1·1 for 2135 and 2136 degrees of freedom at the 99% level. Of the major elements, it is noticeable that Al has the lowest F value: this reflects, first, the relatively high analytical variability for Al

Table 1 Analysis of sampling and analytical variance

	σ^2_D	σ^2_{SA}	F σ^2_D/σ^2_{SA}	σ^2_A	σ^2_S	σ^2_S/σ^2_A	$\bar{x}_1$	P	$\bar{x}_2$
Si	6·48	0·97	6·68	0·75	0·22	0·29	31·39	5·7	29·91
Al	0·56	0·17	3·29	0·17	0·00	0·02	8·72	8·9	9·27
Mg	0·53	0·03	17·67	0·01	0·02	3·82	1·03	11·9	1·33
Fe	1·26	0·12	10·50	0·01	0·12	23·59	2·59	6·9	2·16
Ca	1·12	0·12	9·33	0·02	0·10	4·06	2·62	12·3	2·49
Na	0·20	0·03	6·67	0·01	0·03	5·76	1·97	4·9	2·75
K	1·34	0·13	10·31	0·01	0·12	20·51	3·75	5·3	2·83
Ti	0·086	0·007	12·29	0·002	0·005	2·49	3·415	2·4	3·419
Mn	0·041	0·006	6·83	0·003	0·003	0·94	2·760	4·1	2·537
Zn	0·044	0·008	5·50	0·002	0·006	3·01	1·772	4·7	1·900
Cu	0·113	0·028	4·04	0·004	0·024	6·09	0·888	9·1	1·372
Pb	0·050	0·013	3·85	0·017	−0·004	−0·22	1·506	18·4	1·386

σ^2_D, Overall data variance. σ^2_{SA}, Combined sampling and analytical variance. σ^2_A, Analytical variance. σ^2_S, Estimate of on-site sampling variance. $\bar{x}_1$, Level at which analyses of variance were carried out. P, Analytical precision at 95% confidence level. $\bar{x}_2$, Level at which analytical precision was determined. Data for major elements recorded in per cent; minor and trace elements in ppm. Data for Ti, Mn, Zn, Cu and Pb have been $\log_{10}$-transformed.

and, second, the rather small total variability for Al in the granitoid environment. The percentage precision figures given in Table 1 were determined at the 95% confidence level at the analytical levels shown. These analytical levels are not identical to the overall data means at which the main test of variability is carried out. When the overall range of the data is considered, however, the differences are small and are not viewed as significant.

As variances are additive, it is possible to determine the local geological or sampling variability at the site for each element from the combined sampling and analytical variance and the analytical variance. Only in the cases of Fe and K is the sampling variability markedly higher than the analytical variance—indicating that only in the instance of these two elements could the sample sites not be considered homogeneous in terms of the measurement errors.

With regard to Pb, the analytical variance is greater than the combined sampling and analytical variance—thus leading to a negative site variance. This negative variance has no meaning and only emphasizes that the analytical variance is high with respect to the combined variances. Of the twelve elements determined, eight show sampling and local geological variability to be more than double the analytical variability. This feature serves to illustrate the importance of good sampling practice; in a general sense analysis is no longer the limiting factor that it was in geochemical surveys. Rather our comprehension of, and success in handling, sampling problems will govern our ability to successfully undertake effective surveys.

On the basis of these analyses of variance it was considered that the data were worthy of more rigorous analysis.

An investigation of the accuracy of the major- and minor-element data was undertaken. Ten samples selected from across the range of the data for each element were submitted for special analysis as sub-standards to the Analytical Chemistry Section of the Geological Survey of Canada. Determination of the major and minor elements was made after the method of Abbey[1] by use of the appropriate international standard rocks to bracket the unknowns. If it is assumed that the analyses so provided are a reasonable estimate of the actual amounts present, the percentage precision figures derived from the ten pairs of samples would be an estimate of the absolute percentage accuracy of the Yukon granitoid rock data (Table 2). It must be pointed out, however, that the accuracy figures are only an estimate, as at least 30 samples should be carefully treated in this fashion. Notwithstanding these limitations, the accuracy estimates do give a measure of the uncertainty involved in comparing the data with those derived by other workers.

Table 2 Inter-laboratory accuracy test

	$\bar{x}_1$	$\bar{x}_2$	Δx	$\bar{X}$	σ^2	σ	A
Si	29·02	29·24	−0·22	29·13	0·3632	0·6027	4·68
Al	8·96	8·51	0·45	8·74	0·2272	0·4767	12·34
Fe	3·99	4·09	−0·10	4·04	0·0466	0·2159	12·09
Mg	1·47	1·27	0·20	1·37	0·0326	0·1806	29·82
Ca	2·97	2·90	0·07	2·94	0·0471	0·2170	16·70
Na	1·76	1·70	0·06	1·73	0·0029	0·0539	7·05
K	3·76	3·61	0·15	3·69	0·0189	0·1375	8·43
Ti	3·4728	3·4472	0·0256	3·460	0·0023	0·0480	3·14
Mn	2·8015	2·7654	0·0361	2·784	0·0041	0·0640	5·20

$n = 10$. $t(9, 0{\cdot}95) = 2{\cdot}262$. $\bar{x}_1$, Determinations by Geochemistry Section. $\bar{x}_2$, Determinations by Analytical Chemistry Section. σ^2, Mean sum of squares of differences. A, Estimate of accuracy, made at 95% confidence level. Data for Ti and Mn have been $\log_{10}$-transformed.

Distribution of base metals in granitoids

The base-metal content of granitoids varies with position in the differentiation series, quartz-diorite to granite, and diorite to syenite. Clarkes computed for the base metals, together with the results of this study, are given in Table 3. Additionally, figures published by Tauson[22] are quoted which indicate the between-phase variations of base-metal content for three granitoid complexes in the U.S.S.R. (Table 4). Similar data have been published by Kuzmin[12] and Ivanov.[9] That the base-metal content may vary commonly by factors of two or more is quite apparent.

Table 3 Mean base-metal content (ppm) of acid plutonic rocks

	Zn	Cu	Pb
Granitoids (Vinogradov[25])	60	20	20
Granites (Krauskopf[11])	40	10	20
Granites (Taylor[23])	40	10	20
Low Ca granites (Turekian and Wedepohl[24])	39	10	19
High Ca granites	60	30	15
Syenites	130	5	12
This study	64	10	35

Table 4 Mean base-metal content (ppm) of some U.S.S.R. granitoids. After Tauson[22]

	Zn	Cu	Pb
Susamir batholith			
Dioritic phases	96	33	9
Porphyritic granodiorites	56	12	25
Leucocratic granites	30	9	34
Vein granito-aplites	12	10	34
Shakhtaminski massif			
Diorites and monzonites	54		20
Granodiorites and quartz-monzonites	40		24
Late-stage granites	33		28
Soktuy massif			
Biotite granites	61		30
Late-stage granites	42		19
Grano-syenites	85		22

Many workers in the field of bedrock geochemistry have pondered over the problems of whether they should be looking for areas of anomalously high or low trace-element content. Some maintain that areas containing mineralization of a particular element will be characterized by the rocks of the area having higher than normal amounts of that element, whereas others claim that mineralized areas will have lower levels of the trace elements in the rocks, as the elements in question will have been depleted at some stage to form the mineralizing solutions. Both these views may be true—the former on a regional scale and the latter on a more local scale intimately associated with the mineral deposits in question. A third alternative arises in the cases of mineral deposits which are essentially strata-bound and pre-intrusive in age. In such cases anomalously high trace-element values may be found due to the assimilation of sedimentary material which itself is anomalously high in such trace elements, or to the involvement of the hot intrusive in some plumbing system that draws metal-rich water from mineralized host rock. There are obviously problems of mass transfer and subsequent dilution in the intrusive body; however, the writer feels that the possibility should not be ignored. In this particular study, which is of a broad regional nature and aimed at delineating areas of increased mineral potential rather than individual mineral deposits, it was decided to look for plutons associated with anomalously high base-metal contents.

In the field area significant deposits of tungsten (scheelite) occur, together with gold, which is placer-mined by small operators. An interpretation of the tungsten data has been published elsewhere,[8] but it should be noted that these deposits contain varying amounts of the base-metal sulphides, and in the current case the base metals may be considered pathfinder elements for areas of tungsten or gold–tungsten mineralization.

Initial investigation of the data

In order to assess the gross geochemical features of the data and the degree to which the data could be considered to be drawn from a single magmatic series a *Q*-mode principal-component analysis was undertaken. The 2136 samples involved in the study area are drawn from 74 distinct plutonic bodies: thus, for each of these plutons the arithmetic and geometric means, together with Fisher's *t* estimator, based on the theory of maximum likelihood,[20] were computed. The value of the *t* estimator lies above the geometric mean, but below the arithmetic mean. It has a higher reliability than the arithmetic mean, i.e. fewer samples are required to attain the same precision of determination, and is less sensitive to occasional high values. In the case of the South African gold deposits this estimator yields, in most cases, a value lying nearer the true mean grade as determined by mining.

