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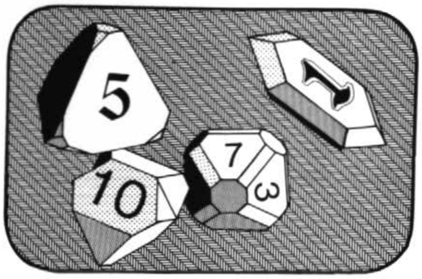

Metallogeny by Numbers

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Introduction

Metallogeny is a legitimate offspring of economic geology and tectonics. It is more synthetic and esoteric than either and in most ways has been less useful. Its practitioners have chiefly sought general explanations for the genesis of mineral deposits within the framework of existing theory of tectonics and the origins of individual mineral deposit types. It has scarcely tried to fly on its own and certainly has not developed into the predictive science that it must become if we are to find the buried ore deposits we will need in our future.

Metallogeny has been an aspect of some economic geology studies as long as these have existed but it was first conceptualized as a distinct field by De Launay in 1900. In spite of this, metallogenic studies in the first half of this century were rarely identified as such, for example A. F. Buddinton's 1933 paper "Correlation of Kinds of Igneous Rocks with Kinds of Mineralization". Today the very reverse is true. This is attributable in my view to two factors. The slow but steady diffusion of knowledge of the work of Y. A. Bilibin, e.g., McCartney and Potter, 1962, and the stimulus supplied by plate tectonic theory (e.g., Guild, 1971; Sillitoe, 1972; Strong, 1976; Walker, 1976). Sangster (1979) recently attempted to loosen the grip of plate tectonics as the sole mechanism in metallogenesis and perhaps future metallogenic studies will be less doctrinaire. It will be necessary to get back to the numbers game to develop metallogenic theory that is both sound and less tied to fashionable theories in economic geology or tectonics.

Metallogenic theory will develop after accumulation and study of abundant data of the distribution of mineral showings on a regional and camp basis, of metal ratios of mineral production, of regional gradients in geochemistry, and of many radiogenic and stable isotopes. We need studies of these types in different tectonic regions and we need a synthesis with genetic ore modelling theory developed by modern economic geology. This paper presents a preliminary attempt to integrate regional geochemical data into a metallogenic framework for British Columbia.

Tectonics

Concepts of tectonics of the Canadian Cordillera are in a period of flux again but the five sub-parallel tectonic belts are still a useful framework (Fig. 1). These belts were identified before the paradigm of plate tectonics theory was developed and they have survived a variety of plate tectonic interpretations (Sutherland Brown *et al.*, 1971). They appear to be surviving even recent concepts that the western three-fifths of the Cordillera (the eugeosyncline) is a collage of terrains of differing history and place of origin that were accreted to the western margin of North America, mainly in the Mesozoic (Monger and Price, 1979). The critical division of the Cordillera has generally been recognized as that between the miogeocline (two eastern belts) and the eugeosyncline (three western belts). This is recognized now more clearly than ever as the approximate suture between continental crust and its offboard volcanic and magmatic arcs and modified oceanic crust (Price, 1979). In regard to metallogenesis, whether these terrains developed in situ, were swept in from offshore or slid up from California or Timor is less important than their nature and the amount and complexity of crustal processes they have been subjected to before and since their emplacement.

Regional Geochemistry

Metal gradients must be considered one of the most useful parameters on which metallogenic models can be built and tested. To date most thinking in regard to gradients has been related to the distribution of mines and mineral production. Gabelman and Krusiewski (1968) were among the first to fully express such concepts of regional metal zoning and gradients relative to cratons. Similar concepts of parallel copper (eugeosynclinal) and lead (miogeoclinal) belts were developed by Wilson and Laznicka (1972). Concepts relative to geochemistry need abundant available regional data and so are still developing. This

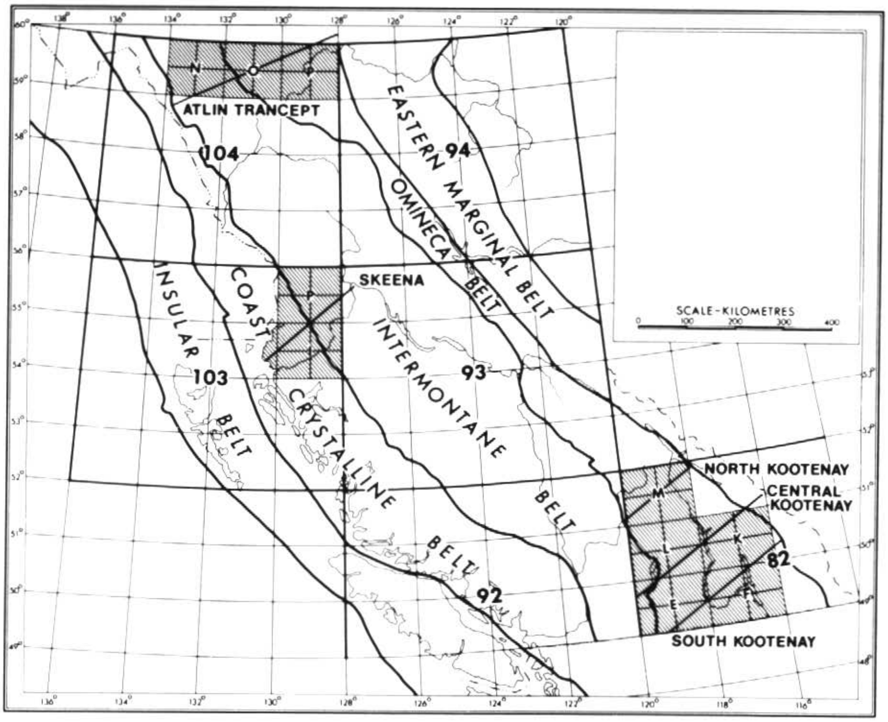

Figure 1
Tectonic belts of the Cordillera in British Columbia showing areas with available reconnaissance geochemical data (lined), the NTS grid and section lines.

report is based on regional geochemical data now available in British Columbia.