The input data to the *Q*-mode principal-component analysis was therefore 74 sets of maximum-likelihood estimators of the major, minor and trace elements. No transformations, other than for range, were applied to the estimators: thus, on computation of the similarity matrix all the elements were scaled to between zero and one, so giving them equal weight in the analysis. The first two varimax-rotated principal components account for 87·8% of the total variability, and a plot of the loadings on these two components is shown in Fig. 2. The arcuate distribution of the points coincides with a trend in the rocks from basic in the upper left to more acidic in the lower right. This general trend was taken as evidence that the rocks could be viewed as being drawn from one, or several overlapping, magmatic series. One drawback with the presentation of *Q*-mode principal components is that they tend to emphasize the common features, but do not lead to a presentation which allows the data to be clustered into geologically meaningful groups. To achieve this end a technique known as non-linear mapping, which was developed by Sammon,[19] was employed. Two matrices of Euclidian distances are computed—one from the initial transformed data and the other from the two principal-component loadings. Corrections are made iteratively to the second matrix until the Euclidian distances of that matrix most closely match those of the initial data. In doing this a two-dimensional projection of the *n*-dimensional initial data is found which most closely preserves the data structure as exhibited by the inter-point

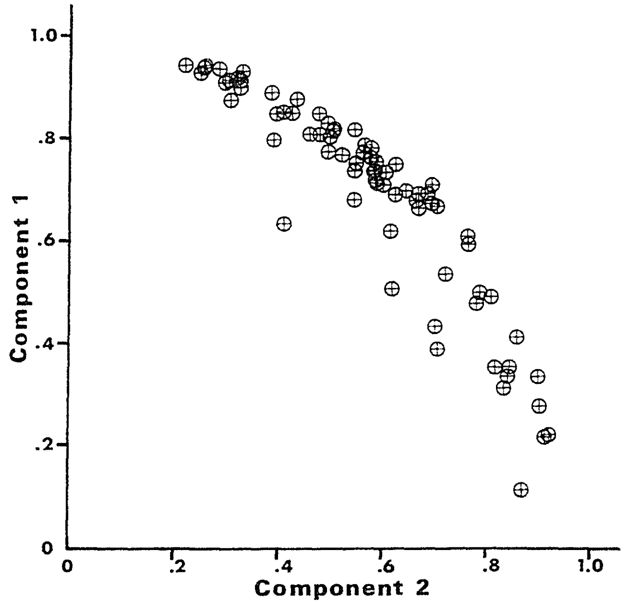

Fig. 2 Plot of rotated Q-mode principal component 1 versus principal component 2

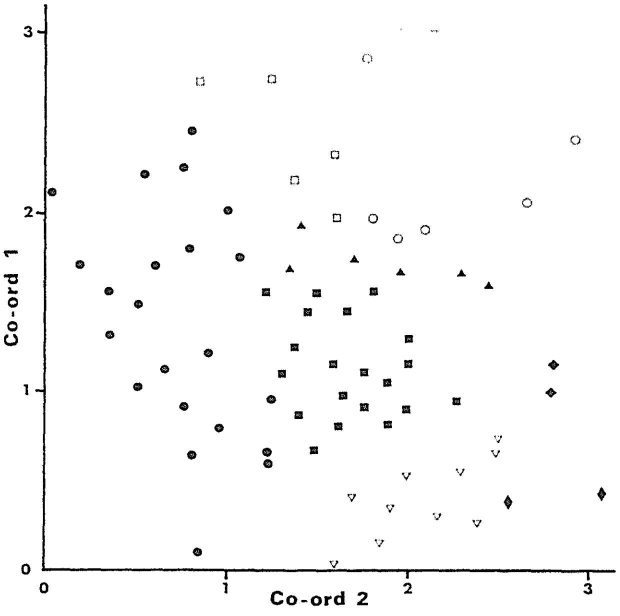

Fig. 3 Non-linear mapping presentation of Q-mode data (see Fig. 4 for description of symbols)

distances. The resulting computation leads to the presentation shown in Fig. 3. The plutons represented on the new data presentation were divided into groups on the basis of geological similarity and areal proximity, the areal distribution of these groups being shown in Fig. 4 and the average base-metal content for each group in Table 5. The data indicate twofold variations between different groups for zinc and up to fourfold and threefold variations for copper and lead, respectively. Thus, at this point the specific magnitude of the problem in the Selwyn Belt granitoids has been established and the data have been shown to be drawn from a single, or several overlapping, magmatic series.

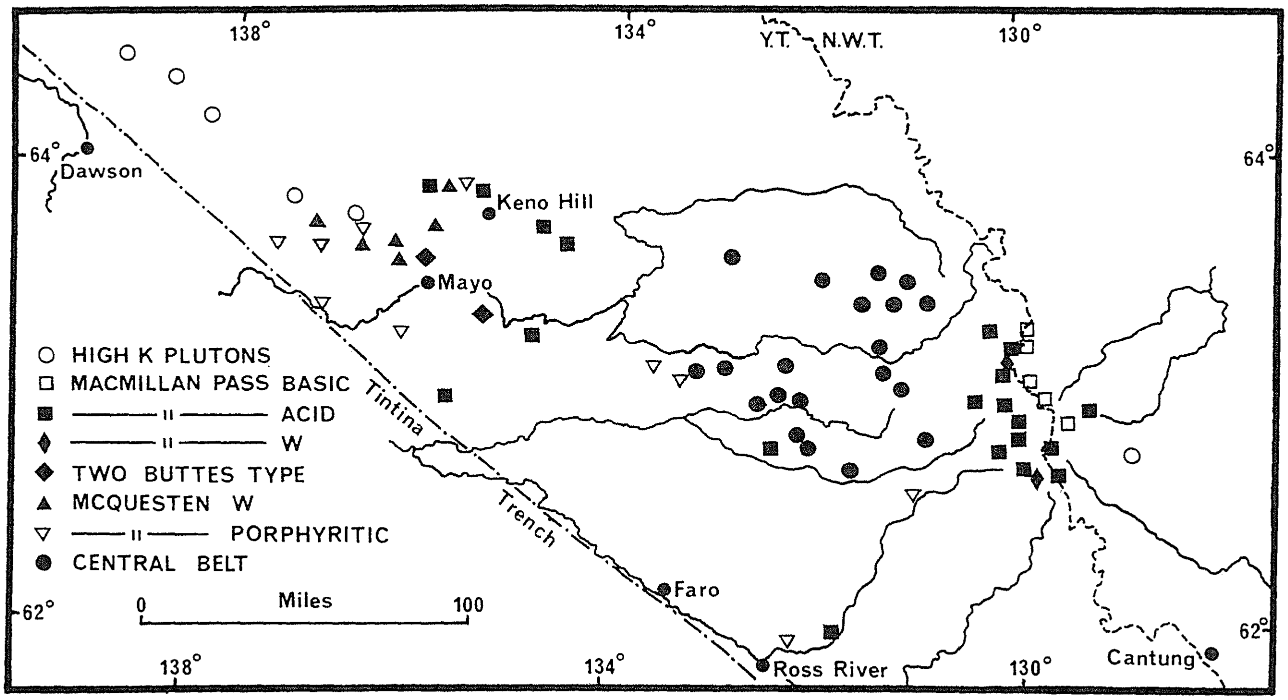

Fig. 4 Areal distribution of sub-groups derived from the non-linear mapping presentation

Table 5 Mean base-metal content (ppm) of acid plutonic rocks of various sub-groups

	Zn	Cu	Pb
High K granitoids	90	18	49
Macmillan Pass basic phase	61	17	38
Macmillan Pass acid phase	58	7	33
Macmillan Pass tungsten belt	47	7	59
Two Buttes type	73	4	36
McQuesten Porphyry tungsten belt	111	8	34
McQuesten porphyritic type	47	6	35
Central belt	63	11	23

Statistical analysis to identify anomalous plutons and samples

Multiple regression has been shown to be a useful tool in allowing for variations in background in stream sediments by Rose and co-workers[17, 18] and by Nichol.[16] Previously, the independent variables have been elemental data, sometimes combined with a quantification of the relative importance of lithological units in the stream catchment areas. Because of the inherent redundancy in the major- and minor-element data for plutonic rocks, it was decided to minimize these effects by computing a new set of uncorrelated orthogonal variables by the use of *R*-mode principal-component analysis, i.e. where a correlation matrix with unities in the diagonal is used as a starting point. A beneficial product of this approach is the generation of new independent variables that are more closely related to the geological processes dominant in the environment. The computation of the *R*-mode principal-component analysis followed standard procedures. No attempt was made to allow for closure in the data such as was demonstrated by Miesch and co-workers,[14] as it was considered that Al would have been the most suitable element to use as a denominator for ratio generation, and in this data set the error variance associated with the Al data was large. The principal-component analysis was followed by a Varimax rotation and the computa-