As a result of the Federal/Provincial Uranium Reconnaissance Program (Darnley, 1976) and its successor, the Regional Geochemical Surveys of the B.C. Ministry of Energy, Mines and Petroleum Resources, reconnaissance silt and water geochemical data are available for a considerable portion of British Columbia. These surveys are carried out to a common standard. Samples are collected on secondary and tertiary stream drainage with a density of one sample per 13 km^2; one kg of active silt and 0.25 l of water are collected at each site. Collection and analysis are carried out with rigorous control. Silts are analysed for 11 to 13 metals including Zn, Cu, Pb, Ni, Co, Ag, Mn, Fe, As, Mo, W, Hg, and U, and waters are analysed for F, U, and pH. The various surveys have collected about 15,300 silt samples (Sutherland Brown *et al.*, 1979) and have covered some 165,000 km^2 to date or about 22 per cent of cordilleran British Columbia.

The areas surveyed for which data have been released (up to April 1980) are shown in Figure 1. The coverage, though extensive in area, does not include significant parts of the Rocky Mountain Belt and includes none of the Insular Belt. However, the three central belts are adequately covered and because these include major parts of both the "eugeosyncline and miogeocline" the results are useful for metallogenic thinking.

A tenet of exploration geochemistry is that a properly collected stream sediment sample represents the best composite of materials from the catchment area upstream from the sample site (Levinson, 1974, p. 16). On this basis the sampling of large areas on a scale of 1 per 13 km can properly portray regional geochemical gradients. Reconnaissance surveys give emphasis to geochemical provinces rather than specific metal sources, hence their importance in metallogeny.

In this study I wished to examine the data with a window large enough that each cell included a broad spectrum of common rock types but small enough for each to be a discrete district with characteristic geology. To this end a cell was chosen to be a 1 NTS sheet (quadrant) with an average of about 300 sample sites. These quadrants vary slightly in size from south to north (i.e., 3248 * 342 km) but are easily retrievable in a computer program and size is not a critical variable. Rock types that are present in most quadrants surveyed, and hence have adequate representation, include acid granitic, intermediate volcanic and fine-grained sedimentary rocks. Less adequate are till, gneiss and limestone. These types are identified as the bedrock at each sample site thus were easy to retrieve. Among other things the program listed for each rock type were the total population in the quadrant, the arithmetic mean, and standard deviation of all analysed metals. The age or affiliation of these standard types was not considered. The metals that seemed most useful and appear in the following diagrams are Zn, Cu, Ni, Mo, Pb, and U. Because Hg and As were not analysed in all surveys, they are not included in the diagrams.

The geochemical data was plotted on graphs representing sections normal to the regional strike (Fig. 1). The arithmetic mean and standard deviation for each metal from each bedrock type in each quadrant were plotted as if they were collected at the centre of the quadrant and projected onto the plane of section. Sections were constructed for the Atlin transept, the Western Skeena Arch and three for the Kootenay district. Twenty-three sections resulted. Examples are shown for granitic rocks in the Central Kootenay area (Fig. 2) and the West Skeena Arch (Fig. 3).

The resulting sections were then compiled into uniform composite sections having average widths for the tectonic belts in B.C. The composite sections were plotted for the selected rock types showing mean abudance for the selected six metals (Figs. 4-7) and also for each metal showing the distribution of mean abundance for each rock type (Figs. 8-10).

Figures 4 to 7 are compiled respectively for granitic, volcanic, fine-grained sedimentary rocks and for till. The striking feature of all of them is the compatibility and continuity of curves from one section to another. This indicates that they fairly represent transverse trends in metal abundance across the Cordillera. It also illustrates how these trace metal abudances of standard rock types differ in a systematic manner across the province. However, the relative abundances of one metal to another display a general relationship grossly similar to their crustal abundances.

The composite sections (Figs. 8-10) with the same data plotted to compare abundances of each metal for the various rock types are more interesting. The similarity of the curves of any metal for

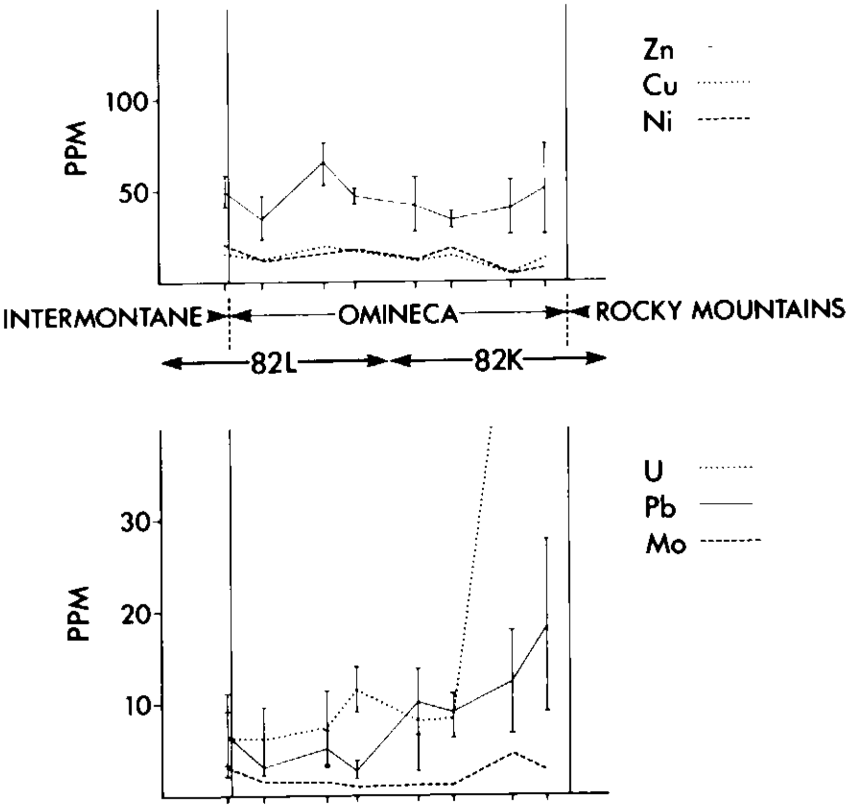

Figure 2

Mean metal abundances in silts per NTS quadrant for granitic rock areas, central Kootenay section.

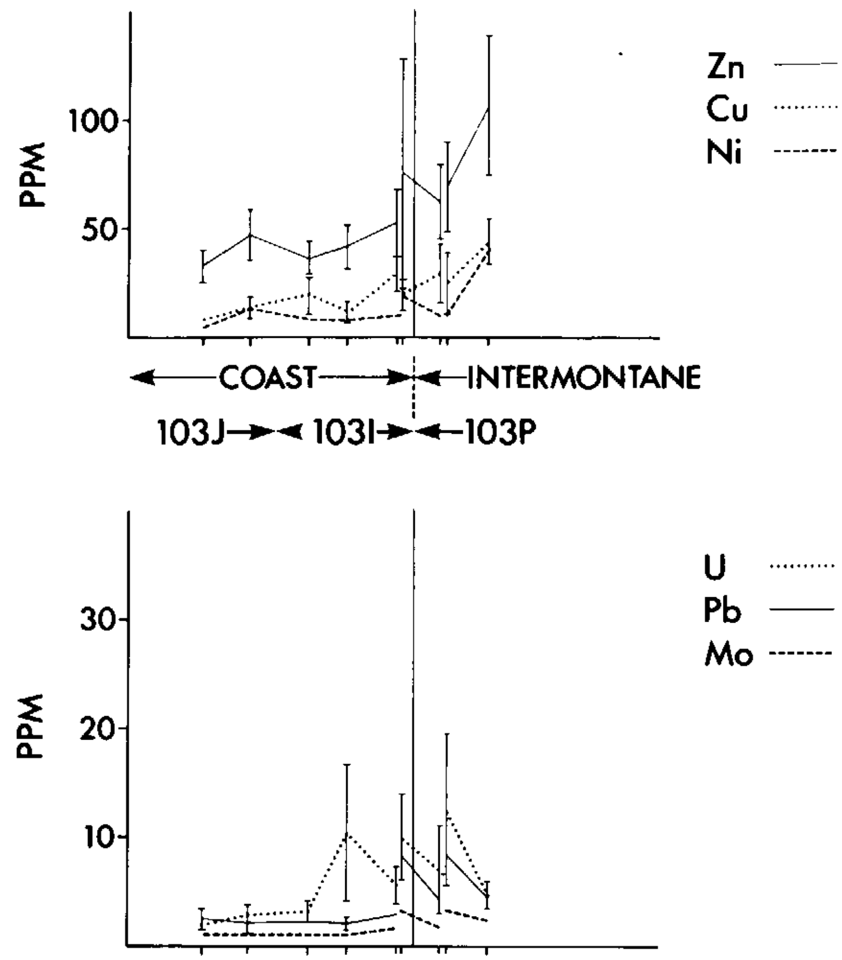

Figure 3
Mean metal abundances in silts per NTS quadrant for granitic rock areas, west Skeena Arch.

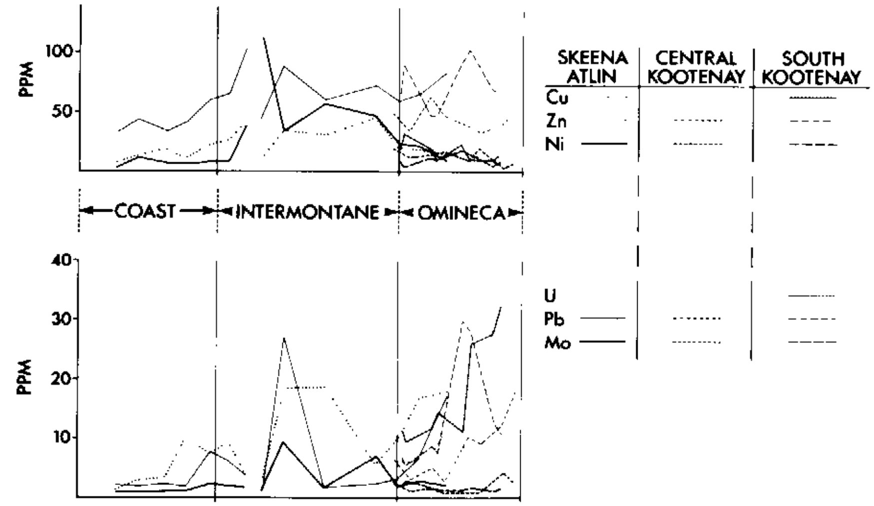

Figure 4
Composite proportional section of mean metal abundance in silts for granitic rock areas.