Table 6 Varimax-rotated principal-components matrix

	1	2	3	4	5	6	7	8	9
Si	−0·56	−0·11	0·13	0·03	−0·28	0·76	0·05	−0·01	0·03
Al	0·13	0·01	−0·98	0·09	0·09	−0·07	−0·02	0·01	−0·01
Fe	0·73	−0·03	−0·15	−0·20	0·44	−0·29	−0·01	0·04	−0·34
Mg	0·91	−0·05	−0·01	−0·26	0·18	−0·18	0·06	−0·19	0·07
Ca	0·80	−0·14	−0·15	−0·13	0·26	−0·25	−0·41	−0·01	−0·01
Na	−0·27	0·09	−0·10	0·95	−0·19	0·02	0·02	−0·01	0·02
K	−0·07	0·99	−0·01	0·08	0·08	−0·05	0·02	0·00	0·00
Ti	0·86	−0·02	−0·17	−0·21	0·27	−0·16	0·04	0·32	−0·04
Mn	0·40	0·13	−0·11	−0·01	0·88	−0·18	−0·04	0·01	−0·01
Sum of squares	3·31	1·04	1·07	1·09	1·23	0·82	0·17	0·14	0·13
% of variability	36·7	11·6	11·9	12·1	13·7	9·1	1·9	1·6	1·4
Cumulative %	36·7	48·3	60·2	72·3	86·0	95·1	97·0	98·6	100·0

tion of the component scores for each of the 2136 samples on the nine orthogonal axes.[10] The Varimax-rotated principal-component loadings are given in Table 6. Component 1 accounts for some 36·7% of all the major- and minor-element variability, and appears to be inversely related to the degree of differentiation of the rocks. Larsen's differentiation index was computed for the 2136 rocks and the correlation coefficient between these and the scores on component 1 was found to be −0·79, which yields a value of Student's *t* of 58·7 with 2135 degrees of freedom and is considered highly significant. Component 2 is almost entirely related to the K content of the rock and is related to the presence of porphyritic microcline, and, as such, is considered to be a measure of porphyricity of the rocks. This latter component and the following four account for approximately 11% of the total data variability each, whereas the last three account for less than 2% each. All these components, with the exception of the fifth, are essentially single-element loaded, and no ready explanation is available for them in common petrologic terms or relationship to mineralization. Only component 5, which is a Mn–Fe association, is possibly explainable in terms of colour index or magnetite content of the rock. The correlation coefficients of the logarithmically transformed base metals with the rotated principal-component scores are given in Table 7. Component 1 is one of the largest correlations in all three elements, and component 2 is prominent in the cases of Cu and Pb, especially the latter. Zinc does not conform, having an important correlation with component 5, which may have some petrologic significance (see above).

Table 7 Correlation coefficients between logarithmically transformed base metals and rotated principal-component scores

	1	2	3	4	5	6	7	8	9
$\log_{10}$ Zn	0·31	0·07	−0·20	−0·13	0·38	−0·24	0·03	−0·06	−0·11
$\log_{10}$ Cu	0·45	0·23	0·04	−0·16	0·12	−0·18	0·00	−0·14	−0·02
$\log_{10}$ Pb	−0·27	0·45	0·03	0·05	0·06	0·07	0·03	−0·15	0·08

Stepwise multiple regression was undertaken by use of the forward addition of independent variables as described by Efroymson.[6] It was noted that all rotated principal components with absolute correlation coefficient values in excess of 0·03 were included as contributing to a significant decrease in the error sums of squares of the regressions. This is due to the very small value the mean sums of squares of the residuals will assume when large numbers of samples are used in the regression. Although this situation is statistically valid, it is not satisfying to a geologist undertaking an interpretation as it is doubtful if petrological processes, or significant meanings, can be attached to any other than the first two principal components with confidence. It was therefore decided to use only the first two rotated principal-component scores in the multiple-regression equation. Thus, samples that yielded residuals within ±2 standard deviations of the regression could have their base-metal content explained in terms of the differentiation of a magmatic series

Table 8 Percentage of variability explained by regressions

	Zn	Cu	Pb
Variability explained by all 9 elements	37·50	34·66	32·04
Variability explained by principal components 1 and 2	9·82	25·31	27·84
Percentage of explainable variability that is contained in principal components 1 and 2	26·19	73·02	86·89

and the amount of porphyritic feldspar present in the rock. Attention would therefore be focussed on samples which contain some component of non-standard rock-forming processes, one of which could be a mineralization process. Although only two variables are included in the regression equation, these contain 48·3% of the total data variability (Table 6) and account for varying amounts of the regression variability explainable by all the major and minor elements (see Table 8). For Cu and Pb the first two components account for approximately 75% of the variability explainable by the major and minor elements, whereas in the case of zinc only some 25% of the explainable variability is contained in the first two components.

The standardized residuals, i.e. the regression residuals divided by the square root of the mean sums of squares of the residuals, were computed for all samples for each of the base metals. These data were then used to determine the arithmetic mean score and maximum and minimum standard score values for each of the 74 plutons of the field area. Maps have been prepared for each element showing the maximum-likelihood value (hereafter referred to as the mean), the highest observed result, the mean score and maximum observed standard score for each pluton (Figs. 5–16).

Description of results

The data for zinc are presented in Figs. 5–8. The most noticeable feature of the regional zinc distribution is the concentration of plutons with high mean zinc content in the northwest of the field area (Fig. 5). A less conspicuous area of high mean zinc content lies in the Central belt (17, see Fig. 1). The distribution of means is positively skewed, and plutons with means in excess of 90 ppm must be considered anomalous. The map of the maximum observed zinc values (Fig. 6) reveals generally similar features as the means. Where relatively low maximum values are found in conjunction with high means, a low data