the general rock types is remarkable and the overall closeness of one to another is striking. The latter correlation is strongest for Cu and Mo; slightly less so for Pb and U and least but still significant, for Ni and Zn. As would be expected, U is almost universally highest in areas with granitic bedrock, Zn in areas of fine-grained sedimentary rocks and Ni in areas of intermediate volcanic rocks. The other metals are less consistent or only marginally higher in one type than another. It is evident that the samples from till localities represent mixed provenance because of their average values. Samples from gneiss localities are confined to the crystalline belts and incomplete but fairly consistently display the lowest values. Mercury values are available in less than half the map areas so are not plotted on these figures. In areas where analyses do exist patterns are similar to those of Pb. The W pattern was similar to that of Mo.

Generalized Curves

As all the curves for the individual metals for the various rock types are so similar in shape they can readily be averaged and smoothed to give the general gradients shown in Figure 11. This emphasizes the similarity of the Cu and Zn curves although that of Cu is of a more subdued nature; both rise to a smooth culmination in the Intermontane Belt. Molybdenum is most abundant in the Intermontane Belt but has its culmination more easterly than Cu or Zn. Similarly Pb and U rise to local highs in the Intermontane Belt but unlike Cu, Zn and Mo, they have a steep upward gradient through the Omineca Belt towards the craton. Nickel abundance is more erratic but it rises to a broad multiple high in the Intermontane Belt. In general the Coast Crystalline Belt appears to be depleted in metals compared to the other belts. Perhaps this is due to the dominance of major plutons at the present level of erosion.

Conclusions

These curves of regional geochemical abundances can be compared to graphs of relative density of mineral occurrences (Fig. 12) in B.C. (Sinclair *et al.*, 1978) derived from a statistical study of some 7,000 mineral showings in the MINDEP file (Computerized Mineral deposit file, Department of Geological Sciences, University of British Columbia). The overall shape for geochemical abundance and relative density of showings is similar. It is virtually the same for Cu, Mo, Pb and U and similar for Zn and Ni. The earlier study also showed that

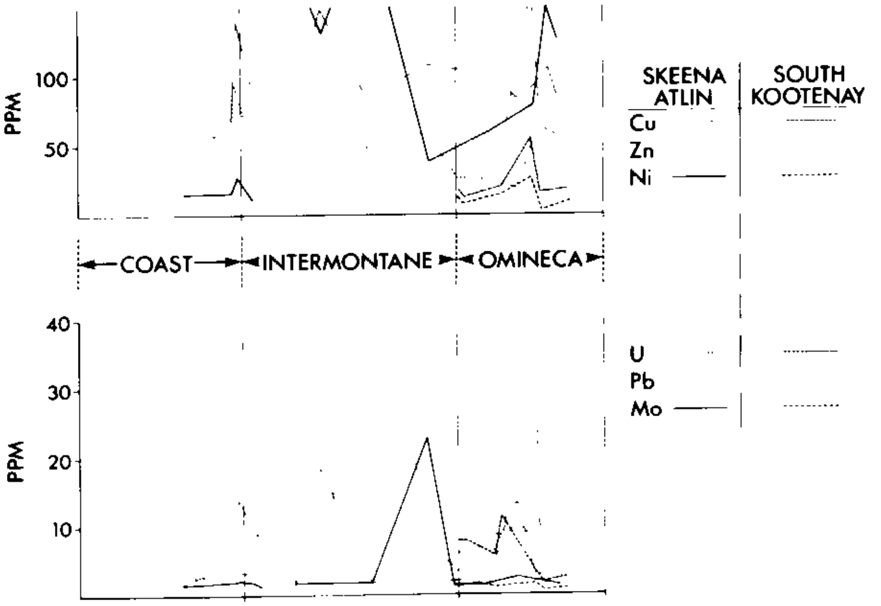

Figure 5
Composite proportional section of mean metal abundance in silts for volcanic rock areas.

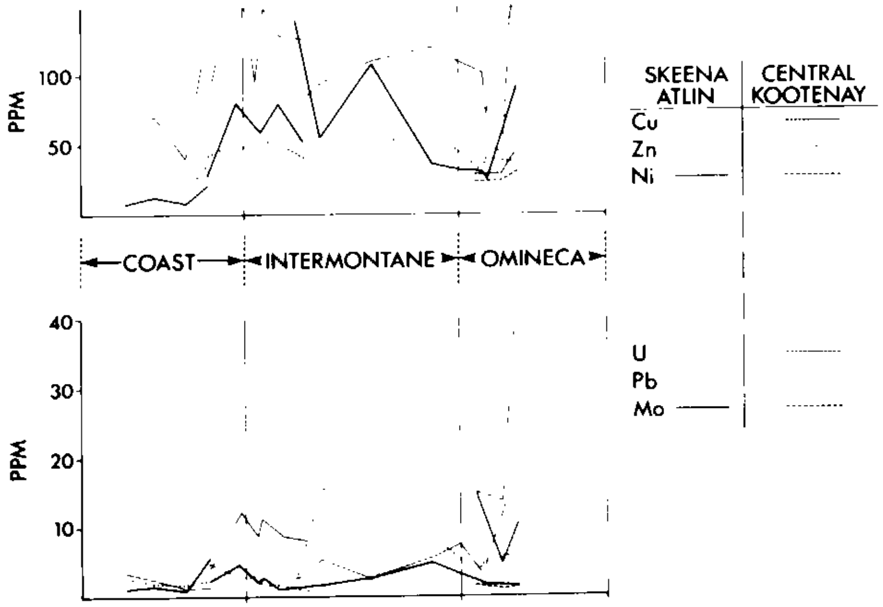

Figure 6
Composite proportional section of mean metal abundance in silts for fine-grained sedimentary rock areas.