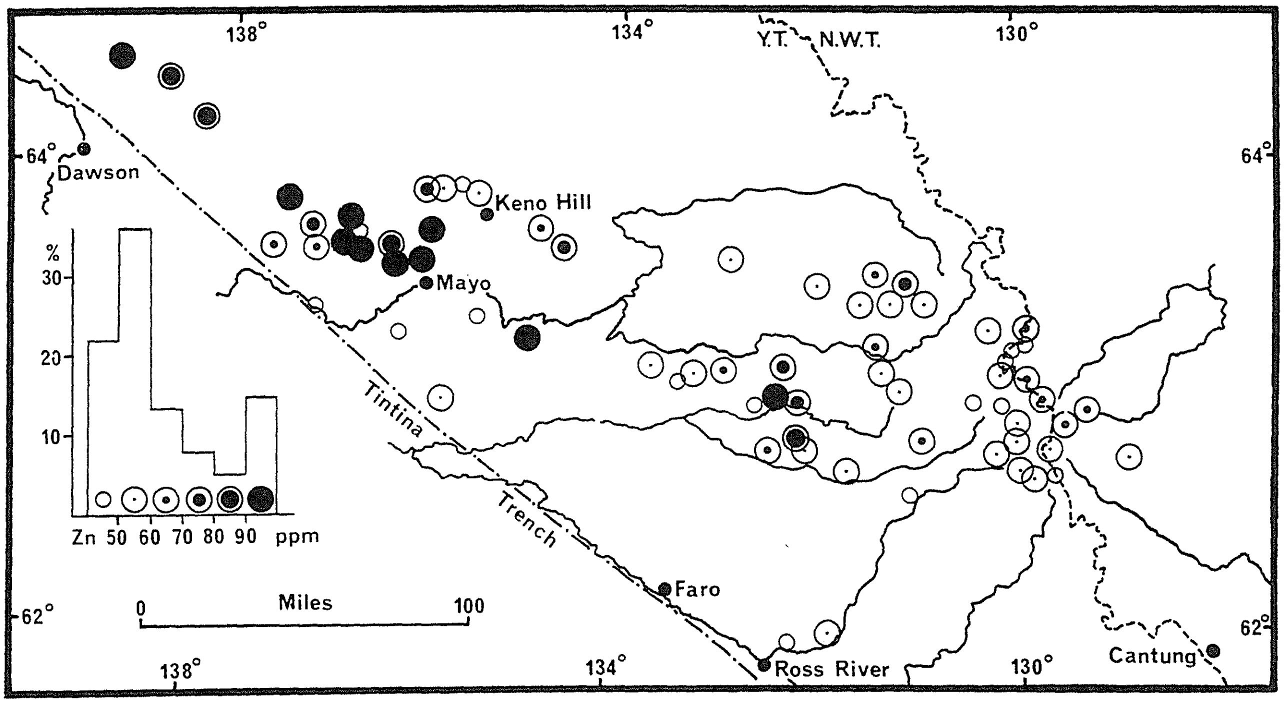

Fig. 5 Mean zinc content of granitoids

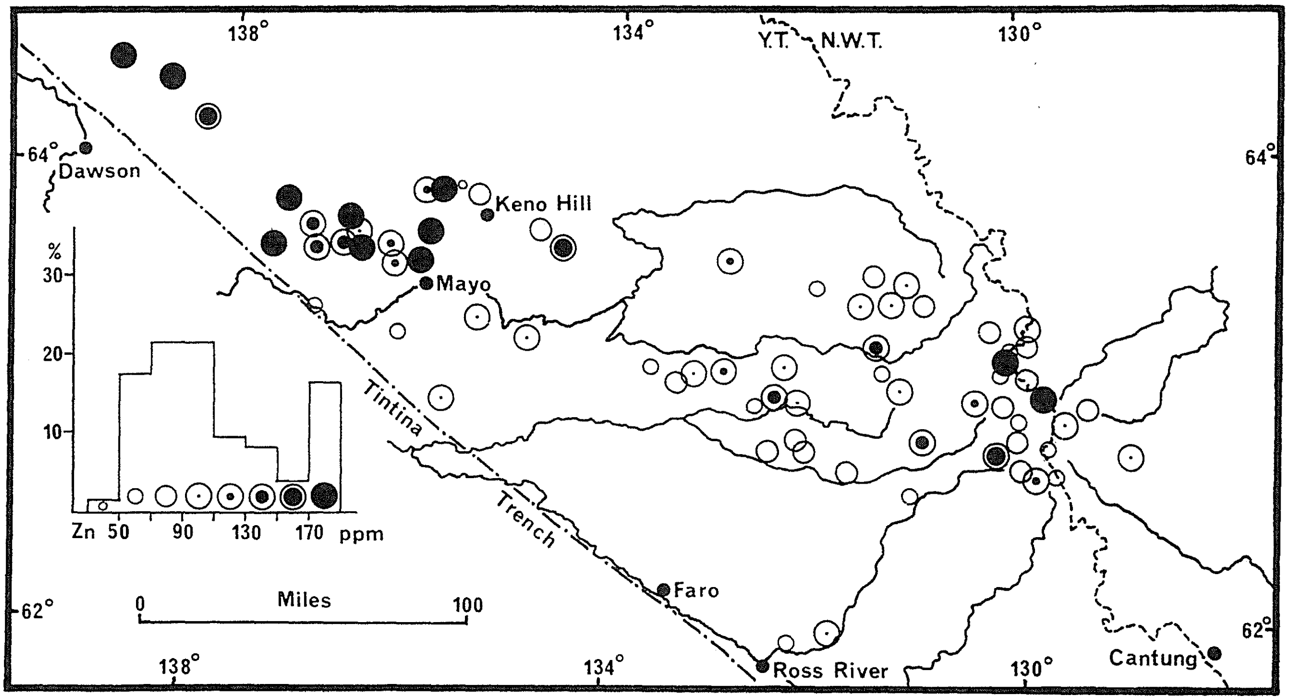

Fig. 6 Maximum zinc content of granitoids

variance is indicated. Conversely where high maximum values are found associated with either high or low means, a higher data variance or positive skew in the data is indicated. It is now generally recognized that the variance, or dispersion, and positive skewness of geochemical data sets are criteria of great importance in recognizing data derived by sampling mineralized areas. In many cases only very small changes in means may be observed, but the data variance and positive skewness are distinct diagnostic features.[2, 3, 8, 12, 22] Thus, the plutons of the Central belt (16, 17) become less interesting and others to the east (21, 23) more attractive. Similar general findings are apparent in the northwestern parts of the field area.

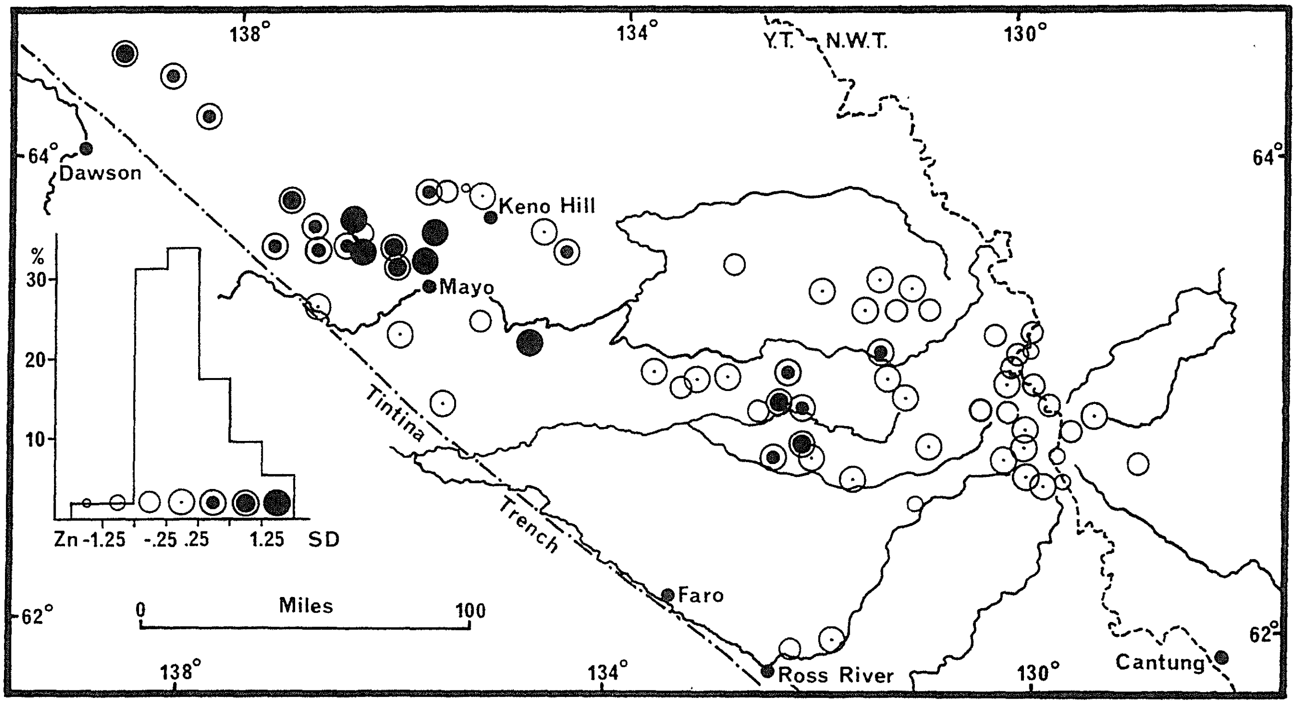

Fig. 7 Mean residual scores for zinc in granitoids

Fig. 7 depicts the mean residual scores for each pluton and indicates the mean residual zinc in the pluton after allowance for the effects of crystallochemical differentiation (principal component 1) and the presence of porphyritic microcline (principal component 2). The majority of the plutons in the eastern half of the field area appear to have near the expected zinc contents. The exceptions to this general trend are a reduced number of plutons showing higher than expected means in the Central belt (16, 17). The number of anomalous (>90 ppm Zn) plutons in the northwestern part of the field area are reduced by almost half and those remaining with means in excess of 0·75 standard deviation units are, with one exception, associated with the McQuesten