the distribution of mine production was similar. We concluded, on the basis of less rigorous geochemical data that there was a causal relationship between high metal background, the distribution of mineral showings of all sorts and the distribution of major mineral deposits. The distribution was also compared with crustal abundances and the ratio of concentration of metals shown in Table I. In general the metals with the lowest concentration ratios are characteristic of the Insular Belt whereas those with higher ratios occur in more easterly belts.

These empirical relationships had led to speculation (Sutherland Brown, 1974) that an understanding of metallogenic processes in the Cordillera could be obtained by consideration of Taylor's diagram (1964). This diagram of ionic radius plotted against ionic charge for lithophile and some siderophile elements shows that there is an orderly arrangement of depletion and enrichment in the crust of these elements in relation to terrestrial abundance, governed principally by ionic size but also by valency. Taylor (1964) concluded that there was a strong upward fractionation of elements unable to enter into 6-fold coordination with oxygen in closely packed structures. The elements Mn, Fe, Cu, Ni, Mg, and Cr are retained in major minerals in the mantle and consequently are depleted in the crust. Elements of too large ionic size or of valency unsuitable for 6-fold coordination are strongly concentrated in the crust, approximately in proportion to their differences in size and valency. Sutherland Brown (1974) plotted the common ore metals on Taylor's diagram (Fig. 13). Although most are largely chalcophile or siderophile and not commonly ionically bonded it does not appear to be critical because the resulting pattern is compatible with that found by Taylor. However, more important to this discussion, the pattern is virtually the same as that for metal abundance and the distribution of mineral deposits in the Canadian Cordillera. Elements showing depletion or only slight enrichment in relation to earth abundances are dominant in the Insular Belt. This belt consists of a large proportion of the most 'primitive' crustal materials in the Cordillera in the sense that it is composed of rocks closest in composition to mantle rocks. In contrast, elements showing the highest enrichment in the crust are those characteristic of the deposits of the Omineca Belt, the tectonic belt most highly evolved by crustal processes. The belts between the Insular and Omineca occupy sequential positions in relation to metal characteristics and space. It should be noted that the

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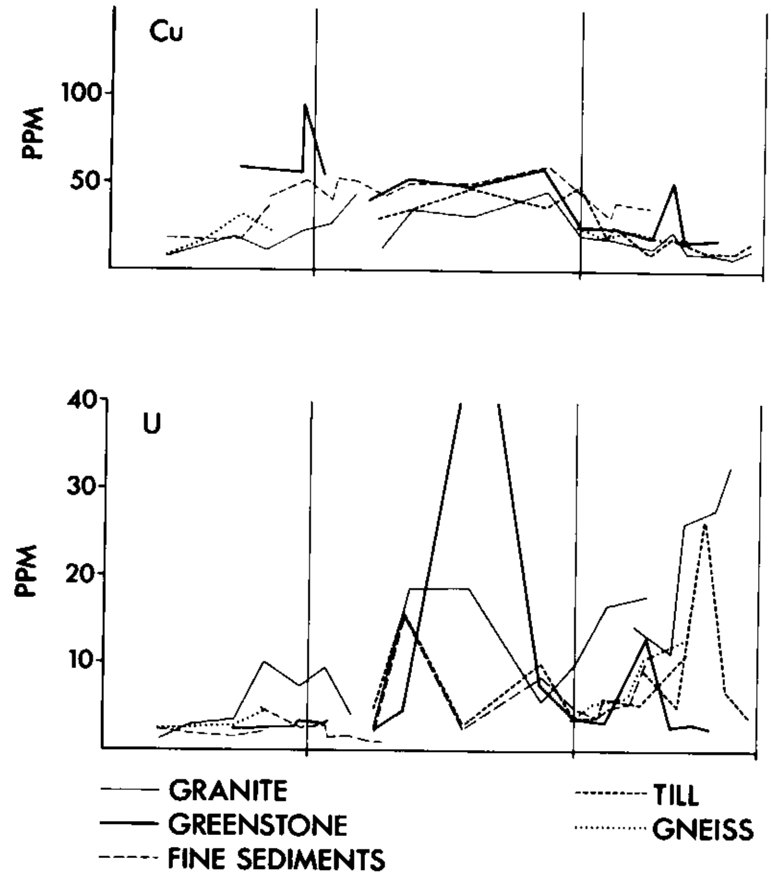


Figure 8
Composite proportional section of copper and uranium abundance for all rock types across the central three tectonic belts.