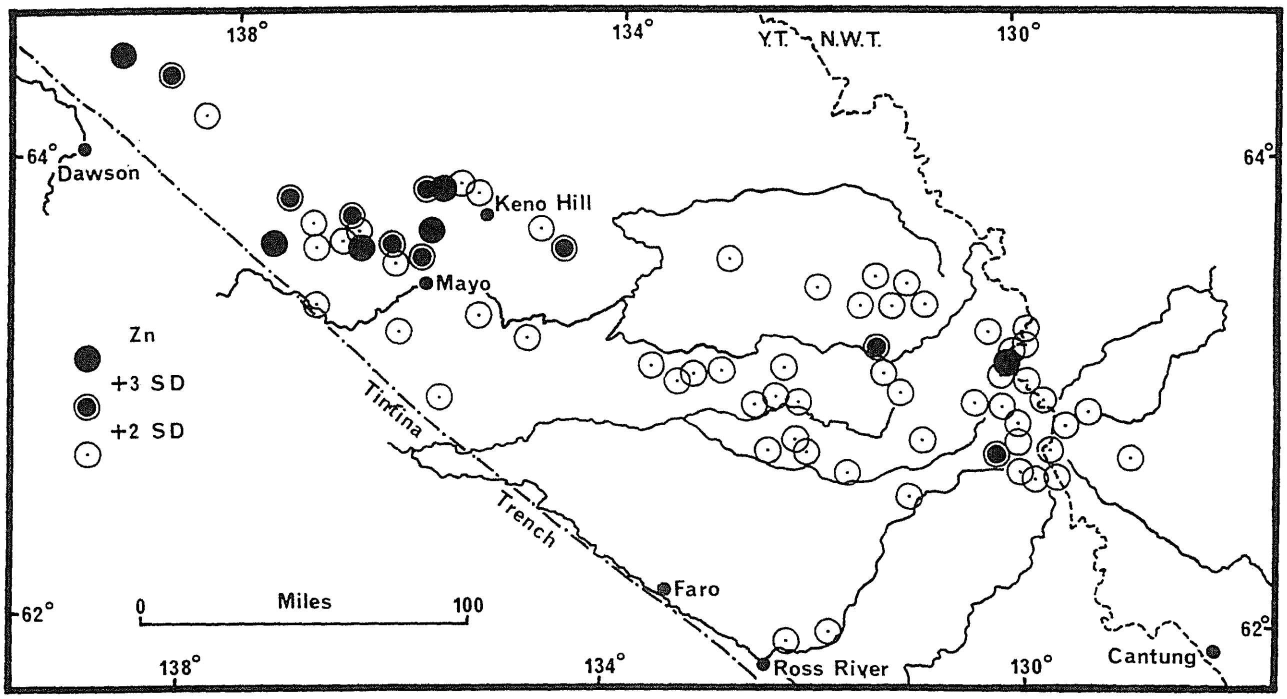

Fig. 8 Maximum residual scores for zinc in granitoids

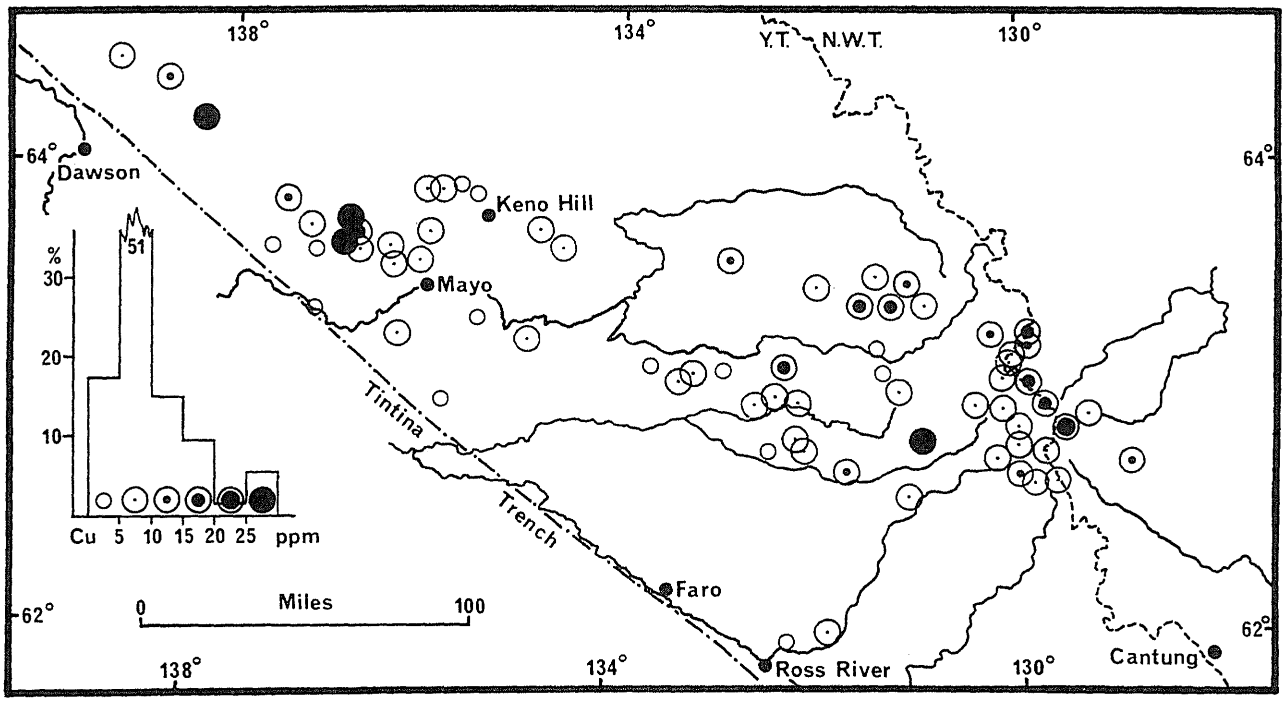

Fig. 9 Mean copper content of granitoids

mineralized belt. The whole of the northwestern part of the field area is characterized by small sulphide showings of lead, zinc and antimony minerals, and it is conjectured that the generally high zinc levels in the area are a reflection of these mineral occurrences. The maximum observable scores are presented in Fig. 8: of the six plutons with maximum scores in excess of 3 standard deviation units, four are known to be associated with mineralization (8, 12, 13, 21). Nine more plutons exhibit maxima between 2 and 3 standard deviation units: of these, five are known to have mineralized showings in the vicinity. Three plutons associated with mineralization (3, 6, 22) do not have anomalous zinc contents—contrary to expectations based on the mineralogy of the associated occurrences; however, these deposits are reflected in the results of at least one of the remaining base metals.

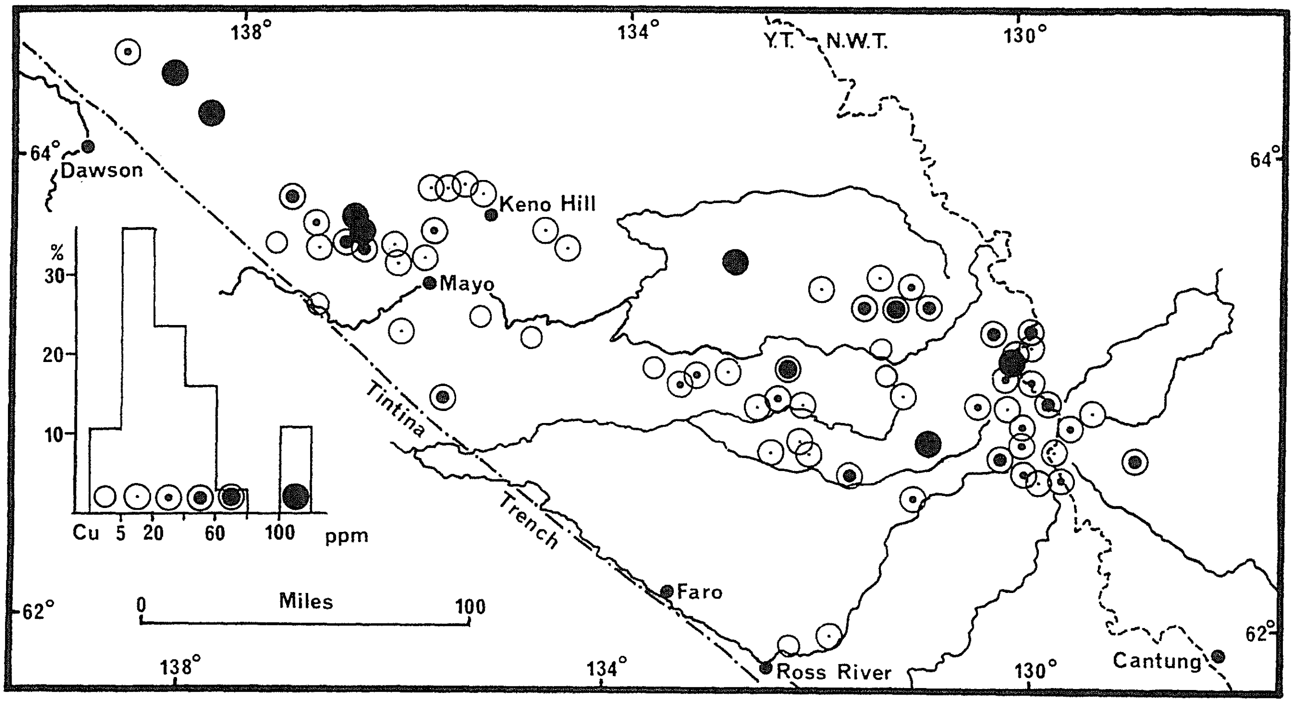

Fig. 10 Maximum copper content of granitoids

The data for copper are presented in Figs. 9–12. The frequency distribution of mean copper contents (Fig. 9) is less skewed and not so prominently bimodal as those for zinc. Copper minerals are not as widespread in the study area as are those of zinc, and the distribution reflects this fact. The area of high mean copper content in the northwest of the field area is less prominent than that for zinc. In the east, however, there are two clusters of higher than average copper content plutons and a single isolated anomalous pluton. The maximum observable values (Fig. 10) define a number of areas of interest. Northeast of Dawson the mineral occurrences associated with the syenites and monzonites (2, 3) are reflected, and farther to the southeast mineral occurrences in the Red Mountain area (5) and on nearby Sunshine Creek are associated with plutons carrying anomalous copper contents (>100 ppm Cu). In the eastern half of the field area three anomalous plutons are present; the northernmost of these contains disseminated chalcopyrite and pyrrhotite, and Mount Allan (21) is genetically related to a large skarn tungsten deposit. The third (19) is not known to be associated with any mineral occurrence, but a pluton to the southwest (18) contains chalcopyrite in a fractured zone in the apical part of the pluton. Two plutons contain high background mean levels—both in the Central belt (16, 17)—and one of these (17) is associated with a contact pyrometasomatic copper–tungsten mineral occurrence. The second lies above an area of limonitic staining on the north shore of Fairweather Lake; extensive soil sampling was undertaken in this area, but no definable target was found.

The mean residual scores for copper in plutons are presented in Fig. 11, the majority of the higher than to be expected copper levels lying in the eastern part of the field area. Three mineralized areas (3, 5, 8) in the west, however, are characterized by high mean scores. In the east there is a well-defined area of higher copper content (17–21) and two more isolated areas (16 and 23, 24). The majority of the known

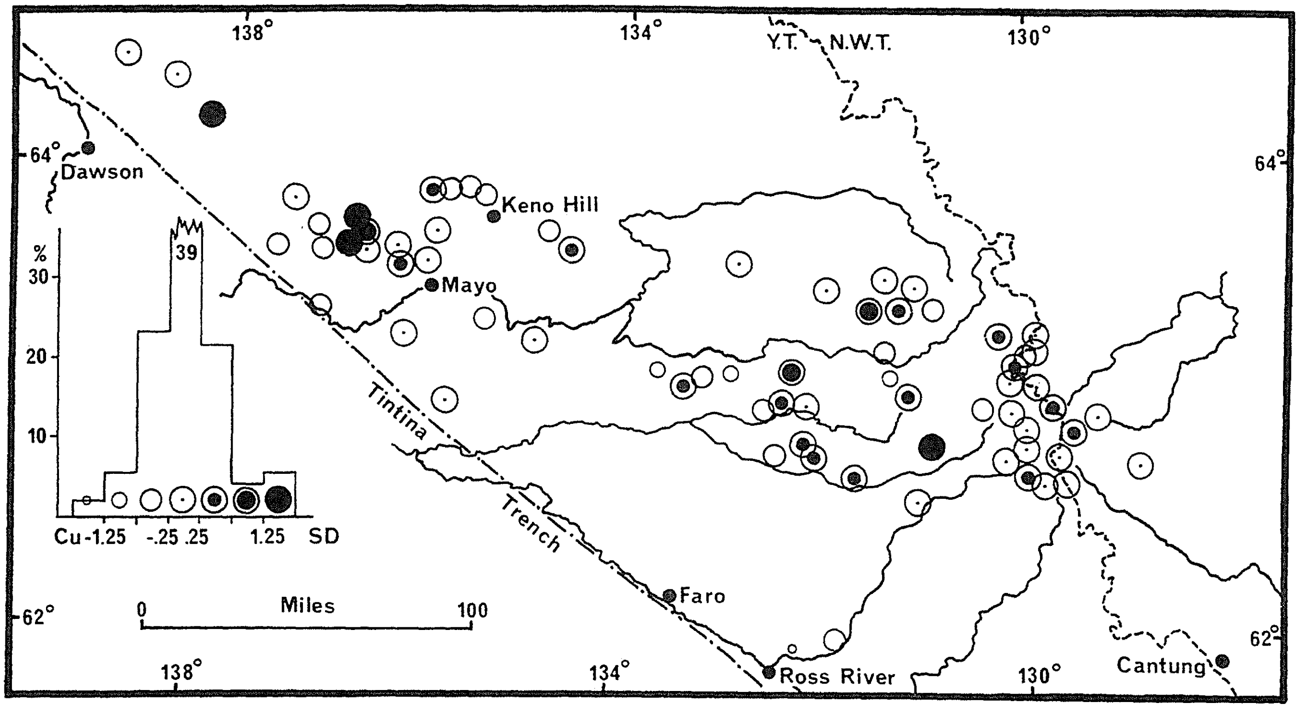

Fig. 11 Mean residual scores for copper in granitoids

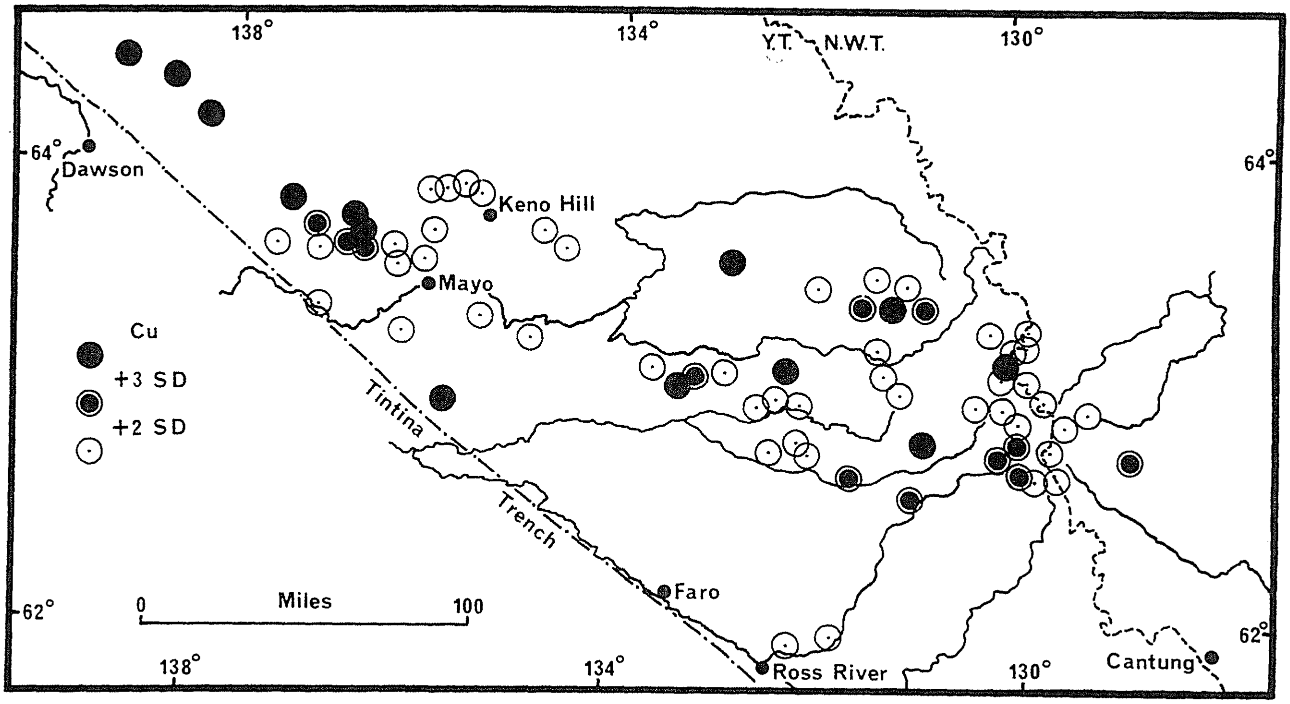

Fig. 12 Maximum residual scores for copper in granitoids

copper occurrences fall within these areas. The maximum observed residual scores are shown in Fig. 12. Thirteen plutons contain anomalously high scores, and eight of these have verified mineral occurrences in their vicinities (including 2, 3, 4, 5, 16, 21). Of the five remaining plutons, mineralization can be reasonably expected to be in the vicinity of three on the grounds of local geology (1, 19) or other geochemical data. The other two (15, northwest of 17) have completely unknown potential; however, there are old reports of mineralization having been found in both areas. Those plutons exhibiting maximum scores between 2 and 3 standard deviation units above the regression are all spatially associated with known mineral occurrences or are close to similar plutonic bodies intruding similar strata. Certain notable exceptions are again present—the most marked in the copper–zinc–tungsten skarn (22) in the southeast of the field area, which