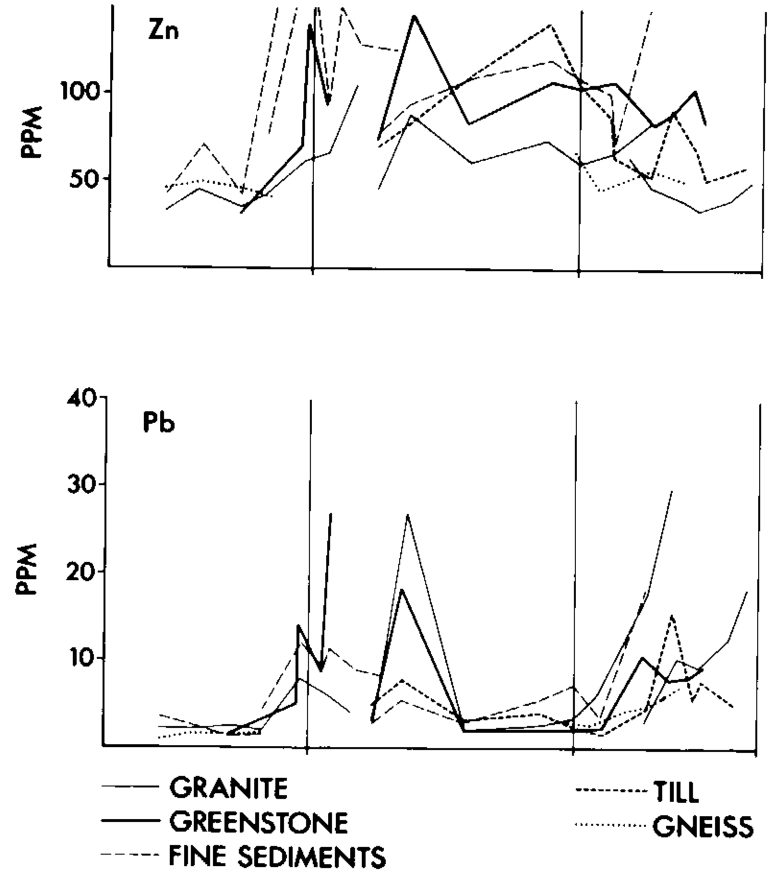


Figure 9
Composite proportional section of zinc and lead abundance for all rock types across the central three tectonic belts.

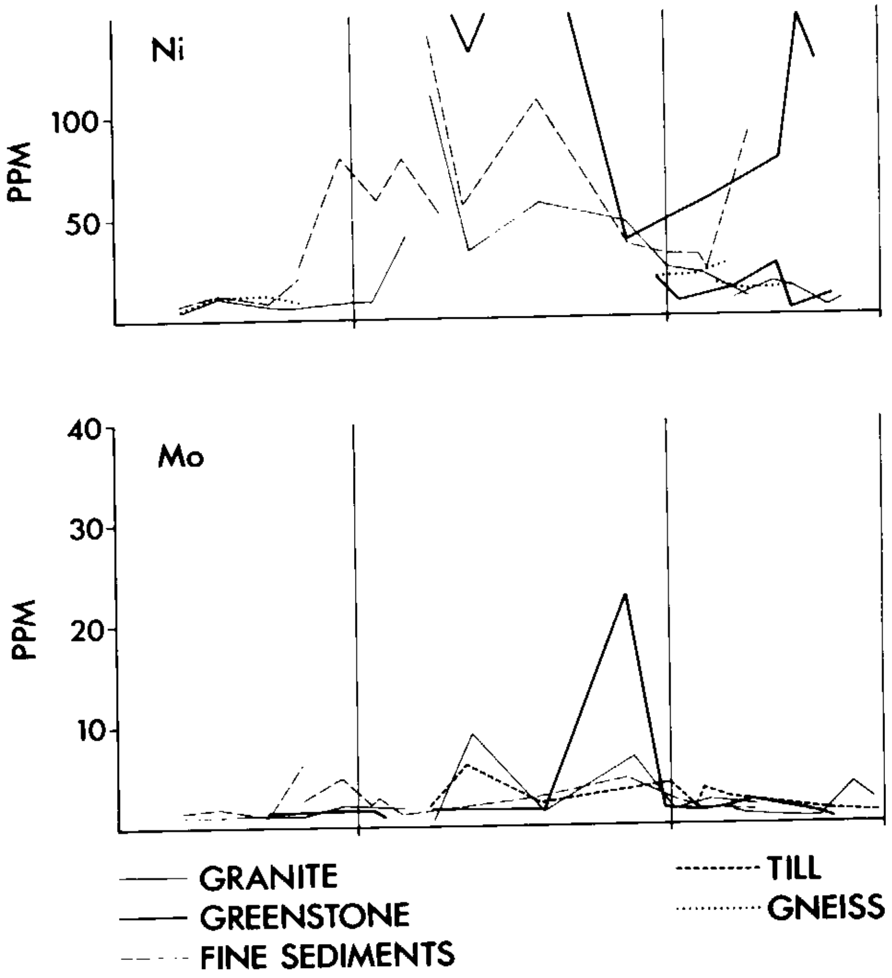


Figure 10
Composite proportional section of nickel and molybdenum abundance for all rock types across the central three tectonic belts.