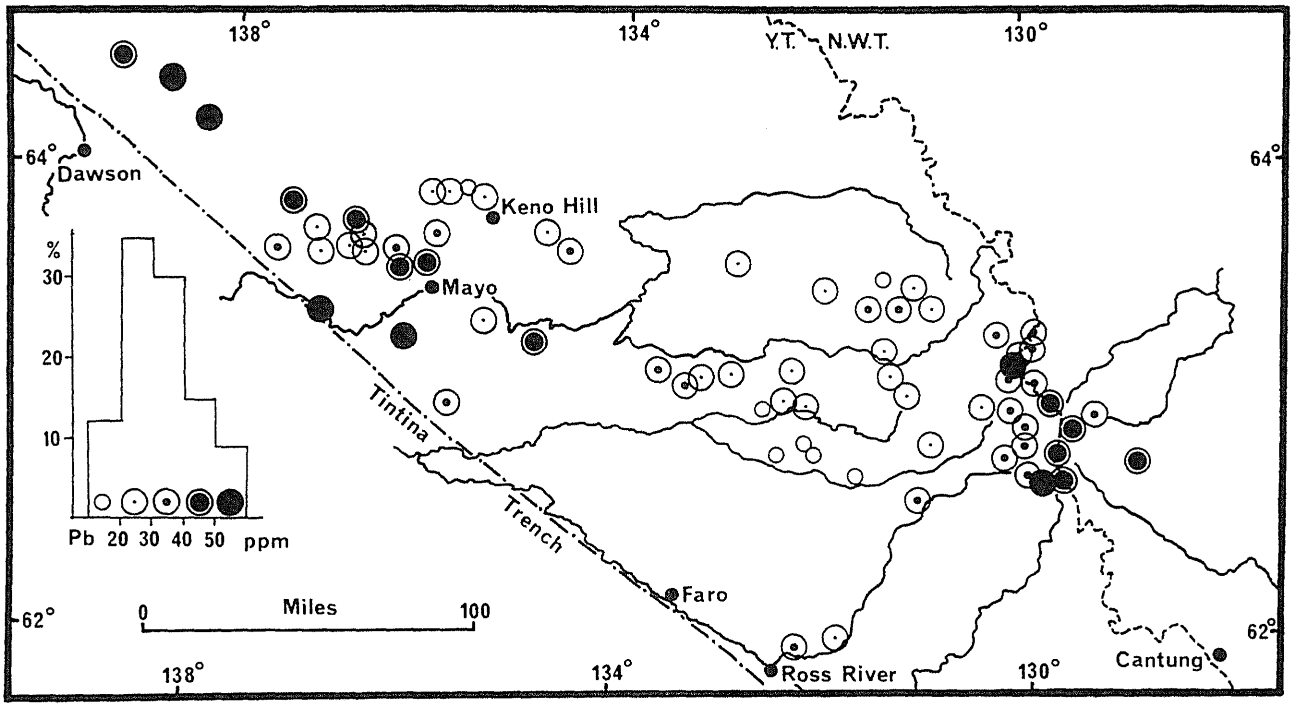

Fig. 13 Mean lead content of granitoids

is not reflected in any way by the copper data. It is perhaps not surprising that the plutons of the eastern part of the McQuesten Belt (9–13) are not anomalous, as copper is not a significant element in these deposits.

The data for lead are presented in Figs. 13–16. Unlike the previous two elements, which are geochemically related to the femic components of the rocks, lead is closely correlated with potassium content. The frequency distribution of the means is not significantly skewed and is unimodal, areas of high lead content being confined to the eastern and western extremities of the field area (Fig. 13). In the eastern area all plutons with major mineral occurrences are reflected by high mean contents (21, 22, 25). In the western area the high mean lead contents fall into two areas—one in the extreme northwest and the other near and south of Mayo. The former of these contains a number of lead-bearing