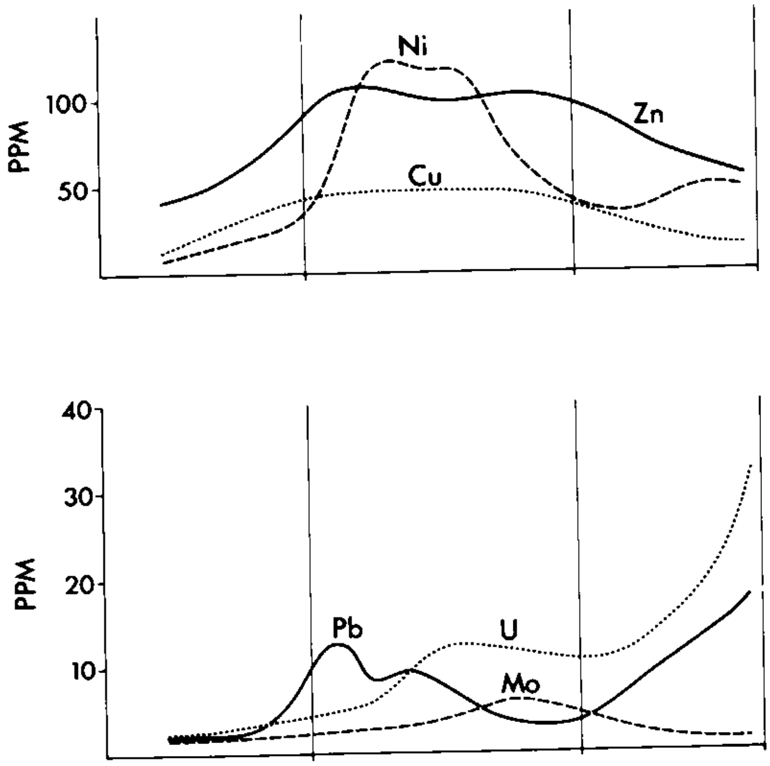
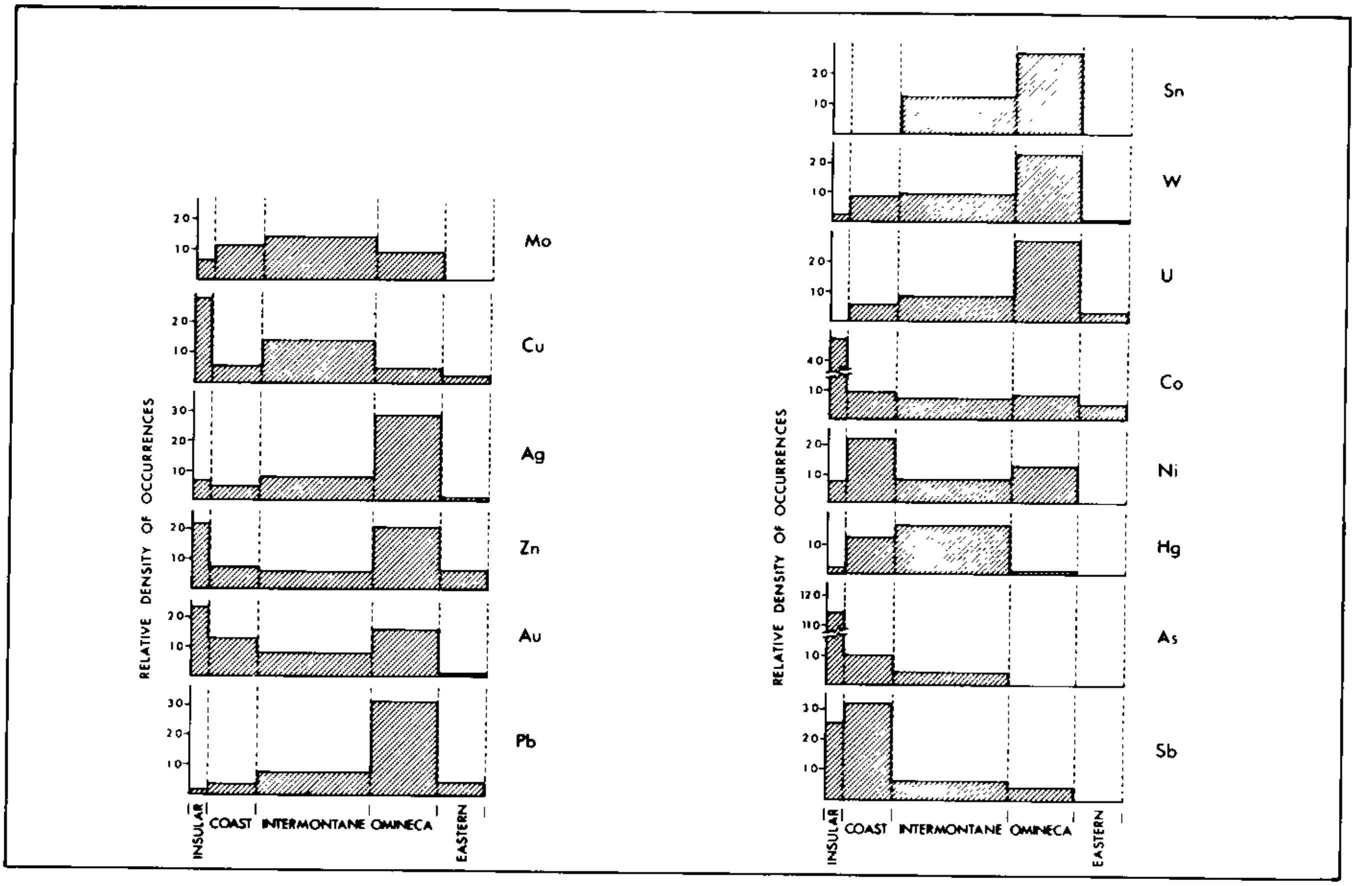


Figure 11
Generalized curves of metal abundance for all rock types across the central three tectonic belts.



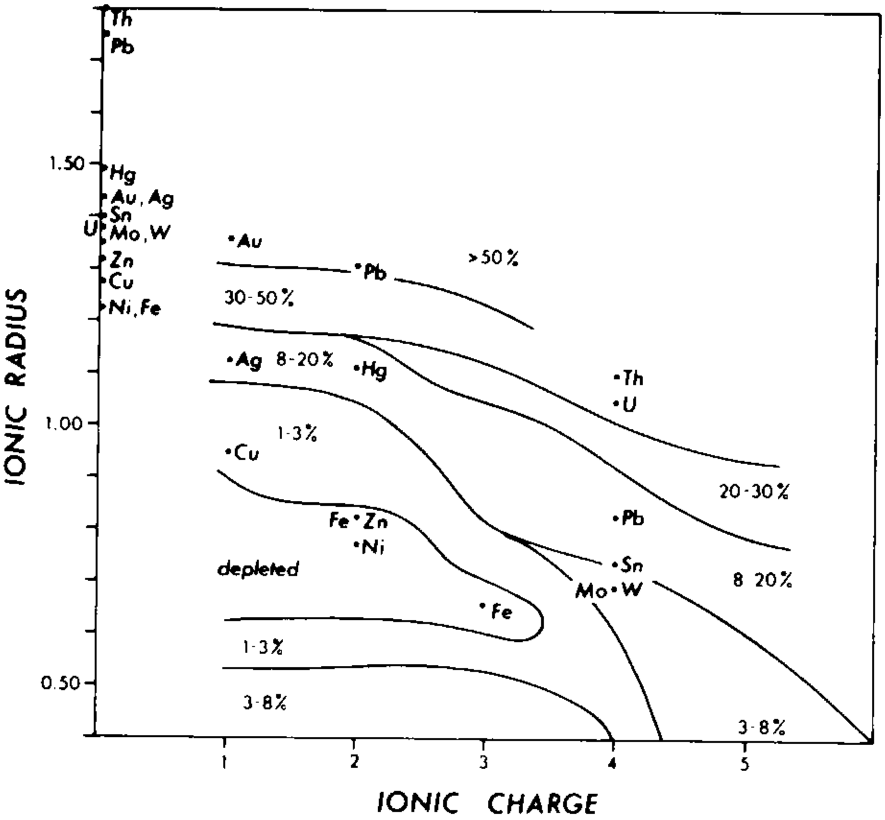


Figure 12

Bar graph showing relative density of mineral occurrences for the major tectonic belts. Bar widths are proportioned to surface area. In all cases a relative density of 1.0 equals average for Cordilleran British Columbia (from Sinclair et al., 1978).

Figure 13

Taylor's diagram, modified for metals, indicating the relationship between depletion or percentage enrichment in the crust relative to earth abundances and ionic radius and charge (after Sutherland Brown, 1974).

Table I. *Crustal Abundance and Ratio of Concentration of Metals*

	Crustal Abundance in ppm	Approximate Ore Grade in ppm	Ratio of Concentration
Iron	50,000	500,000	10
Cobalt	25	18,000	72
Copper	55	5,000	90
Nickel	75	7,500	95
Uranium	2.7	500	185
Molybdenum	1.5	1,500	1,000
Tungsten	1.5	2,000	1,333
Zinc	70	100,000	1,425
Silver	0.07	200	2,850
Gold (lode)	0.005	16	3,200
Lead	12.5	60,000	4,800
Mercury	0.08	2,500	30,000

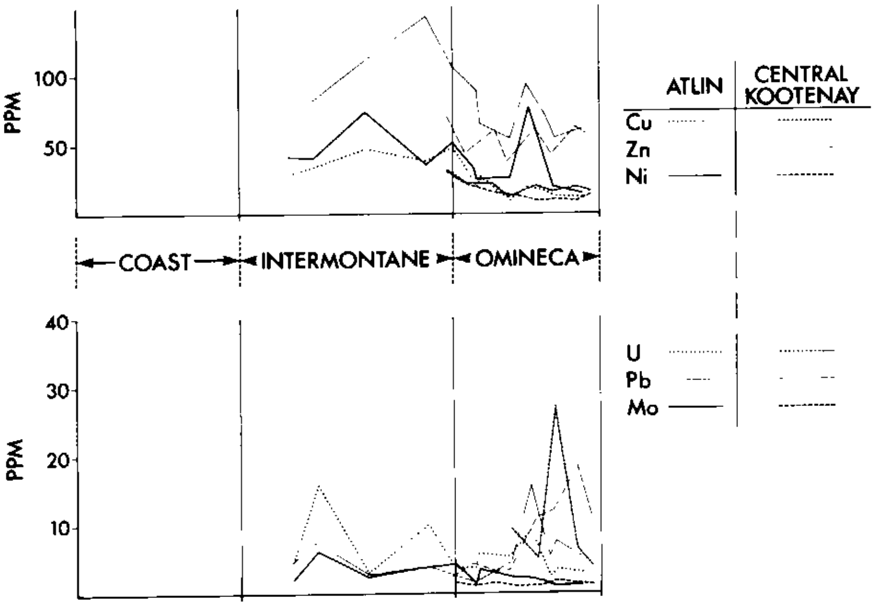


Figure 7
Composite proportional section of mean metal abundance in silts for till covered areas.

order listed on the ordinate for atomic radii of the metals is substantially similar to both the order in the table of the ratio concentrations and to the sequence from west to east of culminating metal abundances shown in Figure II.

Various interpretations are possible to explain this systematic arrangement, but an obvious one is that it results in part from the accretion of Cordilleran crust to a continental margin to the east. Material is cycled from the mantle to the western periphery by one manner or another and then successively reworked and concentrated as it is incorporated. Areas of pre-existing or older continental crust show concentrations of large ions, dilution of medium sized ions, and more selectively enriched domains related to specific lithologies.

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