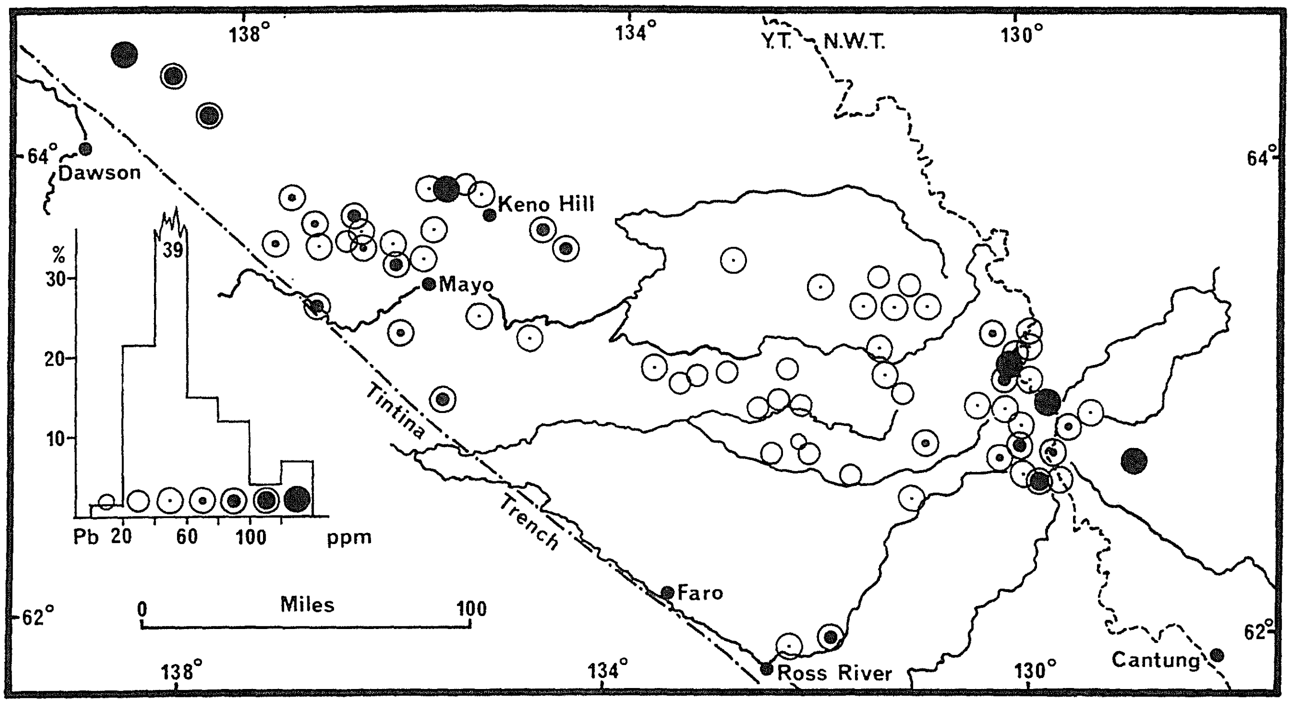

Fig. 14 Maximum lead content of granitoids

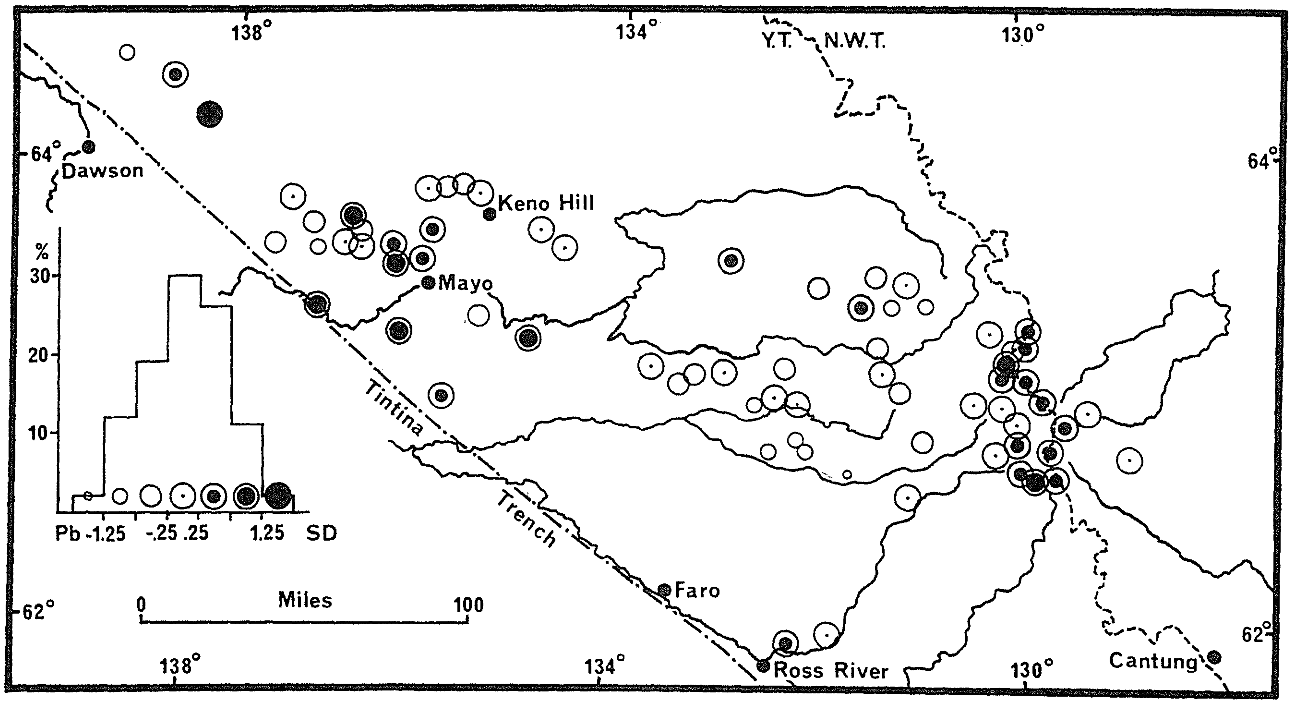

Fig. 15 Mean residual scores for lead in granitoids

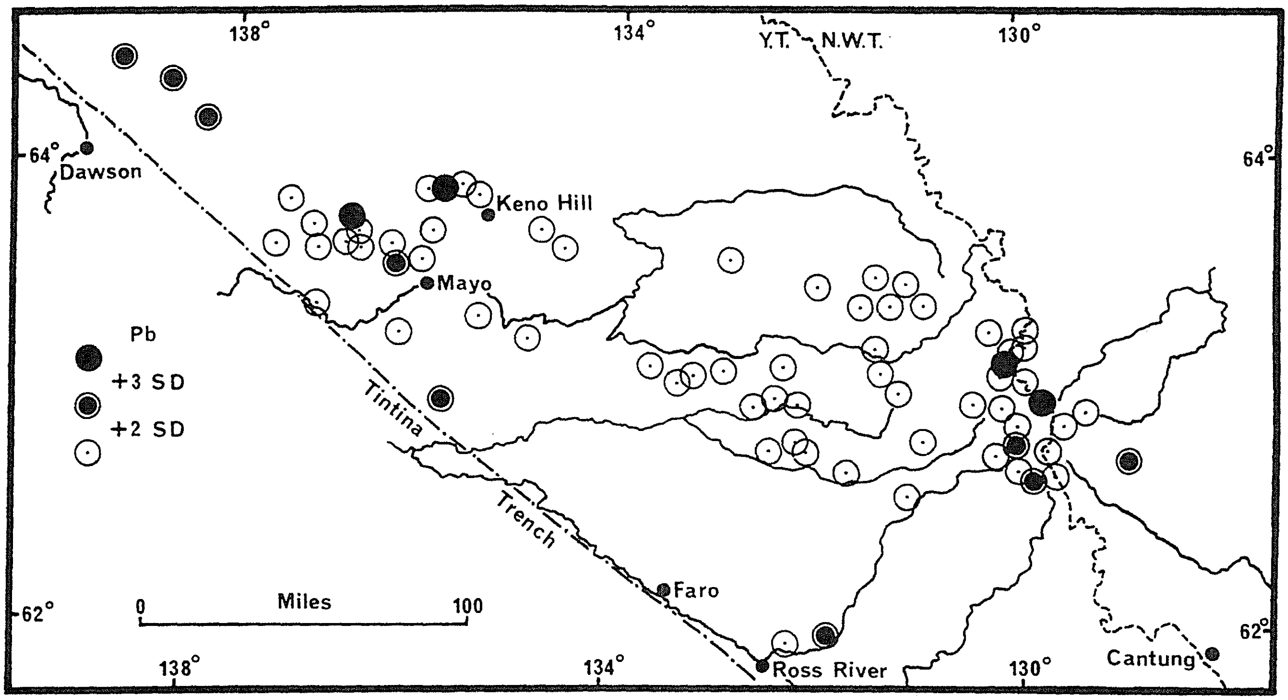

Fig. 16 Maximum residual scores for lead in granitoids

mineral occurrences, but the latter group with plutons south of Mayo has no known relationship to mineral occurrences. The maximum observable lead levels are presented in Fig. 14, and attention is drawn to all plutons containing in excess of 100 ppm Pb. Eight plutons are so characterized and, of these, six have associated mineral occurrences (2, 3, 13, 21, 22, 25), the remaining two (1, 23) being in generally favourable areas and perhaps associated with further mineral occurrences.

The regression approach to interpretation allows the effects of potassium to be taken account of, and the residual score means for each pluton are presented in Fig. 15. Three areas of higher than normal lead are apparent: one in the northwest, one around Mayo and one in the eastern part of the field area. The Central belt is generally characterized by low lead levels. The maximum residuals for each pluton are presented in Fig. 16.

The anomalous (>3 S.D. units) plutons are associated with mineral occurrences (5, 13, 21), with one exception (23), and that area must be considered favourable for exploration. Nine plutons exhibit samples with residual scores in the range 2–3 standard deviation units. Of these, six are associated with mineralization (2, 3, 11, 15, 22, 25); of the remaining three plutons, two are considered favourable target areas (1, north of 22), and the third, near Ross River, is of unknown potential. Of considerable interpretational importance is the elimination of the previously considered anomalous plutons south of Mayo. These plutons, although characterized by high lead levels, do not exhibit the skewness typical of plutons associated with mineralization.

Regional implications

Before concluding, some general points may be made about the regional geochemistry of the base metals in the northern half of the Selwyn Belt. First, the area northwest of Mayo is characterized by higher than average base-metal content, and the fact that this general area contains the largest concentration of mineral occurrences cannot be fortuitous. Secondly, the eastern edge of the field area coincides with the western margin of the miogeosynclinal rocks, and therefore lies close to a hinge-line, the eugeosynclinal rocks of the Selwyn Basin lying to the west. This area along the eastern edge of the field area is characterized by high lead levels, significantly higher copper levels and marginally higher zinc levels. These features could be due to a variety of reasons—the tapping of deeper sources of the elements due to the influence of hinge-line faults, regional differences in magma composition related to original differences in the composition of the crust subjected to palingenesis, and, lastly, the assimilation of miogeosynclinal rocks in contrast to eugeosynclinal rocks assimilated by plutons westward and farther out in the Selwyn Basin. Finally, the central part of the Selwyn Basin is characterized by higher than normal zinc levels, and the reasons for this could be one of those mentioned above with reference to the eastern part of the field area.

Conclusions

The data presented illustrate the application of a number of mathematical–statistical techniques in a planned manner to solve a series of interpretational problems. The final data presentation is shown to have advantages in delineating those plutons known to be associated with mineralization, at the same time eliminating others which appear to be anomalous by use of other presentation methods but which are not considered favourable on other grounds.

The technique of combining *R*-mode principal-components analysis with multiple regression also has a conceptual approach which is naturally appealing to the geologist. First, a transformation of the major and minor elements is made from a response-orientated, and conceptually difficult, form to a process-orientated form more easily understood in broad geological rather than geochemical terms. Secondly, the multiple-regression analysis allows the selection of samples which do not fit within certain bounds (e.g. 2 or 3 S.D. units) of the selected *R*-mode process model. Those samples lying outside the selected bounds must be assumed to have been influenced by some process other than those selected from the *R*-mode model for inclusion as independent variables in the multiple regression. If the processes, as in the present case, are selected on simple petrochemical and petrological grounds, samples outside the bounds must have been influenced by more complex processes, one of which could be related to the formation of mineral deposits.

This approach to data interpretation may be thought of as an extension to very large numbers of samples of *Q*-mode principal-components analysis and the use of communality to indicate the lack of fit of any particular sample to a process model chosen on the basis of *Q*-mode principal components.[15] It does, however, have the advantage of being specific to chosen elements, and there is no reason why elements included in the principal-components analysis could not be used as dependent variables in the regression analysis.

The interpretational scheme outlined contains no radically new data-manipulation technique; rather, it is a logical amalgamation of a number of well-tried methods in an attempt to improve the objectivity of the interpretational step the geochemist must make in moving from response-orientated chemical data to a geological process model. It is hoped that the methodology will have applications to other problems in other areas where the step from response to process is even more difficult than it is with bedrock geochemical data.

Acknowledgment

The author would like to express his sincere thanks to the many individuals who have participated in this study, both in the field and in the laboratory. The enthusiasm and diligence of students and aircraft crew made the field work in mountainous terrain possible, and the laboratory support provided was of the highest order. In this latter respect special thanks are due to the Geochemistry Section analytical team, who provided more than 60 000 determinations for the study, and the Analytical Chemistry Section, who carried out the whole-rock analyses for the accuracy investigation.

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